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Article

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Research in Globalization

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Elsevier

Suggested Citation: Wang, Chenyu (2021) : The role of technological innovation in global climate policy, Research in Globalization, ISSN 2590-051X, Elsevier, Amsterdam, Vol. 3, pp. 1-19, <https://doi.org/10.1016/j.resglo.2021.100066>

This Version is available at:

<https://hdl.handle.net/10419/330998>

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The role of technological innovation in global climate policy

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ARTICLE INFO

This research was supported by the Fundamental Research Funds for the Central Universities

Keywords:

Environmental economics
Economic modelling
Global climate policy
R&D Investments
Technological innovation

ABSTRACT

This research builds 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. The second, the duplication externality. Induced R&D generates a lower abatement cost reduction if we externalize duplication in the business as usual scenario. 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. 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 in the abatement cost reduction of carbon emissions overall.

Introduction

To address the climate change issues, we may use 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 economising the use of a factor which has become relatively expensive." (Hicks, 1963) 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: the elasticity of substitution between energy and other factors of production. The second, the duplication externality. Third, the initial level of research expenditure. Fourth, the inter-firm knowledge spillovers. Fifth, first-best and second-best policies. Sixth, a research

dividend effect and tax burden effect.

In this research, we build a dynamic model of the global economy and climate with three endogenous knowledge stocks that study the role of technological innovation in global climate policy. Based on the General Algebraic Modeling System (GAMS) software platform, we successfully developed a numerical simulation model to study this important social science issue. Through numerical simulations, important findings have been derived from our model. These findings make contributions to relevant literature and improve our understanding of this topic in many aspects. We confirm the conventional wisdom of previous studies and understand that there are six important determinants of induced R&D. Research shows that induced R&D has a limited role in the abatement cost reduction of carbon emissions overall. The important policy implication is that the government needs to consider the effects of essential determinants of induced R&D into their costs and benefits analysis to address the climate change issues.

This research makes the following contributions. First, we build a dynamic model of the global economy and climate with three endogenous knowledge stocks. However, most existing studies only use a single knowledge stock. Second, we use the updated data from OECD (OECD (n.d.); OECD Data. (n.d.)), World Bank World Bank Open Data. (n.d.),

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<https://doi.org/10.1016/j.resglo.2021.100066>

Received 6 June 2021; Received in revised form 14 September 2021; Accepted 20 September 2021

Available online 27 September 2021

2590-051X/© 2021 The Author(s).

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UN Report, and Penn World Table 9.0 (Feenstra et al., 2015). Third, we treat duplication as external in the business-as-usual scenario, while previous studies treated duplication as internal in the business-as-usual scenario. Fourth, we fully account for inter-firm knowledge spillovers, whereas other studies usually ignore these factors. Fifth, we model the business-as-usual scenario in a theoretical consistent modeling framework by excluding the duplication externality, inter-firm spillover effects, and the environmental externality, which is absent from other studies. Sixth, we assess the effects of the determinants listed above on induced R&D in a multiple knowledge stock model of R&D. Seventh, we assess the relative importance of these determinants in terms of consumption levels. Eighth, 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. Finally, we confirm the conventional wisdom of previous studies and understand that there are six crucial determinants of induced R&D. (Goulder & Schneider, 1999; Popp, 2004; Wing, 2006; Gerlagh, 2008; Hart, 2008; Gans, 2012; Shiell & Lyssenko, 2014).

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. The second, the duplication externality. Duplication means that a portion of a firm's knowledge output inevitably duplicates what another firm has already discovered, which is inefficient. 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. 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. Induced innovation is a public policy issue that benefits 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, first-best and second-best policies. 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. 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 in the abatement cost reduction of carbon emissions overall.

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

Literature review

Climate policy and the abatement cost

The environmental economics literature focuses on the relationship between carbon policy and the induced research and development (R&D) in different industries (Jaffe et al., 2005; Fischer and Newell, 2008; Shittu and Baker, 2009; Massetti and Nicita, 2010; Rezai, 2011). Using computable general equilibrium models with R&D investments, Goulder and Schneider (1999) investigate how induced technological change affects the carbon abatement policies. They conclude that carbon abatement policies do not necessarily increase the overall technological progress rate since carbon abatement policies have various effects on different types of R&D. Thus, the study solely focuses on sectors of positive R&D impacts that may lead to under-assessment the abatement costs of carbon policies. For example, Goulder and Schneider (1999) consider that a carbon tax stimulates R&D in alternative energy industries while discouraging R&D in non-energy and carbon-based energy industries. In particular, the R&D reduction in non-energy and carbon-based energy industries leads to slower output growth, implying lower future GDP and consumption levels. Therefore, models that ignore those effects are likely to underestimate the abatement cost from a global climate policy.

Popp (2004) contends that the induced technological change associated with a carbon policy plays an essential role in climate change issues and, therefore, should be considered endogenous in the DICE (Nordhaus, 1994; Nordhaus & Boyer, 2000) model of climate change. This research concludes that market imperfections and the potential crowding out of other R&D are two main factors limiting the potential of induced technological change. Gerlagh (2008) develops an endogenous growth model with a climate module to assess the impact of the induced technological change for a climate policy controlling a maximum level of atmospheric carbon dioxide concentration of 450 ppmv. The results illustrate induced technological change largely reduces the abatement cost of carbon policy, and technology accumulation shifts from carbon-energy production to carbon-energy savings. Notably, Popp (2004) and Gerlagh (2008) have two opposite views toward carbon tax dealing with climate change. Popp (2004) concludes that the effect on the tax path of induced R&D is small, whereas Gerlagh (2008) concludes that the effect on the tax path of 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. Gerlagh (2008) suggests that including the innovation sector in the model creates lots of welfare gain so that induced R&D's contribution to carbon abatement can be substantial. In contrast, Popp (2004) has a pessimistic view and thinks that R&D has a limited role in 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.

Different effects associated with a carbon tax

Gerlagh (2008) indicates two effects of a carbon tax on output and consumption: an excess burden effect and a research dividend effect. Using the carbon tax as the climate policy 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) mentions 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 costs. 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, the study considers 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.

Wing (2006) analyzes the stock of knowledge approach and develops a dynamic model that allows a firm to choose clean and dirty inputs and invest in clean and dirty R&D; this research analyzes how firms perform the innovation themselves in response to the environmental tax's input-price changes. Results show that the carbon tax increases the dirty input price and the induced technological changes occur, crowding out the clean R&D while promoting the dirty R&D. Additionally, in this process-based model of induced R&D, Wing (2006) illustrates four findings. First, 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. Second, the study also shows the bias of the techniques of production: taxing the dirty input biases the techniques of productions in order to conserve the dirty input. Third, 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. Finally, Wing (2006) 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, the research also points out that the knowledge spillover effects and R&D subsidy policies would reduce the impact of the crowding-out effect.

Acemoglu et al. (2012) introduce an endogenous growth model characterized as induced technological change and environmental constraints. Inputs are classified as dirty and clean types. The research illustrates that the optimal climate policy consists of carbon taxes and research subsidies altogether. Also, Acemoglu et al. (2012) describe the market size effect, whereby expenditure on R&D has the highest payoff in the largest input sector. A market size effect, that is, the tax encourages induced R&D 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.

Duplication externality and knowledge spillovers

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) scenario's duplication externality. Shiell and Lyssenko (2014) develop a single-knowledge-stock model of R&D, growth, and climate to evaluate the effects of climate policy on induced R&D in energy-related technologies. The research finds several factors that influence the contribution of induced R&D, for instance, the duplication externality. Shiell and Lyssenko (2014) argue that most environmental modelers have neglected to treat duplication as an externality in the BAU scenario (Goulder & Schneider, 1999; Popp, 2004; Gerlagh, 2008; 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.

Jones and Williams (2000) construct an endogenous growth model and investigate whether a decentralized economy invests too much or too little R&D. The model specifies knowledge spillovers as a significant distortion to R&D and indicates that the decentralized economy generally underinvests in R&D relative to the socially optimal level. Since

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, from the viewpoint of social welfare, the spillover benefits are positive (Jones, 1995).

Climate policies and induced technological change

Gans (2012) studies the relationship between climate policies and induced technological change in environmentally friendly technologies. The results demonstrate that a tighter emissions cap implies (i) lower fossil fuel usage and incentives for improving fossil fuel efficiencies; (ii) higher incentives for improving alternative energy efficiencies; (iii) a positive impact on direct carbon abatement technologies; (iv) lower innovation incentives overall. Thus, Gans (2012) disputes the argument that climate policy will stimulate incentives to develop environmentally friendly technologies. The study finds instead that the carbon policy will usually diminish incentives for fossil fuel augmenting technologies. Furthermore, 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 on fossil fuels, 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 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 policy would reduce the incentives to invest in the fossil-fuel augmenting technologies since the precondition for induced innovation is not satisfied. Climate policy reduces 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. The research 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. Moreover, the study 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.

Using a stochastic energy-economy-environment integrated model, Duan et al. (2018) focus on achieving China's energy and climate policy targets in 2030 in an uncertain environment. The research assesses targets of carbon intensity reduction, carbon emission peaking, and non-fossil energy development and finds that (i) carbon pricing plays a significant role in managing carbon emissions; (ii) the policy mix of carbon pricing and non-fossil energy subsidies is more cost-effective than the single carbon pricing policy. An optimal set of carbon taxes internalizes climate change, corrects market failure, and achieves excellent carbon mitigation tasks. Duan et al. (2014) develop a logistic-induced energy economic hybrid model to explore China's optimal carbon tax trajectory and carbon taxes' impacts on carbon-free technologies. They show that China's (i) optimal carbon tax follows a monotonically increasing, classical, and S-shaped pattern; (ii) carbon-free technologies will take 30 years development or longer to realize the significant transition from fossil fuels to noncarbon energy.

The model

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 derived from the maximization of the Lagrangian function with respect to the choice, state, 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 $t = 1, \dots, 60$. 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.

The final output, Y , is given by the production function:

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

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:

$$M_t = \zeta_M A_{MZ,t}^{\pi_{MZ}} Z_{M,t} \quad (2)$$

$$E_t = \zeta_E A_{EZ,t}^{\pi_{EZ}} Z_{E,t} \quad (3)$$

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 ζ_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 ζ_E .

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

$$(Z_{M,t} + Z_{E,t}) = \gamma K_t^\alpha L_t^{1-\alpha} \quad (4)$$

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

Capital accumulation follows the difference equation

$$K_{t+1} = (1 - \delta_k)^\Delta K_t + \Delta \left(I_t - \frac{\eta}{2} \frac{I_t^2}{K_t} \right) \quad (5)$$

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 and Wilcoxon (1999). The capital adjustment cost increases in I but decreases in K , reflecting increasing in the 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.

$$A_{YE,t+1} = \Delta a_{YE} R_{YE,t}^b A_{YE,t}^\phi + A_{YE,t} \quad (6)$$

$$A_{MZ,t+1} = \Delta a_{MZ} R_{MZ,t}^b A_{MZ,t}^\phi + A_{MZ,t} \quad (7)$$

$$A_{EZ,t+1} = \Delta a_{EZ} R_{EZ,t}^b A_{EZ,t}^\phi + A_{EZ,t} \quad (8)$$

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 the next period. And $b = 1$ is the opposite extreme case of no duplication. No duplication means that the accumulation of knowledge in the next period depends on current R&D expenditure and current knowledge. Shiell and Lyssenko (2014) use 0.7 to represent the modest duplication externality and 0.2 to represent the large duplication externality. Also, ϕ 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 ϕ . In comparison, Gerlagh (2008)'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 an 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 $(1-\omega)$ 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 $\omega = 0.25$, whereas in the optimal scenario, the social planner set $\omega = 1$ to internalize inter-firm knowledge spillovers.

Another major contribution of this research 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:

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

$$V_{YE,t} = a_{YE} R_{YE,t}^{b-1} A_{YE,t}^\phi \quad (6' /)$$

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

$$V_{MZ,t} = a_{MZ} R_{MZ,t}^{b-1} A_{MZ,t}^\phi \quad (7' /)$$

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

$$V_{EZ,t} = a_{EZ} R_{EZ,t}^{b-1} A_{EZ,t}^\phi \quad (8' /)$$

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.

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

$$C_t + I_t + R_{YE,t} + R_{MZ,t} + R_{EZ,t} = Y_t \quad (9)$$

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.

$$L_t = h_t P_t \quad (10)$$

$$P_t = P_{LT} \frac{e^{\gamma_p(t-t_0)}}{1 + e^{\gamma_p(t-t_0)}} \quad (11)$$

Table 1
Experiments.

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	$R_{YE,1} = 0.32R_1$ $R_{EZ,1} = 0.05R_1$ $R_{MZ,1} = 0.63R_1$

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

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

Eq. (10) shows that effective labor supply L is equal to human capital-based productivity h times the total population P . From Eq. (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. Eq. (12) shows the function of human capital growth, where $\gamma_{h,t}$ is the growth rate for human capital h . Eq. (13) shows the human capital growth rate $\gamma_{h,t}$ declining exponentially over time, with $-\delta_\gamma$ as the decline rate.

Eqs. (14) and (15) show Gerlagh (2008)'s climate change module that describes the connections between energy usage E , atmospheric carbon concentration ATM , and the global average surface temperature $TEMP$.

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

$$TEMP_{t+1} = (1 - \delta_T)^\Delta TEMP_t + \Delta \delta_T TEMP_0 \frac{\ln \left(\frac{ATM_t}{ATM_0} \right)}{\ln(2)} \quad (15)$$

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 CO₂ concentration level ATM_0 plus the current period ATM level after we take into account of ATM_0 , atmospheric CO₂ depreciation rate δ_M , plus the current period CO₂ emissions EM , which are set equal to the energy usage E and we also take into account of the retention rate $(1 - \delta_E)$. The variable \overline{EM} represents emissions by other (non-energy) sources. Eq. (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, Eq. (16) is the quantity constraint for the atmospheric carbon concentration level.

$$ATM_t \leq ATM_{TGT} \quad (16)$$

ATM_t represents the atmospheric carbon concentration level, while ATM_{TGT} is the maximum level of atmospheric CO₂ concentration permitted under a quantity-based emissions control policy.

The scenarios include social planner's optimum (OPT), business as usual (BAU), first-best (FB), second-best (SB), and no induced technical change (NOITC). Details are shown in Appendix A.

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 B. There are five types of values in 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 and 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 $ATM_{TGT} = 450ppmv$; the parameter η in the capital adjustment cost function (Cummins et al., 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 the value-added production function, $\gamma = 1$; the parameter b in the knowledge accumulation equation is equal to 0.7 (Shiell and Lyssenko, 2014); the parameter ϕ 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) UNESCO Data. (n.d.) 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

Table 2
Exogenous values and calibration results from benchmark scenario (EXP1).

Exogenous Parameters	Initial Values	Normalized Values	Exogenous Growth Rates	Calibrated Parameters				
$\rho = 0.03$	$q = 0.1163$ trillionUS\$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
$ATM_{TGT} = 450ppmv$	$h_0 = 0.48$	$M_1 = 2$	$\gamma_{h,0} = 0.042$	π_{MZ}	0.1212	0.1055	0.1978	0.1450
$\eta = 2$	$Y_1 = 9.285$ trillionUS\$2011	$\gamma = 1$	$-\delta_\gamma = -0.27$	π_{EZ}	0.0040	0.1170	0.0065	0.1678
$\Delta = 1, \Delta = 5$	$E_1 = 4.48$ tenGtCO ₂			aa_{YE}	3.9332	0.4805	3.9172	0.4667
$b = 0.7$	$K_1 = 32.418$ trillionUS\$2011			aa_{MZ}	0.1944	0.2580	0.1926	0.2593
$\phi = 0.0$				aa_{EZ}	15.3572	1.7621	15.2950	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
$Share_R = 0.021$				ζ_M	0.1284	0.1104	0.1139	0.1098
$s^* = 0.643$				ζ_E	5.2490	4.1254	4.8994	4.0725
				α	0.6713	0.7416	0.7004	0.7320

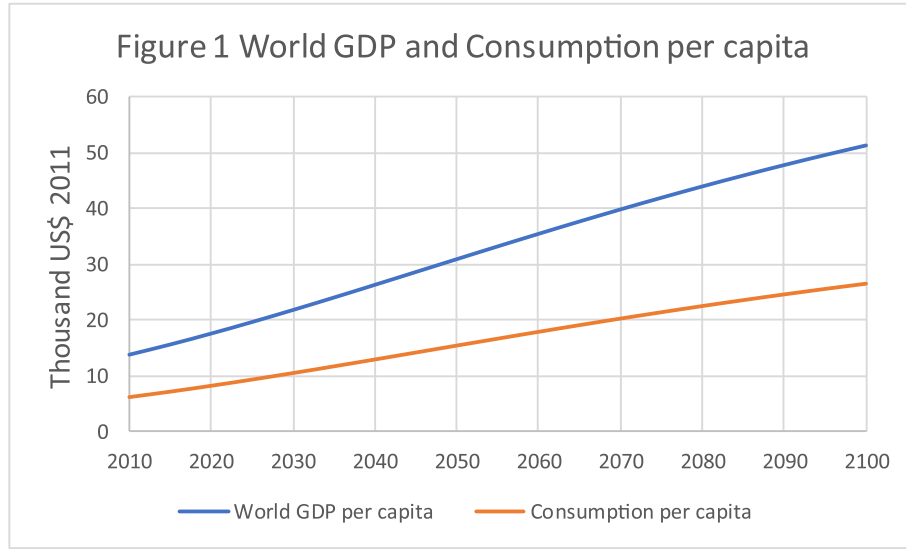


Fig. 1. World GDP and Consumption per capital.

Bank Data, 2015), $P_1 = 6.7$ billions of people; the long-run population (UN Report) (United Nations Department of Economic and Social Affairs/Population Division, 2004) 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 GtCO₂) (WRI 2015 CAIT Climate Data Explorer) CAIT Climate Data, (n.d.). E_1 takes the 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 a 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 the 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 $\Delta = 1$ 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 B. Eqs. (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,

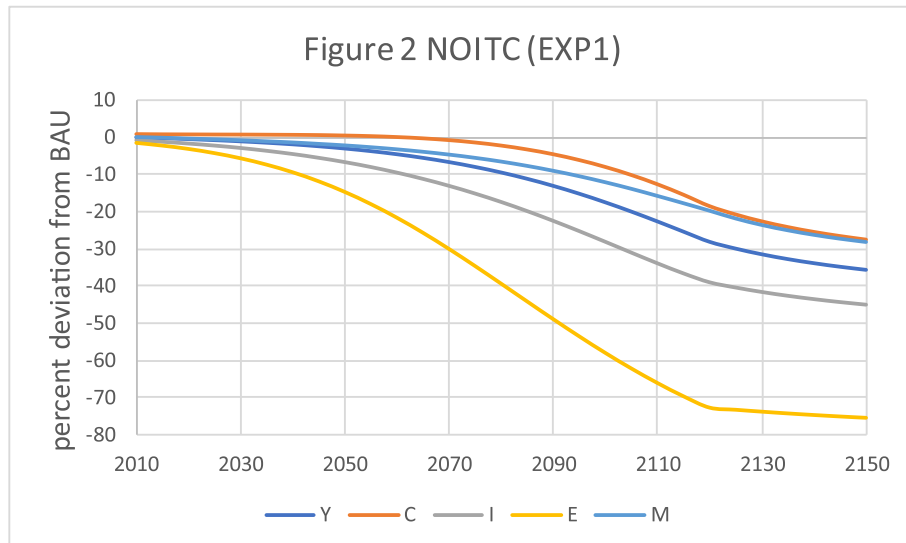


Fig. 2. NOITC (EXP1).

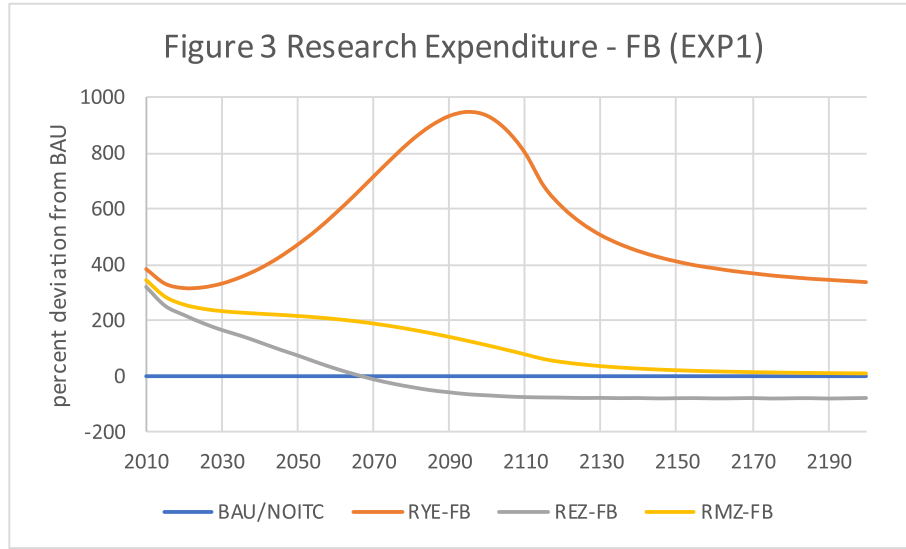


Fig. 3. Research Expenditure - FB (EXP1).

$R_{MZ,1}$ (OECD Statistics). 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 Report). 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 $g_{p_1} = \frac{dp_1}{p_1} = \gamma_p \left(\frac{p_{LT} - p_1}{p_{LT}} \right)$. Rearranging yields,

$$\gamma_p = \frac{g_{p_1} p_{LT}}{p_{LT} - p_1} = 0.269. \text{ Then we solve } P_1 = P_{LT} \frac{e^{\gamma_p (1-t_{p0})}}{1+e^{\gamma_p (1-t_{p0})}} \text{ to obtain } t_{p0} = -3.02.$$

Results

We carry out four experiments (See Table 1). Experiment 1 is our benchmark case and is represented above. Experiment 2 uses Gerlagh (2008)'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 (2008)'s shares into our model. Experiment 3 shows our findings if we internalize the duplication externality in BAU (Popp, 2004; Gerlagh, 2008; Hart, 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 (2008)'s approach into our model in order to 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.

Experiment 1

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

Fig. 2 describes variables of Y , C , I , E , M from the NOITC compared with their corresponding values in the BAU. The NOITC from EXP1 has the same levels of R&D investments and knowledge stocks for each period as the BAU 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 availability for other variables such as investment in capital accumulation. In the next period, NOITC generates less output than BAU due to less capital investment and because NOITC has less energy. That means NOITC performances worsen on a compounded basis. In addition, there is an effect of the carbon tax getting higher in subsequent periods. As discussed in Section 3, the quantity constraint of atmospheric carbon translates into a path of the carbon tax that starts very small but grows over time until the quantity constraint becomes binding. Therefore, we expect variables should have negative deviations from BAU with values decreasing over time. Fig. 2's results confirm our expectations.

Fig. 3 shows the research expenditure of the FB 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 Wing (2006) suggests that R_{YE} , R_{MZ} , and R_{EZ} would decrease. Gans (2012) examines fossil fuel and alternative fuel augmenting technological change for the production function. Proposition 3 shows that a more stringent climate change policy (quantity constraint) will reduce innovation incentives in alternative energy augmenting technology (R_{MZ}) and in fossil fuel augmenting technology (R_{YE}) if products are gross complements. However, 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 to the carbon tax level; 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 in R_{EZ} . Wing (2006) shows the bias of techniques of production: taxing the dirty input E biases the techniques of productions to conserve the dirty input, so if we tax fossil fuel, we should expect a decrease in R_{EZ} . We should see

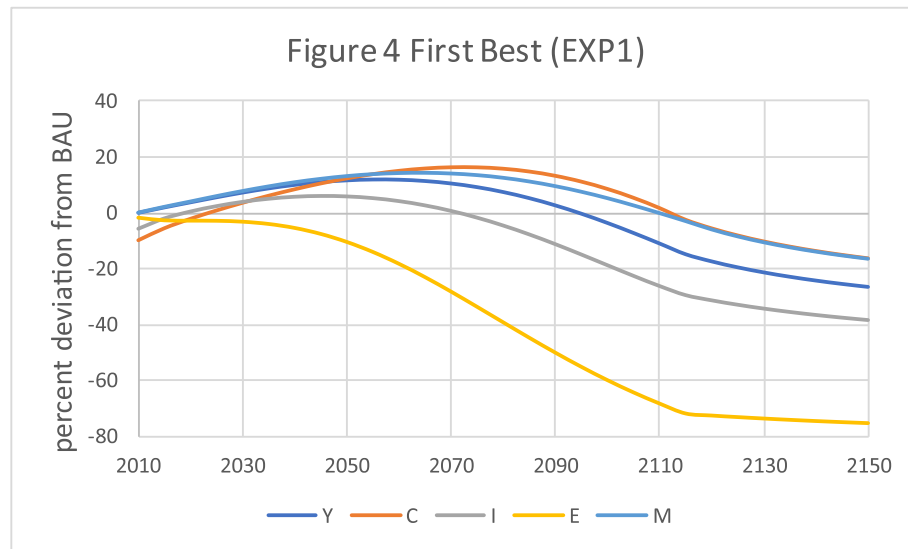


Fig. 4. First Best (EXP1).

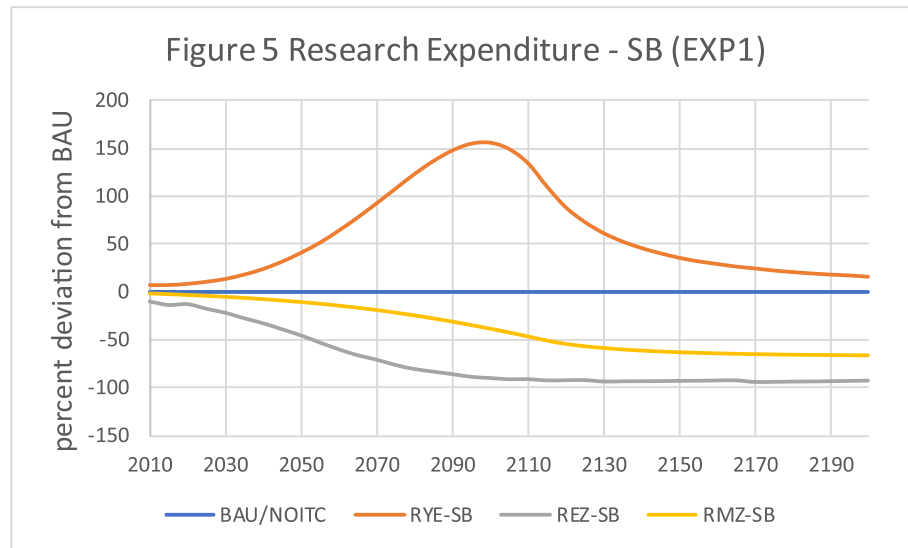


Fig. 5. Research Expenditure - SB (EXP1).

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. Fig. 3 is 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 Wing (2006).

Fig. 4 describes the variables of Y , C , I , E , M from the FB compared with their corresponding values in the BAU in EXP1. In the long run, according to Wing (2006) and Gans (2012), we expect a reduction in Y , C , I , E , and M 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 increase 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 R_{YE} , R_{MZ} , and R_{EZ} values in early periods 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.

Second, Gerlagh (2008) points out a negative effect of the excess burden associated with the global climate 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 over time, the negative effect of the excess burden increases and comes to dominate the research subsidies effect. Also, according to 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 of Fig. 4, we see that consumption goes up above the BAU in the early years, but in the long-term, consumption falls below the BAU.

Fig. 5 shows the research expenditure of the SB in EXP1. According to Wing (2006), Gerlagh (2008), and Gans (2012), we expect decreases in R_{MZ} , R_{EZ} , and a hump shape of R_{YE} . (Fig. 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

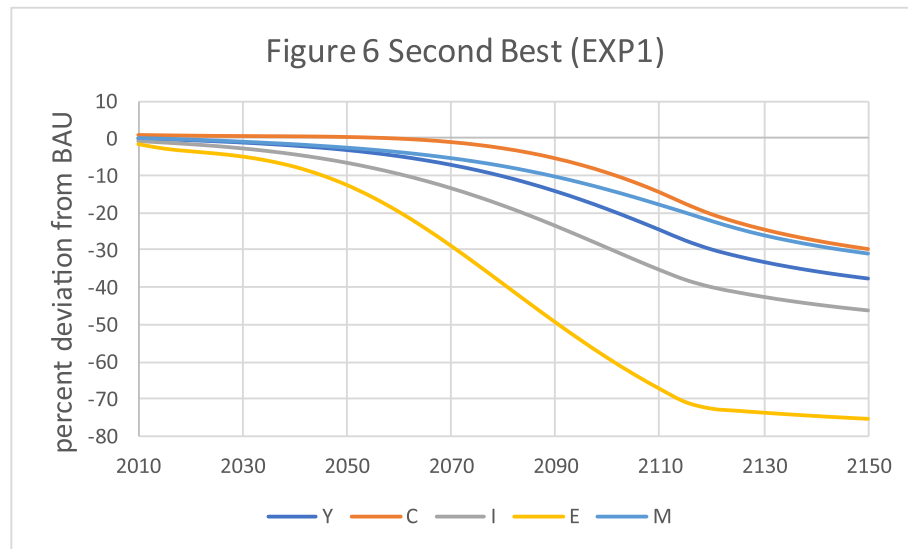


Fig. 6. Second Best (EXP1).

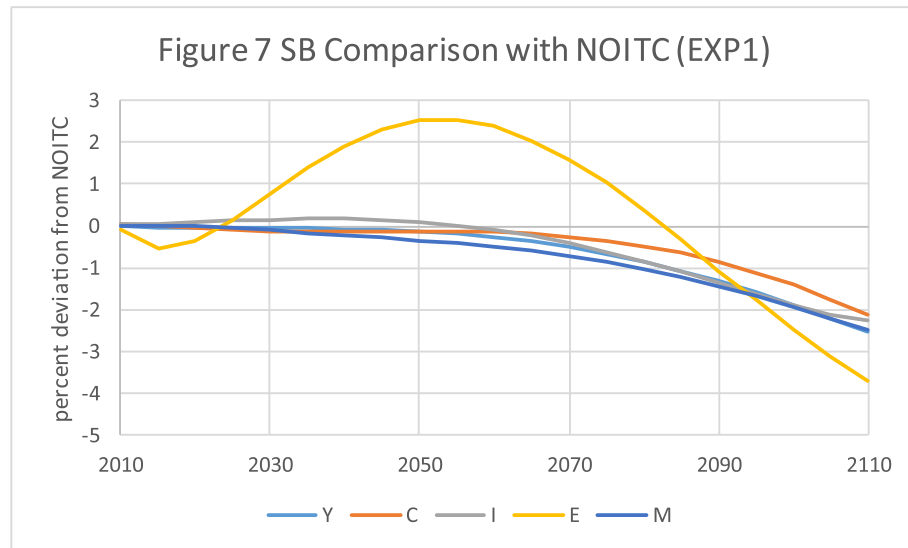


Fig. 7. SB Comparison with NOITC (EXP1).

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. Fig. 5 illustrates that (i) the magnitudes of R_{YE} , R_{MZ} , and R_{EZ} are lower in Fig. 5 than in Fig. 3; (ii) SB leads to decreases of R_{MZ} , R_{EZ} , and a hump shape of R_{YE} .

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

Fig. 7 describes the variables of Y, C, I, E, and M from the SB, as compared with their corresponding values in the NOITC. SB and NOITC both have the same global climate policy but differ in terms of induced innovation; there is no induced innovation in the NOITC. 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 global climate policy will affect pre-existing market distortions and lead to a research dividend. However, we do not have a significant research dividend effect in EXP1, as discussed above in relation to Fig. 5. There is also an excess burden effect from the global climate policy. Therefore, we should expect the overall performance of SB to be worse than the NOITC. The Fig. 7 results show that the empirical finding is consistent with our hypothesis.

Fig. 8 shows EXP1's carbon tax in FB, SB, and NOITC. In FB, there are two instruments to treat both environmental externality and knowledge market externalities, whereas SB and NOITC only have one instrument for treating 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.

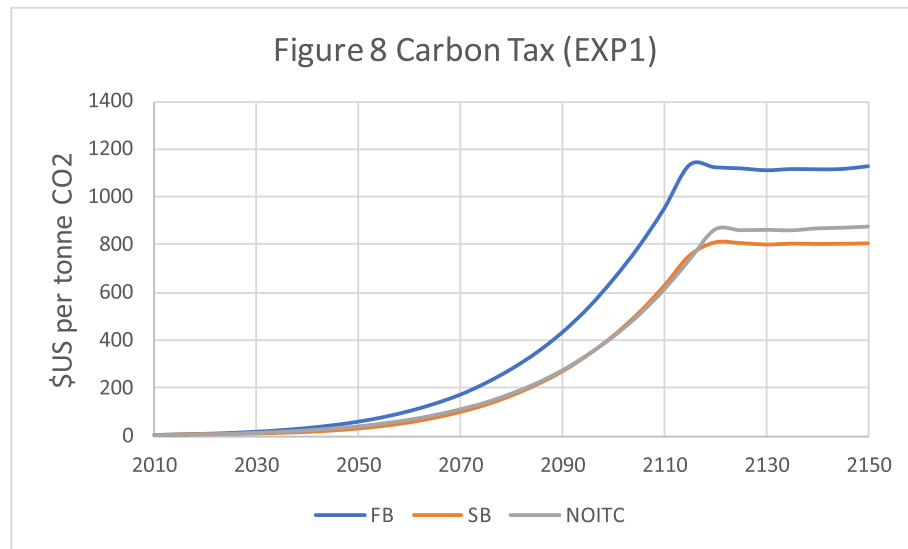


Fig. 8. Carbon Tax (EXP1).

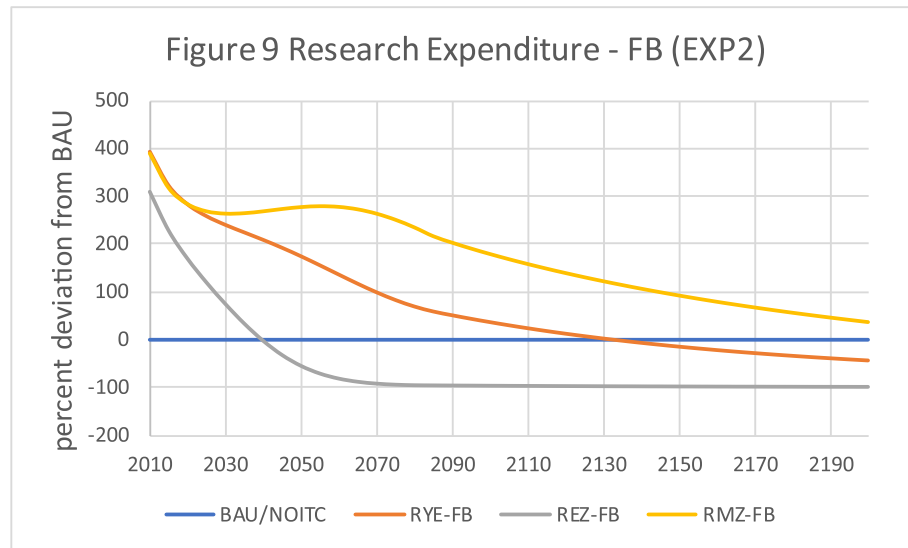


Fig. 9. Research Expenditure - FB (EXP2).

Experiment 2

Experiment 2 uses Gerlagh (2008)'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} , compared with EXP1, since we want to know the impacts on the results by incorporating Gerlagh (2008)'s shares into our model. Fig. 9 shows the research expenditure of the FB in EXP2. The calibrated value of the elasticity of substitution σ in EXP2 is 1.2497, which implies inputs are gross substitutes. Proposition 3 from Gans (2012) 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 global climate policy reduces researches. As tax increases, the excess burden effect dominates the positive research subsidies effect. Besides, Wing (2006) shows the bias of the techniques of production, and we should expect a decrease in R_{EZ} . 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. Fig. 9's results reflect what we have learned from these theories.

Fig. 10 describes the variables of Y , C , I , E , and M from the FB as compared with their corresponding values in the BAU in EXP2. In the long run, according to Wing (2006), Gerlagh (2008), and Gans (2012), we expect a reduction in Y , C , I , E , and M , as compared with BAU. Similarly, as discussed in Fig. 4, 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 a negative effect of the excess burden associated with the global climate policy, leading to reductions in Y , R , C , etc. Moreover, 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. Additionally, according to Wing (2006), increasing the tax levels reduces the scale of

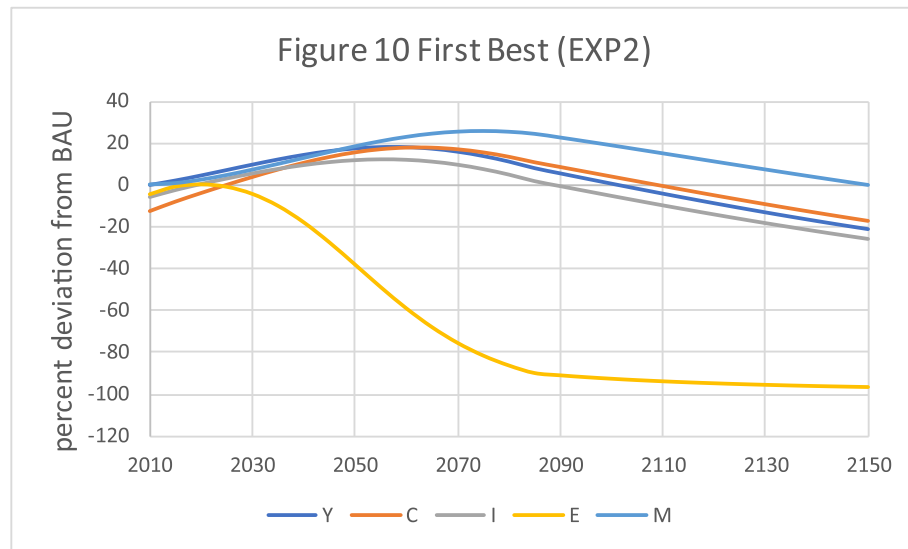


Fig. 10. First Best (EXP2).

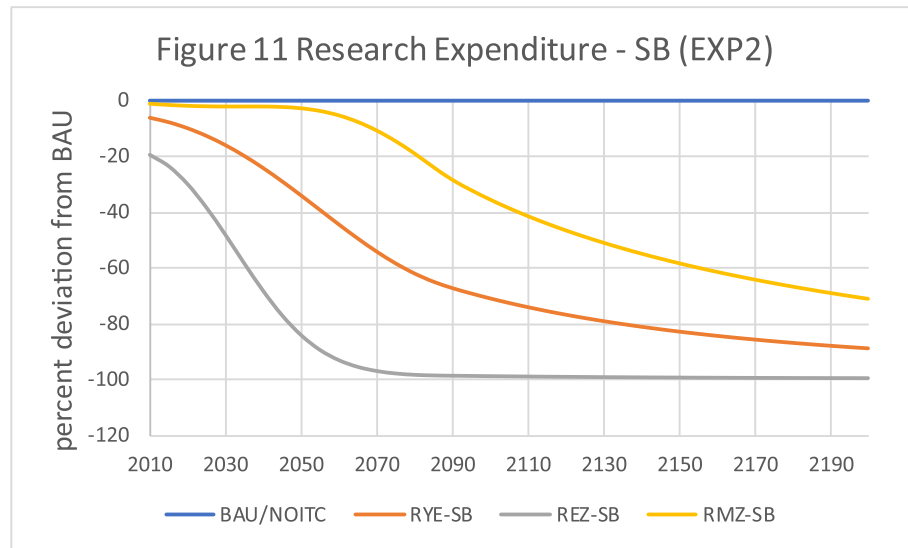


Fig. 11. Research Expenditure - SB (EXP2).

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.

Fig. 11 shows the research expenditure of the SB in EXP2. According to Wing (2006) and Gans (2012), we form three expectations (Fig. 9 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 a 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). Fig. 11's results reflect that (i) the

magnitudes of R_{YE} , R_{MZ} , and R_{EZ} are lower in Fig. 11 compared with Fig. 9; (ii) SB leads to decreases in R_{YE} , R_{MZ} , and R_{EZ} compared with BAU; (iii) SB generates large reductions for R_{YE} and R_{EZ} .

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. Fig. 12 shows the research expenditure of the FB in EXP3. As discussed in Fig. 3, we form the following expectations. First, our calibrated value of elasticity of substitution parameter in EXP3 is 0.6451, implying 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. Fig. 12 shows the empirical results, which are consistent with the above expectations. First, R_{YE} , R_{MZ} , and R_{EZ} have large positive

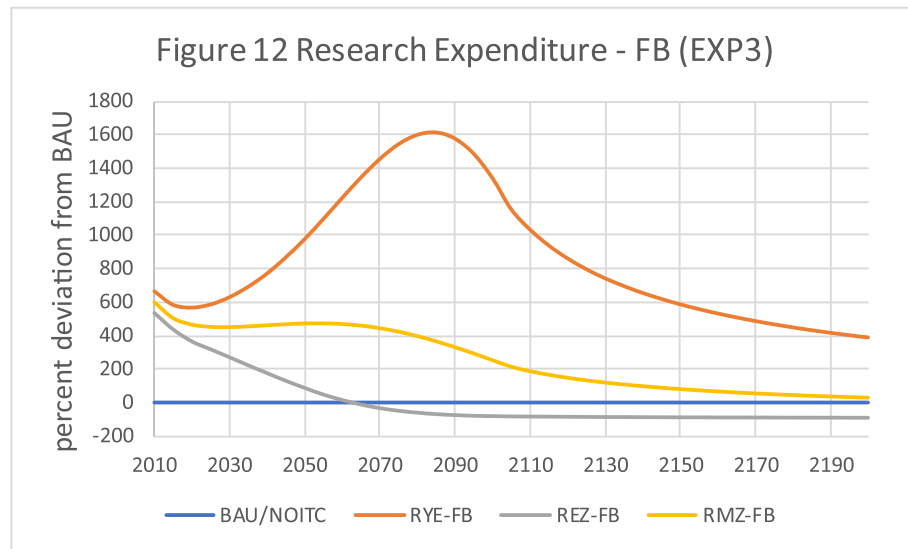


Fig. 12. Research Expenditure - FB (EXP3).

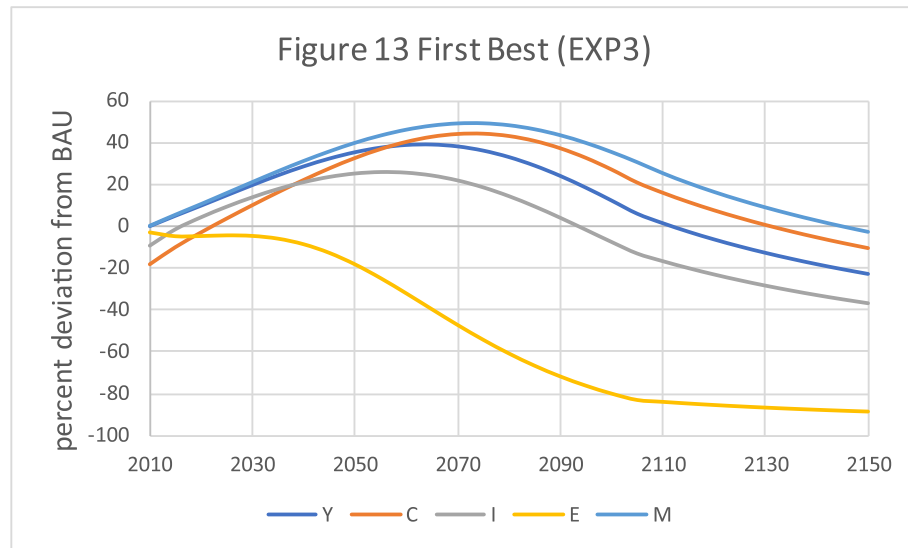


Fig. 13. First Best (EXP3).

deviations in the early periods. Second, FB leads to a decrease of R_{MZ} and R_{EZ} in the long run and a hump shape of R_{YE} .

Fig. 13 describes the variables of Y , C , I , E , and M from the FB compared with their corresponding values in the BAU in EXP3. According to 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 Fig. 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 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 is 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. Fig. 13's results show that the empirical finding is consistent

with our initial hypothesis.

Fig. 14 shows the research expenditure of the SB in EXP3. Based on theories from Wing (2006), Gerlagh (2008), and Gans (2012), we expect decreases of R_{MZ} and R_{EZ} and a hump shape of R_{YE} (a more detailed discussion of this is in Fig. 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). Fig. 14's results reflect what we learned from the theory.

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 (2008)'s approach into our model to see how large the overestimated impact of induced R&D is. Fig. 15 shows the research expenditure of the FB in EXP4. Based on theories from Wing (2006), Gerlagh (2008), Gans (2012), we form the following expectations (Fig. 9 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, our calibrated value of elasticity of the substitution parameter in EXP4 is 1.1356, which

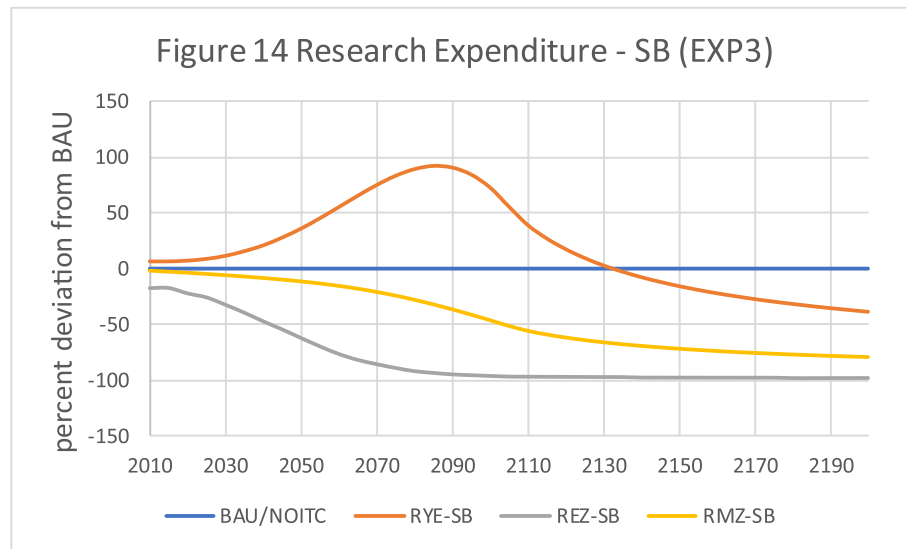


Fig. 14. Research Expenditure - SB (EXP3).

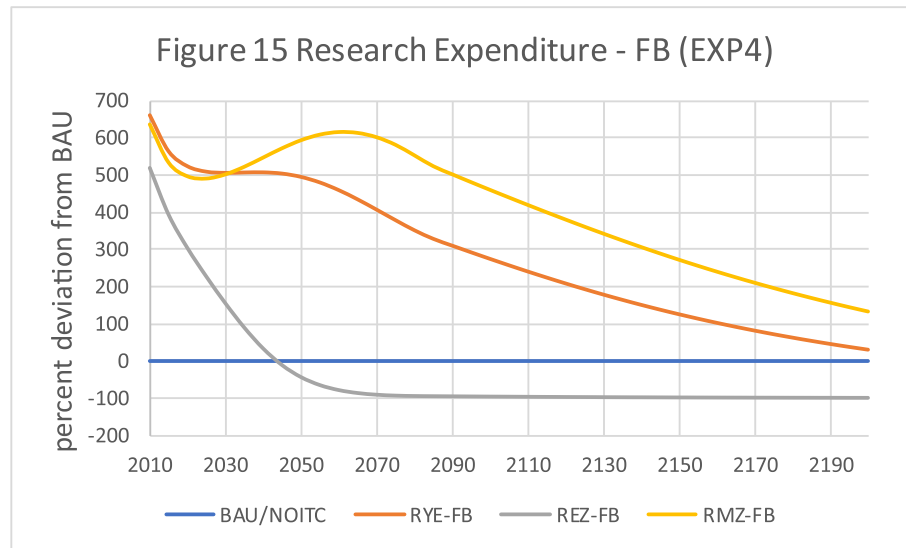


Fig. 15. Research Expenditure - FB (EXP4).

implies that inputs are gross substitutes. Therefore, we expect to observe decreases in R_{YE} and R_{EZ} but anticipate that R_{MZ} will be higher than its BAU level following Wing (2006) and 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 is in place, there are small positive jumps in all types of R&D. Fig. 15 shows the empirical results, which are consistent with the above expectations.

Fig. 16 describes the variables of Y , C , I , E , and M from the FB as compared with their corresponding values in the BAU in EXP4. According to 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 Fig. 10). 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. Fig. 16's results show that the empirical finding is consistent with this hypothesis.

Fig. 17 shows the research expenditure of the SB in EXP4. Based on theories from Wing (2006), Gerlagh (2008), and Gans (2012), we form the following expectations (Fig. 11 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. Fig. 17's results reflect those expectations.

Conclusion

In this research, we build a dynamic model of the global economy and climate with three endogenous knowledge stocks that study the role of technological innovation in global climate policy. Based on the General Algebraic Modeling System (GAMS) software platform, we

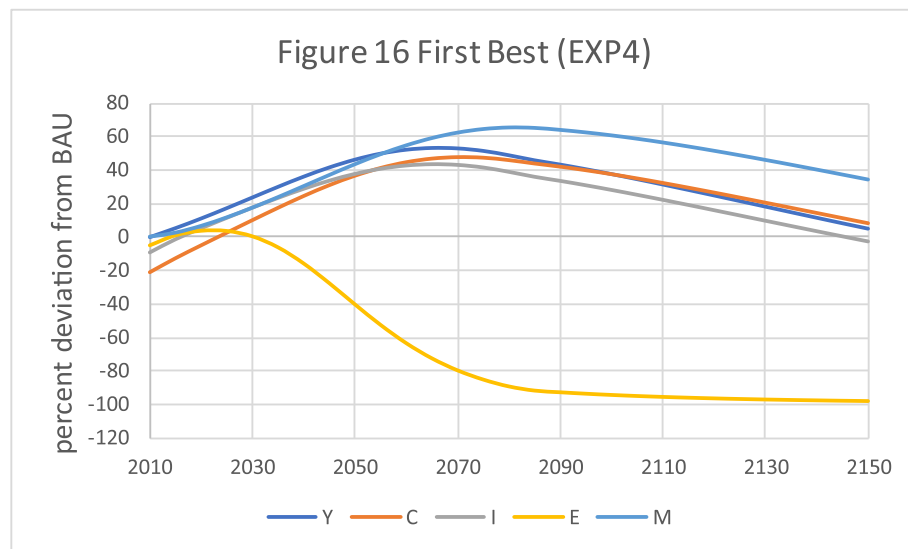


Fig. 16. First Best (EXP4).

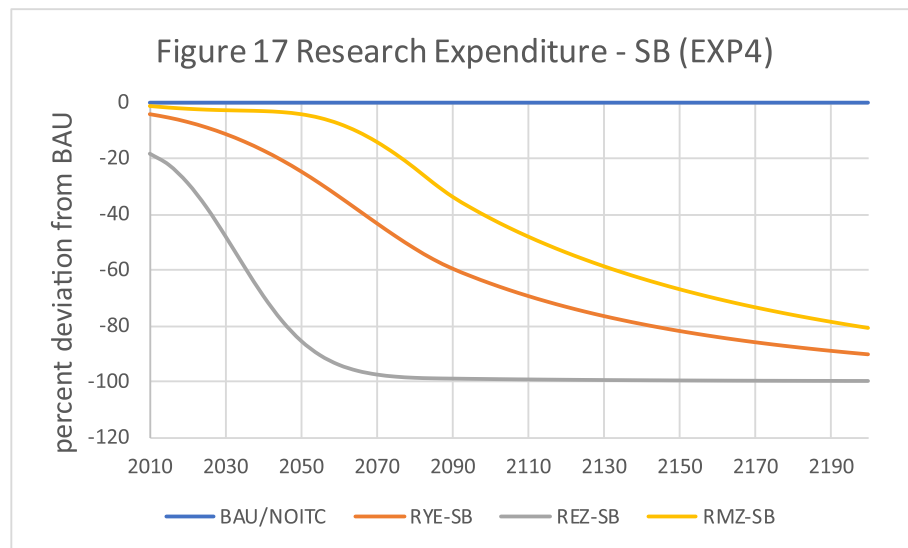


Fig. 17. Research Expenditure - SB (EXP4).

successfully developed a numerical simulation model to study this important social science issue. Through numerical simulations, important findings have been derived from our model. These findings make contributions to relevant literature and improve our understanding of this topic in many aspects. We confirm the conventional wisdom of previous studies and understand that there are six important determinants of induced R&D. Research shows that induced R&D has a limited role in the abatement cost reduction of carbon emissions overall. The important policy implication is that the government needs to consider the effects of essential determinants of induced R&D into their costs and benefits analysis to address the climate change issues.

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. By comparing 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.

CRedit authorship contribution statement

Chenyu Wang: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

I would like to thank my thesis supervisor, Professor Michael Leslie Shiell, my thesis co-supervisor, Professor Gamal Atallah and my thesis committee members, Professor Ida Ferrara, Professor Louis Hotte, Professor Yazid Dissou, and Professor Zhiqi Chen. I also thank Professor Carolyn Fischer, seminar participants at the University of Ottawa and the School of Economics and Trade of Hunan University for providing me with high-quality scientific research conditions. This research was supported by the Fundamental Research Funds for the Central Universities (531118010465).

Appendix A. Scenarios

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)

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

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 Eqs. (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 $\omega = 1$. In addition, the planner internalizes the duplication externality by using the true knowledge accumulation Eqs. (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

$$\begin{aligned} L = & \sum_{t=1}^{T-1} \left\{ \frac{1}{(1+\rho)^{\Delta t}} P_t \ln \left(\frac{C_t}{P_t} \right) + P_t^Y \left[\left(\zeta_{YM}(M_t)^{\frac{\sigma-1}{\sigma}} + \zeta_{YE} \left(A_{YE,t}^{\pi_{YE}} E_t \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} - Y_t \right] + \mu_t \left[\zeta_M A_{MZ,t}^{\pi_{MZ}} Z_{M,t} - M_t \right] + q_t \left[\zeta_E A_{EZ,t}^{\pi_{EZ}} Z_{E,t} - E_t \right] + \xi_t \left[\gamma K_t^a L_t^{1-a} - Z_{M,t} - Z_{E,t} \right] + \right. \\ & \Psi_t \left[(1 - \delta_k)^{\Delta} K_t + \Delta \left(I_t - \frac{\eta}{2} \frac{I_t^2}{K_t} \right) - K_{t+1} \right] + \theta_{YE,t} \left[\Delta a_{YE} R_{YE,t}^b A_{YE,t}^{\phi} + A_{YE,t} - A_{YE,t+1} \right] + \theta_{MZ,t} \left[\Delta a_{MZ} R_{MZ,t}^b A_{MZ,t}^{\phi} + A_{MZ,t} - A_{MZ,t+1} \right] + \theta_{EZ,t} \left[\Delta a_{EZ} R_{EZ,t}^b A_{EZ,t}^{\phi} + \right. \\ & \left. A_{EZ,t} - A_{EZ,t+1} \right] + P_t^I \left[Y_t - C_t - I_t - R_{YE,t} - R_{MZ,t} - R_{EZ,t} \right] + \theta_{ATM,t} \left[ATM_0 + (1 - \delta_M)^{\Delta} (ATM_t - ATM_0) + (1 - \delta_E)^{\Delta} (CVS_1 E_t + CVS_2 E_{BAR}) - ATM_{t+1} \right] + \\ & \left. \bar{P}_t [ATM_{TGT} - ATM_t] \right\} + \Psi_T K_T + \theta_{YE,T} A_{YE,T} + \theta_{MZ,T} A_{MZ,T} + \theta_{EZ,T} A_{EZ,T} + \theta_{ATM,T} ATM_T \end{aligned}$$

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 \bar{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:

$$\theta_{YE,t} \Delta a_{YE} b R_{YE,t}^{b-1} A_{YE,t}^{\phi} - 1 = 0 \quad (18)$$

$$\theta_{MZ,t} \Delta a_{MZ} b R_{MZ,t}^{b-1} A_{MZ,t}^{\phi} - 1 = 0 \quad (19)$$

$$\theta_{EZ,t} \Delta a_{EZ} b R_{EZ,t}^{b-1} A_{EZ,t}^{\phi} - 1 = 0 \quad (20)$$

$$\beta_t Y_{t+1}^{\frac{1}{\sigma}} \zeta_{YE} \left(A_{YE,t+1}^{\pi_{YE}} E_{t+1} \right)^{\frac{\sigma-1}{\sigma}} \pi_{YE} + \beta_t \theta_{YE,t+1} \Delta a_{YE} R_{YE,t+1}^b A_{YE,t+1}^{\phi} + \beta_t \theta_{YE,t+1} A_{YE,t+1} = \theta_{YE,t} A_{YE,t+1} \quad (21)$$

$$\beta_t \mu_{t+1} \pi_{MZ} M_{t+1} + \beta_t \theta_{MZ,t+1} \Delta a_{MZ} R_{MZ,t+1}^b A_{MZ,t+1}^{\phi} + \beta_t \theta_{MZ,t+1} A_{EZ,t+1} = \theta_{MZ,t} A_{MZ,t+1} \quad (22)$$

$$\beta_t q_{t+1} \pi_{EZ} E_{t+1} + \beta_t \theta_{EZ,t+1} \Delta a_{EZ} R_{EZ,t+1}^b A_{EZ,t+1}^{\phi} + \beta_t \theta_{EZ,t+1} A_{EZ,t+1} = \theta_{EZ,t} A_{EZ,t+1} \quad (23)$$

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

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

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

$$\mu_t M_t = \xi_t Z_{M,t} \quad (27)$$

$$q_t E_t = \xi_t Z_{E,t} \quad (28)$$

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

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

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

$$\overline{P}_t [ATM_{TGT} - ATM_t] = 0 \quad (32)$$

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 Eq. (25). In Eq. (25), we can think β as the intertemporal marginal rate of substitution of consumption. Then, combining (25) with (29) gives the Keynes-Ramsey rule.

Eq. (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.

Eq. (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 Eqs. (18)–(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 Eqs. (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 $\omega = 0.25$.

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

$$\begin{aligned} L = \sum_{t=1}^T \{ & \frac{1}{(1+\rho)^{\Delta t}} P_t \ln \left(\frac{C_t}{P_t} \right) + P_t^Y \left[\left(\zeta_{YM} (M_t)^{\frac{\sigma-1}{\sigma}} + \zeta_{YE} (A_{YE,t}^{\pi_{YE}} E_t)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} - Y_t \right] + \mu_t [\zeta_M A_{MZ,t}^{\pi_{MZ}} Z_{M,t} - M_t] + q_t [\zeta_E A_{EZ,t}^{\pi_{EZ}} Z_{E,t} - E_t] + \xi_t [\gamma K_t^\alpha L_t^{1-\alpha} - Z_{M,t} - Z_{E,t}] \\ & + \Psi_t \left[(1 - \delta_k)^\Delta K_t + \Delta \left(I_t - \frac{\eta}{2} \frac{I_t^2}{K_t} \right) - K_{t+1} \right] + \theta_{YE,t} [\Delta \omega V_{YE,t} R_{YE,t} + A_{YE,t} - A_{YE,t+1}] + \theta_{MZ,t} [\Delta \omega V_{MZ,t} R_{MZ,t} + A_{MZ,t} - A_{MZ,t+1}] + \theta_{EZ,t} [\Delta \omega V_{EZ,t} R_{EZ,t} + A_{EZ,t} \\ & - A_{EZ,t+1}] + P_t^I [Y_t - C_t - I_t - R_{YE,t} - R_{MZ,t} - R_{EZ,t}] \} \end{aligned}$$

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

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

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

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

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

$$\beta_t \mu_{t+1} \pi_{MZ} M_{t+1} + \beta_t \theta_{MZ,t+1} A_{MZ,t+1} = \theta_{MZ,t} A_{MZ,t+1} \quad (37)$$

$$\beta_t q_{t+1} \pi_{EZ} E_{t+1} + \beta_t \theta_{EZ,t+1} A_{EZ,t+1} = \theta_{EZ,t} A_{EZ,t+1} \quad (38)$$

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

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

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

$$\mu_t M_t = \xi_t Z_{M,t} \text{ or } \mu_t \zeta_M A_{MZ,t}^{\pi_{MZ}} = \xi_t \quad (42)$$

$$q_t E_t = \xi_t Z_{E,t} \text{ or } q_t \xi_t A_{EZ,t}^{\pi_{EZ}} = \xi_t \quad (43)$$

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

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

The solution in BAU is characterized by the structural equations of (1)–(13), (6''), (7''), (8'') plus the behavioral Eqs. (33)–(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:

$$\begin{aligned} L = \sum_{t=1}^T \{ & \frac{1}{(1+\rho)^{\Delta t}} P_t \ln \left(\frac{C_t}{P_t} \right) + P_t^Y \left[\left(\zeta_{YM} (M_t)^{\frac{\sigma-1}{\sigma}} + \zeta_{YE} (A_{YE,t}^{\pi_{YE}} E_t)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} - Y_t \right] + \mu_t [\zeta_M A_{MZ,t}^{\pi_{MZ}} Z_{M,t} - M_t] + q_t [\zeta_E A_{EZ,t}^{\pi_{EZ}} Z_{E,t} - (1 + \tau_t) E_t] + \xi_t [\gamma K_t^\alpha L_t^{1-\alpha} - Z_{M,t} \\ & - Z_{E,t}] + \Psi_t \left[(1 - \delta_k)^\Delta K_t + \Delta \left(I_t - \frac{\eta}{2} \frac{I_t^2}{K_t} \right) - K_{t+1} \right] + \theta_{YE,t} [\Delta \omega V_{YE,t} R_{YE,t} + A_{YE,t} - A_{YE,t+1}] + \theta_{MZ,t} [\Delta \omega V_{MZ,t} R_{MZ,t} + A_{MZ,t} - A_{MZ,t+1}] + \theta_{EZ,t} [\Delta \omega V_{EZ,t} R_{EZ,t} \\ & + A_{EZ,t} - A_{EZ,t+1}] + P_t^I [Y_t - C_t - I_t - (1 - s_{YE,t}) R_{YE,t} - (1 - s_{MZ,t}) R_{MZ,t} - (1 - s_{EZ,t}) R_{EZ,t} + TF_t] \} \end{aligned}$$

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

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

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

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

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

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

$$ns_j^* = \theta_j \Delta a_j R_j^{b-1} A_j^\theta (b - \omega), \quad (j = (Y, E), (M, Z), (E, Z))$$

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 Eqs. (1)–(16) and BAU behavioral Eqs. (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 Eqs. (1)–(16), behavioral Eqs. (39)–(45) (replace (41) with (41')), plus transversally conditions, initial values of the state variables, and the environmental target condition.

Appendix B: Calibration

Structural equations in “Steady State”:

1. $Y = (\zeta_{YM} (M)^{\frac{\sigma-1}{\sigma}} + X_1 (E)^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}}$
2. $X_1 = \zeta_{YE} (A_{YE}^{\pi_{YE}})^{\frac{\sigma-1}{\sigma}}$
3. $M = X_2 Z_M$
4. $X_2 = \zeta_M A_{MZ}^{\pi_{MZ}}$
5. $E = X_3 Z_E$

6. $X_3 = \varsigma_E A_{EZ}^{\pi_{EZ}}$
7. $(Z_M + Z_E) = \gamma K^\alpha L^{1-\alpha}$
8. $(e^{\Delta g_K})K = (1 - \delta_K)^\Delta K + \Delta \left(I - \frac{\eta}{2} \frac{I^2}{K} \right)$
9. $(e^{\Delta g_{AYE}}) = \Delta a_{YE} R_{YE}^b A_{YE}^{\phi-1} + 1$
10. $V_{YE} = a_{YE} R_{YE}^{b-1} A_{YE}^\phi$
11. $(e^{\Delta g_{AMZ}}) = \Delta a_{MZ} R_{MZ}^b A_{MZ}^{\phi-1} + 1$
12. $V_{MZ} = a_{MZ} R_{MZ}^{b-1} A_{MZ}^\phi$
13. $(e^{\Delta g_{AEZ}}) = \Delta a_{EZ} R_{EZ}^b A_{EZ}^{\phi-1} + 1$
14. $V_{EZ} = a_{EZ} R_{EZ}^{b-1} A_{EZ}^\phi$
15. $Y = C + I + R$
16. $R = R_{YE} + R_{MZ} + R_{EZ}$
17. $R = s s_R Y$
18. $R_{YE} = s s_{YE} R$
19. $R_{EZ} = s s_{EZ} R$
20. $L = h_0 P_0$

Behavioral equations in “Steady State”:

1. $\beta = \frac{e^{\Delta(g_{OP} - g_C)}}{(1+\rho)^\Delta}$
2. $Y = \left(\frac{\mu}{\varsigma_{YM}} \right)^\sigma M$
3. $X_1 = q \left(\frac{E}{Y} \right)^{\frac{1}{\sigma}}$
4. $\mu X_2 = \xi$
5. $q X_3 = \xi$
6. $\Delta \left(1 - \eta \frac{I}{K} \right) \xi \gamma \alpha \left(\frac{I}{K} \right)^{1-\alpha} + (1 - \delta_K)^\Delta + \Delta \left(\frac{\eta}{2} \frac{I^2}{K^2} \right) = \frac{1}{\beta} \frac{\left(1 - \eta \frac{I}{K} \right)}{\left(1 - \eta \frac{I}{K} e^{\Delta(g_K - g_I)} \right)}$
7. $\beta Y^{\frac{1}{\sigma}} X_1(E)^{\frac{\sigma-1}{\sigma}} \pi_{YE} = \theta_{YE} A_{YE} (e^{-\Delta g_{OYE}} - \beta)$
8. $\beta \mu \pi_{MZ} M = \theta_{MZ} A_{MZ} (e^{-\Delta g_{OMZ}} - \beta)$
9. $\beta q \pi_{EZ} E = \theta_{EZ} A_{EZ} (e^{-\Delta g_{O EZ}} - \beta)$
10. $\theta_{YE} \Delta \omega V_{YE} - 1 = 0$
11. $\theta_{MZ} \Delta \omega V_{MZ} - 1 = 0$
12. $\theta_{EZ} \Delta \omega V_{EZ} - 1 = 0$
13. $\Psi \Delta \left(1 - \eta \frac{I}{K} \right) = 1$

Growth equations in “Steady state”:

1. $g_Y = \left(\frac{1}{Y} \right) \left[g_\mu \mu M + \mu M g_M + g_q q E + q E g_E \right] = \left(\frac{M}{Y} \right)^{\frac{\sigma-1}{\sigma}} g_M + \left[1 - \left(\frac{M}{Y} \right)^{\frac{\sigma-1}{\sigma}} \right] (\pi_{YE} g_{AYE} + g_E)$
2. $g_M = \pi_{MZ} g_{AMZ} + g_{ZM}$
3. $g_E = \pi_{EZ} g_{AEZ} + g_{ZE}$
4. $\left[\frac{Z_M}{Z_M + Z_E} \right] g_{ZM} + \left[\frac{Z_E}{Z_M + Z_E} \right] g_{ZE} = \alpha g_K + (1 - \alpha) g_L$
5. $[e^{g_K} - (1 - \delta_K)] g_K K - \frac{\eta}{2} \frac{I^2}{K} g_K = I \left(1 - \eta \frac{I}{K} \right) g_I$
6. $(1 - \phi) g_{AYE} = b g_{RYE}$
7. $g_{VYE} = (b - 1) g_{RYE} + \phi g_{AYE}$
8. $(1 - \phi) g_{AMZ} = b g_{RMZ}$
9. $g_{VMZ} = (b - 1) g_{RMZ} + \phi g_{AMZ}$
10. $(1 - \phi) g_{AEZ} = b g_{REZ}$
11. $g_{VEZ} = (b - 1) g_{REZ} + \phi g_{AEZ}$
12. $g_Y = g_C \left(\frac{C}{Y} \right) + g_I \left(\frac{I}{Y} \right) + g_{RYE} \left(\frac{R_{YE}}{Y} \right) + g_{RMZ} \left(\frac{R_{MZ}}{Y} \right) + g_{REZ} \left(\frac{R_{EZ}}{Y} \right)$
13. $g_R = g_{RYE} \left(\frac{R_{YE}}{R} \right) + g_{RMZ} \left(\frac{R_{MZ}}{R} \right) + g_{REZ} \left(\frac{R_{EZ}}{R} \right)$
14. $\sigma g_\mu + g_M = g_Y$

$$15. \sigma g_q + g_E = (\sigma - 1)\pi_{YE}g_{AYE} + g_Y$$

$$16. g_\mu + \pi_{MZ}g_{AMZ} = g_\varepsilon$$

$$17. g_q + \pi_{EZ}g_{AEZ} = g_\varepsilon$$

$$18. \xi \gamma \alpha \left(\frac{I}{K} \right)^{1-\alpha} \left[g_\varepsilon \left(1 - \eta \frac{I}{K} \right) - \eta \frac{I}{K} (g_I - g_K) - \left(1 - \eta \frac{I}{K} \right) (1 - \alpha) g_K \right] + \eta \left(\frac{I}{K} \right)^2 (g_I - g_K) = \frac{\eta \left(\frac{I}{K} \right) (g_I - g_K) (e^{g_K - g_I} - 1)}{\beta \left(1 - \eta \frac{I}{K} e^{g_K - g_I} \right)^2}$$

$$19. \frac{\beta}{\sigma} Y^\sigma X_1(E)^{\frac{\sigma-1}{\sigma}} \pi_{YE} \left[g_Y + (\sigma - 1)(\pi_{YE}g_{AYE} + g_E) \right] = \theta_{YE} A_{YE} (e^{-g_{\theta YE}} - \beta) (g_{\theta YE} + g_{AYE})$$

$$20. \beta \mu \pi_{MZ} M(g_\mu + g_M) = \theta_{MZ} A_{MZ} (e^{-g_{\theta MZ}} - \beta) (g_{\theta MZ} + g_{AMZ})$$

$$21. \beta q \pi_{EZ} E(g_q + g_E) = \theta_{EZ} A_{EZ} (e^{-g_{\theta EZ}} - \beta) (g_{\theta EZ} + g_{AEZ})$$

$$22. g_{\theta YE} = -g_{VYE}$$

$$23. g_{\theta MZ} = -g_{VMZ}$$

$$24. g_{\theta EZ} = -g_{VEZ}$$

$$25. g_\Psi \left(1 - \eta \frac{I}{K} \right) = \eta (g_I - g_K) \frac{I}{K}$$

References

- Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. *American Economic Review*, 102(1), 131–166.
- 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.
- Duan, H. B., Zhu, L., & Fan, Y. (2014). Optimal carbon taxes in carbon-constrained China: A logistic-induced energy economic hybrid model. *Energy*, 69, 345–356. <https://doi.org/10.1016/j.energy.2014.03.022>
- Duan, H., Mo, J., Fan, Y., & Wang, S. (2018). Achieving China's energy and climate policy targets in 2030 under multiple uncertainties. *Energy Economics*, 70, 45–60. <https://doi.org/10.1016/j.eneco.2017.12.022>
- Feenstra, R. C., Inklaar, R., & Timmer, M. P. (2015). The next generation of the Penn World Table. *American Economic Review*, 105(10), 3150–3182.
- 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), 125–145.
- 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, J. R. (1963). *The Theory of Wages* (London, 1932). Chap. VII.
- 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.
- Massetti, E., & Nicita, L. (2010). The optimal climate policy portfolio when knowledge spills across sectors.
- McKibbin, W. J., & Wilcoxon, P. J. (1999). The theoretical and empirical structure of the G-Cubed model. *Economic Modelling*, 16(1), 123–148.
- Nordhaus, W. D. (1994). *Managing the Global Commons: The economics of the greenhouse effect*. Cambridge, MA: MIT Press.
- Nordhaus, W. D., & Boyer, J. (2000). *Warming the world: Economic models of global warming*. MIT Press.
- 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.
- Shiell, L., & Lyssenko, N. (2014). Climate policy and induced R&D: How great is the effect? *Energy Economics*, 46, 279–294.
- Shittu, E., & Baker, E. (2009). Optimal energy R&D portfolio investments in response to a carbon tax. *IEEE Transactions on Engineering Management*, 57(4), 547–559.
- United Nations Department of Economic and Social Affairs/Population Division. (2004). *World Population To 2300*. New York, 18(3), 553–561. <http://linkinghub.elsevier.com/retrieve/pii/S1049007807000358>.
- Wing, I. S. (2006). Induced technological change: Firm innovatory responses to environmental regulation. Unpublished Manuscript, Available at [Http://People. Bu. Edu/Is/w](http://People.Bu.Edu/Is/w).
- OECD Statistics. (n.d.). <https://stats.oecd.org/>.
- CAIT Climate Data Explorer. (n.d.). <http://cait.wri.org/>.
- World Bank Open Data. (n.d.). <https://data.worldbank.org/>.
- UNESCO Data. (n.d.). <https://data.worldbank.org/>.
- OECD Data. (n.d.). <https://data.oecd.org/>.