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Knowledge Diffusion, Endogenous Growth, and the Costs of Global Climate Policy

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This paper examines the effects of knowledge diffusion on growth and costs of climate policy. We develop a general equilibrium model with endogenous growth which represents knowledge diffusion between sectors and regions. Knowledge diffusion depends on accessibility and absorptive capacity which we estimate econometrically using patent and citation data. Knowledge diffusion leads to a "greening" of economies boosting productivity of "clean" carbon-extensive sectors. Knowledge diffusion lowers the costs of global climate policy by about 90% for emerging countries (China) and 20% for developed regions (Europe and USA), depending on the substitutability between different knowledge types. (JEL O33, O44, Q55, C68).

Knowledge capital accumulation and technology are important drivers for economic growth. In open economies, sharing knowledge—in contrast to acquiring rival factor inputs such as human and physical capital—provides an inexpensive way of fostering endogenous innovation (Eaton and Kortum, 1999; Keller, 2002). To the extent that knowledge diffusion enhances the productivity of "clean" carbon-extensive relative to "dirty" carbon-intensive inputs, it can also lower the costs of environmental regulation, in particular of policies that act on an international level, such as global carbon mitigation policies to combat climate change. While leading economic analyses have scrutinized the interactions between the environment, growth, and technology,[1] the role of knowledge diffusion for economic growth and

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[1] See, for instance, Acemoglu et al. (2012) introduces endogenous and directed technical change in a growth model to study the response of different types of technologies to environmental policies. Stokey (1998) shows that endogenous growth can be limited by environmental constraints, while Aghion and Howitt (1998) argue that this may not be the cases if "environmentally-friendly" innovations are allowed. Early work by Bovenberg and Smulders (1995, 1996) and Goulder and Schneider (1999) examine endogenous innovations in carbon dioxide abatement technologies. Popp (2002) shows that ignoring directed innovation in the energy sectors may overstate the costs of environmental regulation. Newell, Jaffe and Stavins (1999) study product innovation in energy efficiency in response to energy price changes at the sectoral level. Bretschger, Ramer and Schwark (2011) study the costs of carbon mitigation policies in an endogenous growth framework based on the increasing specialization of sector-specific capital varieties. Other works investigating the response of technology to environmental regulation include Manne and Richels (2004),

the costs of environmental regulation has received surprisingly little attention.

This paper develops a multi-sector multi-region endogenous growth model to study the effects of knowledge accumulation and diffusion for growth and the costs of global climate policy. Following endogenous growth theory (Romer 1990, Aghion and Howitt 1992, Helpman 1992), knowledge, or technology, is non-rival in the sense that the marginal costs for an additional firm or individual to use the technology are negligible. In addition to knowledge spillovers among firms within a sector, we represent knowledge diffusion between sectors and regions. We distinguish between knowledge flows originating from a shared knowledge pool (Adam 1990; Stiglitz 1999) and their subsequent effects on knowledge creation reflecting the idea of accessibility and absorptive capacity of external knowledge (Lane and Lubatkin 1998; Haskel, Pereira and Slaughter 2007). These technology effects are included in a fully specified general equilibrium model which is (1) based on econometrically estimated knowledge diffusion processes using patent and citation data and (2) calibrated to sectoral production, consumption, and international trade patterns of four major world regions.[2]

Our model highlights *scale effects* and *competition effects* through which knowledge diffusion affects growth and costs of climate policy. Scale effects positively impact the productivity of firms which benefit from knowledge flows, hence lowering the production costs of production. Competition effects change the pattern of comparative advantage between sectors and regions to the extent that the accessibility and absorptive capacity of knowledge differs among firms, both across sectors and regions. While for a closed one-sector economy knowledge diffusion works solely through a scale effect, the direction of the competition effect and relative magnitudes of both effects are a priori unclear in a multi-sector and multi-region general equilibrium framework. To the best of our knowledge, our paper is the first to develop a systematic framework for the analysis of domestic and international knowledge diffusion in a fully specified general equilibrium model with endogenous growth that permits investigating the costs of global climate policy.

Our analysis shows that knowledge diffusion, through both scale and competition effects, leads to a “greening” of economies. Sectors with relatively low carbon intensities are characterized by high knowledge capital intensities, implying a large absorptive capacity. Knowledge diffusion thus boosts the productivity of these “clean” carbon-extensive sectors by more than it does for “dirty” carbon-intensive sectors. This, in turn, decreases the production costs of “clean” (non-energy) relative to “dirty” (energy) goods. When energy (carbon) inputs become more expensive under a climate policy regime, the costs of substituting away from carbon-intensive goods are hence lowered because “clean” goods can be produced at lower costs. This positive effect is re-enforced over time and across markets and space: “clean” sectors with higher productivity increase market shares in total output over time

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Fischer and Newell (2008), and Massetti, Carraro and Nicita (2009). None of these studies, however, considers knowledge diffusion.

[2] We include China, Europe, USA, and an aggregate world region.

and benefit from increased competitiveness on domestic and international markets.

Notably, we find that the costs of a global climate policy, achieving a given (absolute) reduction of carbon dioxide (CO_2) emissions, can be substantially lowered through this "greening" effect arising from domestic and international knowledge diffusion. For regions with relatively little own knowledge (e.g., China), reductions can be up to 90%. For developed regions (e.g., Europe and the U.S.), policy costs can decrease but also increase depending on the strength of the "greening" effect. If the substitutability between different types of knowledge is high, costs are reduced by up to 20%. However, the costs of climate policy for these regions slightly increase when the substitutability is low. A simple but important implication of our analysis is, that in order to control emissions, carbon pricing policies should be complemented by R&D policies aimed at promoting knowledge diffusion. While this general insight is not novel (see, e.g., Acemoglu et al., 2012), we provide further support for this argument view by focusing on the effects from knowledge diffusion that could be created through R&D policy.

The impacts of knowledge spillovers on economic growth are substantial, corresponding to welfare gains for the global economy of about 4-10%; they depend on the substitutability between different types of knowledge. Regions with initially relatively low knowledge (e.g., China) benefit the most from knowledge diffusion whereas developed regions (e.g., Europe and U.S.) gain relatively less. In line with previous analyses (Eaton and Kortum, 1999; Keller, 2002), we find that the major sources of technical change leading to productivity growth are not domestic but, instead, lie abroad: international knowledge spillovers account for two thirds of the increase in knowledge capital due to knowledge diffusion, domestic spillovers contribute one third.

Our paper is related to the literature in several ways. We introduce knowledge spillovers between sectors and regions into the endogenous growth model (Romer 1990; Rebelo 1991; Aghion and Howitt 1992; Helpman 1992) in which profit-motivated industrial innovations in R&D *within a sector* lead to the accumulation of technological knowledge which is only partially excludable and non-rival, and hence, becomes a source of growth. Investigating knowledge diffusion in an endogenous growth model is important because gains from endogenous innovation are compounded to the extent that knowledge can be shared.

We focus on disembodied knowledge spillovers that represent technical change driven by the diffusion of knowledge accumulated in a shared knowledge pool.[3] The idea of "knowledge pools" as platforms for knowledge spillovers has been widely used in the literature. Adam (1990) posits the existence of "learning pools" for industries which consist of the findings from basic research. Similarly, Stiglitz (1999) argues that knowledge should be viewed as a global public good rather than as a public good whose accessibility is restricted by (geographical and political) boundaries. Through modern information technology, new knowledge can be easily diffused without being

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[3] Embodied spillovers, in contrast, represent technological change that is triggered by technological know-how embodied in foreign products or directly transferred innovations (patents).

embodied in a particular product (Griliches, 1992).[4]

Building further on the knowledge diffusion literature, we adopt the concept of absorptive capacity which reflects a firm's ability to recognize the value of new information, assimilate it, and apply it to commercial ends (Cohen and Levinthal, 1989). We adopt the view that absorptive capacity of a sector positively depends on prior related own knowledge (Lane and Lubatkin 1998; Haskel, Pereira and Slaughter 2007; Mancusi 2008). The process of transforming the external inflow of knowledge from the knowledge pool into usable knowledge depends in our model on knowledge but also on the accessibility of knowledge sources, in turn reflecting geographical and technological barriers for diffusion. We further contribute by operationalizing these concepts in a fully specific general equilibrium model.

Our analysis is related to the empirical literature on estimating knowledge diffusion using "micro-data" on patents and citations at the technology and regional level and across time. Various channels for knowledge spillovers are emphasized in the literature. For instance, Coe and Helpman (1995), Coe, Helpman and Hoffmaister (1997), Keller (1998, 2004), and Lumenga-Neso, Olarreaga and Schiff (2005) find evidence that knowledge spillover is associated with trade. Markusen (2002) and Fosfuri, Motta and Ronde (2001) state that knowledge spills over through patents sharing among multi-national firms and is linked to foreign direct investment. To provide a basis for investigating knowledge diffusion within a numerical general equilibrium framework, we use basic regression analysis to derive sector- and region-specific parameters describing the accessibility and elasticity of innovative outcomes with respect to different types of knowledge spillovers (domestic intra-sectoral spillovers, domestic inter-sectoral spillovers domestic, and foreign intra-sectoral spillovers).

Our paper is more closely related to the literature on modeling technology innovation and the economic effects of climate policy. Besides the empirical work by, for example, Popp (2004) and Zwaan et al. (2002), numerical modeling of impacts of climate policy predominantly adopts an exogenous growth framework and assumes that knowledge diffusion is entirely absent or limited (Bosetti et al. 2008; Carbone, Helm and Rutherford 2009). Bretschger, Ramer and Schwark (2011) assumes a small open economy with endogenous growth but abstracts from international and intersectoral knowledge spillovers. Somewhat similar to our paper, Diao, Roe and Yeldan (1999) and Bye, Faehn and Heggedal (2009, 2011) account explicitly for cross-border technological spillovers within a numerical endogenous growth model. These studies, however, assume a small open economy setting which does not enable the explicit analysis of international knowledge diffusion; moreover, empirical estimates for spillovers are based on previous, rather old studies (Coe and Helpman, 1995; Keller, 2004).

The remainder of this paper is organized as follows. Section I develops a styl-

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[4] The flow of new information and ideas, contributing to a single worldwide research sector, has been shown to have positive effects on growth (Rivera-Batiz and Romer, 1991). In fact, Grossman and Helpman (2015) view international knowledge spillovers as a key mechanism tightly linking globalization and regional development through scale and competition effects.

ized theoretical framework for intra- and international knowledge diffusion. Section II describes our empirical approach to estimate knowledge diffusion. Section III describes how we embed knowledge diffusion into a numerical general equilibrium model of endogenous growth. Section IV presents and discusses our simulation results. Section V concludes. Appendix A contains further econometric results from estimating knowledge diffusion. Appendix B provides a complete algebraic description of the equilibrium conditions for the numerical model used in the text.

I. Theoretical Framework

We begin by developing a theoretical model to formalize the basic mechanisms governing the effects of knowledge diffusion and climate policy in a multi-region setting. Importantly, our framework identifies the exogenous parameters we use to describe knowledge diffusion processes. These parameters are then estimated econometrically and then used to parameterize knowledge diffusion within our numerical endogenous growth model.

A. Basic setup

CONSUMPTION AND WELFARE.—To determine the impact of international knowledge spillovers and of climate policies in terms of welfare we need to formalize the utility of households in a growing economy. We consider an infinite-horizon discrete-time economy with multiple regions where each region is inhabited by a continuum of identical households (or regional economies admit a representative household). In each region, household utility U depends on consumption C according to:[5]

$$U = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho} \right)^t \frac{C_t^{1-\theta} - 1}{1-\theta} \tag{1}$$

where $\rho > 0$ is the utility discount rate, t the time index, and θ the inverse of the elasticity of intertemporal substitution. The period-by-period budget constraint of the representative household is:

$$p_{W,t+1} W_{t+1} = (1 + r_{t+1}) p_{Wt} W_t + w_{Zlt} Z_{lt} - p_{Ct} C_t \tag{2}$$

where W denotes the assets of the household, p_W is the price of the assets, p_C the price of consumption, and r is the interest rate; Z_l denotes the different inputs supplied by the household and w_{zl} corresponding input prices.

Maximizing (1) under the restriction (2) yields standard first order conditions,

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[5] To simplify notation, we suppress the region index whenever no ambiguity arises.

from which we calculate the growth index of consumption g $(= C_{t+1}/C_t)$ as:

$$g = \left[\frac{1 + r_{t+1}}{1 + \rho} \frac{p_{C,t}}{p_{C,t+1}}\right]^{\frac{1}{\theta}} \tag{3}$$

which is the usual Keynes-Ramsey rule. Consumption growth increases with the interest rate r and the rate of intertemporal substitution $(1/\theta)$ and decreases with the discount rate ρ.

OUTPUT.—We build on the well-known increasing varieties approach (Romer, 1990) whereby endogenous growth is driven by knowledge accumulation and increasing gains from specialization. Following Dixit and Stiglitz (1977), output Q_i in sector i is produced by combining varieties of the intermediate goods, x_{ji}, according to

$$Q_{it} = \left[\int_{j=0}^{J_{it}} x_{jit}^{\kappa} dj\right]^{\frac{1}{\kappa}} \tag{4}$$

where J_{it} is the total number of intermediate varieties in sector i available at time t and $\kappa \in (0, 1)$ measures the gains from diversification. Assuming symmetric intermediate goods, i.e. $x_{jit} = x_{it}$, output can be written as:

$$Q_{it} = J_{it}^{1/\kappa - 1} X_{it} \tag{5}$$

where $X_{it} = J_{it} x_{it}$ measures the aggregate input of intermediate goods. (5) shows that output Q can be increased by either producing a larger quantity per firm (x) with given number of varieties or by increasing the number of varieties (J) with given total input (X). The term $J^{1/\kappa - 1}$ measures the gains from diversification on the aggregate industry level. Each goods variety is produced by a specific firm and each new firm needs additional knowledge capital, i.e. a patent or a blueprint, to become operational. Note that J has different interpretations: it measures knowledge capital, the number of varieties, and the number of intermediate firms.

With g_{Ji} denoting the growth index of knowledge $(= J_{t+1}/J_t)$ in sector i and g_{xi} the growth index for an intermediate good in sector i, it follows from (5) that g_{Qi} is given by

$$g_{Qi} = (g_{Ji})^{\frac{1}{\kappa}} \cdot g_{xi} \, . \tag{6}$$

Hence, if the supply of inputs, like labor and energy, in the intermediate goods sector is limited, g_{xi} becomes unity and long-run growth is solely driven by the accumulation of knowledge, g_{Ji}. It is also straightforward to see that the growth rate of output, g_{Qi} is the higher, the faster grows the knowledge stock J_i. On a balanced growth path, the growth rates of sectoral outputs equal growth rate of consumption g given by (3).

INTERNATIONAL GOODS TRADE.—Regional economies are fully open to goods trade, and we assume that all goods can be traded. Labor is treated as perfectly mobile between sectors within a region, but not mobile between regions. Bilateral international trade by commodity is represented following the Armington (1969) approach where goods produced at different locations (i.e., domestically or abroad) are treated as imperfect substitutes. Each consumption good is a constant-elasticity-of-substitution aggregate of domestically-produced and imported varieties. The domestic variety is nested with within region imported variety where the latter is itself an aggregation of imported varieties from different regions.

B. *Knowledge Diffusion*

BASIC IDEA.—We now discuss the knowledge-driven growth process of our model by introducing the mechanics of knowledge accumulation and diffusion. We assume that new knowledge is created as a function of specific investments and existing knowledge—following the standard view in the literature on endogenous innovation (Romer, 1990). Due to the non-rivalry property of technologies, anyone engaged in the research sector has access to the economy's entire stock of knowledge which we will refer to as spillover from own knowledge.

We are specifically interested in knowledge capital for open economies. There are mainly two reasons to focus on knowledge capital in this context. First, compared to other production factors such as physical capital or labor, international transmission of knowledge is inexpensive and less bounded by political barriers. Second, due to the non-rivalry property, marginal returns are often assumed to be constant for knowledge but decreasing for physical capital; under these assumptions it is knowledge accumulation that determines long-run development. As a consequence, when one evaluates the effects of political measures with global outcomes such as climate policies, induced changes in international knowledge transmission become important. Climate policies could induce additional knowledge creation and diffusion, counteracting the negative cost effects of higher energy prices.

The model endogenously determines the innovative output in each sector and region. Investments in knowledge production are based on a purposeful decision, reflecting a decision trade-off of rational agents. In addition, we allow for free exchange of ideas between regions by assuming open communication networks. That means that, in order to produce knowledge, each region has access to the other regions stock of knowledge which we will refer to as interregional spillover. The innovative outcome for one region in one period is thus defined as a function of the own knowledge stock and the knowledge stock of the other region. As has been shown by Rivera-Batiz and Romer (1991), if the stocks of ideas in each country are not perfectly overlapping, the effective stock of knowledge that could be used in research through integration would be larger than in the case of isolation. This, in turn, increases productivity in the research sector, which shifts inputs from manufacturing into knowledge production, inducing economic growth.

Table 1. Four types of knowledge spillovers

	Intra-sectoral	Inter-sectoral
Domestic	A	B
Inter-regional	C	D

SCALE AND COMPETITION EFFECTS OF KNOWLEDGE DIFFUSION.—In a one-sector closed economy, knowledge build-up fully determines the growth rate. Accordingly, the growth effects of environmental policies can be obtained by looking at the effects on knowledge accumulation only. In an economy with multiple sectors and multiple regions, knowledge diffusion between sectors and regions has an additional effect on growth: knowledge inflow from external sources increases g_{Ji} which in turn increases the sectoral growth rate g_{Qi} as can be seen from (6). We refer to this as the *scale effect* of domestic and international knowledge diffusion.

Knowledge diffusion has important indirect effects on the competitiveness of sectoral production. If, for example, a sector receives more knowledge from the knowledge pool than another sector, it obtains a comparative advantage which improves its position on domestic and international markets: higher J yields higher productivity (see (5)) which allows for lower output prices. We refer to this as the *competition effect* of domestic and international knowledge diffusion. Note that while knowledge itself is a non-rival good, and hence the scale effect can be viewed as being "non-rival", the competition effect is not neutral as traded goods are fully rival.

INTERTEMPORAL KNOWLEDGE ACCUMULATION.—Knowledge capital J in region r, sector i and time $t+1$ is determined by positive innovative investments in time t, I_t, the knowledge increment (ΔJ_t) in time t due to interregional knowledge diffusion, the size of the (beginning-of-period) knowledge stock in time t, J_t, and a time-varying depreciation of knowledge, δ_t:

$$J_{ir,t+1} = I_{irt} + (1 - \delta_{irt})(\Delta J_{irt} + J_{irt}). \tag{7}$$

CONTEMPORANEOUS KNOWLEDGE DIFFUSION.—To study growth effects in a multi-regional and multi-sectoral economy, we extend the notion of knowledge diffusion to cover the following four channels for the exchange of ideas (Table 1): domestic intra-sectoral spillovers (A), domestic inter-sectoral spillovers domestic (B), foreign intra-sectoral spillovers, i.e. knowledge spillovers from foreign regions of the same sector (C), and foreign inter-sectoral spillovers, i.e. knowledge spillovers from foreign regions of other sectors (D).

When operationalizing our theoretical framework in the context of a numerical simulation model that is based on econometrically estimated knowledge diffusion processes, we are constrained by data availability issues. First, spillovers of type D cannot be estimated due to lack of data and are thus omitted from the subsequent analysis. Second, available data do not allows us to identify intertemporal knowledge spillovers.[6] Thus, while knowledge is accumulated over time according to (7), we assume that spillovers of types A to C materialize contemporaneously, i.e. within a given period. Also note in following the endogenous growth approach by Romer (1990), type-A spillovers are already embedded in the knowledge stock J due to sharing knowledge on the basis of gains from specialization at the sectoral level.

The stock J is taken to reflect the absorptive capacity of a region or sector. Following this idea, the knowledge increment from knowledge spillovers in region r and sector i is determined by:[7]

$$\Delta J_{irt} = f\left(J_{irt}, J_{irt}^{B}, J_{irt}^{C}\right) . \tag{8}$$

Sectoral and regional diversity in the spillover process is represented by assuming imperfect accessibility of external knowledge stocks. Following a concept from the empirical literature on knowledge flows and innovation (e.g., Griliches, 1992 or Peri, 2005), we distinguish between *knowledge flows* and their subsequent *effects* on innovative outcomes. The *knowledge flow* describes the process whereby an idea generated by a certain region and sector is learned by another region and sector.[8] The *effect* of these knowledge flows represents the impact of the idea which has been learned by a region and sector on its innovative output.

We capture the diversity in bilateral *knowledge flows* between sectors and regions by constructing *accessible external knowledge stocks.* For sector i in region r, the inter-sectoral domestic accessible knowledge stock J_{ir}^{B} and the intra-sectoral foreign accessible knowledge stock J_{ir}^{C} are given by:

$$J_{irt}^{B} = \sum_{h \neq i} \phi_{hir}^{B} J_{hrt}, \tag{9}$$

$$J_{irt}^{C} = \sum_{s \neq r} \phi_{isr}^{C} J_{ist}, \tag{10}$$

where s is an index for the regions and h is an index for the sectors. If knowledge is completely and immediately diffusible to all sectors and regions, then $\phi_{hir}^{B} = 1$ and $\phi_{isr}^{C} = 1 \ \forall \ r, i, h,$ and s; otherwise $\phi_{hir}^{B}, \phi_{isr}^{C} \in (0, 1)$. The ϕ terms can be viewed as “accessibility parameters” representing weights for bilateral accessibility, in turn reflecting geographical and technological barriers for knowledge diffusion between regions and sectors.

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[6] While the patent data we use to estimate knowledge spillovers is available for different years, we have to pool data over time to yield a sufficient sample size (see Section II for details).

[7] We explore alternative specifications of the function f by means of numerical analysis.

[8] As has been shown by the empirical literature, these knowledge flows depend on bilateral characteristics of regions, such as distance and languages, as well as on the bilateral characteristics of the sectors, such as technological similarities (Jaffe 1993, Maurseth 2002).

The *effects* of these accessible knowledge stocks on the innovative output can be formalized as elasticities which describe the responsiveness of the innovative output to changes in the different pools of ideas.[9] Based on (8), the partial elasticity of innovative output in sector i in region r with regard to the different knowledge stocks is defined as:

$$\frac{J_{irt}}{\partial J_{irt}} \frac{\partial \Delta J_{irt}}{\Delta J_{irt}} = \varepsilon_{it}^{J} \tag{11}$$

$$\frac{J_{irt}^{B}}{\partial J_{irt}^{B}} \frac{\partial \Delta J_{irt}}{\Delta J_{irt}} = \varepsilon_{it}^{B} \tag{12}$$

$$\frac{J_{irt}^{C}}{\partial J_{irt}^{C}} \frac{\partial \Delta J_{irt}}{\Delta J_{irt}} = \varepsilon_{it}^{C} \,. \tag{13}$$

In summary, knowledge at each point in time is propagated via intersectoral and international knowledge diffusions. Both accessible knowledge and self-knowledge stock matter when transforming the external inflow knowledge into usable knowledge. Barriers of knowledge flows are reflected by ϕ_{hir}^{B} and ϕ_{isr}^{C}, and the effect of accessible knowledge stocks on innovative output is reflected by elasticities ε_{i}^{J}, ε_{it}^{B}, and ε_{it}^{C}. We next turn to the empirical estimation of these parameters.

II. Empirical Estimation

A. Data

We use patent data to empirically derive the knowledge spillover parameters. The idea of measuring innovation processes by patent data has a long tradition in the economic literature (Griliches, 1991).[10] For the purpose of investigating knowledge diffusion in a multi-sector and multi-regional context, we see the main advantage of patent data in the high degree of disaggregation at which they are available (at the technological and regional level, as well as across time).

We use patent applications at the European Patent Office (EPO) and corresponding citation data from the EPO World Patent Statistical Database (PATSTAT) and

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[9] We use elasticities as they represent relative changes in the variables and do not depend on the units of variables. This property will be useful later when we combine parameters derived from patent data—where knowledge is approximated by count data—with a continuous representation of knowledge in the numerical model.

[10] The advantages and limitations of using patent data have been broadly discussed in the literature (Jaffe 1999; Keller 2004; Mancusi 2008). A critical appraisal includes recognizing that not all innovations are patented as firms may prefer to hide their ideas for strategic reasons. Moreover, the "propensity to patent" differs across countries, industries, and firms. Also, not every patent has the same value in terms of commercial applications with some patented technologies never being used at large scale.

Table 2. Mapping of countries to regions

Region label	Countries
EUR	Austria, Belgium, Switzerland, Czech Republic, Denmark, Germany, Estonia, Spain, Finland, France, Great Britain, Greece, Ireland, Iceland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Sweden, Slovenia, Slovakia
USA	USA
CHN	China
ROW	Rest of the World

the OECD Citations Database. The selection of European patents is an appropriate choice to approximate international knowledge diffusion as it implies a focus on international patents representing high quality innovations (Mancusi, 2008).[11] In order to rigorously account for patents with international potential, we further restrict our focus to EPO patents which are part of the "Triadic Patent Family". These are patents which have been filed in US, European, and Japanese patent offices.[12] Our data set contains information on patents applied for at the EPO in the period from 1978 to 2013 by applicants located in a set of 37 countries. We aggregate applicants into four country groups (see Table 2) that correspond with the regional structure of the numerical model.

Each patent is assigned its priority data, which describes the date of first application in any country worldwide. This date is relevant from an economic and technological point of view as it is the closest to the date of invention. Following Dernis and Guellec (2001), we assign each patent to the country of residence of the first-named inventor in the patent document as it represents a good indicator for the innovative performance within a given country.

Following the sectoral structure of the numerical model, we assign patent data to different sectors by using the technology-based "International Patent Classification (IPC)". As the numerical model reflects an aggregated macroeconomic growth-framework, our approach is based on a highly generalized sectoral specification which implies a simple mapping from IPC sections and subsections into the economic sectors shown in Table 3.

B. Estimation Strategy and Results

KNOWLEDGE FLOWS AND ACCESSIBILITY.—We use citation counts to calculate the accessibility parameters. It is well-documented in the empirical literature that backward citation can be interpreted as a paper trail of knowledge flows between different regions or technologies as they reveal the relatedness between specific innovations

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[11] Typically applicants at the EPO follow a two-stage procedure. First, they apply to their national patent office and afterwards to the EPO, which acts as a single intermediary to all participating country. Thus, the additional costs of the second application serve as a selection mechanisms for "good" innovation.

[12] Triadic patents have been used extensively as a way to identify high-value patents (Grupp, Muent and Schmoch (1996); Dernis and Guellec (2001); Dernis and Khan (2004)).

Table 3. Mapping of IPC sections to sectors

Sector label	Description	IPC sections (subsections)
AGR	Agriculture	A01 (Agriculture, Animal Husbandry, Hunting, Trapping, Fishing)
TRN	Transportation	B (Performing Operations, Transportation)
EIS	Energy-intensive manufacturing	C (Chemistry), D (Metallurgy), E (Textiles, Paper, Fixed Construction)
MAN	Other manufacturing	F (Mechanical engineering, Lighting, Heating, Weapons, Blasting)
ELE	Electricity	H (Electricity)

(Keller, 2004). More specifically, a patent document contains references (citations) to prior inventions as the inventors are required to declare previous patents, which have been used to develop the new technology. This informs us that the researcher knows about an existing idea and that the idea has some relevance in the corresponding research process. Following prior empirical contributions (Peri, 2005), we measure the weights ϕ by calculating relative frequencies of patent citation between regions and sectors.

To further illustrate this idea, consider the weight for inter-sectoral domestic knowledge accessibility (type B spillover): for a given region r the accessibility of the knowledge stock in sector i from sector h is assigned the weight ϕ^B_{hir}. Using citation counts c, we calculate the corresponding accessibility weight between the two sectors as:

$$\hat{\phi}^B_{hir} = \frac{c_{hir}}{\sum_{n \neq h} c_{nir}} \tag{14}$$

where c_{hir} represents the citation number from patents classified into sector i to patents classified into technological field h within region r. Thus, the higher the share of citations from sector i to sector h relative to all other sectors n, the higher is the corresponding weight and, thus, the higher implied accessibility. For calculating the weights ϕ^C_{irs} cross-sectoral citations are included to ensure a large enough number of inter-regional citations. Furthermore, we correct the inter-regional citation for country fixed effects thereby controlling for country-specific characteristics which are constant over time.

EFFECTS OF ACCESSIBLE KNOWLEDGE STOCKS ON INNOVATIVE OUTCOME.—Based on (8), we derive in a next step the effects of accessible knowledge stocks on the innovative output of sectors and regions (ε parameters). These estimates will be used to inform the numerical model on the magnitudes of the diffusion process and do not necessarily represent the structural parameters.

Using the weights for accessibility $\hat{\phi}^B_{hir}$ and $\hat{\phi}^C_{irs}$, we derive the external knowledge stocks based on (9) and (10). We use cumulative patent counts to construct region- and sector-specific knowledge stocks J_{ir}. The knowledge stock at the beginning of

Table 4. Summary statistics and pairwise correlations

	Mean	Std.Dev	dJ	J	J^B	J^C
dJ	1462.2	2410.0	1.00			
J	8861.9	16847.8	0.96	1.00		
J^B	3230.8	6892.3	0.43	0.45	1.00	
J^C	20643.2	19835.4	0.15	0.22	-0.06	1.00

period t, J_{irt}, is calculated from the application of patents in the previous period $(dJ_{(ir,t-1)})$ with the perpetual inventory method:

$$J_{irt} = (1-\delta)J_{ir,(t-1)} + dJ_{ir,(t-1)} \tag{15}$$

where for $t = 1$ we use:

$$J_{ir1} = \frac{dJ_{ir,(t-1)}}{\delta + g_{ir}}\,. \tag{16}$$

We assume a depreciation rate δ of 15% (Hall and Mairesse,1995). g_{ir} is the region- and sector-specific growth rate of knowledge which we calculate as the average growth rate over the time period of our sample.

The elasticities of the innovative output with regard to the different knowledge stocks (ε^J, ε^B, and ε^C), as described in (11)–(13), are derived from regression analysis. We measure the increment of new knowledge (dJ_{irt}) by means of patent counts. Since the number of patents are non-negative integers, we assume that patent counts follow a Poisson distribution which results in the following Poisson estimation equation:

$$E\left(dJ_{irt}|J_{irt}, J^B_{irt}, J^C_{irt}, \omega_i, \mu_t\right) = \exp\left(\beta_J J_{irt} + \beta_B J^B_{irt} + \beta_C J^C_{irt} + \omega_i + \mu_t\right) \tag{17}$$

where r, i and t index region, sector, and time, respectively. ω_i and μ_t capture unobserved sector- and time-specific heterogeneity.

RESULTS.—Table 4 provides summary statistics and pairwise correlations for variables in our sample. The number of observations N is 1190 with 7 regions[13], 5 sectors, and 34 time periods (from 1977-2010).

Table 5 shows estimation results for β's which represent the contemporaneous sensitivity of the innovative output with regard to the different knowledge stocks. It is evident that innovative output is positively associated with the own and the external knowledge stocks. The effects are highly significant for the own and domestic

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[13] In order to have a large enough number of observations, the regions used in the estimation are grouped into seven regions instead of four. The final values used in our numerical model are sector-specific elasticities which are averaged over all regions, so that the estimated parameters can be used directly in the numerical model. The 7 regions are Europe, US, Russia, China, India, Other annexe 1 countries (Australia, Canada, Japan, New Zealand), and Other middle income countries (Brazil, South Korea, Turkey and South Africa)

Table 5. Estimation results

	Estimates Poisson regression			Implied elasticities by sector				
	Estimate	Standard error		AGR	TRN	EIS	ELE	MAN
β_J	0.036***	0.006	ε_i^J	0.112	0.408	0.496	0.399	0.195
β_B	0.069***	0.016	ε_i^B	0.541	0.224	0.093	0.083	0.186
β_C	0.011*	0.002	ε_i^C	0.066	0.337	0.341	0.242	0.157
Constant	4.600***	0.615						
AIC	1040517							

Notes: The model includes a full set of sector and year dummies. We use cluster-robust standard errors. All explanatory variables are expressed in per thousand units. $^{***}p < 0.01$. $^{*}p < 0.15$. AIC stands for the Akaike information criterion.

knowledge stock. The parameter for the inter-regional elasticity is only significant at the 15% level. The parameters of the Poisson regression can be interpreted as semi-elasticities: an unit increase in the knowledge stocks corresponds to a relative change in output of approximately $100 * \beta\%$. We use this property to calculate the partial elasticities ε_i^J, ε_i^B and ε_i^C—governing the transformation of external accessible knowledge into usable knowledge—in terms of average effects.

Consider the example of sectoral averages. Note that $1/\overline{J_i}$ is the average relative value of an unit increase of the own knowledge stock for sector i. Exploiting the property of semi-elasticities, the implicit (sector-specific) average elasticity of innovative outcome with regard to the own knowledge stock can then be expressed as:[14]

$$\beta_J \overline{J_i} = \varepsilon_i^J. \tag{18}$$

The presented concept of elasticities in the knowledge production function helps to bridge the gap between the different functional forms of the spillover process in the numerical growth model (Cobb-Douglas or CES functions) and the empirical specification (Poisson regression).

Table 5 displays the estimated implied elasticities for each sector. Apart from the agricultural sector, the sensitivity of innovative output appears to be highest with regard to the own knowledge stock (same region, same sector). For the agricultural and manufacturing sector, innovative output is more sensitive to international and intrasectoral than to intranational and intersectoral knowledge stocks, whereas the converse applies to the remaining sectors. Tables A1 and A2 in an appendix show additional estimation results for $\hat{\phi}_{hir}^B$, and $\hat{\phi}_{irs}^C$.

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[14] Similarly, we can calculate the implicit average elasticity of innovation outcomes with regard to type B and C knowledge stocks, respectively, as: $\beta_B \overline{J_i^B} = \varepsilon_i^B$ and $\beta_C \overline{J_i^C} = \varepsilon_i^C$. Note that our econometric approach only allows us to estimate average effects for the partial elasticities.

III. Numerical Model

A. Overview

This section describes how we extend the theoretical framework presented in Section I to a numerical general equilibrium model that features Romer-type (1990) endogenous growth, domestic and international knowledge diffusion, and international trade. Moreover, the model resolves energy production and use—which is important for investigating climate policies—and recognizes the heterogeneity of regions and industries within each region. While the model is a fully-fledged multi-region multi-sector dynamic general equilibrium, the model description in this section focuses on aspects of the model that are related to the representation of knowledge diffusion and knowledge accumulation. Appendix B contains a complete algebraic description of the model, detailing all model variables and parameters and equilibrium conditions.

TECHNOLOGY AND ENDOGENOUS GROWTH.— Each sector is characterized by a production structure as shown in Figure 1. The production process is divided into three stages. At the first stage, final output Y in each sector and region is produced with a sector-specific output Q, as given by (4), and a composite input from other sectors B:[15]

$$Y_t = [\alpha_Q Q_t^{\frac{1-\gamma}{\gamma}} + (1-\alpha_Q)B_t^{\frac{1-\gamma}{\gamma}})]^{\frac{\gamma}{1-\gamma}} \tag{19}$$

where α_Q is a share parameter. Producers of final good Y_t maximize profits under perfect competition:

$$\max_{Q,B} p_{Yt}Y_t - p_{Qt}Qt - p_{Bt}B_t \tag{20}$$

taking prices of Q, p_{Qt}, and B, p_{Bt}, as given.

The profit maximization problem for intermediate composite producers in sector i is:

$$\max_{x_{ijt}} p_{Q_{it}}Q_{it} - \int_{j=0}^{J_{it}} p_{x_{ijt}}x_{ijt}dj \tag{21}$$

subject to the constraint (4). Since each of the intermediate firm j operates under monopolistic competition, $(1/\kappa - 1)$ represents the optimal markup over marginal costs in the intermediates' sector. We generalize the assumption of J being pure knowledge capital (Romer (1990)) to J representing broad capital—including knowledge and physical capital—as we want to capture not only investments into non-physical but also into physical capital. $(1-\kappa)$ then represents the share of capital

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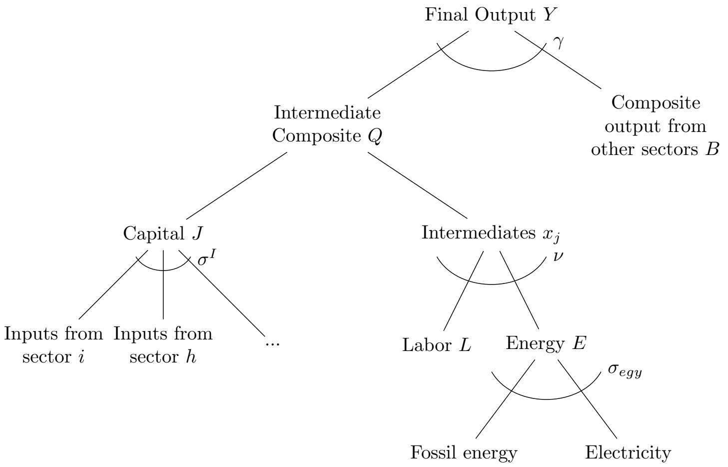
[15] We omit sector and region indices whenever no ambiguity arises.

Figure 1. Nesting structure of sectoral production



in production.

At lower levels of the multi-stage production processes, intermediate goods x_{it} are produced by combining labor L and energy E with a CES production function:

$$X_{it} = J_{it}[\phi L_{it}^{\frac{\nu-1}{\nu}} + (1-\phi)E_{it}^{\frac{\nu-1}{\nu}}]^{\frac{\nu}{\nu-1}} \tag{22}$$

where ϕ and $1-\phi$ are share parameters and ν is the elasticity of substitution. The aggregate energy input E is a CES composite of electricity and fossil energy.

J_{it} here reflects the productivity in the production of intermediates at the sectoral level. J_{it} thus reflects domestic intra-sectoral knowledge spillovers (type A) that are commonly assumed in the Romer (1990) setup. For example, if the quantity of inputs (besides J) remains constant over time, the output of intermediate goods increases with positive investments.

INTERTEMPORAL ACCUMULATION OF KNOWLEDGE CAPITAL.—The model endogenously determines the innovative output in each sector and region (J_{it}). Investments in knowledge production are thus based on a purposeful decision by rational agents. The accumulation of knowledge capital is characterized through positive investments into new varieties ($I_{it} > 0$) and a depreciation rate δ, given by (7). Total investments equal investments in physical and non-physical capital. Income from endowments and capital is equal to consumption plus investments.

CONTEMPORANEOUS KNOWLEDGE DIFFUSION.—Besides type-A spillovers, knowledge at each point in time diffuses through intersectoral (type B) and international knowledge (type C) spillovers. Equation (8) reflects the fundamental idea that both accessible knowledge and the self-knowledge stock matter when transforming the external knowledge inflow into usable knowledge. We operationalize (8) by assuming that the function $f(\cdot)$ follows a CES form. Usable knowledge in region r and sector i at time t is hence given by:

$$\Delta J_{irt} = [\varepsilon_i^J (J_{irt})^{\frac{\lambda-1}{\lambda}} + \varepsilon_i^B (J_{irt}^B)^{\frac{\lambda-1}{\lambda}} + \varepsilon_i^C (J_{irt}^C)^{\frac{\lambda-1}{\lambda}}]^{\frac{\lambda}{\lambda-1}} \,. \tag{23}$$

A number of remarks with respect to (23) are in order. First, barriers to the diffusion of the same type of knowledge (either type B or C) are captured through (9) and (10) which define accessible knowledge stocks J_{irt}^B and J_{irt}^C, respectively, based on estimated parameters ϕs. Second, usable knowledge increases with different types of knowledge, including own knowledge. The partial effect of each accessible knowledge stock on usable knowledge, holding other knowledge stocks fixed, is measured by (estimates of) the partial elasticities ε_i^J, ε_i^B, and ε_i^C.[16] For example, given the CES form of (23) the marginal product of knowledge spillovers from knowledge type J_t is given by: $\partial \Delta J_t / \partial J_t = \varepsilon^J (J_t/\Delta J_t)^\lambda$. Third, transforming various knowledge flows into usable knowledge for production depends on the size of the own knowledge stock. This captures the notion of absorptive capacity as, for example, put forward in Cohen and Levinthal (1989).

Lastly, $\lambda \geq 0$ measures the degree of substitutability or complementarity between different types of knowledge. From the literature on knowledge diffusion there does not seem to emerge a clear view regarding λ. For example, Cohen and Levinthal (1989) and Spence (1984) assume that own R&D capital and spillovers are perfect substitutes. Other, mostly theoretical studies tend to assume a Cobb-Douglas function which embeds an unitary elasticity of substitution to characterize the transformation process between different types of knowledge (Adam, 1990; Bretschger, 1999; Branstetter, 2001; Bosetti et al., 2008; Mancusi, 2008).[17]

In absence of a consensus view from the literature and, in particular, given the lack of empirical estimates for λ, it is a central theme of our analysis to examine the implications of alternative assumptions with regard to substitutability or complementarity between different types of knowledge. We consider a range of cases covering a situation in which different knowledge types are relatively poor substitutes ($\lambda = 1$) and an extreme case with perfect substitutability ($\lambda \to \infty$). Note also that our econometric approach to estimate the partial elasticity parameters ε and barriers to knowledge diffusion ϕ does not invoke any assumption or restriction on λ. For the purpose of the numerical analysis, we thus treat λ as a free parameter.

B. Data, Calibration, and Computational Strategy

This study makes use of social accounting matrices (SAMs) that are based on data from the Global Trade Analysis Project (GTAP, 2008). The GTAP dataset provides consistent global accounts of production, consumption, and bilateral trade

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[16] Note that ε_i^J does not reflect the effects from type-A knowledge spillovers; it rather measures the partial elasticity with respect to the own knowledge stock.

[17] In theoretical work, the assumption of an unitary elasticity of substitution is often convenient as it eases analytical tractability.

as well as consistent accounts of physical energy flows and energy prices. Version 8 of the database, which is benchmarked to 2007, identifies 113 countries and regions and 57 commodities. Besides the sectors shown in Table 3, the model resolves four energy sectors (coal, natural gas, crude oil, refined oil) and the service sector which are aggregations of commodities in the GTAP data. Primary factors in the dataset include capital and labor. The regional aggregation follows the mapping shown in Table 2.[18]

As is customary in applied general equilibrium analysis, we use economic value flows (=quantity × price) and choose units for goods and factors to separate price and quantity observations[19]. Based on this normalization, we then calibrate the value share and level parameters for the base year of the model. Response parameters in the functional forms which describe production technologies and consumer preferences are determined by exogenous elasticity parameters, the values of which are shown in Table B3 in the appendix.

We calibrate the model with endogenous growth (type-A spillovers) but without type-B and type-C knowledge spillovers to a steady-state baseline extrapolated from the set of 2007 social accounting matrices using exogenous assumptions on the growth rate of output (γ), the interest rate ($\overline{r}$), and the capital depreciation rate (δ). This ensures that solving the model without any shock gives a solution that replicates a balanced growth path. Along the balanced growth path all regional economies and sectors within an economy grow with the same rate. The balanced growth path assumption requires that benchmark investment expenditure covers growth plus depreciation on the capital stock and that the gross return to capital covers interest plus depreciation: $I(\overline{r} + \delta) = K(\gamma + \delta)$.

The choice of the annual interest rate is important for the results of a long-term analysis like the present one. We use a value of $\overline{r} = 0.05$ for the net of tax return.[20] The annual capital depreciation rate is set to 7%, but in contrast to $\overline{r}$ this parameter has little impact on the results. γ is set to 2% reflecting roughly an average of the European or U.S. economic growth experience between 2004 and 2012. The mark-up rate of the firms is implicitly set to be 0.14 with the rate of elasticity of substitution between intermediate goods being 7. According to our calibration, the optimum rate of economic growth in the long run, in the absence of any of policy shocks and type-B and type-C spillovers is 2.34% per year with the growth of capital being 2%. We solve the model for 100 years.[21]

As we cannot directly observe or measure knowledge capital, we take an indirect

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[18] The exact aggregation schemes for sectors and regions and the aggregated benchmark data is available on request from the authors.

[19] We normalize base-year prices for all goods and factor to unity such that values readily transfer into quantities

[20] Altig et al. (2001) argue for using a value around 7-8 percent based on the historical real rate of return to capital, while others (e.g., Fullerton and Rogers, 1993) use a much smaller rate around 3-4 percent. With no account for risk in this model it is not clear which value should be used. Also it should be kept in mind that with these kind of models there is no "correct" value.

[21] Solving the model for a longer time horizon when policy shocks are imposed does not produce different results thus indicating that the model has been given enough time to settle on a new balanced growth path. To reduce computational complexity, we solve the model with a 10-year time step.

approach to impute initial capital stocks. More specifically, we use assumed the interest rate, growth rate of capital, and the depreciation rate to infer initial capital stocks from observed base-year capital earnings given by the set of regional SAMs from the (GTAP, 2008) data.

To approximate the infinite horizon global economy by a finite-dimensional computational problem, we use the state-variable targeting approach put forward by Lau, Pahlke and Rutherford (2002). Importantly, this allows us to target the terminal capital stocks by sector, and thus an *endogenous* growth rate of the overall economy on a new balanced growth path, by using a series of complementarity constraints on the growth rates of sectoral investments. We use the General Algebraic Modeling System (GAMS) software and the GAMS/MPSGE higher-level language (Rutherford, 1999) together with the PATH solver (Dirkse and Ferris, 1995) to solve the numerical mixed-complementarity problem.

IV. Simulation Results

A. *Impacts of knowledge diffusion on welfare and economic growth*

To quantitatively investigate the impact of domestic and international knowledge diffusion on economic welfare and growth, we use counter-factual analysis comparing worlds with and without knowledge spillovers.[22] We focus on obtaining insights into the relative importance of domestic and international spillovers, regional differences in knowledge accumulation over time, and ensuing economic impacts through changing productivity in the production of goods and services and through changing comparative advantages in international trade.

GLOBAL IMPACTS.—Figure 2 reports global and regional welfare impacts (measured as percentage change of lifetime utility) from comparing a world with and without domestic and international spillovers for alternative values for λ. The following insights emerge. First, and not surprisingly, knowledge diffusion increases welfare in all regions as higher levels of knowledge capital increase at zero costs the productivity with which non-knowledge inputs (labor and materials) can be combined to produce industry outputs. Welfare gains for the global economy are substantial ranging from about 4 to 10 percent depending on λ.

Second, welfare gains strongly increase with λ. A higher λ reflects the idea that different knowledge types can be combined more effectively. The case of perfect substitutes indicates that sizeable welfare gains from knowledge diffusion are possible; however, as there seem to be significant overlaps when combining knowledge, the notion of perfect substitutability between different types of knowledge should prob-

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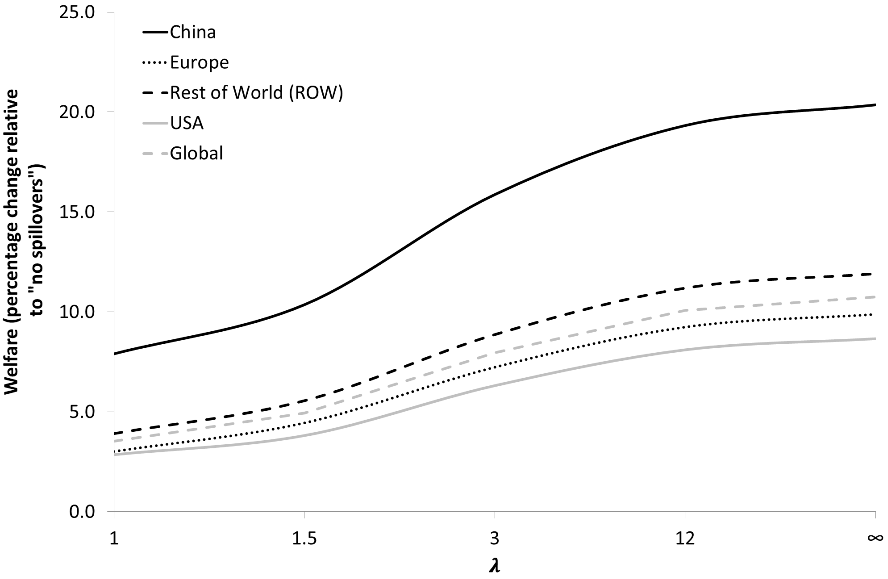
[22] In the (hypothetical) world without spillovers, we assume that the global economy is on a balanced growth path and contemporaneous type-B and type-C spillovers are suppressed (i.e., all ϕ's are zero). In all scenarios we assume that Romer-type spillovers between firms in the same industry (type A) are present thus giving rise to endogenous long-run growth. Our assessment of knowledge diffusion thus only pertains to domestic and international spillovers that are added to an otherwise standard Romer-type endogenous growth framework.

Figure 2. Global and regional welfare impacts of knowledge spillovers for different λ

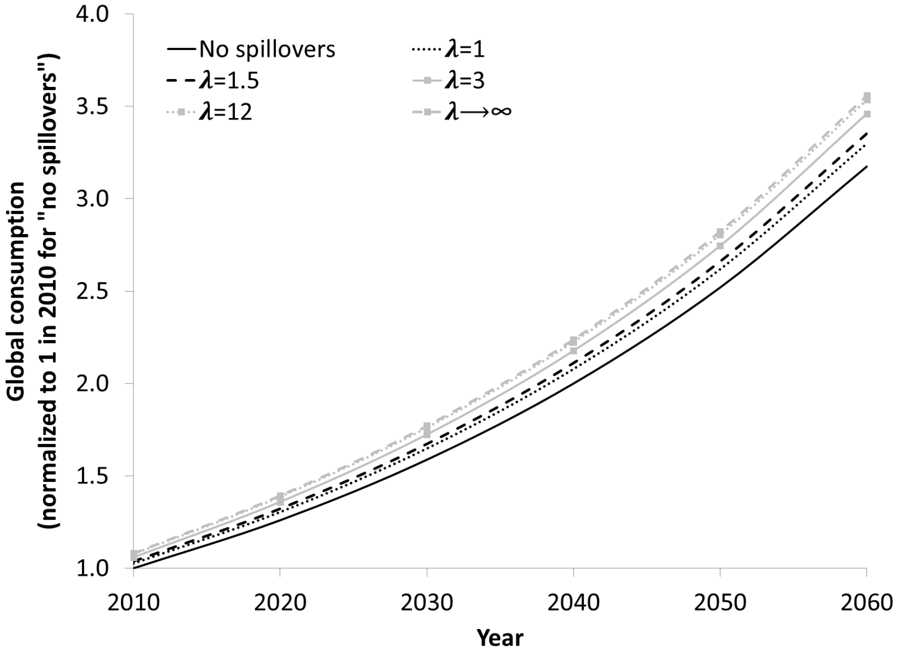


ably be best viewed as a limiting case which provides an upper bound for welfare gains.

Third, the marginal product of knowledge diffusion is always positive, and is first increasing and then decreasing in λ (S-shaped pattern of impacts in Figure 2). Increasing λ enables to better substitute with other types of knowledge, hence preventing diminishing returns to knowledge diffusion *from all types of knowledge*. Hence, marginal returns to *total* knowledge diffusion first increase as declining marginal returns of diffusion from one type of knowledge can be avoided. For high λ's, substitution possibilities between different knowledge types have been exhausted and the overall marginal product declines and eventually falls to zero (see almost flat parts of welfare impact curves as $\lambda \to \infty$). This reflects our assumption that while more knowledge becomes accessible through knowledge diffusion, the increments of *effective* new knowledge become smaller.

Figure 3 echoes the above points at the global level by showing global private consumption over time for different values of λ. It is evident that the impacts of knowledge diffusion hinge crucially on the degree of substitutability with which different types of diffused knowledge are combined. If $\lambda = 1$ the time paths on global consumption are relatively similar in a world with and without knowledge spillovers. For slightly higher λ's, the consumption paths are on average about 2 (for $\lambda = 1.5$) and 8 (for $\lambda = 3$) percent higher as compared to $\lambda = 1$. It is also evident that relatively low values of λ, on the order of 3, are sufficient to reap most of the gains from knowledge spillovers. Figure 3 also shows that the benefits from a higher λ, materialize in the form of compounding growth effects over time as the

Figure 3. Annual global consumption over time with and without knowledge spillovers for different λ



more effective knowledge spillovers increase the productivity bringing about higher investments and hence increase the size of regional economies. This is reflected by an increasing distance between consumption paths in the “spillovers” and “no spillovers” cases over time as λ is increased.

REGIONAL IMPACTS.—Why do regions benefit differently from knowledge spillovers? What are the patterns of regional knowledge diffusion in the global economy? How important are different types of knowledge spillovers for enhancing productivity and regional welfare?

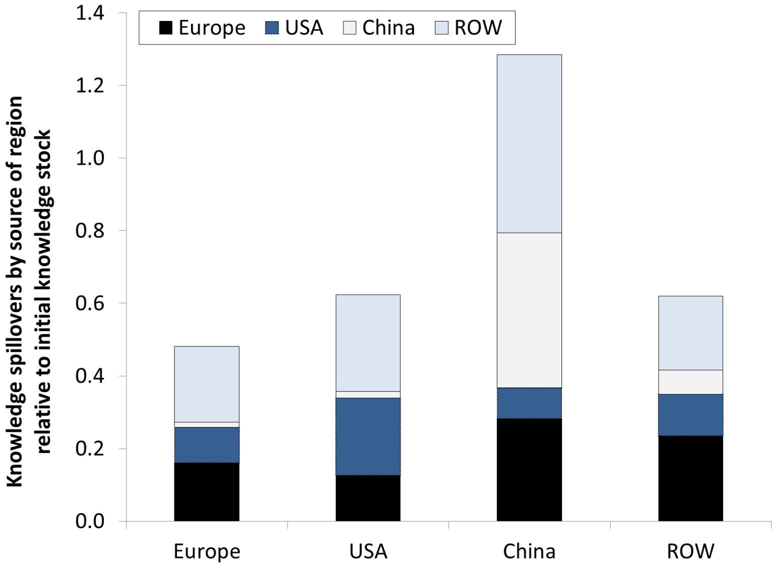
A major determinant of regional welfare impacts is the amount of knowledge each region receives due to spillovers. The first line in Table 6 reports the relative size of knowledge increases due to domestic and international spillovers for each region. ROW obtains the largest increase, followed by Europe and the USA. China’s increase in knowledge due to spillovers is about four times smaller compared to the ROW, about three times smaller than in Europe and roughly the half of the increase in the USA (depending on λ). These differences are mainly driven by the size of domestic spillovers. As China has by far the smallest initial capital stock (i.e., existing knowledge stock, see the second line in Table 6) the size of domestic inter-industry spillovers in China is much smaller as in other regions, regardless of differences in inter-industry spillover intensities. Focusing on the size of regional knowledge spillovers is, however, not a good indicator for regional welfare impacts. As Figure 2 shows, the welfare impacts from knowledge diffusion in China are about

Table 6. Summary of simulation results

	Europe			USA			China			ROW		
	$\lambda = 1$	$\lambda = 3$	$\lambda \to \infty$	$\lambda = 1$	$\lambda = 3$	$\lambda \to \infty$	$\lambda = 1$	$\lambda = 3$	$\lambda \to \infty$	$\lambda = 1$	$\lambda = 3$	$\lambda \to \infty$
Knowledge capital accumulation												
Relative size of knowledge increase due to spillovers^d	0.67	0.66	0.69	0.45	0.42	0.44	0.40	0.31	0.30	1.00	1.00	1.00
Relative size of initial capital stock^c	0.34	–	–	0.18	–	–	0.08	–	–	0.40	–	–
Regional capital stock over time^a												
Year 2030	2.7	6.0	7.8	3.9	8.1	10.4	7.3	13.6	16.6	3.7	8.0	10.2
Year 2060	3.1	7.2	9.4	4.2	9.2	11.9	7.6	15.1	18.5	4.1	9.3	11.8
Private consumption												
Private consumption over time^a												
Year 2030												
Year 2060	3.28	3.44	3.53	3.28	3.41	3.49	3.44	3.72	3.87	3.31	3.49	3.60
Average annual growth rate (%)	2.35	2.37	2.38	2.35	2.37	2.38	2.35	2.37	2.38	2.35	2.37	2.38
Welfare decomposition by spillover type^a												
Full spillovers	3.0	7.2	9.9	2.9	6.3	8.7	7.9	15.9	20.4	3.9	8.9	11.9
Only domestic spillovers ($\phi^c = 0$)	0.2	1.9	3.7	0.2	1.5	2.7	0.5	2.2	3.8	0.2	2.3	4.2
Only international ($\phi^b = 0$)	1.8	4.8	7.1	1.7	4.5	6.8	6.3	13.0	17.6	1.9	6.0	8.8
International trade												
Terms of trade^{a,b}	-0.12	-0.12	-0.16	-0.32	-0.15	-0.34	-0.39	-0.64	-0.82	0.32	0.34	0.48
Export shares in world market^a	-1.28	-1.07	-1.08	2.33	3.39	4.18	3.86	5.41	5.56	-0.05	-0.55	-0.69

Notes: ^{a}Percentage change relative to "no spillovers". ^{b}Export price index divided by import price index where we use a Laspeyres price index with quantities from "no spillovers" baseline as weights. Values shown refer to 2060. ^{c}Share in base-year global capital stock. ^{d}Based on cumulative (year 2010-2060) knowledge spillovers and normalized to 1 for ROW.

Figure 4. Source-destination patterns of domestic and international knowledge spillovers (all sectors aggregated and for $\lambda = 1$)



twice as large as compared to Europe and about 2.5 times bigger than those in the USA.

What matters is the size of regional knowledge spillovers *relative* to the existing stock of knowledge capital. Figure 4 shows the additions to regional knowledge capital due to domestic inter-industry spillovers and international same-industry spillovers where the latter is broken down source (i.e., region). Knowledge spillovers shown here comprise spillovers to all sectors and refer to cumulative spillovers in the period from 2010-2060. Moreover, we normalize knowledge flows relative to the initial existing knowledge stock in each respective region.

Three main insights are borne out by Figure 4. First, for all regions the increase in knowledge capital is substantial, i.e. cumulative knowledge spillovers between 2010-2060 amount to roughly the size of the (annual) existing knowledge capital stock. Second, the increase in knowledge due to spillovers in China relative to its own, existing capital stock is about 1.3—which is significantly larger as compared to the other regions. As China has a relatively low share of capital in the global economy (see the second line in Table 6), the marginal productivity of the added knowledge is larger in China than in the other world regions. This explains why welfare gains due to knowledge diffusion are the largest in China. Third, it is evident that international knowledge diffusion constitutes an quantitatively important channel relative to domestic spillovers: only about one third of the knowledge increase relative to existing knowledge capital comes from domestic inter-industry spillovers (this is roughly similar for all regions and increases up to about 40% as $\lambda \to \infty$);

about two thirds of the knowledge increase stem from international spillovers.

Why are the welfare gains the smallest for the USA—although Figure 4 shows that the knowledge increase in the USA is of comparable magnitude? The difference between Europe and the USA can be traced back to the international spillover intensity (ϕ^c's) between both regions.[23] The USA has much smaller coefficients vis-à-vis Europe than Europe has vis-à-vis the USA. Although the existing capital stock in Europe is almost twice as large in the USA (see the second line in Table 6), the knowledge flows from Europe to the USA are much smaller than from the USA to Europe. This explains why the USA benefits in our model less from international knowledge diffusion than Europe. The ROW exhibits the second largest welfare gains as the knowledge increase relative to its existing capital stock are relatively high (see Figure 4).

Figure 5 sheds some light on the interplay of contemporaneous knowledge spillovers and the intertemporal knowledge capital accumulation: it also quantifies the relative contributions of different types of knowledge. For each region, we compare the evolution of the knowledge capital stock over time in a world without (lower contour of the plots) and with (upper contour or black line) spillovers. We again normalize regional capital stocks relative to the existing knowledge capital stock in in each region. In our endogenous growth framework, knowledge diffusion leads to productivity increases within industries. While the size of these *additional* "Romer-type" intra-industry spillovers is smaller than knowledge increases emanating from international and domestic inter-industry spillovers, they increase the growth rate of capital stocks. This can be seen in Figure 5 by noting that without the intra-industry spillovers (light-grey shaded area), the addition of knowledge due to domestic inter-industry and international spillovers would result in a (roughly) parallel shift of the lower contour; with "Romer-type" spillovers, the slope increases. The increase in the growth rate is the largest for China, consistent with the relatively large welfare gains in China. While Figure 5 shows only the case for $\lambda = 1$, Table 6 shows that the increases in the knowledge capital stock for all regions increase with λ. Figure 5 also underscores our finding that international spillovers bring about larger knowledge increases as compared to domestic (intra- and inter-industry) spillovers.

A potentially important channel through which knowledge diffusion can impact regional welfare and growth is international trade. As knowledge spillovers enhance productivity, the cost of producing goods and service are reduced, in turn affecting the comparative advantage of regions in international markets. Table 6 shows the change in the terms of trade due to knowledge diffusion. Given our Armington specification for international trade[24], changes in the terms of trade are rather

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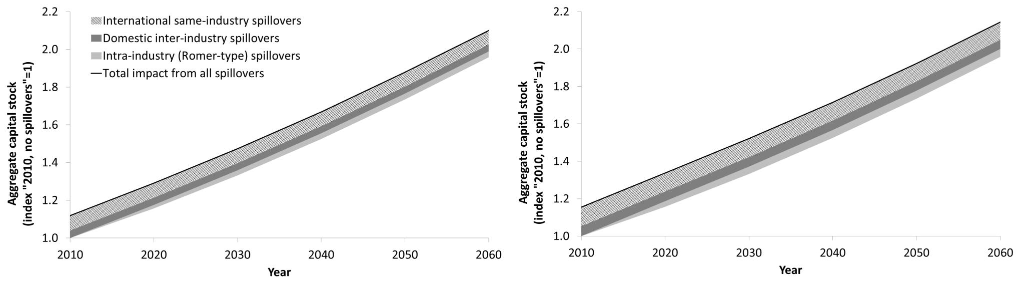
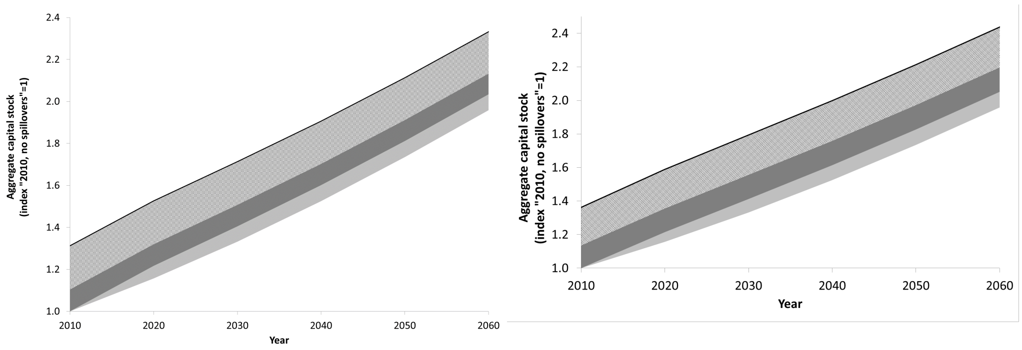
[23] The international industry-specific spillover coefficients for Europe and the USA vis-à-vis the ROW, which has the largest capital stock, are relatively similar. The USA shows slightly higher spillover coefficients than Europe vis-à-vis China; however, the capital stock in China is relatively small, hence this does not have a large effect on the difference in welfare gains between the two countries.

[24] Substitution elasticities for Armington aggregation are relatively low and, together with the share-preserving nature of the CES function, imply a relatively "tight" approach to modeling (changes in) international trade.

Figure 5. Contemporaneous knowledge spillovers by type and intertemporal knowledge accumulation with and without spillovers


(a) Europe

(b) USA


(c) China

(d) ROW

Note: Lower contour indicates capital stock in "no spillovers" case. Upper contour (=black line) indicates capital stock in world with spillovers. Cases shown assume $\lambda = 1$.

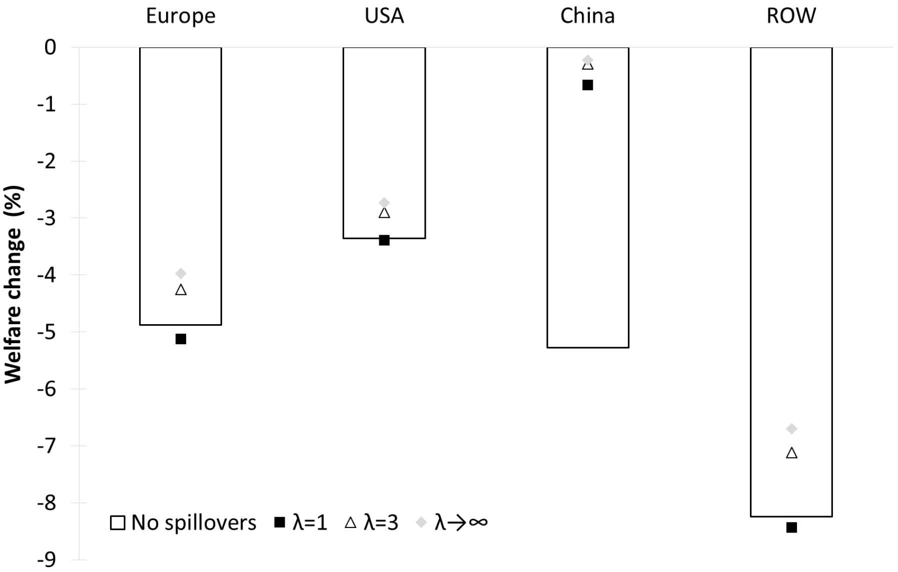
small, even if different knowledge types are assumed to be perfect substitutes. As China receives the large knowledge spillovers relative to its existing capital stock, terms of trade changes are also the largest for China. Accordingly, the increase in China's share of total exports in the world market is the largest among all countries, but is relatively small with about 4-5.5 percent.

B. Knowledge diffusion and the costs of climate policy

To what extent does knowledge diffusion affect the ways in which economies are able to substitutes for carbon-intensive inputs? What are the potential channels through which knowledge spillovers can alter the costs of climate policy? Does knowledge diffusion reduces the cost of carbon abatement? If so, by how much and how do impacts differ across regions?

In examining these questions, we focus on a global carbon-pricing climate policy with a relatively aggressive environmental target, i.e., we assume that CO_2 emissions

Figure 6. Welfare impacts from climate policy with and without knowledge spillovers for different λ



Note: All scenarios achieve the same absolute amount of year-on-year global CO_2 emissions relative to the respective "no climate policy" baseline.

in 2050 are reduced by 50 percent relative to 2010.[25] Due to the positive growth effects discussed in the previous Section IV.A, CO_2 emissions are higher in a world with spillovers as compared to the "no spillovers" case. Moreover, emissions in the "no policy" cases depend on λ. To ensure comparability across scenarios and to focus on the change in the costs of climate policy due to the presence of knowledge spillovers, we assume that all scenarios achieve the same *absolute amount of* CO_2 *reductions* in each year. We can hence compare the cost-effectiveness of climate policy in light of different assumptions about knowledge spillovers.[26] We further assume full trading of carbon permits between regions.[27]

Figure 6 shows the welfare impacts by region of the global climate policy in a world with and without knowledge spillovers, and for alternative assumptions about λ. Welfare costs for the ROW and China are the highest in the carbon policy scenario reflecting the fact that these regions bear the largest emissions reductions under a global carbon-pricing policy.[28] Comparing the costs of climate policy with and

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[25] Annual emissions caps for the intermediate years are assumed to follow a linear reduction path between 2010 and 2050.

[26] We use the scenario without spillovers to determine the amount of annual emissions reductions which then defines the carbon targets for all scenarios with knowledge diffusion.

[27] Our scenarios can thus be equivalently thought of as a global carbon tax which achieves the same year-on-year emissions reductions as the global cap-and-trade policy. Carbon revenues are assumed to be returned lump-sum to regions in proportion to their historic (i.e., year 2010) CO_2 emissions.

[28] Both China and the ROW are characterized by a relatively large number of abatement options with

without knowledge spillovers shows cost reductions of up to 96 percent (or about 5 percentage points of welfare) for China. For other regions, whether costs are reduced or not depends on the degree of substitutability between different types of knowledge spillovers. If knowledge spillovers from different sources can be combined more effectively (i.e., $\lambda = 3$ and $\lambda \to \infty$), the welfare costs of climate policy decrease by up to 20 percent. If, however, the substitutability is limited ($\lambda = 1$), knowledge diffusion slightly increases the welfare costs of climate policy by up to 5%, 1%, 2% for Europe, the US and the ROW, respectively.

To understand why knowledge diffusion affects the welfare costs from climate policy differently across regions, it is instructive to look at how knowledge diffusion changes the carbon intensity of economies and the sectoral composition of output *in the absence of carbon policy.* First, knowledge spillovers increase CO_2 emissions in all regions as economies grow faster. For example, for $\lambda = 3$, emissions in 2050 increase by 2.8 percent for Europe, 4.4 percent for the USA, 15 percent for China, and 3.9 percent for the ROW relative to "no spillovers" emissions in year 2050. The emissions increase in China is the largest as knowledge diffusion leads to the highest increase in the growth rate of output for China. Second, higher emissions do not imply, however, a higher CO_2 intensity of output as knowledge diffusion brings about a change in the sectoral composition of output with changes towards a "greener" economy. For $\lambda = 3$, the emissions intensity of output (ton of $CO_2/\$$) in year 2050 is reduced by 7.6 percent for Europe, 11 percent for the US, 7.7 for China, and 7.4 for the ROW.

Figure 7 shows the underlying changes in the sectoral composition of output (on the vertical axis) for China and the USA that is brought about by knowledge diffusion (in the absence of climate policy).[29] The horizontal axis shows the change in the emissions intensity of industry output (measured in ton of $CO_2/\$$) while the size of bubbles indicates the share of CO_2 emissions by industry in economy-wide emissions in the "no spillovers" reference case. The reduction in the overall carbon intensity due to knowledge diffusion is the larger, the more of the industries that account for large emission shares reduce either their CO_2 intensity or their share in total output (or ideally a combination of both). Figure 7 shows that knowledge diffusion indeed spurs industry dynamics that lead a to lower emissions intensities in both regions. This "greening" of the economy is much more pronounced in China as compared to the USA as the knowledge diffusion adds more knowledge relative to the existing capital stock for China (see the discussion in Section IV.A). It is also apparent that with $\lambda = 1$, relatively little structural change is brought about by knowledge diffusion in the US economy (i.e., the black solid bubbles mostly cluster around the origin).

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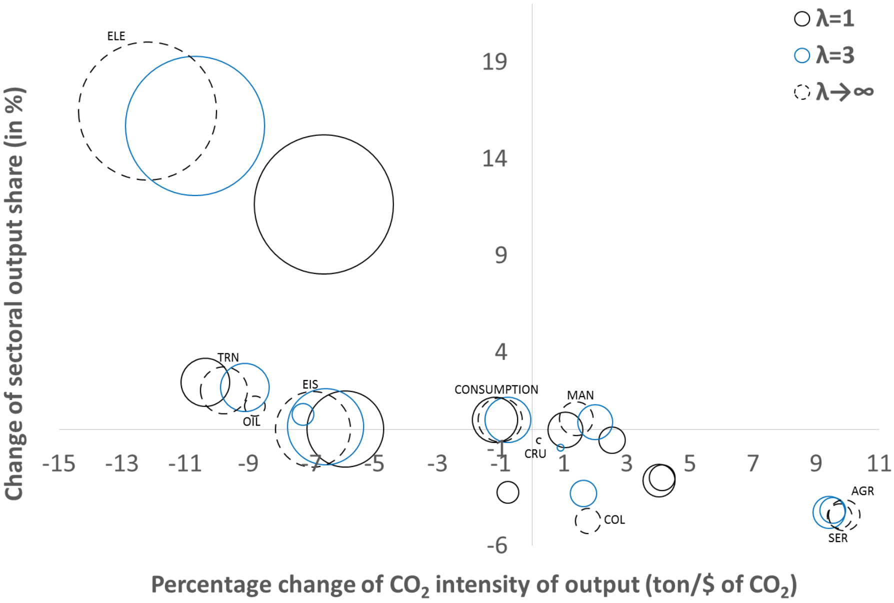
relatively low marginal costs. Equalizing marginal abatement costs globally hence shift large parts of the abatement to these regions whereas the lower substitutability between fossil fuels and non-carbon inputs in Europe and the US implies in general implies higher marginal abatement costs in the latter regions. This finding is consistent with a large number of studies, for example, PUT REFs HERE.

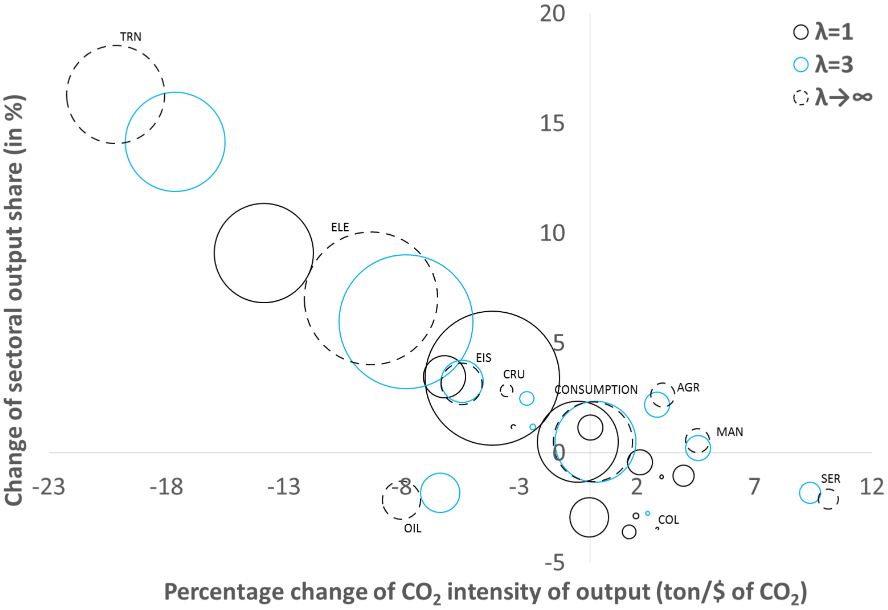
[29] Results for Europe and the ROW are shown in the Appendix B as they are qualitatively similar to the ones for the USA.

Figure 7. Impact of knowledge spillovers on industry composition of total output and industry-level CO_2 emissions intensity

(a) China



(b) USA



Notes: Size of bubbles show the share of CO_2 emissions by industry in economy-wide emissions in the "no spillovers" reference case. For clarity of exposition, sectoral labels next to bubbles are shown only for the case "$\lambda \to \infty$". Changes for variables on horizontal and vertical axes refer to the year 2050 comparing a world with spillovers to the "no spillovers" reference case.

Knowledge diffusion leads to a "greener" economy because the sectors with relatively low carbon intensities tend to be the sectors which are (1) relatively knowledge-intensive and (2) comprise a large share of economy-wide output. If spillover coefficients, both for the international and domestic knowledge diffusion channel, would be identical across sectors, (1) and (2) imply that larger *flows* of knowledge are generated for sectors with low carbon intensities. This in turn increases the productivity of these sectors and reduces production costs. As a result, their share in total output increases. Even if spillover coefficients are not identical across sectors—as is in fact borne out by our empirical estimation—this size effect dominates potential differences in sectoral impacts that may result from differences in sector-specific spillover intensities. Moreover, as knowledge diffusion tends to increase more strongly the productivity of industries with a relatively low energy- (and CO_2-) intensity, it effectively increases the relative price of energy goods. This triggers a substitution away from energy (and CO_2) towards inputs with a low (or zero) carbon content, and hence explains the decline in the CO_2 intensity of most industries.

Only if the "greening" effect from knowledge diffusion is sufficiently strong, the costs of climate policy are reduced. An overall lower carbon intensity and higher productivity of sectors, in particular for those with relatively low carbon intensities reduces the costs of climate policy for four reasons. First, for a given CO_2 price and a given substitutability between inputs in production, a lower cost share of carbon implies lower costs. Second, a higher productivity of energy-intensive sectors means that less energy is needed to produce the same amount of output. Third, the carbon policy shift resources to non-energy sectors, which have become more productive with knowledge diffusion (as compared to a world without knowledge diffusion). Fourth, knowledge diffusion improves the comparative advantage for regions that export "clean" (i.e., low carbon) goods which increases gains from trade with positive impacts on welfare (thus contributing to a reduction of welfare losses from climate policy).

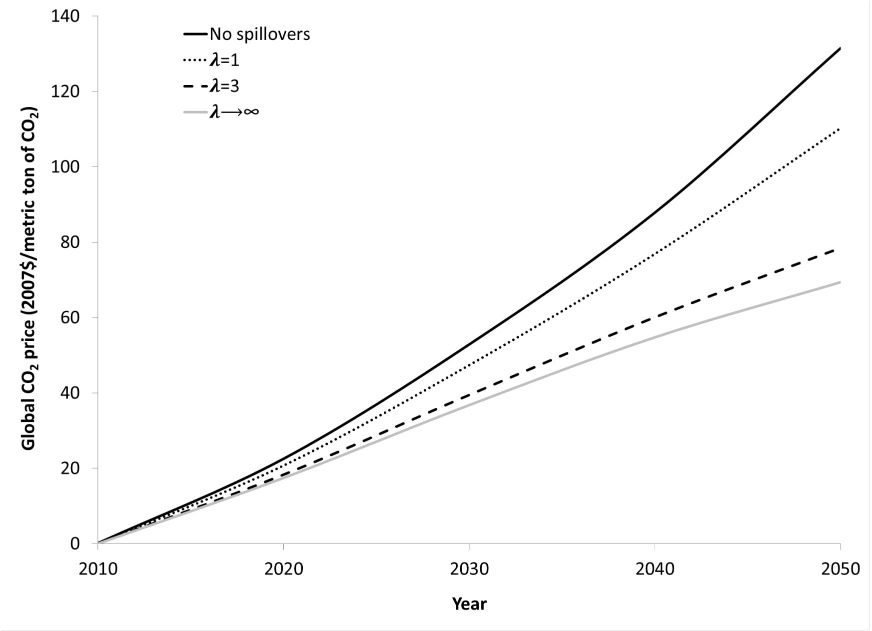
In summary, as the knowledge increase relative to existing knowledge without spillovers is by far the largest for China, its welfare cost of climate policy is reduced significantly. For other regions, the "greening" effect is much weaker, and only produces small reductions in welfare costs if different types of knowledge spillovers are strong enough substitutes (i.e., $\lambda > 3$).

Figure 8 shows that assessing the impacts of climate policy in a world with or without knowledge diffusion has drastic implications for carbon prices. For the same quantity of CO_2 emissions reduced, the carbon price in year 2050 for $\lambda = 1$ ($\lambda \to \infty$) is 16 (47) percent lower with knowledge diffusion as compared to a world without knowledge diffusion. This underscores the importance of sharing knowledge for limiting the costs of climate policy.

C. Sensitivity Analysis

Here we consider the sensitivity of results to parameters affecting how knowledge diffusion affects regional and sectoral changes in productivity and in turn the welfare

Figure 8. Global CO_2 price under climate policy with and without knowledge spillovers for different λ



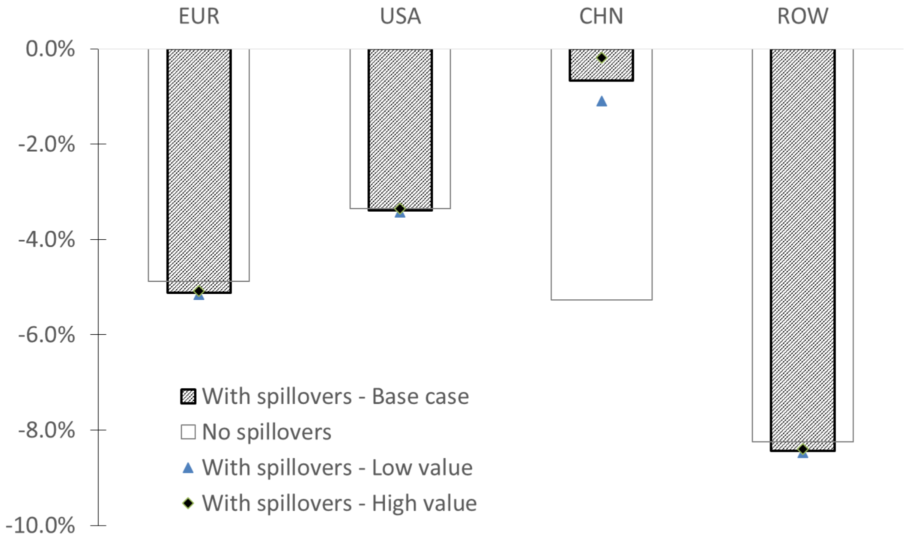
Note: All carbon price trajectories achieve the same absolute amount of year-on-year global CO_2 emissions relative to the respective "no climate policy" baseline.

costs of climate policy. We explore the extent to which welfare costs depend on the substitutability between foreign and domestic goods and the ease with which carbon-intensive energy can be substituted for non-energy inputs in production and consumption. Finally, we investigate the role of endogenous growth in lowering welfare costs of climate policy in the presence of knowledge diffusion. Here, we contrast a formulation of our model in which the long-run growth rate is exogenous with endogenous growth specifications based on alternative assumptions about the extent of gains from specialization at the sectoral level.

TRADE ELASTICITIES.—The extent to which knowledge diffusion affects the costs of climate policy could well be affected by how sensitive international trade pattern react to productivity and price changes. As knowledge diffusion affects the relative productivity between regions and sectors, it can improve or negatively affect the international competitiveness of trade-exposed industries. To explore this possibility, we performed sensitivity analysis with respect to the Armington elasticity parameters considering two additional "low" and "high" scenarios which assume that central cases parameter values are halved and doubled, respectively.

We find that our results are not much affected. Lowering (increasing) elasticities only very slightly decreases (increases) welfare gains from knowledge diffusion if no climate policy is present. For a given economy, higher elasticities increase the

Figure 9. Sensitivity of the welfare cost of climate policy with respect to Armington trade elasticity parameters (assuming $\lambda = 1$).



demand for imported goods, resulting in increased exports of other regions. The expansion of the production in foreign regions boosts investment and innovation leading to larger knowledge stocks. This in turn implies larger knowledge spillovers for the domestic economy whose positive effects are propagated through international trade. Quantitatively, and relative to our central case parametrization, these effects are, however, negligible.

Figure 9 shows the sensitivity of the costs of climate policy for "low" and "high" Armington trade parameters. Lower values tend to increase the costs for carbon mitigation while higher values reduce the welfare cost. The impacts on regional welfare are small with the exception of China which is characterized by a relatively low share of capital in the global economy, implying that its marginal productivity with respect to knowledge inflows is larger than that of other regions. The higher (lower) are Armington trade elasticities, the larger (smaller) are knowledge inflows to China. Finally, while Figure 9 reports the case of $\lambda = 1$, our finding that welfare costs are not much affected by our assumptions on Armington trade parameters also obtains for $\lambda > 1$.

ELASTICITIES OF SUBSTITUTION IN PRODUCTION AND CONSUMPTION.—We find that degree of substitutability between energy and non-energy inputs in production has a relatively large impact for the change in costs of climate policy brought about by knowledge diffusion (Table 7). With low elasticity of substitution between Q and inputs from other sectors (γ) and low elasticity of substitution between energy and labor ν, the cost reduction for China is larger and for the other countries smaller than in the central case. While for all countries a lower γ or ν makes it harder

Table 7. Sensitivity of change in costs of climate policy due to knowledge diffusion[a]

	Europe		USA		China		ROW	
Central case	-13		-14		-94		-14	
Alternative cases								
	low	high	low	high	low	high	low	high
Production parameters[b]								
γ	0	-28	0	-28	-104	-76	-3	-27
ν	9	-33	4	-26	-166	-53	3	-27
Consumption parameters[b]								
σ_{ec}	-12	-14	-13	-15	-105	-82	-13	-14
σ_c	-13	-13	-14	-14	-94	-94	-14	-14
Growth (variety) parameter[c]								
Markup ($=1-\kappa$)	9	-28	9	-28	-30	-95	7	-29

Notes:

[a] All figures refer to percentage change of welfare costs relative to a "no climate policy" baseline assuming $\lambda = 3$.

[b] "low" ("high") case assumes that parameters are halved (doubled) relative to the respective central case parameter value.

[c] "low" case assumes that mark-up is zero in line with an exogenous growth model; "high" case assumes a mark-up of 20% over marginal costs (central case value is 14%).

to substitute away from energy which becomes more costly under a climate policy, China is better off due to the large knowledge inflows relative to other countries. This boosts productivity and lowers the cost of producing goods in China by more than in other countries. As a result, China gains market shares by increasing its exports while other countries increase their imports. For low values of γ or ν, the loss in market shares and ensuing negative impacts on welfare for Europe, USA, and the ROW in fact imply that knowledge diffusion slightly increases the costs of climate policy. For high substitution elasticities, knowledge diffusion leads to a smaller increase in the comparative advantage of Chinese exports thereby resulting in smaller reductions in welfare costs of climate policy for China, and in larger cost reductions for Europe, USA, and the ROW.

We find that changing elasticities of substitution in consumption between energy and non-energy goods (σ_{ec}) and between non-energy goods (σ_c) does have only negligible quantitative effects.

ENDOGENOUS GROWTH.—Lastly, we examine the interplay between knowledge diffusion and endogenous growth. We vary the markup parameter κ in (4) which reflects the substitutability between different varieties in the production of sectoral outputs or, alternatively, the market power of monopolistic producers. A higher market power means that firms are able to charge a higher markup ($= 1 - \kappa$) over marginal costs, in turn implying larger incentives for specialization driving endogenous growth. By setting $\kappa = 1$, the markup is zero, and hence our model collapses to a standard exogenous growth model (Ramsey, 1928). In this case, knowledge diffusion still alters the costs of climate policy but to a much smaller extent than in the central case: it lowers costs for China and slightly increases the costs of other countries as, again, these latter countries become less competitive on international export markets. For higher markups the effects of knowledge diffusion are magnified resulting in about twice as large cost reductions for Europe, USA, and the ROW. This is simply because higher markups imply that more knowledge is accumulated which can be shared through knowledge diffusion. This underscores the importance of investigating knowledge diffusion in a setup that represents an endogenous mechanism for accumulating knowledge over time.

V. Conclusion

This paper has introduced domestic and international knowledge diffusion at a sectoral and regional level in an endogenous growth model. Knowledge diffusion depends on accessibility and absorptive capacity; we have empirically estimated these processes using patent and citation data to inform parametrization of our numerical general equilibrium model. The sectoral and regional detail of the model allowed us to examine the impacts of knowledge diffusion, through scale and competition effects, on economic growth and the costs for global climate policy.

Importantly, we find that knowledge diffusion leads to a "greening" of economies that is characterized by increased market shares of "clean" carbon-extensive sectors and lower sectoral (and economy-wide) emissions intensities. "Clean" sectors with relatively low carbon intensities exhibit high knowledge capital intensities, implying a large absorptive capacity. Knowledge diffusion thus boosts the productivity of these "clean" (non-energy) sectors by more than it does for "dirty" (energy) sectors. This, in turn, decreases the production costs of "clean" relative to "dirty" goods. When energy (carbon) inputs become more expensive under a climate policy regime, the costs of substituting away from carbon-intensive goods are lowered because "clean" goods can be produced at lower costs.

The "greening" effect has the potential to substantially lower the costs for global carbon mitigation policies. We found that for regions with relatively little own knowledge (e.g., China), reductions in policy costs can be up to 90%. For developed regions (e.g., Europe and the U.S.), policy costs can decrease but also increase depending on the strength of the "greening" effect. If the substitutability between different types of knowledge is high, costs are reduced by up to 20%, while the costs slightly increase when the substitutability is relatively low. A simple but important implication of our analysis is that in order to control emissions, carbon pricing policies should be complemented by R&D policies aimed at promoting knowledge diffusion. The impacts of knowledge spillovers on economic growth are substantial corresponding to welfare gains for the global economy of about 4-10% depending on the substitutability between different types of knowledge (spillovers).

Our paper is a first step toward a comprehensive framework that can be used for the analysis of environmental regulation in the context of domestic and international knowledge diffusion with endogenous technology. Several directions for future research appear fruitful. First, it would be interesting to study a differentiate between a larger number of world regions to obtain more detailed regional results. Second, the presented framework could be used to analyze more explicitly the role of R&D policy providing economic incentives for sharing knowledge internationally. A particularly interesting direction is to discuss the issue of policy coordination between climate and energy policy and R&D policy. Another line of important future research would be to include renewable energy technologies. This would enable examining knowledge diffusion processes for clean energy and the interactions with climate policies in a carbon-constrained world.

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APPENDIX A: ESTIMATION RESULTS FOR KNOWLEDGE SPILLOVER PARAMETERS (ϕ^b_{hi}, ϕ^c_{sj})

Table A1. Estimation results for ϕ^b_{hir} (accessibility of domestic inter-sectoral knowledge spillovers (type B)[a]

	AGR	EIS	ELE	MAN	TRN
Europe					
AGR	0	0.11	0	0	0
EIS	0.95	0	0.6	0.29	0.67
ELE	0	0.25	0	0.16	0.19
MAN	0.01	0.04	0.1	0	0.14
TRN	0.05	0.6	0.3	0.55	0
USA					
AGR	0	0.12	0	0.01	0
EIS	0.95	0	0.53	0.28	0.62
ELE	0	0.24	0	0.13	0.15
MAN	0.01	0.07	0.12	0	0.22
TRN	0.03	0.58	0.36	0.57	0
China					
AGR	0	0	0	0	0.59
EIS	0	0.31	0	0	0.09
ELE	0	0	0	0	0.32
MAN	0	0.69	1	1	0
TRN	0	0	0	0	0
ROW					
AGR	0	0.05	0	0	0
EIS	1	0	0.4	0.19	0.66
ELE	0	0.23	0	0.16	0.03
MAN	0	0	0.11	0	0.31
TRN	0	0.71	0.48	0.66	0

Note: [a] Due to data availability, we have to make assumptions about the accessibility intensity of sectors which are not listed in the table and for which there is no patent data. We assume that energy sectors (including coal, crude oil, refined oil and gas) have the same intensity as the electricity sector. Spillover coefficients for the service (SER) sector is assumed to be of the smallest value across sectors for one region.

Table A2. Estimation results for ϕ^{c}_{irs} (accessibility of international same-industry knowledge spillovers (type C)[a]

	Europe	USA	China	ROW
Europe				
AGR	–	0.28	0.09	0.31
EIS	–	0.32	0.07	0.37
ELE	–	0.26	0.12	0.27
MAN	–	0.31	0.11	0.28
TRN	–	0.30	0.09	0.22
USA				
AGR	0.19	–	0.22	0.55
EIS	0.18	–	0.08	0.34
ELE	0.19	–	0.15	0.37
MAN	0.17	–	0.11	0.31
TRN	0.19	–	0.12	0.27
China				
AGR	0.22	0.08	–	0.13
EIS	0.18	0.10	–	0.29
ELE	0.17	0.11	–	0.35
MAN	0.17	0.13	–	0.41
TRN	0.14	0.10	–	0.51
USA				
AGR	0.59	0.65	0.69	–
EIS	0.64	0.57	0.85	–
ELE	0.64	0.63	0.73	–
MAN	0.66	0.57	0.77	–
TRN	0.68	0.60	0.80	–

Note: [a] Due to data availability, we have to make assumptions about the accessibility intensity of sectors which are not listed in the table and for which there is no patent data. We assume that energy sectors (including coal, crude oil, refined oil and gas) have the same intensity as the electricity sector. Spillover coefficients for the service (SER) sector is assumed to be of the smallest value across sectors for one region.

Appendix B: Equilibrium conditions of numerical endogenous growth model

We formulate the model as a system of nonlinear inequalities and characterize the economic equilibrium by two classes of conditions: zero profit and market clearance. Zero-profit conditions exhibit complementarity with respect to activity variables (quantities) and market clearance conditions exhibit complementarity with respect to price variables. We use the "$\perp$" operator to indicate complementarity between equilibrium conditions and variables.[30] Model variables, parameters, and sets are defined in Tables B1 and B2.

B1. Zero-profit conditions

Zero-profit conditions for the model are given by following nonlinear inequalities:

$$c^Y_{irt} \geq P^Y_{irt} \qquad \perp Y_{irt} \geq 0 \qquad \forall i, r, t \tag{B1}$$

$$c^I_{irt} \geq P^I_{irt} \qquad \perp I_{irt} \geq 0 \qquad \forall i, r, t \tag{B2}$$

$$c^Q_{irt} \geq P^Q_{irt} \qquad \perp Q_{irt} \geq 0 \qquad \forall i, r, t \tag{B3}$$

$$c^X_{irt} \geq \kappa \cdot P^X_{irt} \qquad \perp X_{irt} \geq 0 \qquad \forall i, r, t \tag{B4}$$

$$c^A_{irt} \geq P^A_{irt} \qquad \perp A_{irt} \geq 0 \qquad \forall i, r, t \tag{B5}$$

$$c^T_{it} \geq P^T_{it} \qquad \perp T_{it} \geq 0 \qquad \forall i, t \tag{B6}$$

$$c^S_{irt} \geq P^S_{irt} \qquad \perp F_{irt} \geq 0 \qquad \forall i, r, t \tag{B7}$$

$$c^C_{rt} \geq P^C_{rt} \qquad \perp C_{rt} \geq 0 \qquad \forall r, t \tag{B8}$$

where c denotes respective unit cost functions.

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[30] Following Mathiesen (1985) and Rutherford (1995), we formulate the model as a mixed complementarity problem. A characteristic of many economic models is that they can be cast as a complementary problem, i.e. given a function F: $\mathbb{R}^n \longrightarrow \mathbb{R}^n$, find $z \in \mathbb{R}^n$ such that $F(z) \geq 0$, $z \geq 0$, and $z^T F(z) = 0$, or, in short-hand notation, $F(z) \geq 0 \perp z \geq 0$. The complementarity format embodies weak inequalities and complementary slackness, relevant features for models that contain bounds on specific variables, e.g. activity levels which cannot a priori be assumed to operate at positive intensity.

Unit cost functions for final product on activities are given as:

$$c^Y_{irt} = [\theta^Y_{ir}(c^Q_{irt})^{1-\gamma} + \theta^S_{ir}(c^S_{irt})^{1-\gamma} + (1-\theta^Y_{ir}-\theta^S_{ir})(\sum_{h\in ne}\theta_{hir}\frac{P^A_{hrt}}{\overline{p}^A_{hr}})^{1-\gamma}]^{1/(1-\gamma)}\,.$$

Sectoral-specific intermediate composite Q_{irt} is produced with a Dixit-Stiglitz production function $Q_{irt} = [\int_{j=0}^{\tilde{J_{irt}}} q^{\kappa}_{jirt}dj]^{\frac{1}{\kappa}}$. κ is the markup over marginal costs. The unit cost production of intermediate aggregate is reduced due to endogenous growth factor:

$$c^Q_{irt} = P^X_{irt}\cdot\kappa(\frac{1}{\tilde{J_{irt}}})^{(1-\kappa)/\kappa}\,.$$

Due to monopolistic competition, the relation between the market price of intermediate goods and the cost of production is $P^X_{irt} = c^X_{irt}/\kappa$ Intermediate goods q_{jit} is manufactured with following unit cost function:

$$c^X_{irt} = [\theta^{XL}_{ir}(\frac{(1+t^L_{ir})P^L_{rt}}{\overline{p}^L_{r}})^{1-\nu} + \theta^{XE}_{ir}(P^E_{irt})^{1-\nu}]^{1/(1-\nu)}$$

where P^E_{irt} is price for sector-specific energy composite in the intermediate goods production, given as follows:

$$P^E_{irt} = [\theta^E_{ir}(P^{fos}_{irt})^{1-\sigma_{egy}} + (1-\theta^E_{ir})(\frac{P^A_{ele,rt}}{\overline{p}^A_{ele,r}})^{1-\sigma_{egy}}]^{1/(1-\sigma_{egy})}$$

and

$$P^{fos}_{irt} = \sum_{h\in\tilde{e}}(\frac{P^A_{hrt}}{\overline{p}^A_{hr}} + \psi_h P^{CO_2}_t)^{\theta^{\tilde{e}}_{ir}}\,.$$

Trading commodity i from region r to region s requires the usage of transport margin j. Accordingly, the tax and transport margin inclusive import price for commodity i produced in region r and shipped to region s is given as:

$$P^M_{ist} = (1+t^e_{ir})P^Y_{irt} + \zeta^T_{hirs}P^T_{ht}\,.$$

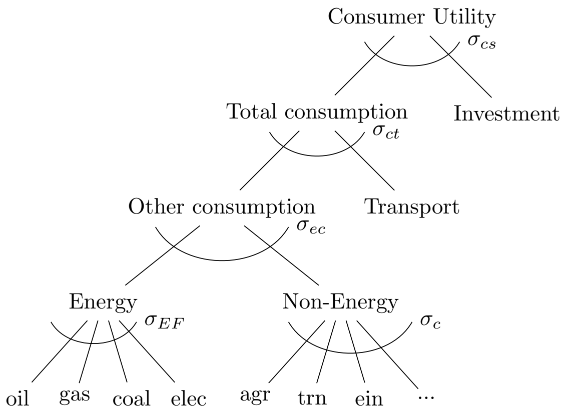
t^e_{ir} is the export tax raised in region r, ζ^T_{hirs} is the amount of commodity h needed to transport to commodity i, and t^m_{is} is the import tariff raised in region s. The unit cost function for the Armington commodity is:

$$c^A_{irt} = [\theta^A_{ir}(P^Y_{irt})^{1-\eta_i} + (1-\theta^A_{ir})(c^M_{irt})^{1-\eta_i}]^{1/(1-\eta_i)}$$

where

$$c^M_{irt} = [\sum_s \theta^M_{is}((1+t^m_{ir})\frac{P^M_{ist}}{\overline{p}^M_{is}})^{1-\sigma_m}]^{1/(1-\sigma_m)}\,.$$

Figure B1. Nesting structure of private consumption



International transport services are assumed to be produced with transport services from each region according to a Cobb-Douglas function:

$$c^T_{it} = \sum_s (P^Y_{ist})^{\theta^T_{is}} .$$

Sluggish factor transformation produces sector-specific factor inputs by using primary factor resources. The unit value of sector-specific factors is defined as a CET revenue function based on the base year value shares (θ^S_{ir})

$$c^S_{irt} = [\sum_f \theta^S_{fir} (P^F_{firt})^{1+\sigma_{tr}}]^{1/(1+\sigma_{tr})} .$$

Investment requires inputs from all sectors:

$$c^I_{irt} = [\sum_h \theta^{I_R}_{hr} (\frac{P^A_{hrt}}{p^A_{hr}} + \psi_h P^{CO_2}_t)^{1-\sigma^I_{ir}}]^{1/(1-\sigma^I_{ir})} .$$

Capital stock accumulation for sector i ($J_{irt} \geq 0 \quad \text{if} \quad t < T$) is given by:

$$(d_{irt} + \bar{r}) r_{irt} + (1 - d_{irt}) P^K_{ir,t+1} = P^K_{irt} .$$

Capital stock accumulation for sector i ($J^T_{irt} \geq 0 \quad \text{if} \quad t = T$) is given by:

$$(d_{irt} + \bar{r}) r_{irt} + (1 - d_{irt}) P^{TK}_{ir} = P^K_{irt} .$$

According to the nesting structure of private consumption (see Figure B1), the expenditure function for representative consumers in each region is defined as:

$$c^C_{rt} = (c^{CO}_{rt})^{\theta^C_r}(c^{CT}_{rt})^{1-\theta^C_r}$$

where

$$c^{CO}_{rt} = [\theta^{CO}_r (c^{CE}_{rt})^{1-\sigma_{ec}} + (1-\theta^{CO}_r)(c^{CNE}_{rt})^{1-\sigma_{ec}}]^{1/(1-\sigma_{ec})}$$

(expenditure for all consumption except transport)

$$c^{CE}_{rt} = [\sum_{i\in e} \theta^{CE}_{ir}(\frac{P^A_{irt}}{\overline{p^A_{ir}}} + \psi_i P^{CO_2}_t)^{1-\sigma_{EF}}]^{1/(1-\sigma_{EF})} \quad \text{(expenditure for energy goods)}$$

$$c^{CNE}_{rt} = [\sum_{i\in ne} \theta^{CNE}_{ir}(\frac{P^A_{irt}}{\overline{p^A_{ir}}})^{1-\sigma_c}]^{1/(1-\sigma_c)} \quad \text{(expenditure for non-energy goods)}\,.$$

Lifetime utility for a region r is defined as the accumulative discounted consumption:

$$P^U_r = [\sum_{t=0}^{T} \theta^U_{rt}(c^U_{rt})^{1-\sigma_U}]^{1/(1-\sigma_U)}\,.$$

B2. Market clearance conditions

Denoting consumers' initial endowments of factors as $\bar{L}_r$ (labor), and $\bar{V}_r$ (other inputs, respectively, and using Shephard's lemma, market clearance equations become as follows:

(B9) $$Y_{irt} \geq \sum_s \frac{\partial c^A_{ist}}{\partial P^Y_{irt}} A_{ist} + \frac{\partial c^T_{it}}{\partial P^Y_{irt}} T_{it} \qquad \perp P^Y_{irt} \geq 0 \qquad \forall i,r,t$$

(B10) $$Q_{irt} \geq \frac{\partial c^Y_{irt}}{\partial P^Q_{irt}} Y_{irt} \qquad \perp P^Q_{irt} \geq 0 \qquad \forall i,r,t$$

(B11) $$X_{irt} \geq \frac{\partial c^Q_{irt}}{\partial P^X_{irt}} Y_{irt} \qquad \perp P^X_{irt} \geq 0 \qquad \forall r,t$$

(B12)
$$A_{irt} \geq \sum_j \frac{\partial c^Y_{jrt}}{\partial P^A_{irt}} Y_{jrt} + \frac{\partial c^C_{rt}}{\partial P^A_{irt}} C_{rt} + \sum_j \frac{\partial c^I_{jrt}}{\partial P^A_{irt}} I_{jrt} \qquad \perp P^Y_{irt} \geq 0 \qquad \forall i,r,t$$

(B13)
$$\overline{L_{rt}} \geq \frac{\partial c_{irt}^X}{\partial P_{rt}^L} X_{irt} \qquad \perp P_{rt}^L \geq 0 \qquad \forall r, t$$

(B14)
$$T_{it} \geq \sum_{j,r} \frac{\partial c_{jrt}^A}{\partial P_{it}^T} A_{jrt} \qquad \perp P_{it}^T \geq 0 \qquad \forall i, t$$

(B15)
$$J_{irt} \geq \frac{\partial c_{irt}^I}{\partial r_{irt}} J_{irt} \qquad \perp r_{irt} \geq 0 \qquad \forall i, r, t$$

(B16)
$$I_{irt} \geq \frac{\partial c_{irt}^I}{\partial P_{irt}^I} I_{irt} \qquad \perp P_{irt}^I \geq 0 \qquad \forall i, r, t$$

(B17)
$$\overline{CARB_t} \geq \sum_r (C_{rt} \frac{\partial c_{rt}^C}{\partial P_t^{CO_2}} + \sum_i I_{irt} \frac{\partial c_{irt}^I}{\partial P_t^{CO_2}} + \sum_i Y_{rt} \frac{\partial c_{rt}^Y}{\partial P_t^{CO_2}}) \qquad \perp P_t^{CO_2} \geq 0 \qquad \forall t\,.$$

B3. Auxiliary conditions

International and domestic inter-sectoral spillovers increase the knowledge stock at sector i region r after transforming into usable knowledge:

(B18)
$$\tilde{J_{irt}} = J_{irt} + [\varepsilon_i^A (J_{irt})^{\frac{\lambda-1}{\lambda}} + \varepsilon_i^B (J_{irt}^B)^{\frac{\lambda-1}{\lambda}} + \varepsilon_i^C (J_{irt}^C)^{\frac{\lambda-1}{\lambda}}]^{\frac{\lambda}{\lambda-1}} \qquad \perp \tilde{J_{irt}} \geq 0 \qquad \forall i, r, t\,.$$

Terminal conditions for post-terminal capital stocks:

(B19)
$$\frac{I_{ir,T+1}}{I_{ir,T}} = \frac{Y_{ir,T+1}}{Y_{ir,T}} \qquad \perp KT_{ir} \geq 0 \qquad \forall i, r$$

where T denotes the terminal period.

Lifetime income constraints of regional representative households:

(B20)
$$\begin{aligned} P_r^U U_r = & \sum_i (P_{ir0}^K \overline{K_{ir0}}) + \sum_t [P_{rt}^L \overline{L_{rt}} + \sum_{i \in pe} (P_{irt}^{PE} \overline{e_{irt}^{PE}}) \\ & + P_t^{CO_2} \overline{CARB_t} + \overline{B_{rt}}] - \sum_i (P_{ir}^{KT} KT_{ir})\,. \end{aligned}$$

Table B1. Sets, price and quantity variables

Parameter	Description
Sets	
$i \in I$	Commodities
h	Alias for i
$j \in J$	Firms or varieties
$r \in R$	Regions
s	Alias for r
$ne \subset I$	Non-energy commodities
$e \subset I$	Energy commodities
$\tilde{e} \subset e$	Fossil fuels
$ele \subset e$	Electricity input commodities
f	Factors such as land, and resources
Prices	
P^Y_{irt}	Price of final goods of sector i in region r at time t
P^Q_{irt}	Price of intermediate composite of sector i in region r at time t
P^X_{irt}	Price of intermediate goods of sector i in region r at time t
P^A_{irt}	Price of Armington good of sector i in region r at time t
P^M_{irt}	Price of import of sector i in region r at time t
P^M_{irt}	Price of import of sector i in region r at time t
P^K_{irt}	Setor-specific capital purchase price in region r at time t
P^{KT}_{ir}	Setor-specific capital purchase price in region r in post-terminal period
r_{irt}	Setor-specific capital rental rate in region r at time t
P^U_r	Price for lifetime utility in region r
P^C_{irt}	Consumer price index in region r at time t
P^K_{irt}	Setor-specific capital purchase price in region r at time t
P^L_{irt}	Wage rate in region r at time t
P^T_{it}	Price index international transport service i at time t
P^S_{irt}	Price index for sector-specific primary factors in sector i at time t
P^F_{firt}	Factor Prices for land and resources in sector i at time t
P^I_{irt}	Investment consumption price index in region r at time t
$P^{CO_2}_{rt}$	Price for carbon dioxide emissions in region r at time t
Quantities	
Y_{irt}	Index for final goods of sector i in region r at time t
Q_{irt}	Index for intermediate composite of sector i in region r at time t
X_{irt}	Index for intermediate goods of sector i in region r at time t
I_{irt}	Investment index of sector i in region r at time t
C_{rt}	Total consumption index in region r at time t
A_{irt}	Armington index of commodity i in region r at time t
J_{irt}	Index for region- and sector-specific knowledge stock (including Romer-type A spillovers) in region r at time t
$\tilde{J}_{irt}$	Index for region- and sector-specific knowledge stock (including Romer-type A and type B and C spillovers) in region r at time t
T_{it}	Index for international transport services in sector i at time t

Table B2. Model parameters

Parameter	Description
Elasticity of substitution parameters	
γ	Substitution between Q and inputs from other sectors B
ν	Substitution between energy E and labor L
σ_{egy}	Substitution between electricity and fossil fuels in intermediate production
σ_{fos}	Substitution among fuels in intermediate production
σ_{cs}	Substitution between consumption and investment
σ_{ec}	Substitution between energy (F) and non-energy goods (D) in consumption
σ_{EF}	Substitution between electricity and fossil fuels in consumption
σ_{c}	Substitution between non-energy goods in consumption
σ_{ct}	Substitution between transportation and other consumption
η	Substitution between domestic goods and imports (varies by good)
tr	Elasticity of transformation
υ	Substitution between sectoral outputs for the input B
θ	Intertemporal elasticity of substitution
Other parameters	
θ^{Y}_{ir}	Share of intermediate composite in final good production
θ^{S}_{ir}	Share of sector-specific inputs in final good production
κ	the markup over marginal cost in intermediate good production
θ^{XL}_{ir}	Share of labor in intermediate goods production
θ^{XE}_{ir}	Share of energy input in intermediate goods production
θ^{E}_{ir}	Share of fossil energy in sector-specific energy composite for intermediate goods production
ψ_i	Carbon content of energy good i
t^{L}_{ir}	Labor use tax in production i in region r
t^{e}_{ir}	Export tax for commodity i in region r
t^{m}_{ir}	Import tax for commodity i in region r
ζ^{T}_{hirs}	Amount of commodity h needed to transport commodity i from region r to s
$\overline{p}^{A}_{is}$	Tax-inclusive reference price of Armington commodity i in region s
θ^{A}_{ir}	Share of domestic produced goods in Armington goods demand
$\overline{p}^{M}_{is}$	Tax-inclusive reference import price commodity i shipped to region s
$\overline{p}^{L}_{s}$	Tax-inclusive reference price of labor in region s
θ^{T}_{is}	Share of transport services of sector i of region s
θ^{S}_{fir}	Share of land or resources in total sector-specific input production
$\theta^{I_R}_{ir}$	Share of sectoral input in investment expenditure
$\bar{r}$	Steady-state baseline rental rate of capital
d_{irt}	Depreciation rate of sector i in region r at time t
θ^{C}_{r}	Share of non-transport commodities in total expenditure
θ^{CO}_{r}	Share of energy commodities in non-transport expenditure
θ^{CE}_{ir}	Share of commodity i in total energy expenditure
θ^{CNE}_{ir}	Share of commodity i in total non-energy expenditure
θ^{U}_{rt}	Share of time t's full consumption in lifetime income
$\overline{L_{rt}}$	Baseline period-t labor endowment of region r
$\overline{CARB_t}$	Cap on carbon dioxide emissions (exogenous supply of CO_2 emissions permits
$\overline{K_{ir0}}$	Household capital stock in period-0 of sector i in region r
$\overline{e^{PE}_{irt}}$	Baseline period-t primary energy used in sector i in region r
$\overline{B_{ir}}$	Baseline period-t trade deficit

Table B3. Central case values for elasticity of substitution parameters[a]

Parameter	Description	Value
γ	Substitution between Q and inputs from other sectors B	0.5
ν	Substitution between energy E and labor L	1
σ_{egy}	Substitution between electricity and fossil fuels in intermediate production	0.5
σ_{fos}	Substitution among fuels in intermediate production	1
σ_{cs}	Substitution between consumption and investment	0
σ_{ec}	Substitution between energy (F) and non-energy goods (D) in consumption	0.25
σ_{EF}	Substitution between electricity and fossil fuels in consumption	0.4
σ_{c}	Substitution between non-energy goods in consumption	0.25
σ_{ct}	Substitution between transportation and other consumption	1.0
η	Substitution between domestic goods and imports (varies by good)	1.9-3.6
σ^{I}	Substitution between sectoral goods for investment	0.5
υ	Substitution between sectoral outputs for the input B	0
$1/\theta$	Intertemporal elasticity of substitution	0.5

Notes: [a] Reference values of production and consumption sector substitution elasticities are taken from Paltsev et al. (2005). The intertemporal elasticity of substitution in the utility function is based on the estimates of Hasanov (2007). Remaining parameters are taken from Narayanan, Badri and McDougall (2012).

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