The impact of capital trade and technological spillovers on climate policies

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Abstract

In this paper, we present an intertemporal optimization model that is designed to analyze climate policy scenarios within a globalized world which is characterized by the existence of technological spillovers. We consider a type of technological spillovers that is bound to bilateral capital trade. Importing foreign capital that increases the efficiency of energy use represents a mitigation option that extends the commonly modeled portfolio. The technical details of the model are presented in this paper. The model is solved numerically. First model applications highlight the differences between climate policy analyses which either take or do not take technological spillovers into account. In the final part, we apply the model to investigate first-mover advantages and commitment incentives in climate policy scenarios. The existence of both is supported by simulation results.

keywords: climate policy, multi-region model, technological spillovers, international trade

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1 Introduction

Recently, increasing attention in both research and policy-making has been given to the interaction of international trade and climate change (cf. Copeland and Taylor, 2005; Weber and Peters, 2009). Climate policies are challenged by competitiveness and carbon leakage concerns. A number of studies deal with these trade-related issues (e.g. Böhringer and Rutherford, 2002; Peters and Hertwich, 2008). In climate policy modeling, less attention is paid to other interregional effects like technological spillovers.

However, within the discussion about promising climate protection strategies, technological spillovers come to the fore. Spillovers are expected to foster the diffusion of new technologies and hence represent a component of endogenous technological change to be included into climate policy models (cf. Löschel, 2002; Popp, 2006; Gillingham et al., 2008). The concept of technological spillover is based on the idea that technological externalities, coming along with the process of capital and knowledge accumulation, slow down the decrease of the marginal returns on capital. Keller (2004) provides a comprehensive overview on international technology diffusion and spillovers. Principally, the literature distinguishes between embodied and disembodied spillovers [1]. The former is rooted in the theoretical and empirical work by Coe and Helpman (1995) and Grossman and Helpman (1991), the latter is linked to the work on R&D investments and human capital done e.g. by Romer (1990).

Disembodied spillovers represent a kind of technological change that is driven by international diffusion of knowledge accumulated in a freely available global pool. Embodied spillovers, in contrast, represents technological change that is triggered by technological know-how embodied in foreign products or directly transferred innovations (patents).

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[1] Another classification introduced by Jaffe (1998) distinguishes between knowledge spillovers, market spillovers and network spillovers.

While some empirical evidence is given (cf. Keller, 2004), the processes of disembodied and embodied technology spillovers are far from being fully understood. Therefore, only a few studies exist that investigate climate policies in the presence of technological spillovers. In Rao et al. (2006) the technological learning curves of the model MESSAGE are subject to disembodied spillovers. Cross-sectoral learning (”technological clusters”) is combined with inter-regional learning. Verdolini and Galeotti (2009) and Dechezlepretre et al. (2009) study the diffusion of energy-efficient and climate change mitigation technologies based on patent data. The latter focus on a direct form of embodied spillovers where innovators transfer their inventions for the purpose of a commercial exploitation at a later point in time.

Most prominently studied are R&D spillovers and their effects on the stability of international environmental agreements (e.g. Carraro and Siniscalco, 1997; Kemfert, 2004; Nagashima and Dellink, 2008). Bosetti et al. (2008) model disembodied international energy R&D spillovers in the WITCH model. Knowledge acquired from abroad is combined with domestic R&D capital stock and thus contributes to the production of new technologies at home. For a climate policy scenario stabilizing CO_2 concentration on 450ppm, Bosetti et al. report lower optimal energy R&D investments and strong free-riding effects among High Income countries, when knowledge spillovers are explicitly modeled. However, due to spillovers, total knowledge stocks remain unchanged and mitigation costs are slightly lower due to lower expenditure in energy R&D.

A few other studies exist that take disembodied R&D spillovers into account when analyzing climate policies (e.g. Goulder and Schneider, 1999; Buonanno et al., 2003), but there is hardly any climate policy study that includes embodied technological spillovers. The present study helps to fill this gap. It tries to answer the question whether first-mover advantages and incentives to join international climate agreements can be derived in a model framework that endogenize technological spillovers on the level of world regions. In this study, the first mover-advantage refers to benefits that regions which push energy-efficient technologies can expect in a climate policy setting.

The concept of embodied spillovers as followed in this study can be conceived as a process of expanding technological know-how by capital imports. With increasing economic integration through international trade and foreign direct investments, a country's productivity growth is likely to depend not only on knowledge embedded in its own technology but also in the technology imported from its trading partners.

This paper presents a multi-region growth model that allows analysis of climate policy scenarios in the presence of capital trade and technological spillovers. In the implemented model two spillover channels are considered, leading either to an increase of labor productivity or energy efficiency. While part of the real-world heterogeneity is disregarded, this paper aims to investigate the impacts of modeling embodied technological spillovers in an Integrated Assessment framework built around a stylized Ramsey-type economic growth model, similar to the approach of Bosetti et al. (2008). By focusing on long-run transitional dynamics and going beyond the common approach of studying spillover effects in a reduced-form static model, this paper contributes to both the literature on technological spillovers and on the role of endogenous technological change in climate policy modeling.

The paper is structured as follows: In section 2, we discuss the concept of embodied spillovers, its empirical evidence and the way we implemented this feature. In section 3, the multi-region climate policy model is presented. We apply this model in a setting of four generic regions which are selected in order to address the issues of first-mover advantages and commitment incentives. In section 4, we describe the construction of our baseline scenarios and the definition of the climate policy scenarios. The basic co-operative policy scenario aims at limiting the increase of global mean temperature to 2°C above preindustrial level and is based on an international CO_2 cap-and-trade system. A comprehensive discussion of the results from different model runs is given in section 5. A sensitivity analysis shall help to assess the robustness of the results. We end with some conclusions in section 6.

2 Embodied technological spillover

Embodied technological spillovers refer to situations where the presence of physical capital, produced abroad and imported, affects efficiency or productivity levels of the host economy.

While there are some similarities with the disembodied spillover concept, significant differences exist. Disembodied technological spillovers refer to international knowledge as a public good. Free flow of knowledge fosters technological innovation in places different from where they were originally conceived, thus favoring foreign followers at the expense of domestic R&D investors. In contrast, embodied spillovers are bound to foreign investments and imported goods. This provides innovators with the possibility to appropriate part of the social benefits from their R&D investments, e.g. by additional export opportunities. Embodied spillovers could make the difference that helps investors in new energy technologies to break even (Barreto and Klaassen, 2004). From the macro-perspective adopted in this study, it could thus pay off for single regions to become forerunners in climate policy. Brandt and Svendsen (2006) distinguish two types of first-mover advantages. The first type materializes in exports to countries engaging in emission reductions. The second type exist when newly developed technologies are competitive even in situations where countries do not have reduction targets.

The body of empirical research on spillover externalities has grown rapidly (e.g. Lumenga-Neso et al., 2005; Jordaan, 2005; Takii, 2004). Empirical evidence is indicated for technological spillovers from capital trade and especially for spillovers from foreign direct investments. Both types of transfer of physical capital are thought to be nearly the same, since technological know-how is embodied in the machinery that is built up abroad in either way. Therefore, both support the concept of technological spillovers applied in this paper.

Keller (2004) analyzes empirical methods of measuring technological spillovers and distinguishes three types of econometric studies: association studies, structure studies and the general equilibrium approach. In association studies, the authors ask whether a specific foreign activity leads to a particular domestic technology outcome (e.g. Aitken and Harrison, 1999). Structure studies incorporate structural elements which include a foreign technology variable and the specification of a spillover channel or diffusion mechanism (e.g. Coe and Helpman, 1995). Empirical analyses that apply general equilibrium models are important because instead of focusing on reduced-form relationships within a subset of variables, they allow to study general equilibrium effects (e.g. Eaton and Kortum, 1996). Eaton and Kortum (2001) combine a technology diffusion model and a Ricardian model of trade. In the resulting model, trade augments a country's production possibilities for the classic Ricardian reason: trade gives access to foreign goods or, implicitly, technologies.

A majority of studies indicate positive spillover effects from foreign investments (e.g. Kokko, 1993; Blomström et al., 1999; Hejazi and Safarian, 1999; Takii, 2004; Jordaan, 2005). Takii (2004) demonstrated for several countries that foreign firms, resulting from foreign direct investments, tend to have higher productivity than domestic ones, hence improving the host country's aggregated productivity. Likewise, empirical results presented by Coe and Helpman (1995), Lee (1995), Xu and Wang (1999) and by Eaton and Kortum (2001) indicate that imported capital goods imply technological spillovers that account for significant parts of productivity changes. In contrast, the study of Keller (1998), referring to the findings from Coe and Helpman (1995), casts some doubts on the claim that patterns of international trade are important in driving R&D spillovers.

Recent empirical results have seriously challenged former findings. First, they suggest that positive externalities are less prevalent than previously thought. Second, structural factors were identified that affect the intensity of spillover effects, among them geographical distance and technological proximity (MacGarvie, 2005). Most commonly recognized is the concept of absorptive capacity indicating that spillovers have a positive effect only when domestic firms or the host region possess sufficient knowledge and skills to absorb positive externalities from foreign investments. Jaffe (1998) found that firms that do little R&D themselves suffer from competitive externalities linked to technological spillovers. A recent study by Jordaan (2005) explicitly analyzed existing indicators of absorptive capacity, notably technological differences between the host and foreign economy. The findings of Jordaan, however, are not in support of the notion of absorptive capacity, but indicate again a strong correlation between the extent of the technology gap and positive spillovers. Better proxies are needed to capture the effect of absorptive capacity. Hence, we include the concept of the technology gap but not that of the absorptive capacity in the present framework.

In following the empirical findings, we assume productivity and efficiency parameters as source and target of technological spillovers. Potential spillover gains ($spr_{i,r}$), i.e. productivity improvements, for region *i* depend on the technological gap between the trading partners *i* and *r*. We assume that the higher the productivity differential (A_r-A_i), the higher the potential spillover effect. The realized potential of technological spillovers then increases with intensity of capital trade ($X_{r,i}$) between the regions *r* and *i*. Spillover gains are, on the one hand, due to a direct productivity increase when the more efficient foreign capital is aggregated with domestic capital. On the other hand, additional know-how is generated in the process of using the imported capital stock. Both effects refer to the ratio between the imported capital and the domestic capital stock ($X_{r,i}/K_i$). By introducing spillover elasticity ψ <1 we assume a decreasing marginal spillover effect of capital exports. With spillover intensity Ω, this altogether yields:

$$spr_{i,r} = \left[\frac{X_{r,i}}{K_i}\right]^{\psi} \Omega(A_r - A_i) \qquad \forall i, r : A_i < A_r. \tag{1}$$

The resulting productivity gains are combined with technological progress that is fueled by domestic R&D investments (see next section). This linkage can be found in modified form in Bosetti et al. (2008), Coe and Helpmann (1995). Both elements of technological change are combined additively. This means that domestic R&D

investments are not a prerequisite for spillovers to take effect and thus cannot be interpreted as investments in building up absorptive capacities.

The spillover intensity Ω is a key parameter. Most authors acknowledge its importance, but given the state of the literature, it is difficult to provide sound empirical foundation. Variation of this parameter (cf. Nagashima and Dellink, 2008) reveals sensitivity, yet the selected values for spillover intensity cannot be compared across different models. We provide our own sensitivity analysis in section 5.

In an intertemporal optimizing framework, as it is the subject here, spillovers provide an additional factor of technological change which impacts regional growth dynamics. Commonly, spillovers are dealt with as an externality. This notion involves that spillovers cannot be anticipated and hence controlled by agents. However, while this view may be true for disembodied international knowledge spillovers, it is debatable in the context of embodied technological spillovers. If empirical studies suggest a link between positive productivity gains and capital trade, why should this not be taken into account by agents in decision-making and why should foresighted agents not be more proactive in attracting foreign direct investments and capital exports? Dechezlepretre et al. (2009) show that firms are willing to invest money in order to gain protection in foreign markets for their inventions, thus indicating that they are aware of technological spillovers when trying to market their superior technology there. We apply an approach where technological spillovers are anticipated by the regional actors, hence, influencing the dynamics of the control variables.

3 MIND-RS

MIND-RS is a multi-region model based on the single-region global Integrated Assessment model MIND (Edenhofer et al., 2005). MIND-RS adopts from MIND the structure of the energy system (except for the carbon capture and sequestration technology) and basic investment dynamics including R&D investments which represent a major feature of endogenous technological change. As a new channel of technological change, MIND-RS includes technological spillovers. Unlike MIND, MIND-RS separates the aggregated industrial sector into a consumption goods/service sector and an investment goods sector. Moreover, MIND-RS takes trade interactions into account. While market monopolies are excluded, trade flows represent control variables which are bound to an intertemporal budget constraint. Fig.1 presents most of the new features of the macroeconomic system of MIND-RS.

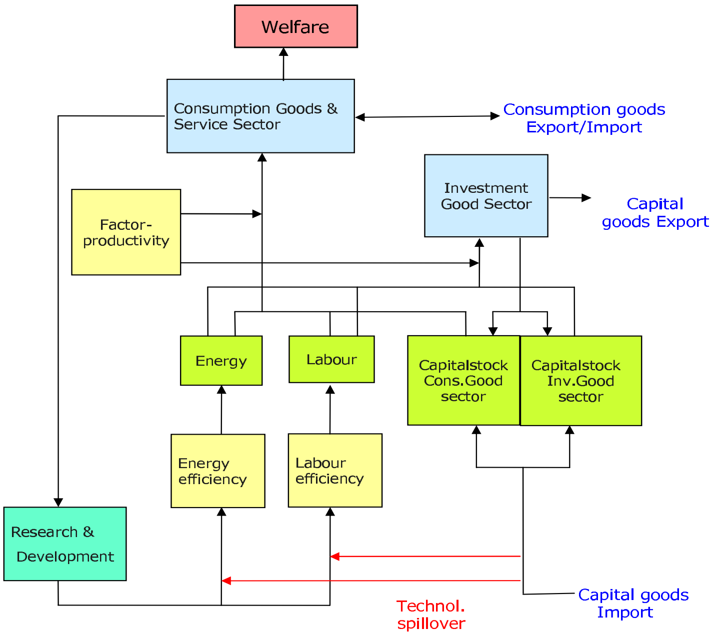

Figure 1: Structure of the macroeconomic system of MIND-RS

MIND-RS represents a dynamic trade model, but does not show the sectoral detail of recursive dynamic computable general equilibrium models. By offering the feature of intertemporal investment dynamics, MIND-RS is classified as an economic growth model suited for long-term analysis. The way bilateral trade and technological spillovers are handled as endogenous variables distinguishes MIND-RS from models of a similar type like RICE (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000) and MERGE (Manne et al., 1995; Kypreos and Bahn, 2003).

3.1 Technical description

We restrict the description here to the relevant macroeconomic model parts. More details about the energy sector are described in Appendix B. Furthermore, in addition to some explanation on variables and parameters in this section, a compact list of them can be found in Appendix A. The following indices are used throughout the model presentation:

t	1,2,...,T	time periods,
i, r	1,2,...,n	regions,
j		tradable goods and sectors,
m	K,L,E,PE	production factors.

With $J = \{C, I, Q, P, f, ren, nf\}$ and $j \in J$ the following sectors and goods are distinguished:

C	consumption goods (tradable),
I	investment goods (tradable),
Q	fossil energy resources (tradable) or extraction sector,
P	emission permits (tradable),
f	fossil energy transformation sector,
ren	renewable energy sector,

nf remaining energy sector.

Capitals from the above list simultaneously represent indices as well as corresponding variables. This also applies to the production factors labor (L), capital (K), final energy (E) and primary energy (PE). We denote the sectoral index and the production factor index by a subscript throughout the model presentation. For transparency reasons, we use a continuous formulation for the time and region index of the variables. Nevertheless, the model is implemented as a discrete one.

In each region, a representative agent is assumed to summarize households' consumption decisions and firms' investment and trade decisions. The objective is to maximize the welfare *W*

$$W(i) = \int_{t=1}^{T} e^{-\sigma t} \cdot L(i,t) \cdot \ln\left(\frac{C(i,t)}{L(i,t)}\right) dt \tag{2}$$

of *n* regions, where σ is the pure rate of time preference and L represents the regions' population which provides the exogenously given production factor labor. C denotes consumption.

Aggregated output is the sum of the output of the consumption goods/service sector and the investment goods sector. The production function Y_j of both sectors is specified as a CES function (with elasticity of substitution parameter ρ and input weight parameters ξ_m):

$$\begin{aligned} Y_j(i,t) =& \Phi_j(i)[\xi_K K_j(i,t)^{\rho(i)} + \xi_L(\theta_{L,j}(i,t)\mathcal{A}_L(i,t)L(i,t))^{\rho(i)} \\ &+ \xi_E(\theta_{E,j}(i,t)\mathcal{A}_E(i,t)E(i,t))^{\rho(i)}]^{\frac{1}{\rho(i)}} \quad \forall j \in \{C, I\}, \end{aligned} \tag{3}$$

Φ represents total factor productivity, *K* the capital stock, $\mathcal{A}_L$ labor efficiency, $\mathcal{A}_E$ energy efficiency and *E* the energy input. $\theta_{m,j}$ represents the share of the respective production factors with

$$\theta_{m,C} = 1 - \theta_{m,I} \quad \forall m \in \{L, E\}. \tag{4}$$

Factor market equilibrium is characterized by $\theta_{L,j} = \theta_{E,j}$. The efficiency variables are subject to R&D investments rd_m (cf. Edenhofer et al. 2005) and technological spillovers sp_m as described by equation

$$\dot{\mathcal{A}}_m(i,t) = \zeta(i)\left(\frac{rd_m(i,t)}{Y_C(i,t)+Y_I(i,t)}\right)^{\alpha}\mathcal{A}_m(i,t) + sp_m(i,t) \quad \forall m \in \{L,E\}. \tag{5}$$

Embodied technological spillovers increase labor efficiency and energy efficiency. These spillover effects are induced by capital exports $X_I(r,i)$ from region *r* to region *i*. As introduced in section 2, we define the spillover function for all $m \in \{L,E\}$:

$$sp_m(i,t) = \begin{cases} \sum_r \left[\left(\frac{X_I(r,i,t)}{K_I(i,t)}\right)^{\psi}\Omega_m(\mathcal{A}_m(r,t)-\mathcal{A}_m(i,t))\right] & : \mathcal{A}_m(i,t) < \mathcal{A}_m(r,t) \\ 0 & : \mathcal{A}_m(i,t) \geq \mathcal{A}_m(r,t) \end{cases} \tag{6}$$

where Ω_m describes the spillover intensity and ψ the spillover elasticity of foreign investments.

The budget constraint of the consumption goods and service sector distributes the sectoral output to domestic consumption, exports $X_C(i,r)$ and R&D investments:

$$Y_C(i,t) = C(i,t) + \sum_r X_C(i,r,t) - \sum_r X_C(r,i,t) + rd_L(i,t) + rd_E(i,t). \tag{7}$$

Imports of goods $X_C(r,i)$ relax this constraint. For transparency reasons we omit trading costs, which actually are assigned to all import variables [2].

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[2] Within the model implemented for numerical simulations, trade costs of 5% are assumed for each traded good. This corresponds to the estimate of ad-valorem costs for ocean shipping in 2000 by Hummels (2007) which amounts to 5.2%.

Output of the investment goods sector, added by capital imports $X_I(r,i)$, is used for domestic investments I_j into the industrial and energy sectors, and for foreign investments $X_I(i,r)$:

$$\begin{aligned} Y_I(i,t) = {} & I_C(i,t) + I_I(i,t) + I_{nf}(i,t) + I_f(i,t) + I_Q(i,t) + I_{ren}(i,t) \\ & + \sum_r X_I(i,r,t) - \sum_r X_I(r,i,t). \end{aligned} \tag{8}$$

Capital accumulation in all sectors other than the renewable energy sector follows the standard equation of capital stock formation

$$\dot{K}_j(i,t) = I_j(i,t) - \delta_j(i) \cdot K_j(i,t) \quad \forall j \in \{C, I, Q, f\}. \tag{9}$$

In modeling the renewable energy sector, the concept of vintage capital is applied (see Appendix B).

Within an international climate policy regime, we assume that each region is allocated an amount of emission permits *P*. For each unit of fossil resources converted into final energy, a permit is needed. Emissions trading X_P provides the opportunity to buy and sell them. The resulting constraint for using fossil resources is given by

$$Q(i,t) + \sum_r (X_Q(r,i,t) - X_Q(i,r,t)) \leq P(i) + \sum_r (X_P(r,i,t) - X_P(i,r,t)) \tag{10}$$

where Q denotes domestic fossil resource extraction and X_Q denotes the export and import of fossil resources.

The above system of equations forms a multi-region optimization problem with a single objective function for each region. The investment and trade variables represent control variables. In order to solve this problem we apply the iterative algorithm developed by Leimbach and Eisenack (2009). In assuming that the spillover effect is taken into account when agents make investment and trade decisions, this decentralized problem is solved as a co-operative game. Trade flows are adjusted endogenously to find a pareto-optimum that provides trade benefits for all regions. The applied trade algorithm iterates between a decentralized model version where each region optimizes its own welfare based on a given trade structure, and a Social Planner model version where the regions' welfare functions are combined by a set of welfare weights. The Social Planner model derives the optimal trade structure for the given set of welfare weights, while being subject to market clearance conditions. The welfare weights are adjusted iteratively according to the intertemporal trade balance of each region which has to be leveled off in the equilibrium point:

$$\sum_r \sum_j \sum_t (p_j(t)X_j(i,r,t) - p_j(t)X_j(r,i,t)) = 0 \quad j \in \{C, I, Q, P\}. \tag{11}$$

Market prices p_j are derived from shadow prices of the decentralized model version. The model provides a first-best equilibrium solution in labor, capital and goods markets implying full employment and converging return rates across regional and sectoral investments.

3.2 Set up of experiments

We want to apply the described model in a set of experiments that aims to assess climate policy implication of technological spillovers. We try to analyse this in a setting of four world regions - two developed and two developing ones.

Productivity enhancing technological know-how spills over mainly from the developed to the developing world regions. However, the two developed world regions are distinguished by different degrees of labor productivity and energy efficiency. Consequently, the export of investment goods contributes relatively more to an increase of labor productivity growth in the one case and of energy efficiency growth in the other case. The interesting question to be answered is than: Does the region that takes the lead in producing energy-efficient technologies benefit in a climate policy setting (first-mover advantage)? The developing regions differ in its starting income level and its growth dynamics with the initially poorer region exhibiting higher economic growth. Assuming that by the means of climate protocols the transfer of technological know-how can be intensified or restricted, the question arises: Are there incentives for developing world regions to join international agreements in the presence of technological spillovers?

To simplify the analysis we make two further assumptions. First, the developed world regions only export investment goods (this is in line with findings by Eaton and Kortum, 2001). Second, the less dynamically growing developing world region is the only exporter of energy resources.

In order to increase the clearness of our study and to avoid to get lost in an anonymous framework of investigation, we selected existing regions as representatives of the above described generic regions: the USA and Europe as the developed world regions, with higher labor productivity in the USA and higher energy efficiency in Europe, China as the fast growing developing region, and finally Rest of the World (ROW) as major resource supplier.

3.3 Empirical foundation

The empirical foundation of MIND-RS starts from calibration results of the global model MIND. Parts of the model parameters are adopted directly (in particular those of the R&D investment functions), others needed to be regionalized.

The calibration is done for the 4 world regions Europe, China, the USA and rest of the world (ROW). This follows the intention of providing a good benchmark for a group of generic region. The lack of good regional data demands for restraining from conclusions that go beyond the generic region level.

Major data sources of MIND-RS are:

WDI	("World Development Indicators") database
CPI	("Common Poles Image") database
GTAP6	("Global Trade Analysis Project") database
PWT	("Penn World Table") database
IEA	("International Energy Agency") database.

Main initial values are shown in Table 1. Deriving sound initial values for the capital stocks in the different energy sectors is most difficult because of a lack of appropriate data. In aggregating sectoral information from GTAP6 we derived estimates that in sum were significantly lower than the MIND values and would result in extreme adjustments of capital stocks in the first simulation periods. Therefore, we only use the regional shares in the global sectoral capital stocks as derived from GTAP6 and adjust the absolute level in order to avoid extreme model behavior.

With respect to the parameters of the production functions we stick to the MIND values in general. However, following findings in the literature (cf. Bernstein et al., 1999) we differentiate between a somewhat higher elasticity of factor substitution (0.4) in the aggregated industrial sectors of the developed world regions and a somewhat lower value (0.3) for the other two regions. The distribution parameters ξ_m are initialized according to the factors' usual aggregated income shares and assumed to be the same in the production functions of the consumption goods sector and the investment goods sector. Within the fossil energy sector, share parameters of 0.5 for capital and energy and substitution elasticities of 0.3 are assumed for all regions. With the elasticity and income share parameters given, we are able to compute the initial efficiency and productivity parameters (see Appendix C for a derivation of the calibration formula). These values are shown in Table 2. China exhibits a remarkably high productivity in the fossil energy sector which is partly due to the fact that labor is not taken into account in this sector. Nevertheless, most of this comparative advantage is consumed by the low energy efficiency in both industrial sectors.

The CPI database provides CO_2 emissions for the base year (see Table 1). Initial resource extraction is derived from the emissions data by using the carbon content coefficient of MIND and taking trade in fossil resources into account. Initial data for resource exports are derived from IEA's World Energy Outlook (2006).

Table 1: Initial values

parameter	Europe	USA	China	ROW
GDP in trill. $US	8.8	10.0	1.16	11.2
investment share of GDP in percent	0.22	0.24	0.27	0.24
industrial capital stock (trill. $US)	25.7	22.4	2.74	33.6
cap. stock in fossil energy sector (trill. $US)	1.4	1.6	0.27	2.8
capital stock in extraction sector (trill. $US)	1.1	1.4	0.22	1.8
invest. cost renew. energy sector ($US/kW)	1320	1383	1400	1330
learning rate (renewable energy sector)	0.15	0.13	0.1	0.11
industrial CO_2-emissions in GtC	1.14	1.54	0.87	2.81

Table 2: Calibrated initial values of efficiency and productivity parameters

parameter	Europe	USA	China	ROW
total factor productivity (industrial sectors)	0.34	0.45	0.42	0.33
labour efficiency	0.5	0.8	0.02	0.85
energy efficiency	5.24	3.45	0.64	2.55
total factor productivity (fossil energy sector)	3.12	3.82	13.0	3.55

Particular attention was paid to the calibration of the parameters of the marginal extraction cost curve and the learning curves in the renewable energy sector. As to the marginal extraction cost curve (see Eq. 17 in Appendix B), we adjusted the χ_3 parameter such that the regional values reflect expected scarcities and sum up to 3500 GtC - the value of global carbon reserves assumed within MIND (Edenhofer et al., 2005). The distribution of reserves follows the IEA World Energy

Outlook (2002) from which we derive shares of around 10%, 20%, 10% and 60% for Europe, USA, China and ROW, respectively.

Given the difference in the learning rates (with highest learning rates for solar and wind technologies) and the different composition of the renewable energy sector in the four regions, we derived regional differentiated initial investment costs and learning rates as shown in Table 1. The learning rates which specify the percentage cost reduction for a doubling of cumulated capacities are assumed to be constant over time. The regional learning curves are not subject to international spillovers.

Although the body of empirical research on spillover externalities has grown rapidly (see section 2), data are restricted to case studies mostly on the level of firms. On a country level, Coe and Helpman (1995, p.874) estimated that around one quarter of benefits from R&D investments (i.e. productivity increases) in G7 countries accrue due to trade. We selected values for the spillover intensity and the spillover-trade elasticity such that in the baseline scenario around 15% of labor productivity growth in ROW is due to embodied technological spillovers. That is in the range of 10-20% indicated by Kokko (1993, p.161). In the default model setting, we apply the same value for the labor-productivity-enhancing and the energy-efficiency-improving spillover intensity.

4 Scenario definition

4.1 Baseline scenarios

Based on initial data and calibration, we generate a baseline scenario that represents economic dynamics in the presence of technological spillovers. In a first step, we contrast this scenario with another baseline scenario that is based on the same set of parameters and initial values but neglects the spillover effect. Missing this aspect of endogenous technological change results in fundamentally different growth dynamics in the spillover senario (BAU-S) and the non-spillover scenario

(BAU) as shown in Fig. 2. This Figure combines historic developments and model projections. The growth difference is particulary high in China. China benefits most from technological spillovers with a strong accelerating impact on economic dynamics. Simultaneously, energy consumption and emissions are much higher in the presence of technological spillovers.

Due to this baseline growth effect and the expanded emission mitigation gap, expected mitigation costs in climate policy scenarios would be higher in the spillover than in the non-spillover scenario. Due to the public good characteristics of the atmosphere as a sink of greenhouse gases, increased emission reduction needs would also affect regions that not directly profit from the baseline growth effect. In order to disentangle this baseline effect, we constructed a new non-spillover baseline scenario. We compensate the non-spillover scenario for the missing feature of endogenous technological change by increasing energy efficiency and labor productivity exogenously by the same amount as in the spillover scenario. Consequently, similar GDP paths for the spillover baseline and the non-spillover baseline scenario (BAU-ex) are simulated. Also the CO_2 emission baselines, increasing up to 31.5 GtC in 2100, fit to each other.

However, there are still differences in the internal dynamics. In the spillover scenario, additional growth is induced by capital exports from the USA and Europe. This results in a higher degree of specialization of both regions in investment goods production. Globally, the overall share of investments on GDP is slightly higher in the spillover scenario. Moreover, there are significant differences in the trade structure. E.g., while Europe and USA are importers of the consumption good in the spillover scenario, they become goods exporters in the absence of technological spillovers.

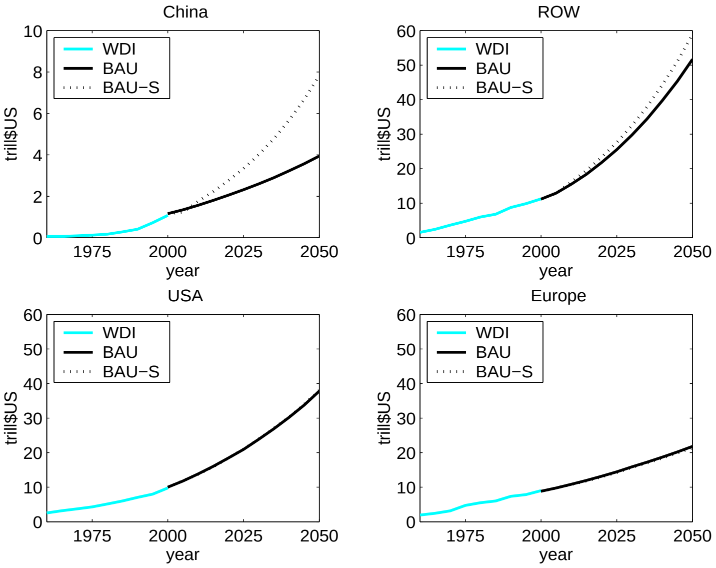

Figure 2: GDP trajectory (until 2000, empirical data from WDI database; thereafter model simulations)

4.2 Policy scenarios

The baseline scenarios represent business-as-usual dynamics by neglecting the climate change problem. Within the policy scenarios this problem is taken into account. By adopting the target of the EU to limit global mean temperature increase to 2°C above preindustrial level, the policy scenarios frame the search for optimal mitigation policies. Technically, we used the optimal emission path that meets the 2°C target in a model run with the global model MIND (Edenhofer et al., 2005). From this global emission path we derive the amount of emission permits that can be allocated between the four regions. In allocating the permits, we follow the contraction & convergence approach (Meyer, 2000; Leimbach, 2003). In the base year 2000, permits are allocated according to the status-quo, providing the USA and Europe with a higher per capita share. Per capita allocation of permits is assumed to converge over time with equal per capita allocation achieved in 2050. The total amount of permits contracts over time, thus requiring emission reduction to keep the 2°C temperature target.

In general, opposite spillover-related impacts affect the costs of climate change mitigation. On the one hand, the growth effect, induced by the spillover channel that increases labor productivity, enlarges the mitigation gap between the baseline and the policy scenario, hence, increases the costs. The energy efficiency effect, on the other hand, helps to fill the mitigation gap more efficiently, hence, reduces the costs. With the construction of the baseline scenario, we disentangled the baseline growth effect, allowing to analyse differences in climate policy implications between spillover scenarios and non-spillover scenarios more clearly.

While in the default setting we investigate climate policies in a co-operative world, we formulate an alternative policy scenario representing fragmented policy regimes. We consider the possibility that a single region will not join the grand coalition. The region that is not willing to accept binding emission reduction commitments is assumed to run in a business-as-usual mode, while all other regions are committed to the same amount of emission reduction as within the full co-operative policy regime. Total emissions increase compared to the co-operative policy regime. Emissions trading is allowed only between partners within the coalition. The non-committed region is partly excluded from technological spillovers. The spillover channel that affects energy efficiency is closed completely and the intensity of spillovers that increase labor efficiency is reduced up to 50%. This is a rather extreme scenario, but it reflects the idea of issue linking by combining a climate policy regime with a technology protocol and some kind of trade sanctions as it is analyzed in the literature on the stability of international environmental agreements (e.g. Carraro and Siniscalco, 1997; Barrett, 2003; Kemfert, 2004; Lessmann et al., 2009).

A list of all scenarios is provided in Appendix A.

5 Policy analysis

5.1 Common results

By discussing the results from model simulations, we first focus on results that are robust across spillover and non-spillover scenarios. Given the policy target, the non-spillover policy scenario COP-ex and the spillover policy scenario COP-S come up with the same optimal emission trajectory (see Fig. 3) as part of the co-operative solution. The gaps between the emission baseline trajectories and the optimal policy paths are huge. Under climate policies, emissions have to be reduced globally by around 50% in 2050 compared to the base year (2000) and up to 85% compared to the baseline.

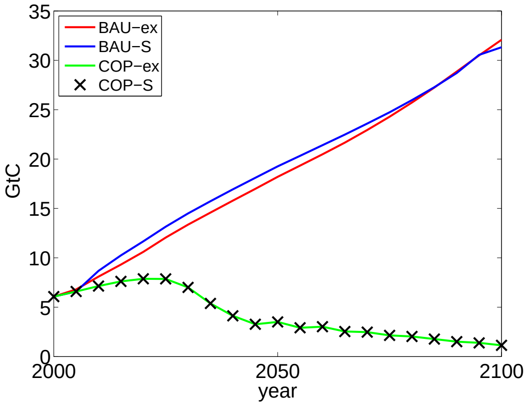

Figure 3: Optimal CO_2 emissions

Fig. 4 shows the regional distribution of mitigation costs. Mitigation costs are measured as the percentage loss of consumption in the policy scenario compared to the corresponding baseline scenario. Note that benefits due to avoided climate change damages are not taken into account, but will probably shift consumption losses into gains when the policy scenario is compared with a reference scenario that includes climate damages.

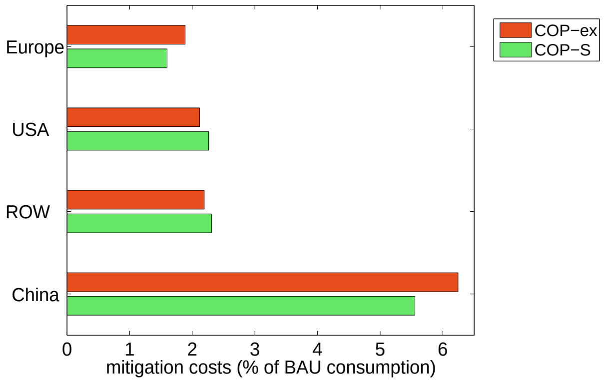

Figure 4: Average mitigation costs in COP-ex and COP-S scenario

Irrespective of the presence or absence of spillovers, Europe faces the lowest costs (between 1% and 2% on average) in the co-operative policy scenarios and China faces the highest costs (between 5% and 6% on average). The high level of mitigation costs in China is mainly due to the high economic growth path and a comparatively low level of energy efficiency. Due to a fast contraction of globally available emission permits, China suffers from a shortage of permits under the applied contraction & convergence allocation rule. Europe benefits from a higher level of energy efficiency and a lower level of carbon intensity compared to the USA. ROW is a quite heterogenous region with slow and fast growing countries. Two opposite effects have a major impact on the level of mitigation costs in ROW. Revenue losses from fossil resources export for one part of countries are accompanied by gains from emissions trading for other parts of countries.

Between 10% and 30% of the mitigation costs can be saved across all regions by emissions trading. Absolute volumes of permits traded in scenario COP-S are shown in Fig. 5. The USA buys permits over the whole time horizon. ROW sells permits of around 1 GtC per year over the whole time span. China starts as a seller of emission rights. However, as the amount of available permits contracts soon, it quickly becomes a buyer of emission permits. The opposite applies to Europe. European permit exports represent, however, only a small volume.

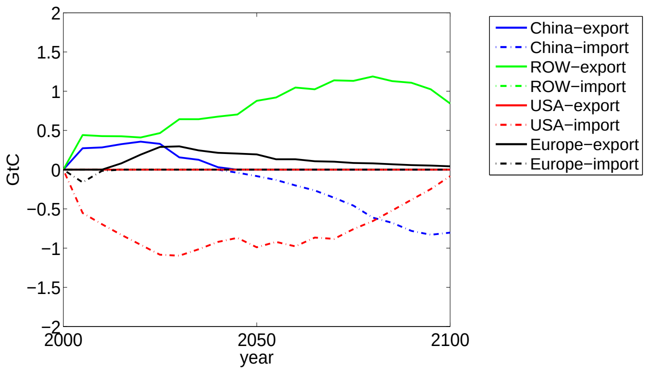

Figure 5: Flow of emission permits in COP-S scenario

Trade pattern differences between the baseline and the policy scenarios are mainly represented by trade in emission permits and differences in the trade of fossil resources. Beyond that, the trade pattern is quite robust between the baseline and the policy scenarios, though it is different between the spillover and the non-spillover scenarios. On the resource market, reduced demand of Europe and USA causes export losses of ROW.

5.2 Spillovers vs. non-spillovers

Even though mitigation cost differences between the spillover and the non-spillover scenario are moderate (cf. Fig. 4), they indicate the impact of spillover-specific mechanisms. Understanding these mechanisms may help in designing effective climate policies.

The major difference between the spillover and the non-spillover scenario in responding to climate policies is the additional possibility of intensifying and redirecting capital trade in order to employ the energy-efficiency-enhancing spillover effect in the spillover scenario.

Figures 6 and 7 show the differences in consumption goods trade and capital trade between the baseline scenarios and the corresponding policy scenarios. In general, there is less capital trade in the policy scenarios. Both the USA and Europe withhold part of their investments for restructuring their domestic energy systems. However, capital trade reduction is less distinct in the presence of technological spillovers. This is mainly due to the fact that, in contrast to the non-spillover scenario, capital trade reductions have a negative impact on the labor productivity and the energy efficiency in the spillover scenario.

Due to the attractiveness of foreign capital in the spillover scenario, trade volumes are much higher in this scenario than in the non-spillover scenario. Higher demands on the capital and permit market cause higher relative capital and carbon prices in the spillover scenario. Higher capital prices favor the capital exporters Europe and USA. Europe can profit from the improved terms-of-trade. For the USA, this positive effect is dominated by higher expenditures on the carbon market.

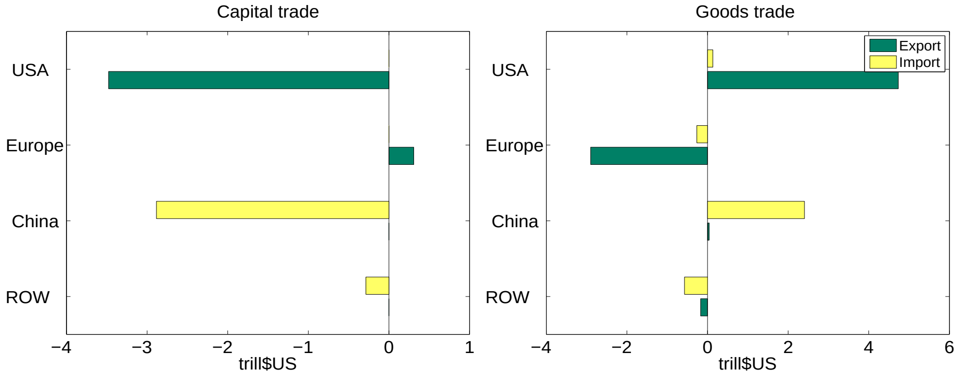

Figure 6: Trade flow differences between policy scenario (COP-ex) and baseline scenario (BAU-ex) - cumulated net present values

In contrast to the capital market, an even qualitatively different reaction can be observed on the goods market. While the USA finances permit imports (cf. Fig. 5) by additional goods exports in the COP-ex scenario, it forgoes goods imports in the COP-S scenario. In contrast, Europe uses revenues from the permit market to reduce goods exports in the non-spillover scenario but uses such revenues to

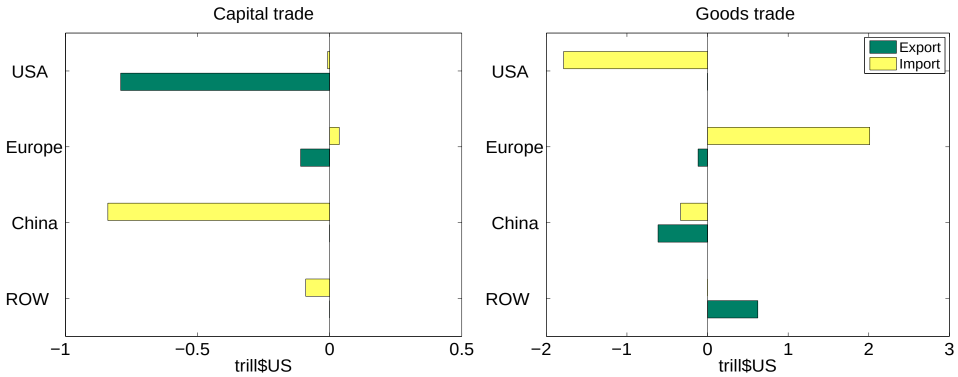

Figure 7: Trade flow differences between policy scenario (COP-S) and baseline scenario (BAU-S) - cumulated net present values

increase imports of goods in the spillover scenario. This indicates better terms-of-trade in the spillover scenario.

Although ROW benefits from higher carbon prices in the spillover scenario, mitigation costs for this region are somewhat higher in the presence of spillovers. ROW suffers from a larger negative difference in resource prices between the COP-S and the BAU-S scenario than between the COP-ex and the BAU-ex scenario. In contrast to ROW, China exhibits less mitigation costs in the spillover scenario than in the non-spillover scenario, even though capital imports are reduced compared to the baseline. Capital trade reduction happens in both policy scenarios but has an efficiency-decreasing impact in the spillover scenario only. The reason for this positive mitigation cost difference is a remaining baseline growth effect. Based on the exogenously given productivity improvements in the non-spillover scenario, China shifts investments across sectors and time. This yields a slightly faster growing consumption path in the non-spillover scenario.

5.3 First-mover advantage

According to available data (see Table 2), Europe has currently a higher energy efficiency than the USA. By interpreting high initial energy efficiency as a result of a first-mover climate policy, we investigate the model results for effects that represent first-mover advantages bound to the presence of technological spillovers. The question arises: Do the lower mitigation costs for Europe in the scenario COP-S compared to scenario COP-ex (cf. Fig. 4) indicate first-mover advantages?

Trade patterns are crucial. Comparing the differences in capital trade in Figures 6 and 7, we do not observe a major redirection of capital trade flows. While this hardly provides an argument for the first-mover advantage, the fact that Europe in contrast or proportion to all other regions and in contrast to its own trade pattern in the non-spillover scenario increases its share on international trade does so.

We run an additional experiment in order to demonstrate the significance of the first-mover advantage and to exclude that Europe's relative gains are due to price effects that relate to the endogenous representation of technological change in general, but not to the energy-efficiency-enhancing spillover channel in particular. The current model design is characterized by the fact that the growth-enhancing and the energy-efficiency-enhancing effect of technological spillovers are jointly bound to capital trade. Each decision for capital imports, intended to access energy-efficient capital and know-how, simultaneously implies productivity growth which can counteract the former intention. The ratio between the intensity of both spillover effects plays therefore an important role.

In the additional experiment, we refrain from assuming a unique spillover intensity parameter Ω, but use an energy-efficiency-related spillover intensity that is tenfold higher than the original value while the labor productivity related spillover intensity is held constant[3]. Based on this single change, we simulate a baseline scenario (BAU-H) that in the same way as described in section 4 is used to create a cor-

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[3] In section 5.5, parameter Ω is subject to a comprehensive sensitivity analysis.

responding non-spillover baseline scenario (BAU-H-ex). Consequently, the latter differs from the BAU-ex scenario mainly due to the increased level of exogenous energy efficiency growth.

Fig. 8 shows the mitigation costs for the new set of policy scenarios (COP-H and COP-H-ex). While mitigation costs compared to the default scenario (see Fig. 4) decrease in general, cost reductions are most remarkable in China. This clearly demonstrates the first order effect of spillovers. China exhibits the highest technology gap in energy efficiency and hence profits most from energy-efficiency-improving technological spillovers. Moreover, it turns out that Europe can furthermore reduce mitigation costs in the presence of spillovers. Mitigation costs are reduced to 1.27% which is 0.44 percentage points less than the mitigation costs in the non-spillover scenario [4]. In particular, Europe's share both in capital exports and in goods imports increases compared to the baseline scenario (see Fig. 9). Why? The reason for this is the differentiated spillover channel.

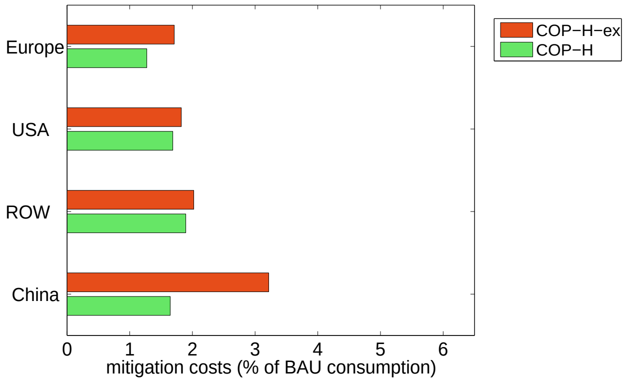

Figure 8: Average mitigation costs of the scenarios COP-H-ex and COP-H

The high labor efficiency of the USA, which is subject to spillovers, made capital exports from the USA most attractive in general. Under the condition of a carbon-

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[4] The mitigation cost difference between the non-spillover and the spillover scenario amounts to 0.13 and 0.14 percentage points for ROW and the USA, respectively. Both regions benefit in the spillover scenario from a shift of capital trade in time.

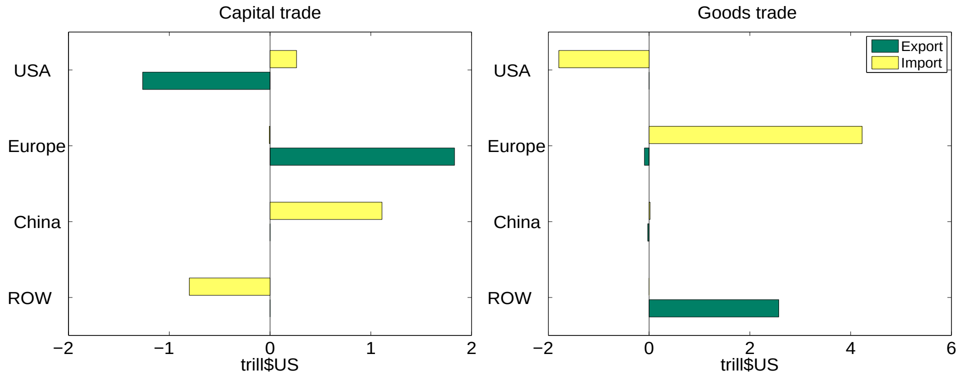

Figure 9: Trade flow differences between policy scenario (COP-H) and baseline scenario (BAU-H) - cumulated net present values

constrained world, however, energy efficiency becomes more important. Foreign investments from Europe become more attractive because they embody technological know-how that contributes to a higher extent to an increase in energy efficiency of capital importing regions than technological spillovers from investments goods of the USA.

This causal relationship explains the higher capital export of Europe in the COP-H scenario compared to the BAU-H scenario and indicates a first-mover advantage in the presence of technological spillovers. It results in substantially less mitigation costs for Europe in scenario COP-H compared to scenario COP-H-ex. Continually improved terms-of-trade allow Europe to increase their shares in global trade at the expense of the USA.

5.4 Fragmented policy regime

We finally investigate fragmented policy scenarios where China does not join the climate policy regime. Under these scenarios, trade pattern and mitigation costs change substantially. China will suffer from receiving less technological spillovers. Unless the labor-productivity-enhancing spillover channel is completely opened (as in scenario NoCH-0 - see Fig. 10), this loss cannot be compensated by a relaxed emission constraint which allows the use of cheap fossil fuels for a longer time. Depending on the design of the restrictiveness of the trade or technology protocol that come into force, the additional mitigation costs can be huge. Closing the energy-efficiency increasing spillover channel and restricting labor-productivity enhancing technological spillovers by 25% (NoCH-25) results in mitigation costs of 14% for China. With a 50% reduction of labor-productivity-increasing spillovers, costs increase to around 27% (see Fig. 10).

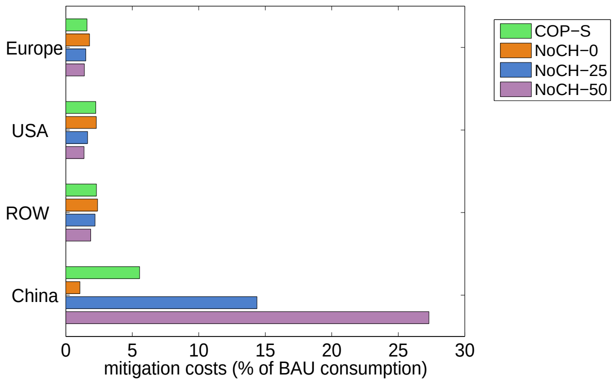

Figure 10: Mitigation costs in fragmented policy regime

For the other regions, losses compared to the co-operative solution slightly change[5]. Nevertheless, Europe cannot fully employ its first-mover advantage. To avoid this situation, it is important that technology protocols and trade sanctions do not only affect energy-efficient technologies but products with embodied technological know-how in general. Under such circumstances, there would be clear incentives for China to accept commitments.

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[5] Partly lower mitigation costs for the commited regions are outweighted by higher climate change risks due to the increased amount of emissions.

5.5 Sensitivity analysis

We carry out sensitivity analyses to test robustness of results. In particular we investigate into the sensitivity of:

- consumption and mitigation costs to spillover intensity Ω
- consumption and mitigation costs to R&D efficiency ζ.

We selected those parameters that presumably have a huge impact, but have a weak empirical foundation. The spillover intensity relates to the extent of endogenous technical progress with a high impact on economic growth. The same applies to the R&D parameter which represents the efficiency of R&D investments into labor efficiency improvements. The variation of parameter values is always the same for each region.

For all variations we see smooth and well-behaved changes[6]. This indicates numerical robustness. Nevertheless, sensitivity is quite high in some cases. With respect to the spillover intensity, significant impacts can be demonstrated for all regions, in particular for China (see Fig. 11 in Appendix D). However, while China faces drastic changes in consumption as well as in mitigation costs, for the USA we observe high sensitivity of mitigation costs but moderate changes in consumption. For Europe even changes in mitigation costs are moderate. Differences in sensitivities of mitigation costs are due to the growth effect of the labor-efficiency-enhancing spillover channel. This spillover channel is more intensively used in the baseline scenario than in the policy scenario.

Within the selected range of variation, economic growth is very sensitive to the R&D efficiency parameter in all regions. The higher the efficiency of R&D investments into labor efficiency improvements, the higher the growth (see Fig. 12

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[6] Changes of differential measures as mitigation costs are obviously not as smooth as those of the basic variables.

in Appendix D). Consequently, a climate-policy-induced shift from R&D investments (and capital imports), that increase labor efficiency, into R&D investments (and capital imports), that increase energy efficiency, results in higher mitigation costs in all regions but Europe. Europe benefits from the redirection of the other regions' expenditures to energy-efficiency-improving capital imports (for which Europe is most attractive).

6 Conclusions

In this paper, we analyzed the implications of modeling embodied technological spillovers. We presented a multi-region growth model with endogenous technological change and discussed its application in a climate policy context. In the presence of spillovers that enhance labor efficiency and energy efficiency, two opposite spillover effects impact mitigation costs. While a growth effect tends to increase mitigation costs, energy efficiency improvements reduce mitigation costs. The higher the ratio between the spillover intensities that either increase energy efficiency or labor productivity, the lower are the mitigation costs for all regions. Importing foreign capital that increases the efficiency of energy use represents a mitigation option that extends the commonly modeled portfolio. In consequence of this option, associated terms-of-trade effects favor capital-exporting regions in climate policy scenarios.

Advantages in energy saving technologies thus pay off in climate policy scenarios. This finding gives support to the hypothesis that there are some benefits for forerunners in climate policies. This relationship would be more distinctive if we considered not only advantages in energy-efficient technologies but also in carbon-free energy technologies. From the sensitivity analysis, it furthermore turns out that this first-mover advantage is the larger the higher the efficiency of domestic R&D investments in labor productivity growth is, making labor-efficiency-enhancing capital imports less attractive and energy-efficiency-enhancing capital imports more attractive. Both results emanate from modeling the embodied type of technological spillovers, but cannot be derived in a model with disembodied spillovers only.

Simulations of policy scenarios that include embodied technological spillovers discover various incentives for single regions to take active part in climate policies. In particular, it turns out that restrictions on technology transfers will provide incentives for developing world regions to join a climate policy regime; this is in line with findings from the literature on the stability of international environmental agreements which are mainly based on disembodied spillovers. In addition, this study showed that it is important that restrictions on technology transfers do not only affect energy-efficient technologies but products with embodied technological know-how in general.

All model results are subject to a number of assumptions and simplifications, in particular:

- limited empirical foundation (this applies for example to the differentiation between the intensity parameters of the labor productivity and the energy efficiency spillover function)
- neglecting the impact of absorptive capacities
- foreign and domestic goods are considered as perfect substitutes, which results in undue specialization
- limited disaggregation of the energy sector; neglect of the option of carbon capturing and sequestration (neglecting this option results in higher average mitigation costs than those simulated by the global reference model MIND).

This list gives rise to future research demand.

References

[1] Aitken, B.J., Harrison, A.E. (1999). Do domestic firms benefit from direct foreign investments ? Evidence from Venezuela. American Economic Review 89, 605-618.

[2] Barrett, S. (2003). Environment and Statecraft. The Startegy of Environmental Treaty-Making. Oxford University Press.

[3] Barretto, L., Klaassen, G. (2004). Emissions Trading and the Role of Learning-by-doing in the ”Bottom-up” Energy-Systems ERIS Model. International Journal of Energy Technology and Policy 2, 70-95.

[4] Bernstein, P.M., Montgomery, W.D., Rutherford, T.F. (1999). Global Impacts of the Kyoto Agreement: Results from the MS-MRT Model. Resource and Energy Economics 21, 375-413.

[5] Blomström, M., Globerman, S., Kokko, A. (1999). The determinants of host country spillovers from foreign direct investments: review and synthesis of the literature. SSE/EFI Working Paper Series in Economics and Finance, No. 339, School of Economics, Stockholm.

[6] Böhringer, C., Rutherford, T. (2002). Carbon Abatement and International Spillovers. Environmental and Resource Economics 22, 391-417.

[7] Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M. (2008). International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. Energy Economics 30, 2912-2929.

[8] Brandt, U.S., Svendsen, G.T. (2006). Climate Change negotiations and first-mover advantages: the case of the wind turbine industry. Energy Policy 34, 1175-1184.

[9] Buonanno, P., Carraro, C., Galeotti, M. (2003). Endogenous induced technical change and the costs of Kyoto. Resource and Energy Economics 25, 11-34.

[10] Carraro, C., Siniscalco, D. (1997). International Environmental Agreements - Strategic Policy Issues, Edward Elgar Publishing, Cheltenham.

[11] Coe, D.T., Helpman, E. (1995). International R&D spillovers. European Economic Review 39, 859-887.

[12] Copeland, B.R., Taylor, M.S. (2005). Free trade and global warming: a trade theory view of the Kyoto protocol. Journal of Environmental Economics and Management 49, 205-234.

[13] Dechezlepretre, A., Glachant, M., Hascic, I., Johnstone, N., Meniere, Y. (2009). Invention and Transfer of Climate Change Mitigation Technologies on a Global Scale: A Study Drawing on Patent Data. Working Paper. FEEM Nota di Lavoro 82.2009, Fondazione Eni Enrico Mattei, Milan.

[14] Eaton, J., Kortum, S. (1996). Trade in Ideas: patenting and Productivity in OECD. Journal of International Economics 40, 251-278.

[15] Eaton, J., Kortum, S. (2001). Trade in capital goods. European Economic Review 45, 1195-1235.

[16] Edenhofer, O., Bauer, N., Kriegler, E. (2005). The Impact of Technological Change on Climate Protection and Welfare. Ecological Economics 54, 277-292.

[17] Gillingham, K., Newell, R., Pizer, W. (2008). Modeling endogenous technological change for climate policy analysis. Energy Economics 30, 2734-2753.

[18] Goulder, L.H., Schneider, S.H. (1999). Induced technological change and the attractiveness of CO_2 abatement policies. Resource and Energy Economics 21, 211-253.

[19] Grossman, G.M., Helpman E. (1991). Innovation and Growth in the Global Economy. Cambridge, MA, MIT Press.

[20] Hejazi, W., Safarian, A.E. (1999). Trade, Foreign Direct Investment, and R&D Spillovers. Journal of International Bussiness Studies 30, 491-511.

[21] Hummels, D. (2007). Transportation Costs and International Trade in the Second Era of Globalization. Journal of Economic Perspectives 21, 131-154.

[22] IEA (2002). World Energy Outlook. International Energy Agency, Paris.

[23] IEA (2006). World Energy Outlook. International Energy Agency, Paris.

[24] Jaffe, A.B. (1998). The Importance of ”Spillovers” in the Policy Mission of the Advanced Technology Program. Journal of Technology Transfer 23, 11-19.

[25] Jordaan, A.J. (2005). Determinants of FDI-Induced Externalities: New Empirical Evidence for Mexican Manufaturing Industries. World Development 33, 2103-2118.

[26] Keller, W. (1998). Are international R&D spillovers trade-related? Analyzing spillovers among randomly matched trade partners. European Economic Review 42, 1469-1481.

[27] Keller, W. (2004). International Technology Diffusion. Journal of Economic Literature XLII, 752-782.

[28] Kemfert, C. (2004). Climate coalitions and international trade: assessment of cooperation incentives by issue linkage. Energy Policy 32, 455-465.

[29] Kokko, A. (1993). Foreign Direct Investments, Host Country Characteristics, and Spillover. Dissertation, EFI/The Economic Research Institute, Stockholm School of Economics, Stockholm.

[30] Kypreos, S., Bahn, O. (2003). A MERGE model with endogenous technological progress. Environmental Modelling and Assessment 19, 333-358.

[31] Lee, J.-W. (1995). Capital goods import and long-run growth. Journal of Development Economics 48, 91-110.

[32] Leimbach, M. (2003). Equity and carbon emissions trading: a model analysis. Energy Policy 31, 1033-1044.

[33] Leimbach, M., Eisenack, K. (2009). A trade algorithm for multi-region models subject to spillover externalities. Computational Economics, Computational Economics 33, 107-130.

[34] Lessmann, K., Marschinski, R., Edenhofer, O. (2009). The Effects of Tariffs on Coalition Formation in a Dynamic Global Warming Game. Economic Modelling 26, 641-649.

[35] Löschel, A. (2002). Technological change in economic models of environmental policy: a survey. Ecological Economics 43, 105-126.

[36] Lumenga-Neso, O., Olarreaga, M., Schiff, M. (2005). On 'indirect' trade-related R&D spillovers. European Economic Review 49, 1785-1798.

[37] MacGarvie, M. (2005). The determinants of international knowledge diffusion as measured by patent citations. Economics Letters 87, 121-126.

[38] Manne, A.S., M. Mendelsohn, R. Richels (1995). MERGE - A Model for Evaluating Regional and Global Effects of GHG Reduction Policies. Energy Policy 23, 17-34.

[39] Meyer, A. (2000). Contraction & Convergence: the Global Solution to Climate Change. Schumacher Briefing No.5, Green Books Ltd., Foxhole.

[40] Nagashima, M., Dellink, R. (2008). Technology spillovers and stability of international climate coalitions. International Environmental Agreements: Politics, Law and Economics 8, 343-365.

[41] Nordhaus, W.D., Boyer, J. (2000). Warming the World: Economic Models of Global Warming. MIT Press, Cambridge, MA.

[42] Nordhaus, W.D., Yang, Y. (1996). A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies. American Economic Review 86, 741-765.

[43] Peters, G.P., Hertwich, E.G. (2008). CO_2 embodied in international trade with implications for global climate policy. Environmental Science and Technology 42, 1401-1407.

[44] Popp, D. (2006). Innovation in climate policy models: Implementing lessons from the economics of R&D. Energy Economics 28, 596-609.

[45] Rao, S., Peppo, I., Riahi, K. (2006). Importance of Technological Change and Spillovers in Long-term Climate Policy. Energy Journal, Special Issue #1, 123-139.

[46] Romer, P.M. (1990). Endogenous technological change. Journal of Political Economy 98, S71-S102.

[47] Takii, S. (2004). Productivity Differentials Between Local and Foreign Plants in Indonesian Manufacturing, 1995. World Development 32, 1957-1969.

[48] Verdolini, E., Galeotti, M. (2009). At Home and Abroad: An Empirical Analysis of Innovation and Diffusion in Energy-Efficient Technologies. Working Paper. FEEM Nota di Lavoro 123.2009, Fondazione Eni Enrico Mattei, Milan.

[49] Weber, C.L., Peters, G.P. (2009). Climate change policy and international trade: Policy considerations in the US. Energy Policy 37, 432-440.

[50] Xu, B., Wang, J. (1999) Capital Goods Trade and R&D Spillovers in the OECD. Canadian Journal of Economics 32, 1258-1274.

A Appendix A - Parameters, variables and scenarios

symbol	set/index
i, r	region
j	sector
m	production factor
t	time
z	time step, five years
τ	vintages of renewable

symbol	parameter
σ	discount rate
δ	depreciation rate
$\rho(i)$	substitution elasticity in consumption and investment goods sector
ρ_f	substitution elasticity in fossil energy sector
ξ_m	weight parameter for factor m in aggregated production function
ξ_m^f	weight parameter for factor m in fossil energy sector
$\Phi_j(i)$	total factor productivity in sector j in region i
$\mathcal{D}(i)$	primary energy efficiency in region i
$\zeta(i)$	productivity of labor-efficiency-augmenting R&D investments in region i
$\eta(i)$	productivity of energy-efficiency-augmenting R&D investments in region i
α	parameter of labor-efficiency-augmenting R&D function
β	parameter of energy-efficiency-augmenting R&D function
ψ	parameter of spillover function
Ω_m	spillover intensity
$\mathcal{K}_{max}(i,t)$	maximum productivity in extraction sector in region i at time t
$k(i,t)$	conversion coefficient in region i at time t
$\nu(i)$	inverse learning rate in resource sector in region i
μ	learning dampening factor
$\chi_1(i)$	parameter of marginal extraction cost curve in region i
$\chi_2(i)$	parameter of marginal extraction cost curve in region i
$\chi_3(i)$	parameter of marginal extraction cost curve in region i
χ_4	parameter of marginal extraction cost curve
$l(t)$	load factors of vintages for renewable energy production
$w(\tau)$	weights for vintages for renewable energy production
$fC(i)$	floor investment costs of vintages in region i
$\gamma(i,t)$	learning parameter in renewable energy sector in region i at time t
λ	learning rate in renewable energy sector

symbol	control variable
θ_m, j	share of factor m in sector j
$rd_L(i,t)$	R&D investments in labor efficiency in region i at time t
$rd_E(i,t)$	R&D investments in energy efficiency in region i at time t
$I_j(i,t)$	investment in sector j in region i at time t
$X_I(i,r,t)$	export of investment goods from region i to region r at time t
$X_C(i,r,t)$	export of consumption goods from region i to region r at time t
$X_Q(i,r,t)$	export of resources from region i to region r at time t
$X_P(i,r,t)$	export of emission permits from region i to region r at time t

symbol	state variable
$K_j(i,t)$	capital stock of sector j in region i at time t
$\mathcal{A}_L(i,t)$	labor efficiency in region i at time t
$\mathcal{A}_E(i,t)$	energy efficiency in region i at time t
$cQ(i,t)$	cumulative resource extraction in region i at time t
$\mathcal{K}(i,t)$	production factor of extraction sector in region i at time t
$V(i,t)$	vintage of renewable energy capacities in region i at time t
$\kappa(i,t)$	variable investment costs of vintages in region i at time t
$cN(i,t)$	cumulative installed capacity in region i at time t

symbol	other variable
W	welfare
$C(i,t)$	consumption in region i at time t
$L(i,t)$	labor in region i at time t - exogenous
$E(i,t)$	total energy in region i at time t
$Y_C(i,t)$	output in consumption goods sector in region i at time t
$Y_I(i,t)$	output in investment goods sector in region i at time t
$I(i,t)$	total investment in region i at time t
$sp_L(i,t)$	spillover in labor efficiency to region i at time t
$sp_E(i,t)$	spillover in energy efficiency to region i at time t
$I_{nf}(i,t)$	investm. in other energy sector in region i at time t - exogenous
$E_f(i,t)$	fossil energy in region i at time t
$E_{ren}(i,t)$	renewable energy in region i at time t
$E_{nf}(i,t)$	energy from other energy sources in region i at time t
$PE(i,t)$	fossil primary energy in region i at time t
$mC(i,t)$	marginal extraction costs in region i at time t
$Q(i,t)$	resource extraction in region i at time t
$EM(t)$	global CO2 emissions at time t
$P(i,t)$	emission permits in region i at time t - exogenous
$p_j(t)$	world market price (net present value) of good j r at time t

symbol	scenario
BAU	business as usual without spillovers
BAU-S	business as usual with spillovers
BAU-ex	bussiness as usual with exogenous technological change
BAU-H	business as usual with spillovers; high energy-efficiency spillovers
BAU-H-ex	bussiness as usual with exog. techn. change; high energy-efficiency spillovers
COP	Co-operative policy scenario without spillovers
COP-S	Co-operative policy scenario with spillovers
COP-ex	Co-operative policy scenario with exogenous technological change
COP-H	Co-operative policy scenario with spillovers; high energy-efficiency spillovers
COP-H-ex	Co-op. pol. scenario with exog. techn. change; high energy-efficiency spillovers
NoCH-0	China is not part of the policy regime; no energy-efficiency-enhancing spillovers
NoCH-25	like NoCH-0; labor-productivity-enhancing spillovers reduced by 25%
NoCH-50	like NoCH-0; labor-productivity-enhancing spillovers reduced by 50%

B Appendix B - Energy sector equations

B.1 Final energy sector

The fossil, renewable and remaining energy production sectors deliver final energy

$$E(i,t) = E_f(i,t) + E_{ren}(i,t) + E_{nf}(i,t). \tag{12}$$

In the fossil energy sector, final energy is generated according to the following CES production function (with the production factors capital K_f and primary fossil energy *PE*):

$$E_f(i,t) = \Phi_f(i)[\xi^f_K K_f(i,t)^{\rho_f} + \xi^f_{PE}(\mathcal{D}(i) \cdot PE(i,t))^{\rho_f}]^{\frac{1}{\rho_f}} \tag{13}$$

In the renewable sector, final energy is produced based on the active vintages *V* and the respective load factors *l*:

$$E_{ren}(i,t) = \sum_{\tau} l(t-\tau) \cdot V(i,t-\tau) \cdot w(\tau). \tag{14}$$

w is a weighting factor that represents the still active part of the vintages. Each vintage is a function of the investments I_{ren} (see Eq. 21) and considered to exist over τ time steps.

The remaining energy sector provides energy E_{nf} from nuclear power, hydro power and traditional biomass sources. Its future supply is given exogenously [7].

B.2 Fossil resource extraction sector

Primary fossil energy is produced from energy resources *Q* and net resource imports X_R:

$$PE(i,t) = k(i,t) \cdot [Q(i,t) - \sum_r (X_Q(i,r,t) - X_Q(r,i,t))]. \tag{15}$$

k represents a conversion factor that converts carbon into Joule. The extraction of fossil resources is restricted by the capacity constraint

$$Q(i,t) \cdot mC(i,t) = \mathcal{K}(i,t) \cdot K_Q(i,t). \tag{16}$$

mC denotes the marginal cost of extraction (i.e. the price of resources) and $\mathcal{K}$ represents the productivity of the capital stock in the extraction sector. The marginal cost of extraction are derived from the so-called Rogner curve

$$mC(i,t) = 1 + \frac{\chi_2(i)}{\chi_1(i)} \left(\frac{cQ(i,t)}{\chi_3} \right)^{\chi_4}. \tag{17}$$

The cumulative amount of extraction *cQ* is given by

$$cQ(i,t+1) = cQ(i,t) + z \cdot Q(i,t). \tag{18}$$

The productivity of the capital stock in the extraction sector is subject to learning-by-doing and evolves according to:

$$\mathcal{K}(i,t{+}1) = \mathcal{K}(i,t) \left[1 + (\mathcal{K}(i)_{max} - \mathcal{K}(i,t)) \left(\frac{z \cdot \nu(i)}{\mathcal{K}(i)_{max}} \left(\left(\frac{Q(i,t)}{Q(i,0)} \right)^{\mu} - 1 \right) \right) \right]. \tag{19}$$

Total anthropogenic CO_2 emissions sum up CO_2 emitted by burning fossil fuels and emissions from land-use change:

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[7] The global value of the production of the remaining energy sector used in MIND is distributed according to the regional shares of this kind of energy consumption in the CPI baseline scenario.

$$EM(t) = \sum_i Q(i,t) + LU(t). \tag{20}$$

Q represents the carbon content of extracted fossil fuels.

B.3 Renewable energy sector

Vintage capital *V* is built up by investments and transformed into capacity units by taking the floor costs *fC* and the variable investment costs κ into account:

$$V(i,t+1) = z \cdot \frac{I_{ren}(i,t)}{fC(i) + \kappa(i,t)}. \tag{21}$$

Similar to the extraction sector, endogenous technological change takes place in the renewable energy sector. Based on the cumulated installed capacity *cN*, with

$$cN(i,t) = cN(i,t-1) + V(i,t), \tag{22}$$

productivity of the renewable energy sector changes:

$$\kappa(i,t) = \kappa(i,0) \cdot \left(\frac{cN(i,t)}{cN(i,0)}\right)^{-\gamma(i)}. \tag{23}$$

C Appendix C - equations of calibration

The first-order partial derivatives of the production function for consumption goods Y_C are

$$\frac{\partial Y_C}{\partial L} = \Phi_C^\rho \xi_L \theta_{L,C}^\rho \mathcal{A}_L^\rho L^{\rho-1} Y_C^{1-\rho}, \tag{24}$$

$$\frac{\partial Y_C}{\partial E} = \Phi_C^\rho \xi_E \theta_{E,C}^\rho \mathcal{A}_E^\rho E^{\rho-1} Y_C^{1-\rho} \tag{25}$$

and

$$\frac{\partial Y_C}{\partial K_C} = \Phi_C^\rho \xi_K K_C^{\rho-1} Y_C^{1-\rho}. \tag{26}$$

So the income shares are

$$\begin{aligned}
\frac{\partial Y_C}{\partial L}\frac{L}{Y_C} &= \Phi_C^{\rho}\xi_L\theta_{L,C}^{\rho}\mathcal{A}_L^{\rho}\left(\frac{L}{Y_C}\right)^{\rho} \\
\frac{\partial Y_C}{\partial E}\frac{E}{Y_C} &= \Phi_C^{\rho}\xi_E\theta_{E,C}^{\rho}\mathcal{A}_E^{\rho}\left(\frac{E}{Y_C}\right)^{\rho} \\
\frac{\partial Y_C}{\partial K_C}\frac{K_C}{Y_C} &= \Phi_C^{\rho}\xi_K\left(\frac{K_C}{Y_C}\right)^{\rho}.
\end{aligned} \tag{27}$$

This can be used for the calibration. Given are the start values Y_{C0}, L_0, E_0, K_{C0}, then it should be

$$\begin{aligned}
&\frac{\partial Y_C}{\partial K_C}\frac{K_C}{Y_C} = \Phi_C^{\rho}\xi_K\left(\frac{K_C}{Y_C}\right)^{\rho} = \xi_K \\
&\Rightarrow \Phi_C^{\rho}\left(\frac{K_C}{Y_C}\right)^{\rho} = 1 \quad \rightarrow \Phi_C = \frac{Y_{C0}}{K_{C0}}
\end{aligned} \tag{28}$$

$$\begin{aligned}
&\frac{\partial Y_C}{\partial L}\frac{L}{Y_C} = \Phi_C^{\rho}\xi_L\theta_{L,C}^{\rho}\mathcal{A}_L^{\rho}\left(\frac{L}{Y_C}\right)^{\rho} = \xi_L \\
&\Rightarrow \Phi_C^{\rho}\theta_{L,C}^{\rho}\mathcal{A}_L^{\rho}\left(\frac{L}{Y_C}\right)^{\rho} = 1 \quad \rightarrow \mathcal{A}_{L0} = \frac{Y_{C0}}{\theta_{L,C}L_0\Phi_C} = \frac{K_{C0}}{\theta_{L,C}L_0}
\end{aligned} \tag{29}$$

$$\begin{aligned}
&\frac{\partial Y_C}{\partial E}\frac{E}{Y_C} = \Phi_C^{\rho}\theta_{E,C}^{\rho}\mathcal{A}_E^{\rho}\xi_E\left(\frac{E}{Y_C}\right)^{\rho} = \xi_E \\
&\Rightarrow \Phi_C^{\rho}\theta_{E,C}^{\rho}\mathcal{A}_E^{\rho}\left(\frac{E}{Y_C}\right)^{\rho} = 1 \quad \rightarrow \mathcal{A}_{E0} = \frac{Y_{C0}}{\theta_{E,C}E_0\Phi_C} = \frac{K_{C0}}{\theta_{E,C}E_0}
\end{aligned} \tag{30}$$

The same applies for Y_I.

D Appendix D - Sensitivity Analysis

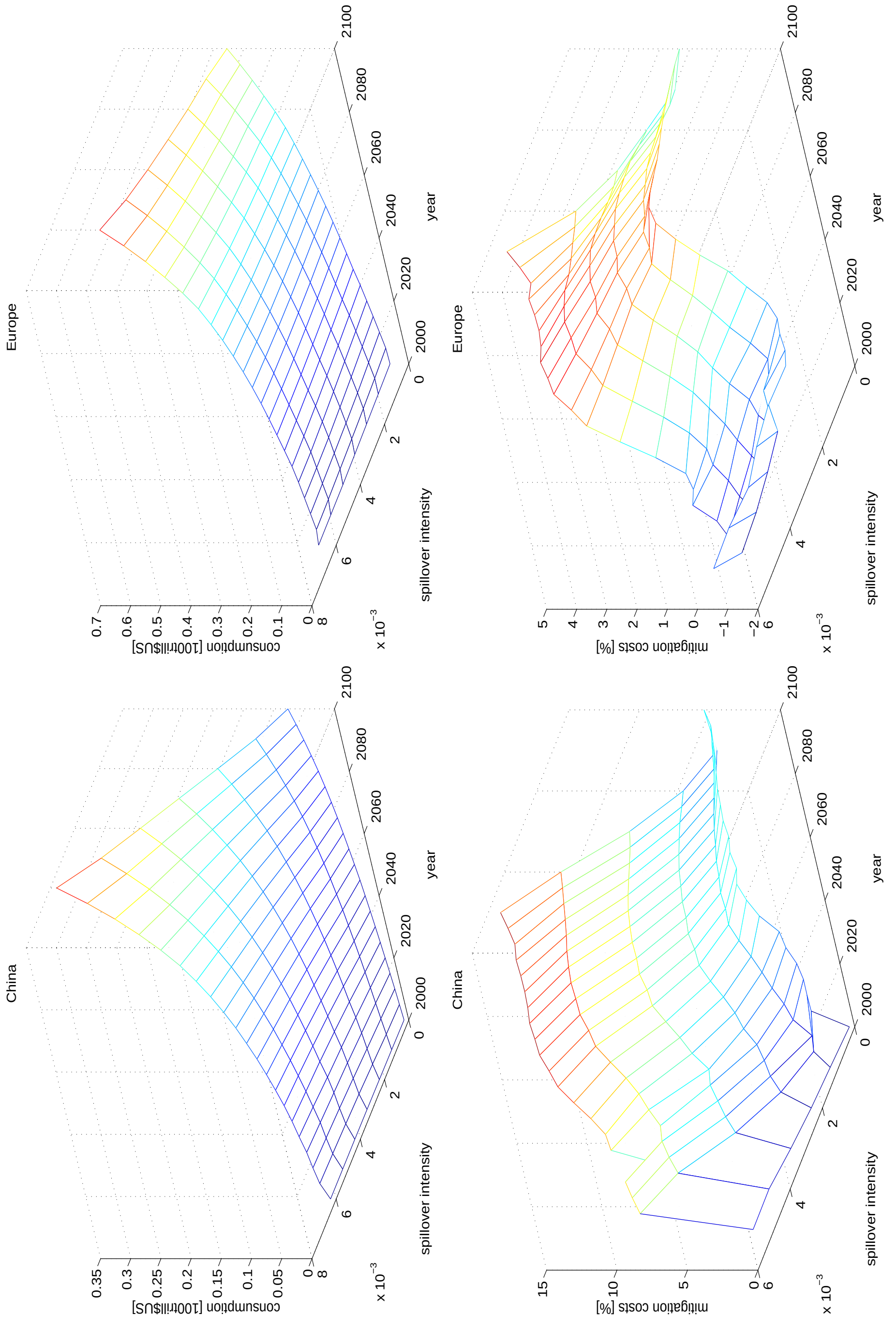

Figure 11: Sensitivity of consumption and mitigation costs to spillover intensity

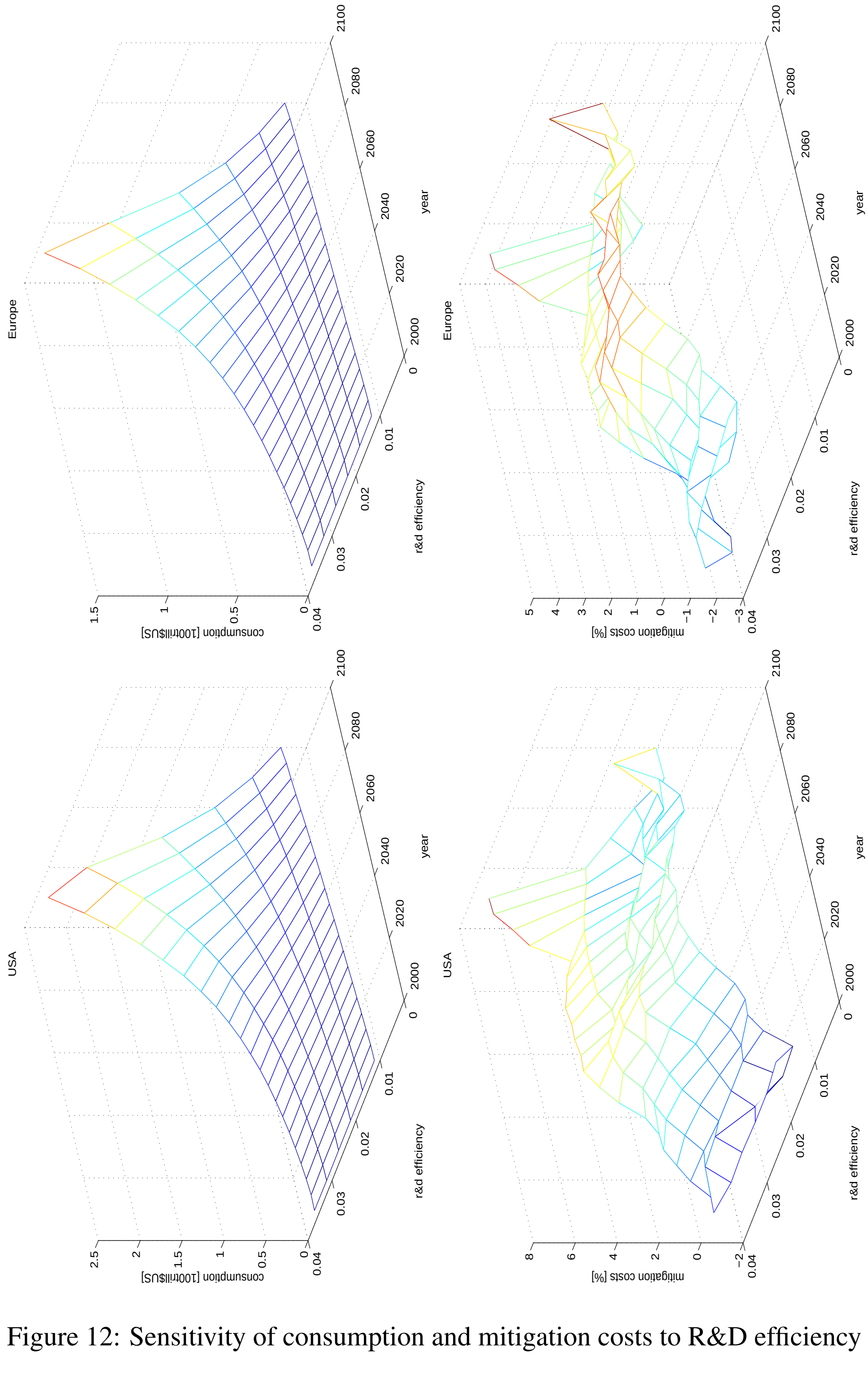

Figure 12: Sensitivity of consumption and mitigation costs to R&D efficiency