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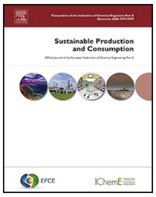

Research article

Using contests to design emission tax mechanisms

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ABSTRACT

In this paper, we propose three novel emissions tax mechanisms aimed at minimizing economic losses, incentivizing green R&D investments and reducing environmental emissions in a sustainable manner. We merge industrial organization theory and contests theory into a new model to explore the implication of three contest mechanisms of endogenous emissions taxation (i.e., *the output contest mechanism, the green R&D investment contest mechanism,* and *the net emission contest mechanism*), in which firms compete in terms of production and green R&D investments in order to pay less taxes. In this context, in order to identify the optimal mechanism, we compare several economic performance indicators like carbon neutrality, total production, emission level, green R&D investment, consumer and producer surplus, welfare, and value added to society. We find that the *net emission contest mechanism* is the best to achieve carbon neutrality, maximize green R&D investments and minimize emissions in situations or industries in which the environmental damages are moderate to relatively large. However, in situations or industries in which the environmental damages are relatively small, the *green R&D investment contest mechanism* could be the best.

1. Introduction

Climate change, resulting from the growing concentrations of greenhouse gases (GHGs) in the atmosphere, has been regarded as one of the major challenges in the 21st century (Zhou and Wang, 2016). Governments all over the world are seeking an effective mechanism to minimize air pollution and mitigate climate change. Further, the Covid-19 pandemic has renewed the urgency to shape more resilient societies and to accelerate the fight against climate change with the goal of building a more inclusive and sustainable future (Gillingham et al., 2020; Obergassel et al., 2021; Mofijur et al., 2021). To limit global warming, the Intergovernmental Panel for Climate Change (IPCC) suggests that achieving carbon neutrality by mid-21st century is essential (Huang and Zhai, 2021; Qin et al., 2021). While several countries have announced dates by which they want to achieve carbon neutrality, they are pursuing a range of environmental policy tools to achieve this goal, including regulatory instruments (or “command-and-control”), market-based instruments, negotiated agreements, subsidies, environmental management systems and informational campaigns. However, no instrument can optimally address every environmental challenge (OECD, 2010; Goulder and Parry, 2020).

Environmental issues are inherently controversial because the economies of most countries are highly dependent on fossil fuel and other greenhouse gas-intensive sectors resulting in the often-conflicting goals of environmental protection, economic development and growth (Hu et al., 2014; Wang et al., 2016; Bowen et al., 2017). At the micro level, policies that tackle emission reduction can impose costs on firms, especially for those with high emissions of greenhouse gases, potentially reducing their competitiveness in global markets and pushing prices up. However, if the policies are well-designed, they may encourage green innovation and investments of firm (Pasurka, 2020; Siedschlag and Yan, 2021; Dechezleprêtre and Sato, 2020). To illustrate, implementing an emissions tax on steel production firms stimulates the firms in this industry to apply and invest in carbon capture and storage technologies to pay less emission taxes. Taken together, market-based policies that incorporate design features to mitigate the exercise of market power and emissions leakage can deliver welfare gains (Fowlie et al., 2016). In this context, it is critical to design sustainable and effective emission taxation mechanisms that fully internalize their complex economic effects and accelerate the transition to carbon neutrality.

To achieve the above stated objectives this paper proposes a novel type of emissions tax mechanisms that aim at having minimum impact on production and economic growth, while maximizing the green R&D investments that are crucial in the transition towards environmental

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Nomenclature

i The index i refers to firm $i = 1$ and $i = 2$
k The index k refers to mechanisms $k = x$, $k = z$ and $k = m$
a This parameter captures the market size
d This parameter captures the severity/intensity/level of pollution damage
γ This parameter captures the cost of green R&D investment
n The number of firms
t The emission tax rate
x Firm's output
p Product market price
z Firm's green R&D investment
e Firm's net emissions
c The unit production cost
π Firm's profits
D Total environmental damages
E Firm's aggregate net emissions
CS Consumer surplus
PS Producer surplus
SW Social welfare
R The total revenue from products sale
I The sum of firms' green R&D investments
Y The created value

neutrality in a sustainable manner. In this context, the emission tax rate paid by each firm is going to depends on each firm "green performance" relative to the rival firms as follows:

1. *Output contest mechanism*: the taxation contest is based on the firms' emission output, in which firms pay proportionally less emission taxes when they produce fewer emissions relative to competitors.
2. *Green R&D investment contest mechanism*: the taxation contest is based on the firms' green R&D investments, in which firms pay proportionally less emission taxes as they commit to more green R&D investments relative to competitors.
3. *Net emission contest mechanism*: the taxation contest is based on the firms' net emission, in which firms pay proportionally less emission taxes as less pollution they generate and more green R&D investments they execute relative to competitors.

Therefore, each firm emissions tax burden is endogenous, and can be reduced, at the expense of the other firms, when the firm decreases its own emissions and increases its green R&D investments relative to other firms. The proposed contest structure aims at incentivizing competition between firms in terms of green R&D investments and lower emissions.

Placing into context, the emission tax acts as an environmental policy. According to United Nation's Framework Convention on Climate Change (UNFCCC, 2015), there are two principal carbon tax approaches, the Fuel Approach (which uses fuels as the tax base and sets the tax rate based on the carbon content of the fuels) and the Emissions Approach (which establishes the tax directly on emissions), usually, governments set a blind tax rate directly according to these two approaches (UN (United Nations), 2021). However, exogenous carbon taxes are less efficient than endogenous taxes in terms of incentivizing firms' green R&D (Lambertini and Tampieri, 2014; Lambertini et al., 2017). However, there are also further challenges in terms of mitigate pollution emissions with minimal impact on production and growth, and simultaneously maintaining the firms' incentives to make green R&D investments and achieve the carbon neutrality targets as quickly as possible. Moreover, in order to be feasible, the emission tax mechanism needs public acceptance, and must be fair and well designed.

Based on the above background and concerns; Firstly, this study seeks to answer the question of how to design an emissions tax mechanism that has less impact on economic growth, incentivises firms' green R&D investments, and achieves carbon neutrality? How to set the tax rate in a fair way, and what should be the tax base? Secondly, how to balance fairness and effectiveness when designing an emission tax mechanism based on the idea of Polluter-Pays-Principle while reducing the negative environmental externalities? Specifically, how does the emission tax mechanism can be proportional in terms of production/pollution and be inversely proportional in terms of green R&D investments relative to competitors. Thirdly, if the emission tax rate is determined by the output and green investment of firms, what impact does the emission tax has on firms' green R&D investment, production, net emissions, producer surplus, consumer surplus and social welfare. Lastly, how do different emission tax mechanisms perform in terms of the firms' green R&D investments, production, net emissions, producer surplus, consumer surplus, social welfare, and created value?

In order to address the above research questions, we build a model that merges industrial organization theory and contests theory. We concentrate on a competitive industry in which each firm offers a homogeneous product and production activities generate pollution. Firms choose their green R&D investments and output simultaneously, and the green R&D investments are directed towards the reduction of emissions. It is important to note that in our approach the emissions tax is endogenous, so that it depends on the firms' behaviors in a competitive way, instead of the usual blind and exogenously set emission taxation. The emission tax base is the sum of all producers' net emissions. In order to complete the analysis, we also consider several extensions of the baseline model.

To the best of our knowledge, this analysis is the first to endogenize the emissions taxation mechanism through a contest that considers the firm's production and green R&D investment decisions in competitive markets. The model and analysis are multi-dimensional, in the sense that take into consideration several aspects of firm performance such as producer surplus, green R&D investments and production, and other aspects that go beyond the simple firm performance such as consumer surplus, social welfare and the created value for the society. Another contribution aspect of the present study is to provide guidance to policy makers and practitioners on how to design and implement optional emission taxation mechanisms not only that are fairer but that also fully internalize their economic effects and that appropriately associates to the level of environmental damages. The literature related to designing emissions taxation mechanisms is limited in this respect, there are no models connecting industrial organization and contest theories to design endogenous and competitive environmental tax mechanisms that address pressing environmental issues. This study fills this gap and opens new avenues of research and thinking in terms of environmental taxation.

In addition to propose a new kind of emission taxation mechanisms, we also analyze and compare three of those mechanisms (i.e., the output contest mechanism, the green R&D investment contest mechanism, and the net emission contest mechanism). Regarding this analysis, our main results are summarized in Fig. 1. When the environmental damages are low, the green R&D investment contest mechanism is the best in terms of firms' production, green R&D investments, net emissions, consumer surplus and the created value, while the net emission contest mechanism is the first best in terms of producer surplus. However, in situations in which the environmental damages are moderate to high, the output contest mechanism is the best but only in terms of production, while the net emission contest mechanism is the best the other indicators, including green R&D investments, net emissions, producer surplus, consumer surplus, social welfare and the created value.

Further, by extending the model to the case of n firms, we found that market competition becomes more intense; consequently, the more efficient the mechanisms become to achieve carbon neutrality. In the case of different production cost, the difference in the cost has distinct effects

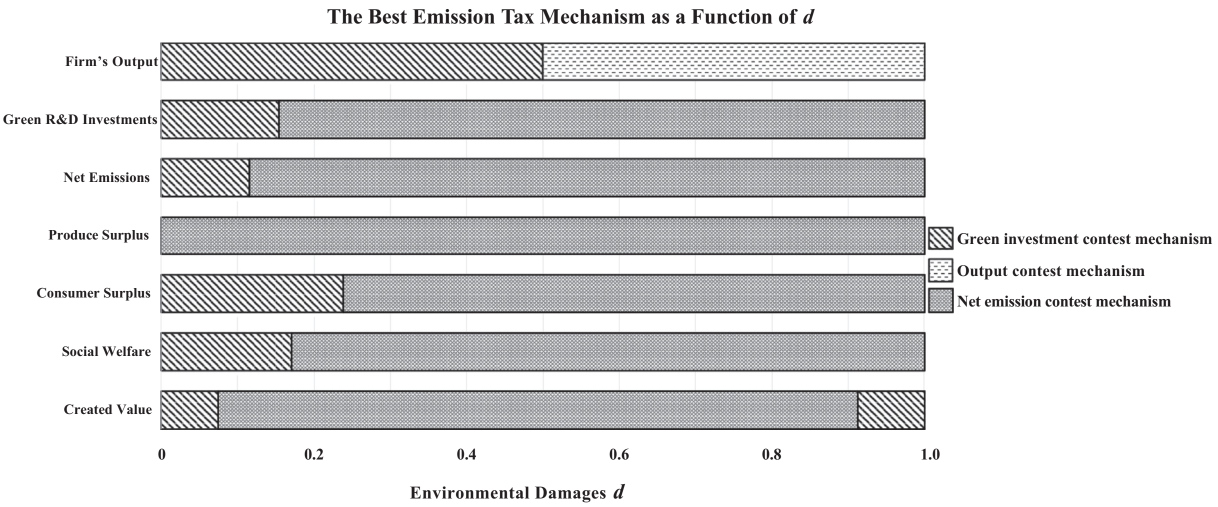

Fig. 1. The best emission tax mechanism for different indicators and varying environmental damages.

on production and green R&D investment of the high-cost firms and low-cost firms, but in general the choice of the best mechanism is not affected. Similarly, in most cases, the choice of the optimal mechanism is not affected when changing the green R&D efficiency parameter. However, the conditions under which the mechanism becomes the best in terms of various indicators will change. Therefore, among the three mechanisms, the net emission contest mechanism is still the most efficient way to achieve carbon neutrality. It is the optimal choice to reduce pollutant emissions, to achieve maximum social welfare and GDP for a relatively large range of environmental damage levels. Besides, the net emission contest mechanism can better help companies overcome capacity constraints and investment constraints.

In a nutshell, the study provides an efficient and intuitive solution to the problem of the emissions taxation by making firms compete for paying less taxes. The proposed solution is fair and implementable. The proposed mechanisms incentivize green R&D investments by firms and accelerate carbon neutrality while minimizing the impact on firms' production and economic growth. Altogether, from the analyzed mechanisms, we recommend the net emission contest mechanism as the optimal mechanism for achieving carbon neutrality and maximizing welfare, among other crucial indicators. Moreover, the proposed type of emission tax mechanisms based on contests focus on present and future production and investment decisions, and not past decision. This is a crucial aspect which makes the proposed approach in this paper more like to be consensual and obtain agreement in the climate negotiation between countries between world powers like the US, China, EU and India. This consensual/agreement issue was one of our main concerns and motivations when we build this new model and approach to emissions taxation. Practical implementation was also one of our main concerns.

The remainder of this paper is organized as follows. Section 2 presents a review of the literature. Section 3 introduces the three emissions tax mechanisms and develops the model used to evaluate them. Section 4 reports the main results of our analysis. Section 5 discusses some extension cases. Section 6 discusses these results. Section 7 concludes and proposes future research objectives. The mathematical proofs can be found in the Appendix.

2. Literature review

The related literature of this study mainly focuses in two areas: the adoption of emission tax among environmental policies and the design of emission tax mechanisms. In the following section, we review the works associated with each stream and analyze how the present study differs from the existing literature.

2.1. The adoption of environmental policies

Environmental issues, such as global warming, climate change, and environmental degradation, have attracted widespread attention of policymakers and scholars, which has resulted in an increase in the environmental policies literature (Wu et al., 2021). The principal goal of environmental policies is to improve environmental outcomes that are driven by the pursuit of objectives of broader wellbeing and sustainable growth (Kozluk and Zipperer, 2015). Environmental policy, green innovation, and renewable energy R&D helps control carbon emissions (Qin et al., 2021). Some stringent environmental policies significantly help curb the CO_2 emission but they can be unduly burdensome to economic performance (Ahmed, 2020; Zhao et al., 2020; Wang and Zhang, 2022). For instance, the command-and-control regulation (CCR) is accused of being costly, inefficient, inflexible and stifling innovations (Pasurka, 2020; Lei et al., 2022). Consequently, environmental self-regulation is a priority in the policy agenda of most developed countries. Even the ideal form of environmental self-regulation is not a viable substitute for effective governance regimes for environmental protection (Sinclair, 1997). In this context, studies such as in Stavins (2003) propose "market-based instruments (MBIs) are instruments or regulations that encourage behavior through market signals rather than through explicit directives". Moreover, some other studies have demonstrated that MBIs are superior to command-and-control approaches (González-Eguino, 2011; Aldy and Stavins, 2012; Wu et al., 2021). In this paper, we go a step further by proposing a MBI taxation mechanism in which firms compete in terms of green R&D investments and emission reductions to pay less taxes.

Enacting market-based environmental regulations, such as environmental taxation or tradable emissions permits, has become a relatively efficient policy tool to control pollution (Pasurka, 2020; Hasan et al., 2021). Both emissions taxation and the cap-and-trade systems can satisfactorily achieve emissions reductions (Haites, 2018; Hasan et al., 2021). However, the allocation of emission allowances is a complex puzzle for any cap-and-trade system employed by environmental agencies (Du et al., 2020). In particular, the optimal weighting in the tradeoff between fairness and efficiency of emission permits is a controversial issue. Moreover, coordinating these solutions on a global scale is an extremely costly and difficult proposition (Du et al., 2020; Zhou and Wang, 2016).

On the other hand, Glazyrina et al. (2006) emphasize that environmental taxation can be considered as a form of Polluter-Pays-Principle (PPP) implementation. PPP means that the polluter should bear the “costs of pollution prevention and control measures” under the OECD recommendations, which is a way of “internalizing the externality”. Shahzad et al. (2021) argue that environmental-related taxes are important factors for renewable energy promotion, investment and incentives that can reduce CO_2 emissions. Environmental tax theory suggests that emission-based Pigouvian taxes rather than other forms of taxation should be pursued for pollution abatement if efficiency gains are the aim (Metcalf, 2021). Nie et al. (2022) argue both carbon and emission taxes reduce energy inputs, outputs, profits, and emission, these two types of taxes affect identically under optimal taxes. For these reasons, we focus on emissions tax in this paper. Emissions taxation incentivizes innovation by targeting the environmentally harmful production activities, which is determinant for the firms' green R&D investments (Requate, 2005; Rubashkina et al., 2015; Zhong and Peng, 2022).

2.2. The design of emission tax mechanism

It is crucial for governments to design and implement optimal tax mechanisms that improve social welfare, because the optimal tax plays an exceedingly important role in the economy (Nie and Wang, 2019; Yang et al., 2020; Nie et al., 2022). To the best of our knowledge, there is limited literature on the design of emission tax mechanisms that consider the balance between fairness and effectiveness. Buchanan (1969) argues that a first-best policy designed that completely internalize external damages should be used only in “situations of competition,” as concentrated industries are already producing below the socially-optimal level, the loss of consumer and producer surplus induced by further restricting output can overwhelm the gains from emissions mitigation. Baranzini et al. (2000) believe that it is necessary to further develop carbon taxes or design new type of carbon taxes in order to gain public support. Arıkan and Kumbaroğlu (2001) present a CES form modelling that attempts to endogenize emission tax within an optimization framework. Kim (2011) uses an endogenous growth model to explore the design of a carbon tax scheme for green growth in Korea, focusing on issues like the tax base, tax rates, and the use of the revenues. Moreover, Annicchiarico and Di Dio (2015) point out that the problem of optimal design of environmental policies can be analyzed from the perspective of social welfare maximization by introducing the Ramsey optimal policy approach in a dynamic stochastic general equilibrium framework. Zhan et al. (2019) apply a dual-oligopoly model to design a tax mechanism in which the government collects taxes from firms based on their carbon emissions and the firms can recycle waste products from consumers to reduce production costs and carbon emission taxes.

Yet, the two principal carbon tax approaches, the Fuel Approach and the Emissions Approach, are exogenous environmental-related taxes and the tax rate are often designed and set by the government. For instance, in 2021 Argentina applies an exogenous carbon tax of US$ 65.54 t/CO_2e (UN (United Nations), 2021; Metcalf, 2021; Partnership for Market Readiness, 2017). Setting emission tax rate is an essential element in the policy design of an emission tax mechanism since it has direct consequences in achieving the environmental objective and affecting corporate profitability, the economy and the social welfare (Ebert and Von Dem Hagen, 1998). Theoretically, a emission tax should be set at the marginal social cost of the damage generated (this is known as the social cost of carbon). Therefore, the optimal tax rate should be such that the marginal benefit of abatement equals to the marginal cost of abatement (Metcalf, 2021). However, as suggested by Metcalf and Weisbach (2009), estimates of such an optimal tax rate vary widely, and the calculations are difficult if the emission tax is set fixed. According to a survey from Intergovernmental Panel on Climate Change (IPCC), such emission tax underestimates the costs of carbon emissions because of the difficulty in quantifying its impact. Alternatively, a sequence of tax rates could be set over time to achieve a given reduction in emissions by some date, which requires significant advances in technology along with strong political will (Metcalf, 2021).

In summary, this paper is closely related to the two streams mentioned above. The first one focus on the choice of emission tax instruments among environmental policies, while the second one emphasizes the effects of emission tax design and its mechanisms on firm's green investments and environment. In light of this information, our study contributes to the growing literature on the design of emissions taxation mechanism. We present a novel approach to emission taxation (that can be even extended to other policy designs like Cap-and-trade systems) through a contest that considers the firm's production and green R&D investment decisions in competitive markets. This paper fills an important gap in the literature and opens new avenues of research and thinking in terms of environmental taxation and policy. Emissions taxation should be determined by firms' competition in terms of green R&D investments and emission reductions in order to pay less emission taxes, rather than exogenously fixed by governments. This competitive mechanism provides the best incentives to green R&D investments and to a faster transition to carbon neutrality.

3. Methods

3.1. The theoretical framework of designing emission taxation mechanisms

We design three tax mechanisms, in which each firm's emission tax rate depends either on its own output, its own green R&D investments, or its own net emissions relative to other firms'.

(i) Mechanism X is a production contest: the emission tax rate t_i^x of firms i is based on its production relative to the other firms'. As shown in Fig. 2, a reduction in the emission tax rate is achieved by reducing in production according to the following contest success function:

$$t_i^x = \frac{x_i}{x_1 + x_2} \tag{1}$$

where $x_i \geq 0$ is the output of firm $i = 1, 2$. More production implies more emissions, therefore, the more tax firms need to pay.

(ii) Mechanism Z is a green R&D contest: the emission tax rate t_i^z of firm i is based on its green R&D investments relative to other firms' investments. As shown in Fig. 3, a reduction in the emission tax rate is achieved by investing more in green R&D according to the following contest success function:

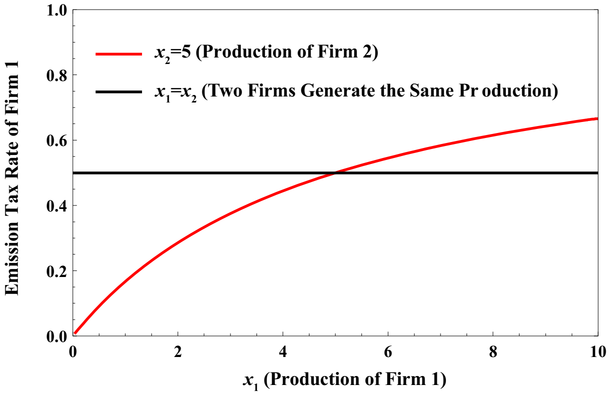

Fig. 2. Mechanism X.
Note: The emission tax rate of firm 1 increases with an increase in the production of firm 1.

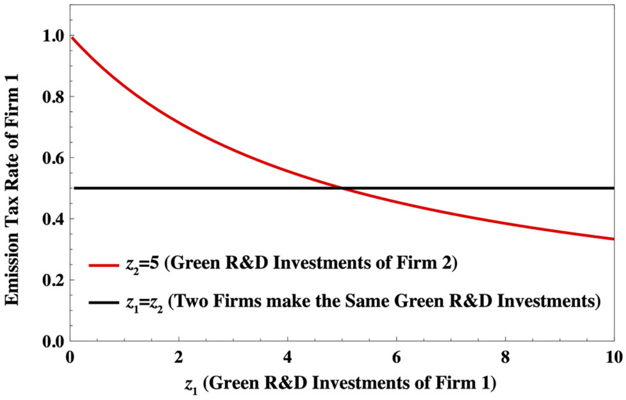

Fig. 3. Mechanism Z.
Note: The emission tax rate of firm 1 decreases with an increase in the green R&D investments of firm 1.

$$t_i^z = \begin{cases} \dfrac{z_{-i}}{z_1 + z_2} & x_i \geq z_i \\ \dfrac{z_i}{z_1 + z_2} & x_i < z_i \end{cases} \qquad (2)-(3)$$

where $z_i \geq 0$ is the green R&D investment of firm $i = 1, 2$, and z_{-i} denotes the rival firm $-i\,'\,s$ green R&D investment effort. Mechanism Z favors green R&D investment. In the case of $x_i \geq z_i$, the higher green R&D investment a firm engages in, the less emission tax the firm pays. However, In the case that $x_i < z_i$, the emission tax becomes an environmental subsidy because the firm is abating more that polluting, the higher green R&D investment a firm engages in, the more environmental subsidy a firm receives. In this case, the firm has reached carbon neutrality.

(iii) Mechanism M is a net emission contest: the emission tax rate t_i^m of firm i is based on its net emissions relative to other firms' net emissions. As shown in Fig. 4, a reduction in the emission tax rate is achieved by reducing net emissions according to the following contest success function:

$$t_i^m = \frac{e_i}{e_1 + e_2} \qquad (4)$$

where $e_i = x_i - z_i$ is the net emissions of firm $i = 1, 2$. The argument is that mechanism M favors firms with lower net emissions. More net emission implies more emission tax a firm needs to pay if $e_i \geq 0$. However, net emissions will become emission reductions if $e_i < 0$, and the more emission reductions imply more environmental subsidy a firm can obtain. Again, in this case, the firm is in a state of carbon neutrality.

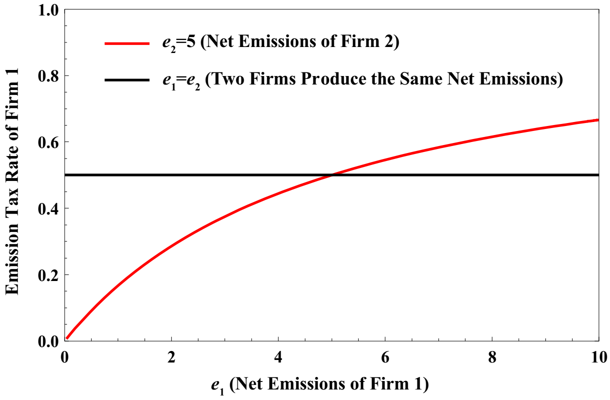

Fig. 4. Mechanism M.
Note: The emission tax rate of firm 1 increases with an increase in the net emissions of firm 1.

Some comments regarding the mechanisms X, Z, and M. Firstly, the outputs of the contest functions are emission tax rate or emission reduction subsidy rate. The inputs of the contest functions are firms' production, green investments and net emissions. Therefore, the emissions tax rate is endogenously determined by firm's production, green R&D investment, or net emissions.

Secondly, using a contest in emissions tax mechanisms weakens the problem of unfairness. This is one criticism of grandfathering scheme, in which some polluters may be rewarded with valuable permits for their previous polluting actions: e.g., heavy polluters typically being awarded more permits than less polluting firms (MacKenzie et al., 2009). A contest emission taxation mechanism appears fairer than alternative mechanisms, since it provides a reward to the firms with investment and efforts towards attaining abatement objectives, than the usual blind tax mechanism that ignore important aspects like green R&D investments.

Thirdly, a contest emission taxation mechanism contains a built-in "punishment" for the firms who are unfriendly to the environment and provides a reward for those firms that perform relatively better. In other words, the contest assigns higher penalties (taxes) to the most environmentally unfriendly firms.

3.2. Model building

We consider a competitive market with profit-maximizing firm 1 and 2. Both firms produce a homogeneous good and face a linear inverse demand function of the type:

$$p = a - (x_1 + x_2)$$

where a is a constant parameter measuring the market size, $x_i \geq 0$ is the output of firm $i = 1, 2$, and $p \geq 0$ is the market price. Production generates pollution and the emission per output ratio is assumed equal to 1. Without loss of generality, we make the common standard assumption that there are no fixed costs of production and the marginal cost of production is normalized to zero (McDonald and Poyago-Theotoky, 2017).

Emissions are taxed by government according to one of the emission tax mechanisms presented before. In this context, both firms can reduce their emissions by undertaking green R&D investments z_i, for $i = 1, 2$, in order to reduce their tax burden. Thus, by investing an amount $\frac{\gamma z_i^2}{2}$ in green R&D, firms can reduce their emissions by the amount z_i for $i = 1, 2$, where $\gamma > 0$ is a parameter capturing the cost of green R&D investment (or the extent of the decreasing returns in green R&D investments). Note that the cost function of green R&D investment is convex, indicating decreasing returns to scale. It implies that the cost per unit of green investment increases with the emission reduction, the higher emission reduction level requires proportionally higher costs of green R&D investments.

We define firm's net emissions as before:

$$e_i = x_i - z_i \qquad (5)$$

for $i = 1, 2$. We allow for $e_i < 0$, which corresponds to the carbon neutrality or negative emission case.

We define total environmental damages as:

$$D = d\,E \qquad (6)$$

where $E = e_1 + e_2$ is firms' aggregate net emissions, and d is proportional to the marginal damage (it captures the severity/intensity/level of pollution damage) (Poyago-Theotoky, 2007). We consider the market for the product that generates CO_2 emissions could be everything from milk to clothes, cars to microprocessors, and so on. In this context, the parameter d transforms CO_2 into monetary units. In order to keep the analysis as simple as possible, we ignore that CO_2 are stock pollutants, and the uncertainty of green R&D investments are disregarded as well (Golombek and Hoel, 2005). To guarantee positive solutions for the output and profits per firm we assume that $0 < d \leq 1$.

Hence, the profit function of firm i is given by:

$$\pi_i = (a - (x_1 + x_2))x_i - \gamma \frac{{z_i}^2}{2} - t_i^k \, d \, E \tag{7}$$

for $i = 1, 2$, and $k = x, z, m$ refers to mechanism X, Z, and M. Each firm pays emission taxes over the total of all firms' net emissions. Based on the three contest mechanisms, the tax rate is proportional to the firm's production and inversely proportional to firm's green R&D investment relative to all other firms.

In addition, we consider a control benchmark or reference case in which the pollution or environmental damage is neglected by firms; in this case, firms do not pay emission taxes. The benchmark case works as a reference for the regulator/policy maker to evaluate the efficiency of each mechanism in terms of different indicators.

The model shows that there are two kinds of benefits. If a firm affects the total net emissions, e.g., by reducing net emissions E, it benefits everybody, and we call it the common benefit effect. On the other hand, a firm can obtain private benefits by decreasing its own emission tax rate t_i^k, we call it the individual benefit effect. A firm can reduce production and obtain private benefits on tax avoidance as well as common benefits from lower the global net emission, but this firm must bear the loss caused by the decrease in sales. Similarly, a firm can increase green R&D investments and obtain private benefits on tax avoidance as well as common benefits on lower net emissions, but this firm must bear the cost of these green R&D investments.

In the sequel, we examine a one-stage game in which firms simultaneously choose output and green R&D investment to maximize their profits. We solve the following optimization problems:

$$\max_{x_i \geq 0, z_i \geq 0} [\pi_i]$$

for $i = 1, 2$.In partial equilibrium analyses, it is common to use *consumer surplus* as a measure of the consumers' gains from consumption. Such a measure reflects the utility gains from consumption at a given market price as compared with not buying at all. Moreover, the product consumption has a negative environmental externality on consumers, which is reflected by an environmental damage D, given by:

$$CS = \frac{(x_1 + x_2)^2}{2} - D \tag{8}$$

In addition, we define *producer surplus* as the sum of firms' profits:

$$PS = \pi_1 + \pi_2 \tag{9}$$

We define *social welfare* as the sum of consumer surplus and producer surplus, given by:

$$SW = CS + PS \tag{10}$$

We define the *created value Y*, which is the sum of the revenue generated from production and from green R&D investments, given by:

$$Y = R + I = p(x_1 + x_2) + \gamma \frac{{z_1}^2}{2} + \gamma \frac{{z_2}^2}{2} \tag{11}$$

for $i = 1, 2$, where R is total revenue from products sales and I is the sum of both firms' green R&D investments. The objective of Y is to proxy for country-specific variables like GDP, employment, and growth, which are important variables in an environmental taxation analysis.

4. Analysis and results

In this section, the objective is to select an optimal emission tax mechanism by comparing the equilibrium of the firms green R&D investments, production, net emissions, total environmental damages, producer surplus, consumer surplus, social welfare and the created value. The proof and the details of the obtained results are shown in the Appendix.

Proposition 1. (a) *Mechanism X and Z deliver carbon neutrality and negative emission results for* $0.5 \leq d \leq 1$.

(b) *Mechanism M delivers carbon neutrality and negative emission results for* $0.25 \leq d \leq 1$.

Proposition 1 states that firms can achieve carbon neutrality by coordinating their production and investment behaviors under mechanisms X, Z, and M. However, the efficiencies of achieving carbon neutrality under the three mechanisms are different.

When environmental damage d is relatively low, the emission tax burden borne by firms is relatively low. Consequently, firms do not have incentive to make green R&D investments to offset the emission pollution. Therefore, firms do not reach carbon neutrality under these situations.

In the case where environmental damage is in the interval $0.5 \leq d \leq 1$, mechanism X and Z provide sufficient incentives for firms' green R&D investments to offset the pollution they cause, consequently, in this interval they achieve carbon neutrality and negative emission. While under mechanism M, firms can achieve carbon neutrality and negative emission with lower level of environmental damage, that is $0.25 < 0.5$. To sum up, the lower the cutoff d the better the mechanism, therefore, mechanism M is the first best to achieve carbon neutrality and negative emission. Mechanism M achieves carbon neutrality within a larger range of environmental damage d.

Proposition 2. *The mechanisms that maximize the green R&D investments are in the following descending order:*

(a) $z_z > z_m > z_x$ *for* $0 < d \leq 0.154$.

(b) $z_m > z_z > z_x$ *for* $0.154 < d \leq 1$.

In general, with an increase in the degree of environmental damage, firms have more incentives to engage in green R&D investments as shown in Fig. 5. This positive effect depends on the magnitude of environmental damages, which is related with the environmental cost; high environmental damages imply high costs and therefore higher tax burden. All the three mechanisms provide incentives for firm's green R&D investments, but the amount of incentives to green R&D investment varies under different mechanisms.

When environmental damages are very low ($0 < d \leq 0.154$), mechanism Z provides the greatest incentives for firm's green R&D investments in order to reduce the emissions tax burden. Mechanism M is the second best to incentivize firm's green R&D investments, while mechanism X is the worst (Part (a) of Proposition 2).

Proposition 3. *The mechanisms that maximize the firm's output are in the following descending order:*

(a) $x_z > x_x > x_m$ *for* $0 < d \leq 0.5$.

(b) $x_x > x_z > x_m$ *for* $0.5 < d \leq 1$.

Since product market price is given by $p = a - (x_1 + x_2)$ and the model results are symmetric, we have the following result, which is an immediate implication of Proposition 3 that we would like to stress:

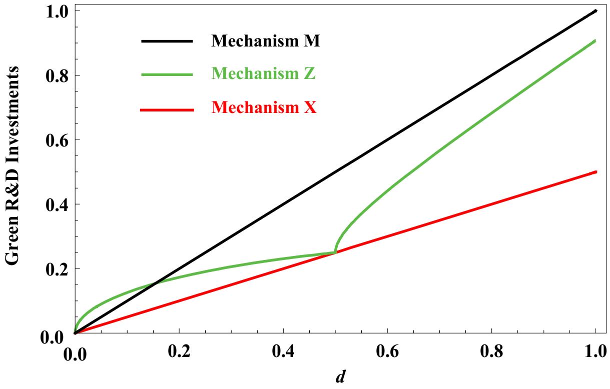

Fig. 5. Green investments under three mechanisms.
Note: (1) The existence of the intersection at point 0.154; (2) The existence of the kink at point 0.5 because at this point mechanism Z changes from a tax system to a subsidy system.

Corollary 1. *The mechanisms that maximize the market price are in the following descending order:*

(a) $p_m > p_x > p_z$ *for* $0 < d \leq 0.5$.
(b) $p_m > p_z > p_x$ *for* $0.5 < d \leq 1$.

When environmental damage is low ($0 < d < 0.5$), firms achieve the maximum output/competition in the product market (or the minimum market price) under mechanism Z as shown in Fig. 6. Since the more environmental R&D investments a firm executes, the more it will be allowed to produce, mechanism Z is preferable because it allows firms to produce more.

As the environmental damages increase, the more intensely firms compete in terms of green R&D investments, the less likely they are to compete in the product market, reducing output and increasing product price. That is why the production under mechanism M is always the lowest, but the price is always the highest.

When environmental damages are high ($0.5 < d < 1$), the emission tax becomes a reward as firms are cleaning more than polluting. In this case, mechanism X achieves the highest production (or the lowest market price). On the other hand, higher levels of green R&D investments under mechanism M tend to reduce emissions taxes of firms, while increasing the marginal cost of green R&D investments, which results in lower production (or higher product price). Note that the maximum production (or the minimum market price) is achieved in the benchmark case (not shown in Proposition 3), since firms do not need to bear the costs of pollution.

Proposition 4. *The mechanisms that minimize the firm's net emissions are in the following ascending order:*

(a) $e_z < e_m < e_x$ *for* $0 < d \leq 0.115$.
(b) $e_m < e_z < e_x$ *for* $0.115 < d \leq 1$.

Since the environmental damage is given by $D = d(e_1 + e_2)$ and the model results are symmetric, we have the following result, which is an immediate implication of Proposition 4 that we would like to stress:

Corollary 2. *The mechanisms that minimize the total environmental damages are in the following ascending:*

(a) $D_z < D_m < D_x$ *for* $0 < d \leq 0.115$.
(b) $D_m < D_z < D_x$ *for* $0.115 < d \leq 1$.

For environmental regulators, net emissions are a prominent indicator when choosing the best scheme among the three mechanisms. In addition, the regulator would like firms to reduce pollution as much/fast as possible. The different mechanisms will reach this objective depending on the level of environmental damage.

From Fig. 7, we can see that when environmental damages are relatively low ($0 < d \leq 0.115$), mechanism Z is the first best option because it provides the greatest incentive for firm's green R&D investments, leading to the lowest net emissions and environmental damages (Part (a) of Proposition 4 and Corollary 2). When environmental damages are moderate ($0.115 < d \leq 0.5$), mechanism M is the first best option. In the beginning, mechanism M enables firms to minimize their net emissions and leads to the lowest environmental damages. When environmental damages are higher, mechanism M provides the highest subsidy to firm's abatements (Part (b) of Proposition 4 and Corollary 2).

To sum up, mechanism Z is the first best to internalize environmental externalities only when environmental damages are very low. Once the environmental damages are significant, mechanism M is the most effective in internalizing the environmental externality.

Proposition 5. *The mechanisms that maximize the producer surplus are in the following descending order:*

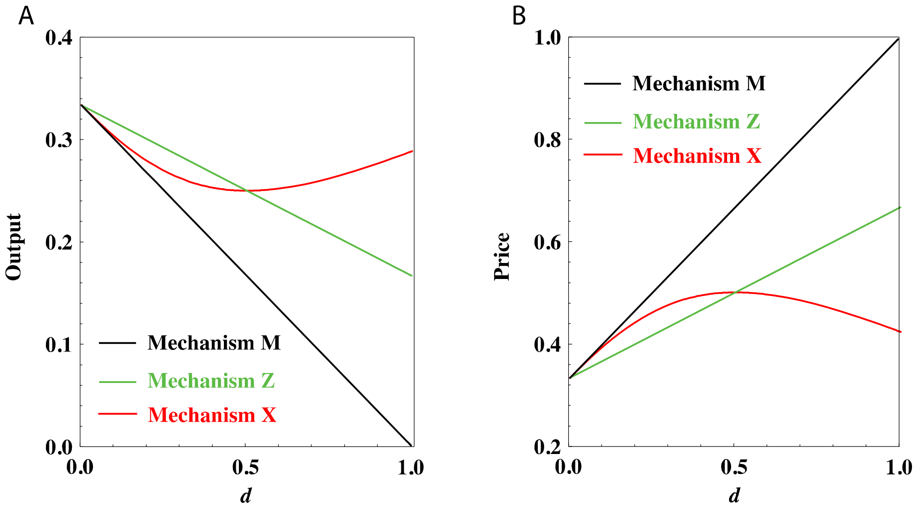

Fig. 6. Output & Price under three mechanisms.
Note: (1) The existence of the kink at point 0.5 because at this point mechanism Z changes from a tax system to a subsidy system.

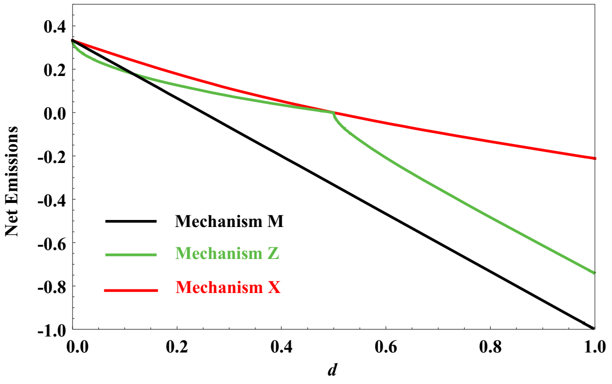

Fig. 7. Net emissions under three mechanisms.
Note: (1) The existence of the intersection at point 0.115; (2) The existence of the kink at point 0.5 because at this point mechanism Z changes from a tax system to a subsidy system.

(a) $PS_m > PS_x > PS_z$ *for* $0 < d \le 0.5$.
(b) $PS_m > PS_z > PS_x$ *for* $0.5 < d \le 1$.

Proposition 5 states that mechanism M is always the first best for any degree of environmental damages. As we described in the model section, there are two kinds of benefits from implementing the emission tax mechanisms based on the contest function: common benefits and private benefits. A firm can reduce production and obtain private benefits on tax avoidance as well as common benefits from lower net emissions, but this firm must bear the loss caused by the decrease in sales. On the other hand, a firm can increase green investments and obtain private benefits on tax avoidance as well as common benefits on lower net emissions, but this firm must bear the cost of these green investments.

When environmental damages are low enough, firms achieve the minimum output under mechanism M (see Part (a) of Proposition 3), consequently, they obtain the maximum private benefits and common benefits excluding the loss in sales. Also, when environmental damages are low enough, because firms are not competing strongly enough in the product market it increases the firm's profits.

When environmental damages become higher, firms increase green investments to achieve the minimum net emissions under mechanism M (see Part (b) of Propositions 2 and 4), then they obtain the maximum private benefits and common benefits. Therefore, through Propositions 2, 3 and 5, we conclude that compared with reducing output, encouraging green R&D investment seems to be the most effective and economic efficient way for a firm to pay less in emission tax.

Proposition 6. *The mechanisms that maximize the consumer surplus are in the following descending order:*

(a) $CS_z > CS_m > CS_x$ *for* $0 < d \le 0.239$.
(b) $CS_m > CS_z > CS_x$ *for* $0.239 < d \le 1$.

Fig. 8 illustrates Proposition 6. The definition of consumer surplus relates not only to production, but also to the environmental damage for consumers. Intuitively, the more products firms produce, the higher benefits the consumers obtain due to the lower price. However, as output increases, also the pollution does, and consumers will face higher environmental damages. Therefore, there is always a tradeoff between benefits from consumption and the negative externality from environment damages.

When environmental damages are low, the added consumer utility from consumption is higher than the negative externality from environmental damages. However, as the environmental damage increases to a moderate level, the environmental negative effects to consumers become stronger. The results show that mechanism Z is the first best because consumers obtain the largest net benefits (Part (a) of Proposition 6).

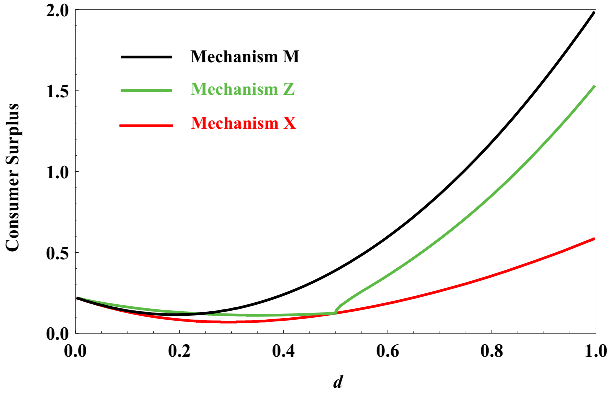

Fig. 8. Consumer Surplus under three mechanisms.
Note: (1) The existence of the intersection at point 0.239; (2) The existence of the kink at point 0.5 because at this point mechanism Z changes from a tax system to a subsidy system.

When environmental damages are relatively high, the negative environmental externality is compensated, and consumers can obtain extra benefits from abatement activities. In this case, mechanism M helps consumer obtain the most benefits since it provides the highest subsidy for a firm's abatement; therefore, it is the first best mechanism (Part (b) of Proposition 6).

Proposition 7. *The mechanisms that maximize the social welfare are in the following descending order:*

(a) $SW_m > SW_x > SW_z$ *for* $0 < d \le 0.0012$.
(b) $SW_m > SW_z > SW_x$ *for* $0.0012 < d \le 0.0013$.
(c) $SW_z > SW_m > SW_x$ *for* $0.0013 < d \le 0.174$.
(d) $SW_m > SW_z > SW_x$ *for* $0.174 < d \le 1$.

Since cases (a) and (b) correspond to tiny small intervals, the main results come from cases (c) and (d).

Since the social welfare consists of the consumer and producer surplus, when the environmental damages are low and in a small region, that is $0.0013 < d \le 0.174$,mechanism Z is the first best to achieve the maximum social welfare because the large consumer surplus is the dominant factor in this case (see Part (a) of Proposition 6).

However, with an increase in environmental damages ($0.174 < d \le 1$), mechanism M achieves the highest welfare in a wide range of environmental damages because both producer and consumer surplus increase gradually under this mechanism (see Part (b) of Propositions 5 and 6).

To sum up, mechanism M is the most effective in correcting the environmental externalities through emission taxes (or providing subsidies) for a large range of environmental damages.

Proposition 8. *The mechanisms that maximize the created value are in the following descending order:*

(a) $Y_z > Y_m > Y_x$ *for* $0 < d \le 0.074$.
(b) $Y_m > Y_z > Y_x$ *for* $0.074 < d \le 0.912$.
(c) $Y_z > Y_m > Y_x$ *for* $0.912 < d \le 1$.

The definition of the created value relates production sales and green R&D investments in unique measure. In the case where environmental damages are very low, mechanism Z generates the largest created value since it provides the highest incentives for green R&D investments and the highest production (Part (a) of Propositions 2 and 3).

However, when environmental damages are in a wide range ($0.074 < d \le 0.912$), the created value under mechanism M is always the largest because of the greatest green R&D investments. The production, however, is at minimum, therefore, it can be inferred that green R&D investments impact the created value in a more significant manner than the revenue from sales/consumption. In short, the incentives that provided by mechanism M to GDP is the largest in this case.

From Fig. 9, the created value increases with increasing environmental damages under the three mechanisms. The formula for the created value can be written as: $Y = p(\mathrm{a}-p) + \gamma {z_i}^2$, so the impact of price p on the created value Y is as follows: there is cutoff at $p = 0.5$ (if we assume $a = 1$), when the market price is low, that is $0 < p < 0.5$, market price has a positive effect on the created value. However, when the market price is high and in the range of $0.5 < p < 1$, market price has a negative effect on the created value. Fig. 6B above shows that the market price has the biggest growth rate under mechanism M, and when $d > 0.5$, the market price is larger than 0.5, it implies that market price exerts a negative effect on the created value and this effect becomes stronger as d increases. On the other hand, the negative effect of price on the created value is relatively small under mechanism Z. Therefore, when environmental damages become gradually larger than 0.912, mechanism Z generates the maximum created value and becomes the best.

In the benchmark case, the created value appears to be minimal since the benchmark case does not provide any incentives for environmental R&D investments. Compared with an increase in production to an increase in the created value, an increase in the green R&D investment seems to be the most effective way.

5. Extension of the basic model

In this section we discuss some extensions of the basic model in order to complete the analysis of the emission taxation mechanisms in this paper.

5.1. The case of n firms

By extending the model to the case of n firms, the results show that the basic model with only two firms does not lose generality and representation. In order to analyze all the extent of environmental damage, we assume $3 \le n \le 8$.

In general, the larger the number of firms, the more intense the market competition, consequently, the larger the range of parameters that achieve carbon neutrality under the three mechanisms. In particular, mechanism X delivers carbon neutrality and negative emission when $\frac{n}{2+n} \le d \le 1$, mechanism Z delivers carbon neutrality and negative emission when $\frac{n}{n+n^2-2} \le d \le 1$, and mechanism M delivers carbon neutrality and negative emission when $\frac{1}{2+n} \le d \le 1$. Since $\frac{1}{2+n} < \frac{n}{n+n^2-2} < \frac{n}{2+n}$, mechanism X achieves carbon neutrality within a relatively small range of environmental damages, while mechanism M achieves carbon neutrality within a relatively larger range of environmental damage. Therefore, mechanism M is the best to achieve carbon neutrality and negative emission, while mechanism Z is better than mechanism X.

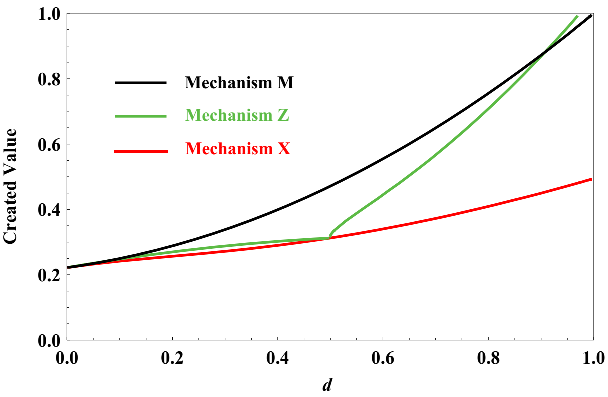

Fig. 9. Created value under three mechanisms.
Note: (1) The existence of the intersection at point 0.074 and point 0.912; (2) The existence of the kink at point 0.5 because at this point mechanism Z changes from a tax system to a subsidy system.

The more intense the market competition, the less green R&D investments firms engages in under mechanism X and Z. However, under mechanism M, firms keep constant their green investments. Consequently, the choice of the best mechanism to maximize green R&D investment is not affected when we vary the number of firms competing in the market, but the conditions vary with the number of firms. For instance, when the environmental damages are relatively small, that is $0 < d < \frac{n^2-n}{1-2n+2n^2+n^3}$, mechanism Z still provides the greatest incentive for firms' green R&D investment, but the damage range gradually decreases with an increase in the number of firms. When environmental damages are relatively large, mechanism M provides the greatest incentive for firms' green investment and the damage range gradually increases with the increase in the number of firms n, that is $\frac{n^2-n}{1-2n+2n^2+n^3} \le d \le \frac{n}{n+n^2-2}$ and $\frac{4n^2-4n}{4n+n^2+n^3-4} \le d \le 1$. Therefore, the superiority of mechanism M over the other mechanisms increases as market competition intensifies.

Production decreases with an increase in the market competition under the three mechanisms, however, the rate of decline in output is minimal under mechanism X. When environmental damages are relatively small, that is $0 < d < \frac{n}{n+n^2-2}$, mechanism Z helps firms generate the maximum output, but the damage range gradually decreases with an increase in the number of firms. When environmental damages are relatively large, the range of damages gradually increases as the number of firm increases, that is $\frac{4n^2-4n}{4n+n^2+n^3-4} < d < 1$, and mechanism X is the optimal choice to maximize firms' output.

Combined with the comprehensive impact of intense market competition on firms' output and green investment under the three mechanisms. When environmental damages are relatively small and the damage range gradually decreases with an increase in the number of firms n, that is $0 < d < \frac{n^3-n}{2+n+2n^2+3n^3+n^4}$, mechanism Z delivers the minimal net emissions, leading to the lowest environmental damages. When the environmental damages are relatively larger and the damage range gradually increases with an increase in the number of firms n, that is $\frac{n^3-n}{2+n+2n^2+3n^3+n^4} \le d \le \frac{n}{n+n^2-2}$, and $\frac{4n^2-4n}{4n+n^2+n^3-4} \le d \le 1$, mechanism M is the most effective in internalizing the negative environmental externality.

In terms of producer surplus, similar to the basic model, mechanism M is always the first best for any degree of environmental damage with n firms competition. The increase in the number of firms, intense market competition strengthens the advantage of mechanism M as the optimal choice to maximize producer surplus. It is worth noting that mechanism Z outperforms mechanism X in helping firms make more profits as market competition intensifies.

For consumer surplus, when environmental damages are relatively low, the consumers' utility from consumption is still higher than the negative externality from environmental damages. When environmental damages are relatively high, the green investments under mechanism X and Z decrease as market competition intensifies, but investments under mechanism M do not vary with the number of firms. In this case, mechanism M helps consumers to obtain the most benefits since it provides the highest subsidy for a firm's abatement; therefore, it is the best mechanism.

Regarding the created value, intense market competition accelerates the speed at which mechanism M is the best to obtain the largest created value. When environmental damages are relatively small, the environmental damage range gradually decreases with an increase in the number of firms n, that is $0<d<\frac{n-2n^2+n^3}{1+n-4n^2+3n^3+n^4}$. In this case, the created value under mechanism Z is the largest. When environmental damages are relatively large and the damage range gradually increases with an increase in the number of firms, that is $\frac{n-2n^2+n^3}{1+n-4n^2+3n^3+n^4}<d<\frac{n}{n+n^2-2}$ and $\frac{4n^2-4n}{4n+n^2+n^3-4}\leq d\leq 1$, the contribution of mechanism M to GDP is the largest.

To sum up, the more firms there are, the more intense the market competition will be. Under the three mechanisms, the output and green R&D investment of firms are affected to varying degrees. However, the choice of the optimal mechanism remains unchanged in most indicators compared to the basic model. But market competition can speed up or slow down the speed/range at which a mechanism is the best by affecting the output production and the green R&D investment.

5.2. Asymmetric case: different production cost

In this section, we consider the case of asymmetric firms in terms of costs. Firm 1 (the low-cost firm) has zero costs of production, while firm 2 (the high-cost firm) has total costs of cx_2, where $c \geq 0$ is the unit production/marginal cost of firm 2. Then, we examine how production cost asymmetries affect the performance of the three mechanisms.

In comparison with the basic model, an increase in production cost leads to an increase in market price to offset the negative impact of higher production cost on profits. In a market where only two firms compete under the three mechanisms, the low-cost firm increases production due to lower production costs (more efficient firm) than its competitors, while high-cost firm reduces production due to the higher production costs (less efficient firm).

For green R&D investment, under mechanism X, the green investment of the low-cost firm increases with an increase in the cost difference between firms, while the high-cost firm reduces green R&D investments with an increase in the cost difference between firms. Under mechanism Z, both low-cost and high-cost firms make the same amount of green R&D investment, and the cost difference has the same negative effect on both firms' green R&D investments, e.g., when the cost difference increases, both firms' green R&D investment decreases. Note that in the case that mechanism Z provides subsidies for emission reduction instead of emission tax, both firms' green investments increase with an increase in the cost difference. The result shows the cost difference between firms does not have impact on firms' green investments under mechanism M, consequently, both firms' green investments remain similar to the basic model.

There are distinct effects of production cost differences on the production and investment of high-cost firms and low-cost firms. Under mechanism X, low-cost firm and high-cost firm achieve carbon neutrality basically under the same conditions, since the production of the low-cost firm increases, resulting in more pollution, on the other hand, its green investment also increases accordingly. As the high-cost firm produces less, so does its green input, resulting in the same conditions for both firms to achieve carbon neutrality. Interestingly, under mechanisms Z and M, it becomes difficult or impossible for the low-cost firm to achieve carbon neutrality since the output of the low-cost firm increases as the production cost difference increases but its green R&D investment decreases or remains constant as mentioned. The cost advantage allows the low-cost firm to relax carbon neutrality. However, for the high-cost firm, vice versa, is easier to achieve carbon neutrality.

Recall that, the objective is to choose the best mechanism in terms of different indicators taking into account the difference in production cost. When the environmental damage is low, mechanism Z provides the two firms with the greatest incentive to make green investments. While, when the damages are high, and in a relatively large range, mechanism M provides the greatest incentive for both firms to make green investments.

In terms of production, the low-cost firm always achieves maximum output under mechanism Z, regardless of the degree of environmental damages. But the high-cost firm achieves maximum output under mechanism X when the environmental damage is high.

As the definition of net emissions is closely related to the production and green R&D investment of firms, when the environmental damages are small, both low-cost and high-cost firms generate the smallest net emissions under mechanism Z. However, when environmental damages are relatively high, both firms produce the least emissions under mechanism M.

Since the other indicators such as total damages, consumer surplus, producer surplus, social welfare and the created value measure the impact of production cost differences on firm's production and green investment, the choice of the optimal mechanism in terms of the different indicator is not affected by cost differences, that is the performance of the three mechanisms X, Z, and M does not change significantly compared with the basic model. Mechanism M is the best when the environmental damages are sufficiently large. The second best is mechanism Z, and the last is mechanism X.

5.3. The impact of green R&D investment efficiency/cost on different mechanisms

In this case, we analyze the impact of the parameter γ that captures the green R&D investment cost on the three mechanisms. Since γ is the extent of the decreasing returns in green R&D investments, the bigger γ a firm face, the lower investment a firm undertake (Lambertini et al., 2017). Based on the results of including the parameter γ, in order to cover all range of environmental damage, the investment cost parameter γ should satisfy $0 < \gamma \leq 8$. In order to simplify the analysis, we assign $\gamma = 2$, and vary this parameter departing from this point. We summarize the main results as follows, which may provide a sufficiently rich overview of the general results.

Compared with the basic model, changing the parameters γ does not affect the choice of the optimal mechanism. For instance, within a relatively large range of environmental damages, mechanism M is still the first best in terms of carbon neutrality efficiency, green investment, net emissions, producer surplus, consumer surplus, social welfare, and created value. However, the conditions under which the mechanism becomes the best in terms of various indicators have changed with an increase in the parameter γ.

Under mechanism X, the larger value of the parameter γ a firm has, the lower output the firm generates. However, under mechanism Z and M, the parameter γ does not have direct impact on firm's output. Therefore, mechanism Z and M prevent this negative effect on production to some extent. Consequently, mechanism Z helps firms achieve the maximum output under a relative wide range of environmental damages.

As mentioned, an increasing in the parameter γ has different negative impact on firms' green R&D investments under the three mechanisms. This negative impact is the greatest under mechanism M, which alters the conditions for mechanism M to be the best. Taking firm's green R&D investment as example, when the environmental damage is small, mechanism Z is first best to provide the most incentives for firm's green R&D investments, when the environmental damage is large, mechanism M is the best. However, compared with the basic model, with an increase in the parameter γ, the range of environmental damage for which mechanism Z is the best becomes larger, while the range of parameters for which mechanism M is the best becomes smaller.

It is worth mentioning that when the parameter γ is relatively high, lower investment efficiency or higher investment cost, the three mechanisms are less efficient at helping firms achieve carbon neutrality.

Finally, regarding other parameters, we must note that the inclusion of the parameter a does not substantially affect or change the model results. All Propositions and Corollary are still valid, the range of the environmental damage parameter is enlarged by a factor of a. For example, the assumption that $0 < d \leq 1$ becomes $0 < d \leq a$, and some conditions, such as $0.154 < d \leq 1$ becomes $0.154a < d \leq a$.

5.4. The possibility of constraints

Taken the energy capacity constraints into account, it is interesting to address the environmental effects (Nie and Wang, 2019). Firms, whether they are in the energy-intensive sector or non-energy-intensive industries sector should focus in understanding their constraints and what they imply in terms of production and investment capacity to survive in a competitive environment. In our basic model, the two competing firms do not have capacity constraints and can produce any amount they wish under the assumed cost structure. In this section, we assume that firms' capacities are limited.

When we consider the possibility of constraints, we must note that constraints may create difficulties regarding the existence of Nash equilibrium. We must also note that our model is not suitable to study constraints. Nonetheless, we found that the effects of capacity constraints on firms' green R&D investment are different under the three mechanisms. When the production capacity is sufficiently scarce, and two firms are symmetric, the production capacity constraints have no effects on firms' green R&D investment under mechanism X and mechanism M. However, under mechanism Z, the green R&D investment increases in the production capacity. To our surprise, when firms engage more in green R&D investment than their output, the firms' green R&D investment decreased with an increase in the production capacity. Therefore, the production capacity has positive effects on the green R&D investment when mechanism Z is an emission tax system; but the production capacity has negative effects on the green R&D investment when mechanism Z is an emission-reduction subsidy system. In some sense, restrictions on production capacity drive the focus of competition towards green R&D investments.

As mentioned, green R&D investment is an effective way to achieve sustainable economic growth, thus, technology and innovation play an important role (Wu et al., 2021). In this context, investment constraints should be considered in this study. In the basic model, the production of the firm is related with the green investments of the firms. On the other hand, according the report of OECD (2017), the capital financing for clean-tech has been declining. For firms that face financing constraints, investment may be sensitive to the average tax burden as well as to the tax rates (Fazzari et al., 1988).

In this case, since high investment means high costs, which the firms need to pay, the investment capacity of firms may be restricted. We find that under symmetric and investment capacity constraints, the production have no relationship to the investment capacity constraints under mechanism Z and M. However, under mechanism X, the production increases in the investment capacity. Therefore, the larger green R&D investment constraint, the more firms produce.

The main purpose of this study is to choose an optimal emission tax mechanism. The change of emission tax can directly affect the after-tax profit of the enterprise. Moreover, the impact on the internal cash flow and external financing of the enterprise is more direct (Kovermann and Velte, 2019). Consequently, when the reduction in emission tax changes the tax burdens of the enterprise, the constraints are reduced, which further promotes green investment by firms. Overall, production capacity constraints and investment capacity constraints have significant effects on mechanisms Z and X, respectively, but not on mechanism M. In general terms, mechanism M remains the best in case of constraints.

6. Discussion

In this section, we further discuss our results and suggest possible solutions to design the emissions tax mechanism. We also consider some limitation regarding the proposed mechanisms.

6.1. An optimal emission tax mechanism

In line with findings of prior research, different emission tax (or subsidy) systems trigger heterogeneous responses by firms, in terms of output and green R&D investments (Dechezleprêtre and Sato, 2020). Regarding carbon neutrality, despite an increasing number of governments proposing a target to reach zero net emissions, only a few have detailed plans on how to get there, actually the leap towards carbon neutrality demands action both at the country level and the firm level (Grainger and Smith, 2021). The prospect of a global green recovery from the Covid-19 crisis and recession is underway as many countries invest money into high-CO_2 activities (Mofijur et al., 2021). Thus, the efficient design of the emission tax mechanism plays an even more critical role. In this context, the emission tax mechanism should be consistent with the target/objective of zero net emissions. We propose a new kind of emission taxation mechanisms in which firms compete through a contest to pay less taxes. We design three emission tax mechanisms based on the idea of Polluter-Pays-Principle and to reduce the negative environmental externalities (i.e., the output contest mechanism, the green R&D investment contest mechanism, and the net emission contest mechanism). We claim that the three proposed mechanisms are feasible mechanisms to reach those objectives, and among them the best in terms of efficiency is mechanism M.

In line with reality, market competition also affects how firms achieve carbon neutrality, the larger the number of firms, the more intense the market competition, consequently, the more efficient the mechanisms achieve carbon neutrality, the result confirms the study by Qiao et al. (2022). Since the differences in production cost have distinct effects on the production and green R&D investment of high-cost firms and low-cost firms, under mechanism X, both low-cost firm and high-cost firm achieve carbon neutrality basically under the same conditions. Interestingly, under mechanisms Z and M, it becomes difficult or impossible for the low-cost firm to achieve carbon neutrality. However, it is easier or faster to achieve carbon neutrality for the high-cost firm. On the other hand, an increase in the parameter of green R&D investments cost, the three mechanisms become less efficient at helping firms achieving carbon neutrality due to the lower investment efficiency.

The net emission indicator aggregates the joint effect of a firm's production activity and green investment, further the decreasing emission level results in a higher profit (Hasan et al., 2021). Both lower output and greater green R&D investments lead to reduced net emissions by firms, and to lower total environmental damages. Combined with the comprehensive impact of intense market competition on firms' output and green investment under the three mechanisms. Mechanism M is also the optimal choice to control net emissions.

Regarding green R&D investments, we conclude that all three emission tax mechanisms provide incentives for firm's green R&D investments, but the amount of the incentives varies under different mechanisms. On the contrary, standard market mechanisms do not stimulate a firm's green innovation (McDonald and Poyago-Theotoky, 2017). Therefore, the three mechanisms give emission taxation an advantage over more rigid and prescriptive environmental policy instruments; thus, the design of an efficient mechanism is relevant and vital for developing realistic and efficient climate policies.

Moreover, we claim that levying taxation on emissions is a process of transfer environmental damages into costs for the firms associated with the production/pollution, which internalizes the environmental externality. The difference in the emission tax rates induces differences in emission tax burden and abatement costs. By comparing the four options (three mechanisms and the benchmark case), we argue that the implementation of an emission tax increases the cost of energy-intensive and high-emission industries and then can adversely affect the competitiveness of these industries. This competitiveness effect can result in negative economic outcomes (Aldy and Stavins, 2012) and an increase in the overall price level (inflation effect). Our results are more consistent with Porter hypothesis (PH). Concretely, well-designed and stringent environmental policy can stimulate innovations, which in turn increases the productivity of firms or the value of products for end users (Porter and Van Der Linde, 1995; Zhong and Peng, 2022). We argue that mechanism Z and M go in favor of the PH, because they can provide significant incentives for firm's green innovation when both firms and consumers seek new and cleaner solutions.

6.2. Policy implications

Emission tax is considered fundamental to support environmental policy and climate mitigation; it is also considered the more cost-efficient policy instruments; thus its use has increased across the world (Qin et al., 2021). However, it has only been implemented in a small number of countries (UN (United Nations), 2021). There are significant variations in acceptability across different types of policy measures and between different policy designs. For instance, in Washington State (United States of America), where a ballot initiative for a carbon tax was rejected in both 2016 and 2018 (Dolšak et al., 2020). It is crucial for policy maker to recognize the importance of policy acceptability. It is necessary to justify the acceptability of the emission tax mechanism in this study.

Firstly, based on the idea of Polluter-Pay-Principle and the reduction of negative environmental externalities, the consequence of the emission tax under the three tax mechanisms perceived as being fair. Secondly, the three mechanisms provide an effective and intuitive solution to the problem of the emission taxation, they provide strong incentives for green R&D investments by firms' and accelerate the transition to carbon neutrality. They minimize the potential negative impact on firms' production and economic growth. Moreover, mechanisms M and Z, because of the way they are designed, and because they focus on the present and future decisions not to the past decision, they are more like to be consensual and receive agreement by world powers such as the United States, the European Union, India or China, which have found difficult to get a consensual way of taxing emissions.

On the other hand, imposing an emission tax based on above three mechanisms has some limitations. Usually, establishing a tax rate is often a political decision that considers many factors. For instance, according to economic theory, the tax rate of a Pigouvian tax should be set equal to the marginal social cost of the pollution (Metcalf, 2021). While the social cost of carbon should be the same everywhere, the costs of carbon emissions mitigation may vary considerably across different jurisdictions resulting in different emission tax rates. Then some jurisdictions need to apply different emission tax rates. This study provides an answer to this type of situation, where the emission tax rate is determined by each firm in a competitive way. Consequently, the emission tax rate varies across different firm. Therefore, these emission tax mechanisms may be more complicated in terms of administrative and implementation reasons in comparison with the usual uniform and blind carbon tax, since they may require a slightly more elaborated monitoring, reporting and verification system. They may also require a specialized institutional system to establish the rules for calculating the tax. However, this issue is not specific to our approach, but general to environmental economics, as firms and countries tend “to hide” their environmental damages/emissions and “to inflate” their green R&D investments. We hope that further research will help tune any implementation issues.

However, the competitive mechanisms proposed in this paper have the advantage of providing stronger incentives for green R&D investments and to the transition to carbon neutrality. It is also a fair and consensual market-based solution to emissions taxation problem.

7. Conclusion

This paper proposes a new type or class of emission taxation mechanisms in which firms compete through a contest to pay less emission taxes. In this context, we compare three novel emission tax mechanisms that endogenize the tax amount paid by firms through a competitive contest. 1) Mechanism X is a production contest in which the emission tax rate is based on firm's output relative to other firms. 2) Mechanism Z consists of a green R&D investment contest in which the emission tax rate depends on firm's green R&D investments relative to other firms' investments. 3) Mechanism M is a net emission contest in which the emission tax rate is based on firm's net emissions relative to other firms' net emissions.

The obtained results are summarized as follows. First, when environmental damages are low, mechanism Z is the first best in terms of firms' production, green R&D investments, net emissions, consumer surplus and the created value, while mechanism M is the first best in terms of producer surplus and social welfare. Second, when environmental damages are moderate to high, mechanism X is the first best only in terms of production, mechanism M is the first best in terms of other indicators (green R&D investments, net emissions, producer surplus, consumer surplus and social welfare and the created value).

In short, mechanism M seems to be the optimal option in most cases. The second best is mechanism Z. Mechanism X is not optimal in general. When environmental damages are low, none of the three mechanisms incentivizes firms to make sufficiently large amounts of green R&D investments to achieve carbon neutrality. However, when environmental damages are sufficiently large, all three mechanisms provide firms with enough incentives to make green R&D investment and achieve carbon neutrality. Among them, mechanism M is the mechanism that achieves carbon neutrality in a larger spectrum of situations and industries (i.e., larger spectrum of environmental damage parameters).

The three mechanisms underline how green investments are critical for achieving emission-reduction targets in a cost-effective way. Also, we show that the role of emissions taxation (or environmental subsidy) is significant in correcting environmental externalities; emissions tax (or environmental subsidy) provides incentives for green R&D investments since environmental regulation can in this way influence the firms' decisions concerning the volume of green R&D investments. Furthermore, the endogenization of the tax mechanism in a truly competitive context as it is proposed in this paper is fundamental because it is the fairest and effective way of taxing polluting firms. Essentially, firms freely compete for paying less tax.

Future research should consider the implications for international relations. In this context, research on CO_2 emission reduction is essential not only at national-firm-level but is also relevant to international trade and to trade policy. For instance, while thinking about multinational enterprises (MNE) the climate policy dynamics of one market, might influence the MNEs' green investments in a foreign market, which means that the competition dynamics are not only a game between national firms, but climate policy in the parent country of the MNE, can generate positive spillovers and impact the competitiveness in the foreign market where the MNE invests and locates its subsidiaries. Other negative spillovers deriving from trade policies are carbon leakage, which may also deserve a more attentive study. Further research may examine the effects of different environmental-related spillover on international trade and economic relations.

One possible practical difficulty of implementation of the contest emission tax mechanism lies in the potential need of a specialized institutional monitor, report and verification system of the production and investment made by firms. However, this issue is not specific to our approach because firms and countries tend “to hide” their environmental damages/emissions and “to inflate” their green R&D investments. National and firm level transparency is crucial for successful environmental policy.

To conclude, this paper provides an effective and intuitive solution to the problem of the emission taxation. The proposed mechanisms provide strong incentives for green R&D investments by firms and accelerate carbon neutrality, while minimizing the potential negative impact on firms' production and economic growth. Moreover, mechanisms M and Z, because of the way they are designed, and because they focus on the present and future decisions, not on the past decision, they are more like to be consensual and receive agreement by world powers such as the United States, the European Union, India or China, which have found difficult to get a consensual way of taxing emissions. This is a crucial aspect regarding implementation that has been taken seriously in this paper and is one of our main objectives.

Finally, we believe that this study will provide researchers and decision-makers with inspiration and new ways of thinking in terms of environmental policy, and that will help designing and implementing optimal emission taxation mechanisms that are fairer and that can accelerate the transition to carbon neutrality.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

In order to prove our results, we first obtain the equilibrium of the model. The following equilibria are obtained for four games, which are the benchmark case, mechanism X, mechanism Z, and mechanism M. The equilibrium results are identical for each firm in these four cases (e.g., in the benchmark case, $x_1 = x_2 = x_0$; under mechanism X, $x_1 = x_2 = x_x$, and so on). Note that we let $\gamma = 1 \textit{ and } a = 1$. This simple assumption is made to reduce the number of parameters and to make the obtained expressions more tractable. The inclusion of the parameter a does not substantially affect or change the model results. All Propositions and Corollaries are still valid, the range of parameters for environmental damage is enlarged by a factor of a. For example, the assumption that $0 < d \leq 1$becomes $0 < d \leq a$. Some conditions such as $0.154 < d \leq 1$ becomes $0.154a < d \leq a$.

In Section 5.3 of the extension section, we assign $\gamma = 2$. The main results are summarized there.

We start by substituting Eqs. (1), (2) and (4) into (7), then we differentiate the obtained expression with respect to x_i and z_i for $i = 1, 2$, under the different cases to obtain first order conditions. The second order condition is satisfied. Subsequently, we impose symmetry and solve the system of two equations and two unknowns with respect to x_j and z_j *for the cases* $j = 0, x, z, m$. Then, we obtain the per-firm equilibrium of green R&D investments and output under different cases, given by:

$$z_0 = 0, z_x = \frac{d}{2}, z_z = \frac{B}{6}, \textit{and } z_m = d \tag{12}$$

$$x_0 = \frac{1}{3}, x_x = \frac{1-d+A}{6}, x_z = \frac{2-d}{6}, \textit{and } x_m = \frac{1-d}{3} \tag{13}$$

where $A = \sqrt{1-2d+4d^2} > 0, B = \sqrt{3d(2-d)} > d$.

In order to ensure that the Expressions (13) are greater than or equal to 0, it is enough to assume that $0 < d \leq 1$.

However, note that from Expressions (12) and (13), we have $z_x \geq x_x$, and $z_z \geq x_z$ for $d \geq 0.5$; and $z_m \geq x_m$ for $d \geq 0.25$. In this case the tax becomes a subsidy. Consequently, when $0.5 < d \leq 1$, we substitute (1) (3) and (4) into (7), and differentiate the obtained expression again with respect to x_i and z_i for $i = 1, 2$,under different cases to obtain first order conditions. The second order condition is satisfied as well. Subsequently, we impose symmetry and solve the associated system of two equation and two unknowns with respect to x_j and z_j *for the cases* $j = 0, x, z, m$. Then, we obtain the per-firm equilibrium of green R&D investments and output under different cases, given by:

$$z_0 = 0, z_x = \frac{d}{2}, z_z = \frac{3d + \sqrt{6d(2d-1)}}{6}, \textit{and } z_m = d \tag{14}$$

$$x_0 = \frac{1}{3}, x_x = \frac{1-d+A}{6}, x_z = \frac{2-d}{6}, \textit{and } x_m = \frac{1-d}{3} \tag{15}$$

Again, in order to ensure that the Expressions (15) are greater than or equal to 0, we must have $0 < d \leq 1$.

A.1. Proof of Proposition 1

Following the previous discussion, to sum up, there is $z_x \geq x_x$ and $z_z \geq x_z$ for $0.5 < d \leq 1$, and there is $z_m \geq x_m$ for $0.25 < d \leq 1$.

In the following proofs, we compare the value of z_j, x_j, e_j, D_j, PS_j, CS_j, W_j, Y_j for $j = x, z, m$, for $0 < d < 1$.

A.2. Proof of Proposition 2

From Expressions (12), if $0 < d \leq 0.5$, then $z_m > z_x$ is always true. If $d \leq 0.154$ then $z_z > z_m$, thus, the green R&D investment in descending order is $z_z > z_m > z_x$ for $0 < d \leq 0.154$, and $z_m > z_z > z_x$ for $0.154 < d \leq 0.5$.

From Expressions (14), if $0.5 < d \leq 1$, the green investment in descending order is $z_m > z_z > z_x$. Therefore, the green R&D investment in descending order is $z_m > z_z > z_x$ for $0.154 < d \leq 1$.

A.3. Proof of Proposition 3

From Expressions (13), if $0 < d \leq 0.5$, then $x_z > x_x > x_m$ is always true.

From Expressions (15), if $0.5 < d \leq 1$, then $x_x > x_z > x_m$ is always true.

Now, we substitute Eqs. (12) and (13) into Eq. (5) to obtain the equilibrium net emissions. If $0 < d \leq 0.5$, we have:

$$e_0 = \frac{1}{3}, e_x = \frac{1-4d+A}{6}, e_z = \frac{2-d-B}{6} \textit{ and } e_m = \frac{1-4d}{3} \tag{16}$$

Then we substitute Eqs. (14) and (15)into Eq. (5) to obtain the equilibrium of net emissions. For $0.5 < d \leq 1$, we have:

$$e_0 = \frac{1}{3}, e_x = \frac{1-4d+A}{6}, e_z = \frac{2-4d-\sqrt{6d(2d-1)}}{6} \textit{and } e_m = \frac{1-4d}{3} \tag{17}$$

Next, we substitute the expressions of net emissions (16) into Eq. (6), to obtain the equilibrium environmental damages for $0 < d \leq 0.5$:

$$D_0 = \frac{2d}{3}, D_x = \frac{d(1-4d+A)}{3}, D_z = \frac{d(2-d-B)}{3} \textit{and } D_m = \frac{2d(1-4d)}{3} \tag{18}$$

By substituting expressions of net emissions (17) into the Eq. (6), we obtain the equilibrium environmental damages for $0.5 < d \leq 1$:

$$\begin{cases} D_0 = \dfrac{2d}{3}, D_x = \dfrac{d(1-4d+A)}{3}, \\ D_z = \dfrac{d\left(2-4d-\sqrt{6d(2d-1)}\right)}{3}, \textit{and } D_m = \dfrac{2d(1-4d)}{3} \end{cases} \tag{19}$$

A.4. Proof of Proposition 4

From Expressions (*16*), if $0 < d \le 0.5$, then $e_x > e_m$ is always true. If $d \le 0.115$, then $e_m > e_z$, hence, the net emissions in descending order are $e_x > e_m > e_z$. Then, if $0.115 < d \le 0.5$,then $e_x > e_z > e_m$.

From Expressions (*17*), if $0.5 < d \le 1$, $e_x > e_z > e_m$ is always true. To sum up, the net emissions in descending order is $e_x > e_z > e_m$ for $0.115 < d \le 1$.

From Expressions (*18*) and (*19*), the proof of Corollary 2 is similar to that of Proposition 4.

A.5. Proof of Proposition 5

We replace the obtained green R&D investment (12), output (13) and net emissions (16) back into the objective function (7) to obtain equilibrium of firm's profit for $0 < d \le 0.5$:

$$\begin{cases} \pi_0 = \dfrac{1}{9}, \pi_x = \dfrac{4(1-d)^2 + 15d^2 - 4dA + 4A}{72} \\ \pi_z = \dfrac{8 - 26d + 11d^2 + 12dB}{72}, \textit{and } \pi_m = \dfrac{9d^2 + 2(1-d)^2}{18} \end{cases} \tag{20}$$

Also, we replace the obtained green R&D investment (14), output (15) and net emissions (17) back into the objective function (7) to obtain equilibrium of firm's profit for $0.5 < d \le 1$:

$$\begin{cases} \pi_0 = \dfrac{1}{9}, \pi_x = \dfrac{4(1-d)^2 + 15d^2 - 4dA + 4A}{72} \\ \pi_z = \dfrac{8 + d\left(23d - 14 + 6\sqrt{6d(2d-1)}\right)}{72}, \textit{and } \pi_m = \dfrac{9d^2 + 2(1-d)^2}{18} \end{cases} \tag{21}$$

Then, we substitute profit Expressions (*20*) into function (9) to obtain producer surplus for $0 < d \le 0.5$:

$$\begin{cases} PS_0 = \dfrac{2}{9}, PS_x = \dfrac{4(1-d)^2 + 15d^2 - 4dA + 4A}{36} \\ PS_z = \dfrac{8 - 26d + 11d^2 + 12dB}{36}, \textit{and } PS_m = \dfrac{9d^2 + 2(1-d)^2}{9} \end{cases} \tag{22}$$

We also substitute profit Expressions (*21*) into function (9) to obtain producer surplus for $0.5 < d \le 1$:

$$\begin{cases} PS_0 = \dfrac{2}{9}, PS_x = \dfrac{4(1-d)^2 + 15d^2 - 4dA + 4A}{36} \\ PS_z = \dfrac{8 + d\left(23d - 14 + 6\sqrt{6d(2d-1)}\right)}{36}, \textit{and } PS_m = \dfrac{9d^2 + 2(1-d)^2}{9} \end{cases} \tag{23}$$

From Expressions (22), if $0 < d \le 0.5$, then $PS_m > PS_x > PS_z$ is always true.

From Expressions (23), if $0.5 < d \le 1$, then $PS_m > PS_z > PS_x$ is always true.

A.6. Proof of Proposition 6

Now, substitute the firm's output (13) and environmental damages (18) into function (8) to obtain consumer surplus for $0 < d \le 0.5$:

$$\begin{cases} CS_0 = \dfrac{2-6d}{9}, CS_x = \dfrac{2 + 2A + d(29d - 10 - 8A)}{18} \\ CS_z = \dfrac{4 - 16d + 6dB + 7d^2}{18}, \textit{and } CS_m = \dfrac{2\left(1 - 5d + 13d^2\right)}{9} \end{cases} \tag{24}$$

Then, substituting the firm's output (15) and environmental damages (19) into function (8) to obtain consumer surplus for $0.5 < d \le 1$:

$$\begin{cases} CS_0 = \dfrac{2-6d}{9}, CS_x = \dfrac{2 + 2A + d(29d - 10 - 8A)}{18} \\ CS_z = \dfrac{4 + d\left(25d - 16 + 6\sqrt{6d(2d-1)}\right)}{18}, \textit{and } CS_m = \dfrac{2\left(1 - 5d + 13d^2\right)}{9} \end{cases} \tag{25}$$

From Expressions (24), if $0 < d \le 0.5$, then $CS_m > CS_x$ and $CS_z > CS_x$ are always true. If $0 < d \le 0.239$, then $CS_z > CS_m$. Therefore, consumer surplus in descending order are: (1) $CS_z > CS_m > CS_x$ for $0 < d \le 0.239$; (2) $CS_m > CS_z > CS_x > CS_0$ for $0.239 < d \le 0.5$.

From Expressions (25), if $0.5 < d \le 1$, $CS_m > CS_z > CS_x$ is always true. To sum up, $CS_m > CS_z > CS_x$ for $0.239 < d \le 1$.

A.7. Proof of Proposition 7

In order to obtain the social welfare, we substitute the consumer surplus (24) and the producer surplus (22) into function (10) for $0 < d \le 0.5$, and then the social welfare is given by:

$$\begin{cases} W_0 = \dfrac{4-6d}{9}, W_x = \dfrac{77d^2 + 8(1+A) - 4d(7+5A)}{36} \\ W_z = \dfrac{16 - 58d + 24dB + 25d^2}{36}, \textit{and } W_m = \dfrac{4 + d(37d - 14)}{9} \end{cases} \tag{26}$$

We also substitute consumer surplus (25) and producer surplus (23) into function (10) for $0.5 < d \le 1$, and then social welfare is given by:

$$\begin{cases} W_0 = \dfrac{4-6d}{9}, W_x = \dfrac{77d^2 + 8(1+A) - 4d(7+5A)}{36} \\ W_z = \dfrac{16 + d\left(73d - 46 + 18\sqrt{6d(2d-1)}\right)}{36}, \textit{and } W_m = \dfrac{4 + d(37d - 14)}{9} \end{cases} \tag{27}$$

From Expressions (26), if $0 < d \le 0.5$, then $W_m > W_x$ is always true. If $0 < d \le 0.0012$, there is $W_x > W_z$. If $0.0013 < d \le 0.174$,there is $W_z > W_m$. To sum up, the total welfare in descending order are: (1) $W_m > W_x > W_z$ for $0 < d \le 0.0012$;(2) $W_m > W_z > W_x$ for $0.0012 < d \le 0.0013$ and $0.174 < d \le 0.5$;(3) $W_z > W_m > W_x$ for $0.0013 < d \le 0.174$.

From Expressions (27), if $0.5 < d \le 1$, $W_m > W_z > W_x$ is always true. Therefore, $W_m > W_z > W_x$ for $0.174 < d \le 1$.

A.8. Proof of Proposition 8

By substituting firm's output (13) and green R&D investment (12) into the function (11) to obtain the created value for $0 < d \le 0.5$:

$$\begin{cases} Y_0 = \dfrac{2}{9}, Y_x = \dfrac{4 + 4(d+A) - 11d^2 + 8dA}{36} \\ Y_z = \dfrac{(2-d)(4+7d)}{36}, \textit{and } Y_m = \dfrac{2 + 2d + 5d^2}{9} \end{cases} \tag{28}$$

By substituting firm's output (15) and green R&D investment (12) into the function (11) to obtain the created value for $0.5 < d \le 1$:

$$\begin{cases} Y_0 = \dfrac{2}{9}, Y_x = \dfrac{4 + 4(d+A) - 11d^2 + 8dA}{36} \\ Y_z = \dfrac{8 + d\left(17d - 2 + 6\sqrt{6d(2d-1)}\right)}{36}, \textit{and } Y_m = \dfrac{2 + 2d + 5d^2}{9} \end{cases} \tag{29}$$

From Expressions (28) if $0 < d \le 0.5$, then $Y_m > Y_x$ and $Y_z > Y_x$ are always true. If $0 < d \le 0.074$, there is $Y_z > Y_m$. Thus, the created value in descending order is (1) $Y_z > Y_m > Y_x$ for $0 < d \le 0.074$; (2) $Y_m > Y_z > Y_x$ for $0.074 < d \le 0.5$.

From Expressions (29) if $0.5 < d \le 1$, then $Y_m > Y_x$ and $Y_z > Y_x$ always hold. If $0.5 < d \le 0.912$, then $Y_m > Y_z$. Thus, the created value in descending order is (1) $Y_m > Y_z > Y_x$ for $0.5 < d \le 0.912$; (2) $Y_z > Y_m > Y_x$ for $0.912 < d \le 1$. To sum up, the created value in descending order is $Y_m > Y_z > Y_x$ for $0.074 < d \le 0.912$.

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