

An Integrated Assessment Model with Endogenous Growth

Michael Hübler*, Lavinia Baumstark,
Marian Leimbach, Nico Bauer, Ottmar Edenhofer

August 5, 2011

Abstract

We introduce endogenous directed technical change into numerical integrated climate and development policy assessment. We distinguish expenditures on innovation (R&D) and imitation (international technology spillovers) and consider the role of capital investment in creating and implementing new technologies. Our main contribution is to calibrate and numerically solve the model and to examine the model's sensitivity. As an application, we assess a carbon budget-based climate policy and vary the begin of energy-saving technology transfer. As a result, most of the consumption gains from endogenous growth are captured in the baseline. Herein, China is a main beneficiary of early technology transfer. Mitigation costs turn out to be insensitive to changes in most of the parameters of endogenous growth. A higher effectivity of energy specific relative to labor specific expenditures on innovation and imitation reduces mitigation costs, though.

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

Keywords: endogenous growth, directed technical change, technology transfer, integrated assessment, carbon budget, China

*Corresponding, leading author, email: huebler@zew.de, tel: +49-621-1235-340, fax: +49-621-1235-4340, Centre for European Economic Research, Postfach 103443, 68034 Mannheim, Germany. All coauthors' affiliation: Potsdam Institute for Climate Impact Research, Telegraphenberg A31, 14412 Potsdam, Germany. We thank Elmar Kriegler for his help regarding IPCC scenarios. We thank the Leibniz Association (WGL) for financial support.

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. Setting up such a model and calibrating it to real world data is the first and main contribution of this paper. Due to the uncertainties in the parameter values in a model of endogenous growth, we conduct a careful sensitivity analysis. This is the second contribution of this paper.

It is widely agreed that OECD countries bear the main responsibility for climate change while the developing countries will bear most of its impacts. Private investment on a national or international scale is expected to bring about the relevant capacities and technologies for climate change mitigation and adaptation. But since many developing countries lack in financial resources, knowledge, technologies and the ability to adopt technologies, international support is required to achieve economic development and carbon emission reduction simultaneously. Therefore, in recent climate negotiations (Bali Roadmap 2007, Copenhagen 2009 and Cancún 2010 summit), developing countries called for financial and technological support for mitigation, and industrialized countries announced to provide such support. Apart from revenues acquired by selling emissions permits, developing countries can receive such support through technology funds like 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 by 2020 in the Copenhagen Accord. 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 of endogenous growth to the assessment of mitigation costs induced by a carbon budget-based policy and the costs of delaying international technology transfer.¹ This is the third contribution of

¹We leave the specific channels – such as FDI – and policy instruments – for instance a technology

this paper.

Our model approach refers to state-of-the-art theoretical models of endogenous growth.² 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 refer to the latter model type, however on a stylized macro level without treating profit maximizing firms explicitly. Acemoglu et al. (2003, 2006) 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 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' term (more specifically a 'technology pool' term) in our model. Herein, the model allows an endogenous simultaneous choice between innovation and imitation which are treated as substitutes. It basically reproduces the findings by Acemoglu et al. (2003, 2006) 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 a supplement 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

fund – for achieving international technology transfer open.

²As comprehensively described by Aghion and Howitt (2009), chapter 4 and Acemoglu (2009), chapters 14, 15 and 18.

(factor-saving technical progress) when the elasticity of substitution between the production factors is smaller than one, which is the case in our model (in the upper CES level).

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 2011). 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 3 and Figure 4 in the Appendix), a Ramsey type model of intertemporally 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. Technology spillovers are controlled in a centralized way. International trade is subject to an intertemporal trade budget restriction following Negishi (1972) which creates a decentralized solution for trade. The macro model 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 of coal, gas and biomass; c.f. Leimbach et al. 2010a, b). The energy system 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 system 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 baseline 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 and carries out a sensitivity analysis. Section 6 concludes by deriving policy implications.

2 Model

We derive the implementation of directed technical change in an intertemporal optimization framework in four steps from economic theory: (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. (Table 6 and Table 7 in the Appendix provide an overview of the sets, variables and parameters of our model of endogenous growth.)

(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 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:³

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

$t = \{2005, 2010, \dots, 2100\}$ denotes time, more specifically years increasing in five-year steps. λ_R determines the impact of R&D expenditures on the probability of success in a linear fashion. σ_R creates a decreasing marginal effect of R&D expenditures on the probability of success with rising expenditures, where $0 < \sigma_R < 1$. 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:

$$A_{t+5}^R = \mu\gamma A_t + (1 - \mu)A_t \Leftrightarrow \frac{A_{t+5}^R - A_t}{A_t} = \mu(\gamma - 1) =: g_R \quad (2)$$

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.⁴ 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 literature based on Arrow (1962) 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:

$$A_{t+5}^{RI} = (1 + g_R)A_t \left(\frac{I_t}{K_{t+5}} \right)^{\sigma_I} + A_t \left[1 - \left(\frac{I_t}{K_{t+5}} \right)^{\sigma_I} \right] \quad (3)$$

I_t is investment in capital, and $K_{t+5} = (1 - \delta)K_t + I_t$ is the new capital stock, where δ is the depreciation rate. We assume $\sigma_I = 1$.⁵ Then, according to the equation above, the

³We will add region and factor specific indexes in the final set of equations.

⁴One may add depreciation of knowledge which is less common in theoretical growth models than in applied assessment models.

⁵Allowing $0 < \sigma_I < 1$ means, it becomes increasingly difficult or costly to replace a larger fraction of the capital stock by the newest technology.

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 :

$$A_{t+5}^{RI} = A_t \left[1 + (\gamma - 1)\lambda_R \left(\frac{R_t}{A_t} \right)^{\sigma_R} \left(\frac{I_t}{K_{t+5}} \right)^{\sigma_I} \right] \quad (4)$$

(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 rate of technical progress now reads:

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

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.⁶ 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

⁶According to Acemoglu (2009), chapter 18 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.

'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:

$$A_{t+5}^{SI} = A_t \left[1 + \lambda_S \left(\frac{S_t}{A_t} \right)^{\sigma_S} \left(\frac{I_t}{K_{t+5}} \right)^{\sigma_I} \left(\frac{\bar{A}_t}{A_t} \right)^{\sigma_A} \right] \quad (6)$$

(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 includes the input factors capital, K , labor, L , and energy, E , and has the following form:

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

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.

After combining the effects (1) to (4), i.e. adding up Equations (4) and (6), $A_{t+5} = A_{t+5}^{RI} + A_{t+5}^{SI}$, and introducing a factor index $i = \{L, E\}$ and a region index r , we obtain the final equation below:

$$A_{rit+5} = A_{rit} \left\{ 1 + \lambda_i \lambda_{rt} \left[\lambda_R \left(\frac{R_{rit}}{A_{rit}} \right)^{\sigma_R} + \lambda_S \left(\frac{S_{rit}}{A_{rit}} \right)^{\sigma_S} \left(\frac{\bar{A}_{it}}{A_{rit}} \right)^{\sigma_A} \right] \left(\frac{I_{rt}}{K_{rt+5}} \right)^{\sigma_I} \right\} \quad (8)$$

Since Equations (4) and (6) are combined in an additive way, innovation and imitation are treated as substitutes. As a result and in accordance with the micro-foundations described by Acemoglu et al. (2003, 2006), imitation is more beneficial farther away from the technology frontier (in our case technology pool), while innovation (Equation 4) is

more beneficial closer to the technology frontier. Moreover, we extend the parameters λ_R and λ_S that determine the strength of innovation and imitation into a factor specific 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.⁷ 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 utility drawn from per capita consumption across all regions, cumulated and discounted over the time horizon. Regional weighting follows Negishi (1972). 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 so that consumption in each region is given by:

$$C_{rt} = Y_{rt} + M_{rt} - I_{rt} - Q_{rt} - R_{rLt} - R_{rEt} - S_{rLt} - S_{rEt} \quad (9)$$

The marginal product of physical capital K_{rt} rises as a consequence of technical progress which stimulates capital investment I_{rt} . Additionally, the ReMIND model encompasses an energy system module that distinguishes several energy sources (coal, gas, oil, uranium, hydro, biomass, solar, wind, geothermal). Investments into capacities of the related energy technologies, fuel, operation and maintenance costs are also subtracted from the budget like investment in physical capital as a production factor. They are subsumed under energy system expenditures Q_{rt} in the equation above. Finally, M_{rt} denotes net imports of each region. The ReMIND model applies an algorithm based on Negishi (1972) that adjusts regional weights in the welfare function

⁷For example, a state-of-the-art washing machine will save energy and save time spent for operating it to different extents.

such that the intertemporal trade budget is equal to zero for all regions in 2150. This algorithm creates a decentralized Nash solution with respect to interregional trade. M_{rt} represents trade in goods and services as well as international transfers. The latter will be important in our analysis of financing international technology diffusion. Obviously, any interregional transfer M_{rt} can be used for consumption and the various kinds of investment in physical capital, energy technology capacities, innovation and imitation such that the resulting investment pattern is optimal.

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. The overall calibration follows the version ReMIND-R 'RECIPE' (Edenhofer et al. 2009). Within our model of endogenous growth, we need to calibrate the parameters λ_i (factor specialty of technical progress), λ_{r2005} (education level in 2005), λ_R (coefficient of innovation expenditures), λ_S (coefficient of imitation expenditures), σ_R (exponent of innovation expenditures), σ_S (exponent of imitation expenditures), σ_A (exponent of the technology gap term) and σ_I (exponent of the investment term). Table 7 in the Appendix summarizes the parameters and the corresponding values that will be derived in the following. 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) Econometric estimations. Griffith et al. (2003) reconcile the theoretical literature on Schumpeterian endogenous growth with the econometric 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 expendi-

tures 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 accordance 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 coefficients translate into the R&D coefficient λ_S for technology diffusion and imitation. 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 econometric specification, we set λ_S to a lower number 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 σ 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 R&D expenditures 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).⁸ Moreover, we assume that regions that lack in education 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 5 in the Appendix).

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 reference data well in many cases, but there are also significant deviations, e.g. the growth rates of energy productivity in Europe and in the USA. Furthermore, Figure 5 and Figure 6 in the Appendix illustrate relevant indicators of the model dynamics. Herein, it is important to note that our optimization model generates the globally, socially optimal allocation of expenditures on imitation and innovation. This means, the positive external effect of international technology spillovers is internalized. International trade, on the contrary, occurs in a decentralized Nash game.

Obviously, the high-income regions USA and EUR follow innovation-based strategies while the low-income regions INA and CHN follow imitation-based strategies as suggested by Acemoglu et al. (2003, 2006). 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 is limited data on R&D expenditures

⁸We 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 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.	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 inno. 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 inno. expd.	BAU:	0.2	0.6	0.1	0.2	0.2
		REF:	0.4	0.5
S_{rL2005}/Y_{r2005}	Labor imit. expd.	BAU:	1.2	3.6	0.3	0.2	0.3
S_{rE2005}/Y_{r2005}	Energy 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). g denotes an average *yearly* growth rate over a five-year period. 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.)

in developing countries. Nevertheless, it is well-known that mainly the industrialized regions drive innovation which is reflected in their R&D expenditures.⁹ Moreover, data sources report total R&D expenditures but not labor specific R&D expenditures as required for our model. Nevertheless, economic growth is mainly driven by labor specific technical progress in our model as in many growth models so that it is a direct substitute for general technical progress. Energy specific R&D expenditures are available from IEA (2010). However, the data cover less than the OECD countries. Finally, there are

⁹SEI (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, Africa 0.6.

probably no data available about expenditures on 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 on 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 $\lambda_L=1$ and $\lambda_E=3$.

(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 to low 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 5 in the Appendix. The resulting baseline emissions are comparatively low.

4 Assessment

This section applies our model exemplarily to the assessment of (1) a carbon budget-based climate policy and (2) an analysis of delayed energy-saving technology transfer.

(1) *Carbon budget-based climate policy*: We first impose a budget of global emissions cumulated from 2005 to 2100 amounting to 400Gt of carbon (following Meinshausen et al. 2009 and Allen et al. 2009). The emissions budget is supposed to translate

Symbol	Explanation	Scen.	Result
L_{2100}	Global population (= labor force) [bill.]	BAU:	9.1
		B1:	7.1
		B2:	10.4
Y_{2100}	Global GDP [trill. US-\$]	BAU:	300
		B1:	339
		B2:	255
E_{2100}	Global primary energy cons. p.a. [EJ]	BAU:	900
		B1:	791
		B2:	1370
$Q_{2005-2100}$	Global cumulated carbon emissions [Gt]	BAU:	1258
		B1:	1345
		B2:	1290

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

into a temperature goal of about two degree in a statistically robust way. Emissions permits are allocated across regions following a Contraction and Convergence approach (GCI 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, the model generates the globally, socially optimal allocation of expenditures on imitation and innovation. This means, the positive external effect of international technology spillovers is internalized. Moreover, this globally, socially optimal solution is independent of distribution matters such as the permit allocation scheme. The permit allocation scheme of course affects regional consumption losses stemming from climate policy. Finally, the ReMIND model applies the Negishi (1972) algorithm such that regions are not allowed to create debts or surpluses beyond 2100. Therefore, international transfers can be interpreted as loans that are granted in earlier periods and payed back in later periods.

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 inno. expd.	-.02	-.03	-.01	-.01	-.03
$\Delta\varnothing(R_{rE2005}/Y_{r2005})$	Energy inno. expd.	.02	.02	.01	.01	.05
$\Delta\varnothing(S_{rL2010}/Y_{r2010})$	Labor imit. expd.	-.002	-.002	-.003	-.012	-.031
$\Delta\varnothing(S_{rE2005}/Y_{r2005})$	Energy imit. expd.	.002	.004	.003	.005	.029

Table 3: Impacts of policy POL (carbon budget) with respect to BAU; changes in yearly 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.)

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 shows 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. Significant changes can be observed for energy productivity growth which is partly due to shifts in R&D investments. 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 tables, the effects have the expected signs: Investments in energy-saving innovation and imitation increase due to the emissions restriction while investments in labor-saving innovation and imitation

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

decrease.¹⁰ As a consequence, GDP growth rates also decrease. Notably, the investment share in GDP increases in some regions and years (and also on average as shown in Table 4), probably since a higher investment share enhances the implementation of energy-saving technologies in physical capital as incorporated in our model of technical progress.

Moreover, we run the following experiment, denoted by 'Fixed':¹¹ We run BAU. Then we fix the expenditures on innovation and imitation (R_{rit} , S_{rit}) at their BAU levels and run POL. We compute differences between POL and BAU and compare the results with the differences between POL and BAU computed previously, denoted by 'Endogenous'. It turns out that all regions benefit from policy induced technical progress in experiment 'Endogenous' compared with 'Fixed'. However, the difference in mitigation costs between 'Fixed' and 'Endogenous' has a similar small magnitude as in the results presented in Table 3 and Table 4, i.e. about 0.01 percentage points.

(2) *Delayed energy-saving technology transfer:* In the following, we will assess in how far postponing energy specific international technology transfer affects mitigation

¹⁰Nevertheless, there can be single cases with opposite signs in general.

¹¹Not explicitly shown in the tables.

costs given the previous climate policy. International technology transfer requires a sufficient absorptive capacity determined among other factors by the business and legal environment. It requires investments in the absorption and imitation of technologies and in physical capital financed from national or international sources. Herein, climate policy can play an active role in creating the necessary absorptive capacity and fostering national and international financing.

Accordingly, in our model, 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 the composite commodity) within the general budget (Equation 9). Postponing international technology transfer is represented in the following stylized way: Energy specific imitation expenditures S_{rEt} 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 energy specific 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 technological knowledge. Second, regions can benefit from technical progress in other regions through international transfers or in other words through commodity trade.

As expected, China 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

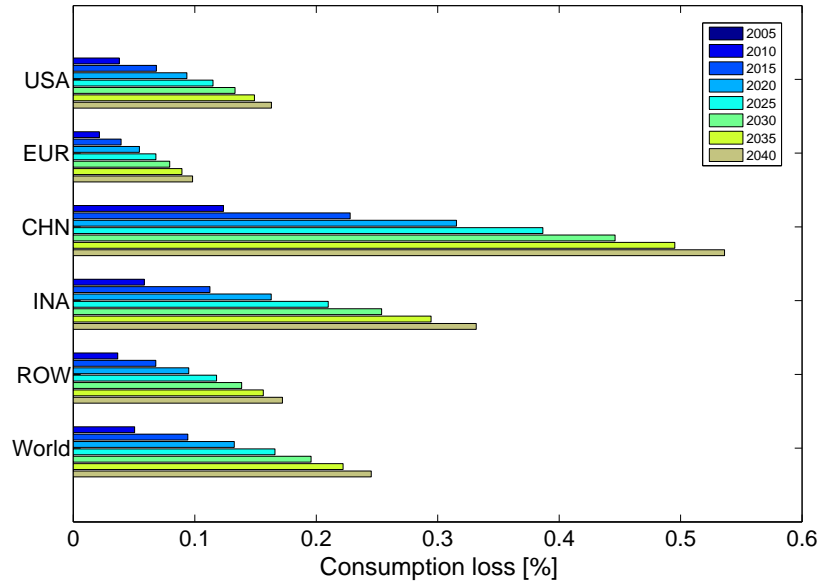


Figure 1: Regional effects of postponing international transfers of energy efficient technologies. Consumption losses are reported as the percentage change between consumption in a baseline scenario BAU where transfers are postponed (as indicated in the legend) and consumption in the baseline scenario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

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. Intuitively, early investments in technical progress are beneficial over the whole time horizon while late investments have a limited remaining scope.

Figure 2 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 financing. Consumption losses obviously slightly rise when postponing the financing of international technology diffusion. Basically, Figure 2 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

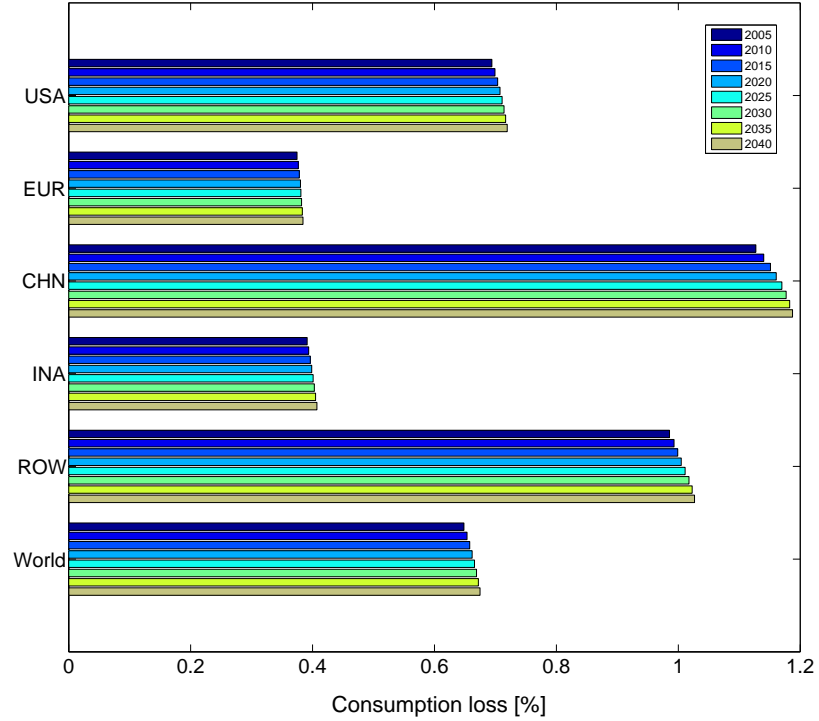


Figure 2: Regional effects of climate policy POL (carbon budget) for different start dates (as indicated in the legend) of international transfers of energy efficient technologies. Consumption losses are reported as the percentage change between POL and BAU consumption for each start date of transfers.

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 in the context of interregional permit trading so that mitigation costs are low. However, most of the consumption gains from early technology transfer have already been exploited in BAU.

5 Sensitivity

This section (I) critically discusses model characteristics and (II) addresses them in a sensitivity analysis.

(I) Our integrated assessment model has the following characteristics:

We represent endogenous innovation and imitation and thus international technology transfer in a stylized fashion. Our functional forms of modeling innovation and imitation follow the Schumpeterian model of endogenous growth. Other functional forms might lead to a different dynamic behavior, though. Also, from a micro-economic point of view, the implementation of the Schumpeterian model does not take profit maximization of *firms* and monopolistic power in intermediate production explicitly into account. In fact, our model reproduces the typical behavior of endogenous growth models on the macro level.

Moreover, in each region production is specified in form of a standard CES structure (as illustrated in Figure 4 in the Appendix) that assumes certain elasticities of substitution which determine the possibility of switching between energy, capital and labor and between specific energy inputs. This structure and the elasticity values influence mitigation costs.

In general, the calibration of any complex, dynamic, numerical models involves uncertainties. This is especially true with respect to modeling innovation and international technology diffusion and related expenditures. We build our calibration on econometric estimates. These estimates provide a range of appropriate parameter values but the estimated models do not match our model one by one. Furthermore, the comparison of model outcomes with reference data reveals a good match in most cases. Initial growth rates of energy productivity in Europe and the USA are slightly lower than in the reference data. In general, the sensitivity of the model with respect to policy induced effects appears small.

Basically, our model shows the typical behavior of North-South growth models, i.e. strong adjustment processes in early periods in terms of investment in capital and technology, and strong North-South transfers (from USA, EUR and ROW to INA and CHN; c.f. Lucas 1990). Consequently, most of the policy induced technology effects occur in early periods, too, while long-run growth paths evolve at low growth rates (c.f. Figure 6 in the Appendix) and are hardly affected by the policy experiments. On the contrary, under the assumption of distant future economic growth at a constant high rate, GDP and emissions and the resulting mitigation costs would be higher (c.f. Hübler 2011). Moreover, discounting gives a lower weight to future consumption and its pol-

icy induced changes and consequently influences mitigation costs as in every economic long-run analysis.

Furthermore, we only capture expenditures on 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 in this analysis. The ReMIND model encompasses a full energy system module, though, which enables the early expansion of renewable energies and the decarbonization of energy supply in every region. Herein, the energy system module is calibrated to benchmark data. The future development of the energy mix represents one possible scenario.

Our policy analysis suggests relatively low mitigation costs of keeping a carbon budget of 400Gt for the time period 2005 to 2100, given a baseline scenario of relatively low emissions.

Therefore, in summary all policy results need to be taken with some caution. They need to be interpreted with respect to the baseline scenario that we have calibrated based on econometric, historical and scenario data.

(II) In the following, we address the aspects discussed above by carrying out a detailed *sensitivity analysis* for regional consumption losses stemming from climate policy POL based on the BAU scenario 'Default' that we have examined so far:

(1) We switch off the availability of all renewable energies and CCS (of coal, gas and biomass) in all regions ('-Renew'). (2) We change the constant elasticity of substitution in the upper CES level (c.f. Equation 7 and Figure 4 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, namely 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.

Region	Default	(1)	(2)		(3)	
		-Renew	$\sigma_Y = 0.2$	$\sigma_Y = 0.8$	$2 \cdot \sigma_{R/S}$	$0.75 \cdot \sigma_{R/S}$
USA	0.69	1.93	0.45	1.20	0.77	0.67
EUR	0.37	1.32	0.28	0.52	0.40	0.36
CHN	1.13	4.14	0.49	2.48	1.25	1.09
INA	0.39	1.55	0.28	0.46	0.42	0.38
ROW	0.99	0.29	0.30	2.11	1.08	0.95
World	0.65	1.64	0.34	1.20	0.71	0.63

Region	(4)		(5)		(6)	
	$1.5 \cdot \lambda_R$	$0.75 \cdot \lambda_R$	$1.5 \cdot \lambda_S$	$0.75 \cdot \lambda_S$	$1.5 \cdot \lambda_E$	$0.33 \cdot \lambda_E$
USA	0.65	0.71	0.63	0.72	0.48	1.20
EUR	0.36	0.38	0.35	0.39	0.28	0.53
CHN	1.07	1.15	1.05	1.15	0.76	2.05
INA	0.39	0.39	0.44	0.32	0.27	0.68
ROW	0.94	1.01	0.88	1.01	0.66	1.64
World	0.62	0.66	0.62	0.65	0.45	1.10

Table 5: Sensitivity analysis for regional mitigation costs reported as the percentage change between POL and BAU consumption. The losses are cumulated from 2005 to 2100 and discounted at a rate of 3% p.a.

The results are reported in Table 5 which shows consumption losses between POL and BAU, cumulated from 2005 until 2100 and discounted at a rate of 3% per year.¹² The baseline scenario 'Default' is the same as in the previous analysis. Accordingly, global consumption losses exceed 0.5%. The most striking increase in mitigation costs to more than 1.5% of global consumption occurs when switching of the availability of renewable energies and CCS in experiment (1) '-Renew'. Herein, China's consumption losses even rise to more than 4%. Moreover, a significant increase in global consumption losses to more than 1% occurs when raising the elasticity of substitution in the upper CES nest in (2). Herein, the peak of global carbon emissions in BAU rises from below 16Gt in the standard scenario to almost 20Gt in experiment (2) where the elasticity of substitution is raised ($\sigma_Y = 0.8$). Obviously, the higher flexibility in the production structure already increases BAU production and emissions which overcompensates the

¹²Energy specific technology transfer is not delayed but allowed from 2005 on. Therefore, scenario 'Default' resembles the 2005 result in Figure 2.

resulting improved possibility to replace fossil fuel inputs in POL. The opposite applies to the scenario where the elasticity of substitution is reduced ($\sigma_Y = 0.2$).

On the contrary, the impact of the variation in most of the coefficients and exponents within our model of endogenous growth is surprisingly small. An exemption is the strength of energy specific technical progress (based on innovation as well as imitation) for a given strength of labor specific technical progress as examined in experiment (6). Accordingly, setting the coefficient that governs the strength of energy specific technical progress equivalent to the coefficient of labor specific technical progress ($0.33 \cdot \lambda_E = \lambda_L$) raises global losses to more than 1% and China's losses to about 2%. On the contrary, mitigation costs are hardly affected in experiments (4) and (5) where the strength of energy and labor specific innovation and imitation is varied simultaneously to the same extent. This result emphasizes the role of energy specific technical progress *relative* to general or labor specific technical progress with respect to mitigation costs.

6 Conclusion

We introduce endogenous directed technical change into integrated assessment based on theory and evidence. We distinguish innovation and imitation, in other words international technology transfer, and take the role of capital investment in creating and implementing new technologies into account. We study the regional pattern of mitigation costs in form of consumption losses induced by a global carbon budget-based climate policy.

Mitigation costs turn out to be robust with respect to a variation in the parameter values within our model of endogenous growth – except the coefficient of energy specific *relative* to the coefficient of labor specific innovation and imitation expenditures. This result suggests that a higher effectivity (in terms of technical progress per unit of investment) of energy specific innovation and imitation expenditures can overcompensate rising emissions due to economic growth and thus reduce mitigation costs. However, the effectivity is exogenously determined by technological restrictions and at best partly susceptible by economic policy in the short-run in reality. In the medium- to long-run, the effectivity could be improved by emphasizing energy efficiency aspects in educa-

tion, basic research, infrastructure, structural change and capacity building for R&D and for the absorption of foreign technologies. While our analysis exogenously adjusts a regional parameter representing education and absorptive capacity, further research may endogenize such a parameter in order to represent fundamental aspects of long-run development.

Motivated by the announcement of providing financial and technological transfers for developing countries at the Cancún 2010 summit, we examine interregional energy-saving technology transfer starting at different points of time. Herein, in general, all regions gain from technology transfer due to its growth effect. China appears as the main beneficiary of early technology transfer, followed by the region of the developing countries. These results suggest that enabling energy-saving technology transfer as soon as possible supports developing countries, which is a desirable goal. The decarbonization of economic development, however, additionally requires the switch from fossil 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.

In general, our results suggest that endogenous energy specific technical progress has already been strongly exploited in the business as usual (BAU) baseline due to its positive effect on consumption. This might be due to perfect foresight and regionally weighted global optimization in combination with energy scarcity. In reality, these baseline gains are not fully exploited on a market base due to risks and frictions and missing information (for possible baseline gains see McKinsey&Company 2009). Realizing these gains may require active policy support in form of an integrated climate and energy policy concept. Due to these baseline gains, the early support of energy-saving technology transfer could be a 'carrot' to encourage developing countries to engage in climate protection.

7 References

Acemoglu, D., P. Aghion and F. Zilibotti (2003). Vertical Integration and Distance to Frontier. *Journal of the European Economic Association* 1(2-3), 630-638.

Acemoglu, D., P. Aghion and F. Zilibotti, (2006). Distance to Frontier, Selection, and Economic Growth. *Journal of the European Economic Association* 4(1), 37-74.

Acemoglu, D. (2002). Directed Technical Change. *The Review of Economic Studies* 69(4), 781-809.

Acemoglu, D. (2009). *Introduction to Modern Economic Growth*. Princeton University Press, New Jersey, USA.

Aghion, P. and P. Howitt (1992). A Model of Growth through Creative Destruction. *Econometrica* 60(2), 323-351.

Aghion, P. and P. Howitt (2009). *The Economics of Growth*. The MIT Press, Cambridge, Massachusetts, USA and London, England.

Allen, M.R., D.J. Frame, C. Huntingford, C.D. Jones, J.A. Lowe, M. Meinshausen and N. Meinshausen (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* 458(7242), 1163.

Arrow, K. (1962). The Economic Implications of Learning by Doing. *Review of Economic Studies* 28, 155-173.

Benhabib, J. and M. Spiegel (2005). Human capital and technology diffusion. In: P. Aghion and S. Durlauf (eds.), *Handbook of Economic Growth*, Elsevier, chapter 13.

Bosetti, V., C. Carraro, E. Massetti and M. Tavoni (2008). International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. *Energy Economics* 30(6), 2912-2929.

Crassous, R., J.-C. Hourcade and O. Sassi (2006). Endogenous Structural Change and Climate Change Targets – Modeling Experiments with Imacim-R. *The Energy Journal* 27, Special Issue: Endogenous Technological Change and the Economics of Atmospheric Stabilisation, 259-276.

Crespo J., C. Martin and F. Velazquez, (2004). International technology spillovers from trade: the importance of the technological gap. *Investigaciones Economicas, Fundacion SEPI* 28(3), 515-533.

Diao, X., J. Rattsø and H.E. Stokke (2005). International spillovers, productivity growth and openness in Thailand: an intertemporal general equilibrium analysis. *Journal of Development Economics* 76, 429-450.

Edenhofer, O., N. Bauer and E. Kriegler (2005). The impact of technological change on climate protection and welfare: Insights from the model MIND. *Ecological Economics* 54, 277-292.

Edenhofer, O., C. Carraro, J.-C. Hourcade, K. Neuhoff, G. Luderer, C. Flachsland, M. Jakob, A. Popp, J. Steckel, J. Strophschein, N. Bauer, S. Brunner, M. Leimbach, H. Lotze-Campen, V. Bosetti, E. de Cian, M. Tavoni, O. Sassi, H. Waisman, R. Crassous-Doerfler, S. Monjon, S. Dröge, H. van Essen, P. del Rio, A. Türk (2009). *RECIPE - The Economics of Decarbonization*, Synthesis Report, 96 pp.

GCI (1990). Contraction and Convergence (C&C) is the science-based, global climate policy framework proposed to the UN since 1990 by the Global Commons Institute. <http://www.gci.org.uk/>.

Greiner, A. and W. Semmler (2002). Externalities of investment, education and economic growth. *Economic Modelling* 19, 709-724.

Griffith, R., S. Redding and J. van Reenen (2003). R&D and Absorptive Capacity: Theory and Empirical Evidence. *Scand. Journal of Economics* 105(1), 99-118.

Griliches, Z. and F. Lichtenberg (1984). Interindustry Technology Flows and Productivity Growth: A Reexamination. *Review of Economics and Statistics* 66(2), 324-329.

Grossman, G. and E. Helpman (1991). *Innovation and Growth in the Global Economy*. The MIT Press, Cambridge, Massachusetts, USA and London, England.

Hübler, M. (2011). Technology Diffusion under Contraction and Convergence: A CGE Analysis of China. *Energy Economics* 33(1), 131-142.

IEA (2010). Data Services. International Energy Agency, Paris, France. <http://data.iaea.org/IEASTORE/DEFAULT.ASP>.

IPCC (2000). Special Report on Emissions Scenarios (SRES). Intergovernmental Panel on Climate Change, Geneva, Switzerland.
http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/.

Kahouli-Brahmi, S. (2008). Technological learning in energy-environment-economy modelling: A survey. *Energy Policy* 36, 138-162.

Kemfert, C. (2005). Induced technological change in a multi-regional, multi-sectoral, integrated assessment model (WIAGEM) Impact assessment of climate policy strategies. *Ecological Economics* 54, 293-305.

Kneller, M. (2005). Frontier technology, Absorptive Capacity and Distance, *Oxford Bulletin of Economics and Statistics* 67(1), 1-23.

Kanaka, K. and E. Kriegler (2007). Aggregated Carbon Cycle, Atmospheric Chemistry,

- and Climate Model (ACC2). Reports on Earth System Science, 40. Max-Planck-Institute of Meteorology, Hamburg, Germany.
- Leimbach, M. and Baumstark, L. (2010). The impact of capital trade and technological spillovers on climate policies. *Ecological Economics* 69, 2341-2355.
- Leimbach, M., N. Bauer, L. Baumstark and O. Edenhofer (2010a). Mitigation Costs in a Globalizing World: Climate Policy Analysis with REMIND-R. *Environmental Modeling and Assessment* 15, 155-173.
- Leimbach, M., N. Bauer, L. Baumstark, M. Lüken and O. Edenhofer (2010b). Technological Change and International Trade: Insights from REMIND-R. *The Energy Journal* 31, Special Issue: The Economics of Low Stabilization, 109-136.
- Lucas, R. (1990). Why Doesn't Capital Flow from Rich to Poor Countries? *The American Economic Review* 80(2), 92-96.
- McKinsey&Company (2009). Pathways to a Low-Carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve, 192 pp.
<https://solutions.mckinsey.com/climatedesk/Default.aspx>.
- Meinshausen, M., N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame, M.R. Allen (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* 458, 1158-1163.
- Negishi, T. (1972). *General Equilibrium Theory and International Trade*. North-Holland Publishing Company, Amsterdam.
- Nelson, R. and E. Phelps (1966). Investment in Humans, Technological Diffusion, and Economic Growth. *The American Economic Review, Papers and Proceedings* 61, 69-75.
- Otto, V.M., A. Löschel and J. Reilly (2008). Directed Technical Change and Differentiated Climate Policy. *Energy Economics* 30 (6), 2855-2878.
- Popp, D. (2004). ENTICE: endogenous technological change in the DICE model of global warming. *Journal of Environmental Economics and Management* 48, 742-768.
- Popp, D. (2006). Innovation in climate policy models: Implementing lessons from the economics of R&D. *Energy Economics* 28, 596-609.
- Romer, P. (1990). Endogenous Technological Change. *Journal of Political Economy* 98, 71-102.
- Schankerman, M. (1981). The Effects of Double-counting and Expensing on the Measured Returns to R&D. *Review of Economics and Statistics* 63(3), 454-458.
- Scherer, F. (1982). Inter-industry Technology Flows and Productivity Growth. *Review of Economics and Statistics* 64(4), 627-634.

Scherer, F. (1984). Using Linked Patent and R&D Data to Measure Inter-industry Technology Flows. In: Z. Griliches (ed.), R&D, Patents, and Productivity, NBER and University of Chicago Press, Chicago, USA.

SEI (2006). Science and Engineering Indicators. National Science Foundation, USA. <http://www.nsf.gov/statistics/seind06/c4/c4s6.htm>.

WDI (2010). World Development Indicators. The World Bank, Washington DC, USA. <http://data.worldbank.org/data-catalog/world-development-indicators>.

World Bank (2010). Climate Investment Funds (CIF). The World Bank, Washington DC, USA. <http://www.climateinvestmentfunds.org/cif/node/2>.

Zachariadis, M. (2003). R&D, Innovation, and Technological Progress: A Test of the Schumpeterian Framework without Scale Effects. The Canadian Journal of Economics 36(3), 566-586.

8 Appendix

Symbol	Explanation
$t = \{2005, 2010, ..2100\}$	Time (years in 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 technical progress (labor, energy)
Y_{rt}	Production (income)
M_{rt}	Net imports
C_{rt}	Consumption
A_{rit}	Technology level
\bar{A}_{it}	Average global technology level (technology pool)
K_{rt}	Capital input
L_{rt}	Labor input
E_{rt}	Energy input
I_{rt}	Investment in capital
Q_{rt}	Investment in the energy system
R_{rit}	Innovation or R&D expenditures
S_{rit}	Imitation expenditures

Table 6: Sets and endogenous variables.

Symbol	Explanation	Value			
λ_i	Factor specificity 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		
λ_R/λ_S	Coefficient of innovation/imitation expd.	R:	0.4	S:	0.12
σ_R/σ_S	Exponent of innovation/imitation expd.	R:	0.1	S:	0.01
σ_A/σ_I	Exponent of tech. gap/investment	A:	1	I:	1

Table 7: Exogenous parameters.

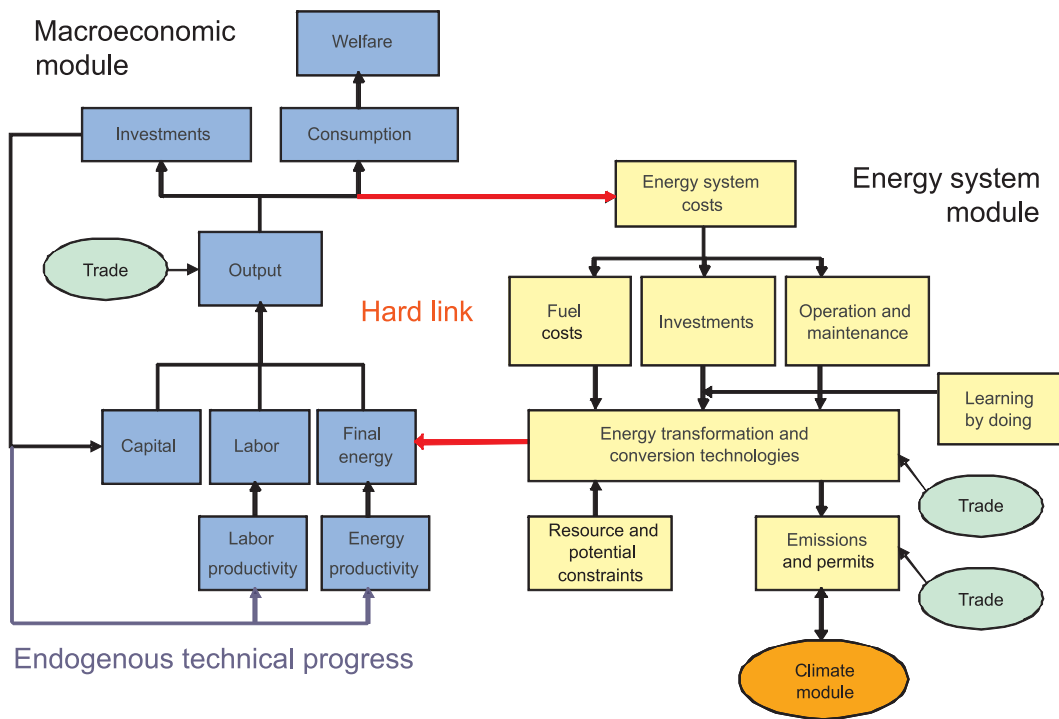


Figure 3: The ReMIND modules and their interaction.

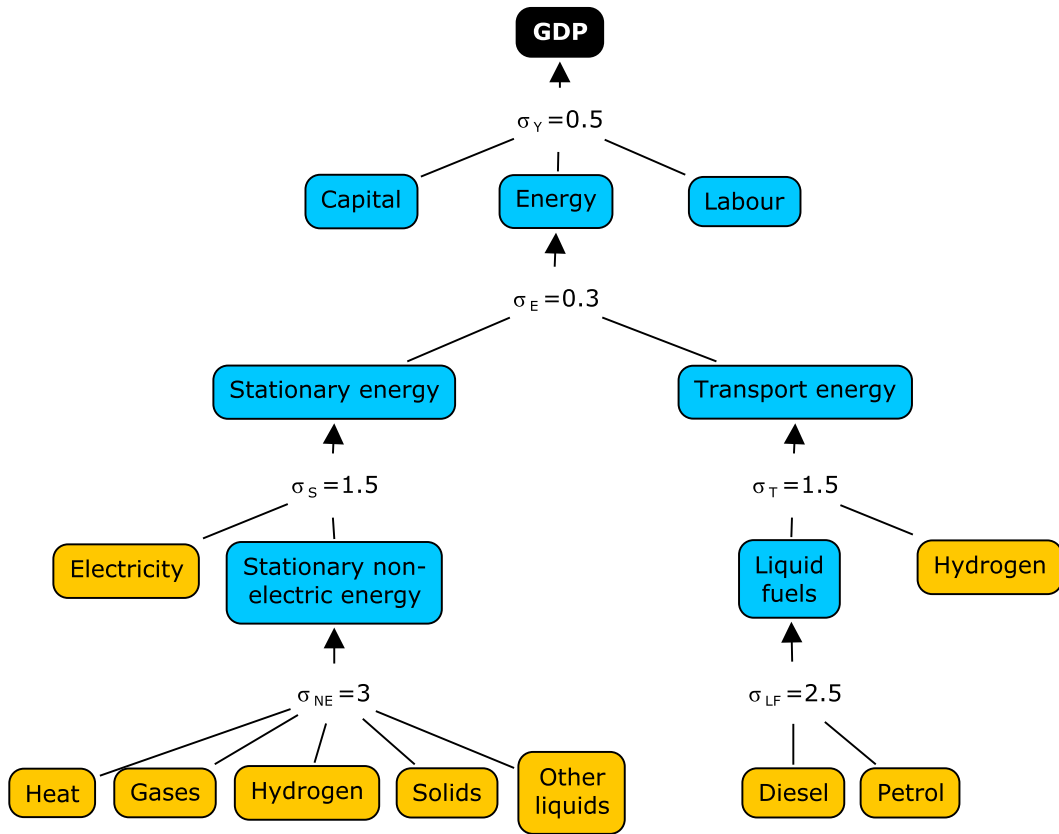


Figure 4: The CES structure of the regional ReMIND production function; σ indicates constant elasticities of substitution.

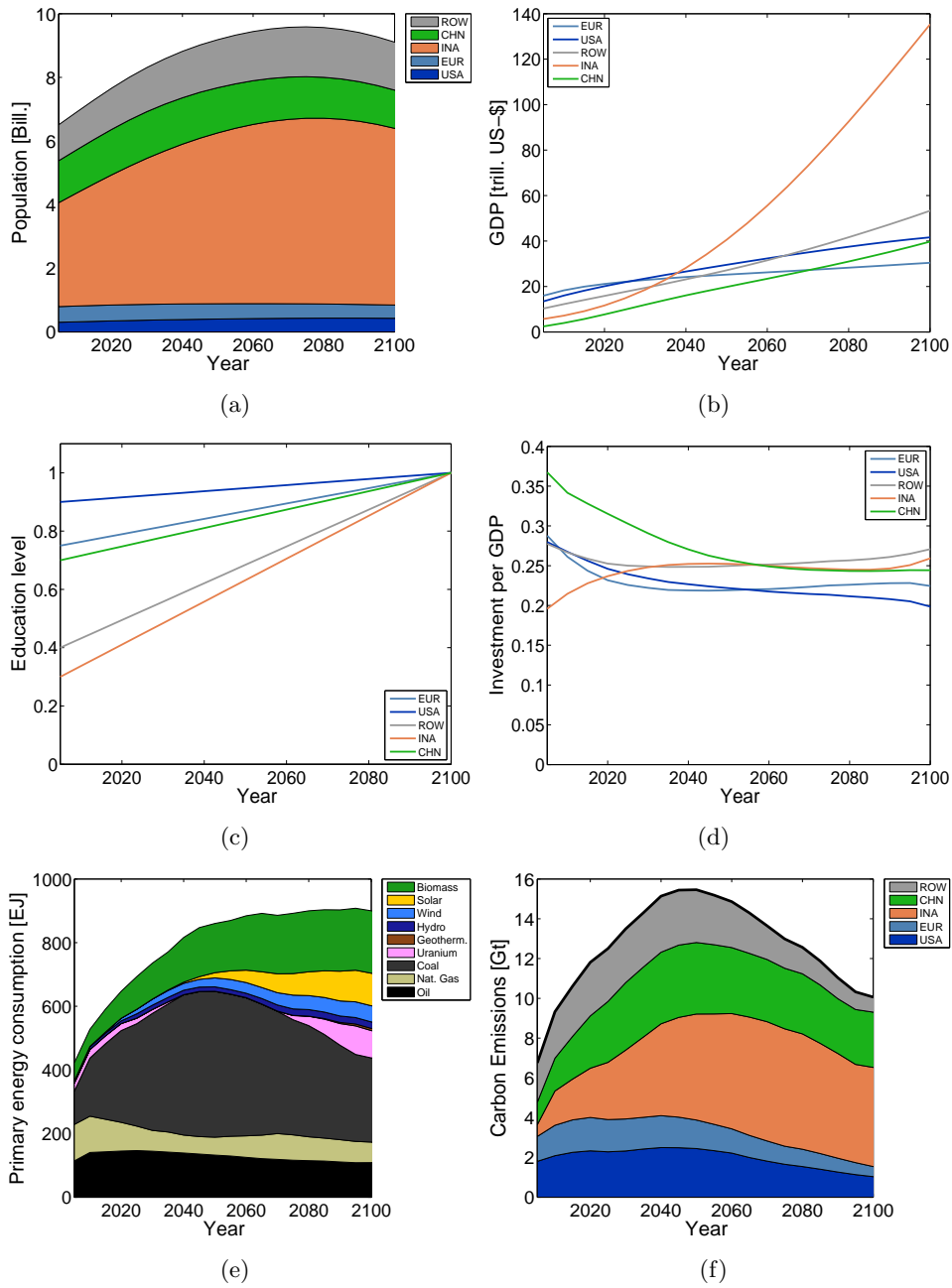


Figure 5: Simulation results for BAU.

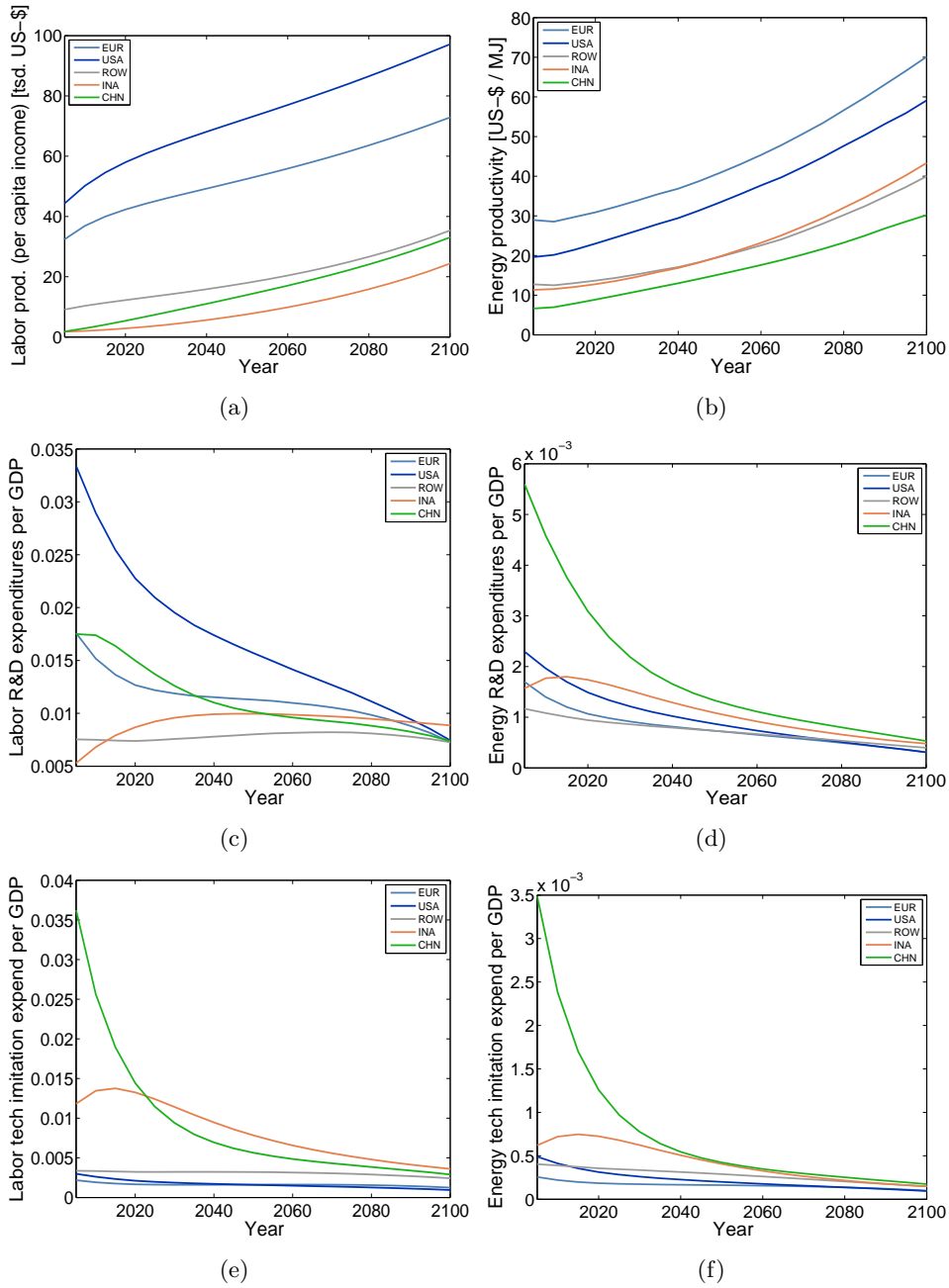


Figure 6: Simulation results for BAU.