International technology diffusion, multilateral R&D coordination, and global climate mitigation

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ABSTRACT

The issues of complementing emission-based international climate agreements with technology-oriented ones have been placed high upon future climate policy and research agenda. This paper is motivated to explore the fundamental mechanism of international technology coordination for global climate mitigation. We first present a partial equilibrium analytical model that intuitively unveils the basic mechanism of multilateral R&D coordination for saving climate mitigation costs. This mechanism is then quantitatively assessed in a multi-region general equilibrium numerical model that explicitly specifies the technology externality resulting from cross-country knowledge diffusion. Results show that: (1) By fully internalizing the technology externality of cross-country knowledge diffusion, multilateral R&D coordination can stimulate country-specific R&D efforts and cross-country technology diffusion; (2) Innovation enhanced by multilateral R&D coordination facilitates knowledge creation, which has a notable effect to boost economic growth and carbon savings in each participating country; and (3) By lowering the climate mitigation costs incurred by traditional emission-based climate policies, the technology-oriented agreements like multilateral R&D coordination can stimulate the incentives for mitigation action and improve the environmental effectiveness of global climate mitigation efforts.

1. Introduction

In pursuit of a knowledge-based economy, both the developing and developed countries have stepped up their efforts to boost technological innovation through massive growth in R&D. While the US, the EU, and Japan remain leaders in innovation, increased competition from the emerging economies – notably the BRICS countries (Brazil, Russia, India, China, and South Africa) – suggests a changing geography of global innovation (National Science Board (NSB), 2012; OECD, 2012). This new landscape has remarkably transcended the former innovation pattern dominated by the “triad regions”, with the emerging economies increasingly engaged in the global innovation platform as the new hubs of R&D.

In the globalized world economy, the emergence of multiple hubs of innovation provides a solid platform for cross-country technology diffusion. On the one hand, the integrated network of production through international trade and FDI (the traditional aspect of globalization) enables extensive dissemination of technologies through cross-border transactions of materials, capital, and products (UNCTAD, 2010a; World Trade Organization (WTO), 2010). On the other hand, the internationalization of R&D (the modern aspect of globalization) offers a new opportunity of transferring advanced technologies, such that individual countries can harness the international mobility of knowledge to build indigenous innovative capacity (OECD, 1997).

This overarching trend of international technology diffusion provides key implications for global climate mitigation. First, it is argued that the existing emission-based international climate agreements (the Kyoto Protocol) are increasingly flawed, since the standalone implementation of emission-based instruments incurs substantial climate compliance costs and discourages climate mitigation efforts made by the major carbon-emitting countries. Technology-oriented agreements like technology cooperation can thus be thought of as an important complement in building the post-Kyoto climate architecture. Given that the global innovation hubs like the US, EU, and China are also major carbon emitters, technology partnership among them can create the potential of stimulating their participations in the campaign of global climate mitigation (Aldy et al., 2003; Barrett, 2003; Barrett and Stavins, 2003; Buchner and Carraro, 2005; Newell, 2008; De Coninck et al., 2008).2

Second, while most of the major countries have implemented R&D-related innovation to address climate mitigation issues, the existing innovation policies adopted by individual nations are unilateral and uncoordinated, paying no attention to the positive externality resulting from the technology cooperation. This trend is characterized by the following three aspects: 1) Absolute levels: R&D spending in Asia surpassed the EU levels, and is likely to overtake the US in the next five years, which is due to striking R&D growth in China; 2) Growth rate: the growth rate of R&D in the emerging market is considerably higher than that in the G7 markets; 3) R&D intensity: a flat level remains in the G7 markets, but the emerging markets have nearly doubled their R&D intensity over the last decade (OECD, 2012).
from cross-country technology diffusion (Buchner and Carraro, 2005; Carraro and Siniscalco, 1997; De Coninck et al., 2008; Newell, 2008; Marucci and Turton, 2013). An international framework of multilateral innovation cooperation should thus be built to internalize the positive technology externality. By doing that, the innovation coordination can enhance country-level R&D efforts and create more knowledge that favors innovation and carbon savings at a global scale.

In this context, we are motivated to explore the underlying mechanism of international R&D coordination for global climate mitigation. In particular, the following issues will be addressed: 1) How does cross-country knowledge diffusion create the mechanism of R&D coordination for saving climate mitigation costs; 2) What are the effects of international R&D coordination on technological innovation, economic growth, and carbon emissions of the participating countries; and 3) To what extent international R&D coordination help mitigate climate mitigation costs incurred by traditional emission-based instruments. To deal with these issues, we first develop a simple partial equilibrium analytical model that intuitively unveils the basic mechanism of international R&D coordination for saving climate mitigation costs. This mechanism is then quantitatively assessed in a multi-region general equilibrium numerical model that explicitly represents the externality resulting from cross-country technology diffusion.

Most of the existing works only focus on modeling endogenous technical change driven by indigenous innovation within an isolated economy, paying little attention to the potential effects of cross-country technology diffusion and coordination (e.g., Goulder and Schneider, 1999; Sue Wing, 2001, Sue Wing, 2006; Popp, 2004; Otto et al., 2007; Bosetti et al., 2008; Jin, 2012). While the literature includes some theoretical expositions on the international environmental technology cooperation (e.g., Xepapadeas, 1995; Barrett, 2006; Kolstad, 2007; Golombek and Hoel, 2005, 2008, 2011; Heal and Tarui, 2010; Hoel and de Zeeuw, 2010; Maria and Werf, 2008; Lessman and Edenhofer, 2011), the efforts of large-scale numerical modeling for policy studies are still insufficient. Hence, this study contributes to filling this gap in the field of modeling innovation for energy/climate policy studies. In particular, the contribution of this paper involves the following three aspects: 1) The "stock of knowledge" approach is used to specify the mechanism of international technology diffusion (ITD) and multilateral innovation coordination in our general equilibrium modeling; 2) A comprehensive modeling framework is built to fully capture ITD through both embodied and disembodied diffusion channels; and 3) The new pattern of global multidirectional technology diffusion is explicitly considered.

The rest of this paper is organized as follows: Section 2 presents a simple partial equilibrium model that analytically examines the mechanism of international R&D coordination for climate compliance cost savings. Section 3 describes the general framework of the multi-region numerical model, with an emphasis on specifications of multilateral R&D coordination. Simulation results and discussion are provided in Section 4. Section 5 concludes.

2. A partial equilibrium model

The methodological basis of modeling technical change (TC) is the "stock of knowledge" method (e.g., Goulder and Schneider, 1999; Sue Wing, 2001, Sue Wing, 2006; Popp, 2004; Otto et al., 2007; Acemoglu et al., 2009; Bosetti et al., 2008; Jin, 2012). It treats TC as an outcome of applying knowledge that is created by purposeful innovative activities. The mechanism of TC thus involves three underlying endogenous processes: 1) Firms first undertake purposeful innovative activities (e.g., indigenous R&D, foreign technology absorption) for the purpose of cost minimization/profit maximization; 2) Innovative activities then accumulate new knowledge asset; 3) The accumulated knowledge is finally applied in the production process to induce a reconfiguration of production factors, which eventually leads to an increase in the Hicks-neutral total factor productivity (the rate of TC) and a decrease in the input intensity of physical inputs (the bias of TC).

In this line, we develop a partial equilibrium model where the production technology of the representative firm in energy sectors is specified as a two-tier nested CES function (see Fig. 1(a)). Given this production technology, the cost minimization problem facing this firm takes a form as:

\[
\min_{E_D, E_Q, C_Q, C_D} \ \frac{1}{\kappa} \left( E_D^{\kappa} + (C_Q^{\kappa})^\sigma + (C_D^{\kappa})^\sigma \right) \quad \text{s.t.} \quad \left( \frac{E_D^{\kappa} + C_Q^{\kappa} + C_D^{\kappa}}{C_D^{\kappa}} \right)^\sigma = Y, \quad E_D \leq \kappa
\]

where in producing end-use, secondary energy goods \( Y \), knowledge \( H \) is used to substitute for a primary energy input composite \( E \) at the top tier, with the degree of substitution indicated by \( \kappa \). The energy input composite is in turn made up of "dirty" fossil energy \( E_D \) and "clean" non-fossil energy \( E_Q \) at the bottom tier, with the degree of substitution between both energy input varieties indicated by \( \sigma \). To minimize the costs of producing an exogenous level of output \( Y \), the firm optimally chooses the inputs of fossil energy and non-fossil energy, given the prices of "dirty" and "clean" energy inputs \( P_D \) and \( P_C \), and the knowledge input \( H \).

Assume that one unit of fossil energy use produces one unit of carbon emission, the level of carbon emissions due to fossil energy use should thus be constrained within the boundary condition, \( E_D \leq \kappa \), when the energy firm is capped by an emission limit \( \kappa \). In the presence of the carbon permit constraint, the marginal cost of carbon abatement faced by this energy firm is characterized by the following result.

\[ \text{Proposition 1.} \quad \text{In the above-described partial equilibrium model, by solving the cost minimization problem subject to production technology and carbon} \]

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3 Beyond the traditional emission-based climate policies that correct for the environmental externality of carbon emissions, a comprehensive climate strategy should also consider technology policies that aim for the internalization of the positive technology externality (Nordhaus, 2011; Popp, 2011).

4 Some international frameworks for climate technology cooperation have been institutionalized in recent years, for example, the Asia-Pacific Partnership on Clean Development and Climate (APP), and the International Energy Agency Implementing Agreements (IEA-IA).

5 The "stock of knowledge" approach adopts R&D and knowledge to explicitly represent technology, where ITD is described as international R&D spillovers to domestic knowledge stock for endogenous TC (e.g., Carraro and Siniscalco, 1997; Buonanno et al., 2003; Bosetti et al., 2008, 2011; De Cian and Tavoni, 2012; Parrado and De Cian, 2014). This explicit treatment is a useful complement to the implicit (parametrical) approach of representing technology, where ITD is described as changes in productivity parameters as a function of the potential drivers such as trade and FDI (e.g., Leimbach and Edenhofer, 2007; Leimbach and Eisenack, 2009; Leimbach and Baumstark, 2010; Höhler, 2011).

6 Most of existing climate modeling works only capture one type of ITD channel in isolation (Höhler, 2011; Leimbach and Baumstark, 2010; Leimbach and Edenhofer, 2007; Bosetti et al., 2008, 2011; De Cian and Tavoni, 2012; Buonanno et al., 2003). But some empirical studies have shown that firms do not merely undertake a single type of economic activity associated with technology diffusion, but perform several such activities simultaneously (Clerides et al., 1998; KELLER, 2004).

7 As most of the existing studies only focus on modeling the North–South unidirectional technology transfer (Yang and Nordhaus, 2006; Kypreos and Turton, 2011; Höhler, 2011; Bosetti et al., 2008, 2011), there is a need to consider the new pattern of global multidirectional technology interaction which potentially involves cross-country technology feedbacks and cooperation.

8 This market-driven view that economic opportunities are the primary determinant of innovation is articulated in the seminal works of Schmookler (1966), Griliches (1957), and Griliches and Schmookler (1963), arguing that innovation is largely an economic activity which, like other economic activities, is pursued for cost reductions or profit gains.
emission permit constraints, the energy firm faces a marginal abatement cost (MAC) of carbon emissions which takes a form as:

$$\lambda = -P_D + P_C \cdot \left( \frac{Y^{o^Y} - H^{oH}}{H^{oH}} \right)^{1-\sigma} \cdot \kappa^{\sigma - 1},$$  \tag{2}

where $\lambda$ is the marginal abatement cost of carbon emissions (the so-called shadow price of carbon permit), which is the additional production costs incurred by marginally tightening emission permits. Moreover, the MAC of carbon emission $\lambda$ is decreasing in fossil energy price $P_D$, carbon permit constraint $\kappa$, and knowledge use $H$.

**Proof.** See Appendix A. 

The economic intuitions of Proposition 1 are as follows. In a context where fossil energy prices are higher and more carbon permits are available, the energy firm will have a lower level of MAC. Meanwhile, an energy firm that intensively applies intangible knowledge in production activity, ceteris paribus, will have a level of MAC that is relatively lower. The reasons are intuitive. First, when regulators charge a higher environmental cost on using the "dirty" primary energy inputs through a carbon tax, firms that produce secondary energy will choose "clean" production technologies by lowering reliance on "dirty" primary energy inputs. Tightening carbon permits thus has little effect to incur additional costs — a lower level of MAC. Second, with more carbon permits issued, there is a lower price of permit in the carbon market, thus the costs incurred by tightening permits will be lower. Third, when energy firms apply more knowledge in producing end-use energy products, the knowledge-intensive production technology translates into a lower reliance on the input of fossil-based primary energy, tightening carbon permits thus has a smaller effect to incur additional production costs.

To proceed in a tractable way, we rewrite Eq. (2) to work with a loglinearized form as:

$$\lambda = -\frac{\lambda}{\lambda} P_D + \frac{1}{\lambda} P_C \cdot \left( \frac{Y^{o^Y} - H^{oH}}{H^{oH}} \right)^{1-\sigma} \cdot \kappa^{\sigma - 1},$$  \tag{3}

where a variable with a bar symbol "_" denotes the rate of change in that corresponding variable. In a partial equilibrium framework, both energy prices, $P_D$ and $P_C$, and carbon permit constraint, $\kappa$, are exogenously given, and the cost minimization problem assumes an exogenous level of output, $Y$. The rates of change are thus equal to zero for $P_D = 0$, $P_C = 0$, $\kappa = 0$, and $Y = 0$, and Eq. (3) can be simplified as:

$$\lambda = -\left( 1 + \frac{P_D}{\lambda} \right) \cdot \left( 1 - \theta_X \right) \cdot \frac{\left( Y^{o^Y} - H^{oH} \right)^{1-\sigma}}{H^{oH}} \cdot \frac{Y^{o^H} - H^{oH}}{H^{oH}} \cdot \frac{1}{\lambda},$$  \tag{4}

and it is straightforward to show that the MAC will decrease, $\lambda < 0$, as the energy firm applies more knowledge to substitutes for energy inputs in the production, $H > 0$.

Next, we introduce a two-country (say, A and B) model of international technology diffusion for climate mitigation. Consider that, for each country $i = A, B$ knowledge creation depends on both indigenous R&D and absorption of foreign knowledge diffusion which takes a form as:

$$H_i = R_i + \frac{R_i}{R_i + R_j} \cdot (R_i + R_j - R_i),$$  \tag{5}

where the gap between global R&D ($R_i + R_j$) and each country $i$’s indigenous R&D ($R_i$) is the remaining amount of R&D in the international knowledge pool that potentially spills over to the country $i$. To determine the amount of foreign knowledge diffusion that is effectively absorbed by
a specific country, we need to consider the knowledge absorptive capacity of a given country. The ratio of country $i$’s R&D to the global R&D total is used as a proxy (measurable) variable for country $i$’s knowledge absorptive capacity.\footnote{In this regard, we follow the works of Bosetti et al. (2008, 2011) where the R&D ratio is used to measure the technological distance of a specific country relative to the global technology frontier. It suggests that the further the technology distance to the global frontier, the weaker the capacity of a specific country to absorb foreign R&D diffused from the international knowledge pool.} Foreign knowledge spillover, adjusted by local knowledge absorptive capacity, becomes country $i$’s effective absorption of foreign knowledge diffusion, which complements indigenous R&D in augmenting knowledge in country $i$. Note that, such a specification appropriately reflects the dual faces of R&D in innovation: indigenous R&D not only consists in-house new knowledge but also enhances the indigenous capacity of assimilating external knowledge diffusion (Cohen and Levinthal, 1989; Keller, 2004).

We proceed to obtaining the loglinearized form of Eq. (5) as (the bar symbol “$\bar{...}$” denotes the rate of change in the corresponding variables):

$$
\bar{H}_i = \frac{R_i - \left( R_i^2 + 2R_iR_j + R_j^2 \right)}{R_i \cdot (R_i + R_j)^2} \bar{R}_i + \frac{R_i^2}{H_i \cdot (R_i + R_j)^2} \bar{R}_j.
$$

(6)

Consider the particular symmetric case where both countries undertake the same levels of R&D $R_i = R_j$ and substituting Eq. (6) into Eq. (4) derives a reduced-form formula that relates MAC reduction to R&D investment in both countries:

$$
\lambda_i = -\bar{R}_i - \epsilon \cdot \bar{R}_j,
$$

(7)

where $\bar{R}_i$, $\bar{R}_j$, and $\bar{R}_k$ are the rate of change in country $i$’s MAC, country $i$’s R&D, and country $j$’s R&D, respectively. The coefficients that correspond to $\bar{R}_j$ and $\bar{R}_k$ are the elasticity of country $i$’s MAC reduction with respect to indigenous (country $i$) and foreign (country $j$) innovation respectively. To simplify the analysis we normalize indigenous innovation elasticity to indigenous (country $i$) knowledge absorptive capacity, becomes country $i$’s knowledge absorptive capacity, becomes country $i$’s desirable target of MAC reduction, and $\bar{R}_i$ is the rate of change in R&D spending. Note that, the MAC will decline and get close to the target when R&D investment induces technical change (according to the subject condition), yet this benefit is at a cost of R&D spending. Accordingly, the objective of this firm is to get the status quo of MAC reduction as close as possible to the desirable target (measured by the squared loss function), without creating a large financial burden due to R&D spending for innovation. Solving this problem derives the following condition that characterizes the non-coordinated level of R&D spending in each country $i$:

$$
\theta \cdot \bar{R}_i = T_{MAC} - \left( \bar{R}_i + \epsilon \cdot \bar{R}_j \right).
$$

(9)

where R&D invested by each country will reach a level where the marginal cost (LHS) equals the marginal benefit (RHS). The cost is due to R&D spending, and the benefit is a reduction in MAC (that gets close to the target) due to R&D-induced innovation. In this non-coordinated innovation equilibrium, R&D decisions made by each country only consider the benefit of domestic MAC reductions by indigenous R&D, paying no attention to the positive externality effect (knowledge created by indigenous R&D may spill over to foreign countries and favor MAC reduction there).

In contrast, both nations relinquish control over R&D to an international coordinating body (a so-called central planner) in the coordinated innovation equilibrium, and R&D investment by each country is coordinated by the central planner that enforces multilateral R&D coordination. In this case, the objective of this central planner is to minimize a global total welfare loss function, $L_i + L_j$:

$$
\min_{\bar{R}_i, \bar{R}_j} L_i + L_j = \frac{1}{2} \left( -\bar{R}_i - T_{MAC} \right)^2 + \frac{1}{2} \left( -\bar{R}_j - T_{MAC} \right)^2 + \frac{1}{2} \left( \bar{R}_i - R_i \right)^2 + \frac{1}{2} \left( \bar{R}_j - R_j \right)^2.
$$

s.t.

$$
\bar{R}_i = -\bar{R}_i - \epsilon \cdot \bar{R}_j, \quad \bar{R}_j = -\bar{R}_j - \epsilon \cdot \bar{R}_i.
$$

(10)

solving this problem yields the characterization of country $i$ and $j$’s R&D spending as:

$$
\left\{ \begin{array}{l}
\theta \cdot \bar{R}_i = T_{MAC} - \left( \bar{R}_i + \epsilon \cdot \bar{R}_j \right) + \epsilon \cdot T_{MAC} - \left( \bar{R}_i + \epsilon \cdot \bar{R}_j \right) \\
\theta \cdot \bar{R}_j = T_{MAC} - \left( \bar{R}_j + \epsilon \cdot \bar{R}_i \right) + \epsilon \cdot T_{MAC} - \left( \bar{R}_i + \epsilon \cdot \bar{R}_j \right)
\end{array} \right. 
$$

(11)

As compared to Eq. (9), Eq. (11) shows that multilateral R&D coordination by the central planner will take explicit account of both within-country internal and cross-country external benefits: 1) Indigenous R&D directly favors internal MAC reduction within the innovating country (the first term on the RHS) — the same as in the non-coordinated innovation; 2) Indigenous R&D also favors external MAC reduction in foreign countries via cross-country knowledge diffusion (the second term on the RHS) — the extra benefit created in the coordinated innovation.

Accordingly, with the same level of marginal costs of R&D, an innovation equilibrium that creates a higher level of marginal benefits will incentivize a higher level of R&D investment. The coordinated innovation equilibrium that creates cross-country external benefits tends to induce a higher level of country-specific R&D and global collective innovative efforts. We thus obtain the following proposition to summarize the result.

**Proposition 2.** In the above-described two-country symmetric model of international technology diffusion for global climate mitigation, the non-coordinated level of R&D invested by individual countries is equal to:

$$
\bar{R}_i^{NC} = \bar{R}_j^{NC} = \frac{T_{MAC}}{1 + \epsilon + \theta}.
$$

(12)

where the superscript “NC” refers to the non-coordinated innovation equilibrium. In the coordinated innovation equilibrium, the central planner instructs R&D investment in each country and chooses the coordinated levels of R&D spending as:

$$
\bar{R}_i^{C} = \bar{R}_j^{C} = \frac{T_{MAC}}{1 + \epsilon + \theta}.
$$

(13)

where the superscript “C” refers to the coordinated innovation. Given that the elasticity of domestic MAC reduction with respect to foreign innovation is positive, $\epsilon > 0$, the coordinated innovation equilibrium involves a higher level of R&D in both countries. Moreover, the higher the value of $\epsilon$, the larger the gap of R&D spending between the coordinated and non-coordinated innovation equilibrium.
Proposition 2 states the following economic intuitions. When individual countries undertake unilateral, uncoordinated innovation for climate mitigation, they take no account of the beneficial effects of indigenous R&D on foreign MAC reduction via cross-country knowledge diffusion. It is the internalization of technology externalities that plays an important role in inducing a higher level of R&D spending by individual countries. As a result, the global collective R&D efforts will be enhanced, creating more knowledge diffusion that favors global climate mitigation.

3. A multi-region general equilibrium model

3.1. Basic framework

In this section, the mechanism of international R&D coordination for climate mitigation will be quantitatively examined in a multi-sector, multi-region general equilibrium model. The model distinguishes six regions, including: USA, EU12, ROECD, CHN, BRIS, and ROW (Appendix C). As compared to the existing studies that only consider unidirectional technology transfers from technologically advanced countries to backward ones (Fig. 1(b)), our work provides a framework that explicitly consider multidirectional technology diffusion across regions, such that the issue of international innovation coordination is addressed (Fig. 1(c)). The economy in each region is represented by multiple sectors and agents, including: Twelve production sectors, an investment sector (that produces capital goods), a R&D sector (that produces R&D goods), a household, a government, and trade. To be relevant to energy/climate studies, the twelve production sectors consist of five energy sectors and seven non-energy sectors (Appendix D).

In each economy, the general equilibrium structure is modeled according to the input–output (IO) circular flows (Fig. 1(d)). There are twelve goods and corresponding production sectors, indexed by the row subscript $j = 1, 2, \ldots, 12$ and the column subscript $i = 1, 2, \ldots, 12$, respectively; three types of primary factors (labor, physical capital, knowledge), indexed by the subscript $f = L, K, H$; five types of end use (consumption, investment, R&D, government, trade), indexed by the subscript $d = C, I, G, X$. Intersectoral transactions in intermediate use are denoted by the $j \times i$ matrix; Primary factor inputs in production are indicated by the $j \times i$ matrix; Final uses of produced goods are described by the $j \times d$ matrix. From this stylized IO structure to a general equilibrium model, we describe the decision problems facing each agent and characterize its economic behavior in a decentralized equilibrium condition.11 As a notable feature, our model will incorporate the mechanism of ETC into the traditional general equilibrium framework, to which we now turn.

3.2. Endogenous technical change

In line with the “stock of knowledge” approach, the mechanism of ETC is conceptualized as the following three interconnected processes: 1) Profit-seeking firms undertake innovative activities like indigenous R&D and foreign knowledge diffusion as an inventive response for profitability; 2) Then the innovative activities augment the stock of economically useful knowledge; 3) Finally the knowledge is applied in the production process to induce a reconfiguration of production factors that affects the rate and bias of TC.12

To represent the above-described mechanism in a multi-sector general equilibrium model, we specify a KLEM–H nested CES production function for each sector. As Fig. 1(e) shows, for a representative firm in each sector $i$ in region $n$ that produces outputs $Q_{i,n}$, knowledge $K_{i,n}$, and intermediate input goods ($energy bundle X_{E,i,n}$, and material bundle $X_{M,i,n}$). $X_{E,i,n}$ comprises five energy goods $X_{E,18}^{i,n}$ and $X_{E,21}^{i,n}$ is composed of seven non-energy goods $X_{X,18}^{i,n}$. Thus the producer problem takes a form as:

$$\max V_{i,n}(t) = \int_t^\infty \exp \left[ - \int_t^s r_n(s) \cdot ds \right] \cdot \Pi_{i,n}(s) \cdot ds$$

s.t. $\Pi_{i,n}(s) = (1 - \tau_5) \cdot P_{i,n}(s) \cdot Q_{i,n}(s) - P_{E,i,n}(s) \cdot X_{E,i,n}(s) - P_{M,i,n}(s) \cdot X_{M,i,n}(s) - P_{L,i}(s) \cdot I_{i,n}(s) - (1 - \tau_5) \cdot P_{R,i}(s) \cdot R_{i,n}(s)$

$$K_{i,n}(s) = J_{i,n}(s) - \delta_K \cdot K_{i,n}(s)$$

$$I_{i,n}(s) = J_{i,n}(s) \cdot \left[ 1 + \frac{\psi_{J_{i,n}(s)}}{2 \cdot K_{i,n}(s)} \right]$$

$$H_{i,n}(s) = -\gamma_{R_{i,n}(s)^\alpha} \cdot H_{i,n}(s)^{\gamma_{R_{i,n}(s)}} + \gamma_{R_{i,n}(s)} \cdot \left[ R_{i,n}(s)^{\alpha} + R_{i,n}^{\delta}(s) + R_{i,n}^{\gamma}(s) \right] - \delta_H \cdot H_{i,n}(s)$$

where the objective of this firm is to optimally choose labor $X_{E,5-n}$, energy $X_{E,18-n}$ material $X_{M,21-n}$, investment $I_{i,n}$ and R&D $R_{i,n}$ for maximizing the intertemporal profit stream $V_{i,n}$. In Eq. (14), $V_{i,n}$ is expressed as the discounted present value of future profit streams from time $t$ to an infinite future. In Eq. (15), current profit flow $I_{i,n}$ is equal to output revenues minus input costs, with $\tau_5$ and $\tau_5$ corporate income tax, fossil energy tax, investment tax credit, and R&D tax credit, respectively. Eq. (16) specifies the law of motion of physical capital $K_{i,n}$, which depends on capital investment $J_{i,n}$ and the rate of capital depreciation $\delta_K$. Eq. (17) describes the process of capital investment that is subject to imperfect capital mobility and investment adjustment cost.

Eq. (18) gives an explicit representation of the process of knowledge creation (the so-called innovation possibility frontier, IFP), where accumulation of domestic knowledge stock $H_{i,n}$ depends on the two drivers: 1) Indigenous innovation: both indigenous R&D spending $R_{i,n}$ and the existing knowledge stock $H_{i,n}$ affect domestic knowledge accumulation. $\delta_H$ is the rate of knowledge obsolescence. Parameters $\gamma_{R_{i,n}(s)}$ govern the efficiency of indigenous innovation. (2) International technology diffusion (ITD): ITD serves to complement indigenous R&D in building domestic knowledge, and ITD occurs through three channels of diffusion: trade $(R_{i,n}^{\delta})$, FDI $(R_{i,n}^{\gamma})$, and disembodied spillovers $(R_{i,n}^{\gamma})$. Only a fraction of foreign knowledge diffusion is absorbed by local knowledge absorption capacity $(\gamma_{R_{i,n}(s)})$.

Note that, the specification of IFP is based on three assumptions: 1) Indigenous R&D reflects the “no free lunch” assumption; to benefit from innovation, domestic firms should commit to indigenous R&D and not solely free ride on foreign T&D; 2) Existing stocks of knowledge

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11 For the detailed exposition of modeling economic behaviors of each agent and the equilibrium condition, see the online Supplementary Materials. The nomenclature that defines model variables has been provided at the beginning of that appendix.

12 For a detailed exposition of the effect of knowledge use on the rate and bias of TC, see Appendix E.
reflects the “standing on the shoulders of predecessors” assumption: the higher the existing stock of knowledge, the higher the possibility of creating new knowledge for TC; and 3) ITD reflects the “pubic good sharing” assumption: domestic firms benefit from absorbing foreign technology spillovers from the international public knowledge pool.

Based on the seminal work of Griliches (1979), the model represents two main mechanisms of ITD: embodied and disembodied ITD. The former refers to the mechanism where domestic firms indirectly absorb foreign technologies by using knowledge-embodied intermediate input goods (via trade) and capital investment goods (via FDI) (Coe et al., 1997; Coe and Helpman, 1995; Aitken and Harrison, 1999; Keller and Yeaple, 2009). In contrast, disembodied ITD refers to the direct learning of disembodied technologies (e.g., formulas, and blueprints), not linking goods (via trade) and capital investment goods (via FDI) (Coe et al., 1997). In terms of disembodied technologies (e.g., formulas, and blueprints), not linking goods (via trade) and capital investment goods (via FDI) (Coe et al., 1997).

Sorptive capacity is modeled as a ratio of R&D between a specific region and the knowledge absorptive capacity, and the knowledge absorptive capacity can be harnessed only if the host country builds national disembodied knowledge pool created by the whole set of regional, and the gap between region-specific R&D and the global R&D total is modeled as the source of disembodied knowledge that potentially spill over to individual countries. Finally, the benefits of embodied and disembodied ITD can be harnessed only if the host country builds the capacity of assimilating foreign knowledge, and the knowledge absorptive capacity is modeled as a ratio of R&D between a specific region and the whole world.

3.3. International R&D coordination

Based on the above-described modeling framework that explicitly represents ITD, this section is set to provide the characterization of international R&D coordination. To do that, we distinguish two alternative equilibria: non-coordinated and coordinated innovation equilibrium.

In the non-coordinated innovation equilibrium, each country chooses the level of indigenous R&D unilaterally, taking no account of the positive technology externality (knowledge created by indigenous R&D may spill over to foreign countries and favor innovation there). In this case, R&D invested by each country in the non-coordinated innovation equilibrium is characterized as:

\[ R(t) = \frac{\alpha}{\eta} R(t-1)^{\eta-1} H(t)^{1-\beta} + \frac{\partial Y(t)}{\partial R(t)} \left( R(t) + R(t-1) + R(t-2) \right) \]

where this optimality condition characterizes R&D investment in sector i, country n, R(t). That is, R&D is set to reach a level where marginal costs (MHS) are equal to marginal benefits (RHS). The marginal costs are expenditure on purchasing an extra unit of R&D goods. The marginal benefits are a product of the shadow price of knowledge asset λ and the innovation possibility gains (the term within the big parentheses). In particular, the innovation possibility gains come from two sources:

13 Embodied ITD corresponds to the first type of knowledge spillovers — rent spillovers: purchase prices of imported intermediate input and capital goods do not completely embody the opportunity cost of producing the product that includes R&D cost of foreign innovation. Disembodied ITD corresponds to the second type of knowledge spillovers — pure knowledge spillovers: learning of foreign disembodied knowledge augments domestic knowledge stocks with the learning cost usually less than the original R&D cost of foreign innovator (Griliches, 1979).

14 The embodied technology theory claims that intangible knowledge has to be embodied in tangible physical products in order to embody economically useful characteristics, thus each unit of physical products has a certain amount of embodied knowledge (Schmookler, 1966; Teveldecy, 1974; Scherer, 1982). In this regard, foreign knowledge is embodied in both imported intermediate input goods and foreign-invested capital goods.

For the details of modeling international technology diffusion (embodied ITD, disembodied ITD, and knowledge absorptive capacity), see Appendix F.

R&D not only directly creates in-house knowledge, but also enhances the indigenous capacity to absorb foreign knowledge diffusion (the dual faces of R&D in innovation).

In contrast, in the coordinated innovation equilibrium R&D spending of individual countries is coordinated by an international coordinating body (the so-called social planner) that enforces multilateral R&D coordination. In this case, the social planner is set to internalize the technology externality due to cross-country knowledge diffusion, and R&D investment in the coordinated innovation equilibrium is characterized as:

\[ (1-T_\alpha) R(t) = \frac{\alpha}{\eta} R(t-1)^{\eta-1} H(t)^{1-\beta} + \frac{\partial Y(t)}{\partial R(t)} \left( R(t) + R(t-1) + R(t-2) \right) \]

where this optimality condition characterizes the levels of R&D spending where marginal costs (LHS) are equal to marginal benefits (RHS). A comparison between Eqs. (19) and (20) shows that multilateral R&D coordination explicitly considers both within-country and cross-country benefits of R&D. First, indigenous R&D facilitates the creation of in-house knowledge within the innovating country (the first term on RHS), which is the same as the non-coordinated innovation case; Second, indigenous R&D also has a beneficial effect on external innovation in other foreign countries through cross-country knowledge diffusion (the second term on RHS), which is the additional benefit of R&D in the coordinated innovation.

It is straightforward to observe that R&D investment in the non-coordinated innovation case only considers pursuing the within-country internal benefit, paying no attention to internalizing the positive externality of cross-nation technology diffusion. In contrast, innovation coordination enables indigenous R&D to create the additional benefit of cross-country knowledge diffusion. With the same level of the marginal cost of R&D spending, an innovation equilibrium that creates a higher level of marginal benefit tends to stimulate a higher level of R&D investment. Hence, the innovation coordination can induce a higher level of R&D investment and the global collective efforts of innovation.

4. Results and discussion

4.1. Model calibration and parameterization

To numerically implement the model, we prepare a benchmark dataset for model calibration. The stylized input–output (IO) data are collected from the GTAP 7 which is the standard database for traditional CGE models calibration. However, this dataset is not well suited to calibration of a model that explicitly represents R&D-related ETC, because it does not separately record the economic flows associated with R&D investment and knowledge input. To remedy this problem, we collect sector-level R&D data from the OECD ANBERD database, and build a transformed IO dataset with an explicit representation of R&D investment and knowledge input.16 Based on this benchmark dataset and exogenous model parameters selected from the literature (Tables 1–2), the model that specifies the mechanism of R&D-related ETC is calibrated and implemented by the CGE modeling software GEMPACK.17
4.2. Alternative scenario settings

To quantitatively assess the respective effect of indigenous R&D, foreign knowledge diffusion, and international innovation coordination, we design the following four scenarios that include one non-innovation scenario and three innovation scenarios (see Fig. 2):

1. Non-innovation scenario: the mechanism of ETC is not incorporated in the model, with both indigenous R&D and ITD setting to null in simulation. Without the process of innovation and ETC, this scenario represents a reference non-innovation-led growth path;

2. Indigenous innovation scenario: the mechanism of ETC is incorporated in the model, but ETC in individual country A is only driven by indigenous R&D investment, without the complement of foreign knowledge inflows.

3. Non-coordinated innovation scenario: innovation in country A is driven by both indigenous R&D and foreign knowledge inflows, but R&D investment in country A only considers pursuing the within-country internal benefits, taking no account of internalizing the positive technology externality (knowledge feedbacks from A to B). This scenario corresponds to the above-described non-coordinated innovation equilibrium.

4. Coordinated innovation scenario: R&D investment in country A not only considers pursuing domestic internal benefits, but also takes account of the internalization of knowledge feedback from A to B (the technology externality effect). This scenario corresponds to the above-described coordinated innovation equilibrium.

Intuitively, a comparison between scenarios (2) and (1) captures the effect of indigenous R&D, the difference between scenarios (3) and (2) indicates the impact of foreign knowledge inflows, and the effect of R&D coordination is examined by comparing the scenario (4) with (3). To assess these effects, we use the numerical model to simulate the economic and emission growth paths in the four scenarios. Section 4.3 analyzes these effects in the absence of emission control climate policies, and Section 4.4 considers these effects when emission control policies are introduced.

4.3. Technology coordination without emissions control policies

As Fig. 3 shows, the time path of global R&D spending is on a rising trend in all three innovation scenarios. The global R&D spreads across nations, with the OECD countries (US + EUW + ROECD) accounting for over 80% of total R&D spending in the short run (2005–2020). However, this share tends to fall in the long run (2020–2030), and it is largely offset by the share gains of the emerging economies (CHN + BRIS) which accounts for 20–30% of global R&D by 2030. Among the three innovation scenarios, the coordinated innovation scenario creates the highest levels of R&D (both worldwide and country-specific) at each time point, such that the positive technology externality resulting from ITD can be internalized.

We turn to the effect of R&D coordination on cross-country knowledge diffusion, which is measured as percentage changes in foreign knowledge inflows (the cumulative amount over the period 2005–2030) in the scenario (4) relative to those in the scenario (3). Table 3 shows, R&D coordination has a positive effect to boost knowledge diffusion across countries, the magnitude, however, varies significantly across countries. R&D coordination induces foreign knowledge inflows to the US by a range of 4–8%, since innovation in the world largest R&D investor mainly depends on indigenous R&D. R&D coordination enables both EUW and ROECD to increase absorption of knowledge diffused from the US by a range of 12–16%, which suggests an intimate relationship among the OECD member nations in technology cooperation. In addition to the North–North technology interaction, Table 3 also shows R&D coordination can boost South–North knowledge diffusion in the sense that knowledge learning by the advanced countries (USA, EUW, ROECD) from the emerging economies (CHN, BRIS)
will increase by a range of 4–7% when the mechanism of multilateral R&D coordination is developed.

For the largest emerging economy, China, R&D coordination enables this country to increase absorption of knowledge diffusion by a range of 15–20% (Table 3). This is particularly notable for knowledge diffusion from the countries located in the Asia-Pacific region which facilitates ITD through trade and FDI. It is also shown that other emerging economies (BRIS) are instructed to raise ITD absorption from China, and this suggests that R&D coordination facilitates knowledge learning and technology adoption among the emerging economies which enjoy the similar levels of technology sophistication.

Having examined the effects of innovation coordination on country-specific R&D investment and cross-country knowledge diffusion, we turn to its effect on economic growth and carbon emission. Since R&D coordination stimulates accumulation of knowledge in individual countries (through indigenous R&D and foreign knowledge inflows), the knowledge is then applied in the production process to induces productivity gains and output growths. This is displayed in Fig. 4 where each economy gains the highest growth momentum in the scenario (4), which implies that R&D coordination has a positive effect to spur economic growth in the participating countries. Meanwhile, knowledge application in production leads to substitution for fossil fuel uses, which in turn gives rise to reductions in carbon emissions. This is shown in Fig. 5 where the scenario (4) creates a carbon emission path with the lowest growth rate, suggesting that multilateral R&D coordination can help save more carbon emissions in the participating countries.

In addition to the economy-wide effect, we also examine the sector-level effects of innovation on carbon abatement, which is measured as percentage changes of sector-level carbon emissions (the cumulative amounts over the period 2005–2030) driven by three innovation scenarios relative to those in the non-innovation scenario. As Fig. 6 shows, the coordinated innovation scenario (4) creates extra carbon emission abatements relative to the non-coordinated innovation scenario (3) which adds further emission reductions on top of the scenarios (2) and (1). Moreover, the sectors of electricity, manufacturing, and transportation have the higher potential of saving carbon from...
innovation, since carbon-intensive production technologies used in these sectors have a large room of applying knowledge to substitute for fossil fuels. Finally, carbon-intensive economies like USA, China, and BRIS can enjoy more carbon-saving benefits from R&D cooperation with the “green” economies like EUW (e.g., Germany) and ROECD (e.g., Japan).

4.4. Technology coordination with emissions control policies

The previous section has discussed the effect of multilateral R&D coordination on cross-country knowledge diffusion. This section proceeds to a further examination of this effect when emission control policies are introduced, with an emphasis on the extent to which R&D coordination helps offset climate compliance costs.20

We consider two types of emission control climate policies (carbon tax, and emission cap), and examine how emission reductions and economic costs will change across scenarios. For the first type of climate policy, we impose a common carbon tax, $20 per ton of carbon from the year 2012 onward, on the six world regions. Fig. 7(a) shows the resultant effect on emissions reductions, measured as percentage reductions of carbon emissions (the cumulative amount over the period 2005–2030) driven by the tax relative to the emission levels without tax distortion. It is notable that the emerging economies (CHN, BRIS) achieve 15–20% emission reductions from the carbon tax, which is higher than that in the OECD (10–15%).21 Cross-scenario comparisons reveal that carbon taxation achieves the highest levels of carbon savings in scenario (4), followed by scenarios (3) and (2) and finally scenario (1). Taking the US as an example, the effects of the carbon tax on emission reductions in four scenarios are −13.4%, −11.9%, −10.3%, and −6.8%, respectively.

Meanwhile, the benefit of carbon savings is at the cost of economic loss (the so-called climate compliance costs). Fig. 7(b) shows the effect of the carbon tax on the economic costs, measured as percentage reductions of outputs (the cumulative amount over the period 2005–2030) driven by the tax relative to the output levels without tax distortion. A cross-country comparison shows that the non-OECD countries are set to lose 2–2.5% of GDP when the carbon tax is imposed, while the OECD has a lower level of climate compliance costs (1–1.5% of GDP).22

A cross-scenario comparison suggests that the lowest levels of climate compliance costs is achieved in scenario (4), followed by scenarios (3) and (2), and finally scenario (1). For example, the effects of the carbon tax on the US output losses in the four scenarios are −1.45%, −1.64%, −1.77%, and −2.15% respectively.

Finally, we put cross-scenario comparisons on a common basis. The no-innovation scenario that has the highest level of climate compliance costs is used as the benchmark, and we examine how the climate compliance costs will change in response to the three innovation mechanisms. As Fig. 7(c) reveals, introductions of the three innovation mechanisms all have a positive effect to reduce the climate compliance costs of the reference scenario, and the coordinated innovation can achieve the highest levels of cost reductions (−5% to −10% for the OECD, and −15% to −20% for the non-OECD). This suggests that R&D coordination facilitates the reduction of climate compliance costs incurred by traditional emission-based climate policies.

For the second type of emission control policy, we impose a sample emission cap on each region that reduces its year 2030 emission levels by 20% relative to the base year 2005 emission levels.23 To do that, a shadow carbon price is put on each economy in year 2012 (the expiring year of the Kyoto Protocol compliance period) and then rises by 5% annually by 2030 (due to a rising MAC), so that each country can finally achieve the target of 20% emission reductions by 2030. Fig. 7(d) shows the shadow carbon price imposed on each economy in order to achieve the above-described reduction target, and it is notable that the economic impacts of emission caps vary significantly across countries and scenarios. China has the highest shadow carbon price, $40 per ton. Next in order of the economic costs incurred by the emission caps are the EU and BRIS, with a carbon price of $30. Somewhat lower are the US and ROECD, both of which have a carbon price of $20. Meanwhile, a cross-scenario comparison shows that the shadow carbon price is the lowest in the coordinated innovation, suggesting that R&D coordination has a large potential to offset the economic costs incurred by certain emission caps.

Moreover, Fig. 7(e) provides an alternative measure of economic costs of complying with the emission caps, measured as percentage reductions of cumulative outputs by the emission caps relative to the output levels without emission caps. By this measure, productions fall in all countries with the largest output losses in the emerging countries (−2.5% to −3%), followed by the EU (−2%), then the US and ROECD (−1.5%). A cross-scenario comparison shows that the cost burden incurred by emission caps has the lowest level in the coordinated innovation, which suggests that R&D coordination can help achieve a given emission cap target with the lowest compliance costs.

Finally, we put cross-scenario comparisons on a common basis — the no-innovation scenario that has the highest climate compliance cost, and then compare how this climate compliance cost will change in response to introducing three innovation mechanisms. As Fig. 7(f) shows, the three innovation mechanisms all help offset the climate compliance cost of the reference scenario, with the highest level of cost reductions achieved by innovation coordination (by a range of 9–13%). It suggests that international R&D coordination has the potential to complement emission-based agreements, so that the emission reductions target can be achieved with the lowest costs. It is also shown that the emerging economies, relative to the OECD, can substantially reduce the climate compliance costs by a range of 17–21% through international R&D coordination. This result thus provides important implications for designing the post-Kyoto climate architecture. As the current climate agreements with an emphasis on emission-based instruments (e.g., emission caps, carbon taxes) discourage climate mitigation efforts of major carbon emitters

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20 The justification of introducing emission control policies is that without an emission-based policy to correct for environmental externality, standalone dependences on innovation to correct for technology externality is not sufficient — the so-called environmental ineffectiveness of climate technology strategies (Buchner and Carraro, 2005; Popp et al., 2010; van den Bergh, 2013). Real implementation of climate mitigation strategies should thus put in particular types of emission control policies.

21 This is because the rapid economic growth in the emerging economies are driven by massive inputs of fossil fuels into energy-intensive production systems, putting a carbon price signal is more likely to induce a technological alternative that lowers fossil energy uses and carbon emissions.

22 The main reason is that the non-OECD countries have less innovative capacities to undertake R&D and technical upgrading for reducing reliance on fossil energy inputs, so reductions of production capacity become the only option to avoid higher cost burdens under carbon tax distortion.

23 This simplifying setting is chosen for comparing the effect of different innovation mechanisms on the economic cost of a specific emission cap level. This hypothetical treatment differs from the studies comparing Copenhagen climate commitments where emission caps are set using different base year and emission reduction levels (e.g., McKibbin et al., 2011).
due to substantial economic costs, the post-Kyoto climate architecture should thus consider technology-oriented agreements (multilateral R&D cooperation) as a promising complement. By doing that, climate compliance costs associated with emission-based climate agreements can be largely offset, which stimulates the participation of major carbon emitters in the campaign of global climate mitigation.

5. Conclusions

The rapid growth of R&D investment in the emerging economies has remarkably transformed the former Triad-region (US, EU, and Japan) global innovation pattern into a new landscape with multiple hubs of innovation. As the emergence of the multiple R&D hubs creates a solid platform for cross-country technology diffusion and coordination, climate strategies should thus harness this opportunity by developing technology-oriented agreement as a promising complement to the existing emission-based climate architecture.

In this context, this paper provides a new attempt to examine the mechanism of international innovation coordination for global climate mitigation. We first present a partial equilibrium model that analytically unveils the mechanism of international R&D coordination for reducing climate mitigation costs. This mechanism is then quantitatively assessed in a multi-region, multi-sector general equilibrium model that explicitly represents the positive externality due to cross-country knowledge diffusion. Results show that: (1) By fully internalizing the technology externality of cross-country knowledge

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Fig. 4. The economic growth paths (measured by GDP) of the six world regions under the four scenarios (one reference non-innovation scenario and three innovation scenarios). Each economy gains the highest growth momentum in the scenario 4 (coordinated innovation), followed by the scenario 3 (non-coordinated innovation), and finally the scenario 2 (indigenous innovation) and the scenario 1 (reference non-innovation).

Fig. 5. The time paths of carbon emissions of the six world regions under the four scenarios (one reference non-innovation scenario and three innovation scenarios). In each world economy, the scenario 4 (coordinated innovation) generates a time path of carbon emissions with the lowest growth rate, which is well below that in the scenario 3 (non-coordinated innovation), the scenario 2 (indigenous innovation), and the scenario 1 (reference non-innovation).
diffusion, multilateral R&D coordination can stimulate country-specific R&D efforts and cross-country technology diffusion; (2) Innovation enhanced by multilateral R&D coordination facilitates knowledge creation, which has a notable effect to boost economic growth and carbon savings in each participating country; and (3) By lowering the climate mitigation costs incurred by traditional emission-based climate policies, the technology-oriented agreements like multilateral R&D coordination can stimulate the incentives for mitigation action and improve the environmental effectiveness of global climate mitigation efforts.

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Appendix A. Proof of Proposition 1

We construct the Lagrangian that corresponds to the cost minimization problem as:

\[
L = -(P_D \cdot E_D + P_C \cdot E_C) + \mu \left( (E_D^{\sigma_2} + E_C^{\sigma_3}) ^ \frac{\sigma_2}{\sigma_3} + H^{\sigma_4} - Y^{\sigma_4} \right) + \lambda \cdot (\kappa - E_D) + \eta \cdot E_C
\]

where \(\mu, \lambda,\) and \(\eta\) denote the Lagrangian multipliers associated with the three constraints. The F.O.C. with respect to the two endogenous control variables yields:

\[
\frac{\partial L}{\partial E_D} = -P_D + \mu \cdot \frac{\sigma_2}{\sigma_3} \cdot (E_D^{\sigma_2} + E_C^{\sigma_3}) ^ \frac{\sigma_2}{\sigma_3 - 1} \cdot \sigma_2 \cdot E_D^{\sigma_2 + 1} - \lambda = 0
\]

\[
\frac{\partial L}{\partial E_C} = -P_C + \mu \cdot \frac{\sigma_2}{\sigma_3} \cdot (E_D^{\sigma_2} + E_C^{\sigma_3}) ^ \frac{\sigma_2}{\sigma_3 - 1} \cdot \sigma_2 \cdot E_C^{\sigma_3 + 1} + \eta = 0
\]

where the complementary slackness conditions with respect to the three costate variables (the shadow price of the corresponding constraint) are as:

\[
\frac{\partial L}{\partial \mu} = (E_D^{\sigma_2} + E_C^{\sigma_3}) ^ \frac{\sigma_2}{\sigma_3} + H^{\sigma_4} - Y^{\sigma_4} \geq 0, \quad \mu \geq 0, \quad \frac{\partial L}{\partial \mu} \mu = 0
\]

\[
\frac{\partial L}{\partial \lambda} = \kappa - E_D \geq 0, \quad \lambda \geq 0, \quad \frac{\partial L}{\partial \lambda} \lambda = 0
\]

\[
\frac{\partial L}{\partial \eta} = E_C \geq 0, \quad \eta \geq 0, \quad \frac{\partial L}{\partial \eta} \eta = 0.
\]

Given that emission abatement occurs in the presence of emission caps, the abatement boundary condition is reached, \(\kappa - E_D = 0, \quad E_D > 0,\) and the \(K-T\) condition becomes:

\[
\frac{\partial L}{\partial E_D} = -P_D + \mu \cdot \frac{\sigma_2}{\sigma_3} \cdot (E_D^{\sigma_2} + E_C^{\sigma_3}) ^ \frac{\sigma_2}{\sigma_3 - 1} \cdot \sigma_2 \cdot E_D^{\sigma_2 + 1} - \lambda = 0
\]

(A.1)

\[
\frac{\partial L}{\partial E_C} = -P_C + \mu \cdot \frac{\sigma_2}{\sigma_3} \cdot (E_D^{\sigma_2} + E_C^{\sigma_3}) ^ \frac{\sigma_2}{\sigma_3 - 1} \cdot \sigma_2 \cdot E_C^{\sigma_3 + 1} + \eta = 0
\]

(A.2)

\[
\frac{\partial L}{\partial \mu} = (E_D^{\sigma_2} + E_C^{\sigma_3}) ^ \frac{\sigma_2}{\sigma_3} + H^{\sigma_4} - Y^{\sigma_4} = 0, \quad \mu > 0
\]

(A.3)

\[
\frac{\partial L}{\partial \lambda} = \kappa - E_D = 0, \quad \lambda > 0
\]

(A.4)

\[
\frac{\partial L}{\partial \eta} = E_C > 0, \quad \eta = 0.
\]

(A.5)

From Eq. (A.4), we have \(E_D = \kappa,\) substitute into Eq. (A.3), yields

\[
E_C = \left( \frac{Y^{\sigma_4} - H^{\sigma_4}}{\kappa^{\sigma_4}} \right)^{\frac{1}{\sigma_4}}
\]

(A.6)

Substitute Eq. (A.6), \(E_D = \kappa, \eta = 0\) into Eq. (A.2), yields

\[
\mu = P_C \cdot \sigma_2 \cdot \left( \frac{Y^{\sigma_4} - H^{\sigma_4}}{\kappa^{\sigma_4}} \right)^{\frac{\sigma_2}{\sigma_4}}, \quad \left( Y^{\sigma_4} - H^{\sigma_4} \right)^{\sigma_4 - 1} \frac{1}{\sigma_4} (A.7)
\]

Substitute Eqs. (A.6)–(A.7), \(E_D = \kappa\) into Eq. (A.1), yields

\[
\lambda = -P_D + P_C \cdot \left( \frac{Y^{\sigma_4} - H^{\sigma_4}}{\kappa^{\sigma_4}} \right)^{\sigma_4 - 1} \cdot \kappa^{-\sigma_4 - 1}.
\]

Appendix B. Normalization of indigenous and foreign innovation elasticity

From Eq. (6), the rate of change in MAC \(\bar{\lambda}_i\) can be written as a function of the rate of change in knowledge \(\bar{H}_i,\) in country \(i:\)

\[
\bar{\lambda}_i = \left[ 1 + \frac{\rho_{\alpha}}{\bar{\lambda}_i} \right] \cdot (1 - \sigma_2) \cdot \frac{Y_i^{\sigma_4} - H_i^{\sigma_4}}{Y_i^{\sigma_4} - H_i^{\sigma_4}} \cdot \frac{H_i^{\sigma_4}}{Y_i^{\sigma_4} - H_i^{\sigma_4}} \cdot \bar{H}_i
\]

(B1)

where the elasticity of MAC reduction with respect to knowledge is simplified as:

\[
\bar{A}_i = \left[ 1 + \frac{\rho_{\alpha}}{\bar{\lambda}_i} \right] \cdot (1 - \sigma_2) \cdot \frac{Y_i^{\sigma_4} - H_i^{\sigma_4}}{Y_i^{\sigma_4} - H_i^{\sigma_4}} \cdot \frac{H_i^{\sigma_4}}{Y_i^{\sigma_4} - H_i^{\sigma_4}}.
\]

where we have \(\bar{A}_i = \bar{A}_j = \bar{A}\) for both countries in a two-country symmetric model. Meanwhile, from Eq. (6), knowledge available in country \(i\) depends on both indigenous (country \(i\)) and foreign (country \(j\)) innovation:

\[
\bar{H}_i = \frac{R_i \cdot (R_i^2 + 2 \cdot R_i \cdot R_j + 2 \cdot R_j^2)}{H_i \cdot (R_i + R_j)^2} \cdot \frac{\bar{R}_i + \frac{R_i^2 \cdot R_j}{H_i \cdot (R_i + R_j)^2}}{\bar{R}_j}
\]

(B2)

Substituting Eq. (B2) into Eq. (B1) derives an expression that relates MAC reductions in each country to R&D invested by both countries:

\[
\bar{\lambda}_i = -A \cdot \left( \frac{R_i \cdot (R_i^2 + 2 \cdot R_i \cdot R_j + 2 \cdot R_j^2)}{H_i \cdot (R_i + R_j)^2} \cdot \frac{\bar{R}_i + \frac{R_i^2 \cdot R_j}{H_i \cdot (R_i + R_j)^2}}{\bar{R}_j} \right)
\]

(B3)

If we normalize the coefficient of \(R_i\) to a value of unity, then the coefficient of \(R_j\) is equal to

\[
\varepsilon = \frac{R_i^2 \cdot R_j}{R_i \cdot (R_i^2 + 2 \cdot R_i \cdot R_j + 2 \cdot R_j^2)} = \frac{R_i^2 \cdot R_j}{R_i^3 + 2 \cdot R_i^2 \cdot R_j + 2 \cdot R_i \cdot R_j^2}
\]

In a symmetric case, \(R_i = R_j, \varepsilon = 0.2.\) The reduced-form formula of Eq. (B3) thus becomes:

\[
\bar{\lambda}_i = -R_i \cdot \varepsilon \cdot R_j.
\]
Appendix C. Country compositions of each world region

<table>
<thead>
<tr>
<th>Region number</th>
<th>Region name</th>
<th>Region description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>USA</td>
<td>United States of America</td>
</tr>
<tr>
<td>2</td>
<td>EUIW</td>
<td>Western Europe</td>
</tr>
<tr>
<td>3</td>
<td>ROECD</td>
<td>Rest of the OECD</td>
</tr>
<tr>
<td>4</td>
<td>CHN</td>
<td>China</td>
</tr>
<tr>
<td>5</td>
<td>BRIS</td>
<td>Brazil, Russia, India, South Africa</td>
</tr>
<tr>
<td>6</td>
<td>ROW</td>
<td>Rest of the world</td>
</tr>
</tbody>
</table>

Western Europe: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom.

Rest of the OECD: Canada, Australia, New Zealand, Japan, Korea, Singapore, Hong Kong, and Taiwan.

Rest of the world: All countries not included in other region groups.

Appendix D. Model sectoral classification and mapping

<table>
<thead>
<tr>
<th>Sector number/name in our model</th>
<th>GTAP sector numbers</th>
<th>OECD ANBERD sector number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Electric utilities</td>
<td>43</td>
<td>40</td>
</tr>
<tr>
<td>2. Gas utilities</td>
<td>44</td>
<td>41</td>
</tr>
<tr>
<td>3. Petroleum refining</td>
<td>32</td>
<td>23</td>
</tr>
<tr>
<td>4. Coal mining</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>5. Crude oil &amp; gas extraction</td>
<td>16–17</td>
<td>11</td>
</tr>
<tr>
<td>6. Mineral mining</td>
<td>18</td>
<td>12–14</td>
</tr>
<tr>
<td>7. Agriculture</td>
<td>01–12, 14</td>
<td>01, 03–05</td>
</tr>
<tr>
<td>8. Forestry &amp; wood products</td>
<td>13, 30</td>
<td>02, 20</td>
</tr>
<tr>
<td>9. Durable manufacturing</td>
<td>34–42</td>
<td>26–37</td>
</tr>
<tr>
<td>11. Transportation</td>
<td>48–50</td>
<td>60–64</td>
</tr>
</tbody>
</table>

Notes: Model sectors are mapped by reference to the sectoral classifications used in the GTAP and OECD ANBERD databases.

Appendix E. Effects of knowledge use on the rate and bias of technical change

Consider any given sector i with a KLEM-H two-tier nested CES technology. To produce final output Yi, knowledge Hi substitutes for a composite of physical inputs Qi, with the first-tier substitution αi. The physical input composite Qi in turn is made up of capital Xki, labor Xli, energy Xei, and material Xmi, with the second-tier substitution αi:

\[
Y_i = A_i^1 \left[ \alpha_i Q_i^{\alpha_i} + \alpha_i H_i^{\alpha_i} \right]^{1/\alpha_i},
\]

when private firms undertake innovative activities (R&D for new knowledge creation) and apply new knowledge in production, the effect of knowledge application on TC can be characterized by the following proposition.

Proposition. In the above-described production sector i with a KLEM-H two-tier nested CES technology, when more knowledge is applied in the production, H_i > H_i, there is an increase in the Hicks-neutral total factor productivity parameter, A_i > A_i (the rate of TC). There is also a reduction in the cost share of each physical input α_j < α_j (j = K, L, E, M) and a rise in that of knowledge α_H > α_H (the bias of TC).

Proof. Given that innovation creates new knowledge and knowledge application will increase in the production H_i > H_i, we have the following decomposition of TC:

\[
Y_i = A_i^1 \left[ \alpha_{Q_i} Q_i^{\alpha_{Q_i}} + \alpha_{H_i} H_i^{\alpha_{H_i}} \right]^{1/\alpha_i} = A_i^1 \left[ \alpha_{Q_i} Q_i^{\alpha_{Q_i}} + \alpha_{H_i} \left( \frac{H_i}{H_i} \right)^{\alpha_{H_i}} \right]^{1/\alpha_i},
\]

\[
= A_i^1 \left[ \alpha_{Q_i} Q_i^{\alpha_{Q_i}} + \alpha_{H_i} \left( \frac{H_i}{H_i} \right)^{\alpha_{H_i}} \right]^{1/\alpha_i},
\]

define the new Hicks-neutral total factor productivity parameter as:

\[
\bar{A}_i = A_i^1 \left[ \alpha_{Q_i} + \alpha_{H_i} \left( \frac{H_i}{H_i} \right)^{\alpha_{H_i}} \right]^{1/\alpha_i},
\]

and substitute Eq. (3) into the second line in Eq. (2) and yields:

\[
\bar{Y}_i = \bar{A}_i = \left[ \alpha_{Q_i} \left( \frac{A_i^{\alpha_{Q_i}}}{\bar{A}_i} \right)^{\alpha_{Q_i}} + \alpha_{H_i} \left( \frac{A_i^{\alpha_{H_i}}}{\bar{A}_i} \right)^{\alpha_{H_i}} \right]^{1/\alpha_i},
\]

\[
= \left[ \alpha_{Q_i} Q_i^{\alpha_{Q_i}} + \alpha_{H_i} H_i^{\alpha_{H_i}} \right]^{1/\alpha_i},
\]

where the new cost share coefficient becomes \( \alpha_{Q_i} = \alpha_{Q_i} \left( \frac{A_i^{\alpha_{Q_i}}}{\bar{A}_i} \right)^{\alpha_{Q_i}} \) for the physical inputs composite and \( \alpha_{H_i} = \alpha_{H_i} \left( \frac{A_i^{\alpha_{H_i}}}{\bar{A}_i} \right)^{\alpha_{H_i}} \) for knowledge. Consider that, knowledge and physical inputs are gross substitutes with the CES substitution parameter \( \alpha_i = (s_i - 1)/s_i > 0 \), we hence have \( \alpha_{Q_i} < \alpha_{Q_i} \). Given that the cost share of each physical input at the second tier remains unchanged, a reduction in the cost share of physical input composite at the first tier will lead to a uniform reduction in the cost share of each physical input \( \alpha_{Q_i} < \alpha_{Q_i} \) (j = K, L, E, M). Using the constraint on the cost share coefficients of all production inputs \( \sum \alpha_{Q_i} + \alpha_{H_i} = \sum \alpha_{Q_i} + \alpha_{H_i} = 1 \), we have \( \alpha_{Q_i} < \alpha_{Q_i} \) given \( \alpha_{Q_i} < \alpha_{Q_i} \) (j = K, L, E, M).

Appendix F. Modeling details of international technology diffusion

F.1. Embodied technology diffusion

F.1.1. Technology diffusion embodied in international trade

ITD embodied in trade refers to the case where domestic firms assimilate foreign technologies by using knowledge-embodied intermediate goods import (Coe and Helpman, 1995; Coe et al., 1997). In other words, foreign knowledge is embodied in the imports of intermediate input goods, and the embodied knowledge is assimilated by the importing country for knowledge accumulation. We thus model ITD embodied in trade as a product of import flows and embodied knowledge intensity as:

\[
R_{i,m}^{j,m} = X_{i,m}^{j,m} \cdot R_{i,m}^{j,m}
\]

where \( R_{i,m}^{j,m} \) is the knowledge embodied in the imports of intermediate goods from source country m into the sector i in destination country n. \( R_{i,m}^{j,m} \) is the intensity of knowledge embodied in import which is...
specified as24:

\[ R_{ij}^f = \frac{R_{ij}}{Y_{ij}} \quad \text{(F2)} \]

where \( R_{ij}^f \) is the intensity of knowledge embodied in intermediate goods \( j \) imported from the source country \( m \), which is estimated as a ratio between R&D investment \( R_{ij} \) and production output \( Y_{ij} \) specific to the sector \( j \) in source country \( m \). Furthermore, the import flows are modeled according to the Armington approach25:

\[
X_{ij,nm}^{\text{RT}} = \left[ \frac{P_{ij,n}^f}{P_{ij,n}^f - (1 + \tau_f^I)} \right]^{\sigma_I^T} \cdot X_{ij,n}^P
\]

\[
= \left[ \frac{P_{ij,n}^f}{P_{ij,n}^f - (1 + \tau_f^I)} \right]^{\sigma_I^T} \cdot \left[ \frac{P_{ij,n}^f}{P_{ij,n}^f - (1 + \tau_f^I)} \right]^{\sigma_T^I} \cdot X_{ij,n}^P
\]

where \( X_{ij,nm}^{\text{RT}} \) is the import of intermediate input good \( j \) into sector \( i \) in destination country \( n \) from source country \( m \). \( P_{ij,n}^f \) is the market price of intermediate good \( j \) in the destination country \( n \). \( P_{ij,n}^f \) is the ideal price index of the import component of that intermediate good \( j \). \( P_{ij,n}^f \) is the price of intermediate good \( j \) in source country \( m \). \( \tau_f^I \) is the rate of import tariff on intermediate good \( j \). \( \sigma_I^T \) is the CES elasticity of substitution between domestic and import component and substitution among foreign source countries. Finally, by summing over foreign source countries \( m \) and intermediate goods varieties \( j \), we model the total amount of knowledge embodied in import flows as:

\[
R_{in}^f = \sum_m \sum_j R_{ij,nm}^f \quad \text{(F4)}
\]

where \( R_{in}^f \) is knowledge embodied in import into the sector \( i \) in destination country \( n \), which is incorporated into Eq. (18) to represent ITD embodied in trade.

F.1.2. Technology diffusion embodied in international investment

ITD embodied in international investment refers to the case where domestic firms assimilate foreign technologies by using knowledge-embodied foreign capital goods via FDI. In other words, foreign knowledge is embodied in physical capital investment by foreign countries, and the embodied knowledge is assimilated by the host country for knowledge accumulation (Haddad and Harrison, 1993; Aitken and Harrison, 1999; Keller and Yeaple, 2009). We thus model ITD embodied in FDI as a product of FDI inflows and embodied knowledge intensity as:

\[
R_{in}^f = I_{in}^f \cdot R_{in}^f \quad \text{(F5)}
\]

where \( R_{in}^f \) is knowledge embodied in FDI in the sector \( i \) from foreign source country \( m \). \( R_{in}^f \) is knowledge embodiment intensity in FDI (the amount of knowledge embodied in each unit of FDI), which is specified as:

\[
R_{in}^f = \frac{R_{in}}{Y_{in}} \quad \text{(F6)}
\]

where \( R_{in}^f \) is the intensity of knowledge embodied in physical capital goods invested by source country \( m \), specified as a ratio between R&D expenditure \( R_{im} \) and production output \( Y_{im} \) in source country \( m \). Furthermore, the FDI inflows are modeled as26:

\[
I_{in}^{R^f} = \left[ \frac{P_{in}^f}{P_{in}^f - (1 + \tau_f^R)} \right]^{\sigma_I^R} \cdot I_{in} = \left[ \frac{P_{in}^f}{P_{in}^f - (1 + \tau_f^R)} \right]^{\sigma_I^R} \cdot \left[ \frac{P_{in}^f}{P_{in}^f - (1 + \tau_f^R)} \right]^{\sigma_T^R} \cdot I_{in} \quad \text{(F7)}
\]

where \( I_{in}^{R^f} \) is the level of FDI invested by foreign source country \( m \) in destination country \( n \). \( P_{in}^f \) is the price of capital good in the destination country \( n \). \( P_{in}^f \) is the ideal price index of FDI composite in the destination country \( n \). \( P_{in}^f \) is the price of capital good invested by the source country \( m \). \( \tau_f^R \) is the rate of preferable tax for foreign investors. \( \sigma_I^R \) and \( \sigma_T^R \) is the CES elasticity of substitution between domestic and foreign investment and substitution among foreign source countries. By summing over foreign source countries \( m \), we specify the amount of knowledge embodied in FDI as:

\[
R_{in}^f = \sum_m I_{in}^{R^f} \quad \text{(F8)}
\]

where \( R_{in}^f \) denotes the total amount of knowledge that is embodied in FDI into the sector \( i \) in the destination country \( n \), which is incorporated into Eq. (18) to describe ITD embodied in FDI.

F.2. Disembodied technology diffusion

Following the work of Bosetti et al. (2008), we postulate that each world region has access to an international disembodied knowledge pool created by the whole set of world regions. Due to the path dependence of innovation, each region creates heterogeneous knowledge that is specific to local techno-economic condition. The international knowledge pool is thus thought of as being constituted by total R&D invested by all regions, and the gap between region-specific R&D and global R&D total is the source of disembodied knowledge that potentially spill over into specific countries. Thus, the disembodied knowledge spillover into a given region \( n \) is modeled as:

\[
R_{in}^D = \sum_m R_{in}^D - R_{in}^D \quad \text{(F9)}
\]

where \( \sum_m R_{in}^D \) is the global R&D as a sum of region-specific R&D \( R_{in}^D \) over regions \( m \). \( R_{in}^D \) is indigenous R&D investment in the region \( n \). The R&D gap constitutes foreign disembodied knowledge that may spill over to region \( n \). \( R_{in}^D \) is incorporated into Eq. (18) to represent disembodied ITD.

F.3. Knowledge absorptive capacity

We have modeled ITD through both embodied and disembodied channels, but foreign diffused knowledge is not the “manna from heaven” that indiscriminately falls on the host country, and only a fraction of foreign diffused knowledge can be effectively absorbed by the host country for augmenting domestic knowledge assets. The benefits of

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24 This estimating formula is based on the theory of Embodied technology hypothesis, which claims that intangible knowledge has to be embodied in specific tangible physical products in order to embody economically useful characteristics, thus each unit of physical products has a certain amount of embodied knowledge (Schmookler, 1966; Terleckyj, 1974; Scherer, 1982).

25 The Armington composite of intermediate goods is a CES aggregate of domestically-produced and imported component of that commodity. The import composite is then modeled as a CES aggregate of imports from all foreign exporting regions. To derive Eq. (F3), we first solve the producer problem for the input of intermediate goods composite. Next, solving the cost minimization problem associated with the Armington goods yields the demand for the import component from each foreign country.

26 Physical capitals invested by domestic and foreign investors are differentiated imperfect substitutes in physical capital formation, we thus use the Armington structure to specify international investment (Markusen, 2002; Lejour et al., 2008). Invested physical capital goods are modeled as a CES aggregate of domestic and foreign components of that capital good. Within a multi-region model distinguishing multiple FDI sources, the composite of foreign-invested capital goods are further modeled as a CES aggregate of FDI from all foreign source countries.

27 Path dependence of innovation: technology progress that occurs within each country tends to follow a specific path that is embedded in local techno-economic context, creating differentiated and heterogeneous technology varieties (Nelson, 1993; Rosenberg, 1994).
ITD can be harvested only if the recipient country has the capacity of assimilating foreign knowledge. In general, knowledge absorptive capacity reflects the technology distance of the country in question relative to the global frontier. Based on the method presented by Bosetti et al. (2008), our modeling framework represents the technology distance as a ratio of country-specific R&D relative to the global R&D total:

$$y_n = \frac{R_{n,m}}{\sum_{m} R_{n,m}} \quad (F10)$$

where $R_{n,m}$ is the R&D invested by country $n$, and $\sum_{m} R_{n,m}$ is the global total. It is stated that a region with a lower R&D ratio has a larger technology gap relative to the world frontier. Therefore, the region with a backward position in the global technology ladder tends to have a weak capacity of assimilating knowledge diffused from abroad.

Appendix G. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.techfore.2015.08.005.

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