A Model of Endogenous Growth for Climate and Development Policy Assessment

January 11, 2011

Abstract

We introduce endogenous directed technical change into integrated climate policy assessment. Our model builds on state-of-the-art theory as well as econometric data. We apply our model to the assessment of a carbon budget based climate policy. Motivated by the announcement of international transfers during recent climate policy negotiations, we vary the begin of endogenous international transfers of energy saving technologies. Our results indicate that most of the consumption gains from early transfers are already captured in the baseline scenario without climate policy. Herein, China appears as a main beneficiary of early transfers. Keeping the emission budget at low consumption losses, however, requires the availability of low-carbon technologies beyond energy savings.

JEL Classifications: O11, O30, O44, O47, Q32

Keywords: endogenous growth, directed technical change, technology transfer, climate policy, carbon budget, China

1 Introduction

Innovation as well as imitation and international diffusion of technologies can be a key for successfully coping with poverty and climate change. Herein, (climate) policy interventions have an impact on the strength and direction of innovation, imitation and technology diffusion. Therefore, a (climate) policy analysis that takes these aspects into account requires a rigorous model of endogenous directed technical progress.

It is widely agreed that OECD countries bear the main responsibility for climate change while the developing countries will bear most of its impacts. Therefore, in recent climate negotiations (Bali Roadmap 2007, Copenhagen 2009 summit and Cancún 2010 summit), developing countries called for financial and technological support for mitigation, and industrialized countries announced to provide such support. Besides through revenues from selling emissions permits, developing countries can receive such support through technology funds such as the World Bank Climate Investment Funds (World Bank 2010) as announced at the Cancún 2010 summit. In particular, industrialized countries announced future transfers amounting to 100 billion US-$ per annum. However, no legally binding commitments have been achieved that settle which countries will pay how much beginning at which date. This gives rise to the question how mitigation costs of different regions are affected by postponing international technology transfer.

Against this background, in this article, we apply our model approach to the assessment of this policy question. Our model approach builds on state-of-the-art theoretical models of endogenous growth.[1] Product variety models in the style of Romer (1990) describe growth as a process that stems from an increasing number of innovative intermediate products (e.g. Grossman and Helpman 1991). Product quality models in the style of Aghion and Howitt (1992) rather describe growth as a process that stems from quality improvements of products wherein new varieties replace old varieties, which is also called 'creative destruction'. We follow the latter model type. (Both types basically lead to equivalent results.) Furthermore, Acemoglu et al. (2003a, b) provide microfoundations and a rigorous analysis of the influence of the distance between the technology in practice and the technology frontier (along the lines of the seminal contribution by

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[1] Comprehensive state-of-the-art textbooks on (endogenous) growth are authored by Aghion and Howitt (2009) and by Acemoglu (2009).

Nelson and Phelps 1966). They show that an imitation based strategy is preferable when being further away from the technology frontier while an innovation based strategy is preferable when being closer to the technology frontier. We follow this idea by including a 'distance to technology frontier' (more specifically a 'technology pool') term in our model. Herein, the model allows an endogenous choice between innovation and imitation and reproduces the findings by Acemoglu et al. (2003a, b) endogenously. Furthermore, we follow approaches in the style of Arrow (1962) such as Greiner and Semmler (2002) that view learning related to capital investment as a driver of technical progress. In our context, the positive impact of capital investment on technical progress in an economy is additionally due to the following consideration: New technologies such as energy saving technologies that exist as blueprints become increasingly used in the economy through capital investment. As a result, they become increasingly embodied in the new capital stock and raise its productivity. We implement this feature in the style of the Schumpeterian model as a novel theoretical detail. Finally, we follow the literature in the style of Acemoglu (2002) that emphasizes the possibility to direct technical change towards specific factors depending on the abundance of factors or relative factor prices. Technical progress directed towards a certain factor will reduce the demand for this factor (factor saving technical progress) when the elasticity of substitution between the production factors is smaller than one, which is the case in our model.

However, endogenous growth along these lines of the theoretical literature has not yet been fully worked out in an integrated assessment framework. Therefore, it is our main contribution to introduce endogenous, directed technical progress resulting in fully endogenous economic growth into multi-region integrated assessment modeling. Therein, our approach contributes to the literature that numerically describes endogenous innovation (e.g. Popp 2004, 2006, Edenhofer et al. 2005, Kemfert 2005, Otto et al. 2008) and international technology spillovers (e.g. Diao et al. 2005, Bosetti et al. 2008, Leimbach and Baumstark 2010, Hübler 2010). In our policy analysis, our model of endogenous growth will be embedded into the integrated assessment model ReMIND (Leimbach et al. 2010a, c.f. Figure 4 and Figure 5 in the Appendix), a Ramsey type model of intertemporarily optimal investment in physical capital and energy technology capacities. The model version under scrutiny consists of five world regions and includes trade (in a composite commodity, coal, gas, oil, uranium and carbon emission permits) between these regions. It is coupled with an energy system module that represents several energy sources and related capacities of energy technologies (coal, gas, oil, uranium, hydro, biomass, solar, wind, geothermal; carbon capture and storage, CCS, of coal, gas and biomass; c.f. Leimbach et al. 2010a, b). The energy module includes endogenous investment into capacities of different energy technologies as well as learning-by-doing of wind and solar technologies following the literature that emphasizes learning effects (e.g. Crassous et al. 2006, Kahouli-Brahmi 2008). The energy module takes increasing costs of resource extraction into account as well as operation and maintenance costs. Carbon emissions stemming from fossil fuels burned in production and consumption processes can be translated into resulting temperature increases in a climate module (Kanaka and Kriegler 2007). The time horizon under scrutiny is 2005 until 2100 in five-year steps.

Section 2 derives our model of endogenous growth from economic theory. Section 3 describes the numerical calibration and shows simulation results. Section 4 applies the model to the assessment of a carbon budget based climate policy and the delay of energy saving technology diffusion within the integrated assessment model ReMIND (Leimbach et al. 2010a). Section 5 critically discusses the model results. Section 6 concludes by sketching policy implications.

2 Model

We derive the implementation of directed technical change in an intertemporal optimization framework from economic theory in four steps: (1) We derive the effect of R&D expenditures on the progress of innovation from a Schumpeterian model of growth. (2) We take investment in physical capital as a driver of innovation into account. (3) We implement interregional technology spillovers. (4) We allow for the direction of technical change towards labor or energy.

(1) R&D expenditures. With respect to modeling endogenous growth, we follow the Schumpeterian view of quality improvements as a driver of economic growth based on the description by Aghion and Howitt (2009), chapter 4. We start with a one-sector production function Y which is increasing in technology A. Both are macroeconomic aggregates so that $A = \int_0^1 A_j dj$ can be interpreted as an unweighted numerical average

of individual productivities of firms or sectors j in the economy. In each period a firm spends R_j on R&D. Each firm is able to keep part of the generated knowledge as firm specific knowledge so that it has some monopolistic power and earns a profit. In other words, each firm holds a patent. The same intuition applies to non-profit research institutions in form of earning non-monetary profits such as publications, reputation and political influence, so that we may also interpret non-profit organizations as firms. Now we aggregate individual expenditures to macroeconomic expenditures $R = \int_0^1 R_j dj$. On the macro level, R may also include public spending on education, basic research, infrastructure etc., which enhances invention and innovation in the economy. By the law of large numbers, expenditures will lead to a successful innovation with probability μ and will not lead to a successful innovation with probability $1 - \mu$ on the macro level. Herein, μ is increasing in R which is endogenously determined. More specifically, following Aghion and Howitt (2009), chapter 4, we write:[2]

$$\mu = \lambda_R \left(\frac{R_t}{A_t} \right)^{\sigma_R} \tag{1}$$

λ_R determines the impact of R&D expenditures on the probability of success in a linear fashion. $0 < \sigma_R < 1$ creates a decreasing marginal effect of R&D expenditures on the probability of success with rising expenditures. Assuming that a new technology is $\gamma > 1$ times as productive as the previous technology, the rate of innovation based technical progress g_R can be derived in the following way:

$$A_{t+1} = \mu\gamma A_t + (1 - \mu)A_t \quad \Leftrightarrow \quad \frac{A_{t+1} - A_t}{A_t} = \mu(\gamma - 1) =: g_R \tag{2}$$

In case of a successful innovation, the new technology γA_t will be applied. In case of no success, the old technology A_t will be used further.[3] However, the implementation in the ReMIND model does not take profit maximization of firms and monopolistic power due to successful innovations explicitly into account.

(2) Investment in physical capital. Additionally, there is an interaction of investment in knowledge creation and investment in capital. On the one hand, the Arrow (1962)

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[2] We will add region and factor specific indexes in the final set of equations.

[3] One may add depreciation of knowledge which is less common in theoretical growth models than in applied assessment models.

based literature sees knowledge as a by-product of capital accumulation. On the other hand, viewing knowledge as a public good, innovations need time to diffusion through the economy, and they require investment in capital in order to be implemented into production facilities. Therefore, we extend the Schumpeterian point of view in a novel setting in the following general form:

$$A_{t+1} = (1 + g_R)A_t \left(\frac{I_t}{K_{t+1}}\right)^{\sigma_I} + A_t \left[1 - \left(\frac{I_t}{K_{t+1}}\right)^{\sigma_I}\right] \tag{3}$$

I_t is investment in capital, and $K_{t+1} = (1 - \delta)K_t + I_t$ is the new capital stock, where δ is the depreciation rate. We assume $\sigma_I = 1$. (Allowing $0 < \sigma_I < 1$ means, it becomes increasingly difficult or costly to replace a larger fraction of the capital stock by the newest technology.) Then, according to the equation above, the fraction of the capital stock remaining after depreciation that is renewed by investment uses the newest technology $(1 + g_R)A_t$. The remaining fraction of the capital stock still uses the old technology A_t. As a consequence, the implementation of existing new technologies in production depends on investment, as observed in reality. We can now simplify the equation above and replace g_R:

$$A_{t+1} = A_t \left[1 + (\gamma - 1)\lambda_R \left(\frac{R_t}{A_t}\right)^{\sigma_R} \left(\frac{I_t}{K_{t+1}}\right)^{\sigma_I}\right] \tag{4}$$

(3) International technology spillovers. In the next step, we will add international technology diffusion following the same line of argumentation and the same specification as before. There are basically two differences to the previous specification. We now assume that expenditures S encompass expenditures on fostering international technology diffusion instead of innovation. They include expenditures of firms for the imitation and adoption of foreign technologies as well as publicly funded projects that enhance the diffusion of technologies. Besides this re-interpretation, a new technology still appears with probability μ as described by equation (1), but we now assume that each productivity increase, previously occurring at the rate $\gamma - 1$, occurs endogenously. This productivity increase depends inversely on the technology level of the recipient economy relative to the world technology pool $\bar{A}$ as suggested by Acemoglu (2009), chapter 18 (c.f. Griffith et al. 2003 reconciling theory and evidence). The total rate of technical

progress now reads:

$$g_S = \lambda_S \left(\frac{S_t}{A_t}\right)^{\sigma_S} \left(\frac{\bar{A}_t}{A_t}\right)^{\sigma_A} \tag{5}$$

In general, it is possible that $\lambda_R \neq \lambda_S$ and that $\sigma_R \neq \sigma_S$ since innovation and imitation or diffusion are driven by different processes. The term $\left(\frac{\bar{A}_t}{A_t}\right)^{\sigma_A}$ implies that the larger an economy's technology gap relative to the world technology pool the higher is its growth rate.[4] As a theoretical result, all economies will grow at the same rate but at different relative distances to the technology pool level depending on their absorptive capacities in the long-run steady state. As suggested by Acemoglu (2009), we compute the world technology pool as the arithmetic average of the technology levels of all regions. As a consequence, all regions contribute to increasing the world technology pool. In the 'technology frontier' specifications often used in the literature, on the contrary, only the technology leader pushes the frontier forward and thus contributes to the global stock of technological knowledge. Herein, we implicitly assume that technological knowledge is heterogenous so that the best available technology does not incorporate all technological know-how but instead all inventors contribute to a common knowledge pool. Taking again the role of investment into account yields:

$$A_{t+1} = A_t \left[1 + \lambda_S \left(\frac{S_t}{A_t}\right)^{\sigma_S} \left(\frac{I_t}{K_{t+1}}\right)^{\sigma_I} \left(\frac{\bar{A}_t}{A_t}\right)^{\sigma_A}\right] \tag{6}$$

As a consequence of our specification and in accordance with the micro-foundations described by Acemoglu et al. (2003a, b), imitation is more beneficial farther away from the technology frontier (pool), while innovation (Equation 4) is more beneficial closer to the technology frontier (pool).

(4) Directed technical change. Following Acemoglu (2002), we take directed, i.e. factor specific technical progress into account. In each region the ReMIND production function has the following form:

$$Y = \phi \left[\alpha_K (A_K K_t)^{\frac{\sigma_Y - 1}{\sigma_Y}} + \alpha_L (A_{Lt} L_t)^{\frac{\sigma_Y - 1}{\sigma_Y}} + \alpha_E (A_{Et} E_t)^{\frac{\sigma_Y - 1}{\sigma_Y}}\right]^{\frac{\sigma_Y}{\sigma_Y - 1}} \tag{7}$$

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[4] According to Acemoglu (2009), one may set $\sigma_A \geq 1$ so that economies farther away from the technology pool level have a stronger advantage with respect to technology diffusion.

While A_K is kept constant, A_{Lt} and A_{Et} rise endogenously representing labor and energy specific technical progress. Each type of endogenous technical progress is modeled as described above. We choose the elasticity of substitution $0 < \sigma_Y < 1$ so that the production factors are gross complements. In this case, according to Acemoglu (2002), energy augmenting technical progress, i.e. growth of A_{Et}, is labor biased, i.e. it creates excess demand for labor rather than for energy and raises the marginal product of labor more than the marginal product of energy. ϕ is a constant that captures total factor productivity in the benchmark year.

After combining all these effects, we obtain the equation below:

$$A_{rit+1} = A_{rit} \left\{ 1 + \lambda_i \lambda_{rt} \left[\lambda_R \left(\frac{R_{rit}}{A_{rit}} \right)^{\sigma_R} + \lambda_S \left(\frac{S_{rit}}{A_{rit}} \right)^{\sigma_S} \left(\frac{\bar{A}_{rit}}{A_{rit}} \right)^{\sigma_A} \right] \left(\frac{I_{rt}}{K_{rt+1}} \right)^{\sigma_I} \right\} \qquad (8)$$

Herein, we write $i = \{L, E\}$ as the factor index, r as the region index (encompassing a number of regions) and t as the time index as before. Moreover, we extend the parameters λ_R and λ_S that determine the strength of innovation and imitation into an intersectoral differential λ_i and an interregional differential λ_{rt}. Herein, λ_i might differ between energy and labor due to technological reasons, i.e. the value of energy saved by a certain volume of R&D investment can differ from the value of labor saved by the same volume of R&D investment.[5] λ_{rt} is determined by the educational level (human capital) of the respective region. The important role of education for innovation and imitation (absorptive capacity) has often been emphasized in the theoretical and empirical literature (Nelson and Phelps 1966, Benhabib and Spiegel 2005, Kneller 2005). Herein, regional education levels may change over time and in particular converge to equal levels across regions in the distant future.

The objective of the Ramsey type optimization model is the weighted sum of per capita consumption of all regions, cumulated and discounted over the time horizon. Expenditures related to knowledge creation, which we call R_{rit} and S_{rit} create costs in form of foregone consumption C_{rt} like usual investment in capital I_{rt}. In other words, final output can directly be used as an intermediate input for the creation of knowledge

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[5] For example, a state-of-the-art washing machine will save energy and save time spent for operating it to different extents.

so that consumption in each region is given by:

$$C_{rt} = Y_{rt} - I_{rt} - R_{rLt} - R_{rEt} - S_{rLt} - S_{rEt} \tag{9}$$

The marginal product of physical capital K_{rt} rises as a consequence of technical progress which stimulates capital accumulation over time. Additionally, the ReMIND model encompasses an energy module that distinguishes several energy sources (coal, gas, oil, uranium, hydro, biomass, solar, wind, geothermal). Investments into capacities of the related energy technologies are also subtracted from the budget like investment in physical capital as a production factor.

3 Calibration

We aggregate the integrated assessment model ReMIND to five world regions: INA consists of Africa, Latin America, India and other Asia. China is denoted by CHN. ROW consists of Middle East, Japan, Russia and the rest of the world. EUR consists of the European Union EU 27. USA denotes the United States of America. Our calibration strategy is based on (1) econometrically estimated values, (2) historical statistical reference values and (3) future reference values derived from existing scenario simulations.

(1) Econometrical estimations. Griffith et al. (2003) reconcile the theoretical literature on Schumpeterian endogenous growth with the econometrical literature on R&D, growth and convergence. They review the empirical findings on the influence of R&D expenditures per GDP on productivity growth as a macroeconomic social benefit and list some examples: Griliches and Lichtenberg (1984) find values of 0.21–0.76, Schankerman (1981) finds 0.24–0.73 and Scherer (1982, 1984) obtains 0.29–0.43. In general, this literature strand finds a positive and statistically significant influence of R&D expenditures on productivity growth. These values translate into the R&D coefficient λ_R in our model. However, the findings differ across studies depending upon the underlying data sample, the definition of R&D (private, public or both) and the inclusion or exclusion of international R&D spillovers (Griffith et al. 2003). Griffith et al. (2000) find values around 0.4 depending upon the model specification (including R&D expenditures per GDP as a lagged variable). Zachariadis (2003) also finds values around 0.4. In accor-

dance with this literature strand, we set $\lambda_R = 0.4$. Note that different to the econometric literature we include R&D expenditures divided by the current technology level as in the theoretical literature instead of R&D expenditures divided by GDP and additionally the share of capital investment in GDP.

Griffith et al. (2000) additionally include R&D expenditures per GDP multiplied by the technology gap which corresponds to the term $\left(\frac{S_t}{A_t}\right)^{\sigma_S}\left(\frac{\bar{A}_t}{A_t}\right)^{\sigma_A}$ in our model. They find coefficients of 0.6–1.2. These values translate into the R&D coefficient λ_S. Herein, different to our specification, Griffith et al. (2000) include the technology gap term in logarithmic form, and they use the technology frontier, i.e. the best available technology, instead of the average technology level. Since our specification deviates from this econometrical specification, we set λ_S to a lower value of 0.12, which yields realistic productivity growth rates as described below.

Furthermore, Zachariadis (2003) regresses the logarithmic rate of patenting in an industry on the logarithmic R&D intensity based on a Schumpeterian model of growth. This helps us set the exponent of R&D expenditures denoted by σ_R. Zachariadis (2003) finds values around 0.2 for own-industry R&D (and about 0.6 for aggregate R&D). We set $\sigma_R = 0.1$ in order to better match the historical data as described below.

(2) Historical data. The theoretical and econometric literature views education (human capital) as an important determinant of productivity growth through R&D and technology diffusion (c.f. Nelson and Phelps 1966, Crespo et al. 2004, Benhabib and Spiegel 2005, Kneller 2005). Herein, the absorptive capacity for the adoption of newly arriving technologies is supposed to increase not only in education and skills but also in the existing infrastructure, especially with respect to access to sources of knowledge and information technologies. Also, the existing technologies in practice are supposed to ease the adoption of new technologies. We follow this view by setting the coefficient λ_{r2005} that effects both, innovation and diffusion of technologies, depending on region specific levels of education and infrastructure as a determinant of the absorptive capacity. We choose the parameters based on education and infrastructure indicators as reported by WDI (2010).[6] Moreover, we assume that regions that lack in education

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[6] We examine primary, secondary and tertiary education enrolment and completion ratios as well as infrastructure indicators such as internet and telephone access ratios. We set the highest value to one and measure the other values relative to one. Then we compute the average of the rankings according to the different indexes. The data in general yield the ranking USA, EUR, ROW, CHN, INA. We follow this

and infrastructure catch up over time so that λ_{rt} converges. Herein, we assume that all regions will reach the maximal value of one in 2100 (as illustrated in Figure 6 in the Appendix).

Symbol	Explanation	Scen.	INA	CHN	ROW	EUR	USA
$g(Y_{r2005})$	GDP growth	BAU:	4.7	10.1	3.5	2.8	3.5
		REF:	4.0	9.2	2.4	2.5	3.0
$g(Y_{r2005}/L_{r2005})$	Labor prod. growth	BAU:	3.0	9.5	2.5	2.6	2.5
		REF:	2.2	8.4	1.3	2.2	2.0
$g(Y_{r2010}/E_{r2010})$	Energy prod. growth	BAU:	0.9	2.6	0.9	0.8	1.3
		REF:	0.8	3.6	0.6	2.2	2.1
I_{r2005}/Y_{r2005}	Investment to GDP	BAU:	20	37	28	29	28
		REF:	22	37	23	20	19
R_{rL2005}/Y_{r2005}	(Labor) R&D expd.	BAU:	0.5	1.7	0.8	1.8	3.3
		REF:	0.7	0.9	2.2	1.8	2.6
R_{rE2005}/Y_{r2005}	Energy R&D expd.	BAU:	0.2	0.6	0.1	0.2	0.2
		REF:	...	...	...	0.4	0.5
S_{rL2005}/Y_{r2005}	(L.) tech. imit. expd.	BAU:	1.2	3.6	0.3	0.2	0.3
S_{rE2005}/Y_{r2005}	E. tech. imit. expd.	BAU:	.06	.30	.04	.03	.05

Table 1: Comparison of regional model results for 2005 under BAU with reference values REF computed as averages from 1996 to 2006 taken from WDI (2010) and for energy specific R&D from IEA (2010); all values are reported in percent. (We report model results for 2010 in case of $g(Y_{r2010}/E_{r2010})$ since the model yields negative energy productivity growth for some regions in 2005 due to initial adjustment effects.)

Table 1 confronts the results of our simulations for business as usual without climate policy, BAU, with the reference data, REF, obtained from WDI (2010) and IEA (2010). Herein, we compute averages over the time span 1996–2006 (in order to avoid the use of outlier values). Obviously, the model results match the the reference data well in

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ranking. However, it is difficult to make a decisive choice on the indicators to be included. Therefore, we adjust the education indicators such that the resulting GDP growth rates better match the historical data. This adjustment may also consider region size effects such that the regional aggregation chosen does not arbitrarily influence the regional innovative performances.

Symbol	Explanation	Scen.	World
L_{r2100}	Population (= labor force) [bill.]	BAU:	9.1
		B1:	7.1
		B2:	10.4
Y_{r2100}	Global GDP [trill. US-$]	BAU:	300
		B1:	339
		B2:	255
E_{r2100}	Primary energy cons. p.a. [EJ]	BAU:	900
		B1:	791
		B2:	1370
$Q_{r2005-2100}$	Cumulated carbon emissions [Gt]	BAU:	1258
		B1:	1345
		B2:	1290

Table 2: Comparison of regional model results for 2100 under BAU with reference values of scenarios B1 (B1T1 ASF) and B2 (B2BC Minicam) by IPCC (2000).

many cases, but there are also significant deviations, e.g. the growth rates of energy productivity in Europe and in the USA. Furthermore, Figure 6 and Figure 7 in the Appendix illustrate relevant indicators of the model dynamics.

Obviously, the high-income regions USA and EUR follow innovation based strategies while the low-income regions INA and CHN follow imitation strategies as suggested by Acemoglu et al. (2003a, b). The reason for this outcome is the advantage of the high-income countries in terms of education, existing technologies and capital on the one hand and the advantage of the low-income countries in terms of the potential to absorb technologies from abroad due to the low quality of their own technologies on the other hand.

While data about population, GDP and energy inputs are available across almost all countries and years under scrutiny, there are only few data about R&D expenditures in developing countries. Nevertheless, it is well-known that mainly the industrialized regions drive innovation which is reflected in their R&D expenditures.[7] Moreover, data

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[7] SEI (2006) reports the global shares in total R&D expenditures of 729 bill. US-$ in the year 2000 as follows: North America 39.1, Asia 28.7, Europe 27.9, South America and Caribbean 2.5, Oceania 1.2,

sources report total R&D expenditures but not labor specific R&D expenditures required for our model. R&D expenditures are available from IEA (2010). However, the data cover less than the OECD countries. Finally, there are probably no data available about expenditures for the adoption and imitation of products and processes (on a country level). Therefore, we suppose that these expenditures have a similar magnitude as R&D expenditures. Therein, in our model R&D expenditures mainly depend on the exponents σ_R and σ_S, i.e. a higher exponent creates ceteris paribus higher R&D and imitation expenditures. Hence, we reduce σ_S to 0.01 (compared with $\sigma_R = 0.1$) so that expenditures for innovation (R&D) and for imitation (adoption) of technologies per GDP generated by the model have a similar magnitude.

Finally, the strength of technical progress across the factors labor and energy is adjusted so that it better matches the historical data in terms of labor and energy productivity growth. Herein, we set λ_L=1 and λ_E=3.

(3) Future scenarios. Table 2 compares our model results with scenarios B1 (B1T1 ASF) and B2 (B2BC Minicam) by IPCC (2000) which come closest to our scenario among the IPCC scenarios.

Scenario B1 assumes low population growth and relatively high economic growth, a low primary energy intensity, a low carbon intensity and a high fossil fuel availability in combination with *global* economic and climate policy solutions. Scenario B2 assumes medium population growth and medium economic growth, a medium to high primary energy intensity, a balanced carbon intensity and a low fossil fuel availability in combination with *regional* economic and climate policy solutions.

In this sense, we follow medium to optimistic assumptions on future socio-economic developments. The regional time paths of important socio-economic indicators created by our model are illustrated in Figure 6 in the Appendix.

4 Assessment

In our policy analysis, we impose a budget of global emissions cumulated from 2005 to 2100 amounting to 400Gt of carbon following Allen et al. (2009). The emissions budget

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Africa 0.6.

is supposed to translate into a temperature goal of about 2 degree in a more reliable way than a concentration target. Emissions permits are allocated across regions following a Contraction and Convergence approach (GDI 1990). Therein, per capita emissions in 2005 follow actually measured per capita emissions in 2000. Per capita emissions then converge to equal levels across regions until 2050 such that the budget constraint is fulfilled. We call this climate policy scenario POL.

Herein, it is important to note that our optimization model generates the globally, socially optimal allocation of expenditures for imitation and innovation. This means, the positive external effect of international technology spillovers is internalized. Moreover, this globally, socially optimal solution is independent of distributions matters such as the permit allocation scheme. (The permit allocation scheme of course affects regional consumption losses – or possibly gains – stemming from climate policy.) Finally, the ReMIND model applies an algorithm based on Negishi (1972) that adjusts regional weights in the welfare function – which is the objective function of the optimization process – such that a pareto optimal solution is achieved. Therein, the regional weights are adjusted in such a way that the intertemporal trade budget is equal to zero for all regions in 2100. This means, regions are not allowed to create debts or surpluses beyond 2100. Nevertheless, industrialized regions are able to finance international technology transfer to developing countries since the model allows for interregional transfers (in form of a composite commodity) in each period. Since no regional debts or surpluses are allowed at the end of the time horizon, these transfers can be interpreted as loans that are granted in earlier periods and payed back in later periods.

Table 3 and Table 4 show the difference between POL as described above and BAU as discussed in the previous section for relevant indicators. While Table 3 shoes the results for the initial periods, Table 4 shows the results as averages over the time horizon 2005 until 2100. In Table 3, the policy effects have an order of magnitude of around 0.001 to more than one percentage points in terms of growth rates or shares in GDP. In Table 4, the policy effects have an order of magnitude of around 0.001 to more than 0.01 percentage points in terms of growth rates or shares in GDP. Obviously, the effects are stronger in earlier periods than in later periods in accordance with the general behavior of growth models, in which the system initially changes strongly until a steady state is reached. In both cases, the effects have the expected signs: Investments in energy saving

Symbol	Explanation	INA	CHN	ROW	EUR	USA
$\Delta\varnothing g(Y_{r2005})$	GDP growth	–.02	–.05	–.09	–.12	–.13
$\Delta\varnothing g(Y_{r2005}/L_{r2005})$	Labor prod. growth	–.02	–.05	–.09	–.12	–.13
$\Delta\varnothing g(Y_{r2005}/E_{r2005})$	Energy prod. growth	1.28	1.23	1.12	1.04	.69
$\Delta\varnothing(I_{r2005}/Y_{r2005})$	Investment to GDP	.17	.08	.01	–.08	–.16
$\Delta\varnothing(R_{rL2010}/Y_{r2010})$	Labor R&D expd.	–.02	–.03	–.01	–.01	–.03
$\Delta\varnothing(R_{rE2005}/Y_{r2005})$	Energy R&D expd.	.02	.02	.01	.01	.05
$\Delta\varnothing(S_{rL2010}/Y_{r2010})$	Labor tech. imit. expd.	–.002	–.002	–.003	–.012	–.031
$\Delta\varnothing(S_{rE2005}/Y_{r2005})$	Energy tech. imit. expd.	.002	.004	.003	.005	.029

Table 3: Impacts of policy POL (carbon budget) with respect to BAU; changes in growth rates and ratios p.a. in the initial years 2005 or 2010 in percentage points (e.g. a change from 1.100% p.a. to 1.099% p.a. is a –0.001 change in the table. We report model results for 2010 in several cases when the values in 2005 deviate from the general model behavior due to initial adjustment effects.)

innovation and imitation increase due to the emissions restriction while investments in labor saving innovation and imitation decrease.[8] As a consequence, GDP growth rates also decrease. Notably, the investment share in GDP increases in the regions INA CHN and ROW, probably since a higher investment share enhances the implementation of energy saving technologies in physical capital as incorporated in our model of technical progress.

In the following, we will assess in how far postponing energy specific international technology transfer affects mitigation costs. Therein, we interpret the spillover term $\left(\frac{\bar{A}_t}{A_t}\right)^{\sigma_A}$ as the channel of international technology transfer under scrutiny. Energy specific imitation expenditures S_{rEt} enable the use of this channel and can be financed within each country as well as through international transfers in form of transfers of the composite commodity. Postponing international technology transfer is represented in the following stylized way: Energy specific imitation expenditures S_{rEt}

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[8] Nevertheless, there can be single cases with opposite signs in general.

Symbol	Explanation	INA	CHN	ROW	EUR	USA
$\Delta\varnothing g(Y_r)$	GDP growth	–.003	–.004	–.001	–.002	–.002
$\Delta\varnothing g(Y_r/L_r)$	Labor prod. growth	–.003	–.004	–.001	–.002	–.002
$\Delta\varnothing g(Y_r/E_r)$	Energy prod. growth	.052	.054	–.001	.042	.036
$\Delta\varnothing(I_r/Y_r)$	Investment to GDP	.002	.017	.006	.001	.003
$\Delta\varnothing(R_{rL}/Y_r)$	Labor R&D expd.	–.006	–.008	–.004	–.008	–.012
$\Delta\varnothing(R_{rE}/Y_r)$	Energy R&D expd.	.010	.019	.005	.007	.009
$\Delta\varnothing(S_{rL}/Y_r)$	Labor tech. imit. expd.	–.005	–.006	–.001	–.001	–.001
$\Delta\varnothing(S_{rE}/Y_r)$	Energy tech. imit. expd.	.004	.007	.002	.001	.002

Table 4: Impacts of policy POL (carbon budget) with respect to BAU; changes in growth rates and ratios p.a. are expressed as averages over the time horizon 2005 to 2100 in percentage points (e.g. a change from 1.100% p.a. to 1.099% p.a. is a –0.001 change in the table).

are exogenously bound to a value close to zero for all periods and all regions before $t_0 = \{2010; 2015; 2020; 2025; 2030; 2035; 2040\}$. From t_0 on, energy specific interregional technology diffusion evolves endogenously as before. Herein, the relaxation of imitation expenditures at t_0 is anticipated.

Figure 1 plots the regionally different effects of postponing technology diffusion in form of the difference between consumption in a baseline scenario BAU where financing is postponed versus consumption in the baseline scenario BAU where financing starts immediately in 2005 relative to consumption in the latter scenario. In all calculations of consumption losses, we cumulate consumption losses between 2005 and 2100 and discount at a rate of 3% per year.

Obviously, postponing creates consumption losses that range from less than 0.1 to more than 0.5 percentage points for all regions due to a higher energy demand per output since energy specific technical progress is hindered. Accordingly, early investment in energy saving technology diffusion is beneficial for all regions, given our model setup. This is probably due to the following reasons: First, our model setup allows all regions to benefit from the global knowledge pool, in this case regarding energy specific technolog-

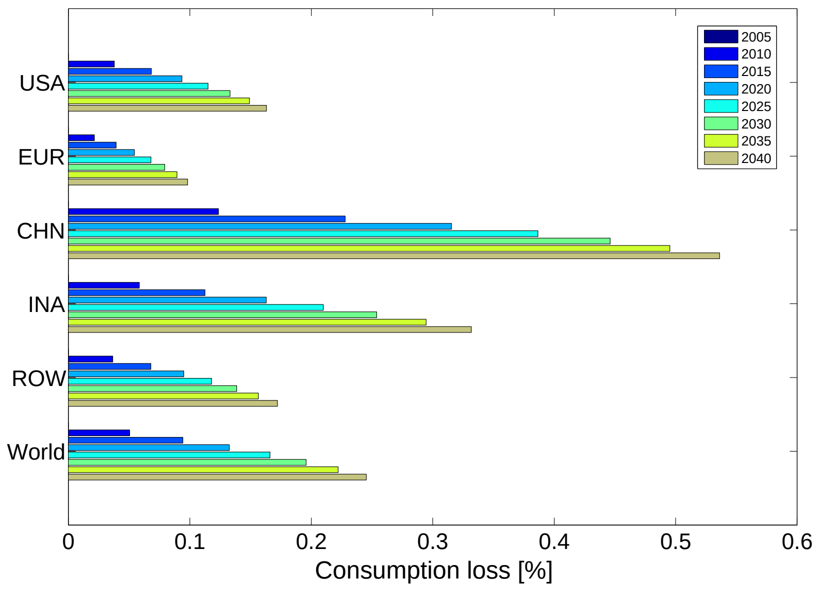

Figure 1: Regional effects of postponing the financing of international transfers of energy efficient technologies. Consumption losses are reported as the difference between consumption in a baseline scenario BAU where financing is postponed (as indicated in the legend) and consumption in the baseline scenario BAU where financing starts immediately in 2005 relative to consumption in the latter scenario. Consumption losses are cumulated from 2005 to 2100 and discounted at a rate of 3% p.a.

ical knowledge. Second, the industrialized countries also benefit from energy efficiency improvements in the developing countries through buying carbon emission permits from the latter. Third, regions can benefit from technical progress in other regions through general international transfers or in other words through commodity trade.

As expected, China is suffers most from postponing international technology diffusion because it starts at a low energy productivity and is able to catch up fast, followed by the developing region INA. Europe suffers least due to its good initial energy productivity, followed by the USA and the Rest of the World. The gains from financing technology transfer appear to be higher in earlier periods since the process of growth and technological catching up is more pronounced in earlier periods than in later periods where growth rates decline.

Meanwhile, global primary energy consumption rises from about 900EJ in the un-

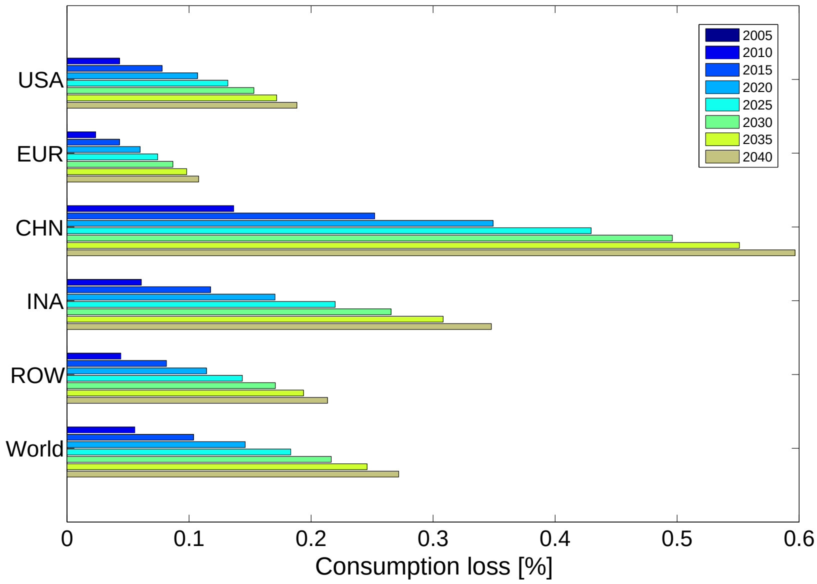

Figure 2: Regional effects of postponing the financing of international transfers of energy efficient technologies. Consumption losses are reported as the difference between consumption in a policy scenario POL where financing is postponed (as indicated in the legend) and consumption in the policy scenario POL where financing starts immediately in 2005 relative to consumption in the latter scenario.

bounded baseline scenario (compare Table 2) to 917EJ in the baseline scenario where energy specific imitation expenditures are allowed from 2040 on. Correspondingly, cumulated (2005-2100) emissions rise from about 1258Gt to 1274Gt of carbon.

Figure 2 plots the effects of postponing technology diffusion in form of the difference between consumption in a policy scenario POL where financing is postponed versus consumption in the policy scenario POL where financing starts immediately in 2005 relative to consumption in the latter scenario. Figure 2 looks similar to Figure 1 in qualitative terms while the consumption losses are higher in Figure 2 in quantitative terms. The increase in the consumption losses in Figure 2 compared with Figure 1 therefore shows in how far meeting ambitious climate policy targets is hindered by postponing technology diffusion. However, the quantitative differences appear small, which is confirmed by Figure 3.

Figure 3 plots the regional effects of climate policy POL as the difference between POL and BAU consumption relative to BAU consumption for each start date of

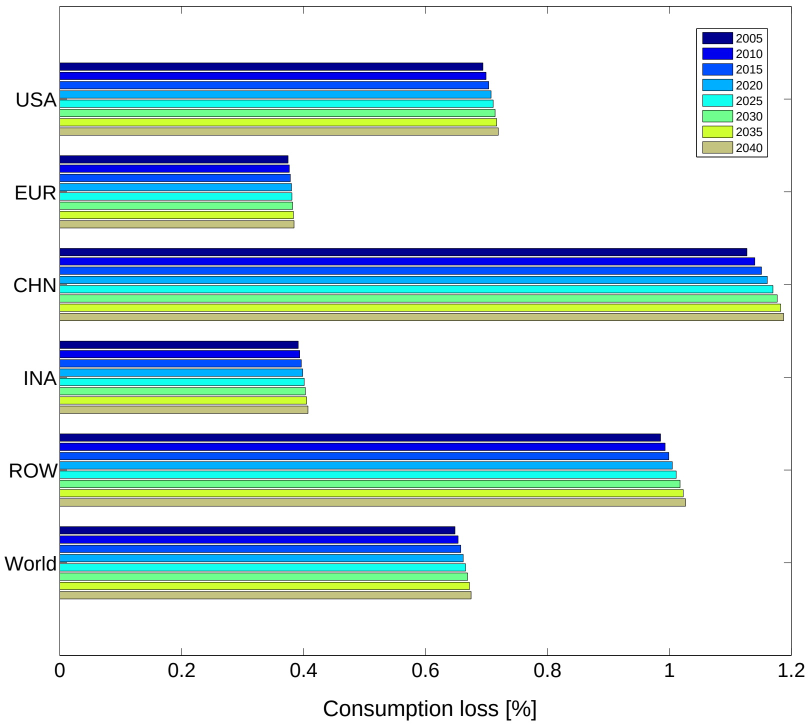

Figure 3: Regional effects of climate policy POL (carbon budget) for different start dates of financing international transfers (as indicated in the legend) of energy efficient technologies. Consumption losses are reported as the difference between POL and BAU consumption relative to BAU consumption for each start date of financing.

financing. Consumption losses obviously slightly rise when postponing the financing of international technology diffusion. Basically, Figure 3 illustrates that our integrated assessment model generates consumption losses of less than one percent for all regions except China. China is accordingly affected most severely, followed by the region Rest of the World and the USA. Europe can probably benefit from its good energy productivity and the developing region INA from its low per-capita emissions.

5 Discussion

Our policy analysis suggests relatively low mitigation costs of keeping a carbon budget of 400Gt for the time period 2005 to 2100. Our analysis also suggests relatively low additionally mitigation costs of postponing investment in international energy specific technology diffusion. However, we represent endogenous innovation and imitation and thus international financial and technological transfers in a very stylized fashion. Moreover, our integrated assessment model has a number of general limitations.

Our functional forms of modeling innovation and imitation follow the Schumpeterian model of endogenous growth. Other functional forms can lead to a different dynamic behavior, though. Also, from a micro-economic point of view, the implementation of the Schumpeterian model in ReMIND does not take profit maximization of *firms* and monopolistic power due to successful innovations explicitly into account. Similarly, production in each region is specified in form of a CES structure (as illustrated in Figure 5) that assumes certain elasticities of substitution. Variations in the CES structure and in the values of the elasticities of substitution principally influence the possibility to substitute the various forms of energy inputs by other forms of energy inputs as well as by capital and labor input. As a consequence, the design of the CES structure and the choice of the elasticity values influence mitigation costs.

Moreover, the dynamic calibration of complex, numerical, economic models always involves uncertainties. This is especially true with respect to international technology spillovers and related expenditures. Herein, we build on econometrical estimates. These estimates provide very useful parameter values but the estimated models do not exactly fit to our model. In particular, we combine R&D investment with capital investment, which is usually not the case in econometric studies. Also, econometrical studies usually use firm-level or industry-level data while we transfer the econometrical estimates to a global multi-region level. Furthermore, the comparison of model outcomes with reference data reveals a good match in many cases but also a few deviations, in particular with respect to growth rates of energy productivity in Europe and the USA. Given our model and our parametrization, the effect of climate policy on productivity growth through *induced* technical progress is small. However, other parameterizations can result in different growth paths and might create stronger induced technical progress.

Basically, our model shows the typical behavior of North-South growth models, i.e. strong adjustment processes in terms of investment and North-South transfers in early periods (c.f. Lucas 1990). This observation also applies to investments in innovation and imitation of labor and energy specific technologies. Consequently, most of the endogenous baseline and policy induced technology effects occur in early periods, while long-run growth paths evolve at low growth rates and are hardly affected by the policy experiments (c.f. Figure 7 in the Appendix). On the contrary, under the assumption of distant future economic growth at a constant high rate, GDP and resulting emissions would be higher in the long-run. This could lead to significantly higher negative welfare effects of climate policy (c.f. Hübler 2010). At the end of the time horizon, we do not impose a terminal condition, but we run the model until 2150 so that we need to consider end effects, also with respect to the carbon budget for the period 2005 until 2100. We do not take capital stocks remaining in 2100 into account, either. Nevertheless, the end effects are small and additionally discounted so that they do not significantly spoil our results.

Moreover, we only capture expenditures for the innovation and imitation of technologies that improve energy productivity on a macro-economic scale. We leave aside the international transfer of energy technologies like wind and solar power. The ReMIND model encompasses a full energy module, though. Herein, the calibration of the energy module is such that the resulting volumes of energy produced match the actually observed volumes in the benchmark period for each region and each energy technology or energy source. Nevertheless, variations in the calibration can produce different future energy mixes. Also, the high flexibility in the energy system enables a large expansion of renewable energies, especially biomass, and a future role of nuclear power, which eases decarbonization. Notably, the benchmark scenario already incorporates a substantial share of biomass as well as solar power in the second half of the 21st century as well as a renaissance of nuclear power. In this sense, our energy scenario is optimistic with respect to the availability of low-carbon energy technologies across regions. Not allowing for renewable energies and CCS in a climate policy analysis, consumption losses can significantly increase (to around 7% according to Edenhofer et al. 2005).

As a matter of course, mitigation costs strongly depend on the choice of the discount rate – which appears to be an open issue in policy modeling without any consensus within reach. Finally, the crude regional aggregation does not allow us to assess country-specific effects except for the major carbon emitters China and the USA.

Therefore, all policy results need to be taken with some caution and need to be interpreted with respect to the exemplary, reasonable base line scenario that we have calibrated based on econometrical, historical and scenario data.

In order to address some of the main aspects discussed above, we carry out a detailed sensitivity analysis for regional consumption losses stemming from climate policy POL: (1) We switch of the availability of all renewable energies and CCS (of coal, gas and biomass) in all regions (-REN). (2) We change all constant elasticities of substitution on all CES levels (c.f. Figure 5 in the appendix) to 0.2 and alternatively to 0.8. (3) We vary the elasticity of technical progress with respect to related investments governed by the exponents σ_R and σ_S simultaneously by the same factors two (twice the previous value) and 0.75. (4) We vary the strength of energy and labor specific innovation governed by λ_R and (5) the strength of energy and labor specific imitation governed by λ_S by the factors 1.5 and 0.75. (6) Finally, we raise the strength of energy specific innovation as well as imitation – keeping the strength of labor specific technical progress unchanged – by the factor 1.5. We then reduce it to one third so that it has the same strength as for labor ($\lambda_E = \lambda_L$). Herein, the range of the parameter value variations is limited by the capability of finding feasible and optimal solutions for the optimization problem as well as by economic reasoning.

The results are reported in Table 7 in the Appendix which shows consumption losses between POL and BAU, cumulated from 2005 until 2100 and discounted at a rate of 3% per year.[9] The most striking increases in mitigation costs occur when switching of the availability of renewables and CCS in (1) and when rasing the elasticities of substitution in the CES structure in (2). Global consumption losses rise to between 1.5 and 2%. China's consumption losses even rise to more than 4 or more than 5%. Herein, the peak of global carbon emissions in BAU rises from below 16Gt in the standard scenario to almost 20Gt in scenario (2) where the elasticities of substitution (σ_Y and all other elasticities of substitution in the CES structure) are changed to 0.8.[10] Obviously, this increase in BAU emissions overcompensates the higher flexibility in the CES structure that allows to shift away from energy inputs more easily. The opposite applies for the scenario with the reduced elasticity of substitution.

On the contrary, the impact of the variation in most of the coefficients and exponents

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[9] Energy specific technology transfer is not delayed but allowed from 2005 on. Therefore, the standard scenario resembles the 2005 result in Figure 3.

[10] Note that in this experiment the upper elasticities increase while the lower elasticities decrease in the CES nest, see Figure 5 in the Appendix.

in our model of endogenous growth is surprisingly small. The exemption is – as expected – the strength of energy specific technical progress (innovation as well as imitation based) for a constant strength of labor specific technical progress as examined in simulation (6). Accordingly, setting the strength of energy to the same value as labor specific technical progress, raises losses to more than 1% globally, and about 2% for China.

To conclude, our model of endogenous growth as it stands leads to relatively robust consumption losses as a measure for mitigation costs given our socio-economic scenario.

6 Conclusion

We have introduced endogenous directed technical change into integrated multi-region climate policy assessment. We have studied the regional consumption losses stemming from a global carbon budget based climate policy. Motivated by the announcement of providing financial and technological transfers for developing countries at the Cancún 2010 summit, we have examined the financing of international energy saving technology diffusion starting at different points of time.

According to our results, the consumption gains from early energy saving technology transfer are already captured in the baseline scenario without climate policy. In general, all regions gain from technology transfer, given our stylized model framework. China appears as the main beneficiary of early financing technology diffusion, followed by the region of developing countries. These results suggest that financing energy saving technology transfer mainly serves economic development and consumption gains of developing countries, which is certainly a desirable goal. The decarbonization of economic development, however, requires the switch from fossil based energies to renewable energies. In our model setup, such renewable energies are – to regionally different extents – available in all regions. Further research may therefore assess in how far the international transfer of renewable energies and the timing of such transfers can affect regional mitigation costs.

Nevertheless – or even more convincingly – financing energy saving technology transfer as assessed in this article could be used as a 'carrot' to encourage developing countries to engage in climate protection.

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8 Appendix

Symbol	Explanation
$t = \{2005, 2010, ..2100\}$	Time (5-year steps)
$r = \{INA, CHN,$ $ROW, EUR, USA\}$	Regions (INA: Africa, Latin America, India and other Asia - CHN: China - ROW: Middle East, Japan, Russia, rest of the world - EUR: Europe - USA: United States of America)
$i = \{L, E\}$	Factors affected by tech progress (labor, energy)
Y_{rt}	Production (income)
A_{rt}	Technology level
$\bar{A}_t$	Average global technology level (technology pool)
K_{rt}	Capital input
L_{rt}	Labor input
E_{rt}	Energy input
I_{rt}	Investment in capital
R_{rit}	Innovation or R&D expenditures
S_{rit}	Imitation expenditures

Table 5: Sets and endogenous variables.

Symbol	Explanation	Value			
λ_i	Factor specialty of technical progress	L:	1	E:	3
λ_{r2005}	Education level in 2005	INA:	0.3	CHN:	0.7
		ROW:	0.4	EUR:	0.75
		USA:	0.9		
$\lambda_{R/S}$	Coefficient of R&D vs. imitation expd.	R:	0.4	S:	0.12
$\sigma_{R/S}$	Exponent of R&D vs. imitation expd.	R:	0.1	S:	0.01
$\sigma_{A/I}$	Exponent of tech. gap and investment	A:	1	I:	1

Table 6: Exogenous parameters.

Region	Default	(1) -REN	(2) $\sigma_Y = .2$	$\sigma_Y = .8$	(3) $2\sigma_{R/S}$	$.75\sigma_{R/S}$	(4) $1.5\lambda_R$	$.75\lambda_R$	(5) $1.5\lambda_S$	$.75\lambda_S$	(6) $1.5\lambda_E$	$.33\lambda_E$
USA	0.69	1.93	0.67	1.41	0.77	0.67	0.65	0.71	0.63	0.72	0.48	1.20
EUR	0.37	1.32	0.45	0.62	0.40	0.36	0.36	0.38	0.35	0.39	0.28	0.53
CHN	1.13	4.14	1.25	5.38	1.25	1.09	1.07	1.15	1.05	1.15	0.76	2.05
INA	0.39	1.55	0.34	0.51	0.42	0.38	0.39	0.39	0.44	0.32	0.27	0.68
ROW	0.99	0.29	0.42	2.85	1.08	0.95	0.94	1.01	0.88	1.01	0.66	1.64
World	0.65	1.64	0.55	1.78	0.71	0.63	0.62	0.66	0.62	0.65	0.45	1.10

Table 7: Sensitivity analysis for regional consumption losses reported as the difference between POL and BAU consumption relative to BAU consumption in %. The losses are cumulated from 2005 to 2100 and discounted at a rate of 3% p.a.

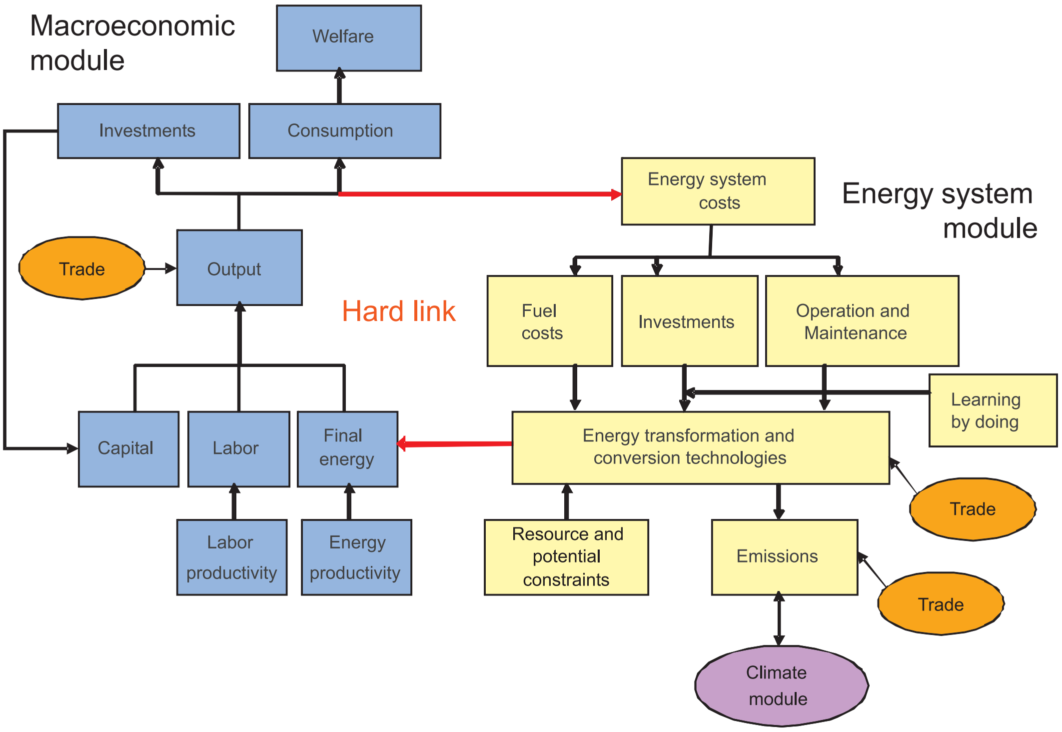


Figure 4: The ReMIND modules and their interaction.

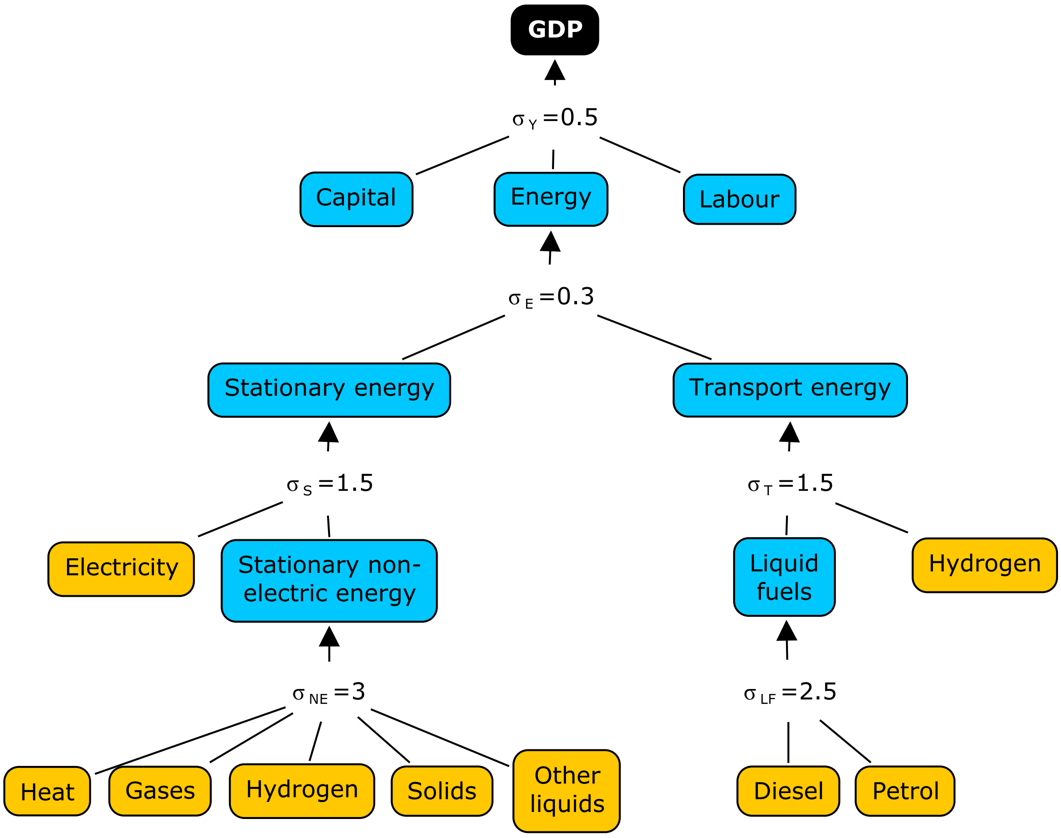


Figure 5: The CES structure of the regional ReMIND production function; σ indicates constant elasticities of substitution.

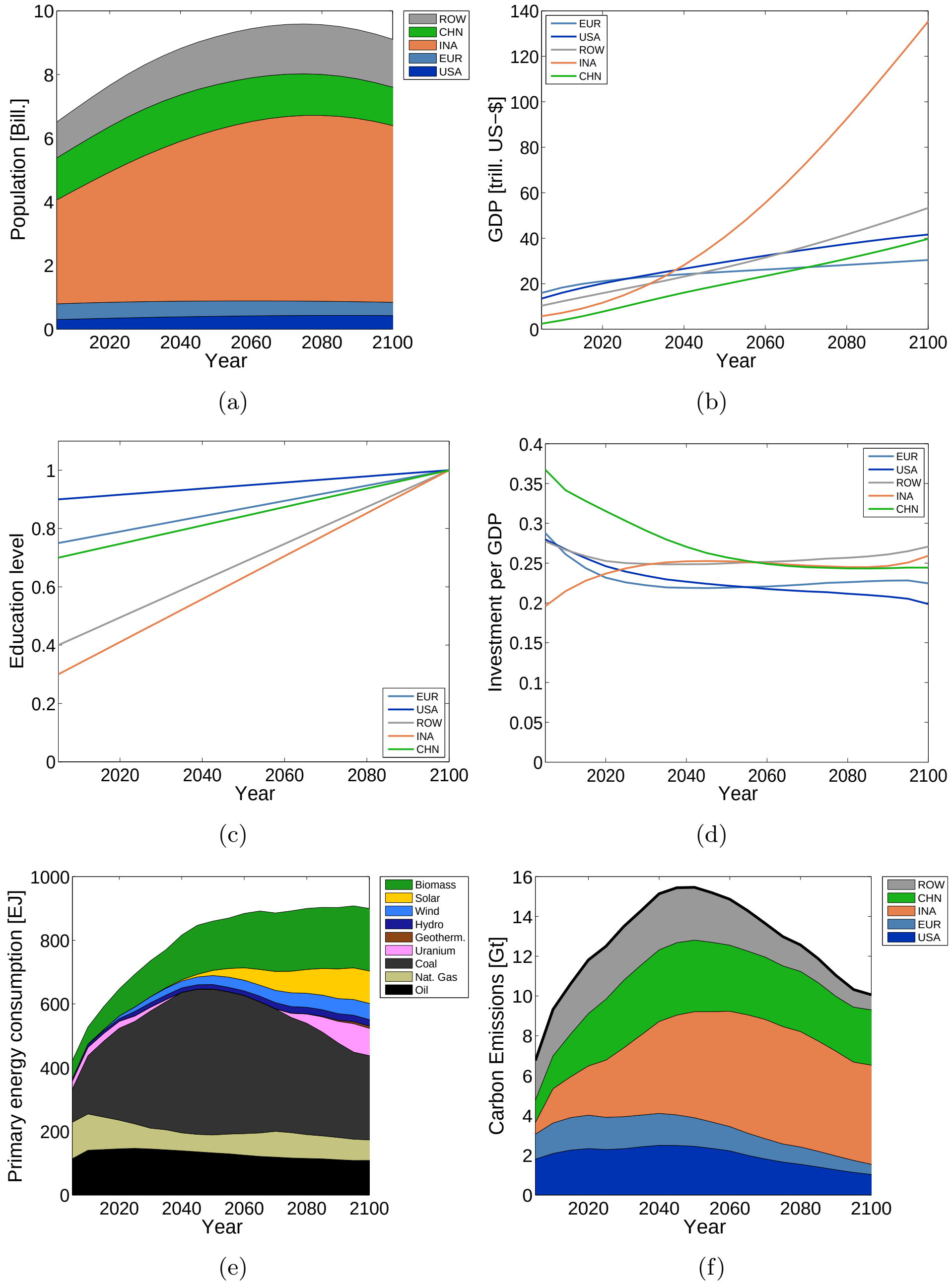
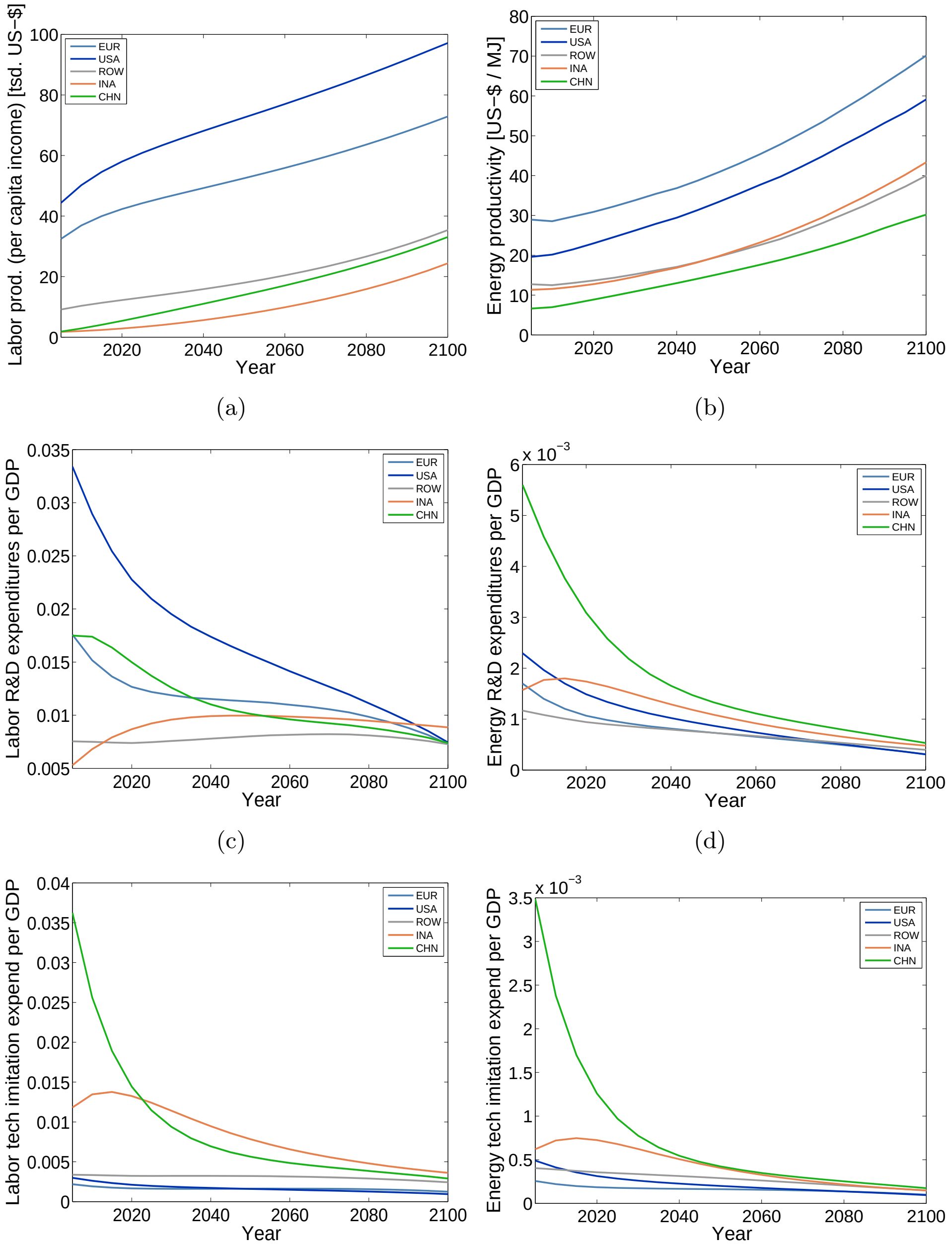


Figure 6: Simulation results for BAU.



(a) (b)

(c) (d)

(e) (f)

Figure 7: Simulation results for BAU.