Three Essays on Global Climate Policy, Environmental R&D, Mergers, and Corporate Social Responsibility

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Abstract

Chapter 1: The Role of Technological Innovation in Global Climate Policy: In the first chapter, we build a dynamic model of the global economy and climate with three endogenous knowledge stocks. We confirm that the contribution of induced R&D in global climate change is shown to be very sensitive to the elasticity of substitution between energy and other factors of production. Since growth patterns of all types of research depend on whether inputs are gross complements or gross substitutes. Second, the duplication externality. Induced R&D generates a lower abatement cost reduction if we externalize duplication in the business as usual scenario. We exclude duplication in the business as usual scenario since a research institute is based on their contract to do their research. As long as they generate research outputs they would receive payments, they recognize the duplication but they think they will get paid for producing it whether their outputs have been duplicated or not. In reality, agents use too much R&D in the business as usual scenario because they do not take into account the duplication externality. Thus, when the social planner does the optimal scenario, the additional benefits of R&D may not be very much at all. Third, the initial level of research expenditure. Higher initial levels of energy related R&D shares would create a market size effect, leading to an increased contribution of induced R&D. Gerlagh (2008) uses much higher initial energy related shares whereas our research's estimates are much lower, we find this difference would affect the size of the effects of the induced R&D. Fourth, the inter-firm knowledge spillovers. Firms are not successful in capturing all the benefits they create, as many benefits flow out into other firms free of charge. These benefits are called inter-firm knowledge spillovers. Fifth, first-best and second-best policies. The first-best policy fully internalizes the inter-firm knowledge spillovers, which leads to increases in the levels of all types of research whereas the second-best policy does not internalize it, which leads to induced changes in research resulting from the carbon tax affecting pre-existing market distortions. Sixth, a research dividend effect and tax burden effect. The tax may induce an increase in research expenditure, which would increase the welfare and consumption levels. Finally, the results demonstrated that induced R&D has a limited role on the abatement cost reduction of greenhouse gas emissions, overall.

Chapter 2: Environmental Policy, Mergers and Environmental R&D with Spillovers: Our research topic is "Environmental Policy, Mergers and Environmental R&D with Spillovers". This project lies at the frontier between environmental economics and industrial organization. We use a duopoly setting of a three-

stage game; in the first stage, the government chooses an emission tax and aims for maximizing welfare; in the second stage, firms use R&D to reduce their emissions; in the last stage, firms compete a la Cournot with differentiated products. We focus on two policy regimes and three scenarios, namely regimes of competition and merger and scenarios of commitment, non-commitment, and exogenous tax. The study focuses on two major questions: (1) what is the effect of merger on R&D, and the effect of commitment on R&D? (2) what is the effect of merger and commitment on the economy? Results are obtained through numerical simulations of the model. We find that: (i) Merger has a positive effect on R&D under non-commitment and the exogenous tax scenarios. (ii) Under commitment, if goods are imperfect substitutes or homogenous, merger has a negative effect on R&D; if goods are complements or independent, merger has a positive effect on R&D. (iii) For any types of goods under any regime, commitment has a negative effect on R&D.

Chapter 3: Monopoly with Corporate Social Responsibility and Environmental R&D: Our research topic is the effect of the monopolist with corporate social responsibility in the presence of environmental R&D. This project lies at the frontier between environmental economics and industrial organization. We model a monopolist with corporate social responsibility setting in a three-stage game; in the first stage, the regulator determines the emission tax to maximize welfare; in the second stage, the monopolist determines R&D to maximize its objective function; in the third stage, the monopolist determines outputs to maximize its objective function. The study focuses on one major question: under the structure of monopoly with corporate social responsibility, if we change the parameters of R&D technology parameter, the degree of social responsibility, and product differentiation, what are the effects on profit, R&D, environmental damage, consumer surplus, and welfare? We find that: (1) increasing R&D technology parameter enhances welfare in terms of higher consumer surplus and lower damage, while also leading to increases in R&D and decreases in profit; (2) increasing the degree of social responsibility increases R&D and welfare in terms of higher consumer surplus and profit, but also increases the damage; and (3) increasing product differentiation increases profit, R&D, and welfare; it also increases the damage but decreases consumer surplus.

To my wife, Zhen Tang, my parents, Xijun Wang and Xiaoming Wang, and my whole family.

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Contents

Introduction

My doctoral thesis consists of three essays at the frontier between environmental economics and industrial organization. The first chapter is a dynamic model of the global economy and climate with three endogenous knowledge stocks that studies the role of technological innovation in global climate policy. The second chapter is a game theory model that studies the effect of environmental policy, mergers to environmental R&D with spillovers. The third chapter is also a game theory model that studies the effect of the monopolist with corporate social responsibility (CSR).

To address the climate change issues, we may use the market-based instruments (MBI) such as carbon taxes or a tradable permit system. The environmental economics literature focuses on the relationship between carbon policy and the induced research and development (R&D) in different industries. Based on Hicks (1932, 124), the induced research and development (R&D) is defined as follows: “A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive”.

The following factors are important determinants of induced R&D: first, the elasticity of substitution of inputs between energy and other factors of production. Second, the effect of crowding out. Since total R&D is supplied inelastically, more rapid accumulation of dirty-input saving R&D may diminish the accumulation of clean-input saving R&D of the economy. Third, the phenomenon of duplication. Duplication means that a portion of a firm’s knowledge output inevitably duplicates what another firm has already discovered, which is inefficient. Fourth, the inter-firm knowledge spillovers. Induced innovation is a public policy issue which generates benefits to all society, but it is usually undertaken by private firms. Firms are not successful in capturing all the benefits they create, as many benefits flow out into other firms free of charge. These benefits are called inter-firm knowledge spillovers. Fifth, a research dividend effect. The tax may induce an increase in aggregate research expenditures, which would increase the welfare level and increase the consumption levels. Sixth, a market size effect, that is, the tax encourages induced R&D in the largest input sector. Seventh, the first-best scenario and the second-best scenario. The first-best scenario consists of a carbon tax or quantity constraint to reduce the consumption of fossil fuel and R&D subsidies to fully internalize inter-firm spillovers. In contrast, the second-best scenario uses a tax as the only instrument to address all market distortions, which means that distortions are only partially internalized.

In the first chapter, we build a dynamic model of the global economy and climate with three endogenous knowledge stocks. Our model is different from previous models in terms of many aspects: for example, we use three knowledge stocks and treat duplication as external in the business as usual scenario whereas Shiell and Lyssenko (2014) use a single knowledge stock and Gerlagh (2008) treats duplication as internal in the business as usual scenario.

The first chapter has several contributions. First, we assess the effects of the determinants listed above on induced R&D in a multiple knowledge stock model of R&D. Second, we assess the relative importance of these determinants in terms of consumption levels. Third, we fully explore the circumstances in which the induced R&D increases or decreases the cost of achieving a given environmental target and the size of the effect.

We confirm that the contribution of R&D is shown to be very sensitive to the elasticity of substitution between energy and other factors of production. Since growth patterns of all types of research depend on whether inputs are gross complements or gross substitutes. Second, the duplication externality. Induced R&D generates a lower abatement cost reduction if we externalize duplication in the business as usual scenario. We exclude duplication in the business as usual scenario since a research institute is based on their contract to do their research. As long as they generate research outputs they would receive payments, they recognize the duplication but they think they will get paid for producing it whether their outputs have been duplicated or not. In reality, agents use too much R&D in the business as usual scenario because they do not take into account the duplication externality. Thus, when the social planner does the optimal scenario, the additional benefits of R&D may not be very much at all. Third, the initial level of research expenditure. Higher initial levels of energy related R&D shares would create a market size effect, leading to an increased contribution of induced R&D. Gerlagh (2008) uses much higher initial energy related shares whereas our research's estimates are much lower, we find this difference would affect the size of the effects of the induced R&D. Fourth, the inter-firm knowledge spillovers. Firms are not successful in capturing all the benefits they create, as many benefits flow out into other firms free of charge. These benefits are called inter-firm knowledge spillovers. Fifth, first-best and second-best policies. The first-best policy fully internalizes the inter-firm knowledge spillovers, which leads to increases in the levels of all types of research whereas the second-best policy does not internalize it, which leads to induced changes in research resulting from the carbon tax affecting pre-existing market distortions. Sixth, a research dividend effect and tax burden effect. The tax may induce an increase in research expenditure, which would increase the welfare and consumption levels. Finally, the results demonstrated that induced R&D has a limited role on the abatement cost reduction of greenhouse gas emissions, overall.

The second chapter is “Environmental Policy, Mergers and Environmental R&D with Spillovers”. This project lies at the frontier between environmental economics and industrial organization. Pollution problems such as carbon emissions have become a major issue faced by modern governments. In order to solve this problem, we need to have a better understanding about the underlying mechanism that leads to carbon pollutions. This includes understanding the economic theories associated with this type of market failure, which are based on environmental economics and industrial organization. Comprehensive study in those two fields would help us to design effective policies to provide both emission-reducing incentives for major polluting industries as well as increases in overall welfare.

We use a duopoly setting of a three-stage game; in the first stage, the government chooses an emission tax and aims for maximizing welfare; in the second stage, firms use R&D to reduce their emissions; in the last stage, firms compete a la Cournot with differentiated products. We focus on two policy regimes and three scenarios, namely regimes of competition and merger and scenarios of commitment, non-commitment, and exogenous tax. Commitment refers to the regulator who chooses a tax in the first stage, before the firm chooses R&D, and then the regulator commits to this tax. Non-commitment is when a firm chooses R&D in the first stage, then the regulator chooses a tax in the second stage. Past industrial merger experiences show that polluting firms have a significant share in the total value and volume of mergers, therefore it is important to study the mergers in the context of environmental regulation. In addition, simulation model suggests that the results depend on whether the government has the commitment ability to an emission tax or not, therefore it is interesting to analyze the commitment vs non-commitment scenarios. We also take into account the exogenous tax scenario since it is relevant when the tax is set based on country-wide considerations or on an international agreement, and hence is not responsive to the specific conditions of the industry under study.

The study focuses on two major questions: (1) what is the effect of merger on R&D, and the effect of commitment on R&D? (2) what is the effect of merger and commitment on the economy? Results are obtained through numerical simulations of the model. We find that: (i) Merger has a positive effect on R&D under non-commitment and the exogenous tax scenarios. (ii) Under commitment, if goods are imperfect substitutes or homogenous, merger has a negative effect on R&D; if goods are complements or independent, merger has a positive effect on R&D. (iii) For any types of goods under any regime, commitment has a negative effect on R&D.

Our paper makes the following contributions to the literature: first, our research focuses on total merger, which is cooperation at all stages. Previously, most studies have only focused on the regime of R&D cooperation. Second, our study fully considers product differentiation. This is different from major strands of the literature which only study a homogenous product. In contrast, our research considers four types of goods: complements, independent, imperfect substitutes, and homogenous. Third, our research includes three different scenarios: commitment, non-commitment, and exogenous tax. Other major studies only focus on one or two of them (e.g. Poyago-Theotoky, 1999, 2007, 2010; Petrakis and Poyago-Theotoky, 2002; and Ouchida and Goto 2011, 2014, 2016a, 2016b).

The third chapter is to study the effect of monopoly with corporate social responsibility (CSR). The World Business Council for Sustainable Development (WBCSD) defines CSR as “corporate commitment to contribute to sustainable economic development, employees and their families, local communities and the whole society in order to improve their quality of life” (WBCSD, 2000). Every country has industries which are operating at different market power; such industries include public transportation, agriculture, natural resources, construction, hydraulic engineering, health and hygiene, aerospace, and nuclear energy. Analyzing monopoly with corporate social responsibility helps us to understand in which circumstances the corporation and society can maintain a sustainable development pace while still achieving better results in terms of profit, R&D, environmental protection, consumer surplus, and welfare.

We use a CSR monopolist setting of a three-stage game. In the first stage, the regulator determines the emission tax to maximize welfare; in the second stage, the monopolist determines R&D to maximize its objective function; in the third stage, the monopolist determines outputs to maximize its objective function.

The study focuses on one major question: under the structure of a CSR monopolist, if we change the parameters of R&D technology parameter, the degree of social responsibility, and product differentiation, what are the effects on profit, R&D, environmental damage, consumer surplus, and welfare? We find that: (1) increasing R&D technology parameter enhances welfare in terms of higher consumer surplus and lower damage, while increasing R&D and decreasing profit; (2) increasing the degree of social responsibility increases R&D and welfare in terms of higher consumer surplus and profit, but increases the damage as well; and (3) increasing product differentiation increases profit, R&D, and welfare; it also increases the damage, but decreases consumer surplus.

References

Gerlagh, R. (2008). A climate-change policy induced shift from innovations in carbon-energy production to carbon-energy savings. *Energy Economics*, *30*(2), 425-448.

Hicks John, R. (1932). The theory of wages. *London: Macmillan.*

Ouchida, Y., & Goto, D. (2011). A note on environmental R&D under time-consistent emission tax. *International Journal of Business and Economics*, *10*(3), 257-260.

Ouchida, Y., & Goto, D. (2014). Do emission subsidies reduce emission? In the context of environmental R&D organization. *Economic Modelling, 36,* 511-516.

Ouchida, Y., & Goto, D. (2016a). Environmental research joint ventures and time-consistent emission tax: Endogenous choice of R&D formation. *Economic Modelling, 55*, 179-188.

Ouchida, Y., & Goto, D. (2016b). Cournot duopoly and environmental R&D under regulator's precommitment to an emissions tax. *Applied Economics Letters, 23*(5), 324-331.

Petrakis, E., & Poyago-Theotoky, J. (2002). R&D subsidies versus R&D cooperation in a duopoly with spillovers and pollution. *Australian Economic Papers, 41*(1), 37-52.

Poyago-Theotoky, J. (1999). A note on endogenous spillovers in a non-tournament R&D duopoly. *Review of Industrial Organization, 15*(3), 253-262.

Poyago-Theotoky, J. (2007). The organization of R&D and environmental policy. *Journal of Economic Behavior & Organization, 62*(1), 63-75.

Poyago-Theotoky, J. (2010). Corrigendum to “The organization of R&D and environmental policy”. *Journal of Economic Behavior & Organization, 76*(2), 449.

Shiell, L., & Lyssenko, N. (2014). Climate policy and induced R&D: How great is the effect?. *Energy Economics*, *46*, 279-294.

WBCSD (World Business Council for Sustainable Development). (2000). Corporate social responsibility: Making good business sense. *WBCSD, Geneva.*

Chapter 1

The Role of Technological Innovation in Global Climate Policy

Abstract

In the first chapter, we build a dynamic model of the global economy and climate with three endogenous knowledge stocks. We confirm that the contribution of induced R&D in global climate change is shown to be very sensitive to the elasticity of substitution between energy and other factors of production. Since growth patterns of all types of research depend on whether inputs are gross complements or gross substitutes. Second, the duplication externality. Induced R&D generates a lower abatement cost reduction if we externalize duplication in the business as usual scenario. We exclude duplication in the business as usual scenario since a research institute is based on their contract to do their research. As long as they generate research outputs they would receive payments, they recognize the duplication but they think they will get paid for producing it whether their outputs have been duplicated or not. In reality, agents use too much R&D in the business as usual scenario because they do not take into account the duplication externality. Thus, when the social planner does the optimal scenario, the additional benefits of R&D may not be very much at all. Third, the initial level of research expenditure. Higher initial levels of energy related R&D shares would create a market size effect, leading to an increased contribution of induced R&D. Gerlagh (2008) uses much higher initial energy related shares whereas our research's estimates are much lower, we find this difference would affect the size of the effects of the induced R&D. Fourth, the inter-firm knowledge spillovers. Firms are not successful in capturing all the benefits they create, as many benefits flow out into other firms free of charge. These benefits are called inter-firm knowledge spillovers. Fifth, first-best and second-best policies. The first-best policy fully internalizes the inter-firm knowledge spillovers, which leads to increases in the levels of all types of research whereas the second-best policy does not internalize it, which leads to induced changes in research resulting from the carbon tax affecting pre-existing market distortions. Sixth, a research dividend effect and tax burden effect. The tax may induce an increase in research expenditure, which would increase the welfare and consumption levels. Finally, the results demonstrated that induced R&D has a limited role on the abatement cost reduction of greenhouse gas emissions, overall.

1.1 Introduction

To address the climate change issues, we may use the market-based instruments (MBI) such as carbon taxes or a tradable permit system. The environmental economics literature focuses on the relationship between carbon policy and the induced research and development (R&D) in different industries. Based on Hicks (1932, 124), the induced research and development (R&D) is defined as follows: "A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive". There are different views toward carbon tax dealing with the climate change problem. We want to build a benchmark model to assess the effects of the important determinants of induced R&D. Also, we want to fully explore the circumstances in which the induced R&D increases or decreases the cost of achieving a given environmental target and the size of the effect.

The following factors are important determinants of induced R&D: first, the elasticity of substitution of inputs between energy and other factors of production. Second, the effect of crowding out. Since total R&D is supplied inelastically, more rapid accumulation of dirty-input saving R&D may diminish the accumulation of clean-input saving R&D of the economy. Third, the phenomenon of duplication. Duplication means that a portion of a firm's knowledge output inevitably duplicates what another firm has already discovered, which is inefficient. Fourth, the inter-firm knowledge spillovers. Induced innovation is a public policy issue which generates benefits to all society, but it is usually undertaken by private firms. Firms are not successful in capturing all the benefits they create, as many benefits flow out into other firms free of charge. These benefits are called inter-firm knowledge spillovers. Fifth, a research dividend effect. The tax may induce an increase in aggregate research expenditures, which would increase the welfare level and increase the consumption levels. Sixth, a market size effect, that is, the tax encourages induced R&D in the largest input sector. Seventh, the first-best scenario and the second-best scenario. The first-best scenario consists of a carbon tax or quantity constraint to reduce the consumption of fossil fuel and R&D subsidies to fully internalize inter-firm spillovers. In contrast, the second-best scenario uses a tax as the only instrument to address all market distortions, which means that distortions are only partially internalized.

We build a dynamic model of the global economy and climate with three endogenous knowledge stocks. Our model is different from previous models in terms of many aspects: for example, we use three knowledge stocks and treat duplication as external in the business as usual scenario whereas Shiell and Lyssenko (2014) use a single knowledge stock and Gerlagh (2008) treats duplication as internal in the business as usual scenario.

This paper has several contributions. First, we assess the effects of the determinants listed above on induced R&D in a multiple knowledge stock model of R&D. Second, we assess the relative importance of these determinants in terms of consumption levels. Third, we fully explore the circumstances in which the induced R&D increases or decreases the cost of achieving a given environmental target and the size of the effect.

We confirm that the contribution of R&D is shown to be very sensitive to the elasticity of substitution between energy and other factors of production. Since growth patterns of all types of research depend on whether inputs are gross complements or gross substitutes. Second, the duplication externality. Induced R&D generates a lower abatement cost reduction if we externalize duplication in the business as usual scenario. We exclude duplication in the business as usual scenario since a research institute is based on their contract to do their research. As long as they generate research outputs they would receive payments, they recognize the duplication but they think they will get paid for producing it whether their outputs have been duplicated or not. In reality, agents use too much R&D in the business as usual scenario because they do not take into account the duplication externality. Thus, when the social planner does the optimal scenario, the additional benefits of R&D may not be very much at all. Third, the initial level of research expenditure. Higher initial levels of energy related R&D shares would create a market size effect, leading to an increased contribution of induced R&D. Gerlagh (2008) uses much higher initial energy related shares whereas our research's estimates are much lower, we find this difference would affect the size of the effects of the induced R&D. Fourth, the inter-firm knowledge spillovers. Firms are not successful in capturing all the benefits they create, as many benefits flow out into other firms free of charge. These benefits are called inter-firm knowledge spillovers. Fifth, first-best and second-best policies. The first-best policy fully internalizes the inter-firm knowledge spillovers, which leads to increases in the levels of all types of research whereas the second-best policy does not internalize it, which leads to induced changes in research resulting from the carbon tax affecting pre-existing market distortions. Sixth, a research dividend effect and tax burden effect. The tax may induce an increase in research expenditure, which would increase the welfare and consumption levels. Finally, the results demonstrated that induced R&D has a limited role on the abatement cost reduction of greenhouse gas emissions, overall.

The paper is structured as follows. The following section discusses about the literature review and Section III introduces our model. Section IV presents the benchmark experiment with four scenarios. Section V is an exploration of the calibration process of parameters in the dynamic model. Section VI presents our results, which are generated from 4 different experiments. Finally, Section VII is the conclusion.

1.2 Literature Review

The environmental economics literature focuses on the relationship between carbon policy and the induced research and development (R&D) in different industries. For example, Goulder and Schneider (1999) consider that a carbon tax stimulates R&D in alternative energy industries while it discourages R&D in non-energy industries and in carbon-based energy industries. In particular, the R&D reduction in non-energy industries and carbon-based energy industries leads to a consequence of a slower growth of output, which implies lower future levels of GDP and consumption. Therefore, models that ignore those effects are likely to under-estimate the abatement cost from an environmental policy.

Popp (2004) and Gerlagh (2008) have two opposite views toward carbon tax dealing with the climate change problem. Popp concludes that the effect on the tax path of induced R&D is small, whereas Gerlagh concludes that the effect on the tax path of introducing induced R&D is large. Gerlagh (2008) presents a very optimistic view about the carbon taxes, concluding that, after induced R&D has been introduced into the model, the abatement cost of achieving the 450 ppmv environmental target becomes negligible in the case of full flexibility.

He suggests that including the innovation sector in the model create lots of welfare gain so that induced R&D's contribution to greenhouse gas emission abatement can be substantial. In contrast, Popp (2004) has a pessimistic view and he thinks that R&D has a limited role for solving this problem, as the R&D component increases the welfare impact of the optimal climate policy by only 9.4 percent in the central scenario, which is a modest change. Market imperfections and the potential crowding out of other R&D are two main factors limiting the potential of induced R&D.

Gerlagh (2008) indicates that there are two effects of a carbon tax on output and consumption: an excess burden effect, and a research dividend effect. By using the carbon tax as the climate change policy, it would distort the carbon-energy market and induce the excess burden effect; therefore, lower output and consumption are generated. In contrast, the research dividend effects occur when overall research levels are increased, output levels are increased, consumption is increased and total emissions are reduced by a carbon tax.

Gerlagh (2008) mentioned that the excess burden effect is the second order effect and the research dividend effect is the first order effect. The excess burden is a second order effect because the tax produces a locally quadratic emission reduction costs curve, small emission reduction has lower abatement cost. The research dividend is a first order effect because the spillover benefits to other firms, from additional R&D, are large. It follows that the effect of the tax on aggregate research expenditure outweighs the excess burden effect. However, we consider this only holds for small values of the carbon tax (small restrictions on carbon emissions). For tax values large enough, the excess burden effect dominates the research dividend effect, due to the quadratic shape of the excess burden function.

Sue Wing (2006) points out that, if both dirty and clean inputs are complements, the scale of dirty R&D exhibits a hump shape in relation to tax. Increasing the tax increases the scale of fossil fuel augmenting technical changes at low levels of taxation but decreases it at high levels of taxation. He also shows the bias of the techniques of production: taxing the dirty input biases the techniques of productions in order to conserve on the dirty input. Thus, if we taxed fossil fuel, we should expect a decrease in fossil fuel production technical changes. Sue Wing (2006) describes that, if substitution among inputs is elastic, a tax on the fossil fuel induces a decrease in the fossil fuel's relative share of research; if substitution among inputs is inelastic, a tax on the fossil fuel induces an increase in the fossil fuel's relative share of research. Sue Wing (2006) analyzes the stock of knowledge approach in process-based models of induced R&D. He argues that there is a "crowding out" effect: since total R&D is supplied inelastically, more rapid accumulation of dirty-input saving R&D may diminish the accumulation of clean-input saving R&D of the economy. However, Sue Wing also points out that the knowledge spillover effects and R&D subsidy policies would reduce the impact of the crowding out effect.

An important issue in the economics of innovation is the phenomenon of duplication. Duplication means that a portion of a firm's knowledge output duplicates what another firm has already discovered, which is inefficient. What is missing from the major strands of literature is how to model a business as usual (BAU)[1] scenario's duplication externality. Shiell and Lyssenko (2014) argue that most environmental modelers have neglected to treat duplication as an externality in the BAU scenario (Goulder and Schneider 1999, Popp 2004, Gerlagh 2008, and Hart 2008). Shiell and Lyssenko (2014) point out that in reality, agents use too much R&D in BAU because they do not take into account the duplication externality. Thus, when the social planner does the optimal scenario, the additional benefits of R&D may not be very much at all.

Jones and Williams (2000) focus on the inter-firm knowledge spillovers externalities. They consider that private firms spend too little on R&D compared to the socially optimal level. To deal with inter-firm knowledge spillovers, the government should subsidize firms to encourage them to undertake more R&D, because the spillover benefits are positive from the viewpoint of social welfare.

Acemoglu et al. (2012) describes the market size effect; whereby expenditure on R&D has the highest payoff in the largest input sector. Since energy is usually a relatively small input sector, the market size effect tends to direct R&D expenditures away from energy toward other inputs.

[1] In the business-as-usual (BAU) scenario, there is no emission control policy.

Gans (2012) disputes the argument that climate policy will stimulate incentives to develop environmentally friendly technologies. He finds instead that the carbon tax policy will usually diminish incentives for fossil fuel augmenting technologies. Gans (2012) examines the impact of a tighter emission cap (quantity constraint) on the equilibrium level of technological choice. If we are going to cut back in fossil fuels, in order for there to be an induced innovation, it must be the case that a decrease in fossil fuel usage increases the marginal product of fossil-fuel saving technologies. If we reduce fossil fuel usage (which is a climate change policy in place), in equilibrium, the only reason that firms are going to invest more in fossil fuel-saving technology is if that reduction of fossil fuel increases the marginal product of fossil fuel-saving knowledge capital. If that marginal product goes down instead, we are going to reduce spending on R&D. In other words, the two marginal products must go in opposite directions in order to have a precondition of induced innovation. The concept of fossil fuel-saving technology is sufficient for the policy to induce innovation.

Gans (2012) examines the impact of fossil fuel augmenting technological change in a CES production function. If two production inputs were substitutes, a more stringent climate change policy would reduce the incentives to invest in the fossil-fuel augmenting technologies, since the precondition for induced innovation is not satisfied. Climate change policy reduces the fossil fuel usage, thereby reducing the corresponding investment demand for complements of fossil fuel and hence, reducing the accumulation of fossil fuel augmenting technology. Gans (2012) also compares fossil fuel and alternative fuel augmenting technological changes in the CES production function. He shows that a restriction on greenhouse gas emissions (quantity constraint) discourages fossil fuel augmenting technologies but will stimulate innovation in alternative energy augmenting technologies (non-emitting energy sources) if the inputs are gross substitutes. In contrast, it will reduce innovation incentives in alternative energy augmenting technologies if the inputs are gross complements. Also, he shows that even when the inputs are gross substitutes, a tighter emissions cap will always reduce the level of output and increases the ratio of output to fossil fuel use. The results obtained from Gans (2012) and Sue Wing (2006) assume that there are no climate damages on production and no inter-firm knowledge spillovers.

1.3 Model-Structure

We build a dynamic model of the global economy and climate with three endogenous knowledge stocks. The model includes structural equations and behavioral equations. All those equations are FOCs which are derived from the maximization of the Lagrangian function with respect to the choice variables, state variables, and co-state variables. FOCs derived from the co-state variables are called structural equations whereas FOCs derived from choice variables and state variables are called behavioral equations. The structural equations are the original equations that describe the structure of the model. Time proceeds in discrete steps of 5 years each, with periods denoted t=1,…, 60. Our initial period is from the years 2011 to 2015 as t=1. The terminal period is from the years 2306 to 2310 as t=60. There are 300 years in total.

Final output, *Y*, is given by the production function:

$$\mathrm{Y_t} = \left(\zeta_{YM}(M_t)^{\frac{\sigma-1}{\sigma}} + \zeta_{YE}\left(A_{YE,t}^{\pi_{YE}}E_t\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{1}$$

As shown, *Y* is a constant elasticity of substitution (CES) production function of a generic intermediate input *M* and carbon-energy *E*. Parameter σ is the elasticity of substitution between *M* and *E*. A_{YE} is the knowledge stock and it augments the productivity of *E*. Parameter of π_{YE} is the elasticity of productivity to A_{YE}. ζ_{YM} and ζ_{YE} are share parameters in the CES output production function.

The production functions for the generic intermediate *M* and carbon energy *E* are:

$$\mathrm{M_t} = \varsigma_M\, \mathrm{A_{MZ,t}^{\pi_{MZ}} Z_{M,t}} \tag{2}$$

$$\mathrm{E_t} = \varsigma_E\, \mathrm{A_{EZ,t}^{\pi_{EZ}}\, Z_{E,t}} \tag{3}$$

For producing *M*, we use the capital-labor composite *Z* as a production factor, denoted as Z_M. A_{MZ} is the technology stock that controls the productivity of Z_M, the parameter π_{MZ} describes the elasticity of productivity to knowledge accumulation, and ς_M is the shift parameter of the production function of *M*. Similarly for *E*, we have the production factor of Z_E, technology stock A_{EZ}, parameter π_{EZ} and shift parameter ς_E.

The total value-added, Z, is shown below as a Cobb-Douglas function of K and L.

$$\left(\mathrm{Z}_{\mathrm{M,t}} + \mathrm{Z}_{E,t}\right) = \gamma \mathrm{K}_t^{\alpha} L_t^{1-\alpha} \tag{4}$$

α is the share parameter of capital in production. γ is the scaling parameter.

Capital accumulation follows the difference equation

$$\mathrm{K}_{\mathrm{t+1}} = (1-\delta_k)^{\Delta} K_t + \Delta\left(I_t - \frac{\eta}{2}\frac{I_t^2}{K_t}\right) \tag{5}$$

with K representing the current stock of capital, δ_K the annual capital depreciation rate, Δ the period duration of 5 years, I the current investment level, and the capital adjustment cost factor $\frac{\eta}{2}\frac{I_t^2}{K_t}$. The last specification follows Mckibbin & Wilcoxen (1999). The capital adjustment cost is increasing in I but decreasing in K, reflecting increasing in marginal cost of adjustment within each period but decreasing cost in the level of existing capital.

Knowledge accumulation is shown below in (6) - (8) as a function of the current level of knowledge and current R&D expenditures.

$$A_{YE,t+1} = \Delta a_{YE} R_{YE,t}^{b} A_{YE,t}^{\o} + A_{YE,t} \tag{6}$$

$$A_{MZ,t+1} = \Delta a_{MZ} R_{MZ,t}^{b} A_{MZ,t}^{\o} + A_{MZ,t} \tag{7}$$

$$A_{EZ,t+1} = \Delta a_{EZ} R_{EZ,t}^{b} A_{EZ,t}^{\o} + A_{EZ,t} \tag{8}$$

This specification follows Shiell and Lyssenko (2014). R_{YE}, R_{MZ} and R_{EZ} represent R&D investments in energy efficiency, generic materials, and energy production respectively. The parameter $b \in [0,1]$ indicates the duplication factor, where b=0 is the case of total duplication. Total duplication means that the R&D has no contribution on the technological level in next period. And b=1 is the opposite extreme case of no duplication. No duplication means that the accumulation of knowledge in next period depends on current R&D expenditure and current knowledge. In Shiell and Lyssenko (2014), they use 0.7 to represent the modest duplication externality and 0.2 to represent the large duplication externality. Also, ø represents the inter-temporal knowledge spillover. Advantages of this approach include that it could distinguish between the duplication externality, which is determined by b, and inter-temporal knowledge spillover, which is determined by ø. In comparison, Gerlagh's version for (6)-(8) is $A_{j,t+1} = R_{j,t}^{\eta} A_{j,t}^{1-\eta}$ $(j = (Y,E),(M,Z),(E,Z))$. It does not distinguish between the duplication parameter and the inter-temporal knowledge spillover parameter.

To represent inter-firm knowledge spillovers, Gerlagh (2008) defines a appropriation parameter $\omega \in [0,1]$ to reflect the share of new knowledge that flows to the firm that undertakes the R&D. The remaining share (1-ω) represents the spillover, i.e. the knowledge that flows to other agents free of charge. In the business as usual scenario, private firms perceive knowledge accumulating according to ω=0.25, whereas in the optimal scenario, the social planner set ω=1 to internalize inter-firm knowledge spillovers.

Another major contribution of this paper is that we correctly model the BAU scenario by excluding the duplication externality. In BAU, agents do not take into account the duplication externality. Therefore, in BAU, agents face the following knowledge accumulation equations when they derive their behavioral equations:

$$A_{YE,t+1} = \Delta\omega\, V_{YE,t} R_{YE,t} + A_{YE,t} \tag{6'}$$

$$V_{YE,t} = a_{YE} R_{YE,t}^{b-1} A_{YE,t}^{ø} \tag{6''}$$

$$A_{MZ,t+1} = \Delta\omega\, V_{MZ,t} R_{MZ,t} + A_{MZ,t} \tag{7'}$$

$$V_{MZ,t} = a_{MZ} R_{MZ,t}^{b-1} A_{MZ,t}^{ø} \tag{7''}$$

$$A_{EZ,t+1} = \Delta\omega\, V_{EZ,t} R_{EZ,t} + A_{EZ,t} \tag{8'}$$

$$V_{EZ,t} = a_{EZ} R_{EZ,t}^{b-1} A_{EZ,t}^{ø} \tag{8''}$$

In (6''), (7'') and (8''), V_{YE}, V_{MZ}, and V_{EZ} are defined as the average product of R&D of R_{YE}, R_{MZ}, and R_{EZ}, respectively. In BAU, agents perceive the payoff to R&D to be given by V_{YE}, V_{MZ}, and V_{EZ} and knowledge to accumulate according to (6') (7') and (8'); however, the true payoffs and accumulation are actually given by (6)-(8). In contrast, the social planner has the correct perception of the payoff of R&D, based on (6)-(8).

The model equations can be divided into two groups: structural equations and behavioral equations. Structural equations have been defined by the model construction, whereas behavioral equations are derived from the optimality conditions. The true knowledge accumulation equations of (6), (7) and (8) are adopted in the structural equations sector for all scenarios.

Equation (9) describes the commodity balance for the final good *Y*.

$$\mathrm{C_t} + \mathrm{I_t} + R_{YE,t} + R_{MZ,t} + R_{EZ,t} = \mathrm{Y_t} \tag{9}$$

The final output *Y* can be used as consumptions *C*, investments *I*, and research expenditures on energy efficient R&D, R_{YE}, materials related R&D, R_{MZ}, and energy production R&D, R_{EZ}.

The population and the effective labour supply are given by the following set of equations.

$$\mathrm{L_t} = \mathrm{h}_t \mathrm{P_t} \tag{10}$$

$$\mathrm{P_t} = P_{LT} \frac{e^{\gamma_p\,(t-t_{p0})}}{1+e^{\gamma_p(t-t_{p0})}} \tag{11}$$

$$\mathrm{h_{t+1}} = (1 + \gamma_{h,t})h_t \tag{12}$$

$$\gamma_{h,t} = \gamma_{h0}\, e^{-\delta_\gamma\,(t-1)} \tag{13}$$

Equation (10) shows that effective labor supply *L* is equal to human capital based productivity *h* times the total population *P*. From equation (11), the total population level is assumed to follow a logistic growth curve, where γ_p is the population growth rate for low population levels, P_{LT} is the long-term population level and t_{p0} is the period at which the population reaches half its maximal size. Equation (12) shows the function of human capital growth, where $\gamma_{h,t}$ is the growth rate for human capital *h*. Equation (13) shows the human capital growth rate $\gamma_{h,t}$ declining exponentially over time, with $-\delta_\gamma$ as the decline rate.

Equations (14) and (15) show Gerlagh's climate change module that describes the connections between energy usage *E*, atmospheric carbon concentration *ATM*, and the global average surface temperature *TEMP*.

$$\mathrm{ATM_{t+1}} = ATM_0 + (1-\delta_M)^\Delta (ATM_t - ATM_0) + (1-\delta_E)^\Delta \left(0.001 \left(\frac{10}{3.67} E_t + \overline{EM_t}\right)\right) \tag{14}$$

$$\mathrm{TEMP}_{t+1} = (1-\delta_T)^{\Delta}\, TEMP_t + \Delta\delta_T\, TEMP_0 \frac{ln\left(\frac{ATM_t}{ATM_0}\right)}{ln(2)} \tag{15}$$

Energy usage E also measures equivalent carbon dioxide emissions. Atmospheric carbon concentration level ATM in the next period of t+1 is determined by the pre-industrial atmospheric CO_2 concentration level ATM_0 plus the current period ATM level after we take into account of ATM_0, atmospheric CO_2 depreciation rate δ_M, plus the current period CO_2 emissions EM, which are set equal to the energy usage E and we also take into account of the retention rate (1-δ_E). The variable $\overline{EM}$ represents emissions by other (non-energy) sources. Equation (15) is the global average surface temperature evolution function, where $TEMP$ means degree Celsius above the pre-industrial steady state, δ_T is the annual temperature adjustment rate resulting from the atmospheric warmth capacity, and $TEMP_0$ is the long run equilibrium temperature change associated with a doubling of ATM_0.

Finally, equation (16) is the quantity constraint for the atmospheric carbon concentration level.

$$\mathrm{ATM}_t \leq ATM_{TGT} \tag{16}$$

ATM_t represents the atmospheric carbon concentration level, while ATM_{TGT} is the maximum level of atmospheric CO_2 concentration permitted under a quantity-based emissions control policy.

1.4 Scenarios

The scenarios include: social planner's optimum (OPT), business as usual (BAU), first-best (FB), second-best (SB), and no induced technical change (NOITC). The planner's problem is represented as the inter-temporal optimization of a representative agent. The agent's preferences are represented by the social welfare function (17)

$$\sum_{t=1}^{T} \frac{1}{(1+\rho)^{\Delta t}} P_t \ln\left(\frac{C_t}{P_t}\right) \tag{17}$$

where ρ is the rate of pure time preference and C_t and P_t are defined previously. The planner's problem is to maximize (17) subject to equations (1)-(16), subject to given initial values of the stocks K_1, $A_{YE,1}$, $A_{MZ,1}$, $A_{EZ,1}$, ATM_1 as well as a fixed horizon T.

Note that in OPT, the social planner fully accounts for inter-firm knowledge spillovers by setting ω=1. In addition, the planner internalizes the duplication externality by using the true knowledge accumulation equations (6), (7), and (8). Finally, the planner implements the exogenous environmental target (16).

The Lagrangian function for the planner's maximization in the emissions control scenario is

$$\mathrm{L}=\sum_{t=1}^{T-1}\{\frac{1}{(1+\rho)^{\Delta t}}P_t\ln\left(\frac{C_t}{P_t}\right)+P_t^Y\left[\left(\zeta_{YM}(M_t)^{\frac{\sigma-1}{\sigma}}+\zeta_{YE}\left(A_{YE,t}^{\pi_{YE}}E_t\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}-Y_t\right]+$$

$$\mu_t\left[\varsigma_M\,\mathrm{A}_{\mathrm{MZ,t}}^{\pi_{\mathrm{MZ}}}\mathrm{Z}_{\mathrm{M,t}}-M_t\right]+q_t\left[\varsigma_E\,\mathrm{A}_{\mathrm{EZ,t}}^{\pi_{\mathrm{EZ}}}\mathrm{Z}_{\mathrm{E,t}}-E_t\right]+\xi_t\left[\gamma\mathrm{K}_t^{\alpha}L_t^{1-\alpha}-Z_{M,t}-Z_{E,t}\right]+\Psi_t\left[(1-\right.$$

$$\left.\delta_k)^{\Delta}K_t+\Delta\left(I_t-\frac{\eta}{2}\frac{I_t^2}{K_t}\right)-K_{t+1}\right]+\theta_{YE,t}\left[\Delta a_{YE}R_{YE,t}^b\,A_{YE,t}^{\o}+A_{YE,t}-A_{YE,t+1}\right]+$$

$$\theta_{MZ,t}\left[\Delta a_{MZ}R_{MZ,t}^b\,A_{MZ,t}^{\o}+A_{MZ,t}-A_{MZ,t+1}\right]+\theta_{EZ,t}\left[\Delta a_{EZ}R_{EZ,t}^b\,A_{EZ,t}^{\o}+A_{EZ,t}-A_{EZ,t+1}\right]+$$

$$P_t^I\left[Y_t-C_t-I_t-R_{YE,t}-R_{MZ,t}-R_{EZ,t}\right]+\theta_{ATM,t}\left[ATM_0+(1-\delta_M)^{\Delta}(ATM_t-ATM_0)+\right.$$

$$\left.(1-\delta_E)^{\Delta}(CVS_1E_t+CVS_2E_{BAR})-ATM_{t+1}\right]+\overline{P}_t[ATM_{TGT}-ATM_t]\}+\Psi_TK_T+$$

$$\theta_{YE,T}A_{YE,T}+\theta_{MZ,T}A_{MZ,T}+\theta_{EZ,T}A_{EZ,T}+\theta_{ATM,T}ATM_T$$

where P^Y is the shadow price of output of final good Y, μ is the shadow price for generic intermediate M, q is the shadow price for energy usage E, ξ is the shadow price for capital-labor composite Z, and Ψ is the shadow price for capital K. θ_{YE}, θ_{MZ}, θ_{EZ} are the shadow prices of knowledge stocks A_{YE}, A_{MZ}, and A_{EZ} respectively. P^I is the shadow price of the commodity balance equation. $\theta_{ATM,t}$, is the shadow price of ATM, and $\overline{P_t}$ is the shadow price of the atmospheric carbon concentration constraint.

Deriving the first-order conditions with respect to the choice and state variables yields the following behavioral equations of the agent:

$$\theta_{YE,t}\,\Delta a_{YE}b\,R_{YE,t}^{b-1}\,A_{YE,t}^{\o}-1=0 \tag{18}$$

$$\theta_{MZ,t}\,\Delta a_{MZ}b\,R_{MZ,t}^{b-1}\,A_{MZ,t}^{\o}-1=0 \tag{19}$$

$$\theta_{EZ,t}\,\Delta a_{EZ}b\,R_{EZ,t}^{b-1}\,A_{EZ,t}^{\o}-1=0 \tag{20}$$

$$\beta_tY_{t+1}^{\frac{1}{\sigma}}\zeta_{YE}\left(A_{YE,t+1}^{\pi_{YE}}E_{t+1}\right)^{\frac{\sigma-1}{\sigma}}\pi_{YE}+\beta_t\theta_{YE,t+1}\Delta a_{YE}R_{YE,t+1}^b\o A_{YE,t+1}^{\o}+\beta_t\theta_{YE,t+1}A_{YE,t+1}=$$

$$\theta_{YE,t}\ A_{YE,t+1} \tag{21}$$

$$\beta_t \mu_{t+1} \pi_{\mathrm{MZ}} M_{t+1} + \beta_t \theta_{MZ,t+1} \Delta a_{MZ} R^b_{MZ,t+1} \text{ø} A^{\text{ø}}_{MZ,t+1} + \beta_t \theta_{MZ,t+1} A_{MZ,t+1} = \theta_{MZ,t} A_{MZ,t+1} \tag{22}$$

$$\beta_t q_{t+1} \pi_{\mathrm{EZ}} E_{t+1} + \beta_t \theta_{EZ,t+1} \Delta a_{EZ} R^b_{EZ,t+1} \text{ø} A^{\text{ø}}_{EZ,t+1} + \beta_t \theta_{EZ,t+1} A_{EZ,t+1} = \theta_{EZ,t} A_{EZ,t+1} \tag{23}$$

$$Y_t^{\frac{1}{\sigma}} \zeta_{YE} \left(A^{\pi_{YE}}_{YE,t} E_t \right)^{\frac{\sigma-1}{\sigma}} = q_t E_t - \theta_{ATM,t} (1-\delta_E)^{\Delta} CVS_1 E_t \tag{24}$$

$$\beta_t = \frac{\frac{P(t+1)}{P(t)}}{(1+\rho)^{\Delta} \frac{C(t+1)}{C(t)}} \tag{25}$$

$$Y_t = \left(\frac{\mu_t}{\zeta_{YM}}\right)^{\sigma} M_t \tag{26}$$

$$\mu_t M_t = \xi_t Z_{M,t} \tag{27}$$

$$q_t E_t = \xi_t Z_{E,t} \tag{28}$$

$$\Delta \left(1 - \eta \frac{I_{t+1}}{K_{t+1}}\right) \xi_{t+1}\, \alpha \left(Z_{M,t+1} + Z_{E,t+1}\right) (K_{t+1})^{-1} + (1-\delta_k)^{\Delta} + \Delta \left(\frac{\eta}{2} \frac{I^2_{t+1}}{K^2_{t+1}}\right) = \frac{1}{\beta_t} \left(\frac{1-\eta \frac{I_{t+1}}{K_{t+1}}}{1-\eta \frac{I_t}{K_t}}\right) \tag{29}$$

$$\Psi_t \Delta \left(1 - \eta \frac{I_t}{K_t}\right) = 1 \tag{30}$$

$$\beta_t \theta_{ATM,t+1} (1-\delta_M)^{\Delta} = \theta_{ATM,t} + \overline{P_{t+1}} \beta_t \tag{31}$$

$$\overline{P_t}\ [ATM_{TGT} - ATM_t] = 0 \tag{32}$$

In this formulation, all shadow prices have been normalized by dividing P_t^Y, which means that all shadow prices are measured in terms of dollars. This approach is the origin of the β condition in equation (25). In equation (25), we can think β as the intertemporal marginal rate of substitution of consumption. Then, combining (25) with (29) gives the Keynes-Ramsey rule.

Equation (32) is a complementary slackness condition. The interpretation is as follows:

if the environmental constraint (16) is binding, then $\overline{P}_t$ is positive, and the product of $\overline{P}_t\ [ATM_{TGT} - ATM_t]$ is zero. In contrast, if (16) is slack, then $ATM_{TGT} > ATM_t$ and $\overline{P}_t$ is zero. If the constraint does not bind, there is no cost to having the constraint in that period, so the shadow value is zero. Similarly, R_{YE}, R_{EZ}, R_{MZ}, and I all have zero values in the final period, which comes from the complementary slackness conditions for the non-negativity constraints on R_{YE}, R_{EZ}, R_{MZ}, and I. For $t=T$, investing in new capital is pointless.

The fact that $\overline{P}_t > 0$ in some periods feeds into non-zero values of $\theta_{ATM,t}$ as well, through (31). One more unit of *ATM* brings us closer to the target *ATM* level, which would reduce the agent's freedom of energy consumption. Therefore, $\theta_{ATM,t}$ is negative.

Equation (24) is the optimality condition with respect to energy. The social planner consumes energy to the point where the marginal product is equal to the marginal cost. The right-hand side of (24) shows that the marginal cost consists of two components: the first is the cost of energy, and the second is equivalent to a carbon tax to discourage consumption of *E*, thus enforcing the quantity constraint. In the OPT scenario, as long as the constraint (16) becomes binding in some future period, it gets transmitted to the present through $\theta_{ATM,t}$ in (31). Thus, in OPT we have in effect a carbon tax that starts very small and then rises gradually until the constraint (16) becomes binding, at which point the tax reaches its highest value. This is how a binding constraint in the future is transmitted to earlier generations as a carbon tax.

The solution in OPT is characterized by the structural equations of (1)-(16), plus the behavioural equations (18) to (32), transversally conditions $\Psi_T = \theta_{YE,T} = \theta_{MZ,T} = \theta_{EZ,T} = \theta_{ATM,T} = 0$, and initial values of the state variables.

In the business-as-usual scenario (BAU) there is no emission control policy, which means that (16) is not applied and the agent ignores the environmental relationships given by (14) and (15). Therefore, the agent's problem in BAU is to maximize (17) subject to equations (1)-(13), subject to given initial values of the stocks K_1, $A_{YE,1}$, $A_{MZ,1}$, and $A_{EZ,1}$, as well as a fixed horizon *T*. The duplication externality has been externalized by replacing (6), (7), (8) with (6'), (7'), (8') in the Lagrangian function and inter-firm spillovers have been externalized by setting ω=0.25.

The Lagrangian function for the agent's maximization in the BAU scenario is

$$\mathrm{L} = \sum_{t=1}^{T} \{ \frac{1}{(1+\rho)^{\Delta t}} P_t \ln\left(\frac{C_t}{P_t}\right) + P_t^Y \left[\left(\zeta_{YM} (M_t)^{\frac{\sigma-1}{\sigma}} + \zeta_{YE} \left(A_{YE,t}^{\pi_{YE}} E_t \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} - Y_t \right] +$$

$$\mu_t \left[\varsigma_M \, \mathrm{A}_{\mathrm{MZ,t}}^{\pi_{\mathrm{MZ}}} \mathrm{Z}_{\mathrm{M,t}} - M_t \right] + q_t \left[\varsigma_E \, \mathrm{A}_{\mathrm{EZ,t}}^{\pi_{\mathrm{EZ}}} \mathrm{Z}_{\mathrm{E,t}} - E_t \right] + \xi_t \left[\gamma \mathrm{K}_t^{\alpha} L_t^{1-\alpha} - Z_{M,t} - Z_{E,t} \right] + \Psi_t \left[(1 - \right.$$

$$\left. \delta_k)^{\Delta} K_t + \Delta \left(I_t - \frac{\eta}{2} \frac{I_t^2}{K_t} \right) - K_{t+1} \right] + \theta_{YE,t} \left[\Delta\omega \, V_{YE,t} R_{YE,t} + A_{YE,t} - A_{YE,t+1} \right] +$$

$$\theta_{MZ,t} \left[\Delta\omega \, V_{MZ,t} R_{MZ,t} + A_{MZ,t} - A_{MZ,t+1} \right] + \theta_{EZ,t} \left[\Delta\omega \, V_{EZ,t} R_{EZ,t} + A_{EZ,t} - A_{EZ,t+1} \right] +$$

$$P_t^I \left[Y_t - C_t - I_t - R_{YE,t} - R_{MZ,t} - R_{EZ,t} \right] \}$$

The first order conditions are as follows. (All shadow values have been normalized.)

$$\theta_{YE,t} \Delta\omega \, V_{YE,t} - 1 = 0 \tag{33}$$

$$\theta_{MZ,t} \Delta\omega \, V_{MZ,t} - 1 = 0 \tag{34}$$

$$\theta_{EZ,t} \Delta\omega \, V_{EZ,t} - 1 = 0 \tag{35}$$

$$\beta_t {Y_{t+1}}^{\frac{1}{\sigma}} \zeta_{YE} \left(A_{YE,t+1}^{\pi_{YE}} E_{t+1} \right)^{\frac{\sigma-1}{\sigma}} \pi_{YE} + \beta_t \theta_{YE,t+1} A_{YE,t+1} = \theta_{YE,t} \, A_{YE,t+1} \tag{36}$$

$$\beta_t \mu_{t+1} \pi_{\mathrm{MZ}} M_{t+1} + \beta_t \theta_{MZ,t+1} A_{MZ,t+1} = \theta_{MZ,t} A_{MZ,t+1} \tag{37}$$

$$\beta_t q_{t+1} \pi_{\mathrm{EZ}} E_{t+1} + \beta_t \theta_{EZ,t+1} A_{EZ,t+1} = \theta_{EZ,t} A_{EZ,t+1} \tag{38}$$

$$\beta_t = \frac{\frac{P(t+1)}{P(t)}}{(1+\rho)^{\Delta} \frac{C(t+1)}{C(t)}} \tag{39}$$

$$Y_t = \left(\frac{\mu_t}{\zeta_{YM}}\right)^{\sigma} M_t \tag{40}$$

$${Y_t}^{\frac{1}{\sigma}} \zeta_{YE} \left(A_{YE,t}^{\pi_{YE}} E_t \right)^{\frac{\sigma-1}{\sigma}} = q_t E_t \tag{41}$$

$$\mu_t M_t = \xi_t Z_{M,t} \; or \; \mu_t \varsigma_M A_{MZ,t}^{\pi_{MZ}} = \xi_t \tag{42}$$

$$q_t E_t = \xi_t Z_{E,t} \; or \; q_t \varsigma_E A_{EZ,t}^{\pi_{EZ}} = \xi_t \tag{43}$$

$$\Delta\left(1-\eta\frac{I_{t+1}}{K_{t+1}}\right)\xi_{t+1}\,\alpha\left(Z_{M,t+1}+Z_{E,t+1}\right)(K_{t+1})^{-1}+(1-\delta_k)^{\Delta}+\Delta\left(\frac{\eta}{2}\frac{I_{t+1}^2}{K_{t+1}^2}\right)=\frac{1}{\beta_t}\left(\frac{1-\eta\frac{I_{t+1}}{K_{t+1}}}{1-\eta\frac{I_t}{K_t}}\right) \tag{44}$$

$$\Psi_t\Delta\left(1-\eta\frac{I_t}{K_t}\right)=1 \tag{45}$$

The solution in BAU is characterized by the structural equations of (1)-(13), (6''),(7''),(8'') plus the behavioral equations (33) to (45), initial starting values and transversally conditions.

In decentralized scenarios, i.e. FB, SE and NOITC, the government can set taxes and subsidies to internalize market distortions. Let τ_t represent the carbon tax, $s_{YE,t}$ $s_{MZ,t}$, $s_{EZ,t}$ three different R&D subsidies, and TF_t represent government transfers.

The Lagrangian function for the decentralized model is:

$$\mathrm{L}=\sum_{t=1}^{T}\{\frac{1}{(1+\rho)^{\Delta t}}P_t\ln\left(\frac{C_t}{P_t}\right)+P_t^Y\left[\left(\zeta_{YM}(M_t)^{\frac{\sigma-1}{\sigma}}+\zeta_{YE}\left(A_{YE,t}^{\pi_{YE}}E_t\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}-Y_t\right]+$$

$$\mu_t\left[\varsigma_M\,\mathrm{A}_{\mathrm{MZ,t}}^{\pi_{\mathrm{MZ}}}\mathrm{Z}_{\mathrm{M,t}}-M_t\right]+q_t\left[\varsigma_E\,\mathrm{A}_{\mathrm{EZ,t}}^{\pi_{\mathrm{EZ}}}\mathrm{Z}_{\mathrm{E,t}}-(1+\tau_t)E_t\right]+\xi_t\left[\gamma\mathrm{K}_t^{\alpha}L_t^{1-\alpha}-Z_{M,t}-Z_{E,t}\right]+$$

$$\Psi_t\left[(1-\delta_k)^{\Delta}K_t+\Delta\left(I_t-\frac{\eta}{2}\frac{I_t^2}{K_t}\right)-K_{t+1}\right]+\theta_{YE,t}\left[\Delta\omega\,V_{YE,t}R_{YE,t}+A_{YE,t}-A_{YE,t+1}\right]+$$

$$\theta_{MZ,t}\left[\Delta\omega\,V_{MZ,t}R_{MZ,t}+A_{MZ,t}-A_{MZ,t+1}\right]+\theta_{EZ,t}\left[\Delta\omega\,V_{EZ,t}R_{EZ,t}+A_{EZ,t}-A_{EZ,t+1}\right]+$$

$$P_t^I\left[Y_t-C_t-I_t-\left(1-s_{YE,t}\right)R_{YE,t}-\left(1-s_{MZ,t}\right)R_{MZ,t}-\left(1-s_{EZ,t}\right)R_{EZ,t}+TF_t\right]\}$$

The FOCs are the same as BAU except those FOCs with respect to R_{YE}, R_{MZ}, R_{EZ} and E:

R_{YE}: $\quad \theta_{YE,t}\Delta\omega\, a_{YE}R_{YE,t}^{b-1}A_{YE,t}^{\emptyset}-(1-s_{YE,t})=0$ (33')

R_{MZ}: $\quad \theta_{MZ,t}\Delta\omega\, a_{MZ}R_{MZ,t}^{b-1}A_{MZ,t}^{\emptyset}-(1-s_{MZ,t})=0$ (34')

$R_{EZ,t}$: $\quad \theta_{EZ,t}\Delta\omega\, a_{EZ}R_{EZ,t}^{b-1}A_{EZ,t}^{\emptyset}-(1-s_{EZ,t})=0$ (35')

E_t: $\quad Y_t^{\frac{1}{\sigma}}\zeta_{YE}\left(A_{YE,t}^{\pi_{YE}}E_t\right)^{\frac{\sigma-1}{\sigma}}=q_tE_t+\tau_t\,q_tE_t$ (41')

Note (6''), (7''), and (8'') have been substituted for V_{YE}, V_{MZ}, and V_{EZ} in (33')-(35').

To make the first best policy equivalent to the planner's optimum, we choose the carbon tax and R&D subsidies so that (33')-(35') and (41') are identical to (18)-(20) and (24) in the planner's model. For the carbon tax, this exercise yields

$$\tau_t = \frac{[-\theta_{ATM,t}(1-\delta_E)^{\Delta}CVS_1]}{q_t}$$

For the R&D subsidies, we obtain

$$\mathrm{n}s_j{}^* = \theta_j \Delta a_j R_j{}^{b-1} A_j{}^{\phi}(b-\omega),\ \ (j = (Y,E),(M,Z),(E,Z))$$

Now, substituting (18)-(20) yields

$$s_{YE,t} = s_{MZ,t} = s_{EZ,t} = s^* = \frac{(b-\omega)}{b}$$

The second-best policy (SB) involves using the carbon tax only (no R&D subsidies) to internalize inter-firm spillover effects and the duplication externality, as well as to meet the environmental target. Following Shiell and Lyssenko (2014), we choose the tax level to maximize the welfare function (17) subject to the original structural equations (1)-(16) and BAU behavioral equations (33)-(45) (replace (41) with (41')), initial values of the state variables, transversally conditions, and the environmental target condition. We fix all the subsidies to be zero and let the carbon tax be a choice variable in our model. In SB, since tax is the only instrument to solve all three distortions, each distortion is only partially internalized. As a result, we expect that welfare in SB will be lower than in FB.

No Induced Technical Change (NOITC) is the last scenario. In this case, R_{YE}, R_{EZ}, R_{MZ}, A_{YE}, A_{EZ}, and A_{MZ} are all fixed at their BAU levels and related first-order conditions are turned off. Then, we choose the tax level to maximize the welfare function (17) subject to original structural equations (1)-(16), behavioral equations (39)-(45) (replace (41) with (41')), plus transversally conditions, initial values of the state variables, and the environmental target condition.

1.5 Calibration

Following Gerlagh (2008), we calibrate our model with a "constant growth" scenario in which each variable is assumed to grow at its own constant exponential rate. In this approach, we set values for certain variables and parameters, which are based on empirical data and are used as inputs in the calibration of the remaining variables and parameters. These values are shown in Table 2 in Appendix A. There are five types of values in the Table 2: (i) exogenous parameters, (ii) initial values, (iii) normalized values, (iv) exogenous growth rates, and (v) calibrated parameters.

Interpretations of exogenous parameter values in Table 2 are as follows: ρ represents the rate of pure time preference (Gerlagh 2008), $\rho = 0.03$; δ_k means the annual depreciation rate (Shiell & Lyssenko 2014), $\delta_k = 0.1$; the appropriation rate (Gerlagh 2008) is ω, $\omega = 0.25$; ATM_{TGT} represents the controlled level for the atmospheric carbon concentration level, which is $ATM_{TGT} = 450\, ppmv$; the parameter η in the capital adjustment cost function (Cummins Hassett & Hubbard 1994) is 2; Δ represents the period duration, $\Delta = 1$ in the calibration model and $\Delta = 5$ in the dynamic model; γ is the coefficient on value added production function, $\gamma = 1$; the parameter b in the knowledge accumulation equation is equal to 0.7 (Shiell & Lyssenko 2014); the parameter ø in the knowledge accumulation equation is equal to 0.0; the share of R_{YE} in total R (OECD data) is 0.014; the share of R_{EZ} in total R (OECD data) is 0.002; the share of R in Y (avg. 2011-2013 UNESCO data from data.worldbank.org) is 0.021; the subsidies used in the FB scenario are defined as follows: $s_{YE,t} = s_{MZ,t} = s_{EZ,t} = s^* = \frac{(b-\omega)}{b}$ for $b = 0.7$ and $\omega = 0.25$, $s^* = 0.643$.

Interpretations of initial values in Table 2 are as follows: q represents the initial price of energy (US$ ten trillion per ten GtC) ($50 per boe), $q = 0.1163$; P_1 represents the initial total population in 2011 (World Bank 2015), $P_1 = 6.7$ billions of people; the long run population (UN report) is P_{LT}, $P_{LT} = 8.97$ billions of people. The human capital-based productivity (Gerlagh 2008) is captured by h_0, $h_0 = 0.48$; Y_1 represents initial output (ten trillion US$ 2011) from Penn World Table 9.0, $Y_1 = 9.285$; carbon-energy use in 2012 (ten $GtCO_2$) (WRI 2015 CAIT Climate Data Explorer) E_1 takes value of 4.48; and K_1 represents initial capital (ten trillion US$ 2011) from Penn World Table 9.0, $K_1 = 32.418$.

Interpretations of normalized values in Table 2 are as follows: $A_{YE,1}$ is energy efficiency knowledge stock, $A_{YE,1} = 2$; knowledge stock for producing generic intermediate input is captured by $A_{MZ,1}$, $A_{MZ,1} = 2$; energy production knowledge stock is $A_{EZ,1}$, $A_{EZ,1} = 2$; intermediate materials M_1 takes a value of 2; for $A_{YE,1}$, $A_{MZ,1}$, $A_{EZ,1}$ and M_1, the units of measurement are normalized arbitrarily so that first period values equal 2.

Interpretations of exogenous growth rates in Table 2 are as follows: the growth rate of effective labour is g_L (Penn World Table 9.0), $g_L = 0.0132$; the growth rate of the total population is g_{POP} (Penn World Table 9.0), $g_{POP} = 0.0132$; g_K represents growth rate of capital stock (Penn World Table 9.0 - avg 1990-2014), $g_K = 0.0388$; and following Gerlagh (2008), we set the initial human capital productivity value h_0, $h_0 = 0.48$. The first period growth rate of human capital γ_{h0} is 0.042 and the decline rate of growth rate of human capital is $-\delta_\gamma$, $-\delta_\gamma = -0.27$.

The constant growth model in the benchmark scenario in which duplication has been externalized in BAU is defined as follows. For calibration, we set Δ=1 and define annual growth rates as g_i where i represents the variable in question. We convert the equations of the model (1)-(45) into a constant-growth format. These equations are shown in Appendix A. Equations (A1)-(A58) constitute a block recursive system, in 58 unknowns. With the exogenous parameters listed in the Table 2, we can solve the system to calibrate the unknown values. See Table 2's section of calibrated parameters for details of the solution.

Our choices of the exogenous values are as follows. First, we constrain the initial value of R&D expenditure, R_1, to be 2.1% of total output, Y_1, based on the 2011-2013 average of UNESCO data reported by the World Bank. Then, based on the 2011 OECD data, we allocate 1.4% of R_1 to energy efficiency R&D, $R_{YE,1}$, and 0.2% to energy production R&D, $R_{EZ,1}$, leaving 98.4% of R_1 allocated to non-energy R&D, $R_{MZ,1}$ (stats.oecd.org). The R_{YE} category in the OECD data includes four groups: energy efficiency R&D; renewable energy sources R&D; nuclear R&D; and hydrogen & fuel cells R&D, while the R_{EZ} category represents fossil fuel energy R&D.

Population growth follows the logistic growth curve (11). Long run population and first period population are $P_{LT} = 8.97$ billion and $P_1 = 6.7$ billion, respectively (UN data). We know the five-year growth rate at 2011 (for period 1) is $g_{P_1} = 0.068$. Then we solve for γ_p and t_{p0}. Firstly, based on (11), we calculate $g_{P_1} = \frac{\frac{dP_1}{dt}}{P_1} = \gamma_p\left(\frac{P^{LT}-P_1}{P^{LT}}\right)$. Rearranging yields, $\gamma_p = \frac{gP_1\,P_{LT}}{P_{LT}-P_1} = 0.269$. Then we solve $P_1 = P_{LT}\frac{e^{\gamma_p\,(1-t_{p0})}}{1+e^{\gamma_p(1-t_{p0})}}$ to obtain $t_{p0} = -3.02$.

1.6 Results.

Table 1.

Experiments	**Duplication in BAU**	**Initial R_{YE}&R_{EZ} shares in BAU**
EXP1- Benchmark	External	$R_{YE,1} = 0.014R_1$ $R_{EZ,1} = 0.002R_1$ $R_{MZ,1} = 0.984R_1$
EXP2- R_{YE}&R_{EZ} shares	External	$R_{YE,1} = 0.32R_1$ $R_{EZ,1} = 0.05R_1$ $R_{MZ,1} = 0.63R_1$
EXP3- Duplication	Internalized	$R_{YE,1} = 0.014R_1$ $R_{EZ,1} = 0.002R_1$ $R_{MZ,1} = 0.984R_1$
EXP4- R_{YE}&R_{EZ} shares and duplication	Internalized	$R_{YE,1} = 0.32R_1$ $R_{EZ,1} = 0.05R_1$ $R_{MZ,1} = 0.63R_1$

We carry out four experiments (See Table 1). Experiment 1 is our benchmark case and is represented above. Experiment 2 uses Gerlagh's R_{YE} and R_{EZ} shares, but leaves everything else as in EXP1. We have higher initial shares for R_{YE} and R_{EZ}, as compared with EXP1, since we want to know what the impacts on the results are by incorporating Gerlagh's shares into our model. Experiment 3 shows our findings if we internalize the duplication externality in BAU (like Popp 2004, Hart 2008, and Gerlagh 2008) but leave everything else as in EXP1 since we want to know the size of the overestimated positive effect of induced R&D on abatement cost reduction. Experiment 4 shows the results if we internalize the duplication externality in BAU and use the higher initial values of R_{YE} and R_{EZ}, since we want to incorporate Gerlagh's approach into our model in order see how large the overestimated impact of induced R&D is.

In each experiment, we solve the four scenarios: BAU, FB, SB, and NOITC. All solutions are generated with the numerical optimization software GAMs. The first period is 2010 and time advances in steps of five years, i.e. 2010, 2015, 2020, etc. Our goal is to assess the sensitivity of our model to the assumptions in Table 1. We begin with an overview of the results in EXP1.

Experiment 1

Figure 1 describes the world GDP and consumption per capita in EXP1's BAU scenario. Since there is no climate change policy in this scenario, we would expect both world GDP per capita and consumption per capita to be increasing over time. Figure 1 shows that both values increase to 51.36 thousand dollars and 26.58 thousand dollars in 2100, respectively.

Figure 1 World GDP and Consumption per capita

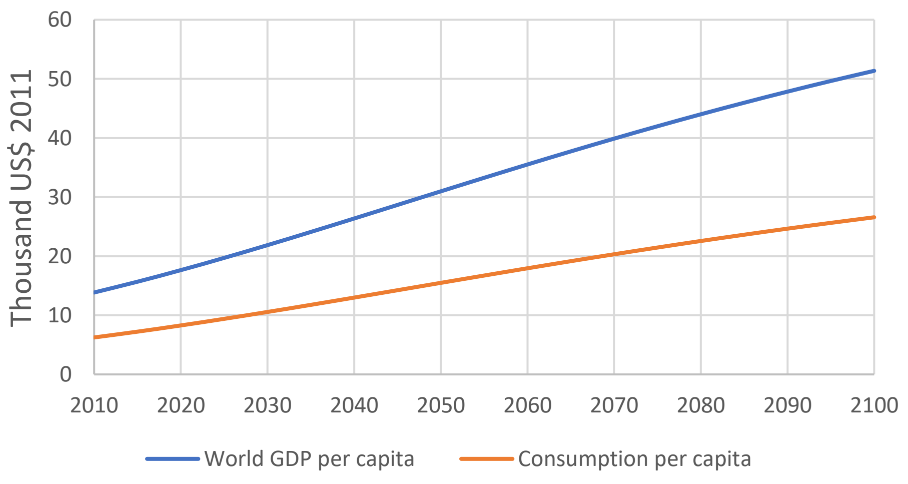


Figure 2 describes variables of *Y*, *C*, *I*, *E*, *M* from the NOITC scenario compared with their corresponding values in the BAU scenario. The NOITC scenario from EXP1 has the same levels of R&D investments and knowledge stocks for each period as the BAU scenario but with a tighter emission constraint. There are two effects at play in NOITC: the energy constraint compounding effect and the effect of the carbon tax. In the first period, NOITC had less energy, and production possibilities are limited, which leads to less output and less available for other variables such as investment in capital accumulation. In the next period, NOITC generates less output compared with BAU due to less capital investment, but also because NOITC has less energy. That means that NOITC performances worsen on a compounded basis. In addition, there is also an effect of the carbon tax getting higher in subsequent periods. As discussed in Section 4, the quantity constraint of atmospheric carbon translates into a path of carbon tax that starts very small but grows over time until the quantity constraint becomes binding. Therefore, we expect variables should have the negative deviations from BAU with values decreasing overtime. Figure 2's results confirm our expectations that each variable will continue to decrease over time.

Figure 2 NOITC (EXP1)

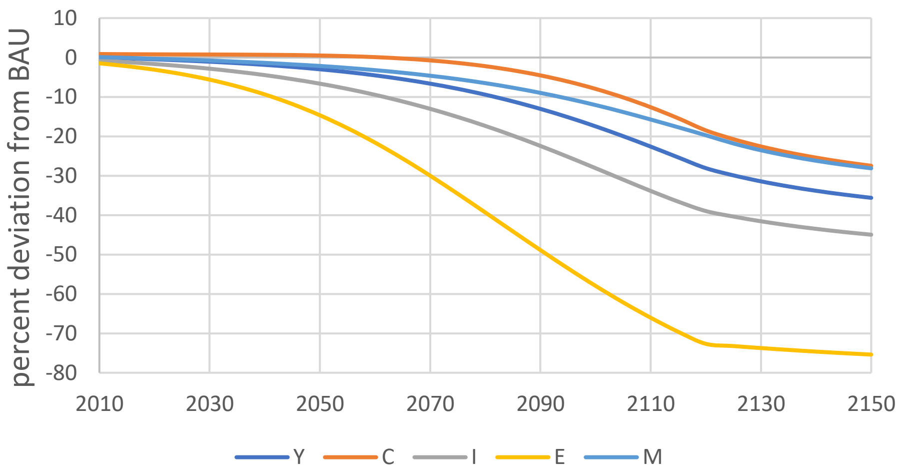


Figure 3 shows the research expenditure of FB scenario in EXP1. In FB, we have research subsidies to address inter-firm knowledge spillovers. In BAU, all types of R&D are reduced compared with their socially efficient levels by the firms' failure to account for inter-firm knowledge spillovers, whereas FB internalizes inter-firm knowledge spillovers. Therefore, all types of R&D should be higher in FB than in BAU, at least in the initial periods.

The calibrated value of the elasticity of the substitution parameter in EXP1 is 0.5083, which implies inputs are gross complements. In this case, the analysis of Gans (2012) and Sue Wing (2006) suggests that R_{YE}, R_{MZ}, and R_{EZ} would decrease. Gans (2012) examines the fossil fuel and alternative fuel augmenting technological change for the production function. His Proposition 3 shows that a more stringent climate change policy (quantity constraint) will reduce innovation incentives in alternative energy augmenting technologies (R_{MZ}) and in fossil fuel augmenting technology (R_{YE}) if products are gross complements. However, Sue Wing (2006) argues that fossil fuel augmenting technological change will increase, but it follows a hump shape in relation to the carbon tax level. The increase in R_{YE} is related with the level of the carbon tax; as the carbon tax becomes larger, the induced R&D effect becomes weaker.

FB has a carbon constraint that reduces the use of fossil fuels. This provides fewer incentives for capital goods that produce the energy input, and hence we expect to observe a corresponding decrease of R_{EZ}. Sue Wing (2006) shows the bias of techniques of production: taxing the dirty input E biases the techniques of productions to conserve on the dirty input and so if we taxed fossil fuel, according to Sue Wing's results, we should expect a decrease in R_{EZ}. We should see the model seeking to bias inputs away from fossil fuels, thus reducing the consumption of E.

This discussion indicates that R_{MZ} and R_{EZ} should be decreasing and R_{YE} should be increasing in the short run and then decreasing in the long run. Figure 3 shows the empirical results, which we found to be consistent with these expectations. FB generates positive percent deviations for R_{YE}, R_{MZ}, and R_{EZ}, but as time goes on there is a decrease in R_{MZ} and R_{EZ}, but an increase in R_{YE} until 2095 and then it decreases in the long run. This pattern replicates the hump shape predicted by Sue Wing (2006).

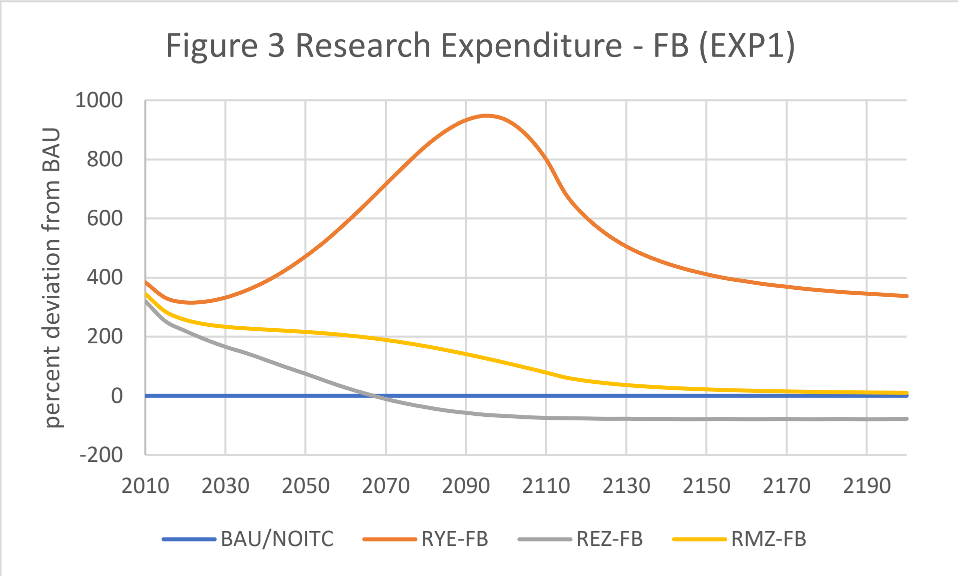


Figure 4 describes the variables of Y, C, I, E, M from the FB scenario compared with their corresponding values in the BAU scenario in EXP1. In the long run, according to Sue Wing (2006) and Gans (2012), we expect a reduction in Y, C, I, E, and M, as compared with BAU. There are four effects at play: the research subsidies effect, the excess burden effect, the changes in the balance between the first two effects due to the increasing in the tax level, and the hump shape of R_{YE} in relation to the tax level.

First, in EXP1's FB, we should expect higher values in R_{YE}, R_{MZ}, and R_{EZ} in early periods when compared with BAU. This is because in BAU, all types of R&D are reduced compared with their social efficient levels, whereas FB internalizes inter-firm knowledge spillovers. The research subsidies internalize research market distortions, leading to increases in the levels of R, Y, C, etc.

However, Gerlagh (2008) points out that there is a negative effect of the excess burden associated with the environmental policy, leading to a reduction of Y, R, C, etc. The balance between the first two effects changes over time as the carbon tax increases. In the early years, the positive effect of the research subsidies dominates the depressing effect of the excess burden. However, as the carbon tax becomes larger overtime, the negative effect of the excess burden increases and comes to dominate the research subsidies effect. Also, according to Sue Wing (2006), increasing the carbon tax level reduces the scale of R_{YE}, thereby reducing the mitigating effect of R_{YE} on R, Y, C, etc. Hence, in FB, the excess burden effect eventually outweighs the effect of the research subsidies. That is why in the FB scenario results of Figure 4, we see that consumption goes up above the BAU in the early years, but in the long-term consumption falls below the BAU. Therefore, we should expect the FB overall performance to be worse than the BAU in the long run. Figure 4's results show that the empirical finding is consistent with our initial hypothesis.

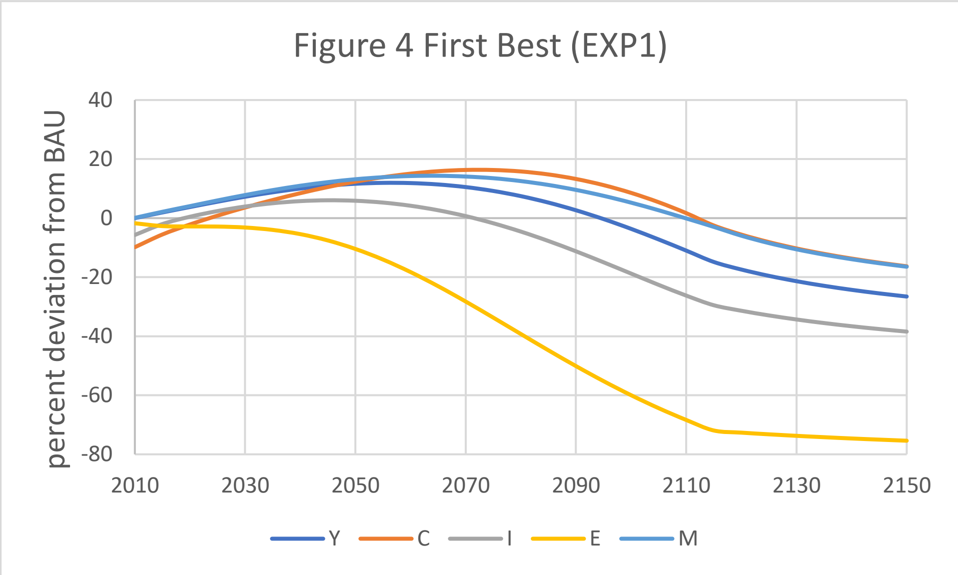


Figure 5 shows the research expenditure of the SB scenario in EXP1. According to Sue Wing (2006), Gerlagh (2008), and Gans (2012), we expect decreases in R_{MZ}, R_{EZ}, and a hump shape of R_{YE}. (Figure 3 has more detailed discussions.) In SB, inter-firm spillovers are not internalized; therefore, induced changes in research resulting from the carbon tax will affect pre-existing market distortions. There are two opposite effects at play: a research dividend effect and an excess burden effect. However, the research dividend effect is not significant compared with the excess burden effect, because we have a large value of π_{MZ} and a relatively small value of π_{YE} (see Table 2). As Gerlagh (2008) shows, this combination implies an adverse condition for a research dividend. Therefore, the excess burden effect dominates the research dividend effect in the long run. Figure 5's results reflect what we have learned from the theory. First of all, we can tell that the magnitudes of R_{YE}, R_{MZ} and R_{EZ} are lower in Figure 5 compared with Figure 3. Second, SB leads to decreases of R_{MZ}, R_{EZ} and a hump shape of R_{YE}.

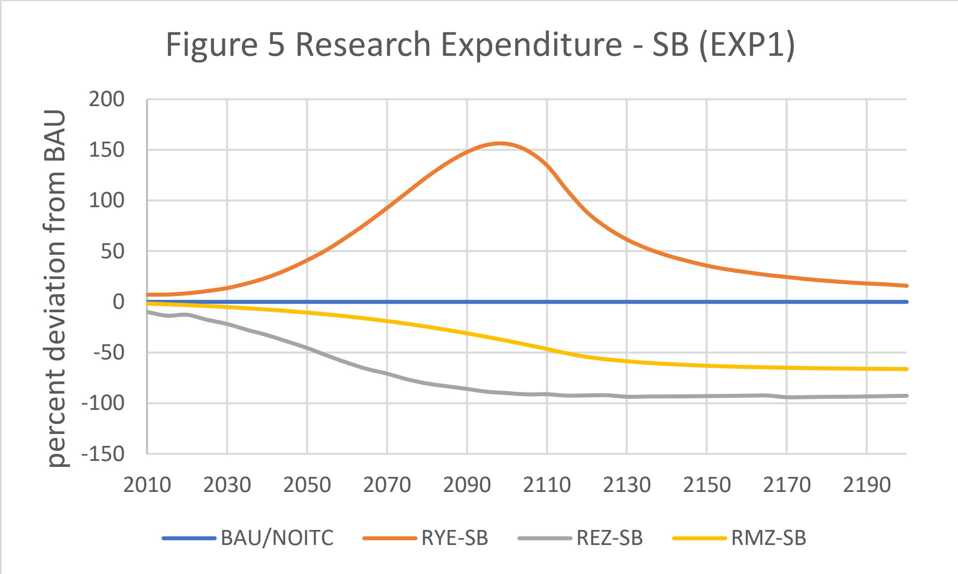


Figure 6 describes the variables of *Y*, *C*, *I*, *E*, and *M* from the SB scenario, as compared with their corresponding values in the BAU scenario. According to Sue Wing (2006), Gerlagh (2008), and Gans (2012), we expect *Y*, *C*, *I*, *E*, and *M* will decrease. (Figure 4 has more detailed discussions.) The results are consistent with our expectations.

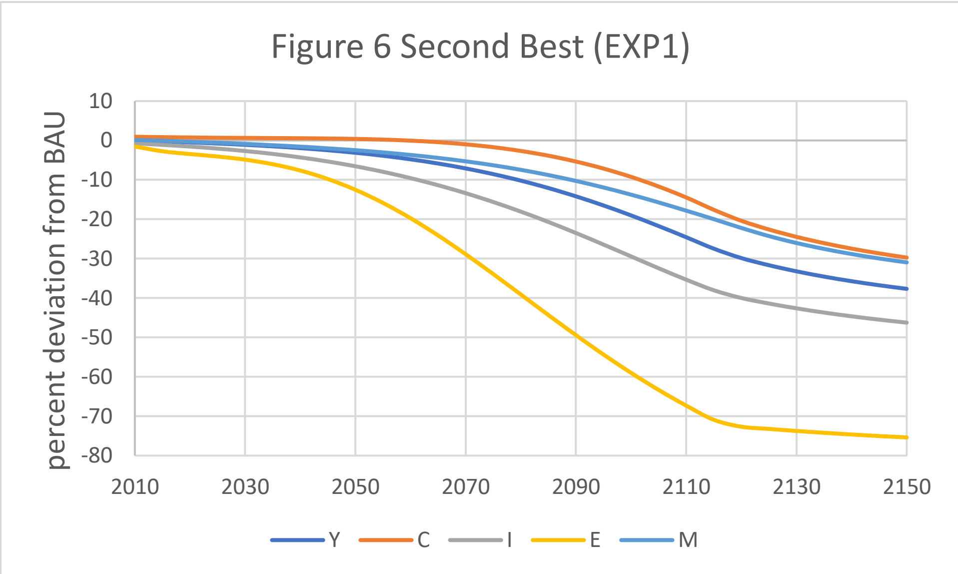


Figure 7 describes the variables of *Y*, *C*, *I*, *E*, and *M* from the SB scenario, as compared with their corresponding values in the NOITC scenario. SB and NOITC both have the same climate change policy but differ in terms of induced innovation; there is no induced innovation in the NOITC scenario. According to Gerlagh (2008), we expect *Y*, *C*, *I*, and *M* will decrease in SB. In SB, inter-firm spillovers are not internalized; therefore, induced changes in research resulting from the environmental policy will affect pre-existing market distortions and could lead to a research dividend. However, we don't have a significant research dividend effect in EXP1, as discussed above in relation to Figure 5. There is also an excess burden effect from the environmental policy. Therefore, we should expect the overall performance of SB to be worse than the NOITC. The Figure 7 results show that the empirical finding is consistent with our hypothesis.

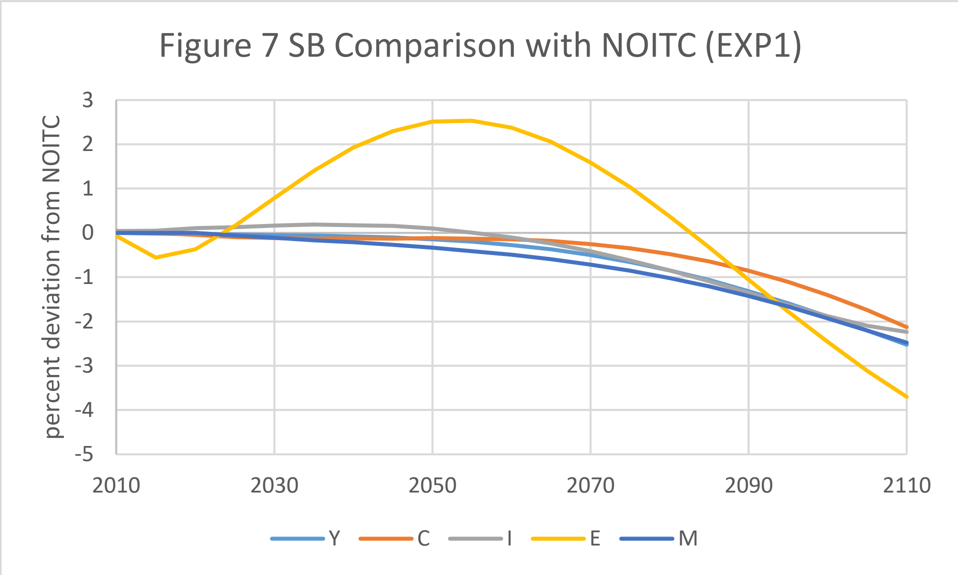
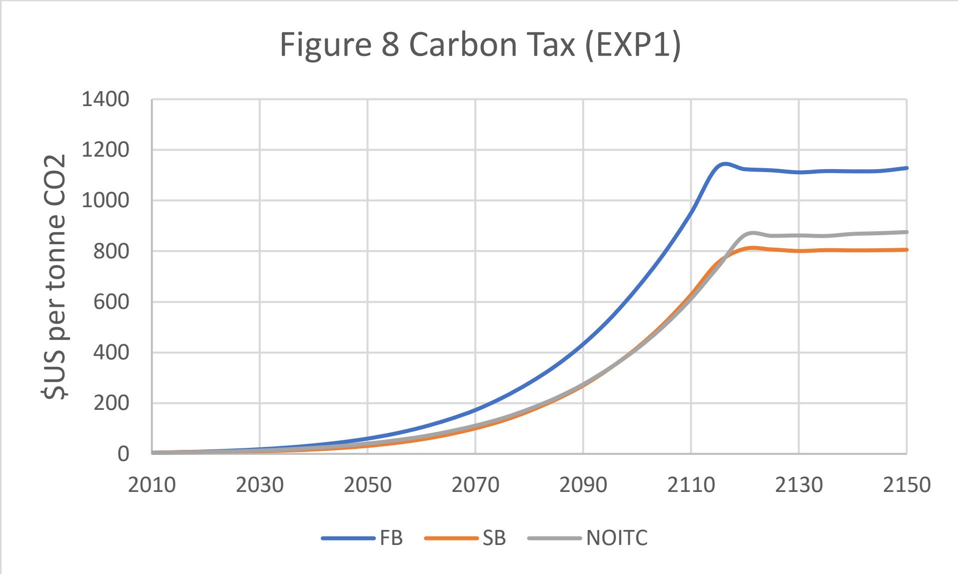


Figure 8 shows EXP1's carbon tax in FB, SB and NOITC. In 2150, FB has the highest carbon tax; NOITC and SB are ranked as second and third. In FB, there are two instruments to treat both environmental externality and knowledge market externalities, whereas SB and NOITC only have one instrument to treat all distortions. Once the carbon hits the environmental limit, the economy is constrained and the value of the tax becomes very high. The higher carbon tax in FB would have more positive effects on pollution reduction and FB's subsidies could treat distortions in the R&D market. In SB and NOITC, since the tax is the only instrument to solve all distortions, each distortion is only partially internalized. As a result, we expect that the carbon tax will be higher in FB than SB and NOITC. Figure 8's results are consistent with our expectations.



Experiment 2

Experiment 2 uses Gerlagh's R_{YE} and R_{EZ} shares, but leaves everything else as in EXP1. We have higher shares for R_{YE} and R_{EZ} but a lower share for R_{MZ}, as compared with EXP1, since we want to know what the impacts on the results are by incorporating Gerlagh's shares into our model. Figure 9 describes the variables of *Y*, *C*, *I*, *E*, and *M* from the NOITC scenario, as compared with their corresponding values in the BAU scenario. As discussed in Figure 2, we expect the variables should have the negative values of the percent deviation from BAU and the values should be decreasing overtime. Figure 9's results confirm our expectations that each variable keeps decreasing overtime.

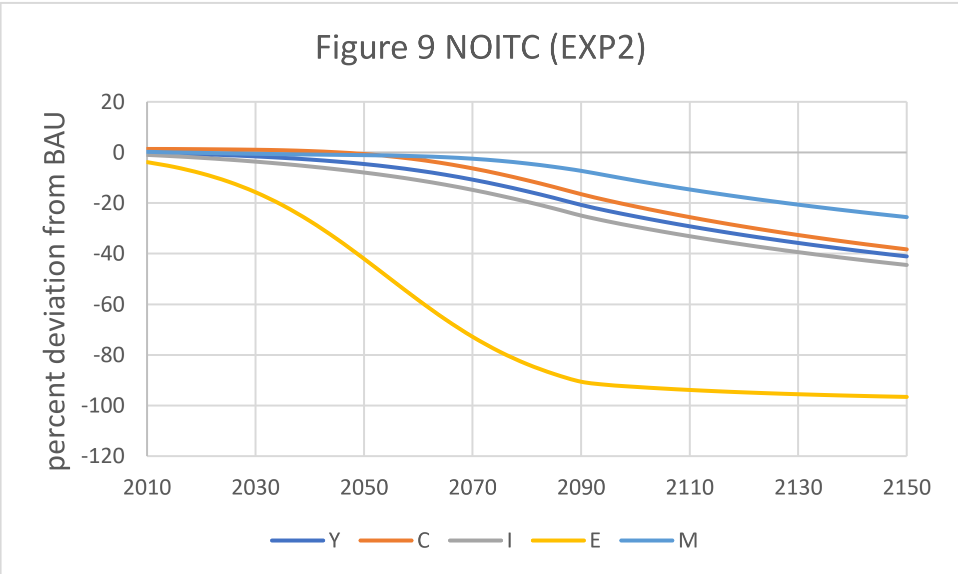


Figure 10 shows the research expenditure of the FB scenario in EXP2. In FB, we have research subsidies to address inter-firm knowledge spillovers. In BAU, all types of R&D are reduced compared with their socially efficient levels by the firms' failure to account for inter-firm knowledge spillovers, whereas FB internalizes inter-firm knowledge spillovers. Therefore, all types of R&D should be higher than their corresponding values in BAU, at least in the initial periods.

The calibrated value of the elasticity of substitution σ in EXP2 is 1.2497, which implies inputs are gross substitutes. Gans (2012) examines the fossil fuel and alternative fuel augmenting technological changes for the production function. Proposition 3 shows that a more stringent climate change policy (quantity constraint) will stimulate innovation incentives in alternative energy augmenting technologies (R_{MZ}) if products are gross substitutes, and will always reduce innovation incentives in fossil fuel augmenting technology (R_{YE}). Therefore, we expect R_{YE} and R_{EZ} will decrease but R_{MZ} will always be higher than its BAU level. At the same time, the excess burden effect of the environmental policy reduces researches. As tax increases, the excess burden effect dominates the positive research subsidies effect.

Sue Wing (2006) shows the bias of the techniques of production: taxing dirty input biases the techniques of productions to conserve on dirty input, and so if we taxed fossil fuel, according to Sue Wing's results, we should expect a decrease in R_{EZ}. We should also see the model seeking to bias inputs away from fossil fuels, thereby reducing the consumption of E. As a result, R_{YE} and R_{EZ} should decrease in the long run, while R_{MZ} will still be higher than its BAU level in the long run. Figure 10's results reflect what we have learned from these theories.

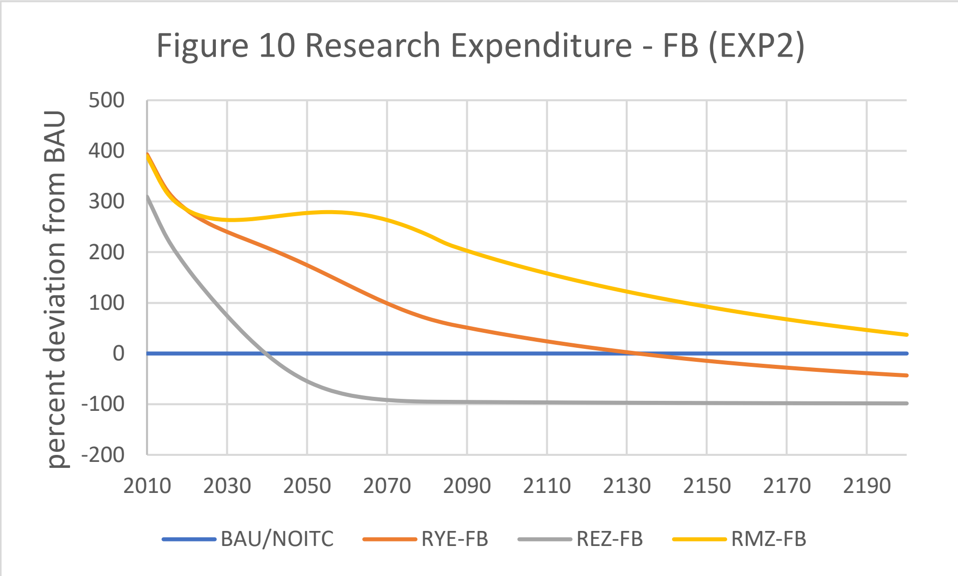


Figure 11 describes the variables of *Y*, *C*, *I*, *E*, and *M* from the FB scenario as compared with their corresponding values in the BAU scenario in EXP2. In the long run, according to Sue Wing (2006), Gerlagh (2008), and Gans (2012), we expect a reduction in *Y*, *C*, *I*, *E*, and *M*, as compared with BAU. There are three effects at play: the research subsidies effect, the excess burden effect, and the changes in the balance between the first two effects due to the increasing tax level.

First, as explained above in EXP2's FB, we should expect higher values in R_{YE}, R_{MZ}, and R_{EZ} in the early periods as compared with BAU. The research subsidies internalize research market distortions, leading to increases in the levels of *R*, *Y*, *C*, etc. Second, Gerlagh (2008) points out that there is a negative effect of excess burden associated with the environmental policy, leading to reductions in *Y*, *R*, *C*, etc. Similarly, Proposition 4 from Gans (2012) shows that when goods are gross substitutes, a tighter emission cap will always reduce the level of output. Third, the balance between the research subsidies effect and the excess burden effect changes over time as the carbon tax increases. In early years, the positive effect of the research subsidies dominates the depressing effect of the excess burden. As time goes on, however, the carbon tax becomes larger. As a result, the negative effect of the excess burden increases and comes to dominate the research subsidies effect. Additionally, according to Sue Wing (2006), increasing the tax levels reduces the scale of R_{YE}, thereby reducing the mitigating effect of R_{YE} on *R*, *Y*, *C*, etc. Hence, in FB, the excess burden effect eventually outweighs the effect of the research subsidies. That is why in the results of Figure 11, we see that the early years consumption in the FB scenario stays above BAU, but in the long-term, consumption falls below the BAU. Therefore, we should expect the FB's overall performance to be worse than the BAU in the long run.

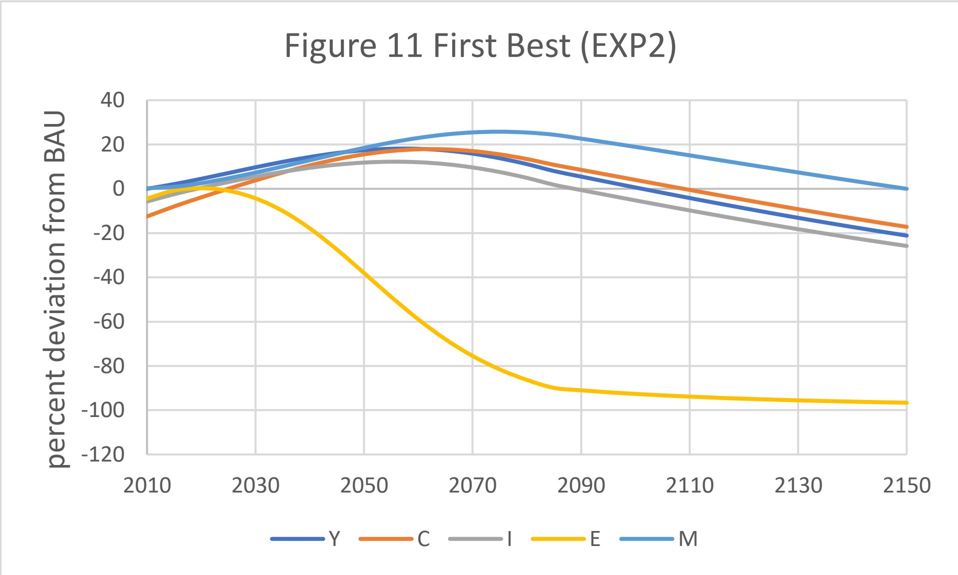


Figure 12 shows the research expenditure of the SB scenario in EXP2. According to Sue Wing (2006) and Gans (2012), we form two expectations (Figure 10 contains more detailed discussions). First, we expect decreases in R_{YE} and R_{EZ}, and increases in R_{MZ}. Second, due to higher initial R_{YE} and R_{EZ} shares and a lower initial R_{MZ} share in BAU, R_{YE} and R_{EZ} from SB in EXP2 have large negative deviations while R_{MZ} has small negative deviation. Besides, SB will yield lower magnitudes of R_{YE}, R_{MZ} and R_{EZ} compared with FB because in SB there are no research subsidies to internalize inter-firm knowledge spillovers. In SB, inter-firm spillovers are not internalized; therefore, induced changes in research resulting from the carbon tax affect pre-existing market distortions. There are two opposite effects: a research dividend effect and an excess burden effect. However, the research dividend effect is not significant if we compare it with the excess burden effect. Therefore, the excess burden effect dominates the research dividend effect in the long run. The research dividend effect is not significant, even though we have a large value of π_{YE} and smaller values of π_{MZ} and π_{EZ} (see Table 2). Figure 12's results reflect what we learned from the theory and we can tell that first, the magnitudes of R_{YE}, R_{MZ} and R_{EZ} are lower in Figure 12 compared with Figure 10. Second, SB leads to decreases of R_{YE}, R_{MZ}, and R_{EZ} compared with BAU. Third, SB generates large reductions for R_{YE} and R_{EZ}.

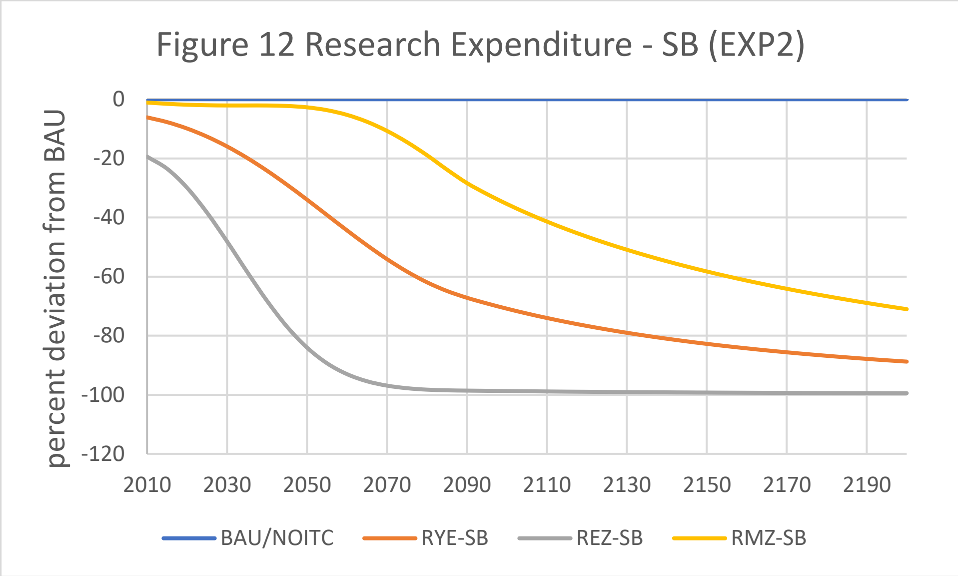


Figure 13 describes variables of *Y*, *C*, *I*, *E*, and *M* from the SB scenario compared with their corresponding values in the BAU scenario. According to Sue Wing (2006), Gerlagh (2008), and Gans (2012), we expect *Y*, *C*, *I*, *E*, and *M* will go down. (Figure 11 has more detailed discussions.) The results are consistent with our expectations.

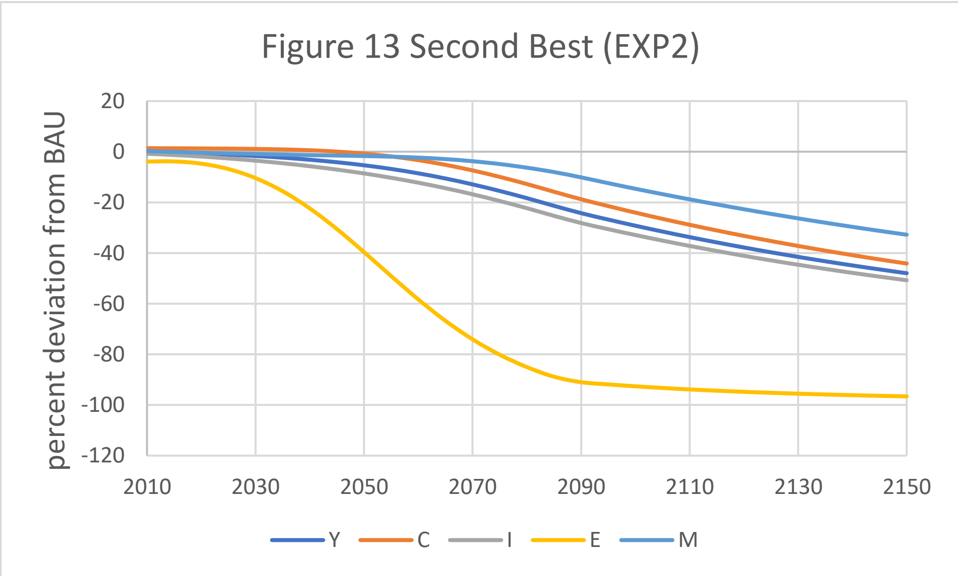
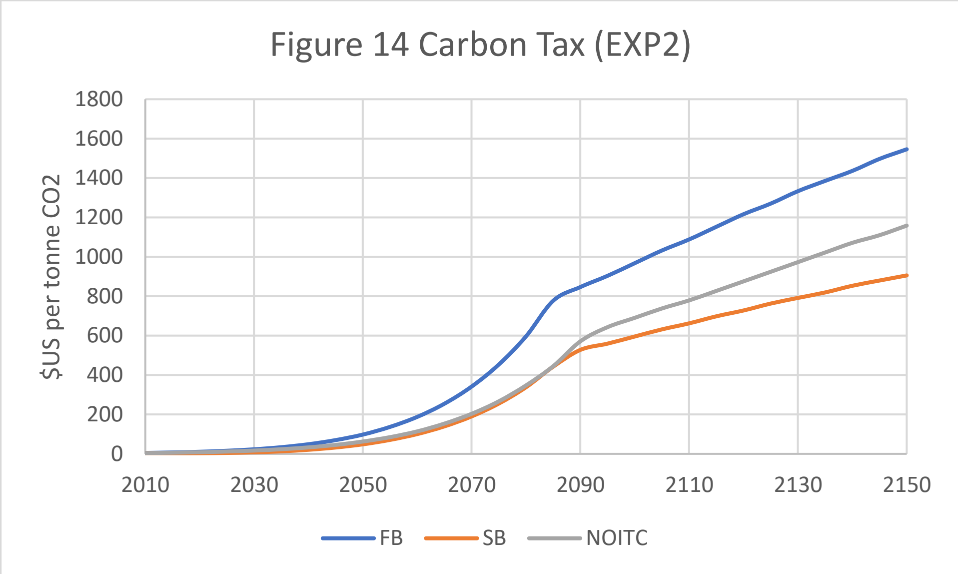


Figure 14 shows carbon tax under FB, SB, and NOITC in EXP2. We have the same expectations and analysis as discussed in Figure 8. The results show that FB has the highest carbon tax, and NOITC and SB are ranked as second and third in the long run.



Experiment 3

Experiment 3 shows our findings if we internalize the duplication externality in BAU but leave everything else as in EXP1 since we want to know the size of the overestimated positive effect of R&D on abatement cost reduction. Figure 15 describes the variables of Y, C, I, E, and M from the NOITC scenario compared with their corresponding values in the BAU scenario. We have the same expectations and analysis as discussed in Figure 2. Figure 15's results confirm our expectations that each variable keeps decreasing over time.

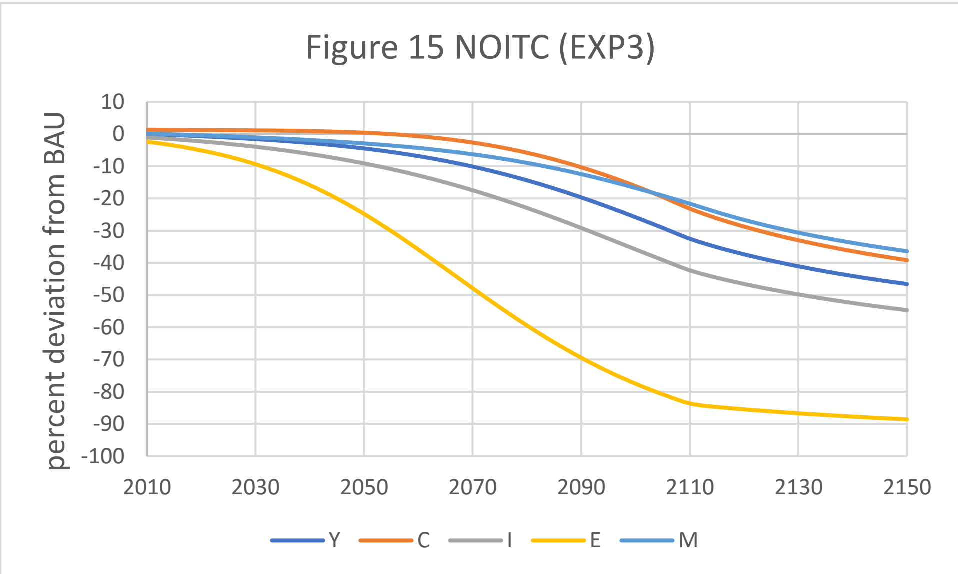


Figure 16 shows the research expenditure of the FB scenario in EXP3. As discussed in Figure 3, we form the following expectations. First, our calibrated value of elasticity of substitution parameter in EXP3 is 0.6451, which implies that inputs are complements. We expect R_{MZ} and R_{EZ} will be decreasing and R_{YE} will be increasing at first, and then decreasing in the long run. Second, according to Shiell and Lyssenko (2014), since duplication has been internalized in EXP3's BAU, all types of R&D are reduced compared with their true BAU levels. Thus, when FB is in place, we should expect large increases in R_{YE}, R_{MZ}, and R_{EZ} in the early periods. Figure 16 shows the empirical results, which are consistent with the above expectations. First, R_{YE}, R_{MZ} and R_{EZ} have large positive deviations in the early periods. Second, FB leads to a decrease of R_{MZ} and R_{EZ} in the long run, which leads to the hump shape of R_{YE}.

Figure 16 Research Expenditure - FB (EXP3)

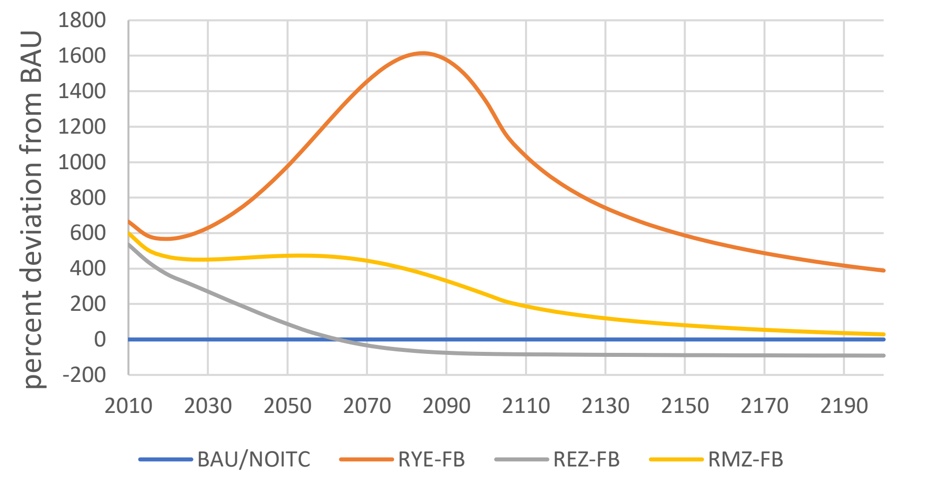


Figure 17 describes the variables of Y, C, I, E, and M from the FB scenario compared with their corresponding values in the BAU scenario in EXP3. According to Sue Wing (2006), Gerlagh (2008), and Gans (2012), we expect to find decreases in Y, C, I, E, and M (a more detailed discussion of this is in Figure 4). In EXP3, inputs are complements and duplication has been internalized in BAU. First, we expect a large increase in Y, C, and I in the early periods due to the research subsidies effect, which internalizes research market distortions. However, as tax increases, the excess burden effect would be greater than the research subsidies effect. Also, according to Sue Wing (2006), increasing tax levels reduce the R_{YE}, thereby reducing its mitigating effect on R, Y, C, etc.

According to Shiell and Lyssenko (2014), we expect to find that the FB overestimates the positive effect of induced R&D on abatement cost reduction. Since duplication has been internalized in BAU in EXP3, when FB in place, there are big jumps in research which lead to an overestimation of the benefits of induced R&D; we expect this to result in a long period of positive percent deviations of Y, C, and I as compared with BAU. Figure 17's results show that the empirical finding is consistent with our initial hypothesis.

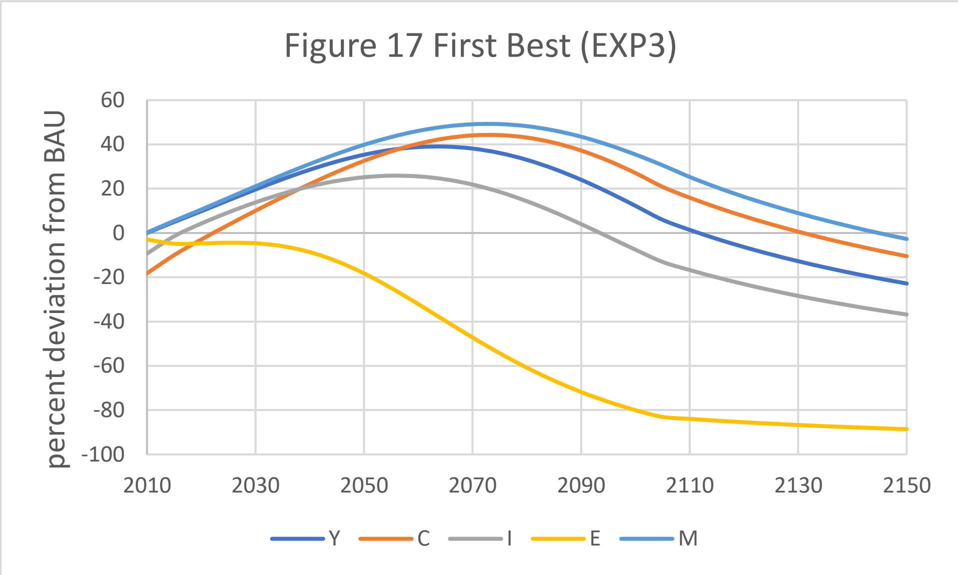


Figure 18 shows the research expenditure of the SB scenario in EXP3. Based on theories from Sue Wing (2006), Gerlagh (2008), and Gans (2012), we expect decreases of R_{MZ}, and R_{EZ}, and a hump shape of R_{YE} (more detailed discussion of this is in Figure 5). The research dividend effect is not significant, because we have a large value of π_{MZ} and a small value of π_{YE} (see Table 2). Figure 18's results reflect what we learned from the theory.

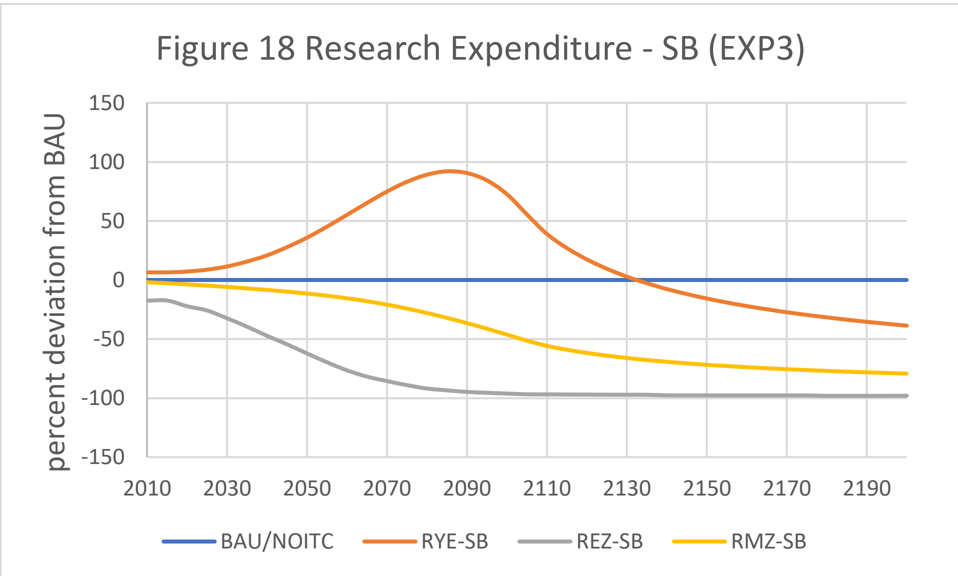


Figure 19 describes the variables of Y, C, I, E, and M from the SB scenario compared with their corresponding values in the BAU scenario. We expect decreases in *Y*, *C*, *I*, *E*, and *M* in the long run (Figure 4 has more detailed discussions of this). Figure 19's results show that the empirical finding is consistent with our initial hypothesis.

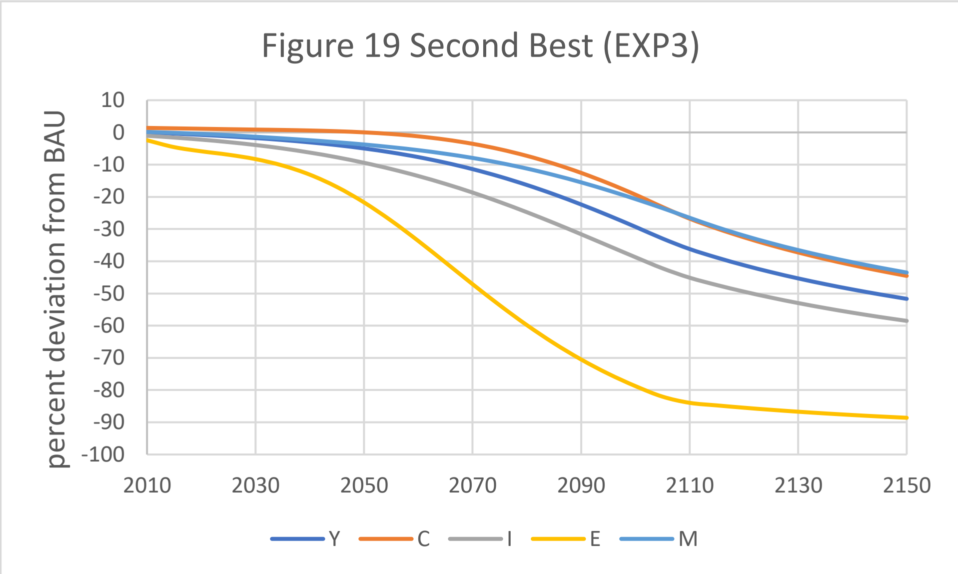
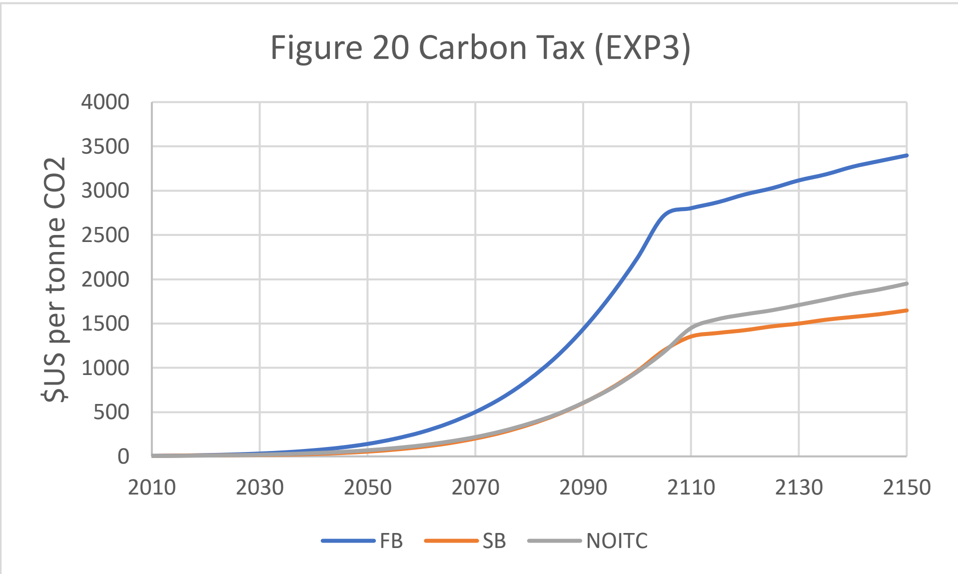


Figure 20 presents the carbon tax in EXP3. We have the same expectations and analysis as discussed in Figure 8. The results show that FB has the highest carbon tax, while NOITC and SB are ranked as second and third.



Experiment 4

Experiment 4 shows the results if we internalize the duplication externality in BAU and use the higher initial values of R_{YE} and R_{EZ}, since we want to incorporate Gerlagh's approach into our model in order see how large the overestimated impact of induced R&D is. Figure 21 describes the variables of Y, C, I, E, and M from the NOITC scenario compared with their corresponding values in the BAU scenario. We have the same expectations and analysis as discussed in Figure 2. Figure 21's results confirm our expectations that each variable decreases over time.

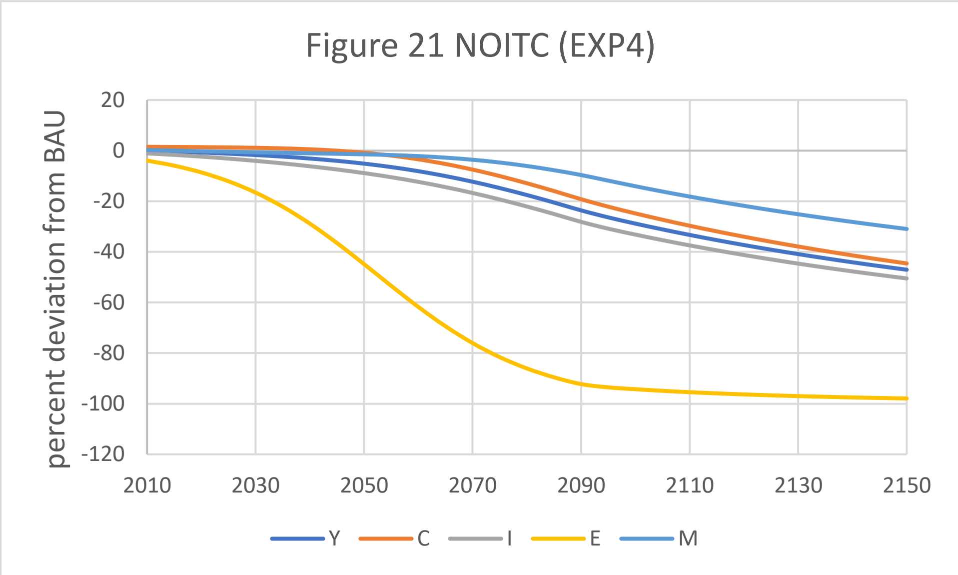


Figure 22 shows the research expenditure of the FB scenario in EXP4. Based on theories from Sue Wing (2006), Gerlagh (2008), Gans (2012), we form the following expectations (Figure 10 has more detailed discussions). First, all types of R&D should be higher than their corresponding values in BAU, at least in the initial periods, due to the research subsidies. Second, we have our calibrated value of elasticity of the substitution parameter in EXP4 is 1.1356, which implies that inputs are gross substitutes. Therefore, we expect to observe decreases of R_{YE} and R_{EZ} but anticipate that R_{MZ} will be higher than its BAU level following Gans (2012). Third, according to Shiell and Lyssenko (2014), since duplication has been internalized in EXP4's BAU, all types of R&D are reduced in BAU compared with their true levels. Therefore, when FB is put in place, we should expect large increases in R_{YE}, R_{MZ}, and R_{EZ} in the early periods. If we compare EXP4 to EXP2, in EXP2 we externalize duplication in BAU; therefore, as FB in place, there are small positive jumps in all types of R&D. Figure 22 shows the empirical results, which are consistent with the above expectations.

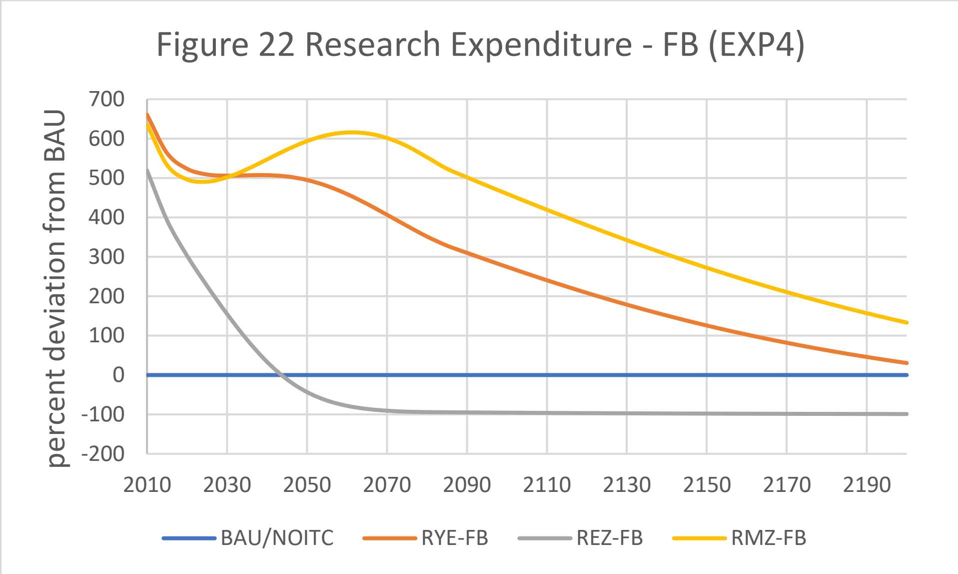


Figure 23 describes the variables of *Y*, *C*, *I*, *E*, and *M* from the FB scenario as compared with their corresponding values in the BAU scenario in EXP4. According to Sue Wing (2006), Gerlagh (2008), and Gans (2012), we expect decreases in *Y*, *C*, *I*, *E*, and *M*, compared with BAU (a more detailed discussion of this is in Figure 11). In EXP4, inputs are gross substitutes and duplication has been internalized in BAU.

According to Shiell and Lyssenko (2014), even though there are decreases in variables, we should expect that the FB would have a better performance than the BAU. This is because in EXP4, duplication has been internalized in BAU, which leads to the overestimation of the benefits of induced R&D and results in positive percent deviations of *Y*, *C*, and *I* in the long run. Figure 23's results show that the empirical finding is consistent with this hypothesis.

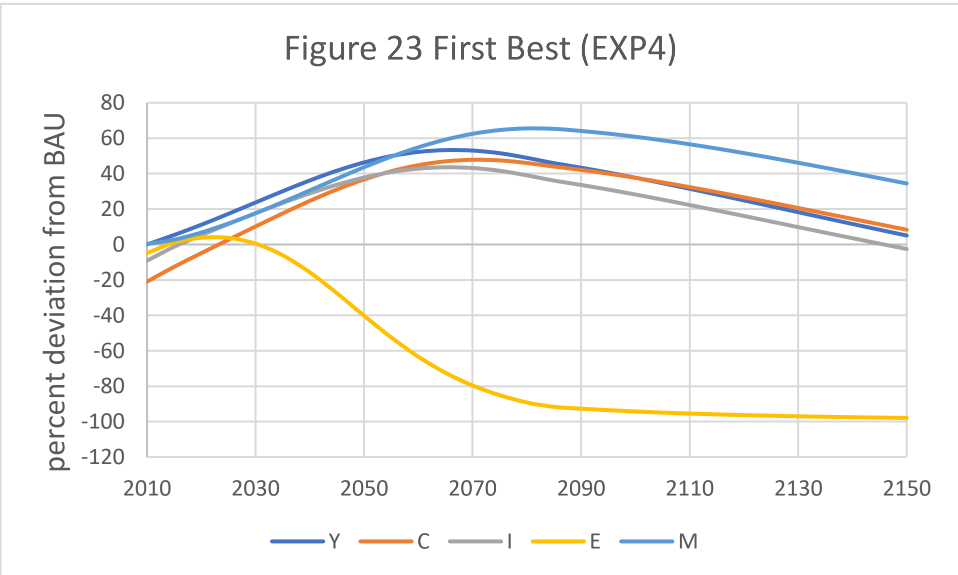


Figure 24 shows the research expenditure of the SB scenario in EXP4. Based on theories from Sue Wing (2006), Gerlagh (2008), and Gans (2012), we form the following expectations (Figure 12 has more detailed discussions). First, we expect decreases in R_{YE}, and R_{EZ}, and increases in R_{MZ}. Second, due to higher initial R_{YE} and R_{EZ} shares and a lower initial R_{MZ} share in BAU of EXP4, R_{YE} and R_{EZ} from SB in EXP4 have large negative deviations, while R_{MZ} has a small negative deviation. The research dividend effect may be operative because we have a relatively large value of π_{YE}, compared with π_{MZ} and π_{EZ} (see Table 2). However, this effect is dominated by the excess burden effect, as discussed previously. Figure 24's results reflect those expectations.

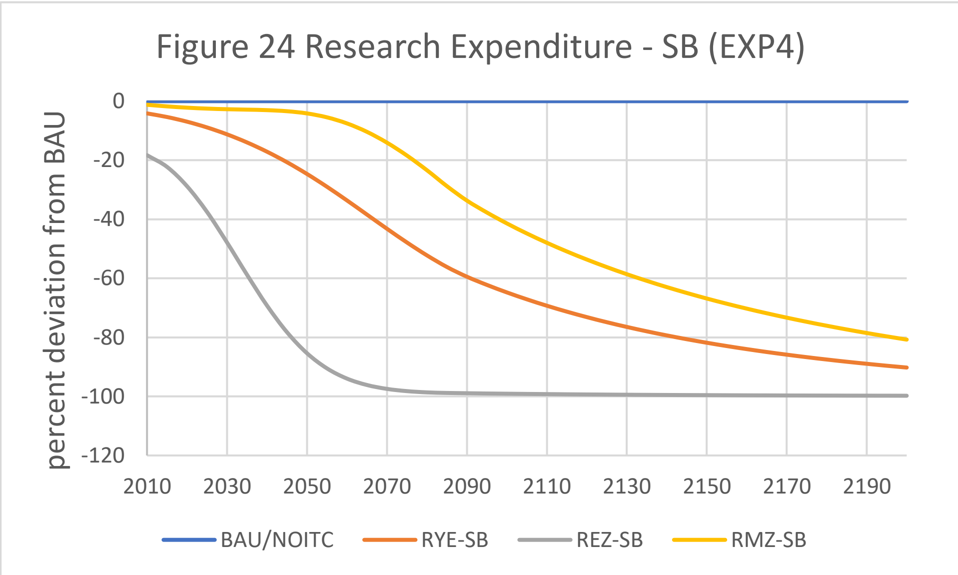


Figure 25 describes the variables of Y, C, I, E, and M from the SB scenario compared with their corresponding values in the BAU scenario. We expect decreases in Y, C, I, E, and M in the long run (Figure 11 has more detailed discussions). Figure 25's results show that the empirical finding is consistent with our initial hypothesis.

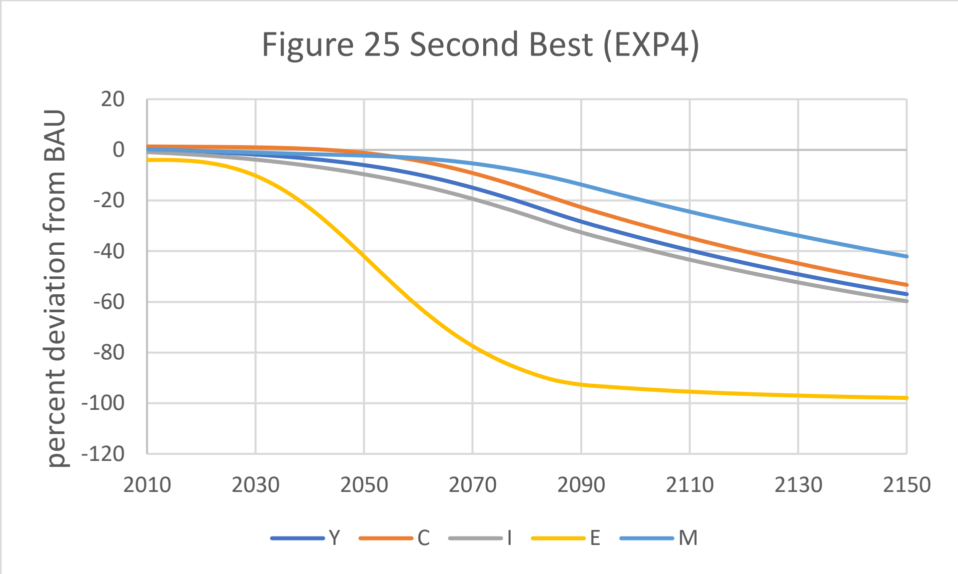
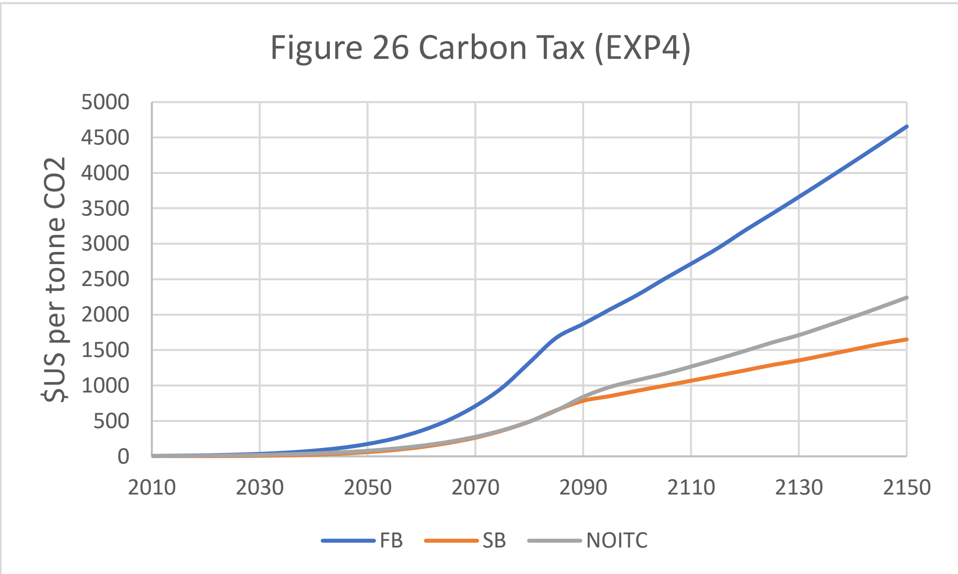


Figure 26 shows carbon tax under FB, SB, and NOITC in EXP4. We have the same expectations and analysis as discussed in Figure 8. The results show that FB has the highest carbon tax, while NOITC and SB are ranked as second and third in the long run.



1.7 Conclusion

In the present paper, we have achieved the following: (i) we fully accounted for inter-firm knowledge spillovers, and (ii) we modeled the business as usual scenario correctly by excluding the duplication externality, inter-firm spillover effects, and the environmental externality. We have the following conclusions regarding the important determinants of induced R&D: first, induced R&D is very sensitive to the elasticity of the substitution parameter. If inputs are gross complements, this will lead to decreases in R&D investments in generic materials, energy production, and a hump shape of R&D investments in energy efficiency with respect to the tax level under the first-best scenario and the second-best scenario. However, if inputs are gross substitutes, this will lead to decreases in R&D investments in energy efficiency, generic materials, and energy production under the second-best scenario, but R&D investments in generic materials will always be higher than its business as usual level under the first-best scenario.

The second conclusion has implications for duplication externality. If we compare experiment 1 and experiment 3, both experiments use lower initial energy related R&D shares, but experiment 3 internalizes duplication in the business as usual scenario. Experiment 3 shows a great role for induced R&D than experiment 1. Then, if we compare experiment 2 and experiment 4, both experiments use larger initial energy related R&D shares, but experiment 4 internalizes duplication in the business as usual scenario. Experiment 4 shows a greater role for induced R&D than experiment 2. These two sets of results indicate that the induced R&D generates a lower abatement cost reduction if we externalize duplication in the business as usual scenario.

The third conclusion regards the initial levels of energy related R&D shares. Through comparisons of the above two sets of results, higher initial levels of energy related R&D shares would create a market size effect, leading to an over-estimated contribution of induced R&D.

Fourth, we have conclusions about the inter-firm knowledge spillovers. From experiment 1 to experiment 4, the first-best scenario fully internalizes inter-firm knowledge spillovers, which leads to increases in the levels of all types of research. The second-best scenario does not internalize it, which leads to induced changes in research resulting from the carbon tax affecting pre-existing market distortions. As a result, some types of research increase while other types decrease.

The important policy implication is that the government needs to take into account the effects of important determinants of induced R&D into their costs and benefits analysis in order to address the climate change issues. Our benchmark experiment suggests that induced R&D has a limited role on the abatement cost reduction of greenhouse gas emissions, overall. First, in first-best scenario, even though in the early years, the positive effect of the research subsidies dominates the depressing effect of the excess burden. However, as the carbon tax becomes larger overtime, the negative effect of the excess burden increases and comes to dominate the research subsidies effect. Also, according to Sue Wing (2006), increasing the carbon tax level reduces the scale of fossil fuel augmenting technology, thereby reducing its mitigating effect on other variables. Therefore, in first-best scenario, the excess burden effect eventually outweighs the effect of the research subsidies. Second, in second-best scenario, the research dividend effect is not significant compared with the excess burden effect, because according to Gerlagh (2008), our calibrated values of parameters implies an adverse condition for a research dividend. Therefore, the excess burden effect dominates the research dividend effect in the long run.

Appendix

Appendix A: Calibration

Structural equations in "Steady State":

1. $\mathrm{Y} = \left(\zeta_{YM}(M)^{\frac{\sigma-1}{\sigma}} + X_1(E)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$
2. $X_1 = \zeta_{YE}\left(A_{YE}^{\pi_{YE}}\right)^{\frac{\sigma-1}{\sigma}}$
3. $\mathrm{M} = X_2\, \mathrm{Z_M}$
4. $X_2 = \varsigma_M\, \mathrm{A_{MZ}^{\pi_{MZ}}}$
5. $\mathrm{E} = X_3\, \mathrm{Z_E}$
6. $X_3 = \varsigma_E\, \mathrm{A_{EZ}^{\pi_{EZ}}}$
7. $(\mathrm{Z_M} + \mathrm{Z_E}) = \gamma \mathrm{K}^{\alpha} L^{1-\alpha}$
8. $\left(e^{\Delta g_K}\right)K = (1-\delta_k)^{\Delta}K + \Delta\left(I - \frac{\eta}{2}\frac{I^2}{K}\right)$
9. $\left(e^{\Delta g_{AYE}}\right) = \Delta\, a_{YE}\, R_{YE}^{b}\, A_{YE}^{\o-1} + 1$
10. $V_{YE} = a_{YE}R_{YE}^{b-1}\, A_{YE}^{\o}$
11. $\left(e^{\Delta g_{AMZ}}\right) = \Delta\, a_{MZ}\, R_{MZ}^{b}\, A_{MZ}^{\o-1} + 1$
12. $V_{MZ} = a_{MZ}R_{MZ}^{b-1}\, A_{MZ}^{\o}$
13. $\left(e^{\Delta g_{AEZ}}\right) = \Delta\, a_{EZ}\, R_{EZ}^{b}\, A_{EZ}^{\o-1} + 1$
14. $V_{EZ} = a_{EZ}R_{EZ}^{b-1}\, A_{EZ}^{\o}$
15. $Y \quad = C \quad + I \quad + R$
16. $\mathrm{R} = \mathrm{R_{YE}} + \mathrm{R_{MZ}} + \mathrm{R_{EZ}}$
17. $R = ss_R Y$
18. $R_{YE} = ss_{YE}R$
19. $R_{EZ} = ss_{EZ}R$
20. $\mathrm{L} = \mathrm{h_0}\, \mathrm{P_0}$

Behavioral equations in "Steady State":

21. $\beta = \frac{e^{\Delta(g_{POP}-g_C)}}{(1+\rho)^{\Delta}}$
22. $Y \; = (\frac{\mu}{\zeta_{YM}})^{\sigma} M$
23. $X_1 = q\left(\frac{E}{Y}\right)^{\frac{1}{\sigma}}$
24. $\mu X_2 = \xi$
25. $q X_3 = \xi$
26. $\Delta\left(1 - \eta\frac{I}{K}\right)\xi\gamma\alpha\left(\frac{L}{K}\right)^{1-\alpha} + (1-\delta_k)^{\Delta} + \Delta\left(\frac{\eta}{2}\frac{I^2}{k^2}\right) = \frac{1}{\beta}\frac{\left(1-\eta\frac{I}{K}\right)}{\left(1-\eta\frac{I}{K}e^{\Delta(g_K-g_I)}\right)}$
27. $\beta Y^{\frac{1}{\sigma}}X_1(E)^{\frac{\sigma-1}{\sigma}}\,\pi_{YE} = \theta_{YE}\, A_{YE}(e^{-\Delta g_{\theta YE}} - \beta)$
28. $\beta\, \mu\, \pi_{\mathrm{MZ}}M = \theta_{MZ}A_{MZ}\left(e^{-\Delta g_{\theta MZ}} - \beta\right)$
29. $\beta\, q\, \pi_{\mathrm{EZ}}E = \theta_{EZ}A_{EZ}\left(e^{-\Delta g_{\theta EZ}} - \beta\right)$
30. $\theta_{YE}\Delta\omega\, V_{YE} - 1 = 0$

31. $\theta_{MZ}\Delta\omega\, V_{MZ} - 1 = 0$
32. $\theta_{EZ}\Delta\omega\, V_{EZ} - 1 = 0$
33. $\Psi\Delta\left(1-\eta\frac{I}{K}\right) = 1$

Growth equations in "Steady state":

34. $\mathrm{g_Y} = \left(\frac{1}{\mathrm{Y}}\right)[g_\mu \mu\mathrm{M} + \mu\mathrm{M} g_M + g_q \mathrm{qE} + \mathrm{qE} g_E] = \left(\frac{\mathrm{M}}{\mathrm{Y}}\right)^{\frac{\sigma-1}{\sigma}} g_M + [1 - \left(\frac{\mathrm{M}}{\mathrm{Y}}\right)^{\frac{\sigma-1}{\sigma}}](\pi_{\mathrm{YE}}\, g_{AYE} + g_E)$
35. $\mathrm{g_M} = \pi_{\mathrm{MZ}}\ \mathrm{g_{AMZ}} + \mathrm{g_{ZM}}$
36. $\mathrm{g_E} = \pi_{\mathrm{EZ}}\ \mathrm{g_{AEZ}} + \mathrm{g_{ZE}}$
37. $\left[\frac{\mathrm{Z_M}}{\mathrm{Z_M+Z_E}}\right]\mathrm{g_{ZM}} + \left[\frac{\mathrm{Z_E}}{\mathrm{Z_M+Z_E}}\right]\mathrm{g_{ZE}} = \alpha \mathrm{g_K} + (1-\alpha)\,\mathrm{g_L}$
38. $[e^{g_K} - (1-\delta_k)]g_K K - \frac{\eta}{2}\frac{I^2}{K} g_K = I(1-\eta\frac{I}{K})g_I$
39. $(1-\phi)g_{AYE} = b g_{RYE}$
40. $g_{VYE} = (b-1)g_{RYE} + ø\, g_{AYE}$
41. $(1-\phi)g_{AMZ} = b g_{RMZ}$
42. $g_{VMZ} = (b-1)g_{RMZ} + ø\, g_{AMZ}$
43. $(1-\phi)g_{AEZ} = b g_{REZ}$
44. $g_{VEZ} = (b-1)g_{REZ} + ø\, g_{AEZ}$
45. $\mathrm{g_Y} = g_C(\frac{C}{Y}) + g_I(\frac{I}{Y}) + g_{RYE}(\frac{RYE}{Y}) + g_{RMZ}(\frac{RMZ}{Y}) + g_{REZ}(\frac{REZ}{Y})$
46. $g_R = g_{RYE}\left(\frac{R_{YE}}{R}\right) + g_{RMZ}\left(\frac{R_{MZ}}{R}\right) + g_{REZ}\left(\frac{R_{EZ}}{R}\right)$
47. $\sigma\, g_\mu + g_M = g_Y$
48. $\sigma\, g_q + g_E = (\sigma-1)\pi_{YE} g_{AYE} + g_Y$
49. $g_\mu + \pi_{MZ} g_{AMZ} = g_\xi$
50. $g_q + \pi_{EZ} g_{AEZ} = g_\xi$
51. $\xi\gamma\alpha\left(\frac{L}{K}\right)^{1-\alpha}\left[g_\xi\left(1-\eta\frac{I}{K}\right) - \eta\frac{I}{K}(g_I - g_K) - \left(1-\eta\frac{I}{K}\right)(1-\alpha)g_K\right] + \eta\left(\frac{I}{K}\right)^2(g_I - g_K) = \frac{\eta\left(\frac{I}{K}\right)(g_I-g_K)\left(e^{(g_K-g_I)}-1\right)}{\beta\left(1-\eta\frac{I}{K}e^{g_K-g_I}\right)^2}$
52. $\frac{\beta}{\sigma}Y^{\frac{1}{\sigma}}X_1(E)^{\frac{\sigma-1}{\sigma}}\pi_{YE}\left[g_y + (\sigma-1)(\pi_{YE}g_{AYE} + g_E)\right] = \theta_{YE}\, A_{YE}(e^{-g_{\theta YE}} - \beta)(g_{\theta YE} + g_{AYE})$
53. $\beta\,\mu\,\pi_{\mathrm{MZ}} M\left(g_\mu + g_M\right) = \theta_{MZ}A_{MZ}(e^{-g_{\theta MZ}} - \beta)(g_{\theta MZ} + g_{AMZ})$
54. $\beta\, q\, \pi_{\mathrm{EZ}} E\left(g_q + g_E\right) = \theta_{EZ}A_{EZ}(e^{-g_{\theta EZ}} - \beta)(g_{\theta EZ} + g_{AEZ})$
55. $g_{\theta YE} = -g_{VYE}$
56. $g_{\theta MZ} = -g_{VMZ}$
57. $g_{\theta EZ} = -g_{VEZ}$
58. $g_\Psi\left(1-\eta\frac{I}{K}\right) = \eta(g_I - g_K)\frac{I}{K}$

Table 2: Exogenous values and calibration results from bench mark scenario (EXP1)

Exogenous Parameters	**Initial Values**	**Normalized Values**	**Exogenous Growth Rates**	**Calibrated Parameters**				
$\rho = 0.03$	q = 0.1163 ten trillion US\$ 2011	$A_{YE,1} = 2$	$g_L = 0.0132$		EXP1	EXP2	EXP3	EXP4
$\delta_k = 0.1$	$P_1 = 6.7$ billion	$A_{MZ,1} = 2$	$g_{POP} = 0.0132$	σ	0.5083	1.2497	0.6451	1.1356
$\omega = 0.25$	$P_{LT} = 8.97$ billion	$A_{EZ,1} = 2$	$g_K = 0.0388$	π_{YE}	0.0279	0.7490	0.0452	1.0737
$ATM_{TGT} = 450\ ppmv$	$h_0 = 0.48$	$M_1 = 2$	$\gamma_{h,0} = 0.042$	π_{MZ}	0.1212	0.1055	0.1978	0.1450
$\eta = 2$	$Y_1 = 9.285$ ten trillion US\$ 2011	$\gamma = 1$	$-\delta_\gamma = -0.27$	π_{EZ}	0.0040	0.1170	0.0065	0.1678
$\Delta = 1, \Delta = 5$	$E_1 = 4.48$ ten $GtCO_2$			$aaYE$	3.9332	0.4805	3.9172	0.4667
$b = 0.7$	$K_1 = 32.418$ ten trillion US\$ 2011			$aaMZ$	0.1944	0.2580	0.1926	0.2593
$ø = 0.0$				$aaEZ$	15.357	1.7621	15.295	1.7113
$Share_{YE} = 0.014$				ζ_{YM}	0.2137	1.2827	0.4057	1.1338
$Share_{EZ} = 0.002$				ζ_{YE}	0.0282	0.0585	0.0382	0.0560
$Share_R = 0.021$				ς_M	0.1284	0.1104	0.1139	0.1098
$s^* = 0.643$				ς_E	5.2490	4.1254	4.8994	4.0725
				α	0.6713	0.7416	0.7004	0.7320

References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. *American Economic Review*, *102*(1), 131-66.

Cummins, J. G., Hassett, K. A., Hubbard, R. G., Hall, R. E., & Caballero, R. J. (1994). A reconsideration of investment behavior using tax reforms as natural experiments. *Brookings Papers on Economic Activity*, *1994*(2), 1-74.

Feenstra, R. C., Inklaar, R., & Timmer, M. P. (2015). The next generation of the Penn World Table. *American Economic Review*, *105*(10), 3150-82.

Fischer, C., & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management*, *55*(2), 142-162.

Gans, J. S. (2012). Innovation and climate change policy. *American Economic Journal: Economic Policy*, *4*(4), 125-45.

Gerlagh, R. (2008). A climate-change policy induced shift from innovations in carbon-energy production to carbon-energy savings. *Energy Economics*, *30*(2), 425-448.

Goulder, L. H., & Schneider, S. H. (1999). Induced technological change and the attractiveness of CO2 abatement policies. *Resource and Energy Economics*, *21*(3-4), 211-253.

Hart, R. (2008). The timing of taxes on CO2 emissions when technological change is endogenous. *Journal of Environmental Economics and Management*, *55*(2), 194-212.

Hicks John, R. (1932). The theory of wages. *London: Macmillan.*

Jaffe, A. B., Newell, R. G., & Stavins, R. N. (2005). A tale of two market failures: Technology and environmental policy. *Ecological Economics*, *54*(2-3), 164-174.

Jones, C. I. (1995). R&D-based models of economic growth. *Journal of Political Economy*, *103*(4), 759-784.

Jones, C. I., & Williams, J. C. (2000). Too much of a good thing? The economics of investment in R&D. *Journal of Economic Growth*, *5*(1), 65-85.

Shiell, L., & Lyssenko, N. (2014). Climate policy and induced R&D: How great is the effect?. *Energy Economics*, *46*, 279-294.

Massetti, E., & Nicita, L. (2010). The optimal climate policy portfolio when knowledge spills across sectors. *FEEM Working Paper 96.2010.*

Popp, D. (2004). ENTICE: endogenous technological change in the DICE model of global warming. *Journal of Environmental Economics and Management*, *48*(1), 742-768.

Rezai, A. (2011). The opportunity cost of climate policy: a question of reference. *The Scandinavian Journal of Economics*, *113*(4), 885-903.

Shittu, E., & Baker, E. (2010). Optimal energy R&D portfolio investments in response to a carbon tax. *IEEE Transactions on Engineering Management*, *57*(4), 547-559.

Wing, I. S. (2006). Induced technological change: Firm innovatory responses to environmental regulation. *Working Paper. Boston University.*

Chapter 2

Environmental Policy, Mergers and Environmental R&D with Spillovers

Abstract

Our research topic is “Environmental Policy, Mergers and Environmental R&D with Spillovers”. This project lies at the frontier between environmental economics and industrial organization. We use a duopoly setting of a three-stage game; in the first stage, the government chooses an emission tax and aims for maximizing welfare; in the second stage, firms use R&D to reduce their emissions; in the last stage, firms compete a la Cournot with differentiated products. We focus on two policy regimes and three scenarios, namely regimes of competition and merger and scenarios of commitment, non-commitment, and exogenous tax. The study focuses on two major questions: (1) what is the effect of merger on R&D, and the effect of commitment on R&D? (2) what is the effect of merger and commitment on the economy? Results are obtained through numerical simulations of the model. We find that: (i) Merger has a positive effect on R&D under non-commitment and the exogenous tax scenarios. (ii) Under commitment, if goods are imperfect substitutes or homogenous, merger has a negative effect on R&D; if goods are complements or independent, merger has a positive effect on R&D. (iii) For any types of goods under any regime, commitment has a negative effect on R&D.

2.1 Introduction

Our research topic is "Environmental Policy, Mergers and Environmental R&D with Spillovers". This project lies at the frontier between environmental economics and industrial organization. Pollution problems such as carbon emissions have become a major issue faced by modern governments. In order to solve this problem, we need to have a better understanding about the underlying mechanism that leads to carbon pollutions. This includes understanding the economic theories associated with this type of market failure, which are based on environmental economics and industrial organization. Comprehensive study in those two fields would help us to design effective policies to provide both emission-reducing incentives for major polluting industries as well as increases in overall welfare.

The related literature focuses on several different aspects of the issue. Atallah (2016) discusses the relationship between competition and innovation. Poyago-Theotoky (1999) analyzes a duopoly where firms are engaged in cost reducing R&D and then compete in quantities. Poyago-Theotoky (2007) concentrates on an industry consisting of two firms selling a homogenous product. Petrakis and Poyago-Theotoky (2002) study the impact of two technology policies of R&D subsidization and R&D cooperation, in a duopoly model with cost-reducing R&D, spillovers and pollution abatement R&D. Additionally, Ouchida and Goto (2011) summarize Poyago-Theotoky (2007): for small environmental damages and inefficient R&D technologies, R&D and welfare are both higher in the R&D cartel than under non-cooperative R&D. They also prove that Poyago-Theotoky's (2007, 2010) results are still robust in a relaxed wider parameter range of environmental damage coefficient. Ouchida and Goto (2016a) is based on Poyago-Theotoky and Teerasuwannajak (2002), and it extends this previous work by considering that the government has a pre-commitment ability to an emission tax into the model of Cournot duopolists with end-of-pipe technology. Ouchida and Goto (2016b) first assume that the regulator has no pre-commitment ability to an emission tax, then they present an examination of four types of R&D in a Cournot duopoly: environmental research joint venture cartelization, R&D competition, R&D cartelization, and environmental research joint venture competition. Following this research line, Puller (2006) analyzes the welfare consequences of the strategic use of innovation by firms to influence regulatory standards. In addition, Ramirez and Kayalica (2001) develop a reciprocal dumping model of trade to analyze the effect of mergers, in the presence of environmental policies, on welfare and the best response of the government. Fikru (2013) analyzes the welfare effect of the merger when participating firms are polluting firms. Fikru (2015) builds a theoretical model of merger process with endogenous policies to study merger decisions among polluting firms. Finally, Fikru and Gautier (2017) analyze the effect of mergers on optimal environmental taxation in a Cournot oligopoly with product differentiation.

We use a duopoly setting of a three-stage game; in the first stage, the government chooses an emission tax and aims for maximizing welfare; in the second stage, firms use R&D to reduce their emissions; in the last stage, firms compete a la Cournot with differentiated products. We focus on two policy regimes and three scenarios, namely regimes of competition and merger and scenarios of commitment, non-commitment, and exogenous tax. Commitment refers to the regulator who chooses a tax in the first stage, before the firm chooses R&D, and then the regulator commits to this tax. Non-commitment is when a firm chooses R&D in the first stage, then the regulator chooses a tax in the second stage. Past industrial merger experiences show that polluting firms have a significant share in the total value and volume of mergers, therefore it is important to study the mergers in the context of environmental regulation. In addition, simulation model suggests that the results depend on whether the government has the commitment ability to an emission tax or not, therefore it is interesting to analyze the commitment vs non-commitment scenarios. We also take into account the exogenous tax scenario since it is relevant when the tax is set based on country-wide considerations or on an international agreement, and hence is not responsive to the specific conditions of the industry under study.

The study focuses on two major questions: (1) what is the effect of merger on R&D, and the effect of commitment on R&D? (2) what is the effect of merger and commitment on the economy? Results are obtained through numerical simulations of the model. We find that: (i) Merger has a positive effect on R&D under non-commitment and the exogenous tax scenarios. (ii) Under commitment, if goods are imperfect substitutes or homogenous, merger has a negative effect on R&D; if goods are complements or independent, merger has a positive effect on R&D. (iii) For any types of goods under any regime, commitment has a negative effect on R&D.

Our paper makes the following contributions to the literature: first, our research focuses on total merger, which is cooperation at all stages. Previously, most studies have only focused on the regime of R&D cooperation. Second, our study fully considers product differentiation. This is different from major strands of the literature which only study a homogenous product. In contrast, our research considers four types of goods: complements, independent, imperfect substitutes, and homogenous. Third, our research includes three different scenarios: commitment, non-commitment, and exogenous tax. Other major studies only focus on one or two of them (e.g. Poyago-Theotoky, 1999, 2007, 2010; Petrakis and Poyago-Theotoky, 2002; and Ouchida and Goto 2011, 2014, 2016a, 2016b).

This paper is organised as follows. The following section reviews the literature and Section 3 introduces the model. The fourth section is an exploration of the model under commitment, while the fifth section is an exploration of the model under non-commitment, and the sixth section presents an examination of the model under the exogenous tax scenario. The seventh section examines Cournot duopolists' equilibrium variables between commitment and non-commitment within each policy regime. The eighth section presents the major results of the relationship between merger and R&D and the relationship between commitment and R&D. The last section presents the conclusions.

2.2 Literature Review

Atallah (2016) discusses the relationship between competition and innovation. This relationship can be analyzed through either the effect of competition on innovation outputs in terms of effective cost reduction or the effect of competition on innovation inputs in terms of R&D expenditure. For example, Vives (2008) examines this relationship through competition and innovation inputs. We also notice that competition can take two forms in his model: an increase in the number of firms as from merger to competition, and a decrease in product differentiation. Atallah's (2016) results show that, for a wide range of parameters, the relationship between competition and innovation is more often negative than positive.

Poyago-Theotoky (1999) analyzes a duopoly where firms invest in R&D and then compete in quantities, in a three-stage game of almost perfect information. In the first stage, two identical firms simultaneously choose their R&D expenditure. In the second stage, the two rivals decide how much of the knowledge created in the first stage to disclose. In the third stage, firms play a standard Cournot game, given the cost levels and spillovers achieved in the previous stages. Results show that when choosing R&D non-cooperatively, firms never disclose any of their information, whereas when choosing R&D cooperatively, firms always fully share their information. As a result, public policies should focus on encouraging pre-competitive R&D cooperation, since R&D cooperation not only leads firms to engage in more R&D in terms of increasing innovation output, but also has the beneficial effect of making firms fully disclose their information which leads to less duplication and more coordination of research activities. Firm profitability and welfare will increase correspondingly. Poyago-Theotoky (1999) shows that R&D cooperation leads to higher innovation output in terms of effective cost reduction compared with R&D competition.

Poyago-Theotoky (2007) concentrates on an industry consisting of two firms selling a homogenous product. One firm undertakes R&D to reduce pollution and receives an abatement benefit from its rival through positive spillovers. Firms choose their emission-reducing R&D non-cooperatively or cooperatively, then the regulator sets the emission tax, and firms compete in quantities. She concludes that for small damages, R&D and welfare are higher in the R&D cartel; for large damages and efficient R&D, R&D and welfare are higher under R&D competition. Poyago-Theotoky (2007) asserts that there are three policy instruments associated with three types of market failures: a pollution tax to address the environmental externality, an R&D subsidy to address the R&D market failure, and a research joint venture to correct the information-sharing market failure. Poyago-Theotoky (2007) also believes competition in an innovation market will result in two market failures: (1) if spillovers are absent, competition leads to a strategic over-investment effect; and (2) under positive spillovers, competition leads to a strategic under-investment effect. Poyago-Theotoky (2007) defines innovation output as R&D contributions towards emission reduction of harmful pollutants, and concludes that a three-stage game of quantity competition will generate a higher innovation output in R&D cartel relative to R&D competition i) if the environmental damage is low as well as ii) if there is a large damage parameter and a large R&D cost parameter.

Poyago-Theotoky (2010) shows that if there is a small damage parameter and R&D is relatively efficient, emission subsidies can partially correct for the inefficiency caused by firms' market power. Under this circumstance, the environmental externality is offset by the under-production market failure.

Poyago-Theotoky and Teerasuwannajak (2002) consider that product differentiation can play a role in the environmental policy design and implementation under both the regulator's full commitment and no commitment. In their model, they do not have spillovers and they assume production cost is zero. Their conclusions are: 1) if products are highly differentiated, the optimal no-commitment tax is always lower than the optimal pre-commitment tax. As products become more and more similar, for both a low level of efficiency parameter and a high level of damage parameter, the optimal no-commitment tax is greater than the optimal pre-commitment tax; and (2) if product differentiation is high, abatement and welfare will be higher under the no-commitment policy regime unless the efficiency parameter is extremely low. As products become less differentiated, abatement and welfare will be higher under the pre-commitment regime. Their paper uses pollution reduction as the innovation output, and by comparing competition between two policies for a given degree of product differentiation, the efficient abatement technology implies more innovation under commitment. However, as the degree of product differentiation decreases, more intensive competition leads to more innovation under non-commitment.

Petrakis and Poyago-Theotoky (2002) study the impact of two technology policies of R&D subsidization and R&D cooperation in a duopoly model with cost-reducing R&D, spillovers and pollution abatement R&D. They model two policy instruments as two different regimes and aim to compare welfare between the two technology policies. They point out that even though cost-reducing R&D could lead to firms generating less pollution per unit of output produced, there can nevertheless be a case where total pollution will still increase due to increased production. They use an exogenous tax combined with an R&D subsidy and a research joint venue to address three types of market failure: environmental externality, innovation market failure and information sharing market failure. They show two important results which are different from the conventional literature pertaining to the positive R&D subsidies and desirability of R&D cooperation: (1) if the carbon tax is exogenous and firms have cost-reducing R&D and abatement innovation, the optimal R&D subsidy can be negative. Too much cost-reducing R&D leads to more production; a negative R&D subsidy is optimal when the damage parameter is large and the exogenous tax is low; and (2) welfare comparison between the two policy regimes hinges on the spillover rate, damage parameter and tax. In most cases, welfare is higher under R&D subsidization than under R&D cooperation.

In their 2011 study, Ouchida and Goto summarize Poyago-Theotoky (2007): for small environmental damages and inefficient R&D technologies, R&D and welfare are both higher in the R&D cartel than under non-cooperative R&D. They also prove that Poyago-Theotoky's (2007, 2010) work is still robust in a relaxed wider parameter range of environmental damage coefficient. They also conclude that as the degree of product differentiation increases, the damage parameter set which guarantees an interior solution of R&D will increase as well. Their paper is different from our model in two aspects: first is the organization of R&D, where we have total merger instead of R&D cooperation; second, in Ouchida and Goto (2011), the regulator is unable to commit to an emission tax, whereas in our paper we have both scenarios of commitment and non-commitment.

Ouchida and Goto (2014) analyze the circumstances in which a negative emission tax occurs and reduces emissions. Several findings are illustrated, including: (1) an emission subsidy under R&D cartelization increases welfare compared with *laissez-faire*, (2) a very small environmental damage parameter implies a negative equilibrium emission tax. The economic intuition is as follows: an emission subsidy is equivalent to the policy combination of a production subsidy and an abatement tax, since pollution is generated by the firm's production minus net abatements. A production subsidy consists of two effects of damage-increasing effect and decreasing effect of market inefficiency. When damage is sufficiently small, the damage-increasing effect is dominated by the improvement in market inefficiency; and (3) if the damage parameter is sufficiently small and R&D cost is low, total emissions under a non-commitment emission subsidy policy are lower than under *laissez-faire*, i.e., the emission subsidy has an emission-reducing effect. The economic intuition underlying the emission-reducing effect is that the emission-increasing effect is dominated by the large abatement effect.

The study of Ouchida and Goto (2016a) is based on Poyago-Theotoky and Teerasuwannajak (2002). It expands on this previous work by considering that the government has a pre-commitment ability to an emissions tax into the model of Cournot duopolists with end-of-pipe technology. Then, they study the model's effects on welfare and other equilibrium values of variables under R&D cartelization and R&D competition. The following conclusions are made: (1) if the spillover parameter is positive, the regulator always prefers R&D cartelization to R&D competition; (2) although environmental research joint venture cartelization creates certain social and private incentives for firms, it cannot guarantee maximum consumer surplus; (3) a large damage parameter and a small R&D cost parameter guarantee that environmental research joint venture cartelization is socially efficient from both a consumer surplus and welfare point of view; and (4) under positive spillovers, Cournot duopolists competition with R&D cartelization generates more innovation outputs in terms of abatements.

Ouchida and Goto (2016b) assume that a regulator has no pre-commitment ability to an emission tax, then examine four types of R&D in a Cournot duopoly: environmental research joint venture cartelization, R&D competition, R&D cartelization, and environmental research joint venture competition. After that, they present a comprehensive evaluation of the welfare performance of the four R&D formations and examine the government's competition policy, concluding that: (1) a large damage parameter and a low R&D cost parameter imply that R&D competition is better than other scenarios in terms of welfare; (2) with a high damage parameter and a high R&D cost parameter, environmental research joint venture cartelization is the optimal policy; (3) environmental research joint venture cartelization yields higher profits; and (4) despite the fact that Japanese antitrust authorities give a slight degree of tolerance to environmental research joint venture cartelization, their paper nevertheless shows that environmental research joint venture cartelization generates welfare benefits and therefore these policy implications should apply to current antitrust policy systems.

Puller (2006) analyzes the welfare consequences of the strategic use of innovation by firms to influence regulatory standards. Environmental regulators may not be able to commit to a specific standard for a certain industry, which would strategically affect firms' behavior. Furthermore, polluting firms may have incentives to suppress R&D innovation to force the regulator to lower the corresponding environmental standard. This strategic movement even lowers welfare. Puller (2006) has illustrated a countervailing incentive, which is that firms would have heightened incentives to make environmental innovation in order to increase the regulator's standards and raise the rival's costs. As a result, a regulator who is unable to commit to an environmental standard can induce more environmental innovation than a regulator with a commitment mechanism.

Ramirez and Kayalica (2001) develop a reciprocal dumping model of trade to analyze the effect of mergers in the presence of environmental policies on welfare and the best response of the government. In a reciprocal dumping model of trade, when the government uses a pollution quota restriction, a local merger will reduce local welfare. The optimal response of the domestic government to compensate the negative effect of the merger on welfare is to decrease its pollution quota. Similarly, when the government uses an environmental policy instrument as a pollution tax restriction, a local merger will reduce local welfare as well. The optimal response of the domestic government is to increase its pollution tax. The magnitude of the negative effect of the merger depends on the parameters of the marginal disutility from pollution and the cost of pollution abatement. Also, these parameters play a role in determining the response to mergers from the government. If the marginal disutility from pollution is small, then the government compensates the monopolistic distortion caused by mergers by strengthening the pollution policy. If the marginal disutility is large, the government may not respond to mergers.

Past industrial merger experiences show that polluting firms have a significant share in the total value and volume of mergers. Fikru (2013) analyzes the welfare effect of the merger when participating firms are polluting firms. A profitable merger can either reduce or increase welfare, depending on the flexibility of environmental policy. Under a passive environmental policy (that is, given a fixed emission tax), the merger decreases welfare. The merger leads to higher prices, lower consumer surplus, and higher industry profits. The merger also leads to lower emission and tax revenue. As a result, the merger decreases welfare due to the reduction in consumer surplus, and lower tax revenue dominates the increase in profit and utility. Under an active environmental policy, policy can adjust to changes in the market structure, making it possible for the merger to be welfare-enhancing. The total effect of the merger on welfare can be expressed as the sum of the direct effect on welfare and the indirect effect through the emission tax. The gain in welfare comes from lower emissions, efficiency gains, higher consumer surplus, and lower tax costs. It is especially important that the post-merger lower emission tax offsets the price-increasing effect.

Fikru (2015) builds a theoretical model of the merger process with endogenous policies to study merger decisions among polluting firms. After the occurrence of the merger, the government adjusts the optimal policy correspondingly, which leads to post-merger optimal policies that are different from pre-merger optimal policies. Fikru (2015) finds that the endogenous policy post-merger provides additional incentives for firms to merge, because post-merger policies provide a lower optimal emission tax and a higher subsidy, which is more profitable. Fikru’s (2015) results show that even though the primary goal of environmental policy is to reduce pollution, it also has an impact on market structure by influencing firms’ decision to merge. The optimal merger is among two highly polluting firms. As a result, in the post-merger market, the merged entity is dirtier compared to a non-merged firm. The important policy implication is that anti-trust agencies need to incorporate environmental variables in their decisions when reviewing the merger proposals involving polluting firms.

Fikru and Gautier (2017) analyze the effect of mergers on optimal environmental taxation in a Cournot oligopoly with product differentiation. Their chief result is that the adjustment in emission tax crucially depends on the relative post-merger output distortion and pollution intensities. That is, (1) if the product differentiation parameter is between 0 and 1, the pollution intensity coefficient post-merger compared with the pre-merger is relatively small, and post-merger has lower pollution damage, then the optimal tax post-merger is smaller than pre-merger; (2) if the product differentiation parameter is between 0 and 1, the pollution intensity coefficient post-merger compared with pre-merger is relatively large, and post-merger has higher output distortion, then the optimal tax post-merger is smaller than pre-merger; (3) if products are independent, the pollution intensity coefficient post-merger is larger than pre-merger, and pollution abatement via tax is small, then the optimal tax post-merger is larger than pre-merger; (4) if products are homogenous, the pollution intensity coefficient post-merger is larger, and the merger exacerbates output distortion, then the optimal tax post-merger is larger than pre-merger; and (5) if products are independent and the pollution intensity coefficient post-merger is the same as pre-merger, then the optimal tax post-merger is the same as pre-merger. However, the purpose of their paper is to compare tax policy pre- and post-merger, and therefore it does not compare other important variables. Also, their paper does not take into account the influence of R&D. In our approach, we explore the role of all variables such as tax, R&D, output, profit, R&D spending, pollution reduction, pollution, and welfare.

Our paper makes the following contributions to the literature: first, our research focuses on total merger, which is cooperation at all stages. Previously, most studies have only focused on R&D cooperation. Second, our study fully considers product differentiation. This is different from major strands of the literature which only study a homogenous product. In contrast, our research considers four types of goods: complements, independent, imperfect substitutes, and homogenous. Third, our research includes three different scenarios: commitment, non-commitment, and exogenous tax. Other major studies only focus on one or two of them (e.g. Poyago-Theotoky, 1999, 2007, 2010; Petrakis and Poyago-Theotoky, 2002; and Ouchida and Goto 2011, 2014, 2016a, 2016b).

2.3 The Model

The model used is a duopoly model with product differentiation. Each firm produces one differentiated product and generates pollution. The government uses an emission tax t as an environmental policy instrument. Each firm makes an R&D investment for pollution reduction[1] and R&D spillovers exist between firms. R&D takes the form of pre-competitive R&D: pre-competitive R&D is done before product market competition. There are three stages in this game: the government chooses the emission tax, firms choose R&D, and firms compete in output. There are two policy regimes and three scenarios. The first regime is competition at all stages, where both firms act non-cooperatively, and each firm chooses R&D and output to maximize its profit. The second regime is merger, where all decisions maximize joint profit. After the merger, the new entity continues to produce two products. In each regime,

[1] The benchmark case of pollution reduction is no tax and no R&D. If there is a tax, there is pollution reduction.

there are three scenarios: (1) the regulator is able to commit to an emission tax, (2) the regulator is unable to commit to an emission tax, and (3) the emission tax is exogenous. Commitment refers to the regulator who chooses a tax in the first stage, before the firm chooses R&D, and then the regulator commits to this tax. Non-commitment is when a firm chooses R&D in the first stage, then the regulator chooses a tax in the second stage. Our goal is (1) to study the effect of merger on innovation and the effect of commitment on innovation; and (2) to study the effect of merger and of commitment on the economy in terms of R&D spending, pollution reduction, pollution, welfare and other variables.

Specifically: Two firms ($i \; and \; j$) are engaged in quantity competition. The firms are selling differentiated goods. Each firm faces a linear demand as

$$p_i\left(q_i , q_j\right) = a - \left(q_i + \theta\, q_j\right), (i, j = 1, 2;\; i \neq j), \tag{1}$$

where $a > 0$ is a market size parameter. Product differentiation is captured by $\theta \epsilon (-1,1]$. If $\theta \in (-1,0)$ products are complements; if $\theta = 0$ products are independent; if $\theta \in (0,1)$ products are imperfect substitutes; if $\theta = 1$ products are homogenous.

Both firms have the same cost structure of

$$C\,(q_i) = c\, q_i. \tag{2}$$

Both firms use end-of-pipe technologies as their emissions-reducing technology. [2] End-of-pipe technologies abate emissions by adsorbing emissions at the end of the production process.

R&D and the cost structure include the following features: the value of each firm's emissions per unit of output is assumed to be one. Firm i's R&D effort is denoted as z_i. R&D effort means firm i can abate its emissions as z_i units. Firm i receives benefits both from its own R&D efforts and from efforts of its rival. Poyago-Theotoky (1999, 2007, 2010) and Ouchida and Goto (2011, 2014, 2016a, 2016b) assume the R&D expenditure function is quadratic, our research follows this path. We assume the R&D expenditures for firm i is increasing in z_i. For z_i units of abatement the associated R&D expenditures for firm i are defined as

$$\left(\frac{\gamma}{2}\right) z_i^2. \tag{3}$$

A lower value of ɣ implies a higher efficiency of R&D, where $\gamma > 0$.

[2] Petroleum and chemical industries typically have end-of-pipe technologies for pollution abatement such as desulfurization equipment and denitrification equipment.

The spillover effect of R&D is $\beta \epsilon [0,1]$. Firm i's positive externality from the rival's R&D efforts is denoted as βz_j. The emission function is

$$e_i (q_i, z_i) = q_i - z_i - \beta z_j. \tag{4}$$

Firm i can abate its emissions from q_i to e_i.

The representative consumer's utility function is

$$U (q_i, q_j) = a (q_i + q_j) - (\frac{1}{2}) (q_i^2 + 2\theta q_i q_j + q_j^2) + m, \tag{5}$$

where m denotes the consumption of a numeraire good. Consumer's utility function does not include pollution effects.

As derived in the Appendix, consumer surplus is given by

$$CS = \left(\frac{1}{2}\right) \left(q_i^2 + 2\theta q_i q_j + q_j^2\right). \tag{6}$$

Total producers' profit is given by

$$Profit = \pi_i + \pi_j, \tag{7}$$

where π_i is defined as

$$\pi_i = p_i \left(q_i , q_j\right) q_i - c\, q_i - t\left(q_i - z_i - \beta z_j\right) - \left(\frac{\gamma}{2}\right) z_i^2, (i, j = 1, 2;\ i \neq j). \tag{8}$$

Emissions cause environmental damage. The environmental damage is

$$D(E) = (\frac{d}{2}) E^2, \tag{9}$$

where E is defined as

$$E = e_i + e_j, \tag{10}$$

and d represents the damage parameter. Government tax revenue is equal to

$$Tax\ Revenue = t\, E. \tag{11}$$

Welfare is defined as

$$W = CS + Profit - Damage + Tax\ Revenue. \tag{12}$$

Based on the welfare function, emission tax is a transfer between firms and the government. That is why in the welfare function, firms' tax expenditures and government's tax revenue cancel out. The tax doesn't have a direct effect on welfare, but it still plays a role because in equilibrium, R&D depends on the emission tax, so changing the emission tax will change R&D, output and pollution.

Under competition, if a regulator is able to commit to an emission tax, in the first stage, the regulator determines the emission tax t to maximize welfare. In the second stage, each firm i determines z_i to maximize its profit π_i. In the third stage, firm i determines output q_i noncooperatively to maximize its profit. Under merger, in the first stage, the regulator determines the emission tax t to maximize welfare. In the second stage, the merged entity determines z_i and z_j to maximize profit π_M . In the third stage, the merged entity determines outputs q_i and q_j to maximize profit π_M. As a result, competition is about competition at all stages, and the merger represents all decisions made to maximize the merged firm's profit.

We also have three scenarios: (1) the regulator is able to commit to an emission tax; (2) the regulator is unable to commit to an emission tax; and (3) the emission tax is exogenous. We are going to make comparisons of equilibrium variables between merger and competition to show the effect of the merger; and comparisons of equilibrium variables between commitment and non-commitment to show the effect of commitment.

2.4 Commitment

2.4.1 Competition

We start our analysis from the competition regime and under commitment. In the first stage, the regulator chooses the emission tax t to maximize welfare. In the second stage, each firm i determines z_i to maximize its profit π_i. In the third stage, firm i determines output q_i noncooperatively to maximize its profit.

In Stage 3, each firm chooses its output to maximize its profit.

$$\pi_1 = \big(a - (q_1 + \theta\, q_2)\big)q_1 - c\, q_1 - (q_1 - z_1 - \beta\, z_2)t - \left(\frac{\text{Ɣ}}{2}\right) z_1^2 \tag{13}$$

$$\pi_2 = \big(a - (q_2 + \theta\, q_1)\big)q_2 - c\, q_2 - (q_2 - z_2 - \beta\, z_1)t - \left(\frac{\text{Ɣ}}{2}\right) z_2^2 \tag{14}$$

From the first-order conditions, we get equilibrium outputs: [3]

$$q_1 = q_2 = \frac{a-c-t}{2+\theta} \tag{15}$$

[3] Second-order conditions for maximization is satisfied and proved in Appendix.

The equilibrium outputs decrease with emission tax, marginal cost, and product differentiation parameter but increase with market size.

In Stage 2, each firm chooses its R&D to maximize its profit. By substituting (15) into (13) and (14) we obtain profit functions for firms.

$$\pi_1 = -\frac{z_1^2\gamma}{2} - \frac{c(a-c-t)}{2+\theta} - t\left(-z_1 - z_2\beta + \frac{a-c-t}{2+\theta}\right) + \frac{(a-c-t)(a-\frac{(a-c-t)(1+\theta)}{2+\theta})}{2+\theta} \tag{16}$$

$$\pi_2 = -\frac{z_2^2\gamma}{2} - \frac{c(a-c-t)}{2+\theta} - t\left(-z_2 - z_1\beta + \frac{a-c-t}{2+\theta}\right) + \frac{(a-c-t)(a-\frac{(a-c-t)(1+\theta)}{2+\theta})}{2+\theta} \tag{17}$$

The first-order conditions engender equilibrium R&D.[4]

$$z_1 = z_2 = \frac{t}{\gamma} \tag{18}$$

R&D increases with the tax (the tax increases the private gain from R&D) and decreases with research costs.

In Stage 1, the regulator determines the emission tax t to maximize welfare. The welfare function has four components: consumer surplus (CS), producer surplus (Profit), environmental damage (D), and tax revenue.

$$CS = \left(\frac{1}{2}\right)(q_1^2 + 2\theta q_1 q_2 + q_2^2) \tag{19}$$

$$Profit = \pi_1 + \pi_2 \tag{20}$$

$$D = \left(\frac{d}{2}\right)\left((q_1 - z_1 - \beta z_2) + (q_2 - z_2 - \beta z_1)\right)^2 \tag{21}$$

$$Tax\ Revenue = t\left((q_1 - z_1 - \beta z_2) + (q_2 - z_2 - \beta z_1)\right) \tag{22}$$

$$W = \left(\frac{1}{2}\right)(q_1^2 + 2\theta q_1 q_2 + q_2^2) + \pi_1 + \pi_2 - (\left(\frac{d}{2}\right)\left((q_1 - z_1 - \beta z_2) + (q_2 - z_2 - \beta z_1)\right)^2) +$$
$$t\left((q_1 - z_1 - \beta z_2) + (q_2 - z_2 - \beta z_1)\right) \tag{23}$$

By substituting (15) and (18) into (23) we can get welfare in terms of t and other parameters:

$$W = -\frac{t^2}{\gamma} - \frac{2c(a-c-t)}{2+\theta} - \frac{1}{2}\left(\frac{2(a-c-t)^2(1+\theta)}{(2+\theta)^2}\right) + t\left(-\frac{2t(1+\beta)}{\gamma} + \frac{2(a-c-t)}{2+\theta}\right) - \frac{1}{2}d\left(-\frac{2t(1+\beta)}{\gamma} + \frac{2(a-c-t)}{2+\theta}\right)^2 -$$
$$2t\left(-\frac{t(1+\beta)}{\gamma} + \frac{a-c-t}{2+\theta}\right) + \frac{2(a-c-t)(a-\frac{(a-c-t)(1+\theta)}{2+\theta})}{2+\theta} \tag{24}$$

[4] Second-order conditions for maximization is satisfied and proved in Appendix.

The regulator maximizes W through t by setting $\frac{\partial W}{\partial t} = 0$. Then, the first-order condition yields the equilibrium tax t.[5]

$$t = \frac{(a-c)\gamma(-\gamma+2d(2+\gamma+\theta+\beta(2+\theta)))}{2d(2+\gamma+\theta+\beta(2+\theta))^2+\gamma(\gamma(1+\theta)+(2+\theta)^2)} \tag{25}$$

As a result, equilibrium values z_1, z_2, q_1, q_2 are:[6]

$$z_1 = z_2 = \frac{(a-c)(-\gamma+2d(2+\gamma+\theta+\beta(2+\theta)))}{2d(2+\gamma+\theta+\beta(2+\theta))^2+\gamma(\gamma(1+\theta)+(2+\theta)^2)} \tag{26}$$

$$q_1 = q_2 = -\frac{-a+c+\frac{(a-c)\gamma(-\gamma+2d(2+\gamma+\theta+\beta(2+\theta)))}{2d(2+\gamma+\theta+\beta(2+\theta))^2+\gamma(\gamma(1+\theta)+(2+\theta)^2)}}{2+\theta} \tag{27}$$

2.4.2 Merger

If the regulator is able to commit to an emission tax, under merger, in the first stage, the regulator determines the emission tax t to maximize welfare. In the second stage, the merged entity determines z_i and z_j to maximize profit π_M. In the third stage, the merged entity determines outputs q_i and q_j to maximize profit π_M.

Profit is given by:

$$\pi_M = (a-(q_1+\theta q_2))q_1 - c\,q_1 - (q_1 - z_1 - \beta z_2)t - \left(\frac{\gamma}{2}\right) z_1^2 + (a-(q_2+\theta q_1))q_2 - c\,q_2 - (q_2 - z_2 - \beta z_1)t - \left(\frac{\gamma}{2}\right) z_2^2 \tag{28}$$

From the first-order conditions, we get equilibrium output.[7]

$$q_1 = q_2 = \frac{a-c-t}{2(1+\theta)} \tag{29}$$

The equilibrium outputs decrease with emission tax, marginal cost, and product differentiation parameter but increase with market size.

In Stage 2, the merged firm chooses environmental R&D z_1 and z_2 to maximize profit π_M. By substituting (29) into (28) we get profit as a function of R&D:

[5] Second-order conditions for maximization is satisfied and proved in Appendix.
[6] The Appendix provides more details of the results of sections 4.1 and 4.2.
[7] Second-order conditions for maximization is satisfied and proved in Appendix.

$$\pi_M = -\frac{\gamma(z_1^2+z_2^2)}{2} - \frac{c(a-c-t)}{1+\theta} - t\left(-\mathrm{z}_2 - \mathrm{z}_1\beta + \frac{a-c-t}{2(1+\theta)}\right) - t\left(-\mathrm{z}_1 - \mathrm{z}_2\beta + \frac{a-c-t}{2(1+\theta)}\right) + \frac{(a-c-t)(a-\frac{(a-c-t)(1+\theta)}{2(1+\theta)})}{1+\theta} \quad (30)$$

Solving the two first-order conditions $\frac{\partial \pi_M}{\partial z_1} = 0$ and $\frac{\partial \pi_M}{\partial z_2} = 0$ yields equilibrium R&D:[8]

$$z_1 = z_2 = \frac{t+t\beta}{\gamma} \quad (31)$$

R&D increases with the tax and spillovers and decreases with research costs. As spillovers increase, firm internalizes R&D leads to more R&D.

In Stage 1, the regulator determines the emission tax t to maximize welfare. We have four components in the welfare function: consumer surplus (CS), producer surplus (Profit), environmental damage (D), and tax revenue. Functions are identical to (19)-(23).

By substituting (29) and (31) into (23), we can get the welfare function in terms of t and other parameters:

$$W = -\frac{(t+t\beta)^2}{\gamma} - \frac{c(a-c-t)}{1+\theta} + \frac{1}{2}\left(\frac{(a-c-t)^2(1+\theta)}{2(1+\theta)^2}\right) + t\left(\frac{(-2-2\beta)(t+t\beta)}{\gamma} + \frac{a-c-t}{1+\theta}\right) - \frac{1}{2}d\left(\frac{(-2-2\beta)(t+t\beta)}{\gamma} + \frac{a-c-t}{1+\theta}\right)^2 - 2t\left(\frac{(-1-\beta)(t+t\beta)}{\gamma} + \frac{a-c-t}{2(1+\theta)}\right) + \frac{(a-c-t)(a-\frac{(a-c-t)(1+\theta)}{2(1+\theta)})}{1+\theta} \quad (32)$$

The regulator maximizes W through t by setting $\frac{\partial W}{\partial t} = 0$. Then, the first-order condition yields the equilibrium tax t:[9]

$$t = \frac{(a-c)\gamma(-\gamma(1+\theta)+2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta)))}{2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta+4\beta(2+\beta)(1+\theta))} \quad (33)$$

Therefore, we can solve for equilibrium values of R&D and output:

$$z_1 = z_2 = \frac{(a-c)(1+\beta)(-\gamma(1+\theta)+2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta)))}{2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta+4\beta(2+\beta)(1+\theta))} \quad (34)$$

$$q_1 = q_2 = -\frac{-a+c+\frac{(a-c)\gamma(-\gamma(1+\theta)+2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta)))}{2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta+4\beta(2+\beta)(1+\theta))}}{2(1+\theta)} \quad (35)$$

[8] Second-order conditions for maximization is satisfied and proved in Appendix.
[9] Second-order conditions for maximization is satisfied and proved in Appendix.

2.4.3 Comparison

In this section, we analyze the effect of the merger on innovation; therefore, we put numerical values for parameters to compare each variable between merger and competition under commitment. By setting $A = a - c = 1000,\ \gamma = 100,\ d = 1$, and $\beta = 0.2$ we consider different levels of product differentiation, θ.

***Proposition* 1:**

(1) When goods are complements ($\theta = -0.5$), the merger increases emission tax, R&D, output, pollution reduction, pollution, and welfare. However, the merger decreases profit.

(2) When goods are independent ($\theta = 0$), the merger increases R&D, output, profit, pollution reduction, and welfare. However, the merger decreases emission tax and pollution.

(3) When goods are imperfect substitutes ($\theta = 0.5$) or homogenous ($\theta = 1$), the merger increases profit but reduces emission tax, R&D, output, pollution reduction, pollution, and welfare.

Table 1. Goods are complements ($\theta = -0.5$) under commitment.

	Merger	**Competition**
t	594.305	399.207
$z_1 = z_2$	7.13166	3.99207
$q_1 = q_2$	405.695	400.529
Industry Profit	169674.2	323078
Pollution Reduction	17.116	9.58096
R&D Spending	5086.06	1593.66
Pollution Level, MSD[10]	794.273	791.477
Welfare	408574	406035

As illustrated by table 1, when goods are complements, the merger increases output, which leads to higher pollution and higher marginal social damage. Higher marginal social damage leads to a higher emission tax. Since the emission tax is higher under merger, equation (31) implies that $\frac{\partial z_i}{\partial t} = \frac{1+\beta}{\gamma} > 0$, meaning that firms will invest more in R&D. The merged entity internalizes the R&D spillovers, which leads to more R&D. Higher R&D implies a larger pollution reduction under merger. Profit is much lower

[10] MSD represents the marginal social damage.

under merger due to the higher emission tax, higher pollution and higher R&D expenditure.[11] A higher value of welfare is generated under merger due to a higher consumer surplus (due to higher output). If goods are complements, then merger is not profitable because it increases output and emission tax.

Table 2. Goods are independent ($\theta = 0$) under commitment.

	Merger	**Competition**
t	333.159	334.061
$z_1 = z_2$	3.99791	3.34061
$q_1 = q_2$	333.42	332.97
Industry Profit	223936	223300
Pollution Reduction	9.59498	8.01746
R&D Spending	1598.33	1115.97
Pollution Level, MSD	657.246	657.922
Welfare	338087	337524

As illustrated by table 2, when goods are independent, the merger increases output and R&D. The merged entity internalizes the R&D spillovers, which leads to more R&D. More R&D means that firms want to reduce their emission tax expenditure, which yields more pollution reduction and less pollution. Lower pollution leads to lower marginal social damage and a lower tax. Profit is higher under merger due to larger operational profit, lower emission tax and pollution. A higher value of welfare is generated under merger because of higher consumer surplus, higher profit, and lower damage.

Table 3. Goods are imperfect substitutes ($\theta = 0.5$) under commitment.

	Merger	**Competition**
t	154.067	287.707
$z_1 = z_2$	1.84881	2.87707
$q_1 = q_2$	281.978	284.917
Industry Profit	238876	163514.4
Pollution Reduction	4.43713	6.90498
R&D Spending	341.808	827.755
Pollution Level, MSD	559.518	562.929
Welfare	287816	288795

[11] Since profit goes down with merger, in this case firms have no incentive to merge.

Table 4. Goods are homogenous ($\theta = 1$) under commitment.

	Merger	**Competition**
t	25.7866	253.034
$z_1 = z_2$	0.309439	2.53034
$q_1 = q_2$	243.553	248.989
Industry Profit	237282	124887.2
Pollution Reduction	0.742654	6.07281
R&D Spending	9.57527	640.26
Pollution Level, MSD	486.364	491.905
Welfare	250186	252361

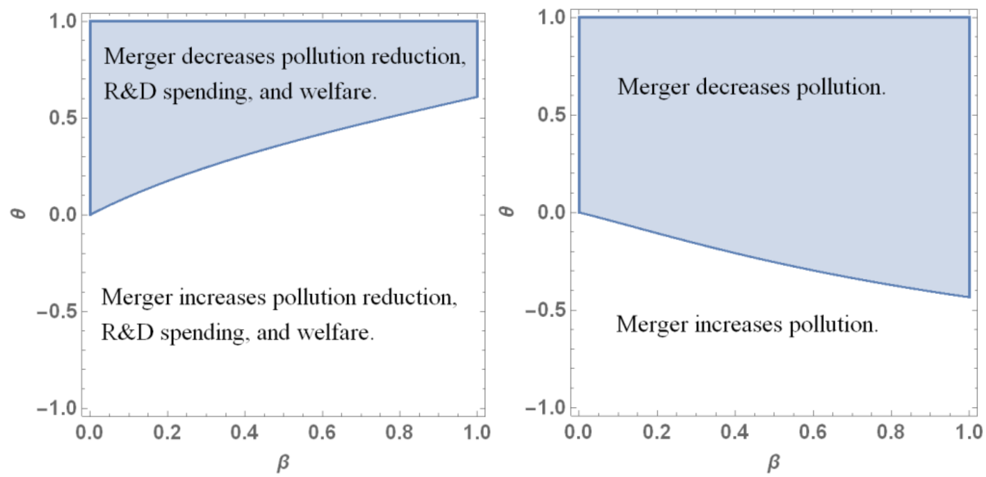
As illustrated by tables 3 and 4, when goods are imperfect substitutes or homogenous, the merger increases profit but decreases output. Lower output implies lower pollution. Lower pollution implies a lower value of marginal social damage, which further leads to reductions in the emission tax and R&D. Under merger, lower R&D implies lower pollution reduction. Profit is much higher under merger due to lower emission tax, lower pollution and lower R&D expenditure. As indicated in Figure 1, the merger generates lower welfare, because the merger generates lower consumer surplus, when $\beta = 0.2$, with $\theta = 0.5$ or $\theta = 1$.

We use a set of graphs to illustrate the effect of the merger on the economy under commitment.

There are five parameters in our model: (1) $\beta \in (0,1)$. (2) $\gamma > 0$, which is fixed at 100. (3) $\theta \in (-1,1]$. (4) We fix the damage parameter $d = 1$. (5) Let $A \equiv a - c > 0$, and fix it as $A = 1000$.

We focus on pollution reduction, R&D spending, pollution, and welfare. Under different levels of $\beta \in (0,1)$, $\theta \in (-1,1]$, there is one frontier and two regions in each graph: the white region indicates that the merger increases the value of that variable, and the blue region indicates that the merger decreases the value of that variable, compared with competition. The figures also summarize the effect of $\beta \in (0,1)$ and $\theta \in (-1,1]$, where β is represented on the horizontal axis, and θ is represented on the vertical axis.

Figure 1. Pollution reduction, R&D spending, pollution, and welfare under commitment.



If there is no merger, the spillovers only affect pollution, but they do not affect R&D costs or competition between firms. Merger internalizes the spillovers and the merged entity wants to invest more in R&D. As β increases the benefits from the merger become higher compared with competition. For given θ, as β increases, merger increases pollution reduction, R&D spending, and welfare, while decreasing pollution.

2.5 Non-Commitment

2.5.1 Competition

In this section, we focus on competition under non-commitment. In the first stage, each firm i chooses z_i to maximize its profit π_i. In the second stage, the regulator determines the emission tax t to maximize welfare. In the third stage, firm i chooses output q_i noncooperatively to maximize its profit.

In Stage 3, given the values of R&D and tax in previous stages, firm i determines output q_i noncooperatively to maximize its profit, and we get identical profit equations as (13) and (14), and equilibrium output results as (15).[12]

$$q_1 = q_2 = \frac{a-c-t}{2+\theta} \tag{15}$$

The equilibrium outputs decrease with emission tax, marginal cost, and product differentiation parameter but increase with market size.

[12] Second-order conditions for maximization is satisfied and proved in Appendix.

In Stage 2, the regulator determines the optimal tax t to maximize welfare (23). By substituting (15) into (23), we get the welfare function in terms of $z_1,\ z_2$ and t:

$$W = -\frac{\gamma(z_1^2+z_2^2)}{2} - \frac{2c(a-c-t)}{2+\theta} - \frac{1}{2}\left(\frac{2(a-c-t)^2(1+\theta)}{(2+\theta)^2}\right) + t\left(-(z_1+z_2)(1+\beta) + \frac{2(a-c-t)}{2+\theta}\right) - \frac{1}{2}d\left(-(z_1+z_2)(1+\beta) + \frac{2(a-c-t)}{2+\theta}\right)^2 - t\left(-z_2 - z_1\beta + \frac{a-c-t}{2+\theta}\right) - t\left(-z_1 - z_2\beta + \frac{a-c-t}{2+\theta}\right) + \frac{2(a-c-t)(a-\frac{(a-c-t)(1+\theta)}{2+\theta})}{2+\theta} \tag{36}$$

The regulator maximizes W through t by setting $\frac{\partial W}{\partial t} = 0$. Then, the first-order condition yields the equilibrium tax t:[13]

$$t = \frac{c-2cd+a(-1+2d)-d(z_1+z_2)(1+\beta)(2+\theta)}{1+2d+\theta} \tag{37}$$

The equilibrium tax decreases with spillovers and R&D efforts. Increase in spillovers leads to more R&D, that implies lower marginal social damage, as a result, the equilibrium tax decreases.

In Stage 1, firm i chooses R&D z_i noncooperatively to maximize its profit. By substituting (15) and (37) into (13) and (14), we obtain profit functions in terms of $z_1,\ z_2$:

$$\pi_1 = -\frac{z_1^2\gamma}{2} + \frac{c(-a+c-d(z_1+z_2)(1+\beta))}{1+2d+\theta} + \frac{(a-c+d(z_1+z_2)(1+\beta))(2ad+c(1+\theta)-d(z_1+z_2)(1+\beta)(1+\theta))}{(1+2d+\theta)^2} + \frac{(a-2ad+c(-1+2d)+d(z_1+z_2)(1+\beta)(2+\theta))(a-c+z_1(-1+d(-1+\beta)-\theta)-z_2(d(-1+\beta)+\beta+\beta\theta))}{(1+2d+\theta)^2} \tag{38}$$

$$\pi_2 = -\frac{z_2^2\gamma}{2} + \frac{c(-a+c-d(z_1+z_2)(1+\beta))}{1+2d+\theta} + \frac{(a-c+d(z_1+z_2)(1+\beta))(2ad+c(1+\theta)-d(z_1+z_2)(1+\beta)(1+\theta))}{(1+2d+\theta)^2} - \frac{(-a+c+d(z_1-z_2)(-1+\beta)+(z_2+z_1\beta)(1+\theta))(a-2ad+c(-1+2d)+d(z_1+z_2)(1+\beta)(2+\theta))}{(1+2d+\theta)^2} \tag{39}$$

Solving $\frac{\partial \pi_1}{\partial z_1} = 0$ and $\frac{\partial \pi_2}{\partial z_2} = 0$ yields equilibrium R&D:[14]

$$z_1 = z_2 = \frac{(a-c)(-1-\theta+2d(1+2d+\beta+\theta))}{\gamma(1+\theta)^2+2d^2(2(2+2\beta+\gamma)+(1+\beta)(3+\beta)\theta)+d(1+\theta)(6+4\gamma+3\theta+\beta(4+\beta)(2+\theta))} \tag{40}$$

Therefore, we can obtain equilibrium values of emission tax and output:[15]

$$t = \frac{c-2cd+a(-1+2d)-\frac{2(a-c)d(1+\beta)(2+\theta)(-1-\theta+2d(1+2d+\beta+\theta))}{\gamma(1+\theta)^2+2d^2(2(2+2\beta+\gamma)+(1+\beta)(3+\beta)\theta)+d(1+\theta)(6+4\gamma+3\theta+\beta(4+\beta)(2+\theta))}}{1+2d+\theta} \tag{41}$$

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[13] Second-order conditions for maximization is satisfied and proved in Appendix.
[14] Second-order conditions for maximization is satisfied and proved in Appendix.
[15] The Appendix provides more details of the results of sections 5.1 and 5.2.

$$q_1 = q_2 = \frac{(a-c)(\gamma+2d((1+\beta)(2+2d+\beta)+\gamma)+(d(1+\beta)(3+\beta)+\gamma)\theta)}{\gamma(1+\theta)^2+2d^2(2(2+2\beta+\gamma)+(1+\beta)(3+\beta)\theta)+d(1+\theta)(6+4\gamma+3\theta+\beta(4+\beta)(2+\theta))} \tag{42}$$

2.5.2 Merger

In the first stage, the merged firm determines z_1 and z_2 to maximize profit π_M. In the second stage, the regulator determines the emission tax t to maximize welfare. In the third stage, the merged firm determines q_1 and q_2 to maximize profit π_M.

In Stage 3, the merged firm chooses outputs to maximize profit π_M. Maximizing (28) over outputs yields:[16]

$$q_1 = q_2 = \frac{a-c-t}{2(1+\theta)} \tag{29}$$

The equilibrium outputs decrease with emission tax, marginal cost, and product differentiation parameter but increase with market size.

In Stage 2, the regulator determines the optimal tax t to maximize the welfare function (23). By substituting (29) into (23), we get welfare in terms of $z_1,\ z_2$ and t:

$$W = -\frac{\gamma(z_1^2+z_2^2)}{2} - \frac{c(a-c-t)}{1+\theta} + \frac{1}{2}\left(\frac{(a-c-t)^2(1+\theta)}{2(1+\theta)^2}\right) + t\left(-(z_1+z_2)(1+\beta) + \frac{a-c-t}{1+\theta}\right) - \frac{1}{2}d\left(-(z_1+z_2)(1+\beta) + \frac{a-c-t}{1+\theta}\right)^2 - t\left(-\ z_2 - z_1\beta + \frac{a-c-t}{2(1+\theta)}\right) - t\left(-z_1 - z_2\beta + \frac{a-c-t}{2(1+\theta)}\right) + \frac{(a-c-t)(a-\frac{(a-c-t)(1+\theta)}{2\,(1+\theta)})}{1+\theta} \tag{43}$$

The regulator maximizes W by setting $\frac{\partial W}{\partial t} = 0$. Solving the first-order condition yields the equilibrium tax t:[17]

$$t = \frac{a(-1+2d-\theta)-2d(z_1+z_2)(1+\beta)(1+\theta)+c(1-2d+\theta)}{1+2d+\theta} \tag{44}$$

The equilibrium tax decreases with spillovers and R&D efforts.

In Stage 1, the merged firm chooses R&D z_1 and z_2 to maximize profit π_M. By substituting (29) and (44) into (28) we get the profit function in terms of z_1 and z_2:

[16] Second-order conditions for maximization is satisfied and proved in Appendix.
[17] Second-order conditions for maximization is satisfied and proved in Appendix.

$$\pi_M = -\frac{z_2^2\gamma}{2} + \frac{c(-a+c-d(z_1+z_2)(1+\beta))}{1+2d+\theta} + \frac{(a-c+d(z_1+z_2)(1+\beta))(2ad+c(1+\theta)-d(z_1+z_2)(1+\beta)(1+\theta))}{(1+2d+\theta)^2} - \frac{(-a+c+d(z_1-z_2)(-1+\beta)+(z_2+z_1\beta)(1+\theta))(c(-1+2d-\theta)+2d(z_1+z_2)(1+\beta)(1+\theta)+a(1-2d+\theta))}{(1+2d+\theta)^2} + \frac{1}{2(1+2d+\theta)^2}(-2c(a - c + d(z_1 + z_2)(1 + \beta))(1 + 2d + \theta) - z_1^2\gamma(1 + 2d + \theta)^2 + 2(a - c + d(z_1 + z_2)(1 + \beta))(2ad + c(1 + \theta) - d(z_1 + z_2)(1 + \beta)(1 + \theta)) + 2(c(-1 + 2d - \theta) + 2d(z_1 + z_2)(1 + \beta)(1 + \theta) + a(1 - 2d + \theta))(a - c + z_1(-1 + d(-1 + \beta) - \theta) - z_2(d(-1 + \beta) + \beta + \beta\theta))) \tag{45}$$

Solving $\frac{\partial \pi_M}{\partial z_1} = 0$ and $\frac{\partial \pi_M}{\partial z_2} = 0$ yields equilibrium R&D:[18]

$$z_1 = z_2 = \frac{(a-c)(1+\beta)(4d^2+4d(1+\theta)-(1+\theta)^2)}{\gamma(1+\theta)^2+4d^2(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))+4d(1+\theta)(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))} \tag{46}$$

As a result, equilibrium values of the emission tax and output are:

$$t = \frac{a(-1+2d-\theta)+c(1-2d+\theta)-\frac{4(a-c)d(1+\beta)^2(1+\theta)(4d^2+4d(1+\theta)-(1+\theta)^2)}{\gamma(1+\theta)^2+4d^2(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))+4d(1+\theta)(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))}}{1+2d+\theta} \tag{47}$$

$$q_1 = q_2 = -\frac{-a+c+\frac{a(-1+2d-\theta)+c(1-2d+\theta)-\frac{4(a-c)d(1+\beta)^2(1+\theta)(4d^2+4d(1+\theta)-(1+\theta)^2)}{\gamma(1+\theta)^2+4d^2(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))+4d(1+\theta)(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))}}{1+2d+\theta}}{2(1+\theta)} \tag{48}$$

2.5.3 Comparison

We use a set of tables to illustrate the effect of the merger on innovation and other variables under non-commitment. We fix $A = 1000, \gamma = 100, d = 1\ and\ \beta = 0.2$ and allow θ to change.

***Proposition* 2:** *Under non-commitment, the merger increases R&D, output, pollution reduction, and welfare. However, the merger decreases pollution. The merger increases profit and decreases the emission tax except if goods are complements.*

[18] Second-order conditions for maximization is satisfied and proved in Appendix.

Table 5. Goods are complements ($\theta = -0.5$) under non-commitment.

	Merger	Competition
$z_1 = z_2$	10.8895	7.7331
t	589.546	388.864
$q_1 = q_2$	410.454	407.424
Industry Profit	172022	333226
Pollution Reduction	26.1347	18.5594
R&D Spending	11858	5980.08
Pollution Level, MSD	794.773	796.288
Welfare	408981	408833

As illustrated by table 5, when goods are complements, if there is a merger, R&D, emission tax, output, and welfare increase. The merged entity internalizes the R&D spillovers, which leads to more R&D. Higher R&D leads to more pollution reduction. The merger reduces pollution, marginal social damage, and profit. A higher value of pollution reduction leads to lower pollution, followed by lower marginal social damage. Profit is much lower under merger due to the higher emission tax and higher R&D expenditure. The merger increases welfare due to larger consumer surplus and lower damage.[19] If goods are complements, then merger is not profitable because it increases output and emission tax.

Table 6. Goods are independent ($\theta = 0$) under non-commitment.

	Merger	Competition
$z_1 = z_2$	9.10036	5.88697
t	318.773	323.914
$q_1 = q_2$	340.614	338.043
Industry Profit	230716	229656
Pollution Reduction	21.8409	14.1287
R&D Spending	8281.66	3465.64
Pollution Level, MSD	659.386	661.957
Welfare	339533	339254

[19] Since profit decreases with the merger, in this case firms have no incentive to merge.

Table7. Goods are imperfect substitutes ($\theta = 0.5$) under non-commitment.

	Merger	**Competition**
$z_1 = z_2$	7.33323	4.7093
t	127.772	277.641
$q_1 = q_2$	290.743	288.944
Industry Profit	250466	167897
Pollution Reduction	17.5997	11.3023
R&D Spending	5377.62	2217.75
Pollution Level, MSD	563.886	566.585
Welfare	290327	289928

As illustrated by tables 6 and 7, when goods are independent or imperfect substitutes, since the government chooses the emission tax after R&D decisions made by firms, equation (44) implies that $\frac{\partial t}{\partial z_i} = \frac{-2d(1+\beta)(1+\theta)}{1+2d+\theta} < 0$, therefore a merged firm has incentives to increase R&D in the first stage. The merger increases R&D, output, and welfare. The merged entity internalizes the R&D spillovers, which leads to more R&D. Moreover, higher R&D implies higher pollution reduction. If higher pollution reduction decreases pollution, then marginal social damage decreases as well. Profit is higher under merger due to larger operational profit, lower pollution and lower emission tax. The merger has a lower tax compared with competition for several reasons. There are two opposite effects on the emission tax. The first effect is the total pollution-reducing effect which leads to emission tax increases; the government increases the emission tax to control pollution, and as a result, total pollution goes down. The second effect is the production-increasing effect, which leads to emission tax decreases. By using an emission tax, the firm's emission expenditure would increase, and, as a result, firms would lower their outputs to minimize emission expenditures. However, the government wants more outputs, therefore by reducing the emission tax, the government could encourage more production by firms; the pollution-reducing effect is dominated by the production-increasing effect in this case. The merger enhances welfare because of higher values of consumer surplus and profit, and a lower value of damage.

Table 8. Goods are homogenous ($\theta = 1$) under non-commitment.

	Merger	**Competition**
$z_1 = z_2$	5.75153	3.90168
t	-13.8037	242.977
$q_1 = q_2$	253.451	252.341
Industry Profit	253450	128105
Pollution Reduction	13.8037	9.36403
R&D Spending	3308.01	1522.31
Pollution Level, MSD	493.098	495.318
Welfare	253546	253138

As illustrated by table 8, when goods are homogenous, normally the merger will reduce output, but the government wants more production, so the government indirectly subsidizes production by using a negative emission tax (i.e., emission subsidy) to encourage production and make production even more profitable (i.e., the pollution-reducing effect is dominated by the production-increasing effect). As in Ouchida and Goto (2014), the economic intuition behind an emission subsidy is as follows: an emission subsidy is equivalent to the policy combination of a production subsidy and an abatement tax since a firm's emission function is defined as pollution generated from production minus abatements generated from R&D. A production subsidy has two effects: a damage-increasing effect and decreasing effect of market inefficiency. When the damage parameter is sufficiently small, the damage-increasing effect is dominated by the improvement effect in market inefficiency. In our model, we have a small damage parameter and in the scenario of a non-commitment emission tax policy towards Cournot duopolists, by using part (ii) of Proposition 1 from Ouchida and Goto (2014), we illustrate the result of a negative emission tax in equilibrium. Therefore, output goes up after the merger. The merger increases R&D, profit, and welfare. The merged entity internalizes R&D spillovers, which leads to more R&D. Higher R&D implies a larger pollution reduction, which leads to lower pollution. Lower pollution implies lower marginal social damage. Profit is much higher under merger due to a negative emission tax and lower pollution. The merger always enhances welfare because of higher consumer surplus and profit, and lower damage.

Figure 2. Pollution reduction, R&D spending, pollution, and welfare under non-commitment.

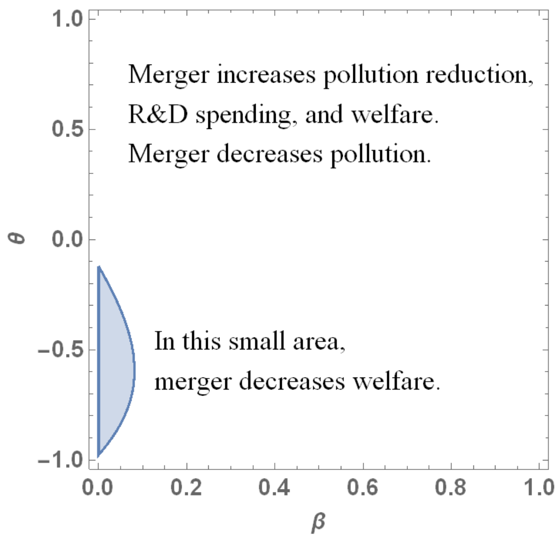

Figure 2 shows that, for any value of spillover and product differentiation parameters under non-commitment, the merger always increases pollution reduction, R&D spending and decreases pollution. The merger always increases welfare except in the small area shown above, in which the merger decreases welfare. In this small area, due to lower profit, the merger generates lower welfare compared with competition.

2.6 Exogenous Tax Scenario

This case is relevant when the tax is set based on country-wide considerations or on an international agreement, and hence is not responsive to the specific conditions of the industry under study. In this section we focus mostly on a positive emission tax, since in the real world the problem seems more often to be how to cut emissions, rather than how to encourage them. Thus, assume $t > 0$.

2.6.1 Competition

If the emission tax is exogenous, in competition, we have equilibrium values of R&D and output:[20]

$$z_1 = z_2 = \frac{t}{\gamma} \tag{49}$$

R&D increases with the tax and decreases with research costs.

$$q_1 = q_2 = \frac{a-c-t}{2+\theta} \tag{50}$$

[20] The Appendix provides more details on the derivation of the results of sections 6.1 and 6.2.

The equilibrium outputs decrease with emission tax, marginal cost, and product differentiation parameter but increase with market size.

2.6.2 Merger

If the emission tax is exogenous, the merger generates the following equilibrium values:

$$z_1 = z_2 = \frac{t(1+\beta)}{\gamma} \tag{51}$$

R&D increases with the tax and spillovers and decreases with research costs.

$$q_1 = q_2 = \frac{a-c-t}{2(1+\theta)} \tag{52}$$

The equilibrium outputs decrease with emission tax, marginal cost, and product differentiation parameter but increase with market size.

The following proposition compares R&D, output, R&D spending and pollution reduction between competition and merger.

***Proposition* 3:** *With an exogenous $t > 0$:*

i) The merger increases R&D and pollution reduction iff $\beta > 0$, and has no effect on them iff $\beta = 0$.

ii) The merger increases output iff $\theta < 0$;

The merger decreases output iff $\theta > 0$;

The merger leaves output unchanged iff $\theta = 0$.

Proof. See the Appendix.

The intuition for these results will be provided in the following subsection.

2.6.3 Comparison

To understand these results, we use numerical values for parameters to compare each variable between merger and competition. We set the emission tax at $t = 20$ along with previous assumptions that $A = 1000, \gamma = 100, d = 1, \beta = 0.2$, and analyze different values of product differentiation parameter, θ.

***Proposition* 4:** *Under a positive exogenous emission tax*

(1) When goods are complements, the merger increases R&D, output, profit, pollution reduction, pollution and marginal social damage, but reduces welfare.

(2) When goods are independent, the merger increases R&D, pollution reduction, and welfare. Output and profit stay the same between the two regimes. The merger reduces pollution and marginal social damage compared with competition.

(3) When goods are imperfect substitutes or homogenous, the merger increases R&D, profit, pollution reduction, and welfare. The merger reduces output, pollution and marginal social damage.

Table 9. Goods are complements ($\theta = -0.5$) under exogenous tax scenario.

	Merger	**Competition**
$z_1 = z_2$	0.24	0.2
$q_1 = q_2$	980	653.333
Industry Profit	960406	853694
Pollution Reduction	0.576	0.48
R&D Spending	5.76	4
Pollution Level, MSD	1959.42	1306.19
Welfare	-439877	240179

As illustrated by table 9, when goods are complements and emission tax is exogenous, the merger increases output. A firm has incentives to reduce pollution tax expenditure, therefore more R&D is generated. The merged entity internalizes R&D spillovers, which leads to more R&D. More R&D implies more pollution reduction. Under merger, more output leads to more pollution, and higher pollution implies higher marginal social damage. The merger increases profit due to higher operational profit. As in figure 3, if goods are complements, the merger greatly decreases welfare due to larger environmental damage.

Table 10. Goods are independent ($\theta = 0$) under exogenous tax scenario.

	Merger	Competition
$z_1 = z_2$	0.24	0.2
$q_1 = q_2$	490	490
Industry Profit	480206	480206
Pollution Reduction	0.576	0.48
R&D Spending	5.76	4
Pollution Level, MSD	979.424	979.52
Welfare	260259	260166

As illustrated by table 10, when goods are independent and the emission tax is exogenous, the merged firm has incentives to internalize R&D spillovers and invest more in R&D in the first stage to reduce emission tax expenditure. The merger increases R&D, which implies more pollution reduction. Equilibrium output stays the same between merger and competition. Pollution is lower under merger because of a higher value of pollution reduction, and lower pollution implies lower marginal social damage. Interestingly, the merger generates profit as competition, due to larger R&D under merger: on the one hand, a larger R&D would reduce the emission tax expenditure, but on the other hand, it involves more R&D expenditure. As a result, the two effects offset each other. As in figure 3, if goods are independent, the merger increases welfare due to less environmental damage compared with competition.[21]

Table 11. Goods are imperfect substitutes ($\theta = 0.5$) under exogenous tax scenario.

	Merger	Competition
$z_1 = z_2$	0.24	0.2
$q_1 = q_2$	326.667	392
Industry Profit	320140	307334
Pollution Reduction	0.576	0.48
R&D Spending	5.76	4
Pollution Level, MSD	652.757	783.52
Welfare	280215	246548

[21] Since profit decreases with merger, in this case firms have no incentive to merge.

Table 12. Goods are homogenous ($\theta = 1$) under exogenous tax scenario.

	Merger	Competition
$z_1 = z_2$	0.24	0.2
$q_1 = q_2$	245	326.67
Industry Profit	240106	213428
Pollution Reduction	0.576	0.48
R&D Spending	5.76	4
Pollution Level, MSD	489.424	652.853
Welfare	250176	226798

As illustrated by tables 11 and 12, when goods are imperfect substitutes or homogenous, the merged firm wants to reduce pollution expenditure; as a result, the merger internalizes R&D spillovers and generates more R&D in the first stage. More R&D implies more pollution reduction. The equilibrium quantity is lower under merger compared with competition. The merger reduces pollution, due to higher R&D and lower ouput; as a result, the merger generates less marginal social damage. Profit is much higher under merger due to higher operational profit and lower pollution compared with competition. As in figure 3, the merger increases welfare because of higher profits and lower environmental damage.

Figure 3. Pollution reduction, R&D spending, pollution, and welfare under exogenous tax scenario.

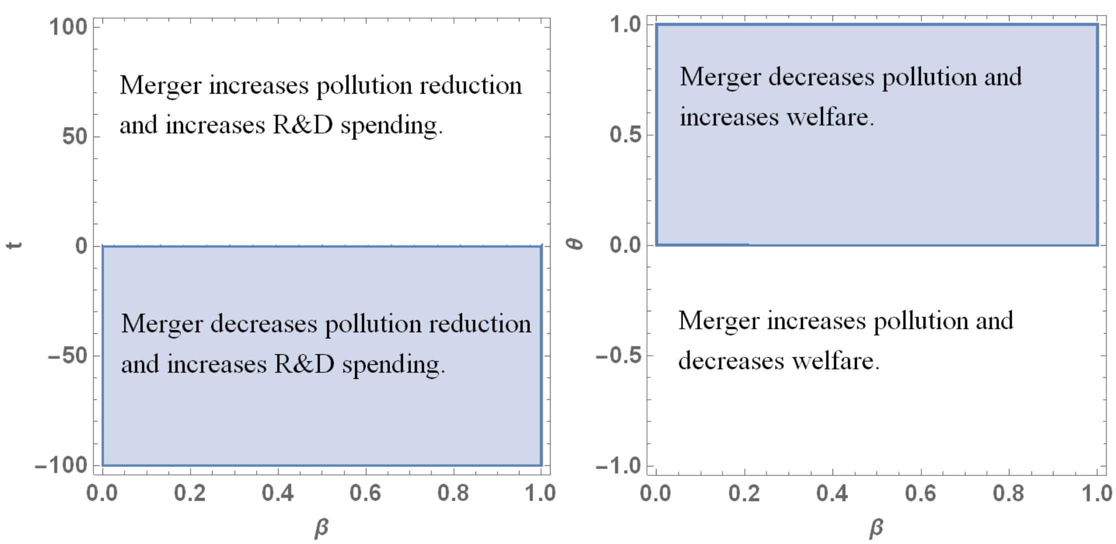

Figure 3 shows that if the exogenous emission tax is positive (negative), for any value of spillovers, the merger always increases (decreases) pollution reduction. Moreover, the merger always increases R&D spending. For any value of spillovers, as products become more similar, the merger decreases pollution and increases welfare.

2.7 Effect of Commitment

Within each regime of merger and competition, we compare variables between the scenarios of commitment and non-commitment. We hold the original assumptions of $A = 1000, \gamma = 100, d = 1, \beta = 0.2$. Since tables share the same pattern that commitment only increases the emission tax and decreases other variables compared with non-commitment, tables are suppressed in this section.

***Proposition* 5:** *For any type of goods, under any regime, commitment generates a higher emission tax, and lower R&D, output, profit, pollution reduction, pollution, and welfare compared with non-commitment.*

For any type of goods, under any regime under commitment, since the emission tax is generated in the first stage, the model structure leads to a higher value of the emission tax. In the second stage, R&D depends on the emission tax only. Equilibrium values of R&D in (18) and (31) show that $\frac{\partial z_i}{\partial t} > 0$, which implies that a higher tax yields higher R&D in the second stage. However, it is still less than the non-commitment value of R&D. In the third stage, optimal output depends on the emission tax only. Equilibrium values of output in (15) and (29) show that $\frac{\partial q_i}{\partial t} < 0$, which implies that a higher tax yields a lower output in the third stage. Lower R&D under commitment leads to less pollution reduction. Under commitment, a small value of output leads to lower pollution. Profit is lower under commitment due to lower operational profit and higher emission tax. Commitment generates lower consumer surplus and lower profit. These components contribute to lower welfare compared with non-commitment.

2.8 The Merger-R&D and Commitment-R&D Relationship

In this section, we emphasize two important relationships. The first one is the effect of the merger on R&D. The second relationship is the effect of commitment on R&D.

***Proposition* 6:**

(1) Merger has a positive effect on R&D under non-commitment and the exogenous tax scenario.

(2) Under commitment, if goods are imperfect substitutes or homogenous, merger has a negative effect on R&D; if goods are complements or independent, merger has a positive effect on R&D.

(3) For any types of goods under any regime, commitment has a negative effect on R&D.

Table 13. The effect of merger on R&D.

	Commitment	Non-commitment	Exogenous emission tax
$\theta = -0.5$	+	+	+
$\theta = 0$	+	+	+
$\theta = 0.5$	-	+	+
$\theta = 1$	-	+	+

Table 13 summarizes the relationship between merger and R&D as predicted by the model. The rows represent different levels of product differentiation, while the columns represent different scenarios. We compare merger's R&D and competition's R&D under different circumstances. As the table suggests, in the model studied here, the sign of the relationship is more often positive than negative. However, the results do suggest there exist two cases where the relationship is negative: if goods are imperfect substitutes or homogenous under commitment.

Table 14. The effect of commitment on R&D.

	Merger	Competition
$\theta = -0.5$	-	-
$\theta = 0$	-	-
$\theta = 0.5$	-	-
$\theta = 1$	-	-

Table 14 summarizes the relationship between commitment and R&D as predicted by the model. The rows represent different levels of product differentiation, while the columns represent different regimes. We compare commitment's and non-commitment's R&D under different circumstances. As the table suggests, in the model studied here, the sign of the relationship is always negative. For any type of goods under any regime, the results suggest a negative relationship between commitment and R&D.

In our setting, non-commitment yields superior innovation performance to commitment, irrespective of product differentiation, market structure (merger versus competition), and R&D spillovers. The intuition for this result is the following. Under non-commitment, firms anticipate that high R&D spending will lead to lower marginal social damage, and hence a lower emission tax. This provides an added incentive for firms to invest more in R&D, to reduce the emission tax.

Under commitment, the government chooses the tax before firms choose R&D. Thus, at the time of investing in R&D, firms take the tax as given, and do not invest more strategically to induce a lower marginal social damage and thus a lower emission tax. It is true that the government, as a leader under commitment, has the incentive to increase the tax in the first stage to increase R&D by firms in the second stage. However, this effect is weaker than the additional incentive of firms under non-commitment, whence the superiority of the latter over commitment. Moreover, for the government, tax revenues ultimately don't matter, since they increase government revenue but reduce profits.

2.9 Conclusion

This paper explores the effect of merger on environmental R&D. In our model, under the policy regimes of merger and competition, firms play a three-stage game by investing in R&D to reduce the carbon emission expenditure. We consider the fact that product differentiation can play a role into the environmental policy design and analyze different policy implementations under the regulator's full commitment, no commitment and exogenous emission tax. We study the relationship between merger and R&D and the relationship between commitment and R&D. We also evaluate the overall effect of merger and the overall effect of commitment.

As the main results, proposition 6 suggests that: (1) Merger has a positive effect on R&D under non-commitment and the exogenous tax scenarios. (2) Under commitment, if goods are imperfect substitutes or homogenous, merger has a negative effect on R&D; if goods are complements or independent, merger has a positive effect on R&D. (3) For any types of goods under any regime, commitment has a negative effect on R&D. Propositions 1-5 compare equilibrium variables between merger and competition. (4) Under commitment, if products are highly differentiated, the tax from the merger is higher. As products become more and more similar, the tax becomes lower under the merger. R&D, output, pollution reduction, pollution, marginal social damage, and welfare follow a similar trend. However, the profit from the merger would increase as products become more and more similar. (5) Under non-commitment, as products become less differentiated, the tax becomes lower under merger. However, profit becomes higher under merger. R&D, output, pollution reduction, and welfare are always higher under merger. Pollution and marginal social damage are always lower under merger. (6) Under the exogenous tax scenario, as products become less differentiated, output, pollution, and marginal social damage become less under merger. And welfare increases with the merger. R&D and pollution reduction are always higher under merger. (7) If we compare commitment to non-commitment**:** for any type of goods, under any regime, commitment generates a higher emission tax, and lower R&D, output, profit, pollution reduction, pollution, marginal social damage, and welfare.

In our paper, there are three aspects which are different from previous studies. First, our research focuses on total merger, which is cooperation at all stages, especially in the output stage. Previously, studies only focused on R&D cooperation (e.g., Poyago-Theotoky, 1999, 2007, 2010; Petrakis and Poyago-Theotoky, 2002; and Ouchida and Goto, 2011, 2014, 2016a, 2016b). Another difference is that our study fully considers product differentiation. This is different from other studies which only focus on homogenous products. Specifically, we consider complements, independent goods, imperfect substitutes, and homogenous goods. Third, our research includes three different scenarios: commitment, non-commitment, and exogenous tax. Other major studies only focus on one or two of them (e.g., Poyago-Theotoky, 1999, 2007, 2010; Petrakis and Poyago-Theotoky, 2002; and Ouchida and Goto, 2011, 2014, 2016a, 2016b). In short, we study full mergers with product differentiation, and study combinations of different policy regimes and scenarios simultaneously.

The results indicate that merger will be profitable for firms, increase R&D investment and welfare (1) if goods are independent under commitment; (2) if goods are independent, imperfect substitutes, or homogeneous under non-commitment; and (3) if goods are imperfect substitutes or homogenous under the exogenous tax scenario. Also, non-commitment will encourage R&D investment, increase profit, and enhance welfare, compared with commitment for any type of goods and under any regime. As a result, public policies should focus on the encouragement of mergers and promote the regulator's non-commitment ability if the market structure satisfies the above conditions, since doing so would not only lead firms to engage in more R&D investments in terms of increasing innovation outputs as pollution reductions, but it also would have the beneficial effect of increasing the firms' profit and welfare.

There are many dimensions in which this research line can be extended. First, our results have been obtained in the context of a duopolistic market. For future research, it seems very promising to extend the analysis to an *n*-firm oligopoly. Second, under the setting with more than two firms, we would have to consider merger encompassing less than the total number of firms in the market and examine the role of insider and outsider firms and how the interplay of these types of firms affects equilibrium variables.

Appendix

Commitment Scenario - Competition Regime

In Subgame Perfect Nash Equilibrium, the equilibrium values of R&D spending, pollution reduction, pollution, and welfare are:

$$R\&D\ spending = \frac{(a-c)^2\gamma(\gamma-2d(2+\gamma+\theta+\beta(2+\theta)))^2}{(2d(2+\gamma+\theta+\beta(2+\theta))^2+\gamma(\gamma(1+\theta)+(2+\theta)^2))^2}$$

$$Pollution\ Reduction = \frac{2(a-c)(1+\beta)(-\gamma+2d(2+\gamma+\theta+\beta(2+\theta)))}{2d(2+\gamma+\theta+\beta(2+\theta))^2+\gamma(\gamma(1+\theta)+(2+\theta)^2)}$$

$$Pollution = \frac{2(a-c)\gamma(3+\beta+\gamma+\theta)}{2d(2+\gamma+\theta+\beta(2+\theta))^2+\gamma(\gamma(1+\theta)+(2+\theta)^2)}$$

$$Welfare = \frac{(a-c)^2(\gamma(3+\gamma+\theta)+2d(3+\gamma+\theta+\beta^2(3+\theta)+2\beta(3+\gamma+\theta)))}{2d(2+\gamma+\theta+\beta(2+\theta))^2+\gamma(\gamma(1+\theta)+(2+\theta)^2)}$$

Commitment Scenario - Merger Regime

In Subgame Perfect Nash Equilibrium, equilibrium values of R&D spending, pollution reduction, pollution and welfare are:

$$R\&D\ spending = \frac{(a-c)^2(1+\beta)^2\gamma(\gamma(1+\theta)-2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta)))^2}{(2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta+4\beta(2+\beta)(1+\theta)))^2}$$

$$Pollution\ Reduction = \frac{2(a-c)(1+\beta)^2(-\gamma(1+\theta)+2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta)))}{2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta+4\beta(2+\beta)(1+\theta))}$$

$$Pollution = \frac{2(a-c)\gamma(3+\gamma+3\theta+3\beta(2+\beta)(1+\theta))}{2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta+4\beta(2+\beta)(1+\theta))}$$

$$Welfare = \frac{(a-c)^2(2d(1+\beta)^2+\gamma)(3+\gamma+3\theta+3\beta(2+\beta)(1+\theta))}{2d(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta+4\beta(2+\beta)(1+\theta))}$$

Consider the level of product differentiation $\theta = 0$, we generate some analytical results from these special cases. Let the superscript C denote variables under competition, and M denote variables under merger.

(1) $R\&D\ spending^M > R\&D\ spending^C$ iff

$$-\frac{A^2\gamma\big(\gamma-2d(2+2\beta+\gamma)\big)^2}{(\gamma(4+\gamma)+2d(2+2\beta+\gamma)^2)^2}+\frac{A^2(1+\beta)^2\gamma\big(\gamma-2d(2+2\beta(2+\beta)+\gamma)\big)^2}{\big(2d(2+2\beta(2+\beta)+\gamma)^2+\gamma(4+4\beta(2+\beta)+\gamma)\big)^2}>0$$

(2) $Pollution\ Reduction^M > Pollution\ Reduction^C$ iff

$$-\frac{2A(1+\beta)\left(-\gamma+2d(2+2\beta+\gamma)\right)}{\gamma(4+\gamma)+2d(2+2\beta+\gamma)^2}+\frac{2A(1+\beta)^2\left(-\gamma+2d(2+2\beta(2+\beta)+\gamma)\right)}{2d(2+2\beta(2+\beta)+\gamma)^2+\gamma(4+4\beta(2+\beta)+\gamma)}>0$$

(3) $Pollution^M > Pollution^C$ iff

$$-\frac{2A\gamma(3+\beta+\gamma)}{\gamma(4+\gamma)+2d(2+2\beta+\gamma)^2}+\frac{2A\gamma(3+3\beta(2+\beta)+\gamma)}{2d(2+2\beta(2+\beta)+\gamma)^2+\gamma(4+4\beta(2+\beta)+\gamma)}>0$$

Non-Commitment Scenario - Competition Regime

In the Subgame Perfect Nash Equilibrium, equilibrium values of R&D spending, pollution reduction, and pollution are:[22]

$$R\&D\ spending=\frac{(a-c)^2\gamma(-1-\theta+2d(1+2d+\beta+\theta))^2}{(\gamma(1+\theta)^2+2d^2(2(2+2\beta+\gamma)+(1+\beta)(3+\beta)\theta)+d(1+\theta)(6+4\gamma+3\theta+\beta(4+\beta)(2+\theta)))^2}$$

$$Pollution\ Reduction=\frac{2(a-c)(1+\beta)(-1-\theta+2d(1+2d+\beta+\theta))}{\gamma(1+\theta)^2+2d^2(2(2+2\beta+\gamma)+(1+\beta)(3+\beta)\theta)+d(1+\theta)(6+4\gamma+3\theta+\beta(4+\beta)(2+\theta))}$$

$$Pollution=\frac{2(a-c)(2d(1+\beta+\gamma)+d(1+\beta)^2\theta+(1+\beta+\gamma)(1+\theta))}{\gamma(1+\theta)^2+2d^2(2(2+2\beta+\gamma)+(1+\beta)(3+\beta)\theta)+d(1+\theta)(6+4\gamma+3\theta+\beta(4+\beta)(2+\theta))}$$

Non-Commitment Scenario - Merger Regime

In the Subgame Perfect Nash Equilibrium, the equilibrium values of R&D spending, pollution reduction, and pollution are:

$$R\&D\ spending=\frac{(a-c)^2(1+\beta)^2\gamma(-4d^2-4d(1+\theta)+(1+\theta)^2)^2}{(\gamma(1+\theta)^2+4d^2(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))+4d(1+\theta)(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta)))^2}$$

$$Pollution\ Reduction=\frac{2(a-c)(1+\beta)^2(4d^2+4d(1+\theta)-(1+\theta)^2)}{\gamma(1+\theta)^2+4d^2(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))+4d(1+\theta)(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))}$$

$$Pollution=\frac{2(a-c)(1+2d+\theta)(1+\gamma+\theta+\beta(2+\beta)(1+\theta))}{\gamma(1+\theta)^2+4d^2(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))+4d(1+\theta)(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta))}$$

Consider the level of product differentiation $\theta = 0$, we generate some analytical results from these special cases.[23]

(1) $R\&D\ spending^M > R\&D\ spending^C$ iff

$$\frac{A^2(1-4d-4d^2)^2(1+\beta)^2\gamma}{(\gamma+4d(2+2\beta(2+\beta)+\gamma)+4d^2(2+2\beta(2+\beta)+\gamma))^2}-\frac{A^2(-1+2d(1+2d+\beta))^2\gamma}{(\gamma+4d^2(2+2\beta+\gamma)+d(6+2\beta(4+\beta)+4\gamma))^2}>0$$

(2) $Pollution\ Reduction^M > Pollution\ Reduction^C$ iff

$$\frac{2A(-1+4d+4d^2)(1+\beta)^2}{\gamma+4d(2+2\beta(2+\beta)+\gamma)+4d^2(2+2\beta(2+\beta)+\gamma)}-\frac{2A(1+\beta)\left(-1+2d(1+2d+\beta)\right)}{\gamma+4d^2(2+2\beta+\gamma)+d(6+2\beta(4+\beta)+4\gamma)}>0$$

[22] The expression for welfare is not shown, due to its length.

[23] Let the superscript C denote variables under competition, and M denote variables under merger.

(3) $Pollution^M > Pollution^C$ iff

$$\frac{2A(1+2d)(1+\beta(2+\beta)+\gamma)}{\gamma+4d(2+2\beta(2+\beta)+\gamma)+4d^2(2+2\beta(2+\beta)+\gamma)}-\frac{2A\left(1+\beta+\gamma+2d(1+\beta+\gamma)\right)}{\gamma+4d^2(2+2\beta+\gamma)+d(6+2\beta(4+\beta)+4\gamma)}>0$$

Exogenous Tax Scenario - Competition Regime

If the emission tax is exogenous, there are two stages under competition: in stage 1, firm i chooses R&D non-cooperatively and maximizes its profit. In stage 2, firm i determines output non-cooperatively to maximize its profit. We have the same profit functions as (13) and (14), solving the first-order conditions $\frac{\partial \pi_1}{\partial q_1}=0$ and $\frac{\partial \pi_2}{\partial q_2}=0$ yields equilibrium values of output in stage 2:[24]

$$q_1=q_2=\frac{a-c-t}{2+\theta} \tag{15}$$

In stage 1, by substituting (15) into profit functions (13) and (14), we generate profit functions (16) and (17) in terms of z_1 and z_2:

$$\pi_1=-\frac{z_1^2\gamma}{2}-\frac{c(a-c-t)}{2+\theta}-t\left(-z_1-z_2\beta+\frac{a-c-t}{2+\theta}\right)+\frac{(a-c-t)(a-\frac{(a-c-t)(1+\theta)}{2+\theta})}{2+\theta}$$

$$\pi_2=-\frac{z_2^2\gamma}{2}-\frac{c(a-c-t)}{2+\theta}-t\left(-z_2-z_1\beta+\frac{a-c-t}{2+\theta}\right)+\frac{(a-c-t)(a-\frac{(a-c-t)(1+\theta)}{2+\theta})}{2+\theta}$$

Solving the first-order conditions $\frac{\partial \pi_1}{\partial z_1}=0$ and $\frac{\partial \pi_2}{\partial z_2}=0$ yields equilibrium R&D, which is the same as equation (18).[25]

As a conclusion, if the emission tax is exogenous, in competition, we have equilibrium values of R&D, output, R&D spending, pollution reduction, pollution and welfare:

$$z_1=z_2=\frac{t}{\gamma}$$

$$q_1=q_2=\frac{a-c-t}{2+\theta}$$

$$R\&D\ spending=\frac{t^2}{\gamma}$$

$$Pollution\ reduction=\frac{2t(1+\beta)}{\gamma}$$

$$Pollution=\frac{-2t(1+\beta)}{\gamma}+\frac{2(a-c-t)}{2+\theta}$$

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[24] Second-order conditions for maximization is satisfied and proved in Appendix.
[25] Second-order conditions for maximization is satisfied and proved in Appendix.

$$Welfare = -\frac{\gamma(2(a-c)t\gamma-(a-c)^2\gamma(3+\theta)+t^2(4+\gamma+(4+\gamma)\theta+\theta^2))+2d((-a+c)\gamma+t(2+\gamma+\theta+\beta(2+\theta)))^2}{\gamma^2(2+\theta)^2}$$

Exogenous Tax Scenario - Merger Regime

If the emission tax is exogenous, there are two stages under merger: in stage 1, the merged firm chooses R&D z_1 and z_2 to maximize profit π_M. In stage 2, the merged firm determines outputs q_1 and q_2 to maximize profit π_M. We have the same profit function as (28). Solving the first-order conditions $\frac{\partial(\pi_M)}{\partial q_1} = 0$ and $\frac{\partial\,(\pi_M)}{\partial q_2} = 0$ yields equilibrium values of output in stage 2:[26]

$$q_1 = q_2 = \frac{a-c-t}{2(1+\theta)} \tag{29}$$

In stage 1, by substituting (29) into profit π_M, we get the profit function (30) in terms of z_1 and z_2:

$$\pi_M = -\frac{\gamma(z_1^2+z_2^2)}{2} - \frac{c(a-c-t)}{1+\theta} - t\left(-\mathrm{z}_2 - \mathrm{z}_1\beta + \frac{a-c-t}{2(1+\theta)}\right) - t\left(-\mathrm{z}_1 - \mathrm{z}_2\beta + \frac{a-c-t}{2(1+\theta)}\right) + \frac{(a-c-t)(a-\frac{(a-c-t)(1+\theta)}{2(1+\theta)})}{1+\theta}$$

Solving the first-order conditions $\frac{\partial(\pi_M)}{\partial z_1} = 0$ and $\frac{\partial(\pi_M)}{\partial z_2} = 0$ yields equilibrium R&D.[27]

As a conclusion, if the emission tax is exogenous, the merger generates the following equilibrium values of R&D, output, pollution reduction, pollution and welfare:

$$z_1 = z_2 = \frac{t\,(1+\beta)}{\gamma}$$

$$q_1 = q_2 = \frac{a-c-t}{2(1+\theta)}$$

$$R\&D\ spending = \frac{(t+t\beta)^2}{\gamma}$$

$$Pollution\ reduction = \frac{(2+2\beta)(t+t\beta)}{\gamma}$$

$$Pollution = \frac{(-2-2\beta)(t+t\beta)}{\gamma} + \frac{a-c-t}{1+\theta}$$

$$Welfare = -\frac{2d((-a+c)\gamma+t(2+\gamma+2\theta+2\beta(2+\beta)(1+\theta)))^2+\gamma(1+\theta)(-3(a-c)^2\gamma+2(a-c)t\gamma+t^2(4+\gamma+4\theta+4\beta(2+\beta)(1+\theta)))}{4\gamma^2(1+\theta)^2}$$

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[26] Second-order conditions for maximization is satisfied and proved in Appendix.
[27] Second-order conditions for maximization is satisfied and proved in Appendix.

Proof of Proposition 3

i) $z^C = \frac{t}{\gamma}$; $z^M = \frac{t\,(\beta+1)}{\gamma}$

$z^M - z^C = \frac{t\,\beta}{\gamma}$

$z^M > z^C$ iff $\beta > 0$

$z^M = z^C$ iff $\beta = 0$

Let S denote R&D spending.

$s^C = \frac{t^2}{\gamma}$; $s^M = \frac{(t+t\beta)^2}{\gamma}$

$s^M - s^C = \frac{t^2\beta(\beta+2)}{\gamma}$

$s^M > s^C$ iff $\beta(\beta + 2) > 0$

$s^M = s^C$ iff $\beta = 0$

ii) $q^C = \frac{a-c-t}{2+\theta}$; $q^M = \frac{a-c-t}{2(1+\theta)}$

$q^M > q^C$ iff $2(1+\theta) < 2+\theta$

$\theta < 0$

$q^M < q^C$ iff $\theta > 0$

$q^M = q^C$ iff $\theta = 0$

Derivation - Consumer Surplus

The representative consumer's utility function is

$U\,(q_1, q_2) = a\,(q_1 + q_2) - (\frac{1}{2})\,(q_1^2 + 2\theta q_1 q_2 + q_2^2)$

The consumer's utility function does not include pollution effects.

The representative consumer chooses outputs q_1 and q_2 to maximize

$U\,(q_1, q_2) - p_1\,q_1 - p_2\,q_2$

The first-order conditions are

$$a - q_1 - \theta q_2 - p_1 = 0$$

$$a - q_2 - \theta q_1 - \ p_2 = 0$$

The inverse demand functions are

$$p_1\ (\ q_1\ , q_2) = \ a - \ (q_1\ +\ \theta\ q_2)$$

$$p_2\ (\ q_1\ , q_2) = \ a - \ (q_2\ +\ \theta\ q_1)$$

Substituting the inverse demand functions for p_1, p_2, we can obtain consumer surplus:

$$CS\ (q_1, q_2) = \ U\ (q_1, q_2) - p_1\ (\ q_1\ , q_2)\ q_1 - \ p_2\ (\ q_1\ , q_2)\ q_2$$

$$= \ U\ (q_1, q_2) - a\ q_1 + \ ({q_1}^2\ +\ \theta\ q_2 q_1) - a\ q_2 + \ ({q_2}^2\ +\ \theta\ q_1 q_2)$$

$$= \ - \left(\frac{1}{2}\right)(q_1^2 + 2\theta q_1 q_2 + q_2^2) + \ ({q_1}^2\ +\ \theta\ q_2 q_1) + \ ({q_2}^2\ +\ \theta\ q_1 q_2)$$

$$= \ - \left(\frac{1}{2}\right)(q_1^2 + q_2^2) - \theta q_1 q_2 + \ ({q_1}^2\ + {q_2}^2) + \ (2\theta q_1 q_2)$$

$$= \ \left(\frac{1}{2}\right)(q_1^2 + q_2^2) + \theta q_1 q_2$$

$$= \ \left(\frac{1}{2}\right)(q_1^2 + 2\theta q_1 q_2 + q_2^2)$$

The Second-Order Conditions - Commitment - Competition

By setting $A = a - c = 1000,\ \gamma = 100,\ d = 1$, and $\beta = 0.2$ we consider different levels of product differentiation, θ.

The second-order conditions of output for maximization are

$$\frac{\partial^2 \pi_1}{\partial {q_1}^2} = -2$$

$$\frac{\partial^2 \pi_2}{\partial {q_2}^2} = -2$$

The second-order conditions of R&D for maximization are

$$\frac{\partial^2 \pi_1}{\partial {z_1}^2} = -100$$

$$\frac{\partial^2 \pi_2}{\partial {z_2}^2} = -100$$

The second-order conditions of tax for maximization is

$$\frac{\partial^2 W}{\partial t^2} = -2.3068 \ \ (\theta = -0.5)$$

$$\frac{\partial^2 W}{\partial t^2} = -1.5686 \ \ (\theta = 0)$$

$$\frac{\partial^2 W}{\partial t^2} = -1.17898 \ \ (\theta = 0.5)$$

$$\frac{\partial^2 W}{\partial t^2} = -0.941465 \ \ (\theta = 1)$$

The Second-Order Conditions - Commitment - Merger

By setting $A = a - c = 1000,\ \gamma = 100,\ d = 1$, and $\beta = 0.2$ we consider different levels of product differentiation, θ.

The second-order conditions of output for maximization are

$$\frac{\partial^2 \pi_M}{\partial {q_1}^2} = -2$$

$$\frac{\partial^2 \pi_M}{\partial {q_2}^2} = -2$$

The second-order conditions of R&D for maximization are

$$\frac{\partial^2 \pi_M}{\partial {z_1}^2} = -100$$

$$\frac{\partial^2 \pi_M}{\partial {z_2}^2} = -100$$

The second-order conditions of tax for maximization is

$$\frac{\partial^2 W}{\partial t^2} = -5.14483 \ \ (\theta = -0.5)$$

$$\frac{\partial^2 W}{\partial t^2} = -1.58723 \ \ (\theta = 0)$$

$$\frac{\partial^2 W}{\partial t^2} = -0.845807 \ \ (\theta = 0.5)$$

$$\frac{\partial^2 W}{\partial t^2} = -0.558429 \ \ (\theta = 1)$$

The Second-Order Conditions – Non-Commitment - Competition

By setting $A = a - c = 1000,\ \gamma = 100,\ d = 1$, and $\beta = 0.2$ we consider different levels of product differentiation, θ.

The second-order conditions of output for maximization are

$$\frac{\partial^2 \pi_1}{\partial {q_1}^2} = -2$$

$$\frac{\partial^2 \pi_2}{\partial {q_2}^2} = -2$$

The second-order conditions of tax for maximization is

$$\frac{\partial^2 W}{\partial t^2} = -2.2222\ \ (\theta = -0.5)$$

$$\frac{\partial^2 W}{\partial t^2} = -1.5\ \ (\theta = 0)$$

$$\frac{\partial^2 W}{\partial t^2} = -1.12\ \ (\theta = 0.5)$$

$$\frac{\partial^2 W}{\partial t^2} = -0.8889\ \ (\theta = 1)$$

The second-order conditions of R&D for maximization are

$$\frac{\partial^2 \pi_1}{\partial {z_1}^2} = -100.979\ \ (\theta = -0.5)$$

$$\frac{\partial^2 \pi_2}{\partial {z_2}^2} = -100.979\ \ (\theta = -0.5)$$

$$\frac{\partial^2 \pi_1}{\partial {z_1}^2} = -101.28\ \ (\theta = 0)$$

$$\frac{\partial^2 \pi_2}{\partial {z_2}^2} = -101.28\ \ (\theta = 0)$$

$$\frac{\partial^2 \pi_1}{\partial {z_1}^2} = -101.479\ \ (\theta = 0.5)$$

$$\frac{\partial^2 \pi_2}{\partial {z_2}^2} = -101.479\ \ (\theta = 0.5)$$

$$\frac{\partial^2 \pi_1}{\partial {z_1}^2} = -101.62\ \ (\theta = 1)$$

$$\frac{\partial^2 \pi_2}{\partial {z_2}^2} = -101.62 \ \ (\theta = 1)$$

The Second-Order Conditions – Non-Commitment - Merger

By setting $A = a - c = 1000,\ \gamma = 100,\ d = 1$, and $\beta = 0.2$ we consider different levels of product differentiation, θ.

The second-order conditions of output for maximization are

$$\frac{\partial^2 \pi_M}{\partial {q_1}^2} = -2$$

$$\frac{\partial^2 \pi_M}{\partial {q_2}^2} = -2$$

The second-order conditions of tax for maximization is

$$\frac{\partial^2 W}{\partial t^2} = -5 \ \ (\theta = -0.5)$$

$$\frac{\partial^2 W}{\partial t^2} = -1.5 \ \ (\theta = 0)$$

$$\frac{\partial^2 W}{\partial t^2} = -0.7778 \ \ (\theta = 0.5)$$

$$\frac{\partial^2 W}{\partial t^2} = -0.5 \ \ (\theta = 1)$$

The second-order conditions of R&D for maximization are

$$\frac{\partial^2 \pi_M}{\partial {z_1}^2} = -100.691 \ \ (\theta = -0.5)$$

$$\frac{\partial^2 \pi_M}{\partial {z_2}^2} = -100.691 \ \ (\theta = -0.5)$$

$$\frac{\partial^2 \pi_M}{\partial {z_1}^2} = -101.28 \ \ (\theta = 0)$$

$$\frac{\partial^2 \pi_M}{\partial {z_2}^2} = -101.28 \ \ (\theta = 0)$$

$$\frac{\partial^2 \pi_M}{\partial {z_1}^2} = -101.763 \ \ (\theta = 0.5)$$

$$\frac{\partial^2 \pi_M}{\partial {z_2}^2} = -101.763 \ \ (\theta = 0.5)$$

$$\frac{\partial^2 \pi_M}{\partial {z_1}^2} = -102.16 \;\; (\theta = 1)$$

$$\frac{\partial^2 \pi_M}{\partial {z_2}^2} = -102.16 \;\; (\theta = 1)$$

The Second-Order Conditions – Exogenous Tax - Competition

By setting $A = a - c = 1000,\ \gamma = 100,\ d = 1, \beta = 0.2$, and $t = 20$ we consider different levels of product differentiation, θ.

The second-order conditions of output for maximization are

$$\frac{\partial^2 \pi_1}{\partial {q_1}^2} = -2$$

$$\frac{\partial^2 \pi_2}{\partial {q_2}^2} = -2$$

The second-order conditions of R&D for maximization are

$$\frac{\partial^2 \pi_1}{\partial {z_1}^2} = -100$$

$$\frac{\partial^2 \pi_2}{\partial {z_2}^2} = -100$$

The Second-Order Conditions – Exogenous Tax - Merger

By setting $A = a - c = 1000,\ \gamma = 100,\ d = 1, \beta = 0.2$, and $t = 20$ we consider different levels of product differentiation, θ.

The second-order conditions of output for maximization are

$$\frac{\partial^2 \pi_M}{\partial {q_1}^2} = -2$$

$$\frac{\partial^2 \pi_M}{\partial {q_2}^2} = -2$$

The second-order conditions of R&D for maximization are

$$\frac{\partial^2 \pi_M}{\partial {z_1}^2} = -100$$

$$\frac{\partial^2 \pi_M}{\partial {z_2}^2} = -100$$

References

Atallah, G. (2016). Endogenous efficiency gains from mergers. *Southern Economic Journal, 83*(1), 202-235.

Fikru, M. (2013). Environmental Policies, Mergers and Welfare. *Economía Mexicana. Nueva Época, 22(2),* 449-461.

Fikru, M. (2016). Modelling mergers among polluting firms when environmental policy is endogenous. *Economic Analysis & Policy*, 49, 1-6.

Fikru, M., & Gautier, L. (2017). Environmental taxation and mergers in oligopoly markets with product differentiation. *Journal of Economics*, 122(1), 45-65.

McDonald, S., & Poyago-Theotoky, J. (2017). Green technology and optimal emissions taxation. *Journal of Public Economic Theory*, *19*(2), 362-376.

Ouchida, Y., & Goto, D. (2011). A note on environmental R&D under time-consistent emission tax. *International Journal of Business and Economics*, *10*(3), 257-260.

Ouchida, Y., & Goto, D. (2014). Do emission subsidies reduce emission? In the context of environmental R&D organization. *Economic Modelling, 36,* 511-516.

Ouchida, Y., & Goto, D. (2016a). Environmental research joint ventures and time-consistent emission tax: Endogenous choice of R&D formation. *Economic Modelling*, *55*, 179-188.

Ouchida, Y., & Goto, D. (2016b). Cournot duopoly and environmental R&D under regulator's precommitment to an emissions tax. *Applied Economics Letters, 23*(5), 324-331.

Petrakis, E., & Poyago-Theotoky, J. (2002). R&D subsidies versus R&D cooperation in a duopoly with spillovers and pollution. *Australian Economic Papers*, *41*(1), 37-52.

Poyago-Theotoky, J. (1999). A note on endogenous spillovers in a non-tournament R&D duopoly. *Review of Industrial Organization, 15*(3), 253-262.

Poyago-Theotoky, J. (2007). The organization of R&D and environmental policy. *Journal of Economic Behavior & Organization, 62*(1), 63-75.

Poyago-Theotoky, J. (2010). Corrigendum to “The organization of R&D and environmental policy”. *Journal of Economic Behavior & Organization, 76*(2), 449.

Poyago-Theotoky, J., & Teerasuwannajak, K. (2002). The timing of environmental policy: A note on the role of product differentiation. *Journal of Regulatory Economics, 21*(3), 305-316.

Puller, S. L. (2006). The strategic use of innovation to influence regulatory standards. *Journal of Environmental Economics & Management, 52*(3), 690-706.

Ramirez, R. & Kayalica, M. (2001). Environmental Policies and Mergers of Local Firms. *Instituto Internacional de Gobernabilidad,* 1-16.

Vives, X. (2008). Innovation and competitive pressure. *The Journal of Industrial Economics*, *56*(3), 419-469.

Chapter 3

Monopoly with Corporate Social Responsibility and Environmental R&D

Abstract

Our research topic is the monopolist with corporate social responsibility in the presence of environmental R&D. This project lies at the frontier between environmental economics and industrial organization. We model a monopolist with corporate social responsibility setting in a three-stage game; in the first stage, the regulator determines the emission tax to maximize welfare; in the second stage, the monopolist determines R&D to maximize its objective function; in the third stage, the monopolist determines outputs to maximize its objective function. The study focuses on one major question: under the structure of monopoly with corporate social responsibility, if we change the parameters of R&D technology parameter, the degree of social responsibility, and product differentiation, what are the effects on profit, R&D, environmental damage, consumer surplus, and welfare? We find that: (1) increasing R&D technology parameter enhances welfare in terms of higher consumer surplus and lower damage, while also leading to increases in R&D and decreases in profit; (2) increasing the degree of social responsibility increases R&D and welfare in terms of higher consumer surplus and profit, but also increases the damage; and (3) increasing product differentiation increases profit, R&D, and welfare; it also increases the damage but decreases consumer surplus.

3.1 Introduction

Our goal is to study the effect of monopoly with corporate social responsibility (CSR). The World Business Council for Sustainable Development (WBCSD) defines CSR as "corporate commitment to contribute to sustainable economic development, employees and their families, local communities and the whole society in order to improve their quality of life" (WBCSD, 2000). Every country has industries which are operating at different market power; such industries include public transportation, agriculture, natural resources, construction, hydraulic engineering, health and hygiene, aerospace, and nuclear energy. Analyzing monopoly with corporate social responsibility helps us to understand in which circumstances the corporation and society can maintain a sustainable development pace while still achieving better results in terms of profit, R&D, environmental protection, consumer surplus, and welfare.

The related literature focuses on several different aspects of the issue. We start with an overview of the different definitions regarding CSR. Székely and Knirsch (2005) examine the best available metrics used by major German multinationals to measure corporate sustainability, while Paton and Siegel (2005) summarize major results based on an interdisciplinary subjects' workshop of CSR. After that, there is an important debate within the literature regarding the relationship between corporate social responsibility activities and financial performance (e.g. Aupperle et al., 1985; Wood and Jones, 1995). Next, Reinhardt et al. (2008) analyze the concept of corporate social responsibility through different aspects, such as the legality of CSR in different countries, motivations for firms to undertake CSR investments, the relationship between CSR investments and corporate financial performances, and policy implications regarding CSR. Lyon and Maxwell (2008) show a theory review paper of the Corporate Social Responsibility and the Environment. Lyon and Maxwell (2008) analyze two different definitions of CSR: "altruistic" CSR with "strategic" CSR. Additionally, Lambertini and Tampieri (2010) analyze how the presence of the CSR firm modifies the industry's equilibrium outcomes. Moreover, Orlitzky et al. (2011) provide a review of three theoretical approaches of strategic CSR and environmental sustainability. Lambertini and Tampieri (2011) discuss stability conditions for mixed oligopoly equilibria with CSR and profit-seeking firms to coexist in the presence of pollution. Lambertini and Tampieri (2015) compare equilibrium profit and welfare between two markets: a pure Cournot oligopoly of profit-seeking firms and a mixed oligopoly with a CSR firm. Following this research line, Lambertini et al. (2016) build a state-linear differential game about an asymmetric Cournot duopoly with capital accumulation a la Ramsey and environmental externality. They analyze the CSR in a dynamic setting through examining the capital accumulation functions between a CSR and a profit-seeking firm. In addition, Zhao et al. (2012) develop a comprehensive set of CSR indicator systems that can be used to measure the CSR performance of construction enterprises and make CSR guidelines fit within a scientific approach.

We use a CSR monopolist setting of a three-stage game. In the first stage, the regulator determines the emission tax to maximize welfare; in the second stage[1], the monopolist determines R&D to maximize its objective function; in the third stage, the monopolist determines outputs to maximize its objective function.

The study focuses on one major question: under the structure of a CSR monopolist, if we change the parameters of R&D technology parameter, the degree of social responsibility, and product differentiation, what are the effects on profit, R&D, environmental damage, consumer surplus, and welfare? We find that: (1) increasing R&D technology parameter enhances welfare in terms of higher consumer surplus and lower damage, while increasing R&D and decreasing profit; (2) increasing the degree of social responsibility increases R&D and welfare in terms of higher consumer surplus and profit, but increases the damage as well; and (3) increasing product differentiation increases profit, R&D, and welfare; it also increases the damage, but decreases consumer surplus.

This paper is organised as follows. The next section reviews the literature and the third section introduces the model. The fourth section is an exploration of the monopolist with corporate social responsibility. The fifth section presents the major results and the last section presents the conclusions.

3.2 Literature Review

Different scholars hold different views regarding the definition of CSR. Friedman (1970) argues that enterprises' primary social responsibility is shareholders' wealth maximization, while Carroll (1979) considers CSR to be a comprehensive typology of economic, legal, ethical, and discretionary responsibilities. Freeman (1984) considers CSR to be related to investments in order to balance a greater number of stakeholder interests or demands. The European Commission (2002) extends this term by integrating economic sustainability, environmental sustainability, and social sustainability: corporations manage their operations in such a way as to enhance economic growth and increase competitiveness whilst ensuring environmental protection and promoting consumer interests.

Székely and Knirsch (2005) examine the best available metrics used by major German multinationals to measure corporate sustainability. Six groups of companies are analyzed: (1) financial companies (i.e., Deutsche Bank); (2) information and communications companies (i.e., Axel Springer); (3) energy companies (i.e. EON Ruhrgas); (4) transportation companies (i.e., Deutsche Lufthansa); (5) manufacturing companies (i.e., Robert Bosch); and (6) pharmaceutical companies (i.e. Schering). Three major metrics are employed in order to determine the sustainable performance for each company: economic sustainability metrics, environmental sustainability metrics, and social sustainability metrics. The economic sustainability

[1] We also can assume in the second stage the monopolist decides on R&D and outputs simultaneously.

metrics are derived primarily from the multinational's annual reports, such as Lufthansa's report of total income, net income, cash flow, and earning per share. The environmental sustainability metrics capture data from a company's polluting emissions to energy consumption. For example, Robert Bosch provides data in energy consumption (GWh), CO_2 emissions (in 1000 m^3), water consumption (mill m^3), wastewater (mill m^3), waste (mill $tons^3$), and environmental protection costs and investment. The measurement of social sustainability focuses on employee numbers, female ratios, accident numbers, and trainee numbers. For example, Axel Springer reports its social sustainability metrics as follows: (1) average fluctuation and net change in employment; (2) proportion of staff covered by industry-wide collective tariff agreements; (3) practice of documentation of industrial accidents and illnesses; (4) lost days/absence rates due to injuries in industrial accidents and work-related deaths; (5) average hours of training/further training per employee; (6) proportion of female/male employees in management and executive positions.

Paton and Siegel (2005) define the CSR as "actions that appear to further some social good, beyond the interests of the firm and that which is required by law." They explore: (1) the economic and managerial implications of the trend that increases a firm's CSR investments to its stakeholders; (2) the optimal level of regulation regarding CSR activities; (3) the relationship between CSR investment and a firm's profitability; and (4) guidance for managers on how to allocate resources to CSR and how to incorporate CSR in their business strategies. They also summarize the following results based on an interdisciplinary subjects' workshop of CSR: the determinants of the propensity to engage in CSR, the history and contributions of CSR investment, the link between environmental performance and a firm's profitability, and how to measure the productivity of CSR.

There is an important debate regarding the relationship between corporate social responsibility activities and financial performance. Carroll (1991) asserts that CSR consists of four categories of social responsibilities: economic, legal, ethical, and philanthropic. Economic responsibilities refer to the idea that corporations produce demanding goods or services and aim for profit-maximizing. Legal responsibilities mean that corporations need to obey the written law. Ethical and philanthropic responsibilities indicate that corporations behave beyond legal requirements and contribute to social norms, resulting in doing the right things and avoiding harm. The four categories of social responsibilities can be depicted as a pyramid, in which economic responsibilities are considered to be the foundation of the other responsibilities; without successfully implementing economic responsibilities, other social responsibilities cannot be achieved. Philanthropic responsibilities are considered to be at the top of the pyramid. Corporations are required to fulfill all social responsibilities simultaneously. Branco and Rodrigues (2006) argue that even if a corporation has a public-minded manager, it is still difficult to make CSR investments if the corporation cannot see the future benefits. Aupperle et al. (1985) illustrate that there are no statistically significant relationships between CSR activities and financial performance. Wood and Jones (1995) stress that bad social performance is detrimental to corporate profitability. Pava and Krausz (1996) suggest that CSR firms do not perform worse than the other firms; in fact, they show some evidence that CSR activities enhance corporate financial performance. In their empirical studies, Margolis and Walsh (2003) and Orlitzky et al. (2003) also confirm this positive relationship. However, McWilliams and Siegel (2000) contend that much of the empirical CSR literature is econometrically flawed due to the omission of strategic variables. After these strategic variables have been taken into account, results show that CSR activities have a neutral effect on financial performance. Waddock and Graves (1997) study the direction of the causation between CSR activities and financial performance. They find that CSR activities depend on financial performance and that this relationship is positive. Orlitzky (2005) gives further insights and concludes that high CSR performance is both a determinant and a consequence of high financial performance. Improved social performance builds reputation, which better serves financial performance, while great financial performance provides enough funding for CSR investments.

Reinhardt et al. (2008) analyze the concept of corporate social responsibility through different aspects, such as the legality of CSR in different countries, motivations for firms to undertake CSR investments, the relationship between CSR investments and corporate financial performance, and policy implications regarding CSR. First, Reinhardt et al. (2008) analyze the legality of CSR in different countries and conclude that the legal basis for the view that corporate directors have a fiduciary duty to maximize profits for shareholders is not very strong. Although the legal system supports corporate directors having a fiduciary duty to maximize profits for shareholders, it still leaves room for firms to sacrifice profits in favour of social interest. In addition, the business judgment rule provides judicial protection for public-minded managers, as long as corporate directors claim some connections to the firm's long-term benefits. Second, under market pressures, CSR firms have to raise prices, reduce wages, and accept smaller profits, resulting in lower stock prices and capital investments. This will lead to reductions in market share in the short term or even push a corporation out of business in the long run. Given this, why would a firm still choose to make CSR investments? Some reasons include: (1) the imposition of public policies may require firms to carry out some socially beneficial investments; (2) CSR investments may not be costly to the firm; (3) the CSR investments may reduce a firm's business expenses more than their cost; (4) CSR investments may improve a firm's reputation, which leads to an increase in revenue; (5) firms may over-comply with environmental, health, or safety laws in order to spur future stricter regulations, which would provide a competitive advantage over competitors; (6) firms may undertake CSR investments voluntarily (Voluntary CSR), or may also be forced to make CSR investments under pressure from external constraints (Reluctant CSR); and (7) principal/agent problems or misjudging the potential profitability by managers may lead to short-term CSR investments (Unsustainable CSR). Evidence suggests that most firms view CSR investments like they view other business activities. Instead of altruistically sacrificing profits, firms engage in CSR activities with the aim of increasing their profits. Reinhardt et al. (2008) consider that the relationship between CSR investments and profitability may be best characterized as some firms will generate long-term profits from some CSR investments some of the time. For policy implications, Reinhardt et al. (2008) consider that additional CSR investments may increase welfare because the existing level of regulations of environmental protection is below the socially optimal level.

Lyon and Maxwell (2008) show a theory review paper of the Corporate Social Responsibility and the Environment. Lyon and Maxwell (2008) analyze two different definitions of CSR: “altruistic” CSR with “strategic” CSR. Altruistic CSR means profit-sacrificing CSR whereas strategic CSR means profit-enhancing CSR. In the discussion of welfare effects of altruistic CSR, Lyon and Maxwell (2008) point out that stock shares in an altruistic CSR firm can be considered as a charity-investment bundle. There are two types of investors may have investments incentives to this charity-investment bundle and make contributions to an altruistic CSR firm: the public minded investors and investors that view the altruistic CSR firm as competing with other non-profits corporations in the charitable donations market. Under these conditions, an altruistic CSR firm may increase welfare. In our model, by internalizing consumer surplus and damage into the objective function for the CSR monopolist, the firm has the features of an altruistic CSR firm.

Lambertini and Tampieri (2010) analyze how the presence of the CSR firm modifies the equilibrium industry’s outcomes. They consider that a CSR firm maximizes its objective function based on its profit, a certain share of the pollution, and a portion of consumer surplus. They find that, in a large market, the presence of a CSR firm would (1) achieve higher profits compared with other profit-seeking firms; (2) improve overall welfare compared with a situation in which all firms are profit-seeking firms; (3) lower the tax rate faced by profit-seeking firms; and (4) encourage other profit-seeking firms to make green R&D investments.

Orlitzky et al. (2011) provide a review of three theoretical approaches of strategic CSR and environmental sustainability. CSR can be strategic, altruistic, or coerced. Strategic corporate social responsibility can be defined as when an enterprise voluntary undertakes CSR investments which would enhance an enterprise’s economic performance, competitiveness, and reputation. The first theoretical approach of strategic CSR is the theory-of-the-firm approach raised by McWilliams and Siegel (2001). They use cost-benefit analysis as an analytic tool to optimize a firm’s CSR activities. In order to apply this strategical tool successfully, enterprises need to consider CSR as a normal good and analyze CSR’s demand and supply conditions. Once the firm receives the correct analyses, then an enterprise conducts a cost-benefit analysis to determine the CSR investments that lead to optimal economic outcomes. Husted and

Salazar (2006) extend this research line and illustrate the superiority of strategic CSR over coerced CSR. The second theoretical approach that helps us to understand the strategic CSR is transaction cost economics. King (2007) points out that an enterprise needs to sacrifice lots of resources in order to increase stakeholders' satisfaction, such as time, financial, and human resources in identifying stakeholder groups, negotiating with representatives from stakeholder groups, and monitoring stakeholder groups' satisfaction. Hosmer (1995) illustrates that, in the long run, CSR can reduce transaction costs through building trust between an enterprise and stakeholder groups, whereas in the short run, an enterprise needs to consider all types of transaction costs in terms of stakeholder management. It is very promising to extend the concept of transaction cost analysis to the dimension of strategic CSR. The third theoretical approach of strategic CSR is the resource-based view of the firm. An enterprise has competitive advantages if it owns valuable, rare, and non-substitutable resources. McWilliams and Siegel (2001) use the resource-based view framework to construct a model of "profit-maximizing" CSR. They posit two companies that produce two identical products, except that one product has its own "social attribute". They find consumers and other stakeholders value the product with "social attribute". As a result, CSR can be a part of a differentiation strategy for products and corporate levels.

Lambertini and Tampieri (2011) discuss stability conditions for mixed oligopoly equilibria with CSR and profit-seeking firms coexisting in the presence of pollution. They compare a matrix of profits which describes two firms that can form in different types of equilibria such as a profit-seeking, a mixed, or a CSR duopoly, concluding that a mixed duopoly equilibrium is stable for low impact of productivity on pollution and high CSR sensitivity to consumer surplus. For their second argument, they obtain the stability conditions of k CSR firms and $n - k$ profit-seeking firms through the requirements for stable cartels (D'Aspremont et al., 1983; Donsimoni et al., 1986). Their results yield that a mixed oligopoly equilibrium is stable conditional on the fewer number of CSR firms.

Lambertini and Tampieri (2015) compare equilibrium profit and welfare between two markets: a pure Cournot oligopoly of profit-seeking firms and a mixed oligopoly with a CSR firm. Their first proposition shows that, in a large market, a CSR firm achieves higher profits than its profit-seeking competitors and increases welfare. The intuition is, a CSR firm takes two factors into account: environmental and social concerns. The environmental concern restrains the CSR firm's output, whereas the social concern promotes production for a CSR firm. In a large market, the social concern more than offsets the environmental concern, because an output expansion with a positive price effect is larger than the negative polluting effect. This leads to more production and a higher profit generated by a CSR firm compared with its competitor. In the presence of the CSR firm, the increase in consumer surplus is greater than the pollution damage, which yields a higher value of welfare. The presence of the CSR firm forces the other profit-seeking firms to implicitly internalize both the negative externality associated with pollution as well as consumer surplus through the intersection of best reply functions and to turn this into higher welfare. Lambertini and Tampieri (2015) then introduce the first-best taxation policy and get their second proposition: in a large market, a CSR firm generates higher profits compared to its competitors, and the presence of one CSR firm increases profits for its profit-seeking competitors.

Lambertini et al. (2016) build a state-linear differential game about an asymmetric Cournot duopoly with capital accumulation a la Ramsey and environmental externality. They analyze the CSR in a dynamic setting through examining the capital accumulation functions between a CSR and a profit-seeking firm. They discover that: (1) in a large-size market, the CSR firm accumulates higher profits and capital than its profit-seeking competitor; (2) in a medium-size market, the CSR firm achieves higher profits but less capital than its profit-seeking competitor; (3) in a small-size market, the CSR firm generates lower profits and capital compared to its profit-seeking competitor.

Zhao et al. (2012) develop a comprehensive set of CSR indicator systems that can be used to measure the CSR performance of construction enterprises and make CSR guidelines. They start with the introduction of the major CSR evaluation system for different categories; for example, the United Nations Global Compact (2000) belongs to the compacts and initiatives of CSR, while the Dow Jones Sustainability Index (DJSI) and Environmental Performance Index (EPI) are the main CSR evaluation indexes. The CSR indicator system is based on each stakeholder group from the construction enterprises, such as employees, shareholders, customers, suppliers and partners, government, environment and resources, community, competitors, and NGOs. Particularly for the stakeholder group of environment and resources, the main CSR performance issues are related to conservation of energy and environment protection. The associated CSR indicators for the conservation of energy and resources are: water conservation in the construction process, land use efficiency, minimizing construction waste and energy consumption, promoting the use of renewable resources, technological innovation for energy conservation, and encouraging environmental protection awareness for labor force. The associated CSR indicators for environmental protection are: reductions in pollution emissions, enhancing the corporate environmental management system, compliance with environmental laws and regulations, corporation engagement in R&D that improves the project's energy efficiency and encourages green construction, and improvement of recycling processes.

Our paper makes the following contributions to the literature: first, our study fully considers product differentiation. This is different from major strands of the literature which only study homogenous products. Second, our research simultaneously includes positive R&D technology parameter and environmental R&D investments into the model design, whereas other studies usually ignore these factors. Finally, there is a government decision stage in our model, which is absent from other studies.

3.3 The Model

We consider a monopolist with corporate social responsibility. The monopolist produces two products and generates pollution. The government uses an emission tax act as an environmental policy instrument. The monopolist makes R&D investment for pollution reduction and R&D technological effects exist between the two products. Instead of profit-maximizing behavior, the monopolist with corporate social responsibility internalizes (partly) consumer surplus and environmental damage into its objective function. The game has three stages. In the first stage, the regulator determines the emission tax to maximize welfare; in the second stage, the monopolist determines R&D to maximize its objective function; in the last stage, the monopolist determines outputs to maximize its objective function. Our goal is to study the effects on profit, R&D, environmental damage, consumer surplus, and welfare in the CSR monopolist and government's tax regulation, if we change the parameters of R&D technology parameter, the degree of social responsibility, and product differentiation.

Specifically: the CSR monopolist produces two differentiated products (i, j). Each product has a linear demand as

$$p_i\left(q_i , q_j\right) = a - \left(q_i + \theta\, q_j\right), (i, j = 1, 2;\ i \neq j) \tag{1}$$

where $a > 0$ is a market size parameter. Product differentiation is captured by $\theta \epsilon (-1,1]$. If $\theta \in (-1,0)$ products are complements; if $\theta = 0$ products are independent; if $\theta \in (0,1)$ products are imperfect substitutes; if $\theta = 1$ products are homogenous.

Both products have the same cost structure of

$$C\ (q_i) = c\, q_i, (i, j = 1, 2;\ i \neq j) \tag{2}$$

The monopolist uses end-of-pipe technologies as its emissions-reducing technology.[2] End-of-pipe technologies abate emissions by adsorbing emissions at the end of the production process.

The value of each product's emissions per unit of output is assumed to be one. Product i's R&D effort is denoted as z_i. Product i receives benefits both from its own R&D efforts and from efforts of product j. The monopolist's R&D expenditures are defined as

$$\left(\frac{\gamma}{2}\right)\ \left(z_i^2 + z_j^2\right) \tag{3}$$

[2] Petroleum and chemical industries typically have end-of-pipe technologies for pollution abatement such as desulfurization equipment and denitrification equipment.

A lower value of ɣ implies a higher efficiency of R&D ($ɣ > 0$).

The R&D spillover rate is $\beta \epsilon [0,1]$. Good i's positive externality from good j's R&D efforts is denoted as βz_j. The monopolist's emission function is

$$E = \left(q_i - z_i - \beta z_j\right) + \left(q_j - z_j - \beta z_i\right) \tag{4}$$

The monopolist's profit is represented as

$$Profit = \left(a - \left(q_i + \theta q_j\right)\right) q_i - c q_i - t\left(q_i - z_i - \beta z_j\right) - \left(\frac{ɣ}{2}\right) z_i^2 + \left(a - \left(q_j + \theta q_i\right)\right) q_j - c q_j - t\left(q_j - z_j - \beta z_i\right) - \left(\frac{ɣ}{2}\right) z_j^2, (i, j = 1, 2;\ i \neq j) \tag{5}$$

As derived in the Appendix, consumer surplus is measured by

$$CS = \left(\frac{1}{2}\right)\left(q_i^2 + 2\theta q_i q_j + q_j^2\right) \tag{6}$$

Government tax revenue is represented as

$$Tax\ Revenue = t\,E \tag{7}$$

Emissions cause environmental damage. The environmental damage is

$$D = g\,E^2 \tag{8}$$

where $g > 0$ represents the marginal polluting intensity of output.

Welfare is defined as

$$W = Profit + CS + Tax\ Revenue - D \tag{9}$$

The objective function for the CSR monopolist is

$$\pi_{OBJ} = Profit + v(CS - D) \tag{10}$$

where $v\ \epsilon\ [0,1]$ represents the degree of social responsibility internalized by the firm. With $v = 0$, the firm becomes a simple profit maximizer. With $v = 1$, the objective function of the firm is close to the social planner's objective function, except that the former does not incorporate tax revenue.

3.4 The Monopolist with Corporate Social Responsibility

In the first stage, the regulator determines the emission tax t to maximize welfare. In the second stage, the monopolist determines R&D z_i and z_j to maximize π_{OBJ}. In the third stage, the monopolist determines outputs q_i and q_j to maximize π_{OBJ}.

In Stage 3, the objective function is given by:

$$\pi_{OBJ} = Profit + v(CS - D) \tag{11}$$

From the first-order conditions, we get equilibrium output.

$$q_1 = q_2 = \frac{a-c-t+2gv(z_1+z_2+z_1\beta+z_2\beta)}{2-v+4gv+2\theta-v\theta} \tag{12}$$

In Stage 2, the monopolist chooses R&D z_1 and z_2 to maximize π_{OBJ}. By substituting (12) into (11) we get the objective function in terms of R&D.[3]

Solving the two first-order conditions $\frac{\partial \pi_{OBJ}}{\partial z_1} = 0$ and $\frac{\partial \pi_{OBJ}}{\partial z_2} = 0$ yields equilibrium R&D:

$$z_1 = z_2 = \frac{(1+\beta)(4(-a+c)gv+t(-2+v)(1+\theta))}{-2\gamma+v(4g(-2+v)(1+\beta)^2+\gamma-4g\gamma)+(-2+v)(4gv(1+\beta)^2+\gamma)\theta} \tag{13}$$

In Stage 1, the regulator determines the emission tax t to maximize welfare as defined by (9).

By substituting (12) and (13) into (9), we can get the welfare function in terms of t and other parameters.[4]

The regulator maximizes W through t by setting $\frac{\partial W}{\partial t} = 0$. Then, the first-order condition yields the equilibrium tax t. Then, we substitute this equilibrium tax back into (12) and (13) to obtain for equilibrium values of R&D and output.

In Subgame Perfect Nash Equilibrium, equilibrium values of emission tax, R&D, output, pollution reduction, pollution, marginal social damage, profit, operational profit, tax expenditure, R&D spending, welfare, consumer surplus, government revenue, and damage are shown in the appendix.

[3] The expression for objective function is not shown, due to its length.
[4] The expression for welfare is not shown, due to its length.

3.5 Results

Table 1. Experiments

Experiments	**Fixed Parameters**	**Variable**
EXP1- R&D technology parameter	$a = 1005$ $c = 5$ $\gamma = 100$ $v = 0.3$ $\theta = 0.5$ $g = 0.6$	R&D technology parameter (β)
EXP2- Degree of social responsibility	$a = 1005$ $c = 5$ $\gamma = 100$ $\beta = 0.2$ $\theta = 0.5$ $g = 0.6$	The degree of social responsibility (v)
EXP3- Product differentiation	$a = 1005$ $c = 5$ $\gamma = 100$ $\beta = 0.2$ $v = 0.3$ $g = 0.6$	Product differentiation (θ)

We carry out three experiments (See Table 1). Experiment 1 investigates the effects on equilibrium outcomes of R&D technology parameter. Experiment 2 examines the effects on equilibrium outcomes of the degree of social responsibility internalized by the firm. Experiment 3 shows the equilibrium outcomes if product differentiation is varied.

3.5.1 Effects of R&D Technology Parameter

Experiment 1: We fix $a = 1005,\ c = 5,\ \gamma = 100,\ v = 0.3,\ \theta = 0.5,$ and $g = 0.6$. We vary β to see what its effects on equilibrium variables are.

Proposition 1.

a) The following variables increase with R&D technology parameter: output, tax, R&D, pollution reduction, operational profit,[5] welfare, and consumer surplus.

b) The following variables decrease with R&D technology parameter: pollution, marginal social damage, profit, tax expenditure, government revenue, and damage.

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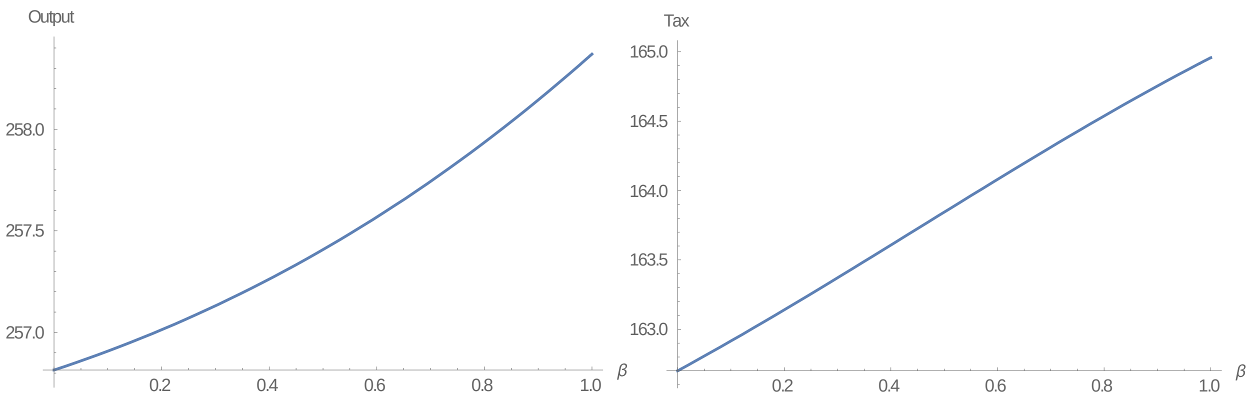
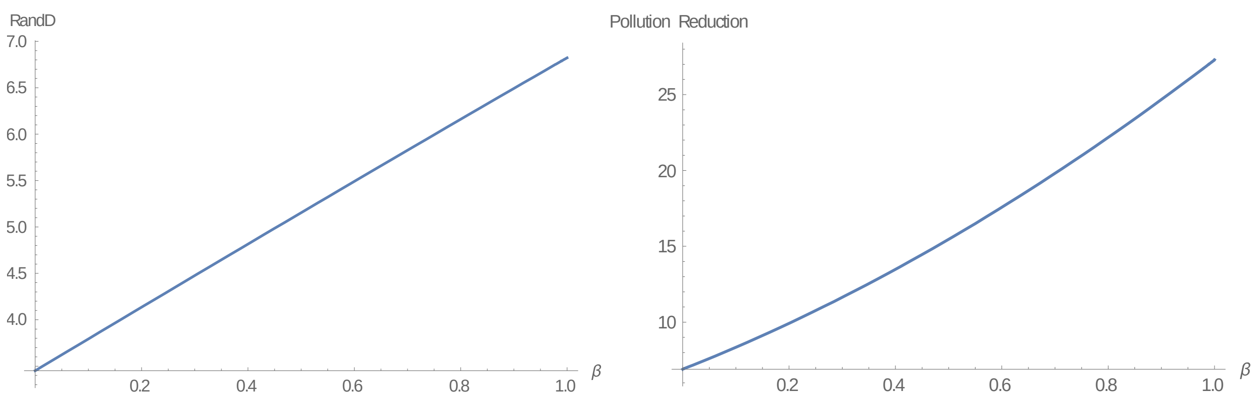
[5] Operational Profit is defined as the monopolist's revenue minus production costs, without considering the emission expenditures and the R&D expenditures.

Figure 1. Comparative statics analysis in output and tax with respect to R&D technology parameter.



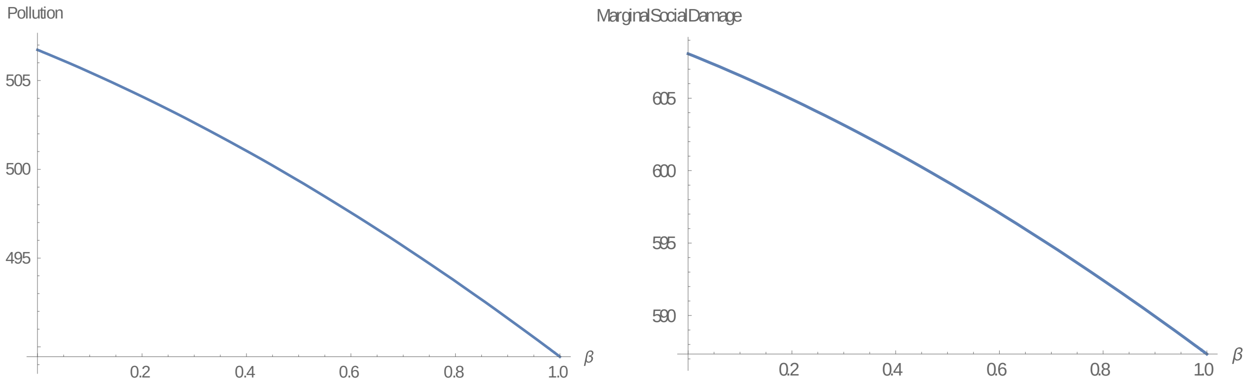
As R&D technology parameter increases, output and tax increases (Figure 1). As R&D technology parameter becomes higher, there is less emission expenditure for each unit of output produced, and the CSR monopolist produces more output. Thus, the government increases tax correspondingly with the aim of reducing emissions.

Figure 2. Comparative statics analysis in R&D and pollution reduction with respect to R&D technology parameter.



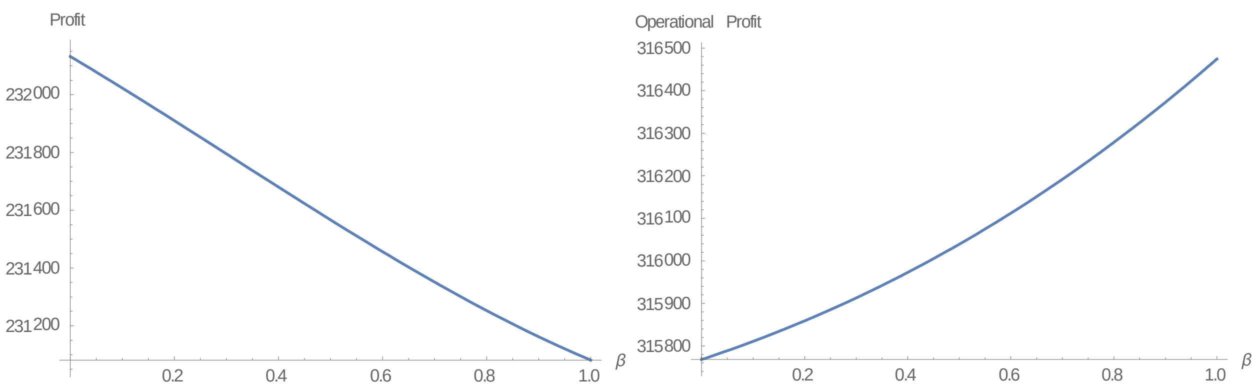
As R&D technology parameter increases, R&D and pollution reduction increase (Figure 2). The firm internalizes the positive R&D technological effects, since output is increasing with R&D technology parameter. Higher tax stimulates more R&D investments and pollution reduction in order to reduce emission expenditure.

Figure 3. Comparative statics analysis in pollution and marginal social damage with respect to R&D technology parameter.



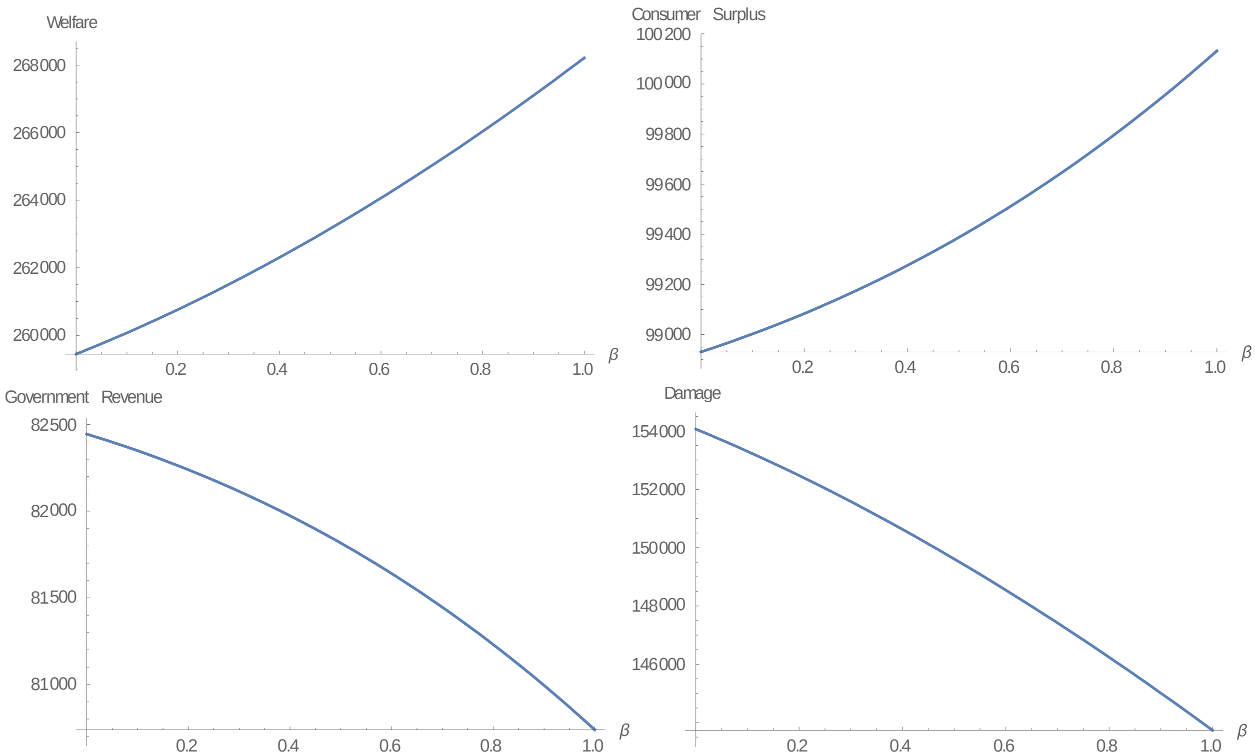
Higher R&D technology parameter leads to less pollution and marginal social damage (Figure 3). As R&D technology parameter increases, even though more R&D and output are generated but tax also becomes higher, eventually, the production-increasing effect is dominated by the pollution-reducing effect, resulting in lower pollution and marginal social damage.

Figure 4. Comparative statics analysis in profit and operational profit with respect to R&D technology parameter.



Profit is deceasing in R&D technology parameter because, as R&D technology parameter increases, negative effects of higher R&D spending dominate the positive effects of operational profit and tax expenditure (Figure 4).

Figure 5. Comparative statics analysis in welfare, consumer surplus, government revenue, and damage with respect to R&D technology parameter.



Welfare is increasing in R&D technology parameter because: as R&D technology parameter increases, the firm partially internalizes consumer surplus and environmental damage, generating less pollution and more outputs. As R&D technology parameter increases, more output leads to a larger consumer surplus, while less pollution leads to less environmental damage. The government revenue is decreasing in R&D technology parameter due to lower pollution. As a result, as R&D technology parameter increases, the positive effects of higher consumer surplus combined with lower environmental damage outweigh the negative effects of lower profit and government revenue, yielding higher welfare (Figure 5).

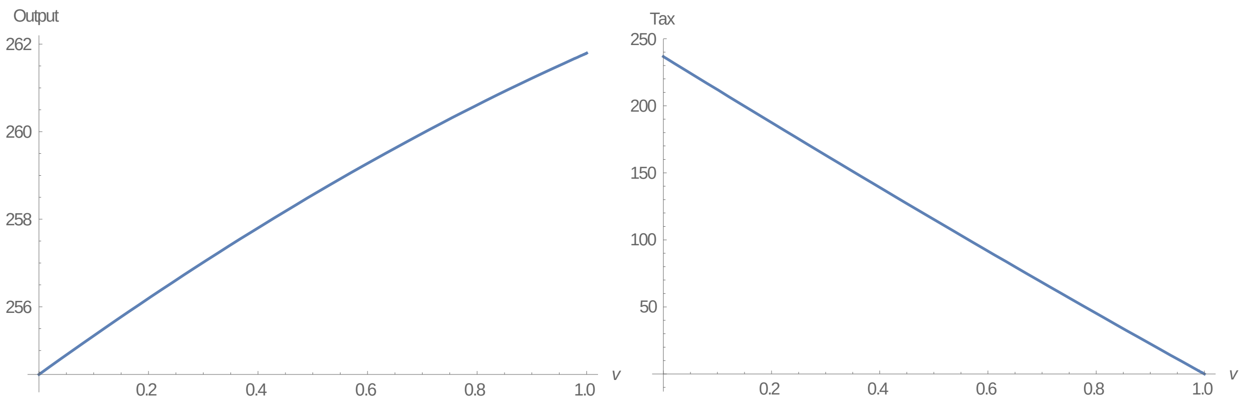
3.5.2 Effects of the Degree of Social Responsibility Internalized by the Firm

Experiment 2: We fix $a = 1005,\ c = 5,\ \gamma = 100,\ \beta = 0.2,\ \theta = 0.5$, and $g = 0.6$. We vary v to analyze its effects on equilibrium variables.

Proposition 2.

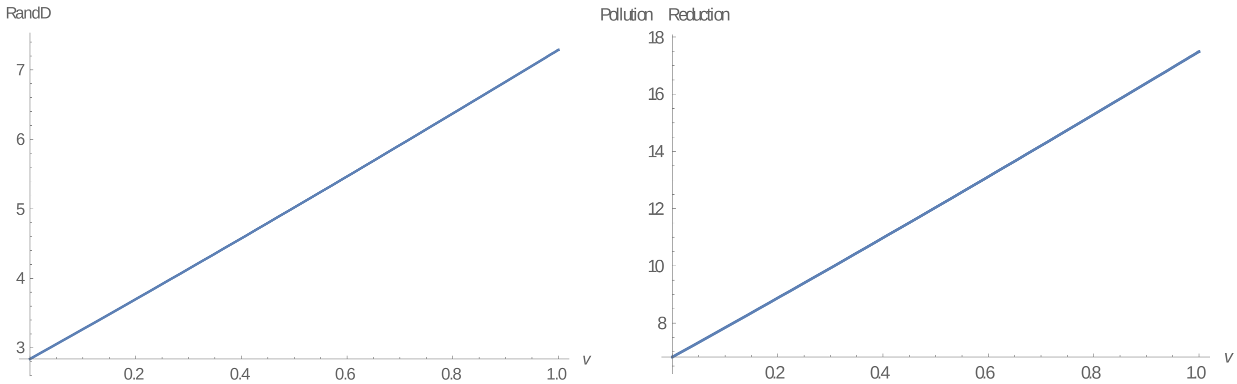
a) *The following variables increase with the degree of social responsibility: output, R&D, pollution reduction, pollution, marginal social damage, profit, operational profit, welfare, consumer surplus, and damage.*
b) *The following variables decrease with the degree of social responsibility: tax, tax expenditure, and government revenue.*

Figure 6. Comparative statics analysis in output and tax with respect to the degree of social responsibility.



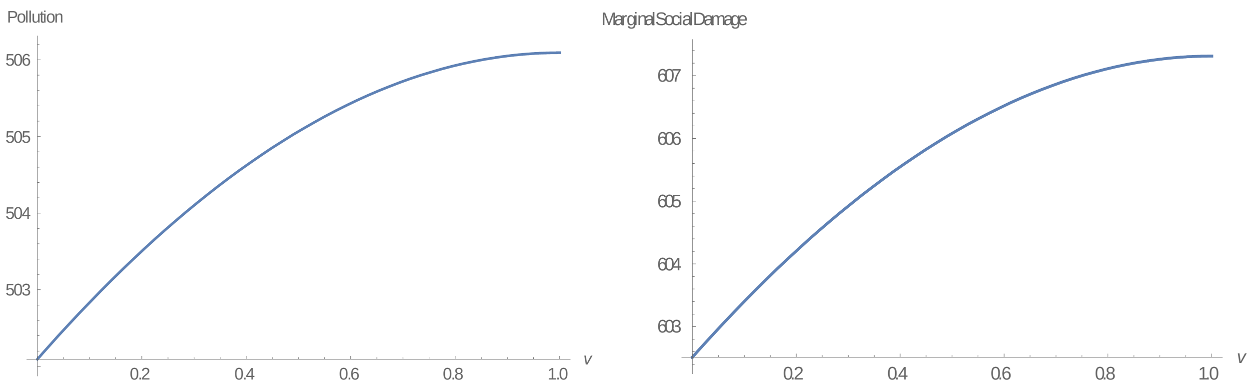
The tax is decreasing in v, but output is increasing in it. As v increases, the government wants more productions (because of higher R&D; see below), and the pollution-reducing effect is dominated by the production-increasing effect, leading to lower tax and higher output. Also, the firm chooses to produce more because it cares more about consumers (Figure 6).

Figure 7. Comparative statics analysis in R&D and pollution reduction with respect to the degree of social responsibility.



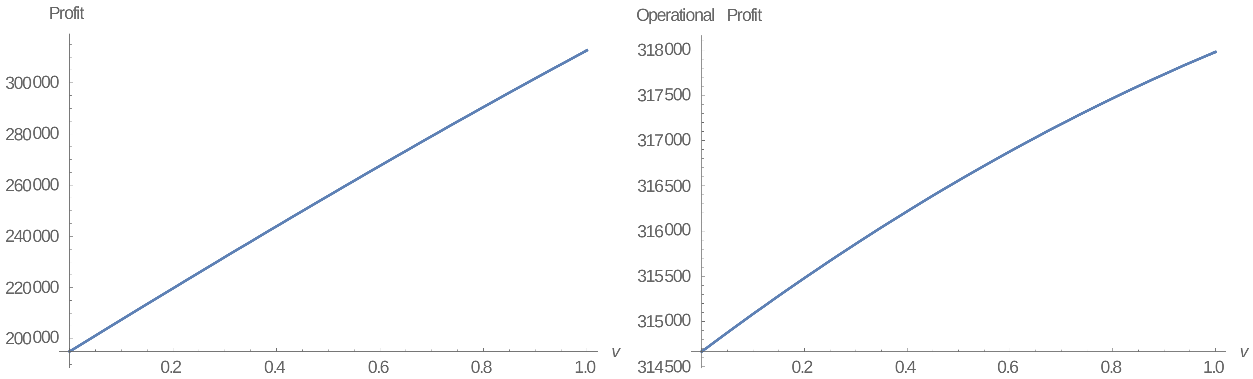
As *v* increases, R&D and pollution reduction also increase. (Figure 7). As *v* increases, firm has a high degree of social responsibility, as a result the firm invests more R&D to make pollution abatement.

Figure 8. Comparative statics analysis in pollution and marginal social damage with respect to the degree of social responsibility.



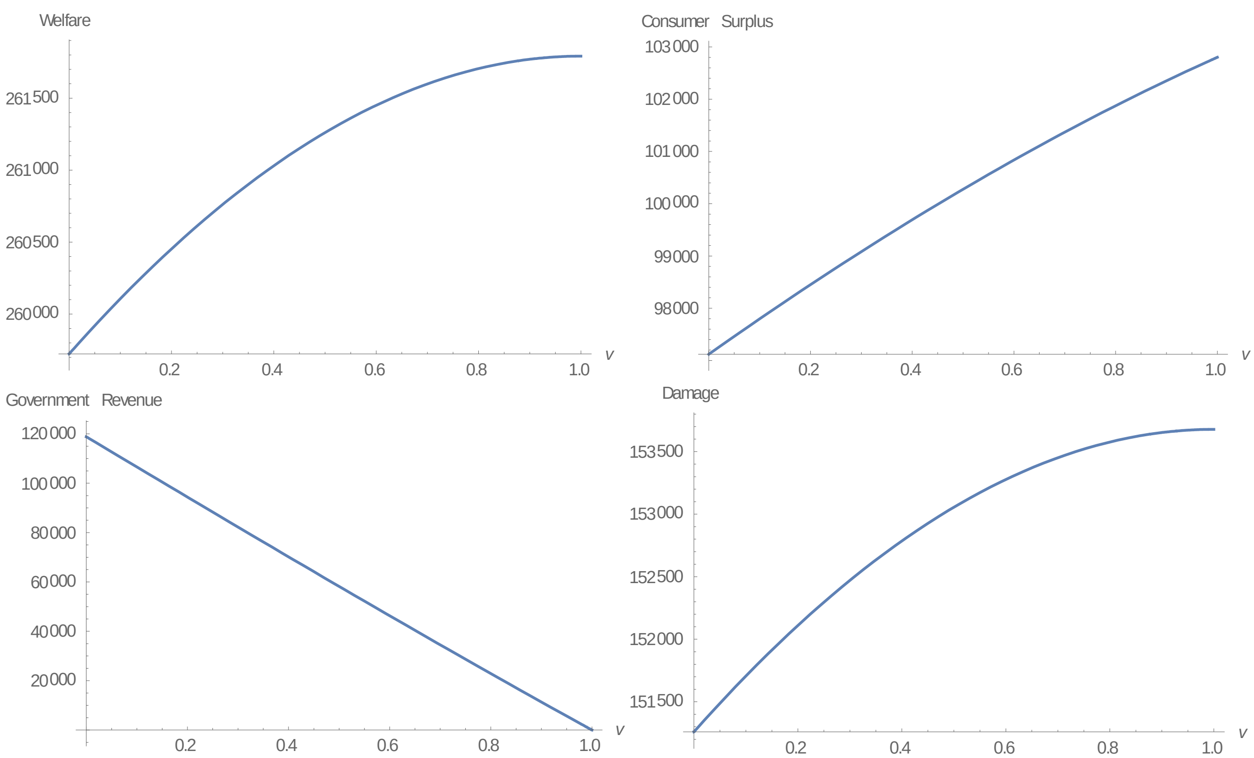
Higher *v* leads to more pollution and marginal social damage (Figure 8). As *v* increases, the increase in output is greater than the pollution reduction, resulting in higher pollution and marginal social damage. Lambertini and Tampieri (2015) provide the intuition for this result, as a CSR firm takes two factors into account: the environmental and social concerns. The environmental concern restrains the CSR firm's output, whereas the social concern promotes the production for a CSR firm. In this case, the CSR monopolist considers the social concern to outweigh the environmental concern.

Figure 9. Comparative statics analysis in profit and operational profit with respect to the degree of social responsibility.



Profit is increasing in *v* because the positive effects of operational profit and tax expenditure dominate the negative effects of R&D spending (Figure 9).

Figure 10. Comparative statics analysis in welfare, consumer surplus, government revenue, and damage with respect to the degree of social responsibility.



Welfare is increasing in *v*. The higher the degree of social responsibility, the more output and consumer surplus are generated. Government revenue is decreasing in *v* due to lower tax. The damage is increasing in v because pollution is increasing in v. As a result, as v increases, the positive effects of consumer surplus combined with profit outweigh the negative effects of government revenue and environmental damage, generating higher welfare (Figure 10).

3.5.3 Effects of Product Differentiation

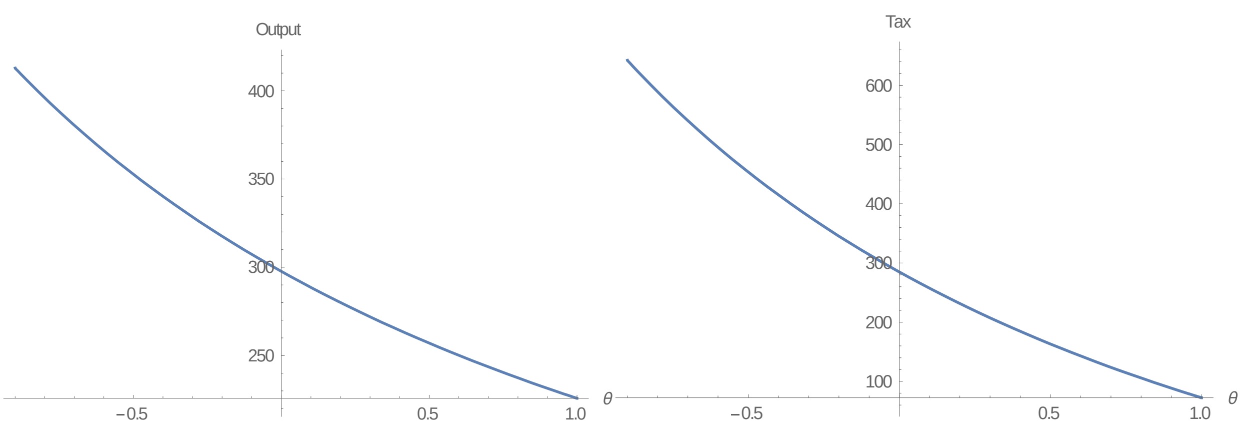
Experiment 3: We fix $a = 1005,\ c = 5,\ \gamma = 100,\ \beta = 0.2,\ v = 0.3$, and $g = 0.6$. We allow θ to change in order to see what its effects on equilibrium variables are.

Proposition 3.

a) Consumer surplus increases with θ.

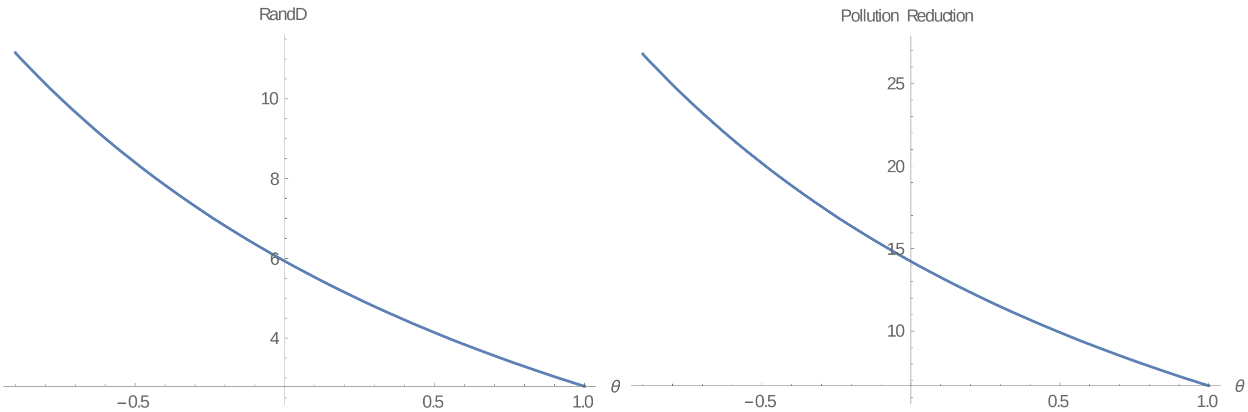
b) The following variables decrease with θ: output, tax, R&D, pollution reduction, pollution, marginal social damage, profit, operational profit, tax expenditure, welfare, government revenue, and environmental damage.

Figure 11. Comparative statics analysis in output and tax with respect to product differentiation.



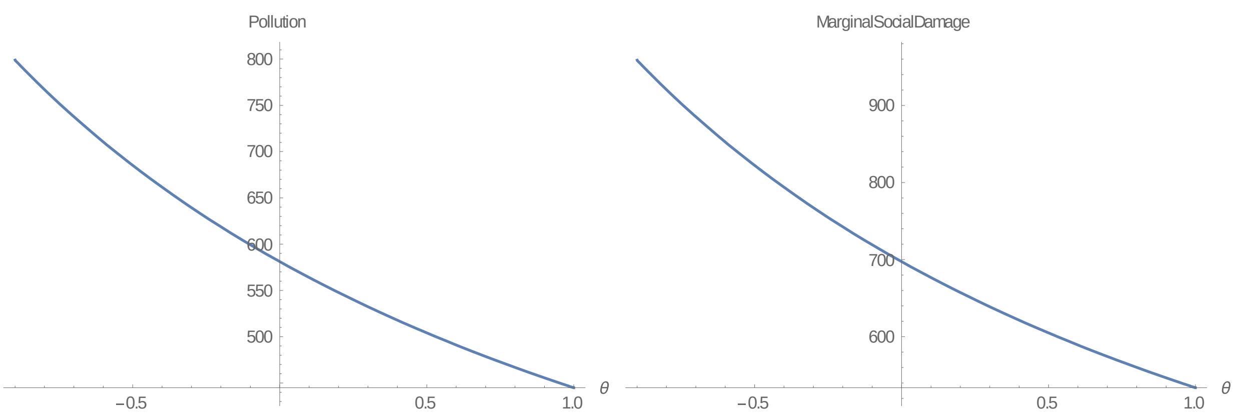
As products become more similar, output and tax decrease. As θ increases, the CSR monopolist produces fewer outputs because consumer demand is lower; however, the government wants more production through reducing the emission tax (Figure 11).

Figure 12. Comparative statics analysis in R&D and pollution reduction with respect to product differentiation.



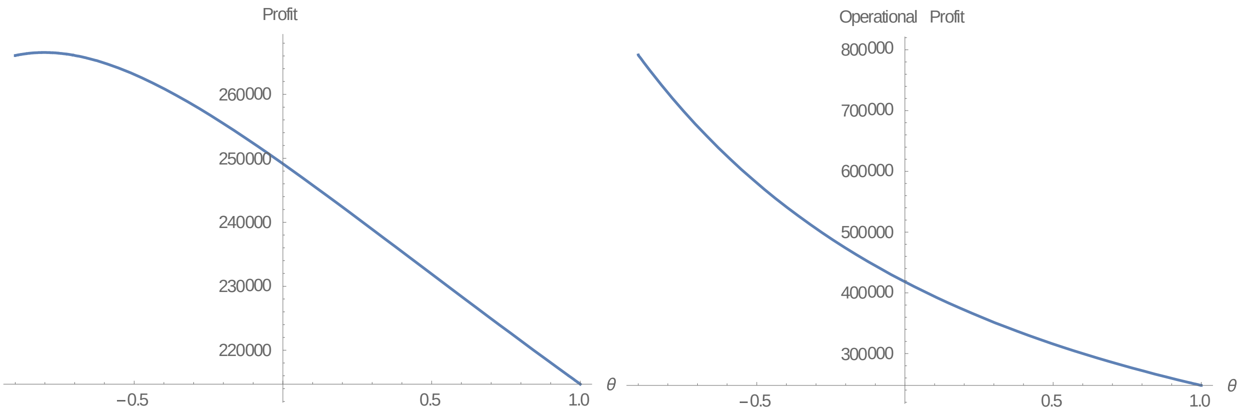
As the products become more similar, and as the emission tax decreases, the CSR monopolist invests less in R&D, generating less pollution reduction (Figure 12).

Figure 13. Comparative statics analysis in pollution and marginal social damage with respect to product differentiation.



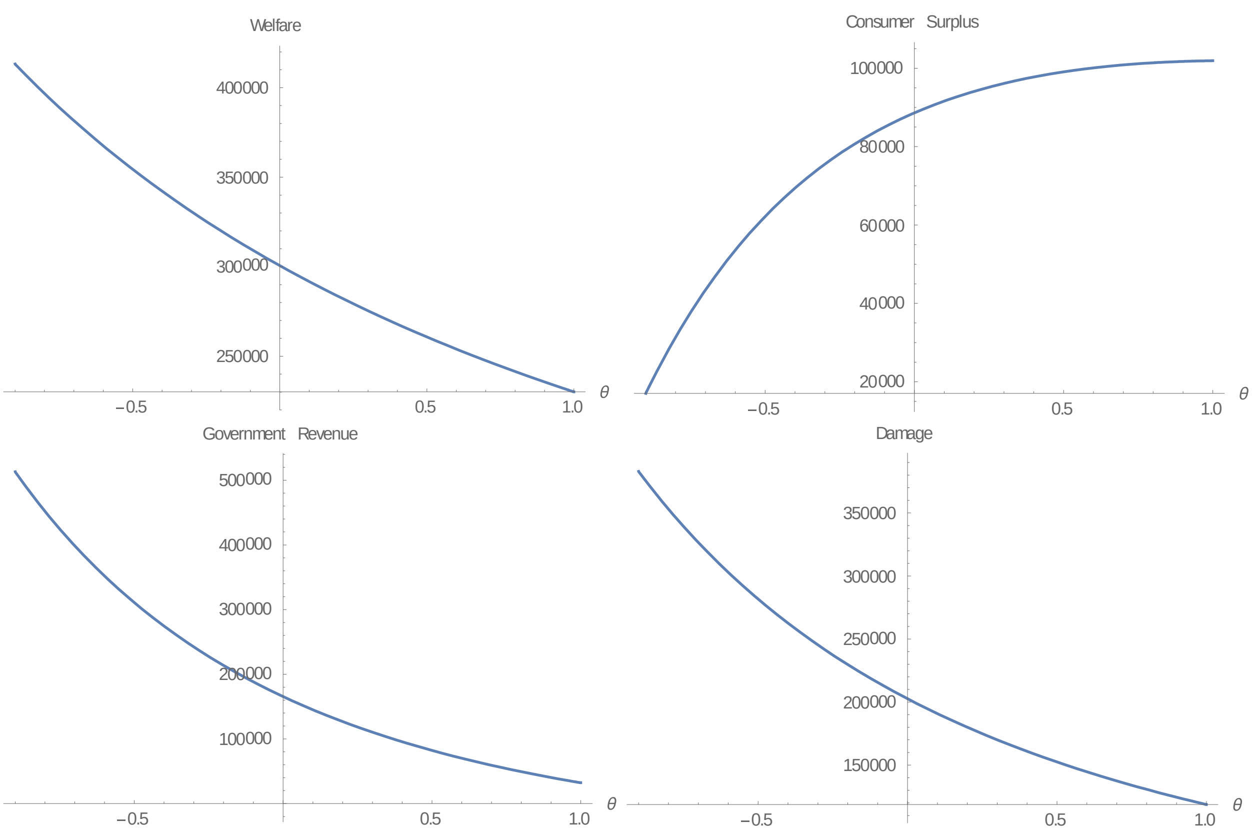
As θ increases, less output leads to lower pollution and marginal social damage. As products become more similar, the decrease in output is more than the decrease in pollution reduction, resulting in lower pollution (Figure 13).

Figure 14. Comparative statics analysis in profit and operational profit with respect to product differentiation.



As products becomes more similar, profit decreases because the negative effect of operational profit dominates the positive effects of lower tax expenditure and R&D spending. As θ increases, it leads to less operational profit and less pollution, and the lower tax leads to less tax expenditure and less R&D (Figure 14).

Figure 15. Comparative statics analysis in welfare, consumer surplus, government revenue, and damage with respect to product differentiation.



As products become more similar, the positive effects of consumer surplus and environmental damage are dominated by the negative effects of profit and government revenue, yielding lower welfare. As θ increases, government revenue decreases due to lower pollution and tax. Additionally, damage is decreasing because pollution is decreasing (Figure 15).

The following table summarizes the comparative statics of the model.

Table 2. Experiments' Results

	Experiment 1 ($\beta\uparrow$)	Experiment 2 ($\upsilon\uparrow$)	Experiment 3 ($\theta\uparrow$)
Output	Increasing	Increasing	Decreasing
Tax	Increasing	Decreasing	Decreasing
R&D	Increasing	Increasing	Decreasing
Pollution Reduction	Increasing	Increasing	Decreasing
Pollution	Decreasing	Increasing	Decreasing
Marginal Social Damage	Decreasing	Increasing	Decreasing
Profit	Decreasing	Increasing	Decreasing
Operational Profit	Increasing	Increasing	Decreasing
Tax Expenditure	Decreasing	Decreasing	Decreasing
R&D Spending	Increasing	Increasing	Decreasing
Welfare	Increasing	Increasing	Decreasing
Consumer Surplus	Increasing	Increasing	Increasing
Government Revenue	Decreasing	Decreasing	Decreasing
Damage	Decreasing	Increasing	Decreasing

3.6 Conclusion

There is an increasing trend for enterprises to engage in social and environment responsibility. Stern (2006) points out that environmental sustainability will become the major social responsibility challenge for enterprises. As a result, enterprises should incorporate actions which contribute to social responsibility, ecologically sustainability, and economic performance.

Our aim is to analyze the effect of the monopolist with corporate social responsibility where the monopolist also invests in environmental R&D. This project lies at the frontier of environmental economics and industrial organization. We use a monopolist with a corporate social responsibility setting of a three-stage game; in the first stage, the regulator determines the emission tax to maximize welfare; in the second stage, the monopolist determines R&D to maximize its objective function; in the third stage, the monopolist determines outputs to maximize its objective function. This study focuses on one major question: under the structure of the monopolist with corporate social responsibility, if we change the parameters of R&D technology parameter, the degree of social responsibility, and product differentiation, what are the effects on profit, R&D, environmental damage, consumer surplus, and welfare?

The main results are summarized in Table 2: Experiment 1 shows output, tax, R&D, pollution reduction, operational profit, welfare, and consumer surplus all increase with R&D technology parameter; Experiment 2 shows output, R&D, pollution reduction, pollution, marginal social damage, profit, operational profit, welfare, consumer surplus, and damage all increase with the degree of social responsibility; Experiment 3 shows consumer surplus increases as products become more similar.

The important policy implication is that the regulator needs to incorporate economic sustainability, environmental sustainability, and social sustainability in their public policies decisions when facing a CSR monopolist. Based on Table 2, three policy implications are developed. First, a policy which encourages increases in R&D technology parameter enhances welfare in terms of higher consumer surplus and lower environmental damage, as well as increases R&D investments. However, the policy lowers profit and government tax revenue. Second, a policy which promotes increases in the degree of social responsibility increases R&D investment and welfare in terms of higher consumer surplus. Also, the policy stimulates the monopolist's profit through increasing its operational profit and reducing its tax expenditure. However, the policy lowers government tax revenue and increases the environmental damage. Third, a policy which promotes increases in product differentiation under the CSR monopolist increases the government's revenue, the CSR monopolist's profit through higher operational profit, R&D investments, and welfare. However, the policy increases environmental damage and lowers consumer surplus.

Under the structure of monopoly with corporate social responsibility where the monopolist invests in environmental R&D to reduce pollution, we analyzed in which circumstances the corporation and society can maintain a sustainable development pace while achieving better results in economic sustainability, environmental sustainability, and social sustainability. The goal for future research is to extend the current CSR model of two products into a CSR model of *n* differentiated products. In addition, we could analyze a larger parameter set: holding everything else constant, if we change the parameters of market size, R&D efficiency, R&D technology parameter, the degree of social responsibility, the marginal polluting intensity of output, and product differentiation, what are the effects on profit, R&D, environmental damage, consumer surplus, and welfare? Following this research line, we can verify the robustness of current results and make new findings.

Appendix.

In Subgame Perfect Nash Equilibrium, equilibrium values of emission tax, R&D, output, pollution reduction, pollution, marginal social damage, profit,[6] operational profit,[7] tax expenditure, R&D spending, welfare, consumer surplus, government revenue, damage are:

$$t=\frac{(a-c)(-1+v)\gamma(8g(-1+v)(1+\beta)^2+\gamma-4g\gamma+(8g(-1+v)(1+\beta)^2+\gamma)\theta)}{4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta))} \tag{14}$$

$$z_1=z_2=$$

$$\frac{(1+\beta)\left(4(-a+c)gv+\frac{(a-c)(-2+v)(-1+v)\gamma(1+\theta)(8g(-1+v)(1+\beta)^2+\gamma-4g\gamma+(8g(-1+v)(1+\beta)^2+\gamma)\theta)}{4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta))}\right)}{-2\gamma+v(4g(-2+v)(1+\beta)^2+\gamma-4g\gamma)+(-2+v)(4gv(1+\beta)^2+\gamma)\theta} \tag{15}$$

$$q_1=q_2=$$

$$-\frac{(a-c)(4g(1+\beta)^2+\gamma)(-\gamma-2(1+\theta)+v(1+\beta)^2(1+\theta)-2\beta(2+\beta)(1+\theta))}{4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta))} \tag{16}$$

$$Pollution\ Reduction=$$

$$\frac{2(1+\beta)^2\left(4(-a+c)gv+\frac{(a-c)(-2+v)(-1+v)\gamma(1+\theta)(8g(-1+v)(1+\beta)^2+\gamma-4g\gamma+(8g(-1+v)(1+\beta)^2+\gamma)\theta)}{4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta))}\right)}{-2\gamma+v(4g(-2+v)(1+\beta)^2+\gamma-4g\gamma)+(-2+v)(4gv(1+\beta)^2+\gamma)\theta} \tag{17}$$

$$Pollution=$$

$$-\frac{2(a-c)\gamma(-\gamma-3(1+\theta)+2v(1+\beta)^2(1+\theta)-3\beta(2+\beta)(1+\theta))}{4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta))} \tag{18}$$

$$Marginal\ Social\ Damage=$$

$$-\frac{4(a-c)g\gamma(-\gamma-3(1+\theta)+2v(1+\beta)^2(1+\theta)-3\beta(2+\beta)(1+\theta))}{4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta))} \tag{19}$$

$$Tax\ Expenditure=$$

$$-\frac{2(a-c)^2(-1+v)\gamma^2(8g(-1+v)(1+\beta)^2+\gamma-4g\gamma+(8g(-1+v)(1+\beta)^2+\gamma)\theta)(-\gamma-3(1+\theta)+2v(1+\beta)^2(1+\theta)-3\beta(2+\beta)(1+\theta))}{(4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta)))^2} \tag{20}$$

[6] The expression for profit is not shown, due to its length.
[7] The expression for operational profit is not shown, due to its length.

$$R\&D\ Spending =$$

$$\frac{(1+\beta)^2\gamma(4(-a+c)gv+\frac{(a-c)(-2+v)(-1+v)\gamma(1+\theta)(8g(-1+v)(1+\beta)^2+\gamma-4g\gamma+(8g(-1+v)(1+\beta)^2+\gamma)\theta)}{4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta))})^2}{(-2\gamma+v(4g(-2+v)(1+\beta)^2+\gamma-4g\gamma)+(-2+v)(4gv(1+\beta)^2+\gamma)\theta)^2} \tag{21}$$

$$Welfare =$$

$$-\frac{(a-c)^2(4g(1+\beta)^2+\gamma)(-\gamma-3(1+\theta)+2v(1+\beta)^2(1+\theta)-3\beta(2+\beta)(1+\theta))}{4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta))} \tag{22}$$

$$Consumer\ Surplus =$$

$$\frac{(a-c)^2(4g(1+\beta)^2+\gamma)^2(1+\theta)(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2}{(4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta)))^2} \tag{23}$$

$$Government\ Revenue =$$

$$-\frac{2(a-c)^2(-1+v)\gamma^2(8g(-1+v)(1+\beta)^2+\gamma-4g\gamma+(8g(-1+v)(1+\beta)^2+\gamma)\theta)(-\gamma-3(1+\theta)+2v(1+\beta)^2(1+\theta)-3\beta(2+\beta)(1+\theta))}{(4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta)))^2} \tag{24}$$

$$Damage =$$

$$\frac{4(a-c)^2g\gamma^2(3+\gamma+3\theta-2v(1+\beta)^2(1+\theta)+3\beta(2+\beta)(1+\theta))^2}{(4g(2+\gamma+2\theta-v(1+\beta)^2(1+\theta)+2\beta(2+\beta)(1+\theta))^2+\gamma(1+\theta)(4+\gamma+4\theta-4v(1+\beta)^2(1+\theta)+v^2(1+\beta)^2(1+\theta)+4\beta(2+\beta)(1+\theta)))^2} \tag{25}$$

Derivation - Consumer Surplus

The representative consumer's utility function is

$$U\ (q_1, q_2)\ =\ a\ (\ q_1 + q_2) -\ (\tfrac{1}{2})\ (q_1^2 + 2\theta q_1 q_2 + q_2^2) \tag{26}$$

The consumer's utility function does not include pollution effects.

The representative consumer chooses outputs q_1 and q_2 to maximize

$$U\ (q_1, q_2) - p_1\ q_1 -\ p_2\ q_2 \tag{27}$$

The first-order conditions are

$$a - q_1 - \theta q_2 - p_1 = 0 \tag{28}$$

$$a - q_2 - \theta q_1 -\ p_2 = 0 \tag{29}$$

The inverse demand functions are

$$p_1\,(q_1\,, q_2) = a - (q_1 + \theta\, q_2) \tag{30}$$

$$p_2\,(q_1\,, q_2) = a - (q_2 + \theta\, q_1) \tag{31}$$

Substituting the inverse demand functions for p_1, p_2, we can obtain consumer surplus:

$$\begin{aligned}
CS\,(q_1, q_2) &= U\,(q_1, q_2) - p_1\,(q_1\,, q_2)\, q_1 - p_2\,(q_1\,, q_2)\, q_2 \\
&= U\,(q_1, q_2) - a\, q_1 + ({q_1}^2 + \theta\, q_2 q_1) - a\, q_2 + ({q_2}^2 + \theta\, q_1 q_2) \\
&= -\left(\frac{1}{2}\right)(q_1^2 + 2\theta q_1 q_2 + q_2^2) + ({q_1}^2 + \theta\, q_2 q_1) + ({q_2}^2 + \theta\, q_1 q_2) \\
&= -\left(\frac{1}{2}\right)(q_1^2 + q_2^2) - \theta q_1 q_2 + ({q_1}^2 + {q_2}^2) + (2\theta q_1 q_2) \\
&= \left(\frac{1}{2}\right)(q_1^2 + q_2^2) + \theta q_1 q_2 \\
&= \left(\frac{1}{2}\right)(q_1^2 + 2\theta q_1 q_2 + q_2^2)
\end{aligned} \tag{32}$$

References

Aupperle, K. E., Carroll, A. B., & Hatfield, J. D. (1985). An empirical examination of the relationship between corporate social responsibility and profitability. *Academy of Management Journal*, *28*(2), 446-463.

Branco, M. C., & Rodrigues, L. L. (2006). Corporate social responsibility and resource-based perspectives. *Journal of Business Ethics, 69*(2), 111-132.

Carroll, A. B. (1979). A three-dimensional conceptual model of corporate social performance. *Academy of Management Review, 4*(4), 497-505.

Carroll, A. B. (1991). The pyramid of corporate social responsibility: Toward the moral management of organizational stakeholders. *Business Horizons*, *34*(4), 39-48.

D'Aspremont, C., Jacquemin, A., Gabszewicz, J. J., & Weymark, J. A. (1983). On the stability of collusive price leadership. *Canadian Journal of Economics*, 17-25.

Donsimoni, M. P., Economides, N. S., & Polemarchakis, H. M. (1986). Stable cartels. *International Economic Review*, 317-327.

European Commission. Directorate-General for Employment, & Social Affairs. Unit D. (2002). *Corporate social responsibility: A business contribution to sustainable development*. Office for Official Publications of the European Communities.

Freeman, R. E. (1984). Strategic management: A stakeholder perspective. *Boston: Pitman*, 13.

Friedman, M. (1970). The social responsibility of business is to increase its profits. *New York Times Magazine*, 13, 122-126.

Hosmer, L. T. (1995). Trust: The connecting link between organizational theory and philosophical ethics. *Academy of Management Review*, *20*(2), 379-403.

Husted, B. W., & de Jesus Salazar, J. (2006). Taking Friedman seriously: Maximizing profits and social performance. *Journal of Management Studies*, *43*(1), 75-91.

King, A. (2007). Cooperation between corporations and environmental groups: A transaction cost perspective. *Academy of Management Review*, *32*(3), 889-900.

Lambertini, L., Palestini, A., & Tampieri, A. (2016). CSR in an asymmetric duopoly with environmental externality. *Southern Economic Journal*, *83*(1), 236-252.

Lambertini, L., & Tampieri, A. (2010). *Corporate Social Responsibility in a Mixed Oligopoly*, Quaderni - Working Paper DSE, No. 723.

Lambertini, L., & Tampieri, A. (2011). *On the Stability of Mixed Oligopoly Equilibria with CSR Firms*, Quaderni - Working Paper DSE, No. 768.

Lambertini, L., & Tampieri, A. (2015). Incentives, performance and desirability of socially responsible firms in a Cournot oligopoly. *Economic Modelling, 50*(2015), 40-48.

Lyon, T. P., & Maxwell, J. W. (2008). Corporate social responsibility and the environment: A theoretical

Perspective. *Review of Environmental Economics and Policy*, *2*(2), 240-260.

Margolis, J. D., & Walsh, J. P. (2003). Misery loves companies: Rethinking social initiatives by business. *Administrative Science Quarterly, 48*(2), 268-305.

McWilliams, A., & Siegel, D. (2001). Corporate social responsibility: A theory of the firm perspective. *Academy of Management Review*, *26*(1), 117-127.

Orlitzky, M. (2005). Social responsibility and financial performance: Trade-off or virtuous circle. *University of Auckland Business Review*, *7*(1), 37-43.

Orlitzky, M., Schmidt, F. L., & Rynes, S. L. (2003). Corporate social and financial performance: A meta-analysis. *Organization Studies*, *24*(3), 403-441.

Orlitzky, M., Siegel, D. S., & Waldman, D. A. (2011). Strategic corporate social responsibility and environmental sustainability. *Business & Society, 50*(1), 6-27.

Paton, D., & Siegel, D. S. (2005). The economics of corporate social responsibility: an overview of the special issue. *Structural Change and Economic Dynamics*, *16*(3), 309-312.

Pava, M. L., & Krausz, J. (1996). The association between corporate social-responsibility and financial performance: The paradox of social cost. *Journal of Business Ethics*, *15*(3), 321-357.

Reinhardt, F. L., Stavins, R. N., & Vietor, R. H. K. (2008). Corporate social responsibility through an economic lens. *Review of Environmental Economics and Policy, 2*(2), 219-239.

Székely, F., & Knirsch, M. (2005). Responsible leadership and corporate social responsibility: Metrics for sustainable performance. *European Management Journal*, *23*(6), 628-647.

Waddock, S. A., & Graves, S. B. (1997). The corporate social performance–financial performance link. *Strategic Management Journal*, *18*(4), 303-319.

WBCSD (World Business Council for Sustainable Development). (2000). Corporate social responsibility: Making good business sense. *WBCSD, Geneva.*

Wood, D. J., & Jones, R. E. (1995). Stakeholder mismatching: A theoretical problem in empirical research on corporate social performance. *The International Journal of Organizational Analysis*, *3*(3), 229-267.

Zhao, Z. Y., Zhao, X. J., Davidson, K., & Zuo, J. (2012). A corporate social responsibility indicator system for construction enterprises. *Journal of Cleaner Production*, *29-30* (2012), 277-289.

Conclusion

My doctoral thesis consists of three essays at the frontier between environmental economics and industrial organization. The first chapter is a dynamic model of the global economy and climate with three endogenous knowledge stocks that studies the role of technological innovation in global climate policy. The second chapter is a game theory model that studies the effect of environmental policy, mergers to environmental R&D with spillovers. The third chapter is also a game theory model that studies the effect of the monopolist with corporate social responsibility (CSR).

In the first chapter, we have achieved the following: (i) we fully accounted for inter-firm knowledge spillovers, and (ii) we modeled the business as usual scenario correctly by excluding the duplication externality and inter-firm spillover effects. We have the following conclusions regarding the important determinants of induced R&D: first, induced R&D is very sensitive to the elasticity of the substitution parameter. If inputs are gross complements, this will lead to decreases in R&D investments in generic materials, energy production, and a hump shape of R&D investments in energy efficiency with respect to the tax level under the first-best scenario and the second-best scenario. However, if inputs are gross substitutes, this will lead to decreases in R&D investments in energy efficiency, generic materials, and energy production under the second-best scenario, but R&D investments in generic materials will always be higher than its business as usual level under the first-best scenario.

The second conclusion has implications for duplication externality. Results indicate that the induced R&D generates a lower abatement cost reduction if we externalize duplication in the business as usual scenario.

The third conclusion regards the initial levels of energy related R&D shares. Higher initial levels of energy related R&D shares would create a market size effect, leading to an increased contribution of induced R&D.

Fourth, we have conclusions about the inter-firm knowledge spillovers. The first-best scenario fully internalizes inter-firm knowledge spillovers, which leads to increases in the levels of all types of research. The second-best scenario does not internalize it, which leads to induced changes in research resulting from the carbon tax affecting pre-existing market distortions. As a result, some types of research increase while other types decrease.

The important policy implication is that the government needs to take into account the effects of important determinants of induced R&D into their costs and benefits analysis in order to address the climate change issues. Our benchmark experiment suggests that induced R&D has a limited role on the abatement cost reduction of greenhouse gas emissions, overall. First, in first-best scenario, even though in the early years, the positive effect of the research subsidies dominates the depressing effect of the excess burden. However, as the carbon tax becomes larger overtime, the negative effect of the excess burden increases and comes to dominate the research subsidies effect. Also, according to Sue Wing (2006), increasing the carbon tax level reduces the scale of fossil fuel augmenting technology, thereby reducing its mitigating effect on other variables. Therefore, in first-best scenario, the excess burden effect eventually outweighs the effect of the research subsidies. Second, in second-best scenario, the research dividend effect is not significant compared with the excess burden effect, because according to Gerlagh (2008), our calibrated values of parameters implies an adverse condition for a research dividend. Therefore, the excess burden effect dominates the research dividend effect in the long run.

The second chapter explores the effect of merger on environmental R&D. In our model, under the policy regimes of merger and competition, firms play a three-stage game by investing in R&D to reduce the carbon emission expenditure. We consider the fact that product differentiation can play a role into the environmental policy design and analyze different policy implementations under the regulator's full commitment, no commitment and exogenous emission tax. We study the relationship between merger and R&D and the relationship between commitment and R&D. We also evaluate the overall effect of merger and the overall effect of commitment.

As the main results, proposition 6 suggests that: (1) Merger has a positive effect on R&D under non-commitment and the exogenous tax scenarios. (2) Under commitment, if goods are imperfect substitutes or homogenous, merger has a negative effect on R&D; if goods are complements or independent, merger has a positive effect on R&D. (3) For any types of goods under any regime, commitment has a negative effect on R&D. Propositions 1-5 compare equilibrium variables between merger and competition. (4) Under commitment, if products are highly differentiated, the tax from the merger is higher. As products become more and more similar, the tax becomes lower under the merger. R&D, output, pollution reduction, pollution, marginal social damage, and welfare follow a similar trend. However, the profit from the merger would increase as products become more and more similar. (5) Under non-commitment, as products become less differentiated, the tax becomes lower under merger. However, profit becomes higher under merger. R&D, output, pollution reduction, and welfare are always higher under merger. Pollution and marginal social damage are always lower under merger. (6) Under the exogenous tax scenario, as products become less differentiated, output, pollution, and marginal social damage become less under merger. And welfare increases with the merger. R&D and pollution reduction are always higher under merger. (7) If we compare commitment to non-commitment**:** for any type of goods, under any regime, commitment generates a higher emission tax, and lower R&D, output, profit, pollution reduction, pollution, marginal social damage, and welfare.

The results indicate that merger will be profitable for firms, increase R&D investment and welfare (1) if goods are independent under commitment; (2) if goods are independent, imperfect substitutes, or homogeneous under non-commitment; and (3) if goods are imperfect substitutes or homogenous under the exogenous tax scenario. Also, non-commitment will encourage R&D investment, increase profit, and enhance welfare, compared with commitment for any type of goods and under any regime. As a result, public policies should focus on the encouragement of mergers and promote the regulator's non-commitment ability if the market structure satisfies the above conditions, since doing so would not only lead firms to engage in more R&D investments in terms of increasing innovation outputs as pollution reductions, but it also would have the beneficial effect of increasing the firms' profit and welfare.

There is an increasing trend for enterprises to engage in social and environment responsibility. Stern (2006) points out that environmental sustainability will become the major social responsibility challenge for enterprises. As a result, enterprises should incorporate actions which contribute to social responsibility, ecologically sustainability, and economic performance. Under the structure of monopoly with corporate social responsibility where the monopolist invests in environmental R&D to reduce pollution, we analyzed in which circumstances the corporation and society can maintain a sustainable development pace while achieving better results in economic sustainability, environmental sustainability, and social sustainability.

The third chapter analyzes the effect of the monopolist with corporate social responsibility where the monopolist also invests in environmental R&D. This project lies at the frontier of environmental economics and industrial organization. We use a monopolist with a corporate social responsibility setting of a three-stage game; in the first stage, the regulator determines the emission tax to maximize welfare; in the second stage, the monopolist determines R&D to maximize its objective function; in the third stage, the monopolist determines outputs to maximize its objective function. This study focuses on one major question: under the structure of the monopolist with corporate social responsibility, if we change the parameters of R&D technology parameter, the degree of social responsibility, and product differentiation, what are the effects on profit, R&D, environmental damage, consumer surplus, and welfare?

The main results are summarized in Table 2: Experiment 1 shows output, tax, R&D, pollution reduction, operational profit, welfare, and consumer surplus all increase with R&D technology parameter; Experiment 2 shows output, R&D, pollution reduction, pollution, marginal social damage, profit, operational profit, welfare, consumer surplus, and damage all increase with the degree of social responsibility; Experiment 3 shows consumer surplus increases as products become more similar.

The important policy implication is that the regulator needs to incorporate economic sustainability, environmental sustainability, and social sustainability in their public policies decisions when facing a CSR monopolist. Based on Table 2, three policy implications are developed. First, a policy which encourages increases in R&D technology parameter enhances welfare in terms of higher consumer surplus and lower environmental damage, as well as increases R&D investments. However, the policy lowers profit and government tax revenue. Second, a policy which promotes increases in the degree of social responsibility increases R&D investment and welfare in terms of higher consumer surplus. Also, the policy stimulates the monopolist's profit through increasing its operational profit and reducing its tax expenditure. However, the policy lowers government tax revenue and increases the environmental damage. Third, a policy which promotes increases in product differentiation under the CSR monopolist increases the government's revenue, the CSR monopolist's profit through higher operational profit, R&D investments, and welfare. However, the policy increases environmental damage and lowers consumer surplus.

This is a theoretical economics thesis. Based on software platforms of The General Algebraic Modeling System and Wolfram Mathematica, we successful developed numerical simulation models to study important social science issues of "Global Climate Policy, Environmental R&D, Mergers, and Corporate Social Responsibility". Through numerical simulations, important findings have been derived from our models. These findings make contributions to relevant literature and improve our understanding of this project in many aspects. In the first chapter, we understand that there are 6 important determinants of induced R&D and induced R&D has a limited role on the abatement cost reduction of greenhouse gas emissions, overall. Because our benchmark model suggests that: (1) in first-best scenario, the excess burden effect eventually outweighs the effect of the research subsidies. (2) In second-best scenario, the excess burden effect dominates the research dividend effect in the long run. In the second chapter, we understand that (1) the relationship between Merger and R&D is more often positive than negative except under the commitment, if goods are imperfect substitutes or homogenous. (2) Merger will be profitable for firms, increase R&D investment, and welfare under different market structures. (3) In our setting, non-commitment yields superior innovation and other performances to commitment, irrespective of product differentiation, market structure, and R&D spillovers. In the third chapter, we see the different impacts of the changes in the technological parameters on economic sustainability, environmental sustainability, and social sustainability in the presence of the monopolist with corporate social responsibility under the environmental regulation.