UNIVERSITAT ROVIRA I VIRGILI

THEORETICAL ESSAYS ON ENVIRONMENTAL POLICIES AND INTERNATIONAL TRADE CONFLICT

Mimi Zhang

Theoretical Essays on Environmental Policies and International Trade Conflict

PH.D. DISSERTATION

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FAIG CONSTAR que aquest treball, titulat "Assaigs Teòrics sobre Polítiques Mediambientals i Conflicte Comercial Internacional", que presenta Mimi Zhang per a l'obtenció del títol de Doctor, ha estat realitzat sota la meva direcció al Departament d'Economia d'aquesta universitat.

HAGO CONSTAR que el presente trabajo, titulado "Ensayos Teóricos sobre Políticas Ambientales y Conflictos Comerciales Internacionales", que presenta Mimi Zhang para la obtención del título de Doctor, ha sido realizado bajo mi dirección en el Departamento de Economía de esta universidad.

I STATE that the present study, entitled "Theoretical essays on Environmental Policies & International Trade Conflict", presented by Mimi Zhang for the award of the degree of Doctor, has been carried out under my supervision at the Department of Economics of this university.

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Theoretical Essays on Environmental Policies and International Trade Conflict

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Introduction

This doctoral dissertation is comprised of two distinct research topics. The first topic investigates the development of mechanisms for environmental policy design and is studied in the first and second chapters of the dissertation. The second topic focuses on the impact of international trade conflict on firm behavior, industry profits, and consumer surplus. This is explored in detail in the third chapter of the thesis.

In the first and second chapters of our research, we focus on the design and formulation of effective environmental policies. Specifically, we examine the design of emission tax mechanisms and environmental investment subsidy mechanisms in order to identify the most effective policies. Chapter one and chapter two respectively delve into these topics.

Policymakers and scholars have placed significant emphasis on environmental issues, including global warming, climate change, and environmental degradation. This has resulted in a growing body of literature on environmental policies (Wu et al., 2021). Market-based regulations, such as environmental taxation and subsidies, have become increasingly popular as efficient tools to curb pollution (Pasurka, 2020; Hasan et al., 2021). Governments must design and implement optimal tax mechanisms that improve social welfare, as the optimal tax plays a vital role in the economy (Nie & Wang 2019; Yang et al., 2020; Nie et al., 2022).

In the first chapter, we propose a new type of emissions tax mechanism that aims to minimize the impact on production and economic growth while maximizing green R&D investments. The output contest mechanism, green R&D investment contest mechanism, and net emission contest mechanism are designed to achieve environmental neutrality sustainably. The emission tax rate for each firm depends on its green performance relative to that of its rivals. Therefore, each firm's emissions tax burden is endogenous and can be reduced at the expense of other firms by decreasing emissions and increasing green R&D investments. Our results suggest that the net emission contest mechanism is most effective in achieving carbon neutrality, maximizing green R&D investments, and minimizing emissions in situations or industries with moderate to relatively large environmental damages.

However, in situations or industries with relatively small environmental damages, the green R&D investment contest mechanism may be more effective.

In the second chapter, we propose two contest-based subsidy mechanisms and evaluate their effectiveness in terms of firms' environmental investments, profits, consumer and producer surplus, environmental damage, and social welfare. The product green features (PGF) subsidy mechanism involves firms competing to invest in product green features to obtain the highest amount of subsidy. In the CO_2 abatement (ABA) subsidy mechanism, firms compete to invest in CO_2 abatement to obtain the highest amount of subsidy. Our results suggest that the PGF subsidy mechanism is more effective in promoting investments in product green features and increasing consumer surplus. However, the ABA subsidy mechanism is more effective in industries or technologies with relatively low emissions. Nonetheless, it is important to observe that these environmental policies may lead to inflation and may not always improve social welfare.

In the third chapter of our research, we shift our focus to the impact of international trade conflict on firm behavior, industry profits, and consumer surplus.

Protectionist measures have been commonly introduced by US presidents early in their first terms (Amiti et al., 2019). In 1971, Richard Nixon imposed a 10% tariff on dutiable imports (Irwin, 2013). Similarly, in 1977, Jimmy Carter imposed a quota on shoe imports (Merry, 2016), and in 1981, Ronald Reagan pressured the Japanese government to implement a "voluntary export restraint" agreement, which limited the exports of Japanese automobiles to the United States (Berry et al., 1999). More recently, George W. Bush imposed tariffs on steel in 2002, and Barack Obama placed 35% tariffs on Chinese tires in 2009 (Amiti et al., 2019). The Trump administration imposed tariffs on $283 billion of US imports in 2018, with rates ranging between 10% and 50%. The Biden administration has also invoked tariffs on US imports from China, continuing the trend of earlier presidential administrations.

These US tariffs have triggered retaliatory measures by many countries, including China, the European Union, Mexico, Russia, and Turkey, who have also imposed tariffs on US exports. Such a tit-for-tat sequence of imposing tariffs is typically referred to as a trade conflict, which has significantly impacted the economies of the US, China, and the rest of the world (Zhang et al., 2019).

Besides, the third chapter of our research focuses on strategic investments in the context of trade conflicts between a leading economy (home country) and a fast-growing economy (foreign country).

Our study examines how the likelihood of trade conflict affects firm behavior, including their exports, domestic sales, investments, industry profits, and consumer surplus. We find that, in symmetrical conditions, an increase in the probability of trade conflict generally has a negative effect on investment, production costs, and exports. As a result, firms in both the leading and fast-growing economies tend to act more conservatively during periods of high uncertainty associated with potential trade conflicts.

Furthermore, our research reveals that the effects of the likelihood of trade conflict differ between the leading and fast-growing economies. Specifically, while an increase in the probability of trade conflict may be relatively beneficial to the home economy, it may not necessarily be beneficial in absolute terms. This relative benefit may prompt firms in the home country to support the initiation of a trade conflict, even if it means merely threatening one. Our findings offer a compelling explanation for the ongoing US-China trade conflict.

The three chapters we have studied discuss various economic models and scenarios, each with specific policies and outcomes related to key indicators such as product market price, output, investment, consumer surplus, producer surplus, and total welfare. Table 0-1 summarizes which indicators are the focus of each chapter, as denoted by a check mark. While the chapters differ in their specific focus, there are also some commonalities and differences to note.

Commonalities:

Each chapter involves investment in some form, which can affect market outcomes and social welfare.

Each chapter studies the product market price, output, and consumer and producer surplus.

Each chapter includes policies that can influence market outcomes and social welfare.

Differences:

Chapter 1 involves green R&D investment, whereas Chapter 2 involves investment in product green features and emission reduction. Chapter 3 involves strategic investments, which could refer to investments aimed at increasing market power or competitiveness.

Chapter 1 and 2 both use an emission tax as a policy tool, but chapter 2 also includes a subsidy to incentivize green investments. Chapter 3 uses a tariff as an exogenous policy tool, which can affect trade and protectionism.

Chapter 2 involves investment in both product green features and emission reduction, which may have different effects on consumer and producer surplus compared to Chapter 1. Chapter 3 involves both domestic and export sales, which could have implications for trade and domestic industries.

Overall, the specific details and assumptions of each scenario can greatly affect the outcomes and implications for different stakeholders. In Chapter 2, investment in both product green features and emission reduction could lead to different market outcomes compared to Chapter 1, which focuses solely on green R&D investment. Chapter 3's inclusion of both domestic and export sales could also have different effects on market outcomes and welfare compared to Chapters 1 and 2.

	Product market price	Output	Investment	Consumer surplus	Producer surplus	Social welfare	Policies
Chapter 1	√	√	green R&D investment	√	√	√	Emission tax (endogenous)
Chapter 2	√	√	green R&D investment	√	√	√	Emission tax & subsidy (endogenous)
Chapter 3		√	strategic investments	√	√		Tariff (exogenous)

Table 0-1 A comparison of the three chapters

Therefore, potential further research is needed to analyze the effectiveness of environmental regulations in the face of trade conflict, the impact of trade conflicts on the adoption and diffusion of sustainable technologies, and the role of trade agreements in reconciling trade and environmental objectives. By addressing these issues, we can promote sustainable development despite the challenges of international trade conflict and environmental issues.

Chapter 1 Using Contests to Design Emission Tax Mechanisms[1]

Overview: In this chapter, we introduce three new emissions tax mechanisms designed to minimize economic losses, encourage green R&D investments, and promote sustainable reduction of environmental emissions. We develop a new model by merging industrial organization theory and contests theory to explore the implications of these mechanisms: the output contest, the green R&D investment contest, and the net emission contest. Firms compete in production and green R&D investments to reduce their tax burden. We compare multiple performance indicators, such as carbon neutrality, production, emissions, green R&D investment, consumer and producer surplus, welfare, and value-added, to identify the optimal mechanism. We find that the net emission contest mechanism is the most effective for achieving carbon neutrality, maximizing green R&D investment, and minimizing emissions in industries with moderate to significant environmental damage. However, in industries with relatively small environmental damage, the green R&D investment contest mechanism may be the most suitable.

Keywords: Emissions tax mechanisms; Contests; Green investments; Carbon neutrality

***JEL classification**:* Q580; Q520; L290

[1] This chapter has been published with co-author António Osório as a research paper in the journal Sustainable Production and Consumption.

1.1 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 & 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 & 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 & 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 at 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 & Yan, 2021; Dechezleprêtre & 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 study 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 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:

(a) *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.

(b) *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.

(c) *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.

Placed into context, the emission tax acts as an environmental policy. According to the United Nations 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, 2021). However, exogenous carbon taxes are less efficient than endogenous taxes in terms of incentivizing firms' green R&D (Lambertini & Tampieri, 2014; Lambertini et al., 2017). Furthermore, there are additional challenges in terms of mitigating pollution emissions with minimal impact on production and growth while maintaining firms' incentives to make green R&D investments and achieve carbon neutrality targets as quickly as possible. Additionally, for the emission tax mechanism to be feasible, it must have public acceptance and be fair and well-designed.

Based on the background and concerns mentioned above, this study aims to answer several research questions. Firstly, it seeks to determine how to design an emissions tax mechanism that has less impact on economic growth, incentivizes firms' green R&D investments, and achieves carbon neutrality. This includes setting the tax rate in a fair way and determining the tax base. Secondly, the study aims to find a balance between fairness and effectiveness when designing an emission tax mechanism based on the Polluter-Pays-Principle, while reducing negative environmental externalities. Specifically, the mechanism should be proportional in terms of production/pollution and inversely proportional in terms of green R&D investments relative to competitors. Thirdly, the study investigates the impact of the emission tax rate on firms' green R&D investment, production, net emissions, producer surplus, consumer surplus, and social welfare if the tax rate is determined by the output and green investment of firms. Lastly, the study evaluates different emission tax mechanisms' performance in terms of firms' green R&D investments, production, net emissions, producer surplus, consumer surplus, social welfare, and created value.

To address these research questions, the study builds a model that combines industrial organization theory and contests theory. The model focuses on a competitive industry where each firm produces a homogeneous product, and production activities generate pollution. Firms make decisions on their green R&D investments and output simultaneously, and the green R&D investments are aimed at reducing emissions. Importantly, the study's approach endogenizes the emissions tax so that it depends on firms' behaviors in a competitive way, rather than the typical exogenous and blind emission taxation. The emission tax base is the sum of all producers' net emissions. The study also considers several extensions to the baseline model to complete the analysis.

This analysis is the first to endogenize the emissions taxation mechanism through a contest that considers firms' production and green R&D investment decisions in competitive markets. The study and analysis are multidimensional, as they consider several aspects of firm performance, such as producer surplus, green R&D investments and production, as well as consumer surplus, social welfare, and the created value for society. Furthermore, the study provides guidance to policy makers and practitioners on designing and implementing optimal emission taxation mechanisms that not only address pressing environmental issues but also fully internalize their economic effects and appropriately associate them with the level of environmental damages. The literature on designing emissions taxation mechanisms is limited in this respect, and this study fills this gap and opens new avenues for research and thinking regarding environmental taxation.

In addition to propose a new kind of emission taxation mechanism, 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 Figure 1-1. 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.

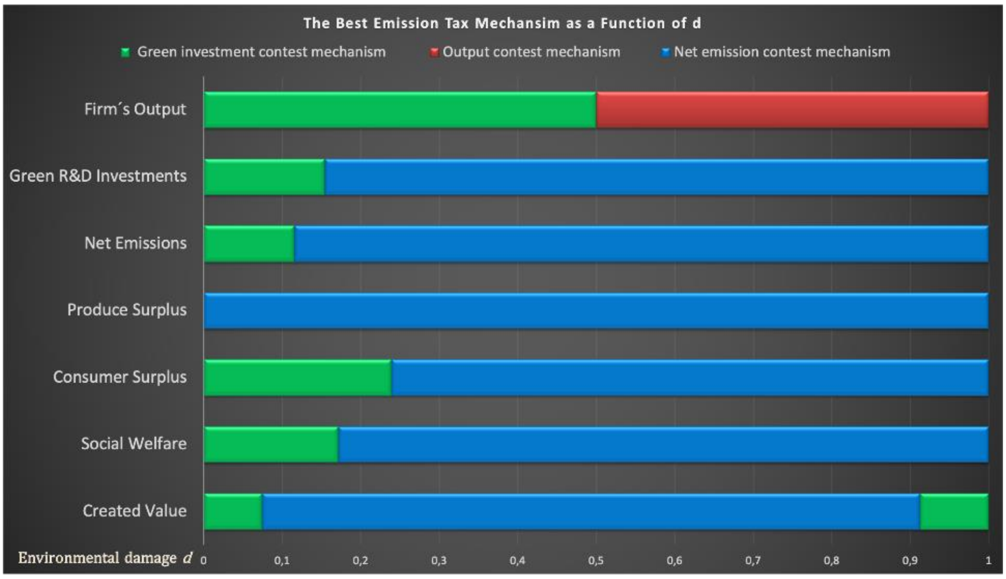

Figure 1-1 The best emission tax mechanism for different indicators and varying environmental damages

Further, by extending the model to the case of n firms, we found that market competition becomes more intense, resulting in more efficient mechanisms to achieve carbon neutrality. In the case of different production costs, the difference in cost has distinct effects on the production and green R&D investments of high-cost 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 remains the most efficient way to achieve carbon neutrality. It is the optimal choice to reduce pollutant emissions, achieve maximum social welfare and GDP, and overcome capacity and investment constraints.

In summary, the study presents an effective and easy-to-understand solution to the problem of emissions taxation by encouraging firms to compete to pay less taxes. The proposed mechanisms are equitable and feasible, as they promote green R&D investments, hasten carbon neutrality, and minimize the impact on firms' economic growth and production. Among the analyzed mechanisms, the net emission contest mechanism is recommended as the optimal approach for achieving carbon neutrality and maximizing social welfare, among other key indicators. Additionally, the proposed emission tax mechanisms are forward-looking, focusing on present and future investment and production decisions rather than past actions. This aspect is crucial for obtaining consensus and agreement in international climate negotiations among major world powers like the US, China, EU, and India. Practical implementation is also a key consideration in the proposed approach.

The remainder of this chapter is organized as follows. Section 1.2 presents a review of the literature. Section 1.3 introduces the three emissions tax mechanisms and develops the model used to evaluate them. Section 1.4 reports the main results of our analysis. Section 1.5 discusses some extension cases. Section 1.6 discusses these results. Section 1.7 concludes and proposes future research objectives. The mathematical proofs can be found in the Appendix 1.8.

1.2 Literature review

Literatures related to this chapter mainly exist in three areas including the adoption of environmental policy, the choice of environmental tax, and the design of emission tax mechanisms. In the following section, we review the works associated with each stream and analyze the difference between our research and existing literatures.

1.2.1 The adoption of environmental policy

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 & 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 & Zhang, 2022). For instance, the command-and-control regulation 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 Stavins (2000) 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 & Stavins, 2012; Wu et al., 2021). In this study, 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., 2018). 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., 2018; Zhou & 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 study. 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 & Peng, 2022).

1.2.2 The design of emission tax mechanism

Designing and implementing optimal tax mechanisms that improve social welfare is crucial for governments, as the optimal tax plays an exceedingly important role in the economy (Nie & Wang, 2019; Yang et al., 2020; Nie et al., 2022). However, 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 to 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 types of carbon taxes to gain public support. Arıkan & 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 such as the tax base, tax rates, and the use of revenues. Moreover, Annicchiarico & 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.

However, the two primary carbon tax approaches, the Fuel Approach and the Emissions Approach, are exogenous environmental-related taxes, and the tax rates are often designed and set by the government. For instance, in 2021, Argentina applied an exogenous carbon tax of US$ 65.54 t/CO2e (UN, 2021; Metcalf, 2021; Partnership for Market Readiness (PMR), 2017). Setting the 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 social welfare (Ebert & Von Dem Hagen, 1998).

Theoretically, an emission tax should be set at the marginal social cost of the damage generated (known as the social cost of carbon). Therefore, the optimal tax rate should be such that the marginal benefit of abatement equals the marginal cost of abatement (Metcalf, 2021). However, as suggested by Metcalf & Weisbach (2009), estimates of such an optimal tax rate vary widely, and the calculations are difficult if the emission tax is fixed. According to a survey from the Intergovernmental Panel on Climate Change (IPCC), such an emission tax underestimates the costs of carbon emissions because of the difficulty in quantifying their 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, our study contributes to the growing literature on the design of emissions taxation mechanisms by bridging two important streams. The first stream focuses on the choice of emission tax instruments among environmental policies, while the second emphasizes the effects of emission tax design and its mechanisms on firms' green investments and the environment. By presenting a novel approach to emission taxation, we fill an important gap in the literature and open new avenues of research and thinking in terms of environmental taxation and policy. Our proposed contest mechanism considers firms' production and green R&D investment decisions in competitive markets, and this approach can even be extended to other policy designs like Cap-and-trade systems. We believe that emissions taxation should be determined by firms' competition in terms of green R&D investments and emission reductions, rather than being exogenously fixed by governments. This competitive mechanism provides the best incentives for green R&D investments and a faster transition to carbon neutrality.

1.3 Model

Nomenclature

All the variables and the symbols are defined in this table.

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 money 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.

Table 1-1 Variables and model parameters

1.3.1 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 the other firm'.

(i) Mechanism X is a production contest: the emission tax rate t_i^x of firm i is based on its production relative to the other firm's. As shown in Figure 1-2, a reduction in the emission tax rate is achieved by reducing production according to the following contest success function:

$$t_i^x = \frac{x_i}{x_1 + x_2} \tag{1.1}$$

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.

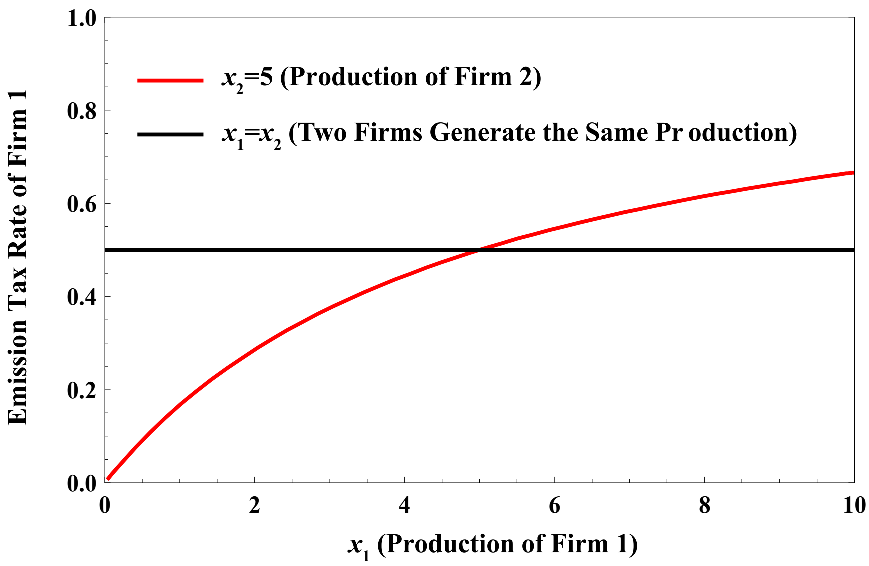

Figure 1-2 Mechanism X

Note: The emission tax rate of firm 1 increases with an increase in its own production.

(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 the other firm's investments. As shown in Figure 1-3, a reduction in the emission tax rate is achieved by investing more in green R&D according to the following contest success function:

$$t_i^z = \begin{cases} \dfrac{z_{-i}}{z_1 + z_2} & x_i \geq z_i, \quad (1.2) \\ \dfrac{z_i}{z_1 + z_2} & x_i < z_i, \quad (1.3) \end{cases}$$

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 smaller the 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.

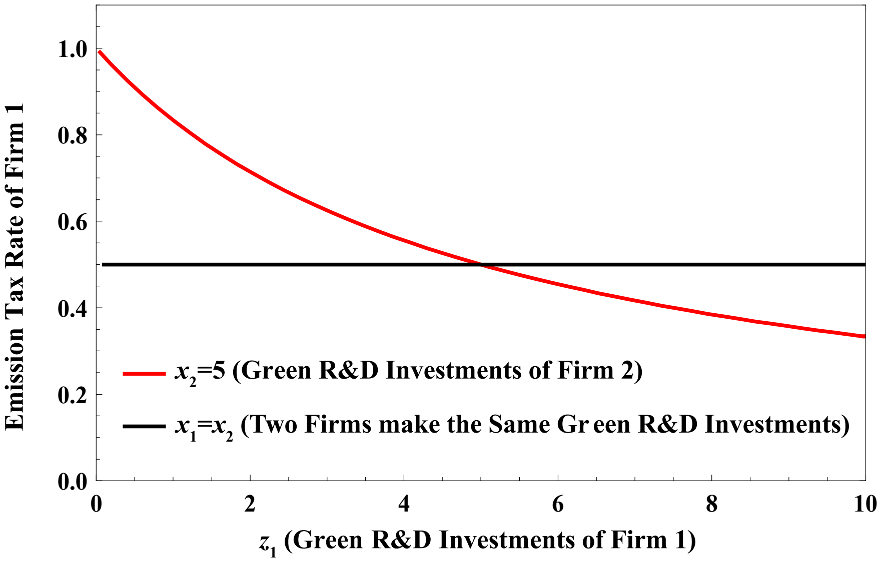

Figure 1-3 Mechanism Z

Note: The emission tax rate of firm 1 decreases with an increase in its own green R&D investments.

(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 the other firm's net emissions. As shown in Figure 1-4, a reduction in the emission tax rate is achieved by reducing net emissions according to the following contest success function:

$$t_i^m = \frac{e_i}{e_1 + e_2} \tag{1.4}$$

where $e_i = x_i - z_i$ is the net emissions of firm $i = 1,2$.

The motivation is that mechanism M favors firms with lower net emissions. A higher net emission implies that a firm needs to pay more emission tax if $e_i \geq 0$. However, net emissions will become emission reductions if $e_i < 0$, and more emission reductions imply that more environmental subsidy a firm can obtain. Again, in this case, the firm reaches in a state of carbon neutrality.

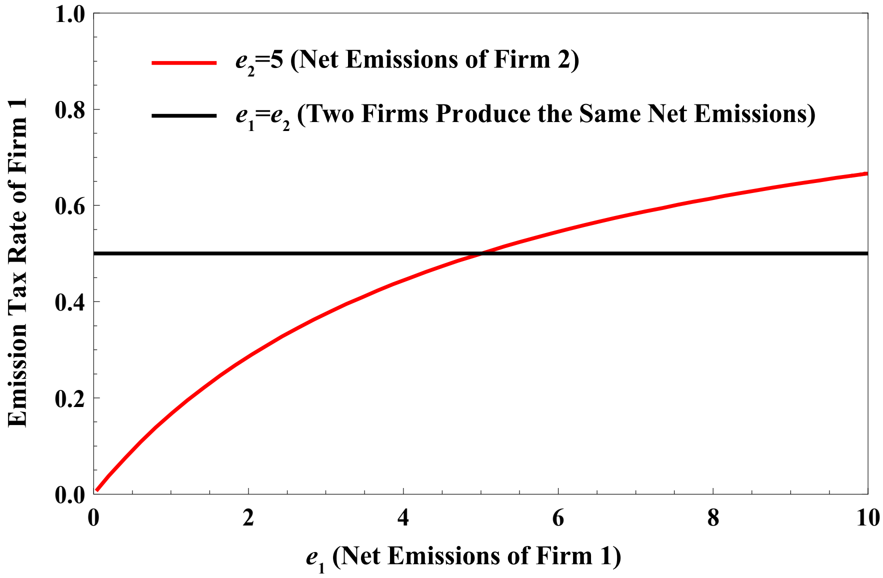

Figure 1-4 Mechanism M

Note: The emission tax rate of firm 1 increases with an increase in its own net emissions.

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

Secondly, using a contest in emissions tax mechanisms mitigates the problem of unfairness. This is a criticism of the grandfathering scheme, in which some polluters may be rewarded with valuable permits for their previous polluting actions. For instance, heavy polluters are typically awarded more permits than less polluting firms (MacKenzie et al., 2009). A contest emission taxation mechanism appears fairer than alternative mechanisms because it rewards firms that invest in and make efforts to attain abatement objectives, rather than the usual blind tax mechanism that ignores important aspects such as 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.

1.3.2 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 & 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:

$$e_i = x_i - z_i \tag{1.5}$$

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:

$$D = d\,E \tag{1.6}$$

where $\mathrm{E} = e_1 + e_2$ 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 & 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:

$$\pi_i = \big(a - (x_1 + x_2)\big)x_i - \gamma \frac{{z_i}^2}{2} - t_i^k\, d\, E \qquad (1.7)$$

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 the other firm.

Furthermore, we include a control benchmark or reference case in which firms do not consider environmental damage, and hence, do not pay any emission taxes. This benchmark serves as a point of reference for regulators and policymakers to assess the efficacy of different mechanisms using various 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:

$$CS = \frac{(x_1 + x_2)^2}{2} - D. \tag{1.8}$$

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

$$PS = \pi_1 + \pi_2. \tag{1.9}$$

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

$$SW = CS + PS. \tag{1.10}$$

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

$$Y = R + I = p(x_1 + x_2) + \gamma \frac{{z_1}^2}{2} + \gamma \frac{{z_2}^2}{2} \tag{1.11}$$

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.

1.4 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 1.1

(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 1.1 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 1.2

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 Figure 1-5. 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 1.2).

However, if there is an increase in the environmental damages, that is $0.154 < d \leq 1$, mechanism M provides the maximum incentives for the firm's green R&D investments in order to reduce the emissions tax burden. Note that when $0.25 < d \leq 0.5$, firm's cleaning is more than pollution under mechanism M; and the emission tax becomes a reward (or subsidy). While if the environmental damages are relatively high ($0.5 < d \leq 1$), all three mechanisms provide incentives enough and firms obtain environmental subsidy on abatements, with mechanism M supporting the maximum potential subsidy that can stimulate a firm's investment in green R&D. Hence, mechanism M is the first best. Mechanism Z is the second best (Part (b) of proposition 1.2).

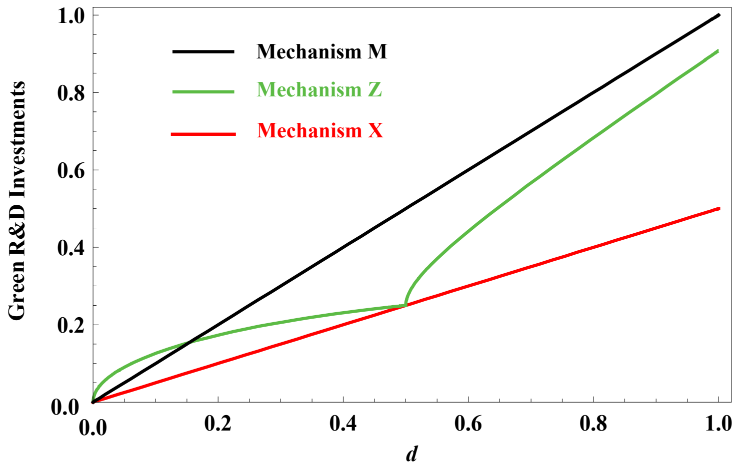

Figure 1-5 Green investments under three mechanisms

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.

Proposition 1.3

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 1.3 that we would like to stress:

Corollary 1.1

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 Figure 1-6. 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.

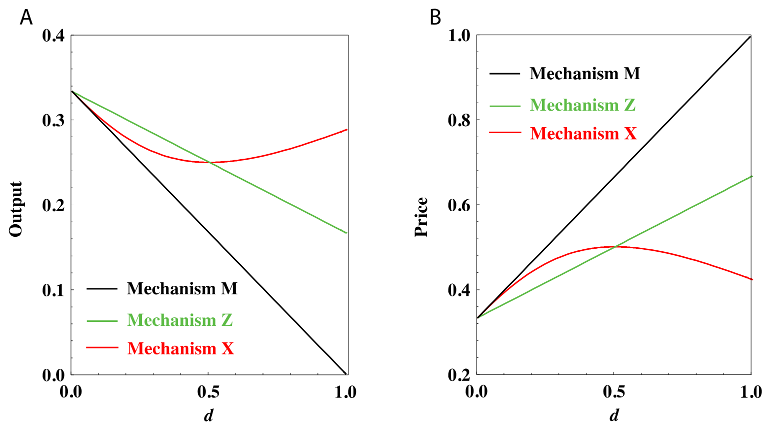

Figure 1-6 Output & Price under three mechanisms

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.

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 1.3), since firms do not need to bear the costs of pollution.

Proposition 1.4

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 1.4 that we would like to stress:

Corollary 1.2

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 Figure 1-7, 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 1.4 and Corollary 1.2). 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 1.4 and Corollary 1.2).

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.

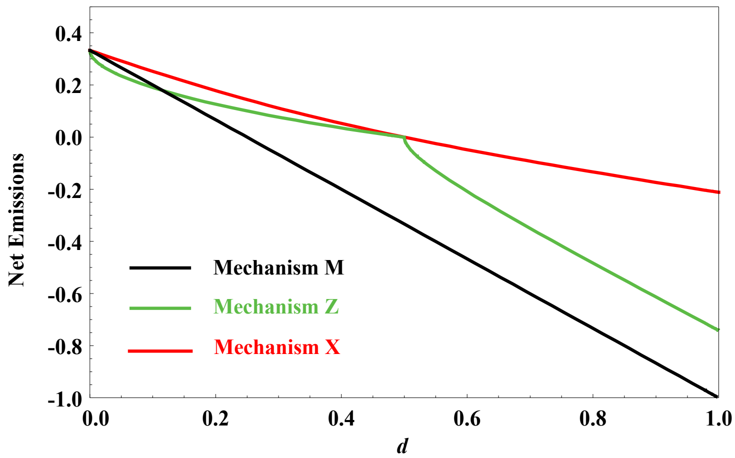

Figure 1-7 Net emissions under three mechanisms

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.

Proposition 1.5

The mechanisms that maximize the producer surplus are in the following descending order:

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

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

Proposition 1.5 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 1.3), 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 Proposition 1.2 and 1.4), then they obtain the maximum private benefits and common benefits. Therefore, through Proposition 1.2, 1.3 and 1.5, 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 1.6

The mechanisms that maximize the consumer surplus are in the following descending order:

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

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

Figure 1-8 illustrates proposition 1.6. 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 1.6).

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 1.6).

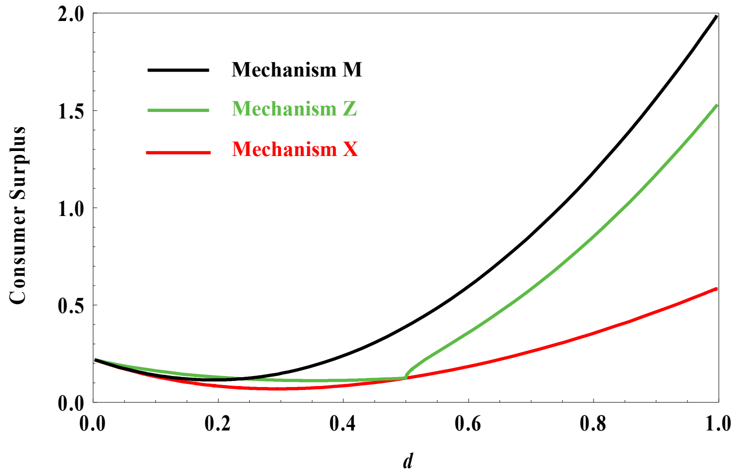

Figure 1-8 Consumer Surplus under three mechanisms

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.

Proposition 1.7

The mechanisms that maximize the social welfare are in the following descending order:

(a) $SW_m > SW_x > SW_z$ *for* $0 < d \leq 0.0012$.

(b) $SW_m > SW_z > SW_x$ *for* $0.0012 < d \leq 0.0013$.

(c) $SW_z > SW_m > SW_x$ *for* $0.0013 < d \leq 0.174$.

(d) $SW_m > SW_z > SW_x$ *for* $0.174 < d \leq 1$.

Since cases (a) and (b) correspond to 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 $0.0013 < d \leq 0.174$, 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 1.6).

However, with an increase in environmental damages ($0.174 < d \leq 1$), 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 Proposition 1.5 and Proposition 1.6).

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 1.8

The mechanisms that maximize the created value are in the following descending order:

(a) $Y_z > Y_m > Y_x$ *for* $0 < d \leq 0.074$.

(b) $Y_m > Y_z > Y_x$ *for* $0.074 < d \leq 0.912$.

(c) $Y_z > Y_m > Y_x$ *for* $0.912 < d \leq 1$.

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 Proposition 1.2 and 1.3).

However, when environmental damages are in a wide range ($0.074 < d \leq 0.912$), 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 Figure 1-9, 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. Figure 1-6B 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.

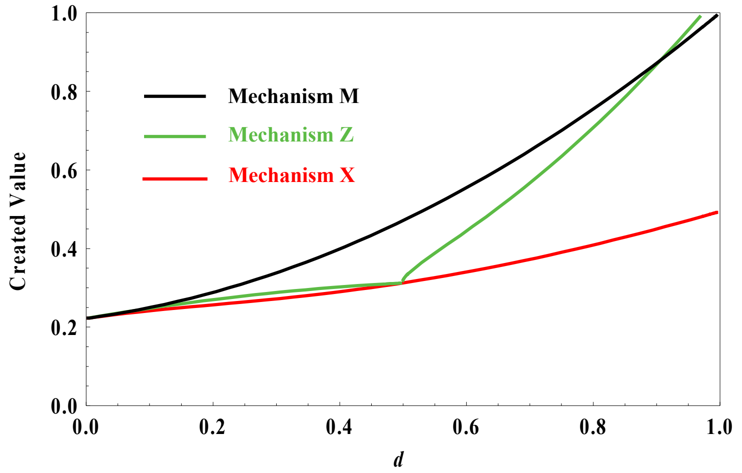

Figure 1-9 Created value under three mechanisms

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.

1.5 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 chapter.

1.5.1 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 $3 \leq n \leq 8$.

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 $\frac{n}{2+n} \leq d \leq 1$, mechanism Z delivers carbon neutrality and negative emission when $\frac{n}{n+n^2-2} \leq d \leq 1$, and mechanism M delivers carbon neutrality and negative emission when $\frac{1}{2+n} \leq d \leq 1$. 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.

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 $\frac{n^2-n}{1-2n+2n^2+n^3} \leq d \leq \frac{n}{n+n^2-2}$ and $\frac{4n^2-4n}{4n+n^2+n^3-4} \leq d \leq 1$. 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 $\frac{n^3-n}{2+n+2n^2+3n^3+n^4} \leq d \leq \frac{n}{n+n^2-2}$, and $\frac{4n^2-4n}{4n+n^2+n^3-4} \leq d \leq 1$, 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.

1.5.2 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.

1.5.3 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 Corollaries 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 $0.154a < d \leq a$.

1.5.4 The possibility of constraints

Taking energy capacity constraints into account, it is important to consider the environmental effects (Nie & Wang, 2019). Firms in both energy-intensive and non-energy-intensive sectors need to understand their constraints and their implications on production and investment capacity to stay competitive. In our basic model, the two competing firms have unlimited capacity to produce any amount they wish based on the assumed cost structure. In this section, we assume that firms have limited capacities.

When we consider capacity constraints, we must note that they may create difficulties regarding the existence of Nash equilibrium. Additionally, 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 with production capacity. Surprisingly, 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, production capacity has positive effects on the green R&D investment when mechanism Z is an emission tax system, but negative effects 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, and 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 firms' production is related to their green investments. However, according to the OECD report (2017), 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 the tax rates (Fazzari et al., 1988).

In this case, since high investment means high costs that firms need to pay, the investment capacity of firms may be restricted. We find that under symmetric and investment capacity constraints, production has no relationship with investment capacity constraints under mechanisms Z and M. However, under mechanism X, production increases with investment capacity. Therefore, the larger the 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 in 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 & 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 option in the case of constraints.

1.6 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.

1.6.1 An optimal emission tax mechanism

In accordance with previous research findings, different emission tax or subsidy systems elicit varying responses from firms in terms of output and green R&D investments (Dechezleprêtre & Sato, 2020). While an increasing number of governments have proposed targets to achieve zero net emissions, only a few have provided detailed plans on how to attain them. Therefore, achieving carbon neutrality necessitates action at both the country and firm levels (Grainger & Smith, 2021). With many countries investing in high-CO_2 activities, the efficient design of emission tax mechanisms is crucial. In this context, the emission tax mechanism should align with the objective of zero net emissions. To this end, we propose a new type of emission taxation mechanism that involves firms competing through a contest to pay fewer taxes. We have designed three mechanisms based on the Polluter-Pays-Principle to reduce negative environmental externalities, including the output contest mechanism, the green R&D investment contest mechanism, and the net emission contest mechanism. We assert that the three proposed mechanisms are feasible for achieving these objectives, with mechanism M being the most efficient.

Market competition affects how firms achieve carbon neutrality, with a greater number of firms leading to more intense competition and greater efficiency in achieving carbon neutrality. This confirms the study by Qiao et al. (2022). Distinct production costs have different effects on the production and green R&D investment of high-cost and low-cost firms. Mechanism X enables both low-cost and high-cost firms to achieve carbon neutrality under similar conditions. However, mechanisms Z and M make it difficult or impossible for low-cost firms to achieve carbon neutrality but make it easier and faster for high-cost firms. An increase in the parameter of green R&D investment cost decreases the efficiency of the three mechanisms in helping firms achieve carbon neutrality due to lower investment efficiency.

The net emission indicator reflects the joint effect of a firm's production activity and green investment. Lowering the emission level results in higher profits (Hasan et al., 2021). Lower output and greater green R&D investments lead to lower net emissions by firms and reduced total environmental damage. In combination with the comprehensive impact of intense market competition on firms' output and green investment under the three mechanisms, mechanism M is the optimal choice for controlling net emissions.

We conclude that all three emission tax mechanisms provide incentives for firms' green R&D investments, but the amount of incentives varies among them. Standard market mechanisms do not stimulate green innovation, which gives emission taxation an advantage over more rigid and prescriptive environmental policy instruments. Therefore, designing an efficient mechanism is crucial for developing realistic and efficient climate policies.

Moreover, we argue that levying taxation on emissions internalizes environmental externality by transforming environmental damages into costs for firms associated with pollution. Different emission tax rates result in different emission tax burdens and abatement costs. By comparing the four options (three mechanisms and the benchmark case), we assert that implementing an emission tax increases the cost of energy-intensive and high-emission industries, potentially harming their competitiveness. This competitiveness effect can result in negative economic outcomes (Aldy & Stavins, 2012) and an increase in the overall price level (inflation effect). Our findings are consistent with the Porter hypothesis, which states that well-designed and stringent environmental policies can stimulate innovation, leading to increased firm productivity or product value for end-users (Porter & Van Der Linde, 1995; Zhong & Peng, 2022). We suggest that mechanisms Z and M favor the Porter hypothesis by providing significant incentives for firms' green innovation when both firms and consumers seek new and cleaner solutions.

1.6.2 Policy implications

The emission tax is considered fundamental to support environmental policy and climate mitigation. It is also considered the most cost-efficient policy instrument; 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 2021), and 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 policymakers to recognize the importance of policy acceptability. Therefore, it is necessary to justify the acceptability of the emission tax mechanism in this study.

Firstly, based on the idea of the Polluter-Pay-Principle and the reduction of negative environmental externalities, the consequences of the emission tax under the three tax mechanisms are perceived as being fair. Secondly, the three mechanisms provide an effective and intuitive solution to the problem of 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 present and future decisions rather than past decisions, are more likely to be consensual and receive agreement by world powers such as the United States, the European Union, India, or China, which have found it difficult to get a consensual way of taxing emissions.

On the other hand, imposing an emission tax based on the 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 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 firms. Therefore, these emission tax mechanisms may be more complicated in terms of administrative and implementation reasons compared to 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 chapter have the advantage of providing stronger incentives for green R&D investments and the transition to carbon neutrality. It is also a fair and consensual market-based solution to the emissions taxation problem.

1.7 Conclusion

This chapter 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 chapter 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 study 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 study 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.

1.8 Appendix

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 $\gamma = 1$ 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 sub-section 1.5.3 of the extension section, we assign $\gamma = 2$. The main results are summarized there.

We start by substituting (1.1), (1.2) and (1.4) into (1.7), 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:

$$z_0 = 0\,, z_x = \frac{d}{2}, z_z = \frac{B}{6}, \text{and } z_m = d. \tag{1.12}$$

$$x_0 = \frac{1}{3}, x_x = \frac{1-d+A}{6}, x_z = \frac{2-d}{6}, \text{and } x_m = \frac{1-d}{3}. \tag{1.13}$$

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

In order to ensure that the expressions (1.13) are greater than or equal to 0, it is enough to assume that $0 < d \leq 1$.

However, note that from expressions (1.12) and (1.13), 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 (1.1) (1.3) and (1.4) into (1.7) 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:

$$z_0 = 0, z_x = \frac{d}{2}, z_z = \frac{3d + \sqrt{6d(2d-1)}}{6}, \text{and } z_m = d. \tag{1.14}$$

$$x_0 = \frac{1}{3}, x_x = \frac{1-d+A}{6}, x_z = \frac{2-d}{6}, \text{and } x_m = \frac{1-d}{3}. \tag{1.15}$$

Again, in order to ensure that the expressions (1.15) are greater than or equal to 0, we must have $0 < d \leq 1$.

Proof of Proposition 1.1

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 $0 < d < 1$.

Proof of Proposition 1.2

From expressions (1.12), 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 (1.14), 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 $0.154 < d \leq 1$.

Proof of Proposition 1.3

From expressions (1.13), if $0 < d \leq 0.5$, then $x_z > x_x > x_m$ is always true.

From expressions (1.15), if $0.5 < d \leq 1$, then $x_x > x_z > x_m$ is always true.

Now, we substitute (1.12) and (1.13) into equation (1.5) to obtain the equilibrium net emissions. If $0 < d \leq 0.5$, we have:

$$e_0 = \frac{1}{3}, e_x = \frac{1-4d+A}{6}, e_z = \frac{2-d-B}{6} \text{ and } e_m = \frac{1-4d}{3}. \tag{1.16}$$

Then we substitute (1.14) and (1.15) into equation (1.5) to obtain the equilibrium of net emissions. For $0.5 < d \leq 1$, we have:

$$e_0 = \frac{1}{3}, e_x = \frac{1-4d+A}{6}, e_z = \frac{2-4d-\sqrt{6d(2d-1)}}{6} \text{ and } e_m = \frac{1-4d}{3}. \tag{1.17}$$

Next, we substitute the expressions of net emissions (1.16) into equation (1.6), to obtain the equilibrium environmental damages for $0 < d \leq 0.5$:

$$D_0 = \frac{2d}{3}, D_x = \frac{d(1-4d+A)}{3}, D_z = \frac{d(2-d-B)}{3} \text{ and } D_m = \frac{2d(1-4d)}{3}. \tag{1.18}$$

By substituting expressions of net emissions (1.17) into the equation (1.6), we obtain the equilibrium environmental damages for $0.5 < d \leq 1$:

$$\begin{cases} D_0 = \frac{2d}{3}, D_x = \frac{d(1-4d+A)}{3}, \\ D_z = \frac{d\left(2-4d-\sqrt{6d(2d-1)}\right)}{3}, \text{and } D_m = \frac{2d(1-4d)}{3} \end{cases} \tag{1.19}$$

Proof of Proposition 1.4

From expressions (1.16), if $0 < d \leq 0.5$, then $e_x > e_m$ is always true. If $d \leq 0.115$, then $e_m > e_z$, hence, the net emissions in descending order are $e_x > e_m > e_z$. Then, if $0.115 < d \leq 0.5$, then $e_x > e_z > e_m$.

From expressions (1.17), if $0.5 < d \leq 1$, $e_x > e_z > e_m$ is always true. To sum up, the net emissions in descending order is $e_x > e_z > e_m$ for $0.115 < d \leq 1$.

From expressions (1.18) and (1.19), the proof of **Corollary 1.2** is similar to that of **Proposition 1.4**.

Proof of Proposition 1.5

We replace the obtained green R&D investment (1.12), output (1.13) and net emissions (1.16) back into the objective function (1.7) to obtain equilibrium of firm's profit for $0 < d \leq 0.5$:

$$\begin{cases} \pi_0 = \frac{1}{9}, \pi_x = \frac{4(1-d)^2 + 15d^2 - 4dA + 4A}{72} \\ \pi_z = \frac{8 - 26d + 11d^2 + 12dB}{72}, \text{and } \pi_m = \frac{9d^2 + 2(1-d)^2}{18} \end{cases} \tag{1.20}$$

Also, we replace the obtained green R&D investment (1.14), output (1.15) and net emissions (1.17) back into the objective function (1.7) to obtain equilibrium of firm's profit for $0.5 < d \leq 1$:

$$\begin{cases} \pi_0 = \dfrac{1}{9}, \pi_x = \dfrac{4(1-d)^2 + 15d^2 - 4dA + 4A}{72} \\ \pi_z = \dfrac{8 + d(23d - 14 + 6\sqrt{6d(2d-1)})}{72}, \text{and } \pi_m = \dfrac{9d^2 + 2(1-d)^2}{18} \end{cases} \tag{1.21}$$

Then, we substitute profit expressions (1.20) into function (1.9) to obtain producer surplus for $0 < d \leq 0.5$:

$$\begin{cases} PS_0 = \dfrac{2}{9}, PS_x = \dfrac{4(1-d)^2 + 15d^2 - 4dA + 4A}{36} \\ PS_z = \dfrac{8 - 26d + 11d^2 + 12dB}{36}, \text{and } PS_m = \dfrac{9d^2 + 2(1-d)^2}{9} \end{cases} \tag{1.22}$$

We also substitute profit expressions (1.21) into function (1.9) to obtain producer surplus for $0.5 < d \leq 1$:

$$\begin{cases} PS_0 = \dfrac{2}{9}, PS_x = \dfrac{4(1-d)^2 + 15d^2 - 4dA + 4A}{36} \\ PS_z = \dfrac{8 + d\left(23d - 14 + 6\sqrt{6d(2d-1)}\right)}{36}, \text{and } PS_m = \dfrac{9d^2 + 2(1-d)^2}{9} \end{cases} \tag{1.23}$$

From expressions (1.22), if $0 < d \leq 0.5$, then $PS_m > PS_x > PS_z$ is always true.

From expressions (1.23), if $0.5 < d \leq 1$, then $PS_m > PS_z > PS_x$ is always true.

Proof of Proposition 1.6

Now, substitute the firm's output (1.13) and environmental damages (1.18) into function (1.8) to obtain consumer surplus for $0 < d \leq 0.5$:

$$\begin{cases} CS_0 = \dfrac{2-6d}{9}, CS_x = \dfrac{2 + 2A + d(29d - 10 - 8A)}{18} \\ CS_z = \dfrac{4 - 16d + 6dB + 7d^2}{18}, \text{and } CS_m = \dfrac{2(1 - 5d + 13d^2)}{9} \end{cases} \tag{1.24}$$

Then, substituting the firm's output (1.15) and environmental damages (1.19) into function (1.8) to obtain consumer surplus for $0.5 < d \leq 1$:

$$\begin{cases} CS_0 = \dfrac{2-6d}{9}, CS_x = \dfrac{2 + 2A + d(29d - 10 - 8A)}{18} \\ CS_z = \dfrac{4 + d(25d - 16 + 6\sqrt{6d(2d-1)})}{18}, \text{and } CS_m = \dfrac{2(1 - 5d + 13d^2)}{9} \end{cases} \tag{1.25}$$

From expressions (1.24), if $0 < d \leq 0.5$, then $CS_m > CS_x$ and $CS_z > CS_x$ are always true. If $0 < d \leq 0.239$, then $CS_z > CS_m$. Therefore, consumer surplus in descending order are: (1) $CS_z > CS_m > CS_x$ for $0 < d \leq 0.239$; (2) $CS_m > CS_z > CS_x > CS_0$ for $0.239 < d \leq 0.5$.

From expressions (1.25), if $0.5 < d \leq 1$, $CS_m > CS_z > CS_x$ is always true. To sum up, $CS_m > CS_z > CS_x$ for $0.239 < d \leq 1$.

Proof of Proposition 1.7

In order to obtain the social welfare, we substitute the consumer surplus (1.24) and the producer surplus (1.22) into function (1.10) for $0 < d \leq 0.5$, and then the social welfare is given by:

$$\begin{cases} W_0 = \dfrac{4-6d}{9}, W_x = \dfrac{77d^2 + 8(1+A) - 4d(7+5A)}{36} \\ W_z = \dfrac{16 - 58d + 24dB + 25d^2}{36}, \text{and } W_m = \dfrac{4 + d(37d - 14)}{9} \end{cases} \tag{1.26}$$

We also substitute consumer surplus (1.25) and producer surplus (1.23) into function (1.10) for $0.5 < d \leq 1$, and then social welfare is given by:

$$\begin{cases} W_0 = \dfrac{4-6d}{9}, W_x = \dfrac{77d^2 + 8(1+A) - 4d(7+5A)}{36} \\ W_z = \dfrac{16 + d(73d - 46 + 18\sqrt{6d(2d-1)})}{36}, \text{and } W_m = \dfrac{4 + d(37d - 14)}{9} \end{cases} \tag{1.27}$$

From expressions (1.26), if $0 < d \leq 0.5$, then $W_m > W_x$ is always true. If $0 < d \leq 0.0012$, there is $W_x > W_z$. If $0.0013 < d \leq 0.174$, there is $W_z > W_m$. To sum up, the total welfare in descending order are: (1) $W_m > W_x > W_z$ for $0 < d \leq 0.0012$; (2) $W_m > W_z > W_x$ for $0.0012 < d \leq 0.0013$ and $0.174 < d \leq 0.5$; (3) $W_z > W_m > W_x$ for $0.0013 < d \leq 0.174$.

From expressions (1.27), if $0.5 < d \leq 1$, $W_m > W_z > W_x$ is always true. Therefore, $W_m > W_z > W_x$ for $0.174 < d \leq 1$.

Proof of Proposition1.8

By substituting firm's output (1.13) and green R&D investment (1.12) into the function (1.11) to obtain the created value for $0 < d \leq 0.5$:

$$\begin{cases} Y_0 = \frac{2}{9}, Y_x = \frac{4 + 4(d + A) - 11d^2 + 8dA}{36} \\ Y_z = \frac{(2 - d)(4 + 7d)}{36}, \textit{and } Y_m = \frac{2 + 2d + 5d^2}{9} \end{cases} \tag{1.28}$$

By substituting firm's output (1.15) and green R&D investment (1.12) into the function (1.11) to obtain the created value for $0.5 < d \le 1$:

$$\begin{cases} Y_0 = \frac{2}{9}, Y_x = \frac{4 + 4(d + A) - 11d^2 + 8dA}{36} \\ Y_z = \frac{8 + d(17d - 2 + 6\sqrt{6d(2d - 1)})}{36}, \text{and } Y_m = \frac{2 + 2d + 5d^2}{9} \end{cases} \tag{1.29}$$

From expressions (1.28) 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 (1.29) 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 $0.074 < d \le 0.912$.

Chapter 2 Incentivizing Environmental Investments: The Contest-based Subsidy Allocation Mechanism[2]

Overview: Governments often provide subsidies to incentivize investments that are considered important for the society. The question is how to distribute those subsidies in the most efficient way. This chapter proposes two novel contest-based subsidy mechanisms and evaluates their effectiveness in terms of firms' environmental investments, profits, consumer and producer surplus, environmental damage and social welfare. In the product green features (PGF) subsidy mechanism firms compete in terms of investment in product green features in order to obtain the highest amount of subsidy. In the CO_2 abatement (ABA) subsidy mechanism firms compete in terms of investment in CO_2 abatement in order to obtain the highest amount of subsidy. Among other results, we found that the PGF subsidy mechanism is more effective to promote investments in product green features and to increase consumer surplus. However, the ABA subsidy mechanism is found to be more effective in industries or technologies in which the level of emissions is relatively low. However, such environmental policies may lead to inflation, and may not always improve social welfare. This chapter opens new avenues of research and thinking in terms of environmental subsidies and policy.

Keywords: Subsidy mechanisms; Product green features; CO_2 abatement; Contests; environmental investment.

JEL classification: Q58; Q52; L29

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[2] This chapter has been published with co-author António Osório as a research paper in the Journal of Cleaner Production.

2.1 Introduction

Society is becoming increasingly concerned with the emission of greenhouse gases and air pollution. In addition to the use of clean energy, environmental investments in green products and in CO_2 emission reductions are other indispensable approaches for improving the environment.[3] While abundant evidence shows that environmental investments help reduce pollution and use resources more efficiently, scholars are still trying to understand and improve how firms' decisions on adopting environmental investments are made (Garcia-Quevedo et al., 2022).

On the demand side of the market, there exist growing consumer demands for sustainable green products that use fewer resources, that are highly recyclable, and that have lower impacts and risk to the environment (Kammerer, 2009; Dangelico, 2016). The automobile industry may be considered as such an example. For instance, Volkswagen, Tesla and several other automobile manufacturers are investing in green product technologies by changing from fossil combustion engines to electric engines. In this way, they meet the growing environmental awareness of consumers, which lead to an increase in the consumers' willingness to pay and stimulate the demand for their products. In the household appliances market, when manufacturers produce household electrical appliances, they generate carbon emissions and pollute the environment. On the same time, these products, such as refrigerators and air conditioners, consume energy while being used. In this context, consumers prefer to buy energy saving and less polluting products (Zhang et al., 2020). In 2005, green consumers have purchased an amount of energy-saving home appliances on Alibaba platform enough to reduce CO_2 emissions by 30 million tons, equivalent to 556 acres of forest (Wang et al., 2021). Green product features, like the use of recycled materials in final products, help the environment in many other ways. Procter and Gamble (P&G) is an example of using recycling materials to seek competitive advantage (Finster & Hernke, 2014). Moreover, the use of recycling and renewable materials is well accepted among consumers because it greatly benefits the environment (Salehi et al., 2021).

On the supply side of the market, environmental policy is a commonly used and important incentive to promote investments in environmental quality (Porter & Van der Linde, 1995; Polzin et al., 2016). Many countries have implemented carbon taxes, provided subsidies to incentivize manufacturers to

[3] Using clean energy to replace traditional fossil fuels is a promising solution to solve the environmental problems. The International Energy Agency predicts that by 2030, clean energy is expected to account for 30% of energy consumption (Khaloie et al., 2020a; Yi et al., 2021).

emit less CO_2 during production, and generally encourage supplying the market with green products (Huang et al., 2016; Wang et al., 2017). Therefore, public environmental protection requirements and governmental regulations pressure firms to pay more attention to the design of green products and CO_2 emission reductions simultaneously.

In this chapter we consider that firms' simultaneous conduct two types of environmental investments: one is product green feature investment (PGF investment), and the other is emission reduction investment (ABA investment) since manufacturers not only have to consider how to reduce carbon emission in production, but also how to save energy and reduce pollution while products are being used by the consumer (Yi & Li, 2018). Moreover, we consider two different environmental policies, emission taxes are imposed to reduce producers' emissions according to the polluter pays principle, and cost-based subsidies are used to encourage firms' environmental-related investment because it has become a joint policy that governments are subsidizing in firms' environmental efforts and taxing on their CO_2 emissions. (Liao, 2018; Yi et al., 2021).

In this context, some interesting academic and practical questions emerge:

1) How to design an efficient mechanism on determining the optimal subsidy rate?
2) From the perspective of firm investments, consumer surplus, producer surplus, environment performance and social welfare, which type of subsidy mechanism is superior: the PGF or the ABA subsidy mechanism?
3) How do governments' subsidy and carbon tax policies affect the decision-making of manufacturers and determine their optimal PGF and ABA investments?
4) How do manufacturers distribute their investments in technologies for designing green products (PGF investments) and technologies for reducing carbon emissions in production (ABA investments)?

To answer these questions, we propose and compare the impacts of two contest-based subsidy allocation mechanisms, in which firms compete in terms of investments to obtain the highest amount of subsidy. In the PGF subsidy mechanism, both firms make investments in PGF and ABA, but the firm that makes the highest investment on PGF obtains the highest amount of subsidy from the government. In the ABA subsidy mechanism, both firms make investments in PGF and ABA, but the firm that makes the highest investment on ABA obtains the highest subsidy from the government. In this context, we study which of these two mechanisms is the most efficient to subsidize firm investments on PGF and on ABA investments, in order to understand which mechanism is the best to reduce environmental damages, increase both consumer surplus and producer surplus, and raise social welfare (Osório & Zhang, 2022).

To the best of our knowledge, the contest approach proposed in this study is completely new to the literature. In general, governments and policymakers define an exogenous and ad-hoc subsidy and tax rate. In this chapter, we do it differently. Firms compete by making investments to obtain higher subsidies. It is this competition process that endogenously determines the fraction of their investment that is going to be subsidized by the government. The emissions tax is also endogenously determined by budget balance. In this context, using the standard Hotelling linear model, we develop a model of price competition with an investment contest that incorporates product green feature and abatement investments.

Our main results are summarized in Figure 2-1. The PGF subsidy mechanism is the first best policy option in terms of incentivizing PGF investments and increasing consumer surplus. The producer surplus under the ABA subsidy mechanism is higher than that under the PGF subsidy mechanism. The emission tax revenues are higher under the PGF mechanism in industries or technologies in which the level of emissions is relatively low, while the ABA mechanism generates the greatest tax revenues in industries or technologies in which the level of emissions is relatively high. For the ABA investment and environmental damage, the ABA subsidy mechanism is the best in industries or technologies in which the level of emissions is relatively low, while the PGF subsidy mechanism is superior when emissions are relatively high. When the government aims to maximize social welfare, zero environmental policy might be optimal if environmental damage is sufficiently low. However, as the environmental damages increase, the ABA subsidy mechanism achieves the highest social welfare. Yet, when both environmental damages and emission are relatively high, the PGF mechanism is optimal.

In this chapter, we also analyze some extensions to the original model. In the asymmetric production cost case, we found that the differences in production costs will not affect the choice of the optimal subsidy mechanism. However, the share of government subsidy paid to a high-cost firm is greater than to a low-cost firm, and the subsidy rate rises with the difference between production costs. Moreover, the advantage of low-cost firms in terms of higher production is more obvious under the ABA subsidy mechanism. Next, the differences in investment efficiency/cost between firms do not affect the government's choice of the optimal subsidy mechanism either, when compared with the symmetric case. While the ABA subsidy mechanism leads to lower prices for products and higher profits for producers in this case.

We have also considered variations in the government subsidies coverage. The results show that in general, changes in the coverage of government subsidies do not affect the choice of the optimal subsidy mechanism but it may add some conditions to the selection of the optimal subsidy mechanism.[4] When comparing the hybrid subsidy mechanism with the other two mechanisms, we found that the hybrid subsidy mechanism is always the best choice for producers, but it has the least incentive for environmental investment, so social welfare is the least under this mechanism.

In practical terms, the proposed subsidy-tax mechanisms may help policymakers achieving sustainable environmental investments, promoting cost-efficient ecological policy designs, properly pricing environmental emissions, making green budgets more effective, decoupling economic growth from the harmful emissions, and generating trade-offs between stabilizing inflation and improving the mix of sustainable environmental policies. This study can also guide governments in designing subsidy-tax policies with different societal targets and objectives like for example increase environmental investments, reduce environmental damages, improve consumers and/or producer surplus, and social welfare.

The remainder of this chapter is organized as follows. Section 2.2 reviews the literature. Section 2.3 presents the theoretical model. Section 2.4 reports the main results of the baseline model. Section 2.5 uses numerical examples to illustrate the results. Section 2.6 reports some extensions from the baseline model. Section 2.7 discusses policy implications, concludes main results, and summarizes the limitations and future research. The mathematical proofs can be found in the Appendix 2.8.

[4] When both emission levels and the range of subsidies allowed by the government are relatively low, the ABA mechanism is optimal for incentivizing a firm's abatement investments, and consumers face a relatively lower product price. However, with an increase in emission and the coverage of the government subsidy, the PGF mechanism helps consumers obtain greater utility than the ABA mechanism. From an environmental perspective, in the case where both the coverage of government subsidies and emission levels are relatively low, ABA subsidy mechanism is the first best option. Yet, when emission levels and coverage of government subsidies are sufficiently high, the PGF mechanism is better than the ABA mechanism.

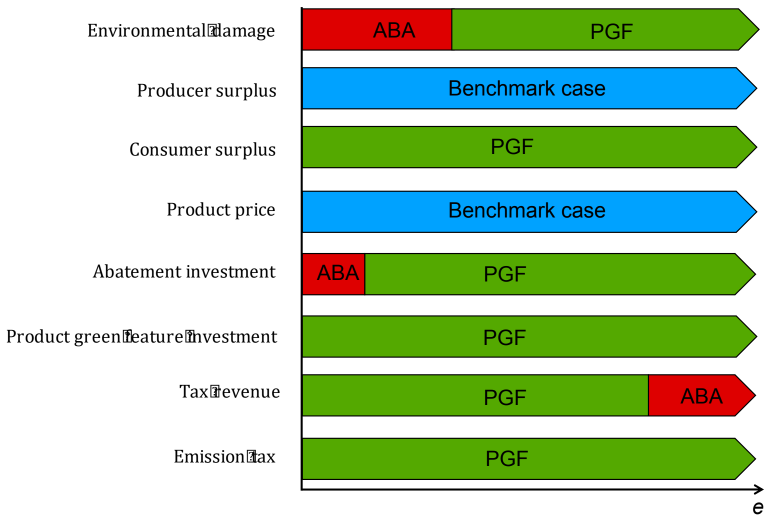

Figure 2-1 The best subsidy mechanism for different indicators and varying emission levels

2.2 Literature review

This study considers the roles of government, firms, and consumers. In the following section, we review the works associated with each stream and analyze how the present study differs from the existing literature along three dimensions: consumer environmental awareness and its effects, the combination of subsidy and emission tax, and the role and determinants of the firms' environmental investments.

2.2.1 Consumer environmental awareness and its effects

Consumers are becoming more environmentally aware and are striving to adopt more sustainable lifestyles (Ling et al., 2022). The rise of such environmental awareness has changed consumer behavior, in that they are more likely to consider environmental protection factors like energy saving and emission reduction when purchasing products (Yenipazarli & Vakharia, 2015). The stronger the environmental awareness of consumers, the higher the prices they are willing to pay for environmentally friendly products (Chitra, 2007, Sheehan & Atkinson, 2012). A global survey from Accenture illustrates that 80% of consumers consider the greenness of the products when purchasing them (Hong & Guo, 2018). Another report shows that 67% of the consumers in the US prefer to buy green products due to environmental considerations and 51% of them are willing to pay a premium for them (Zhang et al., 2015). In Europe, the proportion of consumers willing to pay a higher price for green products increased to 67% in 2008 from 31% in 2005 (Yu et al., 2016). Additionally, Fan et al. (2020) find that consumer acceptance of new energy vehicles increased substantially between 2012 and 2017. The increasing consumers' green awareness has become a market-driven factor that stimulates firms to make green improvements (Sueyoshi & Wang, 2014). By recognizing these shifts in the marketplace, firms have redesigned products to include environmental features that appeal to green consumers (Inman & Green, 2018; Ling et al., 2022). Given the important role of consumer environmental awareness, most studies in this area have been focused on product design and market competitiveness, and government environmental policies (Yenipazarli & Vakharia, 2015). In this chapter, we consider those dimensions. In particular, the consumers preference for greener products is explicitly expressed in their utility function.

2.2.2 The combination of subsidy and emission tax

In recent decades, governments have implemented a variety of policy instruments to minimize pollution and mitigate climate change (Stavins, 2003; Pasurka, 2020). For instance, an emission tax (or Pigovian tax) is an efficient instrument to encourage firms to conduct green investment and reduce pollution (Hasan et al., 2021, Osório & Zhang, 2022). In this context, Osório & Zhang (2022) propose three contest-based emission tax mechanisms. In their chapter, firms compete for paying less taxes. However, they do not consider green subsidies, different environmental investments, or consumers' environmental awareness. A green subsidy is an effective approach to promote product ecological innovation (Joo et al., 2018, Cohen et al., 2016). However, most studies regard government subsidies as exogenous (Joo et al., 2018; Huang et al., 2013), and a highly exogenous subsidies may fail to reach environmental targets (Bigerna et al., 2019). Chen et al. (2019) examine production subsidies and green innovation cost subsidies; and suggest that endogenous government subsidies may have positive effects on product greenness features (Hu et al., 2021).

In different contexts and following different approaches, some studies look at government subsidy as endogenous (Cohen et al., 2016; Chemama et al., 2019; Bian et al., 2020; Chen et al., 2019). Moreover, these studies either consider only one type of environmental investment and one subsidy scheme, or do not consider consumer environmental awareness (Howell 2017; Conti 2018). Therefore, neglecting the differences between different subsidy schemes on the firms' and consumers' green decisions (Bian et al., 2020), and on the government's preference for different green subsidy schemes (Meng et al., 2021, Yu et al., 2021). Recently, some studies have compared the impact of different subsidy programs on corporate investment strategies, environmental performance, and social welfare (Li et al., 2020, Meng et al., 2021, Yu et al., 2021). However, these studies neither distinguish between environmental investment, nor do take into account the joint use of subsidy-tax policy either.

Recently, new literature on policy-mix is emerging (Aldieri et al., 2019; Greco et al., 2020; Yi et al., 2021; Zhou et al., 2021). For instance, Zhou et al. (2021) present the policy mix of a uniform tax and flexible subsidy on the adoption of technology and on pollution spillover effects in order to reach allocation efficiency. Yi et al. (2021) suggest that the joint tax-subsidy policy can lead to higher social welfare and higher green investment in a Cournot market. However, their work considers only one type of green subsidy scheme and green investment, thus neglecting the comparison and the choice of optimal subsidy scheme from the government perspective, they also neglect consumers' environmental awareness effects either. Additionally, some empirical evidence can be found in the literature where complementarities exist between environmental regulations and taxes, as well as environmental regulation and innovation subsidies (Greco et al., 2020; Veugelers, 2012; Costantini et al., 2017, Liao, 2018). In an empirical study based on questionnaires, Liao (2018) suggest that the market-based instrument (emission tax & green subsidy) can lead a sewage enterprise to voluntarily choosing more favourable behaviours for the environment from the perspective of their own benefits.

2.2.3 The role and determinants of firm's environmental investments

Environmental investment in new technologies is important for firms to reduce their energy use and pollution emissions (Bostian et al., 2016). This is not only regarded as an effective way to reduce environmental pollution, but also may lead to an overall increase in firm productivity, profits, and competitiveness (Dechezleprêtre & Sato, 2020). However, there are few studies that distinguish abatement investments made into end-of-pipe technologies and investments made in cleaner production technologies (Frondel et al., 2007; Zhang et al., 2020; Garcia-Quevedo et al., 2022). Both technologies investments mitigate the adverse environmental impacts of production (Frondel et al., 2007). As early as 1992, Kemp and Goodchild have pointed out that firms engaged in environmental practices such as recycling or green product design are more likely to invest in green technologies (Kemp & Goodchild, 1992). When conducting two types of investment, PGF and ABA investments, it is better to allow the producers to shoulder the dual responsibilities of producing greener products and reducing emission levels by balancing the potential subsidy received and emission taxes paid. Inspired by these studies, we distinguish environmental investment in product green features PGF and in abatement ABA investments (mainly including end-of-line technologies).

2.2.4 This study

This study is novel to the literature. It distinguished from the studies discussed above in several ways. In our study, the government subsidy is an endogenous variable and government subsidizes different environmental investments (PGF and ABA investments), while imposing emission taxes on emission pollution. Then, we consider that the consumers' willingness to pay for a given product increases with the perceived value of the product's green features. In addition, we argue that firms compete to obtain more subsidies through two contest-based subsidy mechanisms (the PGF subsidy mechanism and the ABA subsidy mechanism). In this context, we design and compare those subsidy mechanisms, while keeping the government budget balanced. Finally, we consider different objectives and targets for the government (the adoption of green products, environmental performance, maximizing social welfare, minimizing subsidy expenditure, etc.) when choosing the optimal subsidy mechanism. To the best of our knowledge, the contest approach proposed in this study is new to the literature, it contributes to the growing literature on the design of environmental subsidy mechanisms by presenting a novel market approach to subsidy mechanisms through a contest.

2.3 The model

Consider a duopolistic market, where two firms, Firm 1 and Firm 2, compete in prices and in environmental investments including PGF investment and ABA investment. The products in this market are substitutable and horizontally differentiated in the level of greenness that is perceived by consumers. To promote environmental investments, government subsidizes PGF investment and ABA investment separately according to the contest-based subsidy mechanisms, while imposing emission taxes on pollution.

2.3.1 The framework of the government subsidy mechanisms based on the contest success function

We consider the following two government subsidy mechanisms in which the subsidy paid not only depends on the investments made by each firm, but also depends on the investments made by the other firms. The logical foundation of these two subsidy mechanisms is based on the Contest Theory and the associated Contest Success Functions, in which each firm's subsidy rate is based on its investment relative to that of all other firms (For some examples and applications of contest theory see Baik, 1998;

Corchón, 2007; Osório & Zhang, 2022). Therefore, the subsidies are obtained in a competitive way. This competition process endogenously determines the fraction of their investment that is going to be subsidized by the government. This approach or procedure is more reasonable and fairer than the existing exogenous subsidy approaches.

(1) The PGF subsidy mechanism is distributed according to a PGF investment contest in which the share of government payment s_{iz} of firm i is based on its PGF investments relative to other firms' investments. Therefore, the government subsidy A_{iz} to firm i under the PGF contest mechanism z is given by[5]:

$$A_{iz} = v\frac{z_{iz}}{z_{1z} + z_{2z}}\varepsilon_i\frac{{z_{iz}}^2}{2} \tag{2.1}$$

where $v \geq 0$ is a coefficient capturing the coverage of government subsidies, $z_{iz} \geq 0$ is the PGF investment of firm i under the PGF subsidy mechanism, for $i = 1, 2.$ The parameter $\varepsilon_i > 0$ captures the cost of the PGF investment of firm i. Therefore, $\varepsilon_i {z_{iz}}^2/2$ is the PGF investment costs of firm i[6].

(2) The ABA subsidy mechanism is distributed according to an ABA investment contest in which the share of government payment s_{iw} of firm i is based on its abatement investments relative to other firms' investments. Therefore, the government subsidy A_{iw} to firm i under the ABA contest mechanism w is given by:

$$A_{iw} = v\frac{w_{iw}}{w_{1w} + w_{2w}}\gamma_i\frac{{w_{iw}}^2}{2} \tag{2.2}$$

where $w_{iw} \geq 0$ is the ABA investment of firm i under the ABA subsidy mechanism w for $i = 1, 2.$ The parameter $\gamma_i > 0$ captures the cost of ABA investment of firm i. Therefore, $\gamma_i {w_{iw}}^2/2$ is the ABA investment costs of firm i.

Both subsidy mechanisms not only consider the production and investment competition among firms, but also how firms obtain government subsidies through a contest success function.

[5] When "z" and "w" are subscripts, they represent the PGF and the ABA subsidy mechanism, respectively, in which firms compete in terms of PGF and ABA investments, respectively, in order to obtain the highest amount of subsidy from government. When "z" and "w" are variables, they represent firm's PGF and ABA investments, respectively.

[6] The convex investment cost function describes the increasing marginal cost of transforming environmental investments into product green features or reduce emissions. Such quadratic functional form has been widely used in the literature in different contexts (See for instance Sengupta, 2012; Osório & Pinto, 2020).

In addition, we consider a benchmark or reference case o in which the pollution issue and the government partial payment is neglected or absent. In this case, firms neither obtain government subsidies nor pay emission taxes, i.e., $s_{io} = t_{io} = 0$, for $i = 1, 2$. The benchmark case works as a reference for the regulator to evaluate the efficiency of each subsidy strategy in terms of different indicators.

2.3.2 Model building

In the competing market, consumers' willingness to pay for a given product will increase with the perceived value of the product's green features, which motivates firms to develop products with greener characteristics, quality considerations, and economical pricing strategies. In this context, we consider a Hotelling model to capture product differentiation (e.g., Harold, 1929; Belleflamme & Peitz, 2015; Li et al., 2021). We assume that consumer obtain extra utility βz_{ik} by consuming the product from the firm that made the investment z_{ik} in product green features, where β is a positive parameter. Thus, the utility function from purchasing product 1 is as follows:

$$U_{1k} = r + \beta z_{1k} - \alpha \bar{x}_{1k} - p_{1k} \tag{2.3}$$

The utility function from purchasing product 2 is as follows:

$$U_{2k} = r + \beta z_{2k} - \alpha(1 - \bar{x}_{1k}) - p_{2k} \tag{2.4}$$

for $k = o, z, w$,where r represents the consumer valuation from purchasing the product, while α is a parameter that captures the switching cost per unit distance. Thus, a consumer located at $\bar{x}_{1k}$ incurs a cost of $\alpha \bar{x}_{1k}$ when purchasing product 1 and a cost of $\alpha(1 - \bar{x}_{1k})$ when purchasing product 2. There is a continuum of consumers who are uniformly located over the interval [0, 1] (Belleflamme & Peitz, 2015). We can derive the location of the indifferent consumer $\bar{x}_{1k}$ by solving the equation $U_{1k} = U_{2k}$.

Therefore, given the PGF investments (z_{ik}) of firm i and the market prices (p_{ik}) of product i, the indifferent consumer $\bar{x}_{1k}$ is:

$$\bar{x}_{1k} = \frac{p_{2k} - p_{1k} + \alpha + \beta(z_{1k} - z_{2k})}{2\alpha}$$

The demand shares q_{ik} of firm $i = 1, 2$, under mechanism $k = o, z,$ and w, are given by:

$$q_{1k} = \frac{p_{2k} - p_{1k} + \alpha + \beta(z_{1k} - z_{2k})}{2\alpha} \tag{2.5}$$

and,

$$q_{2k} = 1 - \frac{p_{2k} - p_{1k} + \alpha + \beta(z_{1k} - z_{2k})}{2\alpha} \tag{2.6}$$

It is clear from the expression (3.5) and (3.6) that, at given prices, a firm can increase its market share by investing more in product green features than its rival.

In this chapter, the revenue generated from the emission tax is used to pay for the firms' subsidy under the PGF subsidy mechanism and the ABA subsidy mechanism. Therefore, the government budget must be balanced. Budget balance is important to guarantee the comparability of different subsidy-tax policies. Otherwise, we cannot separate policy effects from budget effects (deficit or surplus).

Carbon emissions are discharged by the producer during the production; therefore, we assume government impose the emission tax on the producer carbon emissions, where e_i is the emission per unit of product. To reduce the emission tax burdens, firms make abatement investments to reduce their CO_2 emissions. Then, the profit function of firm i is given by:

$$\pi_{ik} = (p_{ik} - c_i)q_{ik} - \varepsilon_i \frac{{z_{ik}}^2}{2} - \gamma_i \frac{{w_{ik}}^2}{2} - t_k q_{ik}(e_i - w_{ik}) + A_{ik} \tag{2.7}$$

such that $S_k = T_k$, which is the budget balance condition, for $k = o, z, w$. Where p_{ik} is the sale price of product i, c_i is the unit production cost of product i, t_k is emission tax, e_i is emission per unit of product i, for $i = 1, 2$.

In the model, firms face a trade-off between higher subsidy and higher environmental investment costs and potential sales. Concretely, a firm can obtain higher government subsidy by increasing the share on the government payment (contest) and by increasing the investments (subsidy base), but it must incur the cost of the investments, at least partially, which may also increase sales.

In recent years, pollution emissions have become an essential aspect to evaluate the relative achievement of the government policies. Therefore, we define and measure total environmental damages as:

$$D_k = d\left(\sum_{i=1}^{2} q_{ik}(e_i - w_{ik})\right)^2 \tag{2.8}$$

for $i = 1, 2$, and $k = o, z, w$.

We are also interested in evaluating the impact of the PGF and ABA contest-based subsidy mechanisms on several other dimensions. In this context, we define and measure consumer surplus as the sum of consumer utilities:

$$CS_k = \int_0^{\bar{x}_k} U_{1k} dx_k + \int_{\bar{x}_k}^{1} U_{2k} dx_k \tag{2.9}$$

for $i = 1, 2,$ and $k = o, z, w$.

We define and measure producer surplus as the sum of firms' profits:

$$PS_k = \sum_{i=1}^{2} \pi_{ik} \tag{2.10}$$

for $i = 1, 2,$ and $k = o, z, w$.

The government subsidy expenditure is defined and measured as:

$$S_k = \sum_{i=1}^{2} A_{ik} \tag{2.11}$$

for $i = 1, 2,$ and $k = o, z, w$.

The emission tax revenue is defined and measured as:

$$T_k = \sum_{i=1}^{2} t_{ik}\, q_{ik}(e_i - w_{ik}) \tag{2.12}$$

for $i = 1, 2,$ and $k = o, z, w$.

Total social welfare in the present setting consists of the sum of consumers surplus, producer surplus and minus the environmental damages as follows:

$$SW_k = CS_k + PS_k - D_k \tag{2.13}$$

for $k = o, z, w$.

Finally, we consider a two-stage game. In stage one firms simultaneously choose their PGF investment and ABA investment levels, while at the same time competing for the highest share of the subsidy based on the above two contest mechanisms in order to maximize profits. In stage two, firms compete in the product market. Recall that the government budget is balanced, therefore the tax and the subsidy are endogenous.

Nomenclature: All variables and symbols are defined in Table 2-1.

Indices	
$\boldsymbol{i}$	The index i refers to firm $i = 1$ and $i = 2$.
$\boldsymbol{k}$	The index k refers to subsidy mechanism $k = o, k = z$ and $k = w$.
Parameters	
r	Reservation value (we set r sufficiently large).
$\boldsymbol{\beta}$	Consumer utility coefficient from PGF investments.
$\boldsymbol{\alpha}$	Consumer switching cost per unit distance.
$\boldsymbol{c}$	The unit production cost.
$\boldsymbol{e}$	Emission for unit production.
$\boldsymbol{\varepsilon}$	A parameter capturing the cost of product green feature investments.
$\boldsymbol{v}$	A coefficient capturing the interval or coverage of government subsidies.
$\boldsymbol{\gamma}$	A parameter capturing the cost of abatement investments.
$\boldsymbol{d}$	A parameter capturing the severity/intensity/level of pollution damage.
Decision variables	
$\boldsymbol{s}$	Subsidy rate (the share of government payment).
$\boldsymbol{t}$	Emission tax rate.
$\boldsymbol{z}$	Firm's PGF investment.
$\boldsymbol{w}$	Firm's ABA investment.

$\boldsymbol{p}$	Product market price.
Definitions and other variables	
$\boldsymbol{q}$	Firm's production.
A	The total amount of subsidy that firm receives from the government.
π	Firm's profits.
D	Total environmental damages.
CS	Consumer surplus.
PS	Producer surplus.
S	Government subsidy expenditure.
T	Emission tax revenue.
SW	Social welfare.

Table 2-1 Variables and model parameters

2.4 Results and discussions

In this section, we consider the case in which two firms are symmetric, i.e., $\varepsilon_1 = \varepsilon_2 = \varepsilon, \gamma_1 = \gamma_2 = \gamma, c_1 = c_2 = c$ and $e_1 = e_2 = e$. Consequently, we can obtain tractable close form expressions. In order to simplify the analysis, we set $v = 1$.

We also consider the condition $e \geq 8/9\sqrt{2\beta^2/3\gamma\varepsilon}$ in order to rule out negative investments. In what follows we present and discuss the obtained results.

Proposition 2.1

The emission tax rate generated in the contest-based subsidy mechanisms are in the following descending order:

$$t_z > t_w > t_o \; for \; e \geq 8/9\sqrt{2\beta^2/3\gamma\varepsilon}.$$

Proposition 2.1 shows that the emission tax rate under the PGF subsidy mechanism is always higher than under the ABA subsidy mechanism (see Figure 2-2-A).

In this study, the government achieves budget balance, where the revenues generated from the emission tax mechanism are used to pay for firms' obtained subsidy as firms compete in terms of both PGF and ABA investments. Therefore, the subsidy rate is endogenous, making the emission tax rate also endogenously determined by the level of the firm's PGF and ABA investment. Therefore, both PGF and ABA subsidy mechanisms can help governments levy an appropriate emission tax rate that can reduce government financial burden, which is a better and more efficient alternative than to increase the emission tax blindly according to some ad-hoc criteria. For instance, in 2018 Canada designed a carbon tax where the cost of each ton of carbon emissions was set to be initially $10 and would raise by $10 per year to reach $50 per ton in 2022. Many firms strongly objected against this policy and believed it would hamper industrial development (Yi & Li, 2018).

Carbon taxes should be properly designed, imposing carbon tax blindly may generate counterproductive effects. Our results show that from the producers' perspective, the ABA subsidy mechanism is preferred because of the relatively low emission tax rate. We also need to consider that a well-designed environmental policy is the most economically efficient way to reduce carbon emissions. The emission tax and subsidy in this chapter could be considered a production-based emission tax and subsidy, intuitively. However, either such emissions taxes or subsidies will eventually be partially or fully transformed into consumption-based emissions taxes and subsidies.

Proposition 2.2

The contest-based subsidy mechanisms that leads to the highest tax revenue are in the following descending order:

(a) $T_z > T_w > T_o \; for \; 8/9\sqrt{2\beta^2/3\gamma\varepsilon} \leq e < 104/81\sqrt{\beta^2/\gamma\varepsilon}.$

(b) $T_w > T_z > T_o \; for \; e \geq 104/81\sqrt{\beta^2/\gamma\varepsilon}.$

Here, one advantage of an emission tax over other climate policies that could achieve the same environmental outcomes, such as "command-and-control", is that it creates tax revenue. The economic effects of an emission tax vary significantly depending on how the generated tax revenues are used.

Technology-driven cost reductions in fossil fuel production will still lead us to continue using oil, gas, and coal, people and businesses believe it is worth to pay for the benefits of fossil fuels. Even with the implementation of many environmental policies, carbon dioxide, methane, and other greenhouse gases will continue.

Proposition 2.2 indicates that in industries or technologies in which the level of emissions is relatively low, governments can obtain higher emission tax revenue by implementing the PGF subsidy mechanism. Therefore, the combination of PGF subsidy and tax policy is more popular. When the emission level exceeds a certain threshold, governments can obtain higher emission tax revenue from implementing the ABA subsidy mechanism (see Figure 2-2-B), at this point, tax neutrality is easier to achieve, and the combination policy is more acceptable.

For industries or technologies with relatively low emissions, governments should implement simultaneously an emission tax and a subsidy mechanism but should focus on subsidizing the firms through the PGF subsidy mechanism in order to achieve higher revenues. As for industries or technologies with heavy carbon emissions, governments should also implement emission tax and subsidy simultaneously, but through the ABA subsidy mechanism.

Moreover, the combination of subsidy and tax policies based on competitive approaches is designed to achieve government budget balance in this study. If the emission tax-subsidy policy system would not consider government budget balanced, the government would bear a certain portion of the PGF or ABA costs through the provision of subsidies, leaving producers with less financial responsibility, which could be unfair and increases the financial burden on the government and citizens. Is such case, we argue that the emission tax should be levied on producers and the tax revenue should be equal to the subsidy expenditure. In doing so, we could also build support for an emission tax among stakeholders and the public who especially prioritize climate relative to other policy concerns, and finally achieve revenue-neutral emission tax.

Proposition 2.3

The contest-based subsidy mechanisms that lead to the highest product green feature investments are in the following descending order:

$$z_z > z_w = z_o \; for \; e \geq 8/9\sqrt{2\beta^2/3\gamma\varepsilon}.$$

Public environmental policies involving emission taxes and subsidies are considered crucial in incentivizing firms to perform environmental investments. Proposition 2.3 claims that firm's PGF investments under the PGF subsidy mechanism are larger than under the ABA subsidy mechanism (and the benchmark case).

According to the principles of economics, consumers' willingness to pay for a product is equal to the demand for the product. In our model setup, we have assumed that consumers obtain extra utility by consuming the product from the firm that made the investment in PGF. Then, as long as there is a transaction for the product there will occur PGF investment. Investments in PGF are closely related to the demand for the product.

Although there is no carbon tax and no subsidies in the benchmark case, but there is still a market demand for the product, then the firm need to make investment in PGF. In the ABA subsidy mechanism, the subsidy is added to the ABA investment. This subsidy mechanism will not directly affect the demand for the product, so it has no impact on the PGF investment of the enterprise.

In the PGF subsidy mechanism, the subsidy directly added to the PGF investment will increase the utility of consumers, further increase the demand of the product, consequently, lead to the largest PGF investment. On the other hand, since the government subsidies to the firms' PGF is based on a contest approach. The higher the amount of the firm product green feature investment, the higher subsidy the firm obtains from the government. This mechanism motivates firms to make further PGF investments. While the PGF investments under the ABA subsidy mechanism and the benchmark case are the same (see Figure 2-2-C). We conclude that the emission tax and the ABA subsidy mechanism do not provide the needed incentives for the firms PGF investments. The PGF subsidy mechanism is always better than ABA subsidy mechanism in terms of firms' green feature investments.

Proposition 2.4

The contest-based subsidy mechanisms that lead to the highest abatement investments are in the following descending order:

(a) $w_w > w_z > w_o$ *for* $8/9\sqrt{2\beta^2/3\gamma\varepsilon} \leq e < 26/27\sqrt{2\beta^2/3\gamma\varepsilon}$.

(b) $w_z > w_w > w_o$ *for* $e \geq 26/27\sqrt{2\beta^2/3\gamma\varepsilon}$.

Proposition 2.4 indicates that in industries or technologies in which emissions e are relatively low, the ABA subsidy mechanism achieves the optimal level of firms' abatement investments (Part (a) of proposition 2.4 and see Figure 2-2-D). While in industries or technologies in which emissions are high enough, the PGF subsidy mechanism is higher than the ABA subsidy mechanism (Part (b) of Proposition 2.4).

Since there are no firm's ABA investments in the benchmark case $w_o = 0$. We could say the abatement investment is aimed at addressing the environmental objective alone, without offering other benefits to the firm. Moreover, ABA investments are a costly strategy that might trigger a loss in market competitiveness (see in Proposition 2.7). Consequently, abatement investment would not be conducted without emission taxation.

The objective of the firms' PGF investment is to stimulate market demand by exploiting the consumers' awareness of environmental quality issues, but the emissions generated during the production process also need to be taxed. For that reason, the government also needs to incentivize abatement investments. The results show that to motivate firms' abatement investments under low emissions conditions, the government should apply the ABA subsidy mechanism. While to motivate the firms´ abatement investments under high emissions conditions, the government should implement the PGF subsidy mechanism to incentivize firms' abatement. The reason is that the PGF subsidy mechanism leads to higher production, therefore higher taxation, and consequently, higher incentives to make abatement investments.

Proposition 2.5

The contest-based subsidy mechanisms that lead to the lowest product price are in the following ascending order:

(a) $p_o < p_w < p_z \; for \; 8/9\sqrt{2\beta^2/3\gamma\varepsilon} \leq e < 104/81\sqrt{\beta^2/\gamma\varepsilon}$.

(b) $p_o < p_z < p_w \; for \; e \geq 104/81\sqrt{\beta^2/\gamma\varepsilon}$.

In the context of the new green technologies subsidies and emissions taxation inflation has become a central issue. Proposition 2.5 indicates that the product price in the benchmark case is always the lowest because there is no emission tax burden on firms and firms' investments are low. Intuitively, green products are usually more expensive than their conventional counterparts because firms need to make extra investments. The product price under the PGF subsidy mechanism is higher than that under the ABA subsidy mechanism in industries or technologies in which the level of emission is relatively low (see Figure 2-2-E). From Proposition 2.3 we have concluded that the PGF subsidy mechanism provides the maximum incentive on firms' PGF investments, which creates higher demand, consequently, firms set higher prices under this mechanism.

On the same time, since the emissions level e has a positive impact on product price under the ABA subsidy mechanism, because production increases the pollution levels above, and therefore the prices under the ABA subsidy mechanism more than under the PGF subsidy mechanism in industries or technologies in which the level of emission is relatively higher.

Altogether, environmental investments under both the PGF and the ABA mechanisms may cause price inflation. However, the ABA subsidy mechanism can cause less inflation in industries or technologies in which the level of emission is relatively low, while the PGF subsidy mechanism can cause less inflation in industries or technologies in which the level of emission is relatively higher.

Proposition 2.6

The contest-based subsidy mechanisms that lead to the highest consumer surplus are in the following descending order:

$$CS_z > CS_o > CS_w \; for \; e \geq 8/9\sqrt{2\beta^2/3\gamma\varepsilon}.$$

From the perspective of consumer surplus, the PGF subsidy mechanism is always the better choice. Since PGF investments directly increase consumer utility, greater PGF investment leads to greater consumer utility. As Proposition 2.2 has shown, maximum PGF investment occurs under the PGF subsidy mechanism, therefore, maximum consumer utility and surplus (see Figure 2-2-F).

Since the ABA subsidy mechanism operates in the production cost and increases prices, its impact on consumer surplus is weaker. Due to the higher prices effect, its effect on consumer surplus is even weaker than in the benchmark or reference case.

Altogether, firms' PGF investments affect consumers' preferences by enhancing the value of the product in the eyes of the consumer. For that reason, this might be the most efficient subsidy mechanism to improve consumers' surplus. For instance, in 2012, China financed more than 40 billion Yuan in energy-saving appliances and new energy vehicles under its energy-saving program which has benefited consumers (Yi & Li, 2018).

Proposition 2.7

The contest-based subsidy mechanisms that lead to the highest producer surplus are in the following descending order:

$$PS_o > PS_w > PS_z \text{ for } e \geq 8/9\sqrt{2\beta^2/3\gamma\varepsilon}.$$

Proposition 2.7 and Figure 2-2-G show that the benchmark case is the best in terms of producer surplus, but the ABA subsidy mechanism is superior to the PGF subsidy mechanism. The reason is that in the benchmark case, firms do not need to pay emission tax and competition in terms of investments is lower, which is good for firms. Therefore, they can achieve higher profits.

Firms face a trade-off between higher subsidies and higher investment costs when they increase environmental investments. A firm can obtain higher government subsidy by increasing the share of government payment and the subsidy base (that is investment cost), but this firm must bear the cost of the investments because the share of government payment resulting from the contest is in the interval [0, 1]. Then, the subsidy a firm obtains cannot compensate for the investment cost in a competing market. From proposition 2.2, the PGF subsidy mechanism always provides more incentives on firms' PGF investment which causes higher costs, then in terms of profits and producer surplus, firms prefer the ABA subsidy mechanism.

Proposition 2.8

The contest-based subsidy mechanisms that lead to the lowest environmental damages are in the following ascending order:

(a) $D_w < D_z < D_o$ for $8/9\sqrt{2\beta^2/3\gamma\varepsilon} \leq e < e_1$[7].

(b) $D_z < D_w < D_o$ for $e \geq e_1$.

Proposition 2.8-(a) indicates that in industries or technologies in which emissions level e are relatively low, the ABA subsidy mechanism is the first best option because it provides the maximum abatement investments while achieving the lowest emissions levels (see Figure 2-2-H). While, in industries or technologies in which emissions levels e are relatively high, the PGF subsidy mechanism is better than

[7] There exists a value of e_1 in the interval $8/9\sqrt{2\beta^2/3\gamma\varepsilon} < e_1 < 104/81\sqrt{\beta^2/\gamma\varepsilon}$.

the ABA subsidy mechanism in terms of internalizing environmental externalities because of the higher abatement investment in this particular case as explained in the Part (b) of proposition 2.4 (see Figure 2-2-H).

To conclude, the government should impose both the emissions tax and the subsidy mechanism at the same time to improve environmental quality since both the PGF and the ABA subsidy mechanism have a positive effect on environmental quality. The PGF subsidy mechanism improves environmental quality via green product consumption, while the ABA subsidy mechanism reduces emission levels. Further, the PGF subsidy mechanism is superior in most cases. Firms can potentially reduce environmental pollution by increasing the level of investment in environmental technologies, and by shifting investments away from pollution control (ABA investment) towards pollution prevention (PGF investments).

2.5 Numerical analyses

In this section, in order to better illustrate our theoretical results and explore our assumptions, we present a numerical analysis. To this end, we follow Ling et al. (2022) and Ling & Xu (2021) to determine the value range and initial value of each parameter. Then we use the obtained expressions of the variables in equilibrium to simulate the data, adjusting the parameters according to the simulation results until the simulation results of all variables have economic significance. We use the above operations to determine the final assignment of parameters and summarize them in Table 2-2.

r	β	α	c	ε	v	γ	d
2	0.01	1	0.1	0.01	1	0.01	1

Table 2-2 Numerical parameters

The results are given in the following figures. In this section, we mainly focus on analyzing the impact of subsidy mechanisms on social welfare. Propositions 2.1 through 2.8 are illustrated in Figure 2-2-A through Figures 2-2-H, respectively.

The incentive effects of the two subsidy mechanisms on environmental investment, corresponding consumer surplus, producer surplus and environmental damages have been analyzed comparatively in above propositions. It is necessary to analyze the social welfare effects of two contest-based subsidy mechanisms. This chapter constructs social welfare models that include consumer surplus, producer surplus and the environmental quality, which is used to comprehensively analyze both the effect of emission tax and subsidy mechanisms on the related objects and the best choice in terms of different production conditions.

As seen in Figure 2-2-I, the social welfare in the benchmark case is always the lowest. Because environmental pollution does indeed increase the cost of social health and reduce social welfare. Therefore, in terms of overall social welfare, environmental improvement is imperative, and an effective subsidy mechanism is indispensable. The figure 2-2-I show that in industries or technologies in which emissions level e are relatively low, the ABA subsidy mechanism is the best to achieve the highest social welfare. At this time, under the ABA subsidy mechanism, the investment for reducing emissions is the largest, so the effect of less environmental pollution brought about by low emissions is more significant. As mentioned, social welfare consists of the consumer surplus, producer surplus and environmental damages, we can infer that low environmental damage is the dominant factor in this case (see also Figures 2-2-F, G, H).

However, with an increase in the emissions level e, the PGF subsidy mechanism achieves the highest welfare because of the large value of consumer surplus and the decrease in environmental damages are becoming the dominant forces under this mechanism (see Proposition 2.7 and Proposition 2.8). The intuition is, at this time, under both subsidy mechanisms, the PGF investment for improving the green feature of products is the largest. On the one hand, the utility of consumers is maximized with the increase in PGF investment. On the other hand, because consumers are more willing to buy green products, which improves the quality of the environment, the environmental damage gradually decreases with PGF investment. Therefore, under the dual effects of increasing consumer utility and reducing environmental damage, the total social welfare reaches the maximum.

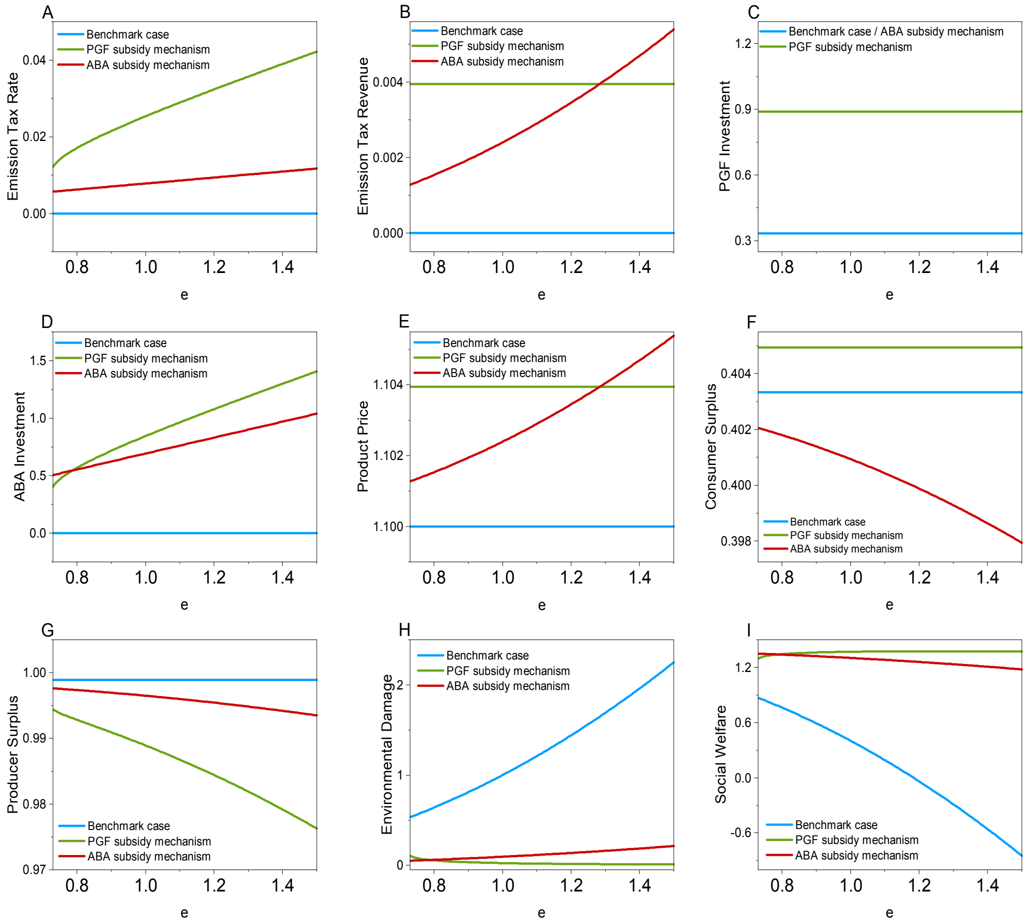

Figure 2-2 The best subsidy mechanism for different indicators

2.6 Extensions of the basic model

In this section, we consider several extensions of the original model proposed in Section 3.4: (1) asymmetric firms in terms of production costs, (2) asymmetric firms in terms of efficiency/cost of investment, (3) varying coverage of the government subsidy and (4) the hybrid subsidy policy.

2.6.1 Asymmetric production costs

In this section, we consider the case of asymmetric firms in terms of production costs. In this context, let us consider that Firm 1 (the low-cost firm) has zero costs of production, while firm 2 (the high-cost firm) has total costs of cq_2, where $c > 0$ is the unit production/marginal cost of firm 2. Then, we examine how production cost asymmetries affect the performance of the two contest-based subsidy mechanisms (see Figure 2-3).

The results show that the low-cost firm has the advantage to produce more than its competitor, which increases as the difference in production cost increases. This advantage is more obvious under the ABA subsidy mechanism. The higher production cost leads to a higher market price to offset the negative impact of higher production cost on profits. As the difference between firm production cost structures increases, the two contest-based subsidy mechanisms favor the low-cost firm to offset the cost effect on price. This counteracting effect was slightly pronounced under the ABA subsidy mechanism (see Figure 2-3-E). The intuition of the counteracting effect is that the production advantages of low-cost firms enhance competitiveness in the entire industry, forcing the product prices of high-cost enterprises to be relatively lower in order to compete.

Results show that emission taxes under the PGF subsidy mechanism are the highest (see Figure 2-3 A). When we assume two firms have different production costs and the emission takes value 1, the government prefers to implement the PGF subsidy mechanism to obtain higher emission tax revenue. This revenue increases as the difference in production costs increases (see Figure 2-3-B).

For the PGF investment, differences in production costs will not affect the choice of the optimal subsidy mechanism. The PGF subsidy mechanism is still superior to the ABA subsidy mechanism because it stimulates firms to make more PGF investments overall (see Figure 2-3-C). However, the high-cost firm is willing to make higher and increasing PGF investments with the production cost difference than the low-cost firm under the PGF subsidy mechanism. However, the situation is reversed under the ABA subsidy mechanism. For the ABA investment, the PGF subsidy mechanism can incentivize enterprises to make more ABA investments than the ABA subsidy mechanism in general, which is also consistent with the symmetric model (see Figure 2-3-D). The difference from the PGF investment is that the low-cost firm makes higher and increasing ABA investment under the PGF subsidy mechanism, and the high-cost firm makes higher and increasing ABA investment under the ABA subsidy mechanism.

Interestingly, in the symmetric cost model, the share of government payment to high-cost firms is higher than to low-cost firms (unlike the symmetric model, which is equal for both firms), and the rate increases with an increase in the difference in production costs. However, for the low-cost firm, the subsidy rate decreases with an increase in the difference.

In terms of consumer surplus, the optimal choice is always the PGF subsidy mechanism, as consumer surplus decreases with an increase in the difference between production cost (see Figure 2-3-F). Overall, the ABA subsidy mechanism is more favorable for producer surplus than the PGF subsidy mechanism (see Figure 2-3-G). Although the profit of high-cost enterprises decreases with the increase of the production cost difference between firms, the profit of low-cost enterprises increases with the increase of cost difference under the two subsidy mechanisms. This advantage is more significant under the ABA subsidy mechanism. Under the assumption of $e = 1$, the ABA subsidy mechanism is also better in terms of environmental quality (see Figure 2-3-H). Therefore, based on those observations, results show that the PGF subsidy mechanism is the most preferred in terms of social welfare (see Figure 2-3-I).

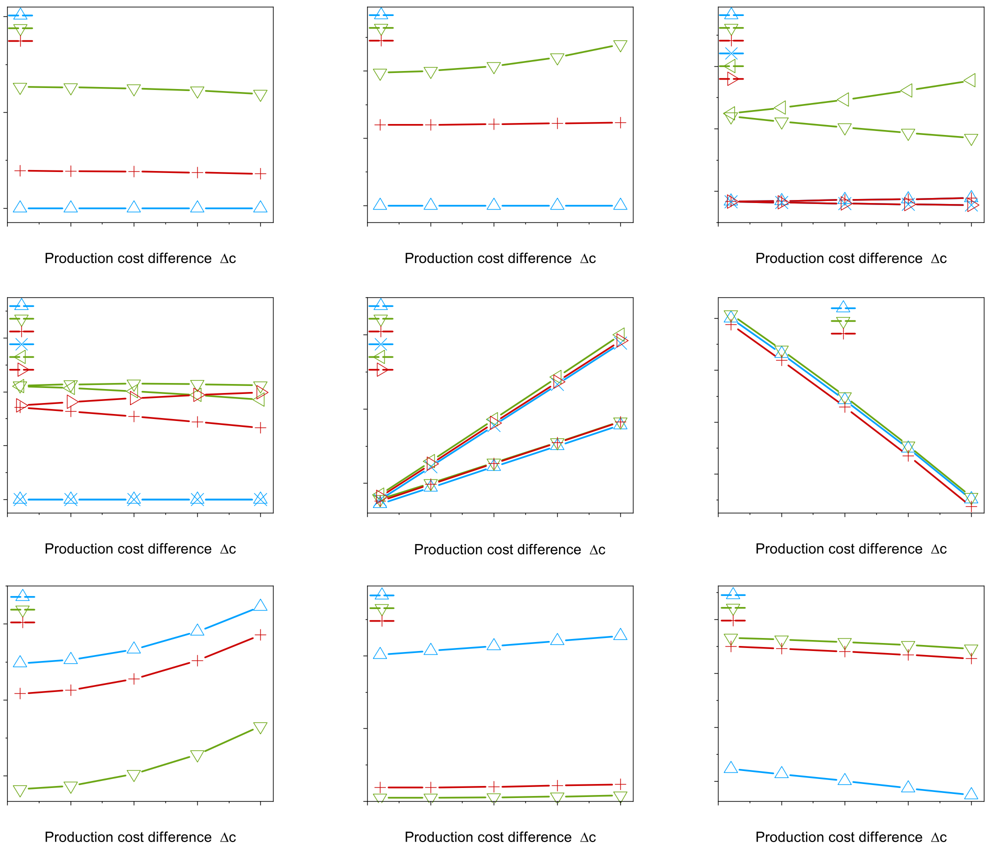

Figure 2-3 The best subsidy mechanism for different indicators and varying production cost difference

2.6.2 Asymmetric investment efficiency/cost

In this case, we analyze the impact of the asymmetric efficiency/cost of investment on producers, consumers, environmental quality and social welfare, under the two subsidy mechanisms.

We assume distinct parameters ε_i and γ_i that capture the different PGF and ABA investment cost of firm $i = 1, 2$, respectively, i.e., $\varepsilon_1 = \gamma_1 = 0.01$ and $\varepsilon_2 = \gamma_2 = 0.009$. We summarize the main results in Table 2-3, which may provide a sufficiently rich overview of the general results. We find that the different investment efficiency/cost of two firms does not affect the government's choice of the optimal subsidy mechanism compared with the symmetric case. The PGF subsidy mechanism is superior to the ABA subsidy mechanism in terms of firms PGF investment, ABA investment, emission taxation, consumer surplus, environmental quality, and social welfare. While the ABA subsidy mechanism will lead to lower prices for products and higher profits for producers.

	Emission tax rate	Emission tax revenue	PGF investment	ABA investment	Product price
PGF subsidy mechanism		✓	✓	✓	
ABA subsidy mechanism	✓				✓
	Consumer surplus	Producer surplus	Environmental damage	Social welfare	
PGF subsidy mechanism	✓		✓	✓	
ABA subsidy mechanism		✓			

Table 2-3 The best subsidy mechanism in the asymmetric efficiency/cost of investment

Since ε_i (γ_i) is the extent of the decreasing returns in the PGF (ABA) investment, the larger ε_i (γ_i) the firm i faces the lower investment efficiency/cost the firm has, therefore, the PGF (ABA) investment of firm 1 is lower than that of firm 2. However, the contest-based subsidy mechanisms may have some unintended effects between the two competing firms. For instance, in the case of ε asymmetry under the PGF subsidy mechanism, both the PGF investment and the ABA investment of firm 1 are more than that of the firm 2, and the output of the firm 1 is also higher. But under the ABA subsidy mechanism, the PGF investment of firm 2 is higher than that of firm 1, while the ABA investment is lower, resulting in more output of firm 2.

In the case of γ asymmetry, under the PGF subsidy mechanism, the PGF investment of firm 1 is more than that of firm 2, but the ABA investment of firm 2 is higher. As a result, the output of firm 2 is then higher. However, under the ABA subsidy mechanism, both the PGF investment and the ABA investment of firm 1 are higher than that of firm 2, resulting in more output from firm 1. Therefore, the market share of the different products is increasing in the different subsidy mechanisms. Under each specific circumstance and proposes, there is always an appropriate subsidy mechanism among the two proposed subsidy mechanisms.

2.6.3 Varying coverage of the government subsidy

In this section, we analyze the impact of the parameter v, which captures the coverage of government subsidy on the two mechanisms, as chosen by the government. The bigger the firm coverage v, the higher the subsidy a firm obtains. For instance, if $v = 0.5$ it means that government refunds 50% of the investment made by the firms, while in the hypothetical and uncommon case of $v = 1.5$ it means that the government refunds 150% of the investment.

In order to have a well-behaved model the coverage of subsidy v should satisfy $0 < v < 1.6$. We summarize the main results as follows, which may provide a sufficiently rich overview of the general results.

Compared with the original basic model, changing the parameters v does not affect the choice of the optimal mechanism. First, the PGF subsidy mechanism is always optimal in terms of the firms' PGF investment. However, abatement investment depends on the emission level and the coverage of the government subsidy. When these two parameters are relatively low, the ABA subsidy mechanism is the best to incentivize firm's abatement investment, and consumers face a relatively lower price under this subsidy mechanism. As emissions level increases, the PGF subsidy mechanism stimulates a higher abatement investment, and the product price under the ABA subsidy mechanism becomes higher than that under the PGF subsidy mechanism.

In terms of producer surplus, the ABA subsidy mechanism is always better than the PGF subsidy mechanism. If the emissions level and the coverage of government subsidies are relatively low, consumers obtain the maximum utility under the PGF subsidy mechanism. However, with an increase in both the emission levels and the coverage of the government subsidy, the PGF subsidy mechanism helps consumers obtain higher utility than the ABA subsidy mechanism.

From an environmental perspective, when both the coverage of government subsidies and emission are relatively low, the ABA subsidy mechanism produces the greatest abatement investments and then achieves the lowest environmental damages. When emission and coverage of government subsidies are sufficiently high, the PGF subsidy mechanism becomes better than the ABA subsidy mechanism in reducing emission levels, since it incentivizes a higher level of firm abatement investment.

2.6.4 The hybrid subsidy policy

In this section, we consider the hybrid subsidy policy case. In other words, we consider both government type of subsidies in simultaneous, i.e., PGF and ABA investments simultaneously, according to the contest-based subsidy mechanisms, while imposing emission taxes on pollution and balanced budget.

In the hybrid subsidy policy case, the profit function of firm i is given by:

$$\pi_i = (p_i - c_i)q_i - \varepsilon_i \frac{{z_i}^2}{2} - \gamma_i \frac{{w_i}^2}{2} - tq_i(e_i - w_i) + \theta\, A_{iz} + (1-\theta)A_{iw} \tag{3.14}$$

where $0 \leq \theta \leq 1$ captures the government's subsidy allocation ratio to PGF investment and ABA investment. If $\theta = 1$, we are in the PGF subsidy case of the baseline model, while if $\theta = 0$, we are in the ABA subsidy case of the baseline model. In order to keep the analysis trackable, we let $\theta = 1/2$, i.e., government distributes subsidies equally among both mechanisms.

In what follows, we compare the hybrid subsidy mechanism with the PGF subsidy mechanism and the ABA subsidy mechanism of the baseline model in terms of firms' environmental investments, product price, consumer and producer surplus, environmental damage and social welfare. We summarize the main results as follows, which may provide a sufficiently rich overview of the general results.

The results show that the emission tax rate under hybrid subsidy mechanism tends to be lower than that under the other two subsidy mechanisms. Moreover, the emission tax revenue created in the hybrid subsidy mechanism is lower than that in the PGF subsidy mechanism and the ABA subsidy mechanism. In terms of firms' PGF investments, the hybrid subsidy mechanism provides a moderate incentive for firms' PGF investments, which is greater than that under the ABA subsidy mechanism, but less than that under the PGF subsidy mechanism. We also found that the ABA investment of firms under the hybrid subsidy mechanism is lower than that under the other two subsidy mechanisms. However, product price under the hybrid subsidy policy is lower than that under the other two subsidy policies. In terms of consumer surplus, the hybrid mechanism is better than the ABA subsidy mechanism but worse than the PGF subsidy mechanism. From the perspective of producer, the hybrid subsidy mechanism is the optimal choice in terms of highest profits.

However, the hybrid subsidy mechanism may not be a good option when comparing its environmental performance with that of the other two subsidy mechanisms, since firms do not have sufficient incentives to improve environmental quality via PGF investments and ABA investments under this mechanism. Finally, through numerical analysis (same parameter assignment as in section 5), we found that the social welfare under the hybrid subsidy mechanism is always the lowest compared with other two subsidy mechanisms, because environmental pollution increases the cost of social welfare with an increase in emission. Therefore, the PGF subsidy mechanism and the ABA subsidy mechanism in the baseline model are more effective subsidy mechanism in terms of overall social welfare.

2.7 Policy implications and Conclusions

This chapter compares two novel subsidy allocation mechanisms in order to incentivize environmental investments based on a competitive contest between firms. The first is the product green feature (PGF) subsidy mechanism in which the subsidy is distributed according to a PGF investment contest in which the firm's subsidy rate is based on its PGF investments relative to other firms' investments. The second is the abatement (ABA) subsidy mechanism in which the subsidy is distributed according to an ABA investment contest in which the firm's subsidy rate is based on its abatement investments relative to other firms' investments.

We found that both the PGF and the ABA subsidy mechanisms provide strong incentives for firms to perform environmental investments, however, the PGF subsidy mechanism tends to be superior.[8] It leads to more PGF investments, and even more ABA investments in industries or technologies in which emissions level are relatively high. In terms of emission tax rates, the PGF subsidy mechanism generates higher tax rates than the ABA subsidy mechanism. Furthermore, the PGF subsidy mechanism achieves a greater level of consumer surplus. When emissions levels are relatively low, the PGF subsidy

[8] In different contexts, Cohen et al. (2016), Li et al. (2020), and Meng et al. (2021) also found that subsidies provide positive incentives for environmental performance.

mechanism helps governments to obtain the highest total tax revenue, but there is a trade-off with higher emissions levels. For abatement investments and environmental damage, the ABA subsidy mechanism is the best in industries or technologies in which emissions levels are relatively low, but the PGF subsidy is superior when the emission levels exceed some threshold. When the government aims to maximize social welfare as emissions increase and environment quality wanes, the ABA subsidy mechanism achieves the highest level of social welfare. In industries or technologies in which emissions levels are relatively high, the PGF subsidy mechanism emerges as the optimal policy choice.

In this study, we also found that subsidies can lead to inflation and lower social welfare.[9] We argue that government subsidy expenditures and environmental policies that aim to increase investment in PGF or ABA and inflation are negatively related, and that the PGF subsidy mechanism is superior to the ABA subsidy mechanism to incentivize environmental investments, reduce environmental emissions, decouple economic growth from harmful emissions, and generate a trade-off between stabilizing inflation and improving the environment through a sustainable mix of environmental policies. Therefore, this study may guide governments to choose the optimal subsidy mechanism for different objectives.[10]

Note that the combination of subsidy and emission tax policies, proposed in this chapter, based on a competitive approach and with government budget balance is fairer and decreases the financial burden on governments and citizens. This is a positive aspect of the mechanism proposed in this study. Another positive aspect is that the subsidy that firms obtain is always less than the total investment cost, which prevent firms from using subsidies or taxes for arbitrage.

We should note that in order to implement the contest-based subsidy-tax mechanism proposed in this chapter, society may need specialized and institutional monitor that can report and verify the production and investment levels made by firms. In this context, national and firm level transparency and better data may be crucial for successful environmental policy implementation. In terms of managerial practices, the proposed approach adds an extra layer of competitiveness inside firms but does not add extra complexity because environment is already a concern in most companies.[11]

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[9] These observations are specific to our study (Li et al., 2020; Meng et al., 2021; Yu et al., 2021; among other).

[10] The diversity of objectives and target analyzed in this study is a distinctive feature from the existing literature (Zhang & Huang, 2021; Yu et al., 2018; among others).

[11] Similarly, from a policy perspective, since firms can choose their PGF investments to enhance their products to affect consumers' preferences and ABA investments to reduce their emission tax bill, firms must anticipate the strategic effects of their decisions on the market price, quantities, product greenness quality, and the emissions

We should also note that our study is theoretical. Our objective is to propose and compare the impacts of two contest-based subsidy allocation mechanisms, in which firms compete in terms of investments to obtain the highest amount of subsidy. This approach is completely new in the subsidy's allocation literature. For that reason, there is no reliable data available on firms competing for subsidies in terms of CO_2 emissions. Nonetheless, an interesting topic of further research would be the empirically study and validate of our approach.

Finally, we hope that the novel contest approach to distribute subsidies proposed in this chapter can be implemented by government authorities and that can inspire policymakers and researchers into designing new market-based subsidy mechanisms that can provide the adequate investment incentives to firms.

level of their competitors. In this context, policy makers could consider increasing public spending to raise consumers' environmental awareness, thereby driving demand and supply of green products.

2.8 Appendix

To prove our results, we need to compute the equilibrium of the model. The following equilibria are obtained for the three games, which are the benchmark case with subscript o, the PGF subsidy mechanism case with subscript z, and the ABA subsidy mechanism case with subscript w. In order to obtain tractable close form expressions, we assume $v = 1, \varepsilon_1 = \varepsilon_2 = \varepsilon, \gamma_1 = \gamma_2 = \gamma, c_1 = c_2 = c$, and $e_1 = e_2 = e$. The equilibrium results are symmetric for each firm in these three cases (e.g., the equilibrium product price in the benchmark case is $p_{1o} = p_{2o} = p_o$, in the PGF subsidy mechanism is $p_{1z} = p_{2z} = p_z$, and so on). The condition $e \geq 0.73\sqrt{\beta^2/\gamma\varepsilon}$ is required to guarantee that PGF and ABA investments are positive.

We solve the associated three two-stage games by backward induction and starting by substituting (2.1), (2.2), (2.5) and (2.6) into (2.7) to have the firm's profit function. In the benchmark case we have:

$$\pi_{io} = (p_{io} - c)\left(\frac{p_{-io} - p_{io} + \alpha + \beta(z_{io} - z_{-io})}{2\alpha}\right) - \varepsilon\frac{{z_{io}}^2}{2} - \gamma\frac{{w_{io}}^2}{2} \tag{2.15}$$

for $i = 1, 2$, and $-i$ denotes the rival firm.

Under the PGF subsidy mechanism, the profit function is given by:

$$\pi_{iz} = \left(p_{iz} - c - t_{iz}\,(e - w_{iz})\right)\left(\frac{p_{-iz} - p_{iz} + \alpha + \beta(z_{iz} - z_{-iz})}{2\alpha}\right) - \left(1 - \frac{z_{iz}}{z_{iz} + z_{-iz}}\right)\varepsilon\frac{{z_{iz}}^2}{2} - \gamma\frac{{w_{iz}}^2}{2} \tag{2.16}$$

for $i = 1, 2$, and $-i$ denotes the rival firm.

Under the ABA subsidy mechanism, the profit function is given by:

$$\begin{gathered}\pi_{iw} = \left(p_{iw} - c - t_{iw}\,(e - w_{iw})\right)\left(\frac{p_{-iw} - p_{iw} + \alpha + \beta(z_{iw} - z_{-iw})}{2\alpha}\right) - \\ \left(1 - \frac{w_{iw}}{w_{iw} + w_{-iw}}\right)\gamma\frac{{w_{iw}}^2}{2} - \varepsilon\frac{{z_{iz}}^2}{2}\end{gathered} \tag{2.17}$$

for $i = 1, 2$, and $-i$ denotes the rival firm.

Then, given the firms' PGF (z_{ik}) and ABA (w_{ik}) investments taken in the first stage, we differentiate the obtained expression (2.15), (2.16), and (2.17) with respect to $p_{i,k}$ for firm $i = 1, 2$, in case $k = o, z, w$. Hence, firm $i's$ profit-maximization problem yields the first-order condition given by:

$$0 = \frac{\partial \pi_{ik}}{\partial p_{ik}} = \frac{c - 2p_{ik} + p_{-ik} + et_k - t_k w_{ik} + \alpha + \beta z_{ik} - \beta z_{-ik}}{2\alpha} \tag{2.18}$$

for $i = 1, 2, k = o, z, w$, and $-i$ denotes the rival firm.

The second order condition is satisfied. Then, by solving equations (2.18) in the three cases, the equilibrium product price of each firm is given by:

$$p_{ik} = \frac{3c + 3e\, t_k - t_k(2w_{ik} + w_{-ik}) + 3\alpha + \beta z_{ik} - \beta z_{-ik}}{3} \tag{2.19}$$

for $i = 1, 2, k = o, z, w$, and $-i$ denotes the rival firm.

Then, we substitute the expression (2.19) into Eq. (2.15), (2.16), and (2.17) in the corresponding case, respectively, to have the profit function for the first stage. Note that there is no emission tax in the benchmark case, that is $t_o = 0$.

In the first stage, both firms simultaneously select the level of PGF and ABA investments z_{ik} and w_{ik} for $i = 1, 2,$ and $k = o, z, w$, in order to maximize their profits. At this stage, we impose symmetry and solve the system of two equations and two unknowns with respect to z_{ik} and w_{ik} for the cases $k = o, z, w$. The firms' profit-maximization problem yields the first-order conditions, which are given by:

In the benchmark case, we have:

$$\begin{cases} 0 = \dfrac{\partial \pi_{io}}{\partial z_{io}} = \dfrac{\beta}{3} - \varepsilon z_{io} \\ 0 = \dfrac{\partial \pi_{io}}{\partial w_{io}} = -\gamma w_o \end{cases} \tag{2.20}$$

for $i = 1, 2$.

Under PGF subsidy mechanism, we have:

$$\begin{cases} 0 = \dfrac{\partial \pi_{iz}}{\partial z_{iz}} = \dfrac{\beta}{3} - \dfrac{3\varepsilon z_{iz}}{8} \\ 0 = \dfrac{\partial \pi_{iz}}{\partial w_{iz}} = \dfrac{t_z}{3} - \gamma w_{iz} \end{cases} \tag{2.21}$$

for $i = 1, 2$.

Under ABA subsidy mechanism, we have:

$$\begin{cases} 0 = \dfrac{\partial \pi_{iw}}{\partial z_{iw}} = \dfrac{\beta}{3} - \varepsilon z_{iw} \\ 0 = \dfrac{\partial \pi_{iw}}{\partial w_{iw}} = \dfrac{t_w}{3} - \dfrac{3\gamma w_{iw}}{8} \end{cases} \tag{2.22}$$

for $i = 1, 2$.

The second order condition is satisfied, that is $\frac{\partial^2 \pi_{ik}}{\partial {z_{ik}}^2} < 0, \frac{\partial^2 \pi_{ik}}{\partial {w_{ik}}^2} < 0$. By solving equation (2.20), (2.21), and (2.22), we obtain each firm equilibrium PGF investment under different cases, given by:

$$z_o = \frac{\beta}{3\varepsilon}, z_z = \frac{8\beta}{9\varepsilon}, \text{and } z_w = \frac{\beta}{3\varepsilon} \tag{2.23}$$

$$w_o = 0, w_z = \frac{t_z}{3\gamma}, \text{and } w_w = \frac{8t_w}{9\gamma} \tag{2.24}$$

Since we assume that the two firms are symmetry, then the endogenous subsidy rate and the output of each firm equal to 1/2 under both the PGF subsidy mechanism and the ABA subsidy mechanism. We substitute $q_{ik} = 1/2$, expressions (2.23) and (2.24) into equation (2.11) and (2.12) to obtain the government total subsidy and emission tax revenue.

Under the PGF subsidy mechanism, we have:

$$S_z = \frac{32\beta^2}{81\varepsilon} \tag{2.25}$$

$$T_z = t_z\left(e - \frac{t_z}{32}\right) \tag{2.26}$$

Under the ABA subsidy mechanism, we have:

$$S_w = \frac{32{t_w}^2}{81\gamma} \tag{2.27}$$

$$T_w = t_w\left(e - \frac{8t_w}{9\gamma}\right) \tag{2.28}$$

Given the government budget-balance constraint, by solving $S_k = T_k$, for $k = o, z, w$. We obtain the endogenous emission tax, given by:

$$t_o = 0, t_z = \frac{1}{6}\left(9e\gamma + \frac{\sqrt{\gamma\varepsilon(243e^2\gamma\varepsilon - 128\beta^2)}}{\sqrt{3}\varepsilon}\right), \text{and } t_w = \frac{81e\gamma}{104} \tag{2.29}$$

Then, we substitute (2.29) into expressions (2.24) to obtain the per-firm equilibrium ABA investment under the different cases, given by:

$$w_o = 0, w_z = \frac{e}{2} + \frac{\sqrt{\gamma\varepsilon(243e^2\gamma\varepsilon - 128\beta^2)}}{18\sqrt{3}\varepsilon\gamma}, \text{and } w_w = \frac{9e}{13} \tag{2.30}$$

Proof of Proposition 2.1

From expressions (2.29), if $e \geq 8/9\sqrt{2\beta^2/3\gamma\varepsilon}$, then $t_z > t_w > t_o$ is always true.

We substitute (2.29) into equation (2.26) and (2.28) to obtain the equilibrium emissions tax revenue.

$$T_o = 0, T_z = \frac{32\beta^2}{81\varepsilon}, \text{and } T_w = \frac{81e^2\gamma}{338} \tag{2.31}$$

Proof of Proposition 2.2

From expressions (2.31), if $8/9\sqrt{2\beta^2/3\gamma\varepsilon} \leq e < 104/81\sqrt{\beta^2/\gamma\varepsilon}$, then $T_z > T_w > T_o$ is always true. If $e \geq 104/81\sqrt{\beta^2/\gamma\varepsilon}$, then $T_w > T_z > T_o$ is always true.

Proof of Proposition 2.3

From expressions (2.23), if $e \geq 8/9\sqrt{2\beta^2/3\gamma\varepsilon}$, then $z_z > z_w = z_o$ is always true.

Proof of Proposition 2.4

From expressions (2.30), if $8/9\sqrt{2\beta^2/3\gamma\varepsilon} \leq e < 26/27\sqrt{2\beta^2/3\gamma\varepsilon}$, then $w_w > w_z > w_o$ is always true. If $e \geq 26/27\sqrt{2\beta^2/3\gamma\varepsilon}$ then $w_z > w_w > w_o$ is always true.

We substitute (2.23), (2.29) and (2.30) into equation (2.19) in the corresponding case to obtain the equilibrium product price.

$$p_o = c + \alpha, p_z = c + \alpha + \frac{32\beta^2}{81\varepsilon}, \text{and } p_w = c + \alpha + \frac{81e^2\gamma}{338} \tag{2.32}$$

Proof of Proposition 2.5

From expressions (2.32), if $8/9\sqrt{2\beta^2/3\gamma\varepsilon} \leq e < 104/81\sqrt{\beta^2/\gamma\varepsilon}$, then $p_o < p_w < p_z$ is always true. If $e \geq 104/81\sqrt{\beta^2/\gamma\varepsilon}$, then $p_o < p_z < p_w$ is always true.

Then, we substitute $q_{ik} = 1/2$, and expressions (2.23) and (2.32) into equation (2.9) to obtain the consumer surplus under different cases.

$$CS_o = r - c + \frac{3\alpha}{2} + \frac{\beta^2}{3\varepsilon},\ CS_z = r - c - \frac{3\alpha}{2} + \frac{40\beta^2}{81\varepsilon}, \text{and } CS_w = r - c - \frac{3\alpha}{2} - \frac{81e^2\gamma}{338} + \frac{\beta^2}{3\varepsilon} \tag{2.33}$$

Proof of Proposition 2.6

From expressions (2.33), if $e \geq 8/9\sqrt{2\beta^2/3\gamma\varepsilon}$ then $CS_z > CS_o > CS_w$ is always true.

Proof of Proposition 2.7

We replace the obtained PGF investment (2.23), ABA investment (2.30), and product price (2.32) back into the objective function (2.7) to obtain equilibrium of firm's profit in the corresponding case, we have:

$$\begin{cases} \pi_0 = \dfrac{9\alpha\varepsilon - \beta^2}{18\varepsilon}, \pi_z = \dfrac{486\alpha\varepsilon - 128\beta^2 - 243e^2\gamma\varepsilon - 9\sqrt{3}e\sqrt{\gamma\varepsilon(243e^2\gamma\varepsilon - 128\beta^2)}}{972\varepsilon} \\ \text{and } \pi_w = \dfrac{\alpha}{2} - \dfrac{81e^2\gamma}{676} - \dfrac{\beta^2}{18\varepsilon} \end{cases} \tag{2.34}$$

Then, we substitute profit expressions (2.34) into function (2.10) to obtain the producer surplus, we have:

$$\begin{cases} PS_0 = \dfrac{9\alpha\varepsilon - \beta^2}{9\epsilon}, PS_z = \dfrac{486\alpha\varepsilon - 128\beta^2 - 243e^2\gamma\varepsilon - 9\sqrt{3}e\sqrt{\gamma\varepsilon(243e^2\gamma\varepsilon - 128\beta^2)}}{486\epsilon} \\ \text{and } PS_w = \alpha - \dfrac{81e^2\gamma}{338} - \dfrac{\beta^2}{9\varepsilon} \end{cases} \tag{2.35}$$

From expressions (2.35), if $e \geq 8/9\sqrt{2\beta^2/3\gamma\varepsilon}$, then producer surplus descending order is $PS_o > PS_w > PS_z$.

Proof of Proposition 2.8

Next, we substitute the expressions of ABA investment (2.32) into equation (2.8) to obtain the total environmental damages, we have:

$$D_0 = de^2, D_z = d(\frac{e}{2} - \frac{\sqrt{\gamma\varepsilon(243e^2\gamma\varepsilon - 128\beta^2)}}{18\sqrt{3}\gamma\varepsilon})^2, and\ D_w = \frac{16de^2}{169} \quad (2.36)$$

There exist e_1 for $8/9\sqrt{2\beta^2/3\gamma\varepsilon} < e_1 < 104/81\sqrt{\beta^2/\gamma\varepsilon}$. From expressions (3.35), if $8/9\sqrt{2\beta^2/3\gamma\varepsilon} \leq e < e_1$, then $D_w < D_z < D_o$ is always true. If $e \geq e_1$, then $D_z < D_w < D_o$ is always true.

In the numerical analyses section, we assign the value to parameters, see from Table 2-2. In sub-section 2.6.1 of the extension section, we assign the value of $c_1 = 0$, and $c_2 = 0.1$, and maintain the other parameter values in Table 2-2. Then, we do the same in sub-section 2.6.2 and assign the value of $\varepsilon_1 = 0.01$, and $\varepsilon_2 = 0.009$. In sub-section 2.6.3 of the extension section, we relax the assumption of v. In sub-section 2.6.4 of the extension section, we assign the value $\theta = 1/2$. All main results are summarized there.

Chapter 3 The Impact of Trade Conflict on Firm Behavior, Industry Profits and Consumer Surplus

Overview: We develop a two-stage Cournot international competition model, wherein a home country (the leading economy) competes against a foreign country (the fast-growing economy), to study the impact of potential trade conflict on firm behavior, industry profits and consumer surplus in each country. In the symmetrical case, we find that an increase in the likelihood of a trade conflict always negatively affects investments and exports and leads to a decrease in domestic sales if investment costs are low. Uncertainty surrounding the likelihood of trade conflict also exerts a positive impact on firm profits, except when the level of uncertainty is sufficiently low, and the investment costs are sufficiently high. In the asymmetrical case, we separately analyze the scenarios in which the leading economy's market size, marginal cost and investment cost are greater than those of the developing economy. The asymmetric case suggests that trade conflict uncertainty is beneficial to the leading economy in relative terms, which may encourage the leading economy to initiate a trade conflict to reinforce its leading position. This result can help us to understand the ongoing US-China trade conflict.

Keywords: trade conflict uncertainty; firm's profit; domestic sales; exports; investments; consumer surplus

JEL classifications*: D50, D81, F13, F51*

3.1 Introduction

Reuters reported on February 10, 2022, that the Biden administration is considering the possibility of imposing new tariffs on China if they cannot persuade Beijing to fulfill its failed commitments under the Phase One trade deal. The threat of trade conflicts creates great political and economic uncertainty in global markets and has been the focus of international trade studies for many decades. Davis (2019) explains how the rivalry between the United States and China illustrates how trade conflict is the primary driver of fluctuations in the degree of economic uncertainty in the global economy. Since 1995, members of the World Trade Organization (WTO) have referred 593 disputes to the Dispute Settlement Body (WTO 2019) in general, which reflects how trade conflicts have significantly affected the economies of the United States, China, and the rest of the world (Zhang et al., 2019).

A large body of literature has estimated the economic effects of trade conflicts. Some scholars consider the duration of the trade conflict's impact and divide it into long-term, medium-term, and short-term effects (Jeong, 2002; IMF, 2018b; Bekkers & Teh, 2019). Others divide the trade conflict's impact into macro and micro-level influences (Rosyadi & Widodo, 2018; Lai, 2019). A third group considers the impact of trade conflicts on various countries and regions, finding both positive and negative influences (Handley, 2014; Ciuriak & Xiao, 2018; Kapustina et al., 2020). Most empirical work analyzes the impact of trade conflicts based on the data collected from previous cases of trade conflicts (Li et al., 2018; Carvalho et al., 2019). This study makes a novel contribution by introducing strategic investments into the analysis to reflect the likelihood of a trade conflict wherein a home country (the leading economy) competes against a foreign country (the fast-growing economy). This study seeks to answer the question of how the relative likelihood of a trade conflict affects firm behavior, mainly observed through exports, domestic sales, investments, industry profits, and consumer surplus, and what are the main reasons for a trade conflict between the leading economy and the fast-growing economy?

To accomplish this objective, we apply an industrial organization approach to address international trade issues, focusing on how international trade conflicts influence firms' competitive behavior (Brander & Krugman, 1983). According to Krugman (1986, 1989), reviewing the relationship between the industrial organization and international trade makes a fundamental difference in the way researchers think about trade and firm behavior.

In our model, firms compete in terms of both investment and products, where these two modes of competition are allowed to have some degree of substitution between each other. This aspect of the analysis allows us to examine how the likelihood of trade conflict impacts firm behavior in the context of international trade. Therefore, this study is the first to analyze the competitive impacts on firm's investment arising from the uncertainty related to trade conflicts, allowing for two separate competition mechanisms to interact (that is, market competition and investment competition). As this relationship is somewhat complicated, the analysis may illuminate counter-intuitive scenarios where a lessening of market competition increases investment competition and consumer surplus.

In the symmetric case, we assume that the two competitors' initial market size, marginal production costs and investment costs are the same. In the first stage, both firms simultaneously select the level of investment to maximize their expected profits. In the second stage, the two firms simultaneously select the levels of domestic output and exports to maximize their expected profits. The equilibrium solution is achieved using backward induction, starting from the second stage of quantity competition. We also assume firms correctly anticipate the equilibrium level of output when deciding on the investment level that maximizes their profits. Then, we analyze the effect of the likelihood of trade conflict on the equilibriums.

In the asymmetric case, we apply a numerical approach. The asymmetry refers to differences between the two countries in terms of market size, marginal production costs or investment costs. Therefore, the equilibrium solution under various combinations of parameters is derived by computation methods and is shown graphically. The numerical simulation of the asymmetric case reveals why the leading economy is motivated to initiate trade conflicts.

Our main results offer valuable insights. First, if two competitors have the same market size, marginal production costs and investment costs, then: (i) an increase in the likelihood of a trade conflict always reduce investments and decreases exports. (ii) when the investment costs are sufficiently high, an increase in the likelihood of a trade conflict generates greater domestic sales and consumer surplus, since firms decrease cost-reduction investments and increase market competition that benefits consumers. By contrast, when the investment costs are sufficiently small, an increase in the likelihood of a trade conflict results in fewer domestic sales and decreases consumer surplus. On the other hand, firms with very low investment costs have more incentives to make investments, which reduce the market competition and then penalize consumers, and (iii) an increase in the likelihood of trade conflict has a positive effect on the firms' profits, since an increase in the likelihood of trade conflict leads to a reduction in market competition and an exclusive dealing effect[12]. The exception occurs only when the likelihood of trade conflict is sufficiently low, and the investment cost is sufficiently high.

Second, in the asymmetric case, we find that firm's domestic sales, exports, investments, and profits, as well as consumer surplus of the leading economy, rises with an increase in the likelihood of trade conflict, at least in relative terms, but not necessarily in absolute terms.

If we connect our analysis to the 2018-2020 US-China trade conflict, with the U.S. as the leading economy, and China as the fast-growing economy, then these relative benefits can stimulate the U.S. to initiate a trade conflict with China. Such a strategy could explain why the U.S. uses trade conflict as an effective instrument to maintain its leading position. This result can help us to understand some of the motivations behind the US-China trade conflict.

The analysis of this chapter is organized as follows: Section 3.2 presents a brief literature review. Section 3.3 sets out the model of international competition. Section 3.4 analyses a two-stage game under the symmetric condition, illuminating the effects of the likelihood of trade conflict on the different variables. Section 3.5 develops a numerical simulation of the effects of trade conflict uncertainty under asymmetry between the leading economy and the fast-growing economy. Section 3.6 provides the discussions. Section 3.7 offers some concluding remarks. All proofs are collected in section 3.8.

3.2 Literature review

3.2.1 The effects of trade conflict

This section briefly reviews the effects of the US-Sino trade conflict. Before the COVID-19 pandemic, the negative effect was expected to peak in 2020, where the global GDP is predicted to decline by 0.8%. Over the long-run, outputs in the U.S. and China will drop by almost 1% and 0.5% (IMF, 2018b). Besides, a full US–Sino trade war escalation (namely, 25% tariff was set on all bilateral trade between the U.S. and China) would decrease just 1% off Chinese GDP and 0.2% off the U.S. GDP (Abiad et al., 2018). Li et

[12] Exclusive dealing has two effects: it reduces the choice set for consumers and leads to a lower wholesale price. If the retail price falls enough to outweigh the reduction in consumer choice, consumers could better off (Sass, 2005).

al (2018) apply a multi-country global general equilibrium (GE) model to numerically simulate the effects of a possible US-China trade war. Results show that the trade conflict significantly hurts China, while the U.S. could benefit from unilateral sanction measures against China.

At a micro level of economic analysis, there are specific effects of trade conflict on income, employment and welfare, since production rises in some sectors of the economy and falls in others (Amiti et al., 2019). Trade conflicts can also lead to a reallocation of resources away from the economy's comparative advantage in many countries, affecting sectoral production in the economy (Bekkers & Teh, 2019). Also, conflicts associated with trade policy changes can alter both goods prices and factor prices under the resulting variation in sectoral demand, which further affects both firms' profits and customers' welfare. For instance, Ciuriak and Xiao (2018) report that trade tariffs could increase the prices of goods and undermine the competitiveness of the corresponding sectors, causing an overall adverse impact on the U.S. economy.

3.2.2 The effects of trade policy uncertainty

The present analysis contributes to the extant literature on the effects of trade or economic policy uncertainty. Al-Thaqeb and Algharabali (2019) observe that a growing number of studies highlight the influence of uncertainty on our lives, e.g., on financial markets, macro and micro level, stock markets, corporate behavior and risk management. Trade policy-related uncertainty is negatively related to firms' investments (Gulen & Ion, 2016). Many investors during this time find themselves in a wait-and-see mode, concerned about the possibility of a negotiated settlement or further escalation of a trade dispute. Corporations act more conservatively during periods of significant uncertainty, thereby slowing investments in production and employment.

Overall, policy uncertainty influences firms' policies and consumer spending significantly (Panousi & Papanikolaou, 2012; Gulen & Ion, 2016; Jeong, 2002). Moreover, policy uncertainty remarkably depresses trade flows across different sectors, where the economic magnitude of the effect can be substantial (Novy & Taylor, 2014). Yet, these corresponding references mainly study the impact of trade policy uncertainty on corporate investments while ignoring the effects of trade policy uncertainty on firms' domestic sales, exports, and consumer welfare. This analysis examines in more detail the impact of trade conflicts to help fill this gap.

3.2.3 The reason for the US-China trade conflict

The US-China trade war has been characterized by the complex interplay of economic and political factors. While economic issues such as trade imbalances and intellectual property theft have been at the forefront of the conflict, the underlying political motivations cannot be ignored. As noted by Layne (2018), Mearsheimer (2010), and Tekdal (2018) in their work on global hegemony competition, the US-China trade war is also a manifestation of the broader struggle for dominance in the international system.

In particular, the rise of China's economy has challenged the US's position as the world's preeminent superpower, leading to tensions in the political and economic spheres. As Kim (2019) and Zhang et al. (2019) highlight, China's economic growth has eroded US influence in shaping the global economic order, which has historically been a key element of US hegemony.

These factors have contributed to the US's perception of China as a strategic competitor and have fueled its efforts to maintain its dominant position in the international system. Therefore, while economic issues have been the ostensible cause of the US-China trade war, the underlying political motivations rooted in the competition for global hegemony cannot be overlooked.

The graph in Figure 3-1 illustrates the relationship between GDP level and real GDP growth (%) for both China and the US over the period from 2007 to 2020 (IMF, 2021). The data highlights the trend of China's economy growing at a faster pace than the US economy, resulting in China's GDP surpassing that of the US in recent years. This convergence in size is significant as China has emerged as a major global economic power and is increasingly challenging the US's dominance in the world economy. The trend is likely to continue in the coming years, with China projected to sustain its economic growth trajectory while the US faces several challenges to maintaining its economic momentum. It is essential for policymakers in both countries to understand this trend and take measures to maximize their respective economic potentials.

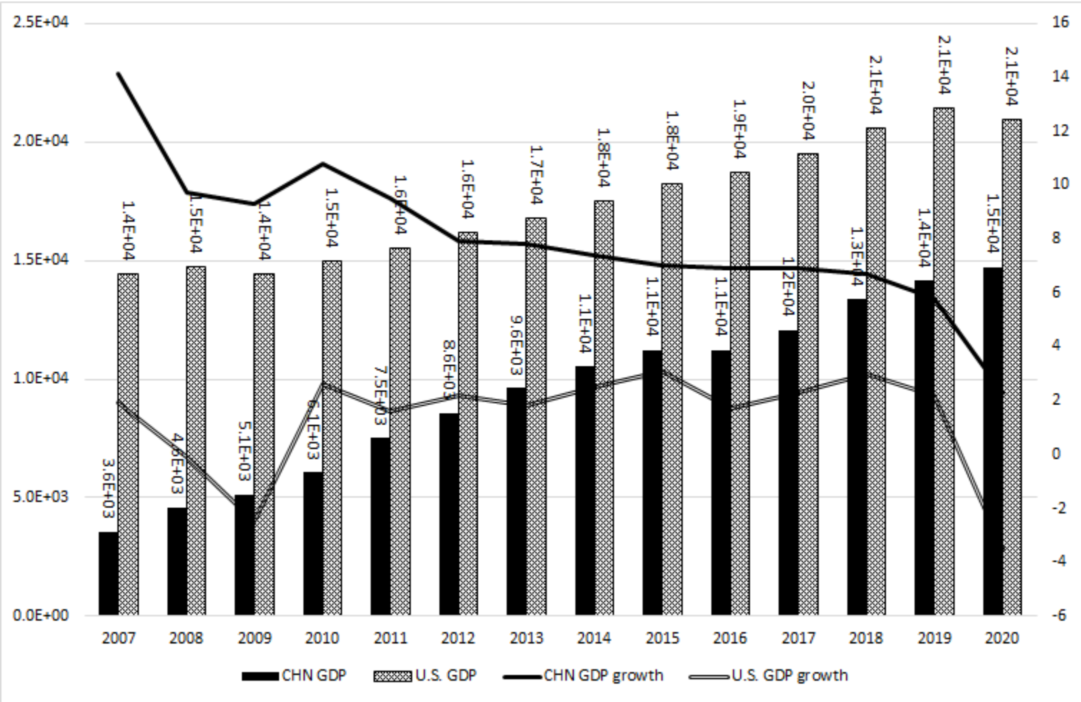

Figure 3-1 U.S. and China GDP (Billion U.S. dollars) and Real GDP growth (%)

Data source: International Monetary Fund (IMF), https://www.imf.org/en/Data

Figure 3-2 depicts the bilateral trade between the US and China over time. The graph shows that China has become an increasingly dominant player in global trade, particularly in the commodity export market, leading to a growing trade deficit for the US. This trend poses a significant challenge to the US economy's hegemony and highlights the need for the US to re-evaluate its trade policies and economic strategies to compete effectively in the global market. As China continues to expand its global influence, it is crucial for the US to take proactive measures to address its trade deficit with China and strengthen its competitiveness in the global trade arena. Failure to do so could lead to further erosion of the US's economic power and influence on the world stage.

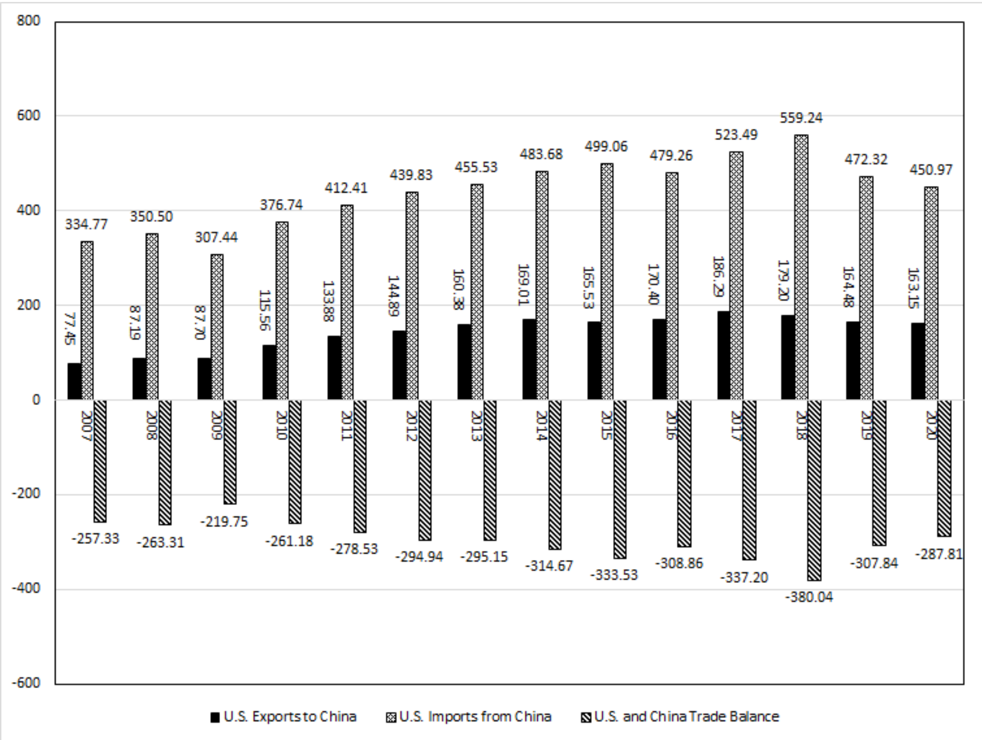

Figure 3-2 U.S. Trade in Goods and services with China and Trade Balance (Millions U.S. dollars)

Data source: The U.S. Census Bureau (BEA) https://www.census.gov/foreign-trade/balance/c5700.html.

Figure 3-3 below shows that investment in the U.S. in recent years has increased weakly as compared to China. Since investment expands the productive capacity of the economy and leads to economic growth and greater competitiveness. China is projected to overtake the U.S. as the world's largest economy with in the next two decades. China's investment trend is a big concern of U.S. China's rise and is increasingly viewed as a harbinger of America's relative decline.

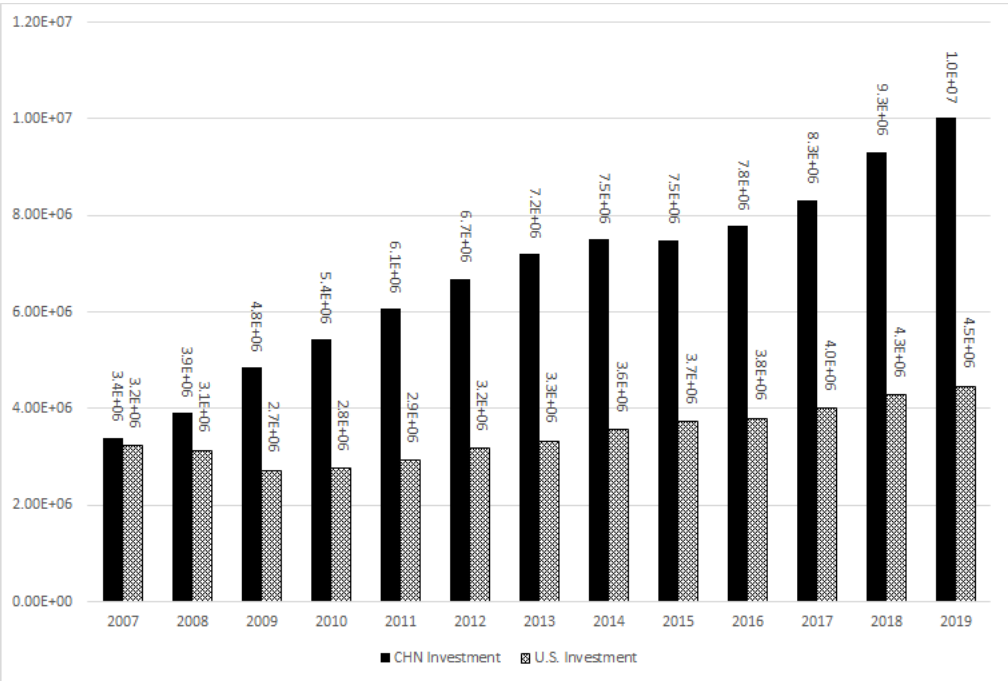

Figure 3-3 U.S. and China Investment (Millions U.S. dollars)

Data source: Organization for Economic Cooperation and Development (OECD), https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm.

Figure 3-4 depicts the expenditures of the US and China over the last decade, in both levels of spending and as a percentage of GDP. Though the U.S. leads the world in R&D spending, its annual growth rate of R&D expenditures is lower than that of China. If the current trend continues, China may pass the U.S. in total R&D expenditures in only the next several years. In order to consolidate its leading position in the technology industry, the U.S. is likely to have friction with China. This may be revealed as the U.S. has recently restricted the business activities of Chinese high-tech companies and the transfer of US technology to China (Kwan, 2020). The current dispute between the world's two largest economies goes far beyond trade tariffs and tit-for-tat reprisals. The underlying driver of this clash appears to be a race for global technological supremacy (Schneider-Petsinger et al., 2019).

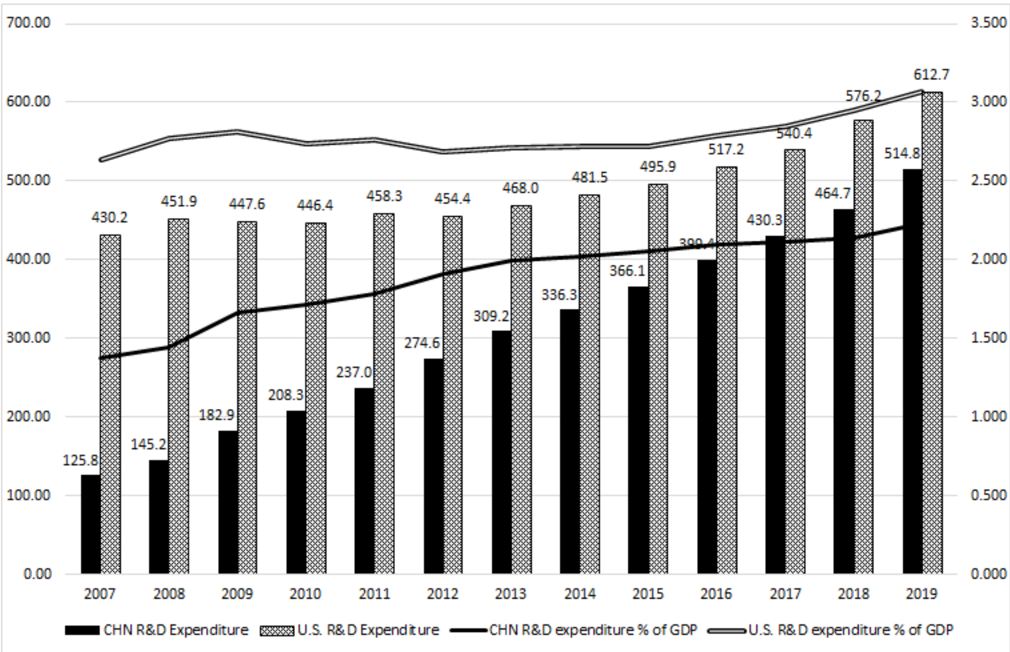

Figure 3-4 The U.S. and China R&D expenditure (Millions U.S. dollars) and % of GDP

Data source: Organization for Economic Cooperation and Development (OECD), https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm.

The above comparison of economic growth and investment between the US and China appears to reflect how China is threatening the U.S. economic hegemony. This implies that, in order to keep the hegemony, the U.S. has a strong incentive to initiate a trade war (Anderlini & Hornby, 2014). In line with our findings, even if trade conflict does not make economic sense, or causes a loss for the U.S. in absolute terms, it still could be part of a strategy to preserve US hegemony.

In summary, this study is closely related to the three streams mentioned above. The first one focus on the effect of trade conflict, the second one emphasizes the effect of trade policy uncertainty, the last one is related to the reason of US-China trade conflict. In light of this information, our study contributes to the growing literature on the analysis of trade conflict theoretically. We present a novel approach to international competition model. This study fills an important gap in the literature and opens new avenues of research and thinking in terms of trade conflict and trade policy.

3.3 Model, notation and assumptions

We consider a two-stage Cournot model of international competition for evaluating the effects of the likelihood of a trade conflict to impact firm's investments, exports, domestic sales, and profits as well as the level of consumer surplus in the economy of a leading and a fast-growing economy. This model is similar to extent models of international competition (Markusen, 1981; Shy, 1995), but has some novel aspects that will prove useful in modeling the US-China rivalry. Suppose that there are two trading countries: the home country with firm h and the foreign country with firm f. The two firms produce a homogeneous product that is sold both domestically and abroad.

The inverse demand function in each country is assumed to be linear:

$$p_i = a_i - (y_i + x_j),$$

for $i, j \in \{h, j\}$, and $i \neq j$, where a_i is constant and $a_i > 0$ for $i = h, f$. Let $y_i \geq 0$ denote firm i's output sold domestically, for $i = h, f$. Let $x_i \geq 0$ denote the output of firm i that is exported, for $i = h, f$. Let $p_i \geq 0$ denote country i's market price for $i = h, f$.

The production process is costly, with marginal cost of production given by:

$$c_i - e_i$$

for $i = h, f$, where c_i is the constant marginal cost and e_i measures the amount of investment effort. In other words, each firm can reduce the marginal cost of production by spending resources on investment activities (for example, R&D investment). Our interpretation is that investments result in cost reductions in the production process. The investment total cost is strictly increasing and convex in the investment effort e_i, and is given by:

$$\gamma_i \frac{{e_i}^2}{2}$$

for $i = h, f$, where the parameter $\gamma_i > 0$ captures the cost of the investment effort. Altogether, the total cost function is given by:

$$(c_i - e_i)(y_i + x_i) + \gamma_i \frac{{e_i}^2}{2}$$

for $i = h, f$.

The profit is the revenue collected in each firm minus the costs of production and the investment costs. Formally, the firm's profit is given by:

$$\pi_i = (a_i - (y_i + x_j))y_i + (a_j - (y_j + x_i))x_i - (c_i - e_i)(y_i + x_i) - \gamma_i \frac{{e_i}^2}{2} \tag{3.1}$$

for $i, j \in \{h, j\}$, and $i \neq j$.

In most partial equilibrium analyses within the industrial organization literature, it is common to use consumer surplus as a measure of the consumers' gains from trade (Shy, 1995). Formally, the consumer surplus expression is given by:

$$CS_i = \frac{(y_i + x_j)^2}{2} \tag{3.2}$$

for $i, j \in \{h, j\}$, and $i \neq j$.

The risk of trade wars is presumed to generate a pervasive uncertainty in the world trade system. In order to capture the uncertainty associated with trade conflict, we assume that $\alpha \in [0,1]$ is the likelihood of trade conflict between two countries. In this context, we assume that there is no trade between firm h and f whenever a trade conflict occurs, i.e., $x_i = 0$, for $i = h, f$. Otherwise, both countries compete in the international markets, i.e., $x_i > 0$, for $i = h, f$.

Hence, the expected profit is given by:

$$E[\pi_i] = \alpha \pi_{i_{|x_i = x_j = 0}} + (1 - \alpha)\pi_{i_{|x_i, x_j > 0}} \tag{3.3}$$

for $i, j \in \{h, j\}$, and $i \neq j$, where E[·] denotes the expectation operator with respect to the probability of trade conflict between firm h and f.

The model involves a two-stage game. In the first stage, both firms simultaneously select the level of investment to maximize their expected profit. Subsequently, in the second stage, the two firms simultaneously set the levels of domestic output and exports to maximize their expected profit. The equilibrium solution is achieved by backward induction, starting from the second stage of quantity competition. We assume firms correctly anticipate the equilibrium level of output when deciding on the level of investment that maximizes their profits.

3.4 Analysis of the symmetric countries case

In this section, we consider the case in which the sectors are symmetric, i.e., $a_h = a_f = a$, $c_h = c_f = c$ and $\gamma_h = \gamma_f = \gamma$. Subsequently, we obtain a tractable close form expression. To ensure the solution of the model is positive and meaningful, we assume the following parameter restrictions: $\gamma(3+\alpha)^2 > 8$ and $a > c$. The symmetric equilibrium solution of the two-stage game is fully described by each firm's investment e_i, domestic sales y_i and exports x_i for $i = h, f$.

The equilibrium of investment for firm h and f is given by:

$$e_h = e_f = \frac{8(a-c)}{\gamma(3+\alpha)^2 - 8} \tag{3.4}$$

The equilibrium of export for firm h and f is given by:

$$x_h = x_f = \frac{\gamma(a-c)(3+\alpha)}{\gamma(3+\alpha)^2 - 8} \tag{3.5}$$

The equilibrium of domestic sales for firm h and f is given by:

$$y_h = y_f = \frac{\gamma(a-c)(1+\alpha)(3+\alpha)}{\gamma(3+\alpha)^2 - 8} \tag{3.6}$$

The equilibrium of expected profits for firm h and f is given by:

$$E[\pi_h] = E[\pi_f] = \frac{\gamma(a-c)^2(\gamma(3+\alpha)^2(2+\alpha+\alpha^2) - 32)}{(\gamma(3+\alpha)^2 - 8)^2} \tag{3.7}$$

The equilibrium of consumer surplus is given by:

$$CS_h = CS_f = \frac{\gamma^2(a-c)^2(2+\alpha)^2(\alpha+3)^2}{2(\gamma(3+\alpha)^2 - 8)^2} \tag{3.8}$$

Then, we analyze the effect of the likelihood of trade conflict on these equilibriums. The following set of results summarizes our findings regarding the impacts of the likelihood of trade conflict on firms' behavior, profits, and consumer surplus. The proof is shown in the Appendix.

Proposition 3.1

In the symmetric case, when $\gamma(3+\alpha)^2 > 8$ *and* $a > c$*, an increase in the likelihood of trade conflict has a negative effect on the firm's investments.*

Proposition 3.1 suggests that a firm's investments in reducing production costs become more conservative as the likelihood of trade conflict increases. This assumption is reasonable given that trade conflicts reduce competition between firms and curtail exports, leading to a subsequent reduction in production levels. As production scale decreases, the incentives to invest in reducing production costs also decrease, resulting in lower profitability of such investments. Thus, the investment effect is always negative, reinforcing the link between product market competition and corporate investment decisions, particularly in terms of risk-taking and investment efficiency when firms face trade conflict uncertainty.

By adopting a conservative investment approach, firms are able to mitigate risks associated with costly investments. The robust negative relationship between the likelihood of trade conflict and firms' investments is consistent with empirical evidence (Leahy & Whited, 1995; Guiso & Parigi, 1999; Handley & Limão, 2012).

Proposition 3.2

In the symmetric case, when $\gamma(3+\alpha)^2 > 8$ *and* $a > c$*, an increase in the likelihood of trade conflict has the following impact on the firm's domestic sales:*

(a) *If* $\frac{8}{(3+\alpha)^2} < \gamma < \frac{8(2+\alpha)}{(3+\alpha)^2}$*, an increase in the likelihood of trade conflict has a negative effect on domestic sales.*
(b) *If* $\gamma > \frac{8(2+\alpha)}{(3+\alpha)^2}$*, an increase in the likelihood of trade conflict has a positive effect on firm's domestic sales.*

The intuition behind Proposition 3.2 is as follows. Firms compete in terms of both investments and output in the product market. In other words, firms need to weight the tradeoff between investment competition and production competition. In Proposition 3.1, we see that an increase in the likelihood of conflict always produces a negative effect on investments. However, the effect in terms of product market competition is not clear. The reason is that these two modes of competition have some degree of substitution between each other. First, intense product market competition decreases profits and lowers the incentives to invest. Second, competition may provide firms with incentives to invest to escape from the competition in the product market.

Regarding the tradeoff, on the one hand, the more firms compete in terms of investments, the less likely they are to compete in the product market, i.e., by supplying lower quantities and charging higher prices. On the other hand, the fewer firms compete in terms of investments, the more likely they are to compete in the product market, i.e., by supplying higher quantities and charging lower prices. Overall, competition in the product market affects firms' incentives for investments.

Part (a) of Proposition 3.2 states that when the investment cost is low (and the likelihood of trade conflict is low enough), the competition reduction effect dominates, and the domestic sales will decrease with an increase in the likelihood of trade conflict. The reason is that firms have more incentives to make investments with low costs of investment, which decreases the incentives to compete in the product market and decreases domestic sales. It is more efficient for the firms to compete in terms of investments (e.g., R&D investments) than in terms of the product market.

On the contrary, Part (b) of Proposition 3.2 states that when the investment cost is high (and the likelihood of trade conflict is high enough), fewer firms compete in terms of investments, the product market competition increases, and domestic sales increase. In this case, the high costs of investment reduce the firms' incentives to invest, which increases the competition in the product market and increases domestic sales. The present model concludes that the product market competition and investment competition can be substitutes when firms face trade conflict uncertainty. The results of the interaction between investment competition and product market competition suggest that an increase in the likelihood of trade conflict leads to lower investments and weaker product market competition.

Proposition 3.3

In the symmetric case, when $\gamma(3+\alpha)^2 > 8$ and $a > c$, an increase in the likelihood of trade conflict has a negative effect on the firm's exports.

Proposition 3.3 states that firms engaging in international trade reduce their exports as the probability of trade conflict increases. While liberalizing barriers to international trade stimulates increased competition, this lowers domestic prices and increases consumer surplus. On the contrary, tightening international trade may decrease competition and benefit domestic import-competing firms. Hence, firms become more cautious as the probability of trade conflict increases. The foreign firms find it more difficult to export their product, while domestic producers benefit from an exclusive dealing effect in their home markets.

In line with the empirical evidence, as the likelihood of trade conflict increases, the two protagonists of the trade conflict—the U.S. and China—are the biggest losers in terms of exports. Abiad et al. (2018) estimate that China exports will suffer a sharper decline than the U.S. exports, i.e., 3.6% and 1.9%, respectively. Countries that are more engaged in trade are more reluctant to trade conflicts.

Proposition 3.4

In the symmetric case, when $\gamma(3+\alpha)^2 > 8$ and $a > c$, an increase in the likelihood of trade conflict has a positive effect on the firm's profits, except if $\alpha \in \left[1, \frac{1}{5}\right]$ and γ is very large.

Proposition 3.4 states that, in general, for a sufficiently low investment cost and high probability of trade conflict, an increase in that probability of trade conflict has a positive effect on the firms' profits. Since the more trade conflict occurs, the less exports appear in the market, and then, lead to reduction in market competition, further results in an increase in firms' profits. The exception occurs only when the likelihood of trade conflict is sufficiently low and the investment cost parameter γ is sufficiently high. In this case, the firms' profits decrease because the reduction in investment competition, on the other hand, the benefits from the exclusive dealing effect are not enough to compensate for the substantial benefits from cost-reduction investment.

These findings help to explain why domestic firms tend to lobby for protectionism and do not oppose trade conflicts. Moreover, changes in trade policies affect the profits of the firms, which leads to changes in the number of firms, market concentration and market shares.

Proposition 3.5

In the symmetric case, when $\gamma(3+\alpha)^2 > 8$ and $a > c$, an increase in the likelihood of trade conflict has the following impact consumer surplus:

(a) If $\frac{8}{(3+\alpha)^2} < \gamma < \frac{8(5+2\alpha)}{(3+\alpha)^2}$, an increase in the likelihood of trade conflict has a negative effect on consumer surplus.

(b) If $\gamma > \frac{8(5+2\alpha)}{(3+\alpha)^2}$*, an increase in the likelihood of trade conflict has a positive effect on consumer surplus.*

Part (a) of Proposition 3.5 states that an increase in the likelihood of trade conflict has a negative effect on consumer surplus. In the case where the investment costs are relatively low, firms prefer to invest; consequently, an intense competition happens in investment, which then leads to a reduction in product market competition and an exclusive dealing effect, which decreases consumer surplus. This seems to be the most likely cause.

Part (b) of Proposition 3.5 states that in the case where the cost parameter γ is sufficiently high, firms substitute competition in cost-reduction investments with competition in the product market to the point that benefits consumers.

To summarize this section, an increase in the likelihood of trade conflict always produces a negative investment effect. The same happens with exports. The direction of the competition effect is not always clear. Nonetheless, competition tends to decrease, favoring producers and penalizing consumers. The exception occurs only when the cost of investment is sufficiently high, in which case, firms may increase product market competition, with negative impact in their profits, but with benefits for consumers. Therefore, competition indeed impacts investments (and consumer surplus) when firms compete both in the product market and in investments. This relationship is complex and may lead to scenarios in which a lessening of competition increases investments and consumer surplus.

3.5 The asymmetric countries case - Numerical analysis

In this section, we analyze the case in which firms have asymmetric characteristics along several dimensions. This mainly refers to differences in terms of market size, production costs structures, and investment costs. We find that these differences alter the outcomes of this two-stage Cournot model analysis.

This two-stage model delivers non-tractable equilibrium solutions when the two countries are endowed with asymmetric characteristics. Therefore, we follow a numerical approach, where the equilibrium under the various combinations of parameters is given by computation and shown graphically. In this context, we consider the following the numerical values for the parameters: $a \in \{100,200\}$, $c \in \{20,40\}$, $\gamma \in \{10,20\}$. The numerical values are chosen without loss of generality with the objective of being sufficiently representative of empirical reality.

To make the exposition clearer, we present the ratio of the two countries' independent variables for varying the likelihoods of the trade conflict.

Scenarios

There are six scenarios under the three parameters combinations:

i. Two countries' market size is asymmetric, i.e., $a_h > a_f$, but marginal cost and investment costs are symmetric, i.e., $c_h = c_f$ and $\gamma_h = \gamma_f$.

ii. Two countries' marginal cost is asymmetric, i.e., $c_h > c_f$, but market size and investment costs are symmetric, i.e., $a_h = a_f$ and $\gamma_h = \gamma_f$.

iii. Two countries' investment costs are asymmetric, i.e., $\gamma_h > \gamma_f$, but market size and marginal cost are symmetric, i.e., $a_h = a_f$ and $c_h = c_f$.

iv. Two countries' market size and marginal cost are asymmetric, i.e., $a_h > a_f$ and $c_h > c_f$, but investment costs are symmetric, i.e., $\gamma_h = \gamma_f$.

v. Two countries' market size and investment costs are asymmetric, i.e., $a_h > a_f$ and $\gamma_h > \gamma_f$, but marginal cost is symmetric, i.e., $c_h = c_f$.

vi. Two countries' marginal cost and investment costs are asymmetric i.e., $c_h > c_f$ and $\gamma_h > \gamma_f$, but market size is symmetric, i.e., $a_h = a_f$.

3.5.1 Asymmetry in market size

In the case where the home country has a larger market size, i.e., $a_h > a_f$, but two firms have symmetrical marginal cost and investment costs, we set $a_h = 200$, $a_f = 100$, $c_h = c_f = 20$ and $\gamma_h = \gamma_f = 10$. Figure 3-5 shows the ratio trend $\frac{\pi_f}{\pi_h}, \frac{y_f}{y_h}, \frac{x_f}{x_h}, \frac{e_f}{e_h}$ and $\frac{CS_f}{CS_h}$ under this setting.

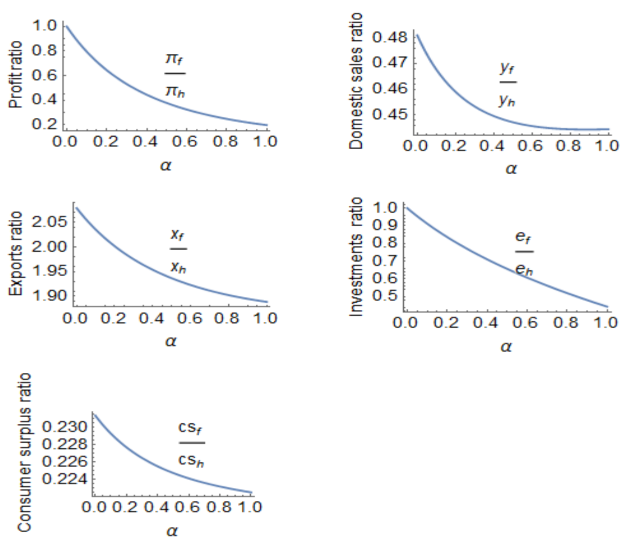

Figure 3-5 Ratio trend when $a_h > a_f, c_h = c_f$ and $\gamma_h = \gamma_f$

We conclude that an increase in the likelihood of trade conflict favors the country with a larger market size, in relative terms. This observation is always true, independent of how the likelihood of trade conflict affects firm behavior and the consumer surplus in absolute terms. For instance, an increase in the likelihood of trade conflict reduces the profits of firm f but increases the profits of firm h, and both firms' domestic sales and consumer surplus increase. Nevertheless, this positive effect is more influential on the firm h than that on firm f. Moreover, both firms' exports and investments decrease when the likelihood of trade conflict increases, but the reduction in firm f is more significant than that in firm h. As a result, the country with a greater market size obtains relative benefits from trade conflict. Note that in Figure 3-5, we also observe that only the ratio of export $\frac{x_f}{x_h}$ is higher than 1, which implies that firm f has a higher demand for exports.

3.5.2 Asymmetry in marginal cost

In the case where firm h has higher marginal costs, that is $c_h > c_f$, both countries face the symmetrical market size and two firms' investment costs are the same, we set $a_h = a_f = 100$, $c_h = 40$, $c_f = 20$ and $\gamma_h = \gamma_f = 10$. Figure 3-6 shows the ratio trend $\frac{\pi_f}{\pi_h}, \frac{y_f}{y_h}, \frac{x_f}{x_h}, \frac{e_f}{e_h}$ and $\frac{CS_f}{CS_h}$ under this setting.

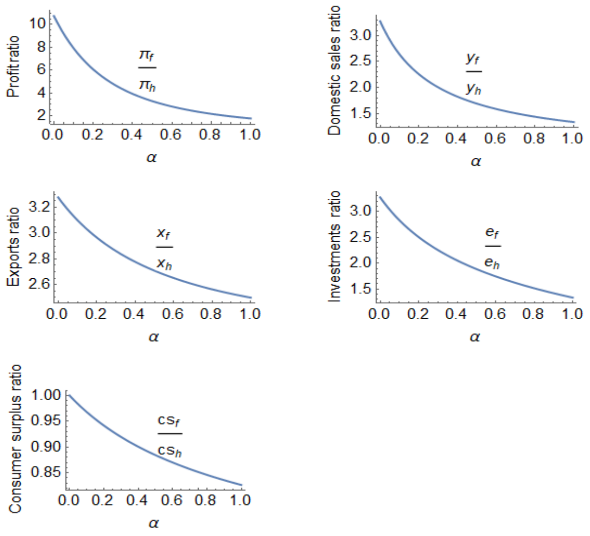

Figure 3-6 Ratio trend when $a_h = a_f, c_h > c_f$ *and* $\gamma_h = \gamma_f$

In this numericalcase, the country with a higher marginal cost obtains an advantage from an increase in the likelihood of trade conflict, in relative terms. Since the values of $\frac{\pi_f}{\pi_h}, \frac{y_f}{y_h}, \frac{x_f}{x_h}, \frac{e_f}{e_h}$ and $\frac{CS_f}{CS_h}$ are larger than 1, firm $f's$ profits, domestic sales, exports and investments are more than those of firm h.However, with an increase in the likelihood of trade conflict, firm $h's$ profit increase but firm $f's$ decrease, in absolute terms.

In addition, both firms' domestic sales expand with an increase in the likelihood of trade conflict, but firm $h's$ domestic sales increase much more, in absolute terms. We conclude that trade conflict uncertainty negatively affects firm's exports and investments, but this negative effects on firm f are always more significant. Also, both countries' consumer surplus always increases with an increase in the likelihood of trade conflict. However, the home country's consumer surplus grows much more. To summarize, trade conflict is beneficial to the firm with the relatively higher marginal cost.

3.5.3 Asymmetry in investment costs

In the case where the firm h has higher investment costs, that is $\gamma_h > \gamma_f$, both countries face the symmetrical market size and two firms' investment costs are the same, we set $a_h = a_f = 100$, $c_h = c_f = 20$, $\gamma_h = 20$ and $\gamma_f = 10$. Figure 3-7 shows the ratio trend $\frac{\pi_f}{\pi_h}, \frac{y_f}{y_h}, \frac{x_f}{x_h}, \frac{e_f}{e_h}$ and $\frac{CS_f}{CS_h}$ under this setting.

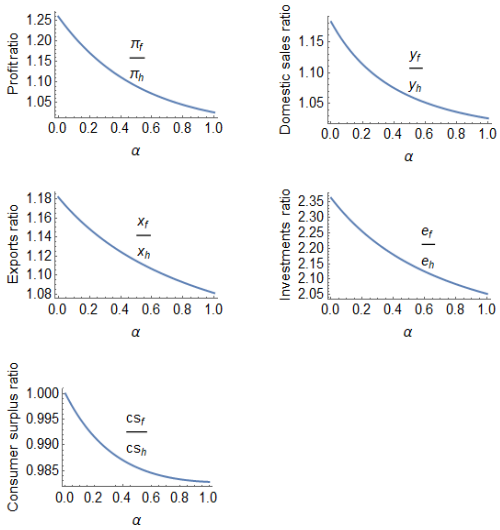

Figure 3-7 Ratio trend when $a_h = a_f, c_h = c_f$ *and* $\gamma_h > \gamma_f$

Similarly, Figure 3-7 shows that the values of $\frac{\pi_f}{\pi_h}, \frac{y_f}{y_h}, \frac{x_f}{x_h}, \frac{e_f}{e_h}$ and $\frac{CS_f}{CS_h}$ are larger than 1 as well, which indicates that firm $f's$ profits, domestic sales, exports and investments are greater than those of firm h in this numerical case. Two firms' profits, domestic sales, and consumer surplus increase with a rise in the likelihood of trade conflict, but these values for firm h increase much more than for firm f. This implies that, a trade conflict favors the home country. On the other hand, an increase in the likelihood of trade conflict has negative effects on the firms' exports and investments. However, these negative effects are more pronounced for firm f.

To sum up, trade conflict uncertainty brings advantages to the home country, in relative terms. Those relative benefits may compensate for some of the adverse effects caused by higher investment costs to firms.

Corollary 3.1 -Asymmetry in market size and marginal cost

The case in which the home country has a larger market size and firm h faces higher marginal cost is a corollary to cases 3.5.1 and 3.5.2. We set $a_h = 200, a_f = 100$, $c_h = 40, c_f = 20$, and $\gamma_h = \gamma_f = 10$. Figure 3-8 shows the ratio trend $\frac{\pi_f}{\pi_h}, \frac{y_f}{y_h}, \frac{x_f}{x_h}, \frac{e_f}{e_h}$ and $\frac{CS_f}{CS_h}$ under this setting.

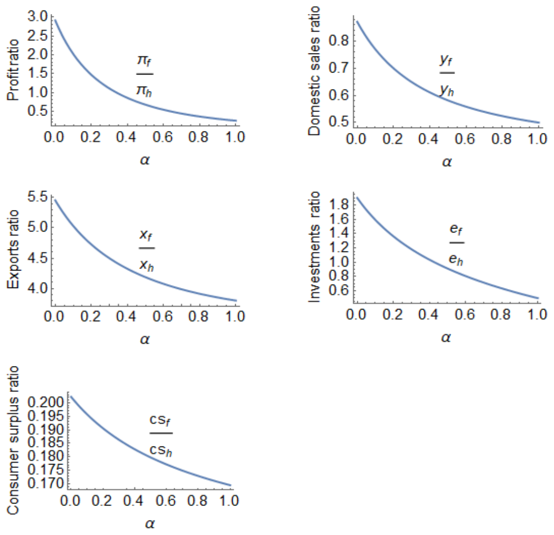

Figure 3-8 Ratio trend when $a_h > a_f, c_h > c_f$ *and* $\gamma_h = \gamma_f$

In Figure 3-8, we observe that all ratios decline as the market size of the home country increases and firm h faces higher marginal costs. Accordingly, an increase in the likelihood of trade conflict is beneficial to the home country in relative terms.

In this case, firm $f's$ profits decline along with an increase in the likelihood of trade conflict, but firm $h's$ profits increase in absolute terms. We also observe that the ratios of profit, domestic sales and investment are smaller than those in case 3.5.2. As mentioned in case 3.5.2, a higher marginal cost may result in decreases in firms' profits, domestic sales, exports, and investments. Thus, a larger market size would lessen the adverse effect of suffering higher marginal production costs. Besides, by comparing these two firms, firm $f's$ exports and investments decline more precipitously when trade conflict uncertainty increases. Moreover, an increase in the likelihood of trade conflict has a positive effect on firms' domestic sales and consumer surplus, and these positive effects are more significant in the home country.

Corollary 3.2 -Asymmetry in market size and investment costs

The case in which the home country has a larger market size and firm h faces higher investment costs is a corollary to cases 3.5.1 and 3.5.3. We set $a_h = 200, a_f = 100, c_h = c_f = 20, \gamma_h = 20,$ and $\gamma_f = 10$. Figure 3-9 shows the ratio trend $\frac{\pi_f}{\pi_h}, \frac{y_f}{y_h}, \frac{x_f}{x_h}, \frac{e_f}{e_h}$ and $\frac{CS_f}{CS_h}$ under this setting.

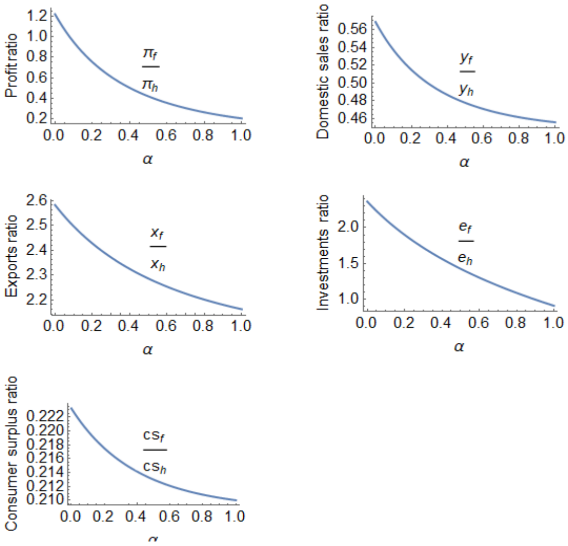

Figure 3-9 Ratio trend when $a_h > a_f, c_h = c_f$ *and* $\gamma_h > \gamma_f$

All ratios show a downward trend in Figure 3-9 as well. Trade conflict is beneficial to the home country, in relative terms.

An increase in the likelihood of trade conflict has a positive effect on the firm $h's$ profits but a negative effect on the profit of firm f. In case 3.5.3, we describe that the higher probability of trade conflict, the more profits firm f obtains. However, the profit of firm f declines in case 3.5.1. Compared with this case, we find that the influence of market size on the firms' profits is dominant. In general, the uncertainty of trade conflicts has harmed firms' exports and investments, which greatly impacts firm f. In addition, domestic sales and consumer surplus always increase with a rise in the likelihood of trade conflicts, but both increase in the home country more than in the foreign country.

Corollary 3.3 -Asymmetry in marginal cost and investment costs

The case in which firm h has higher marginal cost and investment costs is a corollary to cases 3.5.2 and 3.5.3. We set $a_h = a_f = 100$, $c_h = 40, c_f = 20$, $\gamma_h = 20$, and $\gamma_f = 10$. Figure 3-10 shows the ratio trend $\frac{\pi_f}{\pi_h}, \frac{y_f}{y_h}, \frac{x_f}{x_h}, \frac{e_f}{e_h}$ and $\frac{CS_f}{CS_h}$ under this setting.

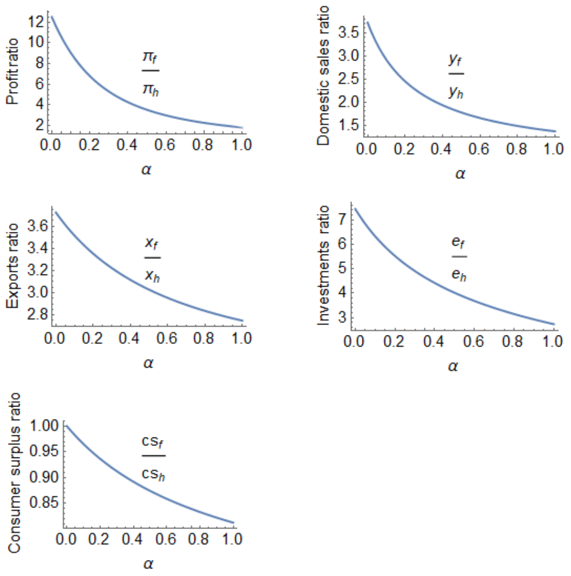

Figure 3-10 Ratio trend when $a_h = a_f, c_h > c_f$ *and* $\gamma_h > \gamma_f$

Given the restrictions $c_h > c_f$ and $\gamma_h > \gamma_f$, Figure 3-10 illustrates a decreasing trend in these ratios, thus, trade conflict is beneficial to the home country, in relative terms. Therefore, the home country has incentives in creating a trade conflict.

Further, Figure 3-10 shows that all ratios (except consumer surplus) are greater than 1. Thus, firm $f's$ profit, domestic sales, exports and investments are more than those of firm h. An increase in the likelihood of trade conflict benefits the firm $h's$ profits but hurts firm $f's$ profits. Besides, an increase in the likelihood of trade conflict generates positive effects on the firms' domestic sales and consumer surplus, but firm h obtains greater benefits. In contrast, an increase in the likelihood of trade conflict causes a more precipitous decrease to firm $f's$ exports and investments.

3.6 Discussion

By comparing the above six scenarios, we find that market size has a dominant influence on consumer surplus and domestic sales. Further, changes in the marginal production costs and investment costs have a significant impact on the firms' behavior. Generally, the relatively large costs may make firms reduce their investments, production, and export activities, thereby reducing their profits.

When discussing these obtained results, we refer the country with a larger market size, higher marginal cost and higher investment costs as the leading economy, and the country with the smaller market size, lower marginal cost and lower investment costs as the fast-growing economy. In this context, the home country is the leading economy (the U.S.) and the foreign country is the fast-growing economy (China). The numerical application to the asymmetric case yields different effects of the likelihood of trade conflict on the leading economy and the fast-growing economy. In absolute terms, trade conflict has a positive effect on the profit of home-country firm h, but the opposite is true for fast-growing country firm f. In most cases, the two firms' exports and investments always decrease as the likelihood of trade conflict increases, but this negative impact is more significant on firm f. In addition, the domestic sales and consumer surplus of the two firms always increase in accordance with an increase in the likelihood of trade conflict, and this positive impact is more significant for firm h. This may explain why some firms may have been committed to lobbying governments to increase international trade barriers. Our results suggest that the actors actually promoting the conflict are the leading country's firms.

Thus, it is entirely plausible that an increase in the likelihood of trade conflict benefits the leading country in relative terms, but not necessarily in absolute terms. This relative benefit stimulates firms in the leading economy to support a trade conflict with the fast-growing country. In this way, trade conflict might be an effective economic and political instrument to maintain the leading economic position for the leading country.

In the current trade situations of the world market, it is in the best interests of the U.S. to maintain the existing hegemony order (Norrlof & Wohlforth, 2019). However, China's rapid ascendance as a potential hegemonic power constitutes a significant challenge to this U.S. hegemony. Therefore, the current US-Sino trade conflict initiated by the U.S. perhaps aims to slow down the rapid economic growth of China.

Although China has become more influential because of rapid development, the U.S.'s hegemony position remains. The historical experience revealed that the expansion of the hegemony order was more oppressive in greater economic sanction and restriction than the status quo (Mastanduno, 2019). Therefore, in order to keep its economic hegemonic position, a trade conflict might represent an effective strategy for the leading economy to protect its domestic economy against the competitive influences exerted by trade with a growing economy. To sum up, the U.S. may have incentives to reinforce its dominant position to maintain the economic benefits of its economic hegemonic position.

3.7 Conclusion

Our results suggest that when the two competing firms have symmetrical conditions, an increase in the likelihood of trade conflict always produces a negative investment effect in lower production costs as well as the level of exports. Therefore, firms in both leading country and the fast-growing country may act more conservatively during the high uncertainty period associated with potential trade conflict.

Further, the impact of trade conflict on the level of all firms' market and investment competition is not always clear. With an increase in the likelihood of trade conflict, firms have less incentive to compete in the product market in subsequent periods and may decrease domestic sales when such investment costs are sufficiently low. However, the firm's domestic sales would increase if such investments became relatively costly. In this scenario, competition tends to decrease, favoring producers and penalizing consumers. Also, an increase in the likelihood of trade conflict positively affects the firms' profits. An exception occurs only when the likelihood of trade conflict is sufficiently low, and the investment costs are sufficiently high.

In addition, an increase in the likelihood of trade conflict hurts consumer surplus, except for the case in which the investment reduction effect is relatively strong.

Our model also provides some valuable insights to better understand current events in global trade relationships, reflecting the potential importance of asymmetry in competition. We show that the effects of the likelihood of trade conflict on the "leading economy" and the "fast-growing economy" are different. First, an increase in the probability of trade conflict can be beneficial to the home economy in relative terms, but not necessarily in absolute terms. This relative benefit would stimulate the firms in the home country to support the initiation of a trade conflict. In this way, even threatening a trade conflict may be an effective instrument to help the home country economy to maintain a leading position in the international trade hegemony. This result offers a persuasive explanation to the present US-China trade conflict.

There are still many unanswered questions leading to potentially fruitful paths of further research. If we apply the same model to a new industrial field, such as the introduction of 5G technologies in the high-tech industry, the potential results may be different, depending upon the assumptions imposed on the model. In this type of industry, the likelihood of trade conflict may be found to affect firms' investments and exports more positively. Moreover, it would be interesting to assume that firms move strategically in sequence rather than simultaneously. This type of strategic relationship would be better suited to a Leader-Follower model, where firm 1 will choose its output level before firm 2, and firm 2 responds. In this case, the impact of trade conflict uncertainty on firms' strategic behavior could produce different results.

Finally, we hope that our result will help researchers better understand the implications and incentives surrounding the perceived likelihood of trade conflicts.

3.8 Appendix

Equilibria of the model

In order to prove our results, we first obtain the equilibrium of the model. We briefly consider the producing countries are symmetrical in market size, marginal cost and investment costs.

Let $E[\pi_i]$ denote the firms' expected profit function. We obtain $E[\pi_i]$ by substituting expression (3.1) into function (3.3), given by:

$$E[\pi_i] = \alpha\big((a - y_i)y_i - (c - e_i)y_i\big) + (1 - \alpha)\Big(a - \big(y_i + x_j\big)\Big)y_i + \Big(a - \big(y_j + x_i\big)\Big)x_i \\ -(c - e_i)(y_i + x_i) - \gamma\frac{{e_i}^2}{2} \quad (3.9)$$

for $i, j \in \{h. f\}, and\ i \neq j.$

Then, let $E[\pi_h]$ denote the expected profit function of firm h, formally, $E[\pi_h]$ is given by:

$$E[\pi_h] = \alpha\big((a - y_h)y_h - (c - e_h)y_h\big) + (1 - \alpha)\Big(a - \big(y_h + x_f\big)\Big)y_h + \Big(a - \big(y_f + x_h\big)\Big)x_h \\ -(c - e_h)(y_h + x_h) - \gamma\frac{{e_h}^2}{2} \quad (3.10)$$

let $E[\pi_f]$ denote the expected profit function of firm f, formally, $E[\pi_f]$ is given by:

$$E[\pi_f] = \alpha\Big((a - y_f)y_f - \big(c - e_f\big)y_f\Big) + (1 - \alpha)\Big(a - \big(y_f + x_h\big)\Big)y_f + \Big(a - \big(y_h + x_f\big)\Big)x_f \\ -\big(c - e_f\big)\big(y_f + x_f\big) - \gamma\frac{{e_f}^2}{2} \quad (3.11)$$

Note that we solve this game backward by first analyzing the last stag, given the action taken in the preceding period. In the second stage, the two firms simultaneously set the levels of domestic sales and exports to maximize their expected profits. Given firms' investments taken in the first stage, firm $h(f)$ chooses $y_h(y_f)$ and $x_h(x_f)$ to maximize the expected profit function (3.10) and (3.11). Hence, firm $h's\ (f's)$ profit-maximization problem yields the first-order condition given by:

$$0 = \frac{\partial E[\pi_h]}{\partial y_h} = \alpha(a - c - 2y_h + e_h) + (1 - \alpha)\big(a - c - x_f - 2y_h + e_h\big) \quad (3.12)$$

$$0 = \frac{\partial E[\pi_h]}{\partial x_h} = (1 - \alpha)\big(a - c - 2x_h - y_f + e_h\big) \quad (3.13)$$

$$0 = \frac{\partial E[\pi_f]}{\partial y_f} = \alpha(a - c - 2y_f + e_f) + (1 - \alpha)(a - c - x_h - 2y_f + e_f) \tag{3.14}$$

$$0 = \frac{\partial E[\pi_f]}{\partial x_f} = (1 - \alpha)(a - c - 2x_f - y_h + e_f) \tag{3.15}$$

The equilibrium output levels in the second stage can be calculated by solving the equations (3.12), (3.13), (3.14) and (3.15). The equilibrium of domestic sales and exports of each firm are given by:

$$y_h = \frac{a - c + \alpha(a - c) + 2e_h - e_f + \alpha e_f}{3 + \alpha} \tag{3.16}$$

$$x_h = \frac{a - c + 2e_h - e_f}{3 + \alpha} \tag{3.17}$$

$$y_f = \frac{a - c + \alpha(a - c) + 2e_f - e_h + \alpha e_h}{3 + \alpha} \tag{3.18}$$

$$x_f = \frac{a - c + 2e_f - e_h}{3 + \alpha} \tag{3.19}$$

In order to obtain the expected payoff of firm h (f), we substitute the expression (3.16), (3.17), (3.18), and (3.19) into the expressions (3.10) and (3.11), $E[\pi_h]$ is given by:

$$E[\pi_h] = \frac{2AD^2 + e_h{}^2(8(\alpha - 2) - \gamma(3 + \alpha)^2) + 4BDe_f + 2e_f{}^2E + 16e_h(D + e_f(\alpha - 1))}{2(3 + \alpha)^2} \tag{3.20}$$

Where $A = \alpha^2 + \alpha + 2$, $B = \alpha^2 + \alpha - 2$, $D = a - c$ and $\mathrm{E} = (\alpha - 1)(\alpha - 2)$

Then, $E[\pi_f]$ is given by:

$$E[\pi_f] = \frac{2AD^2 + e_f{}^2(8(\alpha - 2) - \gamma(3 + \alpha)^2) + 4BDe_h + 2e_h{}^2E + 16e_f(D + e_h(\alpha - 1))}{2(3 + \alpha)^2} \tag{3.21}$$

In the first stage, both firms simultaneously select the level of investments e_i, for $i \in \{h.f\}$, to maximize their expected profits. The firms' profit-maximization problem yields the first-order conditions, which are given by:

$$0 = \frac{\partial E[\pi_h]}{\partial e_h} = \frac{8D + 8e_f(\alpha - 1) - e_h(8(\alpha - 2) + \gamma(3 + \alpha)^2)}{(3 + \alpha)^2} \tag{3.22}$$

$$0 = \frac{\partial E[\pi_f]}{\partial e_f} = \frac{8D + 8e_h(\alpha - 1) - e_f(8(\alpha - 2) + \gamma(3 + \alpha)^2)}{(3 + \alpha)^2} \tag{3.23}$$

From equations (3.22) and (3.23), we obtain the equilibrium of investments levels in the first stage, which is given by expression (3.4).

Then, in order to obtain the equilibrium of export, domestic sales and expected profits, we substitute expression (3.4) into expressions (3.16), (3.17), (3.18), (3.19), (3.20), and (3.21), then we acquire the equilibriums (3.5), (3.6) and (3.7). Then we substitute expression (3.5) and (3.6) into function (3.2) to obtain the equilibrium of consumer surplus (3.8).

Proof of the propositions

Note that under the symmetric condition, the firms' investments, exports, domestic sales, expected profits and consumer surplus in both countries are identical, and we set $y_h = y_f = y$, $x_h = x_f = x$, $e_h = e_f = e$, $E[\pi_h] = E[\pi_f] = E[\pi]$, and $CS_h = CS_f = CS$.

Proof of Proposition 3.1

In order to prove Proposition 3.1, we simplify the expression by taking the first derivative of firms' investments with respect to the likelihood of trade conflict α, which is given by:

$$\frac{\partial e}{\partial \alpha} = -\frac{16(a-c)\gamma(3+\alpha)}{(\gamma(3+\alpha)^2-8)^2} < 0 \tag{3.24}$$

Expression (3.24) is strictly negative for $(3+\alpha)^2 > 8$ and $a > c$.

Proof of Proposition 3.2

In order to prove Proposition 3.2, we simplify the expression by taking the first derivative of firms' domestic sales with respect to the likelihood of trade conflict α, which is given by:

$$\frac{\partial y}{\partial \alpha} = \frac{2(a-c)\gamma\big(\gamma(3+\alpha)^2-8(2+\alpha)\big)}{(\gamma(3+\alpha)^2-8)^2} \tag{3.25}$$

Given $(3+\alpha)^2 > 8$ and $a > c$, expression (3.25) is negative for $\frac{8}{(3+\alpha)^2} < \gamma < \frac{8(2+\alpha)}{(3+\alpha)^2}$, but expression (3.25) is positive for $\gamma > \frac{8(2+\alpha)}{(3+\alpha)^2}$.

Proof of Proposition 3.3

In order to prove Proposition 3.3, we simplify the expression by taking the first derivative of firms' exports with respect to the likelihood of trade conflict α, which is given by:

$$\frac{\partial x}{\partial \alpha} = -\frac{(a-c)\gamma(8+\gamma(3+\alpha)^2}{(\gamma(3+\alpha)^2-8)^2} < 0 \tag{3.26}$$

Expression (3.26) is always negative for $\gamma(3+\alpha)^2 > 8$ and $a > c$.

Proof of Proposition 3.4

In order to prove Proposition 3.4, we simplify the expression by taking the first derivative of firms' expected profits with respect to the likelihood of trade conflict α, which is given by:

$$\frac{\partial E[\pi]}{\partial \alpha} = \frac{(a-c)^2\gamma^2(3+\alpha)^2(24-32\alpha+\gamma(3+\alpha)(5\alpha-1))}{(\gamma(3+\alpha)^2-8)^3} \tag{3.27}$$

Given $(3+\alpha)^2 > 8$ and $a > c$, expression (3.27) is positive for $\alpha \in \left[\frac{1}{5}, 1\right]$. However, the sign of expression (3.27) is not clear for $\alpha \in \left[0, \frac{1}{5}\right]$. Expression (3.27) is positive when investment cost parameter γ is low enough, but it becomes negative if γ is sufficiently large.

Proof of Proposition 3.5

In order to prove Proposition 3.5, we simplify the expression by taking the first derivative of consumer surplus with respect to the likelihood of trade conflict α, which is given by:

$$\frac{\partial CS}{\partial \alpha} = \frac{(a-c)^2\gamma^2(2+\alpha)(3+\alpha)(\gamma(3+\alpha)^2-8(5+2\alpha))}{(\gamma(3+\alpha)^2-8)^3} \tag{3.28}$$

Given $(3+\alpha)^2 > 8$ and $a > c$, expression (3.28) is negative for $\frac{8}{(3+\alpha)^2} < \gamma < \frac{8(5+2\alpha)}{(3+\alpha)^2}$, but expression (3.28) is positive for $\gamma > \frac{8(5+2\alpha)}{(3+\alpha)^2}$.

Further Research

International trade conflict and environmental policies are two crucial issues that have gained increasing attention in recent years. The challenges posed by global environmental issues such as climate change and the depletion of natural resources have resulted in growing demands for sustainable development policies (Omer, 2008). However, international trade conflicts have made it difficult for countries to adopt environmental policies due to the perceived negative impact on competitiveness and economic growth (Charnovitz, 2003; Bown and McCulloch, 2005). Subsequent, we will explore the potential areas for future research on the relationship between international trade conflict and environmental policies.

One potential area for future research is the analysis of the effectiveness of environmental regulations in the face of trade conflict. Environmental regulations, such as emissions standards and resource conservation policies, can create trade barriers and result in tensions between trading partners (Green, 2006). Therefore, it is important to examine how effective these policies are in mitigating environmental degradation while maintaining economic competitiveness in the face of trade conflicts. Researchers can evaluate the effects of different regulatory approaches and investigate the potential for international cooperation in harmonizing environmental regulations to reduce trade tensions.

Another potential area for future research is the impact of trade conflicts on the adoption and diffusion of sustainable technologies. Trade conflicts can create uncertainty and increase transaction costs for businesses, making it more difficult to invest in sustainable technologies (Velut et al., 2022). Furthermore, trade barriers can also prevent the diffusion of sustainable technologies, as countries may be hesitant to adopt foreign technologies due to concerns about losing their domestic markets (Dechezleprêtre et al., 2013). Therefore, it is important to examine how trade conflicts affect the adoption and diffusion of sustainable technologies, and how countries can collaborate to promote technology transfer and innovation.

A third area for future research is the role of trade agreements in reconciling trade and environmental objectives. Trade agreements can create opportunities for countries to collaborate on environmental issues, but they can also create tensions when environmental objectives conflict with trade liberalization (Bernstein, 2002). Therefore, it is important to examine how trade agreements can balance environmental and trade objectives and how they can be designed to promote sustainable development. Researchers can evaluate the effectiveness of different trade agreement provisions, such as environmental clauses and dispute settlement mechanisms, in reconciling trade and environmental objectives.

In conclusion, international trade conflict and environmental policies are two crucial issues that have significant implications for sustainable development. Future research should focus on evaluating the effectiveness of environmental regulations, the impact of trade conflicts on sustainable technologies, the role of trade agreements in reconciling trade and environmental objectives, and the potential for international cooperation in addressing the trade-environment dilemma. By addressing these issues, policymakers and researchers can better understand the relationship between trade and the environment and promote sustainable development in the face of growing global challenges.

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