The impact of capital trade and technological spillovers on climate policies: model analysis with REMIND-S

Marian Leimbach[*], Lavinia Baumstark

April 30, 2007

Abstract

Within this paper, we analyze climate policy scenarios within a globalized world characterized by the existence of technological spillovers. Technological spillovers are bound to capital trade. To our knowledge, this is the first application of a model with embodied technological spillover in a climate policy context. The technical details of the model - REMIND-S - will be presented. In this study REMIND-S is calibrated for a 4-region world distinguishing China, USA, Europe and ROW. Technological spillovers shift trade patterns and terms-of-trade. The definition of climate policy scenarios is based on the EU target of 2°C. In simulating co-operative and fragmented policy regimes it turns out that there is a strong incentive for China to join a climate policy regime. The latter will slightly favor regions that are forerunners in using climate-friendly technologies.

JEL classification: O41;F17;F43;C68;O39
keywords: climate policy, multi-region model, technological spillovers, international trade, emissions trading

[*]PIK - Potsdam Institute for Climate Impact Research, P.O. Box 60 12 03, D-14412 Potsdam, Germany, Tel. ++49/331/288-2566, e-mail: leimbach@pik-potsdam.de

1 Introduction

Starting with such diverse models like DICE (Nordhaus, 1992) and IMAGE (Alcamo et. al., 1994), climate policies and the integrated assessment of climate change are supported by a rising number of tools. Over the last decade, climate policy models were improved in different directions, e.g. multi-region models and multi-gas analyses, integration of energy system models, and integration of endogenous and induced technological change.

However, climate policy modeling fails to take essential interregional effects into account, in particular foreign investments. This, on the one hand, reflects general deficiencies of the economic theory in dealing with regional interactions in a dynamic framework, on the other hand, in view of the role foreign investments play in a globalized world and may play in dealing with the climate change problem. Main climate change mitigation options will affect the energy system. International experts expect investments into the energy systems worldwide to amount to around 16 trillion dollars over the next 30 years (IEA, 2003). 10 trillion dollars alone will be invested into the electricity sector, mainly in China, India, and Africa. As for Africa, these investments would consume half of the domestic savings. Hence, enormous foreign direct investments will be needed. Moreover, pursuing to restructure the energy system in a climate-friendly way results in scenarios that are dominated by investments into the renewable energy sector and other carbon-free technology options. This implies huge foreign investments, because those regions that host the innovators of, for instance, new solar energy technologies, do not correspond with those regions where the solar power plants should be build-up.

Within the discussion about promising climate protection strategies, technological spillovers come to the fore. Recent literature (Blomström et al., 1999; Hejazi and Safarian, 1999) identified a strong link between foreign investments (i.e. trade in investment goods or foreign direct investments) and spillovers. Spillovers could make the difference that helps investors of new energy technologies to break even and can make it profitable for single regions to become forerunners in climate policy.

This paper presents a model that allows to analyse climate policy scenarios. In particular, it shall help to indicate the change of international burden sharing in the presence of capital trade and technological spillovers. In this study, technological spillovers refer to situations where the presence of physical capital, produced abroad, affects efficiency or productivity levels of the host economy. In the implemented model two spillover channels are considered - increasing labour productivity and energy efficiency.

The paper is structured as follows. In section 2 we present a multi-region climate policy model. It contains a macroeconomic system and an energy system part. Both include elements of endogenous technological change. We calibrated this model for the 4 world regions Europe, USA, China and the rest of the world (ROW). In section 3 we define different climate policy scenarios. The basic cooperative policy scenario aims to keep the increase of the global mean temperature below 2°C above the preindustrial level and is based on international emissions trading regime that follows the contraction and convergence principle. A comprehensive discussion of the results from different model runs is given in section 4. We end with some conclusions in section 6.

2 REMIND-S

REMIND-S is the first product of the REMIND model family developed at the Potsdam Institute for Climate Impact Research. REMIND-S is a multi-region model based on the global Integrated Assessment model MIND (Edenhofer et al., 2005). REMIND-S adopts from MIND (version 1.1) the structure of the energy system (except for the carbon capturing 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, REMIND includes technological spillovers. Unlike MIND, REMIND separated the aggregated industrial sector into a consumption goods/service sector and an investment goods sector. Moreover, REMIND takes trade interactions into account. Trade flows represent control variables in addition to investments. Trade flows are only bound to an intertemporal budget constraint. Figure 1 shows the macroeconomic system of REMIND-S which includes most of the new features.

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

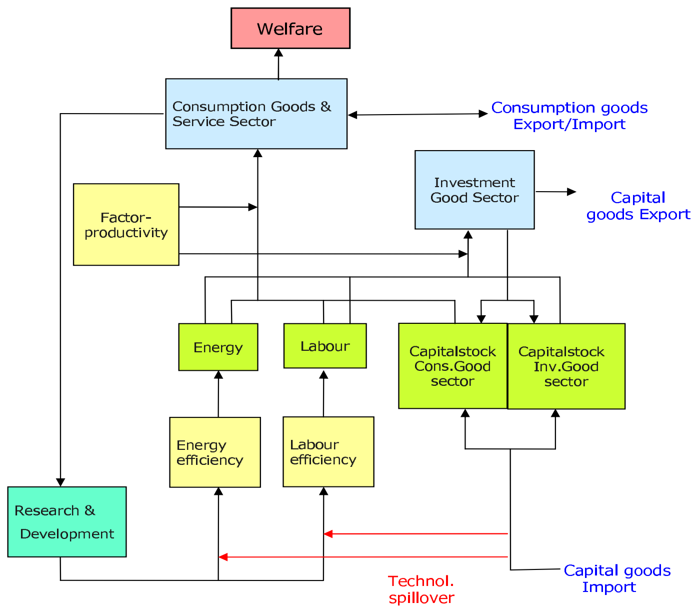

Figure 1: Structure of the macroeconomic system of REMIND-S

2.1 Technical description

In addition to some explanation of 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		tradeable goods/sectors,
k	K,L,E	production factors.

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

C	consumption good,
I	investment good,
Q	fossil energy resources/extraction sector,
P	emission permits,
f	fossil energy sector,
ren	renewable energy sector,
nf	other energy sector.

Capitals from the above list simultaneously represent indices as well as corresponding variables. This also applies to the production factors labour (L), capital (K) and 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 suppress the region index of the parameters and use the 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 of the multi-region model is to maximize the welfare *W*

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

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. The production function Y_C for the consumption goods and service sector is specified as CES function (with elasticity of substitution parameter ρ_C and share parameters ξ_k):

$$\begin{aligned} Y_C(i,t) =& \Phi_C(i)[\xi_K K_C(i,t)^{\rho_C(i)} + \xi_L((1-\theta_L(i,t))\mathcal{A}(i,t)L(i,t))^{\rho_C(i)} \\ &+ \xi_E((1-\theta_E(i,t))\mathcal{B}(i,t)E(i,t))^{\rho_C(i)}]^{\frac{1}{\rho_C(i)}}, \end{aligned} \tag{2}$$

and the production function for investment goods sector as Cobb-Douglas function:

$$Y_I(i,t) = \Phi_I(i)[K_I(i,t)^{\xi_K} \cdot (\theta_L(i,t)\mathcal{A}(i,t)L(i,t))^{\xi_L} \cdot (\theta_E(i,t)\mathcal{B}(i,t)E(i,t))^{\xi_E}]. \tag{3}$$

Φ represents the total factor productivity, *K* the capital stock, $\mathcal{A}$ the labour efficiency, $\mathcal{B}$ the energy efficiency and *E* the energy input. θ_k represents the share of the respective production factor in the investment goods sector. The efficiency variables $\mathcal{A}$ and $\mathcal{B}$ are subject to R&D investments *rd* and technological spillovers *sp* as described by equation

$$\dot{\mathcal{A}}(i,t) = \zeta(i)\left(\frac{1}{0.025}\right)^{\alpha}\left(\frac{rd_{\mathcal{A}}(i,t)}{Y_C(i,t)+Y_I(i,t)}\right)^{\alpha}\mathcal{A}(i,t) + sp_L(i,t) \tag{4}$$

and

$$\dot{\mathcal{B}}(i,t) = \eta(i)\left(\frac{1}{0.01}\right)^{\beta}\left(\frac{rd_{\mathcal{B}}(i,t)}{Y_C(i,t)+Y_I(i,t)}\right)^{\beta}\mathcal{B}(i,t) + sp_E(i,t). \tag{5}$$

Technological spillovers may increase labour efficiency and energy efficiency. These spillover effects are induced by capital imports $X_I(r,i)$ from region *r* to region *i*, but take only effect if $A_i{<}A_r$ and $B_i{<}B_r$, respectively.

Following Leimbach and Eisenack (2007) we define the spillover functions

$$sp_L(i,t) = \sum_r \frac{X_I(r,i,t)}{K_I(i,t)}^{\psi}\Omega(\mathcal{A}(r,t)-\mathcal{A}(i,t)) \tag{6}$$

and

$$sp_E(i,t) = \sum_r \frac{X_I(r,i,t)}{K_I(i,t)}^{\psi}\Omega(\mathcal{B}(r,t)-\mathcal{B}(i,t)), \tag{7}$$

where Ω describes the spillover intensity and ψ the elasticity between foreign investments and technological spillovers.

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:

$$Y_C(i,t) = C(i,t) + \sum_r X_C(i,r,t) - \sum_r X_C(r,i,t) + rd_{\mathcal{A}}(i,t) + rd_{\mathcal{B}}(i,t). \tag{8}$$

Imports of goods from region *r* to region *i* ($X_C(r,i)$) relax this constraint. For transparency reasons we omit trading costs, which actually are assigned to all import variables. 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 ($X_I(i,r)$):

$$
\begin{aligned}
Y_I(i,t) = & I_C(i,t) + I_I(i,t) + I_{nf}(i,t) + I_f(i,t) + I_{res}(i,t) + I_{ren}(i,t) \\
& + \sum_r X_I(i,r,t) - \sum_r X_I(r,i,t).
\end{aligned} \tag{9}
$$

Capital accumulation in all sectors besides the renewable energy sector follow the standard equation of capital stock formation

$$\dot{K}_j(i,t) = I_j(i,t) - \delta_j(i) \cdot K_j(i,t). \tag{10}$$

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

$$E(i,t) = E_f(i,t) + E_{ren}(i,t) + E_{nf}(i,t). \tag{11}$$

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*):

$$E_f(i,t) = \Phi_f(i)[\xi_K^f K_f(i,t)^{\rho_f} + \xi_{PE}^f (\mathcal{D} \cdot PE(i,t))^{\rho_f}]^{\frac{1}{\rho_f}} \tag{12}$$

In modelling the renewable energy sector, the concept of vintage capital is applied. Final energy is generated based on the active vintages *V* and the respective load factors *l*:

$$E_{ren}(i,t) = \sum_\tau l(t-\tau) \cdot V(i,t-\tau) \cdot w(\tau). \tag{13}$$

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 equ. 22 in Appendix B) and considered to exist over τ time steps.

The other energy sector provides energy E_{nf} from nuclear, hydro power and traditional biomass sources. Its future supply is given exogenously. More details about the renewable energy sector and the fossil extraction sector are described in Appendix B.

The carbon content of extracted fossil fuels *Q* are linked, on the one hand, to the primary energy *PE* and, on the other hand, to the amount of CO_2 emitted by burning fossil fuels. Emissions from land use change are added to get total global anthropogenic CO_2 emissions

$$EM(t) = \sum_i Q(i,t) + LU(t). \tag{14}$$

Within an international climate policy regime, we assume that each region is allocated with an amount of emission permits *P*. For each unit of fossil resources which a region converts 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

$$Q(i,t) + \sum_r (X_R(r,i,t) - X_R(i,r,t)) \leq P(i) + \sum_r (X_P(r,i,t) - X_P(i,r,t)) \tag{15}$$

where X_R 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 approach as presented by Leimbach and Eisenack (2007). In assuming that the technological spillovers 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 is an interplay 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 region's welfare functions are combined by a set of welfare weights. This Social Planner model derives the optimal trade structure for the given set of welfare weights. Within an iterative approach, this set is adjusted according to the deviation of each region from its intertemporal budget constraint.

2.2 Empirical foundation

The empirical foundation of REMIND-S starts from calibration results of the global model MIND. Part of the model parameters are adopted directly, others needed to be regionalized. The calibration is done for the 4 world regions Europe, China, USA and rest of the world (ROW).

Major data sources of REMIND-S 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

GDP data for the base year 2000 are taken from GTAP6 and are nearly the same in the WDI database. An exogenous population scenario (until 2100) is taken from the CPI database. The sectoral output for the two industrial production sectors as well as the initial division of the capital stock (again GTAP-based) is conditioned by the consumption-investment-ratio that is given in the PWT database (see Table 1). Deriving sound initial values for the capital stocks in the different energy sectors is most difficult because a lack of appropriate data. In aggregating sectoral information from GTAP6 we derived estimates that in the sum were significantly lower then the MIND value and result in extreme adjustments of capital stocks in the first simulation periods. Therefore, we only apply the regional shares on the global sectoral capital stocks as derived from GTAP and adjust the absolute level in order to avoid extreme model behaviour. The used values are shown in Table 1.

With respect to the parameters of the production functions we stick to the MIND values in general. However, following findings in the international literature (cf. Bernstein and Rutherford, 1999) we differentiate between a somewhat higher elasticity of substitution (0.4) between the production factors in the aggregated industrial sector in the industrialized world regions Europe and USA and a somewhat lower value (0.3) in the other two regions. Share parameters are assumed to be the same in 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. This is in accordance with MIND. With the elasticity and share parameters given, we are able to compute the initial efficiency and productivity parameters (see Appendix C for the derivation of the calibration formula). These values are shown in Table 2. Again, they are the same for both industrial sectors. China exhibits a remarkable 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.

Initial values for the energy production in the different energy sectors are taken from IEA database and from CPI database. For the production of the other energy sector an exogenous scenario is given (WBGU scenario). The global value used in MIND is distributed according to the regional shares of this kind of energy consumption in the CPI baseline scenario. The CPI database provides also CO_2 emissions for the base year (see Table 1). Initial resource extraction is derived from the emission data by using the carbon content coefficient of MIND.

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
capital stock in fossil energy sector (trill. $US)	1.4	1.6	0.27	2.8
capital stock in extraction sector (trill. $US)	1.1	1.4	0.22	1.8
invest. cost renewable energy sector ($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
factor productivity (consumption goods sector)	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
factor productivity (fossil energy sector)	3.12	3.82	13.0	3.55

Initial trade data are derived from WDI (export of consumption goods) and from IEA's World Energy Outlook (2006) for consumption goods export and resources export, respectively.

Particular attention was paid to the calibration of the parameters of the carbon wealth curve and the learning curves in the renewable sector. As to the carbon wealth curve (see equ. 19 in Appendix B), we adjusted the χ_4 parameter such that the regional values reflect expected scarcities and sum up to the global value of 3500 GtC. The division follows the IEA World Energy Outlook (2002) from which we derive the shares of around 10%, 20%, 10% and 60% for Europe, USA, China and ROW, respectively.

Confronted with the learning curve parameters in the renewable energy sector, it turned out that regional specification becomes tricky. First, we had to allow for different stages in progressing on the learning curve. In contrast to the global learning curve, this could not be taken into account by simply counting the installed capacities in the renewable sector. Scale differences matter. Therefore we used the total energy production as a normalization factor. That gives us a fictitious standard cumulated capacity. Based on the learning curve function (see equ. 24 in Appendix B), this standard cumulated capacity *SCC(i)*, the current deviation from this value $\Delta(i)$, learning rate $\gamma(i)$, and the global value of the investment cost parameter κ we can derive the adjusted initial values of the investment cost $\kappa(i,0)$ by

$$\kappa(i,0) = \left(1 - \frac{\Delta(i)}{SCC(i)} \cdot \gamma(i)\right) \cdot \kappa. \tag{16}$$

The learning rate $\gamma(i)$ is assumed to be constant over time. This is a simplification. Even if the same learning rate can be assumed for each renewable energy technology, the different progress of each technology on the learning curve causes an additional unit of hydro power capacity to bear another learning effect than an equal incremental unit in solar power technology. Hence, a constant learning rate assumes a constant composition of the renewable energy sector. Moreover, taking the current decomposition of the renewable sector into account results in regionally differentiated learning rates. Regions (e.g. Europe) that have a higher share of wind power or even solar power are endowed with higher learning rates. The derived initial values for investment costs and the learning rates in the renewable energy sector are shown in Table1.

Although the body of empirical research on spillover externalities has grown rapidly, data are restricted to case studies mostly on the level of firms. A majority of studies indicate positive spillover effects from foreign investments (Lee, 1995; Takii, 2004; Jordaan, 2005). We selected a value for the spillover intensity that in the baseline scenario contributes to 10% of productivity growth on the global level. That is in the range indicated by Kokko (1993, p.160ff).

Based on initial data and calibration we generate a baseline scenario that serve as benchmark for the evaluation of a set of policy scenarios. We distinguish two types of baseline scenarios. On the one hand, a baseline scenario that assumes a world in which technological spillover exist, on the other hand, a baseline scenario that neglects the presence of technological spillovers. While technological spillover represents a kind of endogenous technical change, we did not compensate the non-spillover scenario by increasing some exogenous technology parameter, i.e. a fundamentally different dynamics can be expected in both sceanrios.

The difference between both baseline scenarios is most significant for China. China benefits most from technological spillover with a strong accelerating impact on economic dynamics. Simultaneously energy consumption and emissions are much higher in the presence of technological spillovers. Compared to recent historic developments, the spillover baseline scenario turns out to match the empiric dynamics much better then the non-spillover scenario.

Baseline emissions are quite high, in particular for USA when compared to other studies. This is accompanied by an extensive use of fossil energy resources. At the very end of the century renewable energies would penetrate the market, when either fossil resources are exhausted in some regions or extraction costs increase dramatically.

3 Policy scenario

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 commission of keeping global mean temperature increase below 2°C, the policy scenarios frame the search for optimal mitigation policies. Technically, we used the optimal emission path that keep the above climate goal within a model run with the global model MIND. This global emission path is interpreted as the amount of emission permits that can be allocated between the 4 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 then both other regions. 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 that will keep the 2°C temperature target. This target, however, can only be met within a policy scenario that represents a co-operative (social optimum) solution. We formulate a second and third alternative policy scenario representing fragmented policy regimes. We consider the possibility that either the USA or China will not join the great 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. Emission trading is allowed between all partners in the coalition, whereas the region outside the coalition is excluded from emissions trading. In addition, 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 by 50%. This is a rather extreme scenario, but it reflects the idea of combining a climate policy regime with a technological protocol and some kind of trade sanctions.

Trade exists in consumptions goods, investment goods, fossil resources and emission permits. Subject to an intertemporal trade balance, trade decisions are endogenous with two exceptions that simultaneaously restrict the degree of freedom and avoid unplausible trade flows. We assume that USA, Europe and China are net importers of resources over the entire time horizon and China and ROW are net importers of investment goods.

Finally, in taking recent policy efforts into account, we assume Europe to adopt a policy in support for renewable energy technologies. This is implemented as a lower bound on new vintages build up in the renewable energy sector. Starting from the initial value, this lower bound increases with 2% annually. On the other hand, we restrict the increase of new vintages in the renewable sector to 3% anually in the long run in order to avoid unplausible speed of market penetration. Initially, higher growth rates are possible. The use of renewable energy technologies represent the major mitigation option within the modeled system.

In summary, we investigate the impact of three policy scenarios. For each of these scenarios we distinguish the spillover and the non-spillover case. In total, this provides us with two baseline scenarios and 6 policy scenarios:

- BAU - business as usual
- BAU-S - business as usual with spillover
- CON - Co-operative policy scenario
- CON-S - Co-operative policy scenario with spillover
- No-US - USA is not part of the policy regime
- No-US-S - USA is not part of the policy regime with spillover
- No-CH - China is not part of the policy regime
- No-CH-S - China is not part of the policy regime with spillover.

4 Policy analysis

While we consider the spillover scenarios as more appropriate then the non-spillover scenarios, we use the latter for methodological reasons. Based on the comparison of both types of scenarios, we will get some insights about the value added by integrating a rather complex issue like technological spillovers.

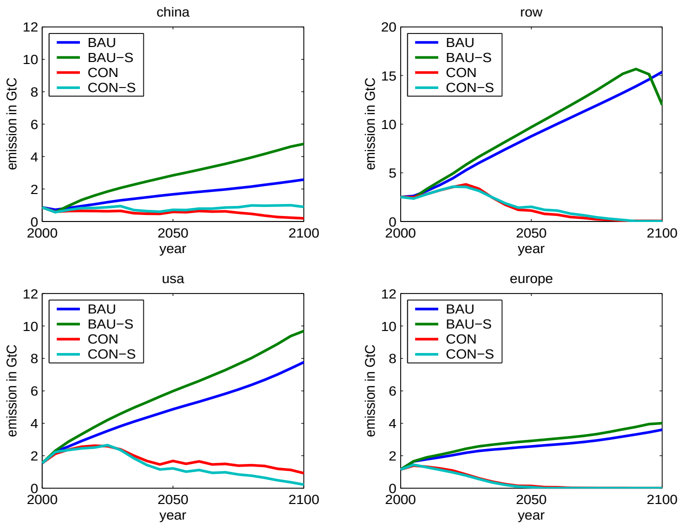

Figure 2: Optimal CO_2 emissions

Starting with the co-operative solution, Fig. 2 shows the optimal emission trajectories of the 4 regions for selected scenarios. Emission gaps between the baseline trajectory and the optimal policy path are huge. Emissions have to be reduced by 50% in 2050 globally, with Europe demonstrating the most rapid reduction. China grows with a higher rate in the spillover scenario. This increases the energy demand of China (see Figs. 3 and 4). While an increasing share of this demand is met by renewable energy, a certain amount is based on fossil fuels even in the second half of the century. With China as competitive consumer on the resource market, the USA reduces its energy demand slightly.

Most important variables within this analysis are the mitigation costs, characterizing the burden sharing between the world regions. 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

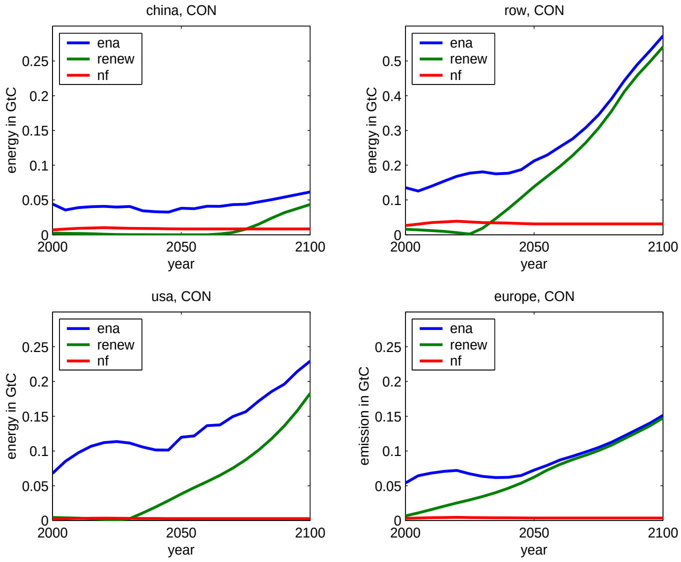

Figure 3: Energy consumption (non-spillover scenario)

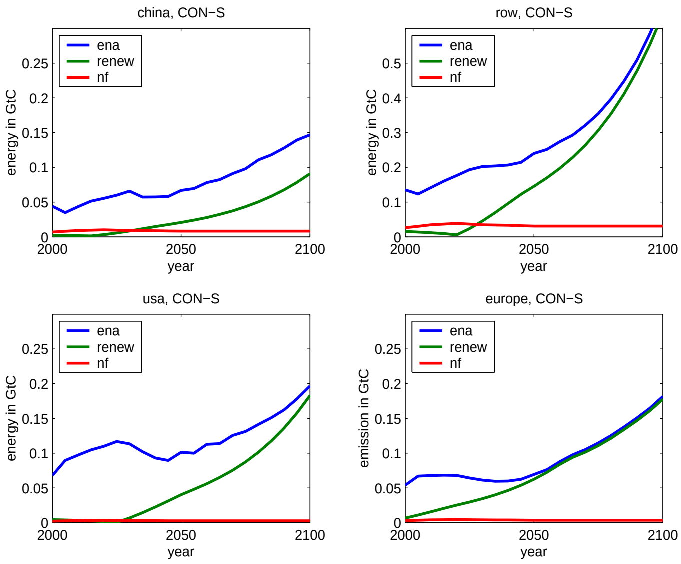

Figure 4: Energy consumption (spillover scenario)

gains when the policy scenario is compared with a reference scenario that includes climate damages. Regional interactions bear the most significant impact on the mitigation costs. While already free trade smoothes regional differences (China and USA benefit most from trade), technological spillovers equalize mitigation costs additionally (see Fig. 5). China faces the highest cost in the co-operative policy scenarios (around 4% in average). Capacities in the renewable energy sector cannot be built up as fast as energy demand increases or are quite expensive. Europe faces the lowest cost (around 1% in average). Across all regions, between 10% and 30% of the mitigation costs can be saved by emissions trading (see Fig. 6).

Absolute volumes of permits traded are shown in Fig. 7. USA buys permits over the whole time horizon. The peak is around 1.7 GtC in 2025. ROW sells permits of around 1 GtC over the whole time span. China starts as an seller, but becomes increasingly a buyer of emission permits. The opposite applies to Europe. Permit exports of Europe represent, however, only a small volume.

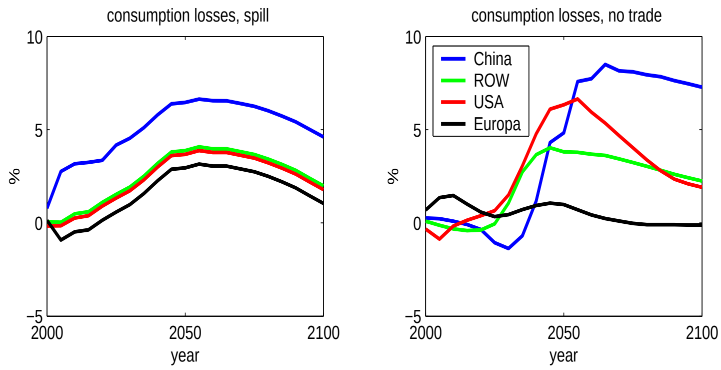

Figure 5: Mitigation costs in CON-S scenario

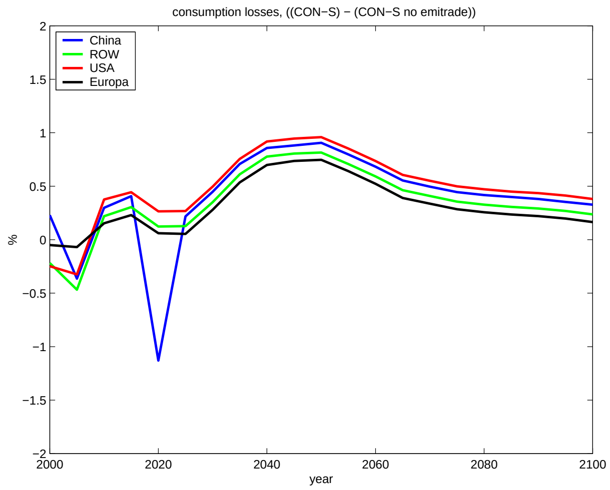

Figure 6: Gains from emissions trading

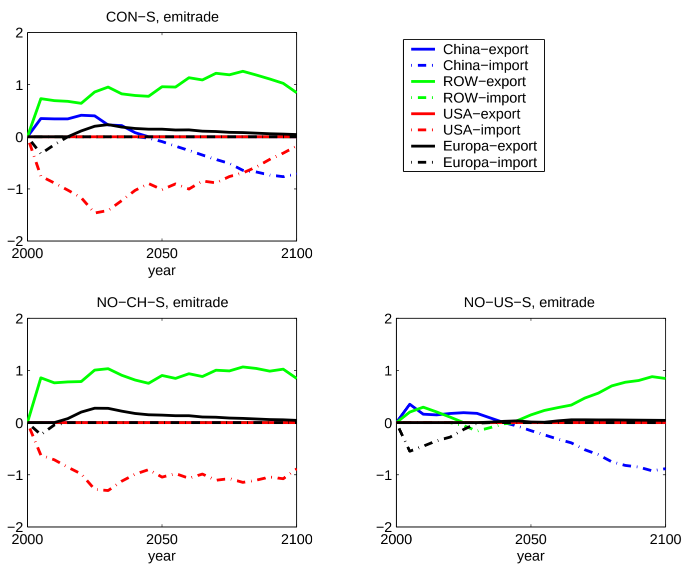

Figure 7: Flow of emission permits

Before we analyze the results from model runs which assume a fragmented climate policy regime, we want to discuss some trade-related aspects of the co-operative solution. First, we observe that including spillover effects overall trade flows increase. Second, trade flows are quite robust, i.e there are similar trade patterns within the baseline and the policy scenarios. The only exception is trade in fossil resources. Due to the impact of a limited number of emission permits the use of fossil fuels (including imported ones) in energy production is restricted. In general, Europe and USA represent importers of consumption goods and exporters of investment goods (see Fig. 8). The opposite applies to ROW and China. ROW, in addition, exports resources to all other regions. Despite of the similar trade pattern, some changes can be observed comparing the co-operative policy scenario with the baseline scenario. Total export in investment goods decreases slightly (see Fig. 9). Since all regions are subject to an intertemporal budget constraint, this decrease is mainly a reaction on the decrease in resources imports. Most remarkably, however, is that Europe's share on capital exports increases. In the second half of the century even the absolute amount of Europe's capital exports grow up. That is explained by the spillover effect and the differentiated spillover channel. Under the condition of a carbon-constrained world, foreign investments from Europe become slightly more attractive. European foreign investments embody technological know-how, that to a higher extent contributes to an increase of energy efficiency than technological spillovers from foreign investments of the USA.

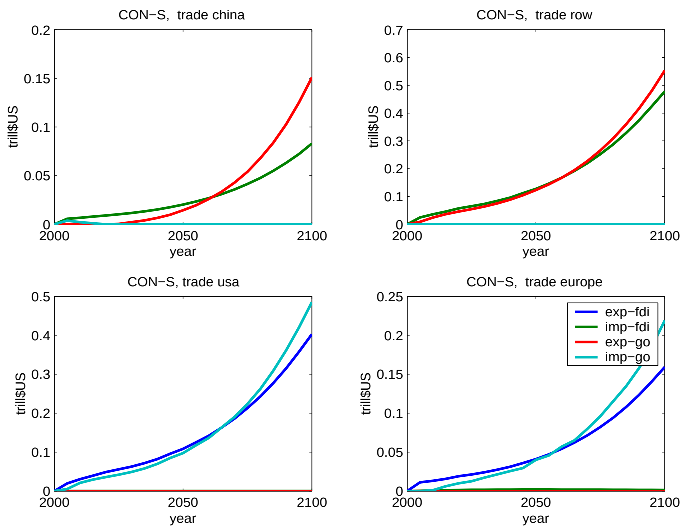

Figure 8: Trade flows (spillover scenario)

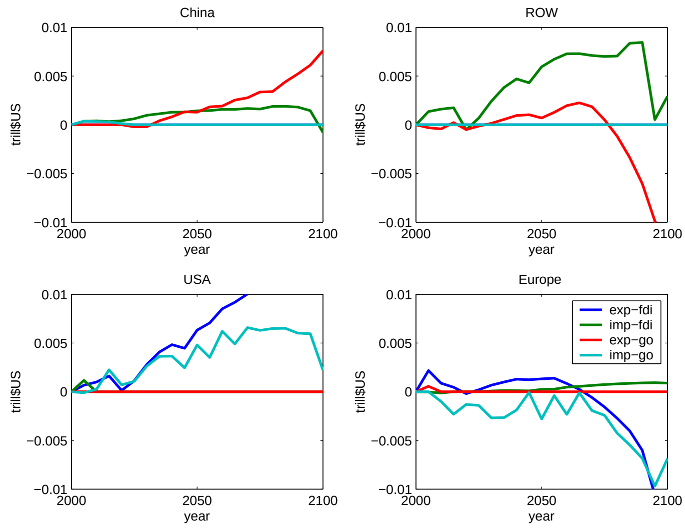

Figure 9: Trade flow differences between baseline and policy scenario

Fragmented climate policy regimes change the trade pattern and mitigation costs substantially. If the USA abstain from joining the climate policy regime, China and ROW face significantly higher mitigation costs, although the amount of required emission reduction is the same as in the co-operative policy scenario (see Fig. 10). The USA, itself, gain in all periods compared to the co-operative policy scenario. High costs for China is mainly due to the lack of technological spillovers from the USA. To a somewhat lower extent this also applies to ROW. Europe benefits from a lower permit price in the beginning and suffers from worsened terms-of-trade effects later on. Due to a lower spillover intensity China and ROW grow at a lower rate. Therefore, the price of consumption goods decrease not as much as in the co-operative scenario. This hits Europe as importer of consumption goods. If China will not join the climate policy regime, it again will suffer from less technological spillovers. This loss cannot be compensated by a relaxed emission constraint which allows to use cheap fossil fuels for a longer time. For the other regions, losses compared to the co-operative solution in later periods are mostly compensated by gains in early periods. Nevertheless, this scenario has no winner, but only losers - China directly, and all regions by the impacts of climate change, which exceeds the 2°C level, indirectly.

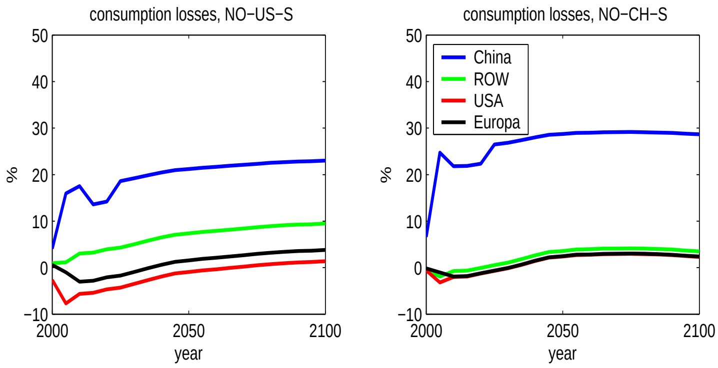

Figure 10: Mitigation costs

5 Conclusions

Within this paper we presented a dynamic trade model that includes technological spillovers and its application in a climate policy context. It turns out that

- Mitigation costs are strongly influenced by terms-of-trade effects
- trade patterns are quite robust between baseline and policy scenarios
- different climate policy regimes differ with respect to the international burden sharing
- including trade sanctions and technology transfer restrictions will provide incentives for developing world regions to join a climate policy regime
- technological spillovers provide an additional channel of smoothing/converging mitigation costs
- advantages in energy saving technologies payoff in climate policy scenarios.

This last finding gives support to the hypothesis that there are some benefits for forerunners in climate policies. This would be even more the case if we not only consider advantages in energy efficient technologies but also in carbon free energy technologies.

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

- parts of the parameters lack of a regional differentiation (e.g. elasticities of substitution, income shares, R&D parameters
- foreign and domestic goods are considered as perfect substitutes which results in undue spezialization
- uncertainty about model parameters (e.g. spillover intensity and learning rates)
- limited disaggregation of the energy sector; neglection of the option of carbon capturing and sequestration.

This list identifies aspects of model elaboration and future research demand.

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A Appendix A - List of parameters and variables

symbol	parameter/variable
i, r	region (Europe, China, USA, ROW))
j	sector
k	production factor
t	time
z	time step, five years
τ	vintages of renewable
σ	discount rate
δ	depreciation rate
W	welfare
$\rho_C(i)$	substitution elasticity in consumption sector
ρ_f	substitution elasticity in fossil energy sector
$C(i,t)$	consumption in region i at time t
$L(i,t)$	labour in region i at time t
$E(i,t)$	total energy in region i at time t
$Y_C(i,t)$	output in consumption sector in region i at time t
$Y_I(i,t)$	output in investment sector in region i at time t
$I(i,t)$	total investment in region i at time t
$K_C(i,t)$	capital stock in consumption sector in region i at time t
$K_I(i,t)$	capital stock in investment sector in region i at time t
$K_f(i,t)$	capital stock in fossil sector in region i at time t
$K_Q(i,t)$	capital stock in resource extraction sector in region i at time t
$\xi_k(i,t)$	distribution parameter for factor X in consumption sector in region i at time t
$\xi_k^f(i,t)$	distribution parameter for factor X in fossil energy sector in region i at time t
θ_k	part of factor X in investment good production function
$\Phi_C(i)$	total factor productivity in consumption sector in region i
$\Phi_I(i)$	total factor productivity in investment sector in region i
$\Phi_f(i)$	total factor productivity in fossil energy sector in region i
$\mathcal{A}(i,t)$	labour efficiency in region i at time t
$\mathcal{B}(i,t)$	energy efficiency in region i at time t
$\mathcal{D}(i,t)$	primer energy efficiency in region i at time t
$\zeta(i)$	productivity of labour efficiency growth rate in region i
$\eta(i)$	productivity of energy efficiency growth rate in region i
α	exponent in research and development labour augmentation
β	exponent in research and development energy augmentation
$sp_L(r,i,t)$	spillover in labour by trade from region r to region i at time t
$sp_E(r,i,t)$	spillover in energy by trade from region r to region i at time t
$rd_{\mathcal{A}}(i,t)$	Research and Development in labour efficiency in region i at time t
$rd_{\mathcal{B}}(i,t)$	Research and Development in energy efficiency in region i at time t

symbol	parameter/variable
$I_C(i,t)$	investment in consumption sector in region i at time t
$I_I(i,t)$	investment in investment sector in region i at time t
$I_{nf}(i,t)$	investment in non fossil energy sector in region i at time t
$I_f(i,t)$	investment in fossil energy sector in region i at time t
$I_Q(i,t)$	investment in resource extraction sector in region i at time t
$I_{ren}(i,t)$	investment in renewable energy sector in region i at time t
$E_f(i,t)$	fossil energy in region i at time t
$E_{ren}(i,t)$	renewable energy in region i at time t
$E_{nf}(i,t)$	non fossil energy 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
$cQ(i,t)$	cumulative resource extraction in region i at time t
$Q()$	resource extraction in region i at time t
$\mathcal{K}(i,t)$	production factor of extraction sector in region i at time t
$\mathcal{K}_{max}(i,t)$	maximal productivity in extraction sector in region i at time t
$\nu(i)$	inverse learning rate in resource sector in region i
μ	learning dampening factor
$V(i,t)$	vintage in renewable energy capacities in region i at time t
$l(t)$	load factors of
$w(\tau)$	weights for renewable vintages
$fC(i)$	floor investment costs of renewables
$\kappa(i,t)$	capital coefficient in renewable energy in region i at time t
$cN(i,t)$	cumulative installed capacity of renewable in region i at time t
$\gamma(i,t)$	learning rate parameter in renewable energy sector in region i at time t
λ	stepping on toes parameter in renewable energy sector
$EM(t)$	global CO2 emissions
$P(i,t)$	emission permits
$X_I(i,r,t)$	export of fdi goods from region i to region r at time t
$X_G(i,r,t)$	export of goods from region i to region r at time t
$X_R(i,r,t)$	export of resources from region i to region r at time t
$X_E(i,r,t)$	export of energy from region i to region r at time t
$p_j(i,r,t)$	price of good j for trade from region i to region r at time t

B Appendix B - equations of some energy sectors

B.1 fossil resource extraction sector

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

$$PE(i,t) = m(i,t) \cdot [Q(i,t) - \sum_r (X_R(i,r,t) - X_R(r,i,t))]. \qquad (17)$$

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

$$Q(i,t) \cdot mC(i,t) = \mathcal{K}(i,t) \cdot K_Q(i,t). \qquad (18)$$

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

$$mC(i,t) = 1 + \frac{\chi_2(i)}{\chi_1(i)} \left(\frac{cQ(i,t)}{\chi_3} \right)^{\chi_4}. \qquad (19)$$

The cumulative amount of extraction *cQ* is given by

$$cQ(i,t+1) = cQ(i,t) + z \cdot Q(i,t). \qquad (20)$$

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

$$\mathcal{K}(i,t{+}1) = \mathcal{K}(i,t) \left[1 + (\mathcal{K}(i)_{max} - \mathcal{K}(i,t)) \left(\frac{z \cdot \nu(i)}{\mathcal{K}(i)_{max}} \left(\left(\frac{Q(i,t)}{Q(i,0)} \right)^{\mu} - 1 \right) \right) \right]. \qquad (21)$$

B.2 renewable energy sector

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

$$V(i,t+1) = z \cdot \frac{I_{ren}(i,t)}{fC(i) + \kappa(i,t)}. \tag{22}$$

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

$$cN(i,t) = cN(i,t-1) + V(i,t), \tag{23}$$

productivity of the renewable energy sector changes:

$$\kappa(i,t) = \kappa(i,0) \cdot \left(\frac{cN(i,t)}{cN(i,0)}\right)^{-\gamma(i)}. \tag{24}$$

C Appendix C - equations of calibration

The first directorial derivations of the production function for consumption goods Y_C are

$$\frac{\partial Y_C}{\partial L} = \Phi_C^{\rho_C} \xi_L (1-\theta_L)^{\rho_C} \mathcal{A}^{\rho_C} L^{\rho_C - 1} Y_I^{1-\rho_C}, \tag{25}$$

$$\frac{\partial Y_C}{\partial E} = \Phi_C^{\rho_C} \xi_E (1-\theta_E)^{\rho_C} \mathcal{B}^{\rho_C} E^{\rho_C - 1} Y_C^{1-\rho_C} \tag{26}$$

and

$$\frac{\partial Y_C}{\partial K_C} = \Phi_C^{\rho_C} \xi_K K_C^{\rho_C - 1} Y_C^{1-\rho_C}. \tag{27}$$

So the income shares are

$$\begin{aligned}
\frac{\partial Y_C}{\partial L}\frac{L}{Y_C} &= \Phi_C^{\rho_C} \xi_L (1-\theta_L)^{\rho_C} \mathcal{A}^{\rho_C} \left(\frac{L}{Y_C}\right)^{\rho_C} \\
\frac{\partial Y_C}{\partial E}\frac{E}{Y_C} &= \Phi_C^{\rho_C} \xi_E (1-\theta_E)^{\rho_C} \mathcal{B}^{\rho_C} \left(\frac{E}{Y_C}\right)^{\rho_C} \\
\frac{\partial Y_C}{\partial K_C}\frac{K_C}{Y_C} &= \Phi_C^{\rho_C} \xi_K \left(\frac{K_C}{Y_C}\right)^{\rho_C}.
\end{aligned} \tag{28}$$

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

$$
\begin{aligned}
&\frac{\partial Y_C}{\partial K_C}\frac{K_C}{Y_C} = \Phi_C^{\rho_C}\xi_K\left(\frac{K_C}{Y}\right)^{\rho_C} = \xi_K \\
&\Rightarrow \Phi_C^{\rho_C}\left(\frac{K_C}{Y_C}\right)^{\rho_C} = 1 \quad \rightarrow \Phi_C = \frac{Y_{C0}}{K_{C0}}
\end{aligned} \tag{29}
$$

$$
\begin{aligned}
&\frac{\partial Y_C}{\partial L}\frac{L}{Y_C} = \Phi_C^{\rho_C}\xi_L(1-\theta_L)^{\rho_C}\mathcal{A}^{\rho_C}\left(\frac{L}{Y_C}\right)^{\rho_C} = \xi_L \\
&\Rightarrow \Phi_C^{\rho_C}(1-\theta_L)^{\rho_C}\mathcal{A}^{\rho_C}\left(\frac{L}{Y_C}\right)^{\rho_C} = 1 \quad \rightarrow \mathcal{A}_0 = \frac{Y_{C0}}{(1-\theta_L)L_0\Phi_C} = \frac{K_{C0}}{(1-\theta_L)L_0}
\end{aligned} \tag{30}
$$

$$
\begin{aligned}
&\frac{\partial Y_C}{\partial E}\frac{E}{Y_C} = \Phi_C^{\rho_C}(1-\theta_E)^{\rho_C}\mathcal{B}^{\rho_C}\xi_E\left(\frac{E}{Y_C}\right)^{\rho_C} = \xi_E \\
&\Rightarrow \Phi_C^{\rho_C}(1-\theta_E)^{\rho_C}\mathcal{B}^{\rho_C}\left(\frac{E}{Y_C}\right)^{\rho_C} = 1 \quad \rightarrow \mathcal{B}_0 = \frac{Y_{C0}}{(1-\theta_E)E_0\Phi_C} = \frac{K_{C0}}{(1-\theta_E)E_0}
\end{aligned} \tag{31}
$$

Same for Y_I.