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Impact assessment of emissions stabilization scenarios with and without induced technological change

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Abstract

The main aim of this paper is to investigate quantitatively the economic impacts of emissions stabilization scenarios with and without the inclusion of induced technological change (ITC). Improved technological innovations are triggered by increased research and development (R&D) expenditures that advance energy efficiencies. Model results show that ITCs due to increased investment in R&D reduce compliance costs. Although R&D expenditures compete with other investment expenditures, we find that increased R&D expenditures improve energy efficiency, which substantially lowers abatement costs. Without the inclusion of ITC, emissions targets are primarily reached by declines in production, resulting in overall welfare reductions. With the inclusion of ITCs, emissions mitigation can result in fewer production and GDP drawbacks.

Keywords: Integrated assessment; Climate policy; Induced technological change

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1. Introduction

A continued accumulation of anthropogenic greenhouse gases (GHGs) will ultimately have severe consequences for the climate as well as ecological and social systems. Irreversible climate changes induce significant economic costs (Kemfert, 2005a). Human-induced climate change is a serious problem. The main goal of the climate convention and of climate policy instruments such as the Kyoto Protocol is to reduce GHG emissions to a level that avoids dangerous climate change. In order to reduce the risks of climate change considerably, the European Union has already declared a GHG emissions reduction target that certifies a maximum global surface temperature increase of 2 °C compared with pre-industrial temperatures. In order to reach this target by 2100, a stabilization of GHG concentrations at 450 ppm would be necessary.

Environmental and climatic interventions create constraints and incentives that affect the process of technological change. The imposition of climate control instruments can stimulate invention and innovation processes. Invention and innovation practices are carried out primarily in private firms through increased research and development (R&D). A technological innovation can become widely available by technological diffusion processes. The induced innovation hypothesis recognizes R&D investments as profit-motivated investments stimulated by relative price changes. Climate policy measures that increase the price of fossil fuels augment the market for low-carbon technologies. This effect creates incentives for increased R&D expenditures in the sectors affected by climate change. Increased R&D expenditures bring about technological changes that lower the costs of low-carbon technologies. These effects reduce compliance costs and can lead to increased profits (Porter and van der Linde, 1995). However, investment in R&D could also “crowd out” other investments (Gray and Shadbegian, 1998). This would reduce firms’ profits. Econometric tests and simulation results confirm these ambiguous results. Jaffe and

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Palmer (1997) found that a carbon tax reduces aggregate R&D, causing a decline in knowledge accumulation and the rate of technological progress, which results in a deterioration of income and output. Recent findings, however, illustrate that environmental policies can have a strong positive feedback on innovation and may induce beneficial economic outcomes (Popp, 2001, 2002).

In economic–energy–environmental modeling approaches, the representation of technological changes is one of the most important sources of uncertainty in determining the economic costs of climate policy strategies (see Jaffe et al., 1995; Jaffe, 2000). In previous modeling approaches, technological changes were treated as exogenous. Economy–climate models that incorporate technological changes determine technological innovations endogenously by investment in R&D as "induced technological progress", by integration of spillovers from R&D or by including technological learning processes, particularly "learning-by-doing" practices. Numerous modeling approaches investigate the economic effects of technological changes. On a micro or bottom-up scale, different kinds of technologies are assessed in detail. On a macro or top-down scale, aggregated economic feedback effects of technological progress are evaluated. In top-down models, technological progress is mostly represented as an innovation to produce the same amount of output (GDP) with smaller amounts of input factors. This means an increase in input factor productivity. In contrast to an exogenous representation of technological progress, induced technological progress triggers endogenously increased productivity from different sources such as investment-induced technological progress or R&D-induced technological progress.

As modeling results confirm, excluding endogenously determined technological changes tends to overestimate compliance costs (Loeschel, 2002; Sue Wing and Popp, 2006). As initial installation of technological innovations is very often expensive, costs decline over time with increasing experience. A learning curve describes technological progress as a function of accumulated experience in production. Many applied modeling concepts, including bottom-up modeling with a detailed representation of energy technologies, apply learning curves as a meaningful description of technological changes (Azar and Dowlatabadi, 1999; Gerlagh and van der Zwaan, 2003; Grübler et al., 1999). Dowlatabadi (1998) finds that emissions abatement costs decline substantially if technological change is induced by technological progress and when learning by doing is considered. Gerlagh and van der Zwaan (2003) find that the learning-by-doing effects that make cheaper non-carbon technologies available have a positive economic impact and reduce the costs of climate policies.

Some models that incorporate induced technological changes (ITCs) by increased investment in R&D and also increased opportunity costs do not find large impacts on abatement costs (Buonanno et al., 2003; Goulder and Schneider, 1999; Nordhaus, 2002). Popp (2004) finds that ITC leads to substantial welfare gains but only small climate impacts in the long run. Goulder and Mathai (2000) find that abatement costs are lower with ITC than without. The main difference between the former and the latter modeling experiments is that some approaches find productivity increases for some sectors that are positively influenced by ITCs but productivity decreases for other sectors that are influenced negatively. These exercises find that ITCs significantly increase the benefits of a specific climate policy strategy but do not largely reduce the costs. Sue Wing (2006) models ITC in a CGE model for the US economy by implementing a backstop technology in the electricity sector. The backstop technology is available as a substitute to conventional technology in near time and is induced by subsidies coming from a CO_2 tax. He finds a substantial reduction of abatement costs.

In this paper, we intend to investigate the economic impacts of international climate policies that induce technological changes through increased R&D investment. The main aim of this paper is to introduce induced technological progress in an applied, multi-regional, multi-sectoral integrated assessment model and to evaluate the differences in regional and sectoral outcomes. One primary objective is to investigate whether or not endogenous technological progress has a substantial impact on compliance costs.

The main feature of this paper is that endogenously determined ITCs are represented using the multi-sectoral, multi-regional integrated assessment model WIAGEM (*w*orld *i*ntegrated *a*ssessment *g*eneral *e*quilibrium *m*odel), which additionally covers the impacts of climate change. The next section of this paper describes the applied multi-regional, multi-sectoral integrated assessment model WIAGEM that includes ITC. The third section illustrates the scenario definition, while the fourth section summarizes the main model outcomes and compares different climate control policies. The last section concludes.

2. Model description and calibration

Model simulations are based on the applied general equilibrium model WIAGEM, an integrated assessment model merging an economy and energy market model with a detailed climate module and ecological impact studies. This approach is based on a recursive dynamic general equilibrium approach. WIAGEM covers a time horizon of 100 years incremented in 5-year time steps. A detailed model description is provided by Kemfert (2002b). The basic idea behind this modeling approach is the evaluation of market and non-market impacts induced by climate change. The economy is represented by 25 world regions aggregated into 11 trading regions (countries), with each region covering 14 sectors. The sectoral disaggregation contains five energy sectors: coal, natural gas, crude oil, petroleum and coal products, and electricity. The dynamic international energy market for oil, coal and gas is modeled by global and regional supply and demand. The oil market

Table 1
Key model parameters of WIAGEM

Trace gas	CO_2	CH_4	N_2O
Atmospheric concentration			
Pre-industrial (ppmv[a], ppb[b])	278	789	275
1992 (ppmv[a], ppb[b])	353	1.720	310
Energy-related emissions 1992 (billion tons)	6.0	0.08	0.0001
Non-energy-related emissions 1992 (billion tons)	1.2	0.454	0.0139
Growth rate, post-1992 (%)	2	0.8	0.2

Type of elasticity	Value
Armington elasticity of substitution	1
Armington elasticity of transformation	2
Elasticity of fossil fuel supply	1 (coal), 4 (gas, oil)
Elasticity of substitution between non-energy and energy composite in production and final demand	0.25–0.5 (Annex B)[c] 0.20–0.4 (non-Annex B)
Inter-fuel elasticity of substitution	0.5 (final demand), 2 (industry)
Autonomous energy efficiency improvement (AEEI) (% per year)	2
Sensitivity parameter for R&D investments (β)	0.5

Source: IPCC (2000), N_2O: natural sources are included.
[a] Parts per million by volume (CO_2, CH_4).
[b] Parts per billion (N_2O).
[c] Annex B: Countries ratified Kyoto protocol.

is characterized by imperfect competition. The model describes OPEC regions as using their market power to influence market prices. Energy-related GHG emissions occur as a result of economic and energy consumption and production activities.

Currently, a number of gases have been identified as having a positive effect on radiative forcing (IPCC, 2001, 2007) and are included in the Kyoto protocol as the "basket" GHGs. The model includes three of these gases: carbon dioxide (CO_2), methane (CH_4), and nitrous dioxide (N_2O) (Table 1). As CO_2 is a long-living gas, we divide the atmospheric lifetime of gases into special time sections. The atmospheric concentrations induced by energy-related and non-energy-related emissions of CO_2, CH_4, and N_2O have impacts on radiative forcing, influencing potential, and actual surface temperature and sea level.

In each region, production of the non-energy macro good is captured by an aggregate production function. It characterizes technology through transformation possibilities on the output side and substitution possibilities on the input side. In each region, a representative household chooses to allocate lifetime income across consumption in different time periods in order to maximize lifetime utility. In each period, households face the choice between current consumption and future consumption, which can be purchased via savings. The trade-off between current consumption and savings is given by a constant intertemporal elasticity of substitution. Producers invest as long as the marginal return on investment equals the marginal cost of capital formation. The rates of return are determined by a uniform and endogenous world interest rate such that the marginal productivities of a unit of investment and a unit of consumption are equalized within and across countries. Domestic and imported varieties of the non-energy good for all buyers in the domestic market are treated as imperfect substitutes by a CES Armington aggregation function, constrained to constant elasticities of substitution. Emissions limits can be reached by domestic action or by trading emissions permits within the countries (initially) allocated according to regional commitment targets. A full description of the regions and sectors and the calibration of the model are shown by Kemfert (2002b).

Goods are produced for the domestic and export markets. Production of the energy aggregate is described by a CES function reflecting substitution possibilities for different fossil fuels (i.e. coal, gas, and oil), capital and labor representing trade-off effects with a constant substitution elasticity. Fossil fuels are produced from fuel-specific resources and the non-energy macro good subject to a CES technology.

ITC is considered as follows. Energy is treated as a substitute of a capital–labor composite determining (together with material inputs) overall output. The CES production structure combines nested capital and labor at lower levels (a mathematical description can be found in Appendix A). The incentives to invest in technology innovations are market driven. Climate policies (emissions mitigation targets) as well as negative climate change impacts induce incentives to invest in knowledge through R&D investments (ITC). We assume that climate change has substantial impacts on the economy. Furthermore, climate policy interventions have an impact on relative factor prices, e.g. fossil fuels becoming more expensive. Countries react to negative climate impacts and climate control policy measures by spending a specific amount of their investments on R&D.[1] In the benchmark year, we assume that R&D investment as a share of total output is 2%.[2]

In the baseline, we do not allow for ITCs, as we do not incorporate any climate protection policy. However, we allow endogenous technological change that is not triggered by climate protection goals but through damage from climate change. There are two driving forces that induce increased expenditures on R&D (ITC): climate impacts and climate policy measured in national emissions reduction targets (the reaction function can be found in Appendix A). This mechanism works as follows: rising sectoral emissions increase climate change impacts. If welfare is negatively affected by climate change, regions start to invest in climate protection, i.e. adaptation expenditures. The greater the damage, the higher the adaptation expenditures and the less the amount spent on R&D investments as they compete with investment in adaptation. However, regions also invest in R&D if they have to meet binding emissions reduction targets. The higher the climate impacts, the more the amount spent on adaptation and the less on R&D investments. The higher the climate protection goals, the more the amount spent on R&D investments and the less the amount spent on adaptation.[3]

New knowledge produces new processes and products, which lower the energy intensity of output.[4] If we assume a high R&D investment share, emissions intensity is decreased substantially. A lower share of R&D investment leads to less significant emissions intensity declines. This methodology is different from other approaches, such as those of Nordhaus (2002), Popp (2004) and Goulder and Schneider (1999). As we do not assume that there is a specific R&D sector to find the optimal spending on R&D, and as we assume that R&D spending leads to a substantial reduction in energy intensity, emissions abatement becomes less costly.

3. Scenario definition

We investigate the economic consequences of four different emissions concentration scenarios.[5] The baseline scenario does not include any climate policy or any emissions stabilization targets. However, in the baseline, an autonomous energy efficiency parameter increases energy efficiency by 2%. The other emissions concentration stabilization scenarios intend to stabilize emissions at 550, 500, 450, and 400 ppm by 2100. Due to the emissions constraint, all regions implement emissions mitigation policies. ITC implies that emissions abatement can be attained with higher energy efficiency standards, as R&D investment is spent on improving energy efficiency in those regions that are negatively affected by climate change. We compare the emissions stabilization scenarios with and without the inclusion of technological change and with a baseline where only a specific percentage change improvement in energy efficiency is considered.

4. Model results

In the baseline, we assume that energy efficiency improves primarily by endogenous investments in R&D that are triggered by damage from climate change (ETC). As in the baseline there is no climate protection goal, damage is higher than in all other scenarios. With high damage from climate change, adaptation expenditures are higher than R&D expenditures. This leads to lower endogenous energy efficiency improvement than in the emissions stabilization scenarios. Although the effect is very small, ETC leads to marginal reductions in emissions (Fig. 1) and a reduction in abatement costs measured as GDP increases (Figs. 2 and 3).

In the emissions stabilization scenarios, emissions reductions are higher with the option of allowing for ITC. As we model emissions reduction targets not as concrete stabilization levels that need to be met in 2100 but as percentage reductions in each time period, we find that decline in emissions is even higher with the inclusion of technological change. The reason for this is that ITCs lead to increased energy efficiency which results in higher emissions reductions. This effect is higher the higher the emissions reduction target is (Fig. 1).

We also find that achieving the Kyoto reduction targets is costly for the developed regions which have to commit to quantified emissions reduction targets (as also found by Carraro et al. (2003) and Kemfert (2002a)). As can be seen from Fig. 3, GDP losses are highest for the high emissions mitigation scenarios (stabilization at 400 and 450 ppm CO_2). This is especially visible within a time horizon of 100 years (in 2100). The 400 ppm scenario triggers the highest

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[1] In this analysis, we assume that emissions mitigation targets are exogenously given to meet the emissions control level. Climate damage does not influence the regional emissions reduction targets. As countries have to meet a global emissions mitigation level, we abandon the modeling of endogenous emissions reduction targets.

[2] We follow Nordhaus (2002), who applied an average share of 2% per year. In 2002, the USA spent 2.7% of national GDP on R&D investment. Japan spent 3%, France 2.2%, Germany 2.5%, the UK 1.9% and Canada 1.8%. *Source*: National Science Foundation.

[3] This approach differs from other CGE model approaches as Sue Wing (2005). Sue Wing (2006) only reflects technological progress in the electricity sector, which is induced by a subsidy. Here, we assume that market impacts trigger investment in technological innovation.

[4] We find a strong relationship between R&D expenditures and energy efficiency improvement: e.g. Germany reduced R&D expenditures drastically at the beginning of the 1990s which resulted in a sharp drop in energy efficiency.

[5] In this modeling comparison exercise, we settle on these different emissions and stabilization scenarios. The synthesis paper elaborates more on the uncertainties of the scenario definition, see Edenhofer et al. (forthcoming).

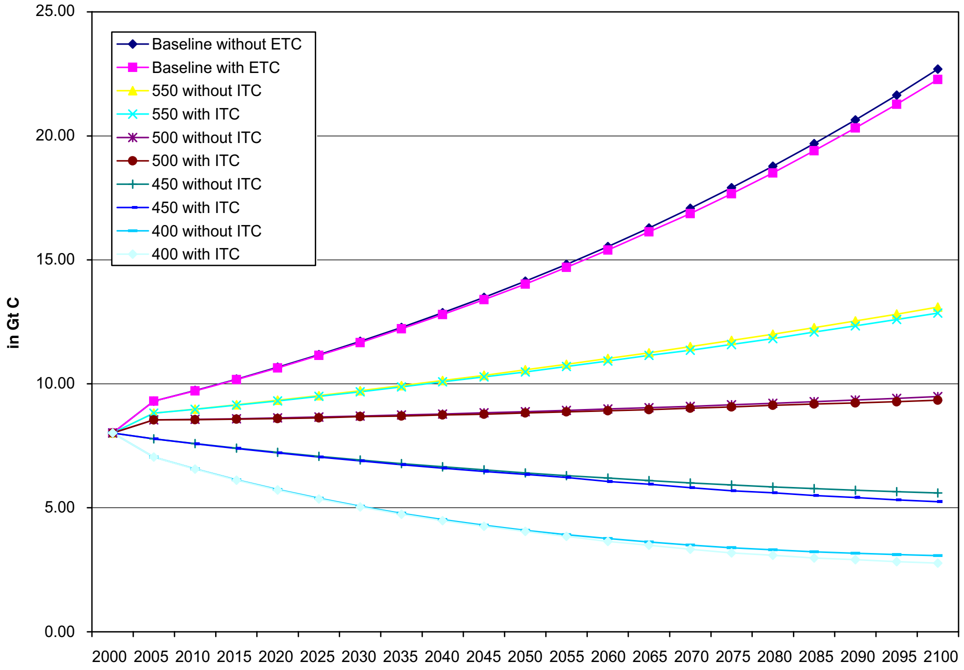

Fig. 1. Carbon dioxide concentrations under different emissions stabilization scenarios with and without technological change.

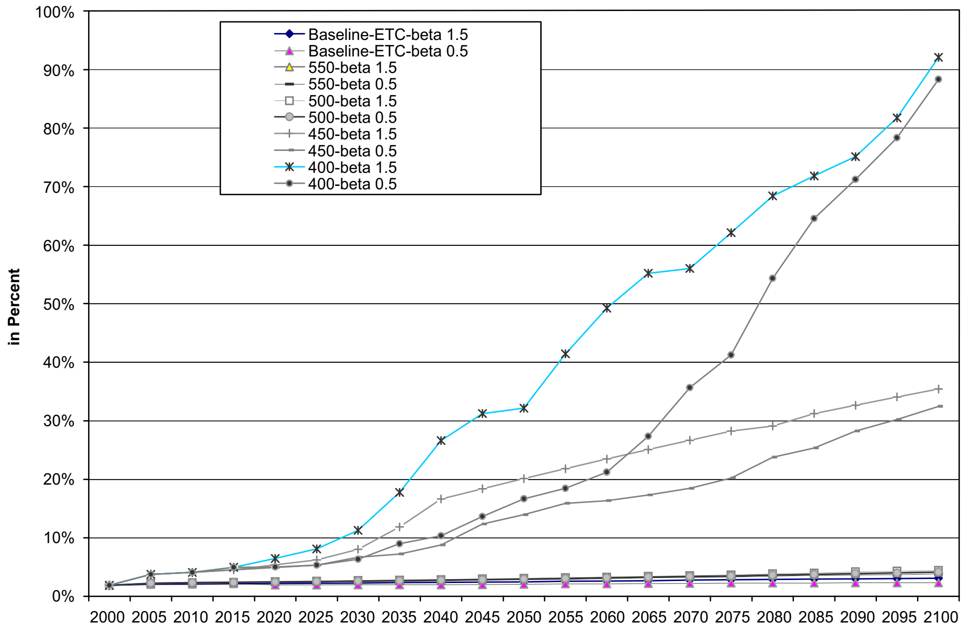

Fig. 2. World R&D investment shares (percentage of total investment): sensitivity to β.

economic costs and can only be met if drastic emissions reduction measures take place as early as possible. If emissions reduction measures start in 2030, the emissions stabilization target of 400 ppm cannot be met.[6] The permit price rises to US\$600/tC in the 400 ppm scenario, but is much lower in the other scenarios (Fig. 4). With high emissions stabilization targets, damage can be reduced substantially (Fig. 5).

GDP losses are less substantial if ITC is allowed. This is because ITC lowers abatement costs. Countries face substantial impacts from climate change (Kemfert, 2005a, b). ITC occurs because countries with binding emissions mitigation targets invest in both adaptation and R&D investments. The higher the climate impact, the more the amount spent on adaptation and the less the amount spent on R&D investments. But countries also

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[6] We found in another study that an emissions stabilization to reach a 2 °C temperature target cannot be met if countries start emissions reduction after 2025; see Kemfert (2005a).

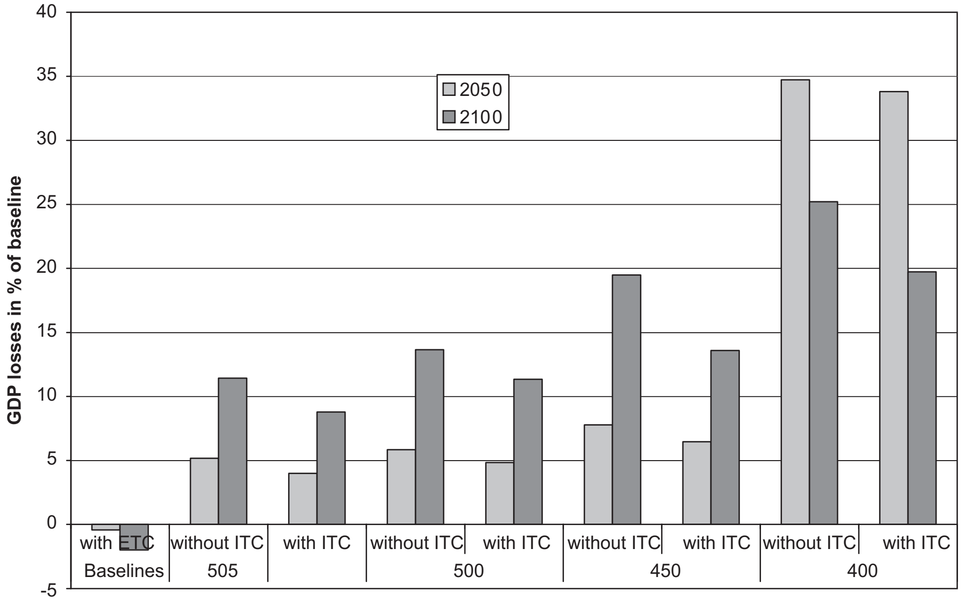

Fig. 3. GDP losses under different emissions stabilization scenarios.

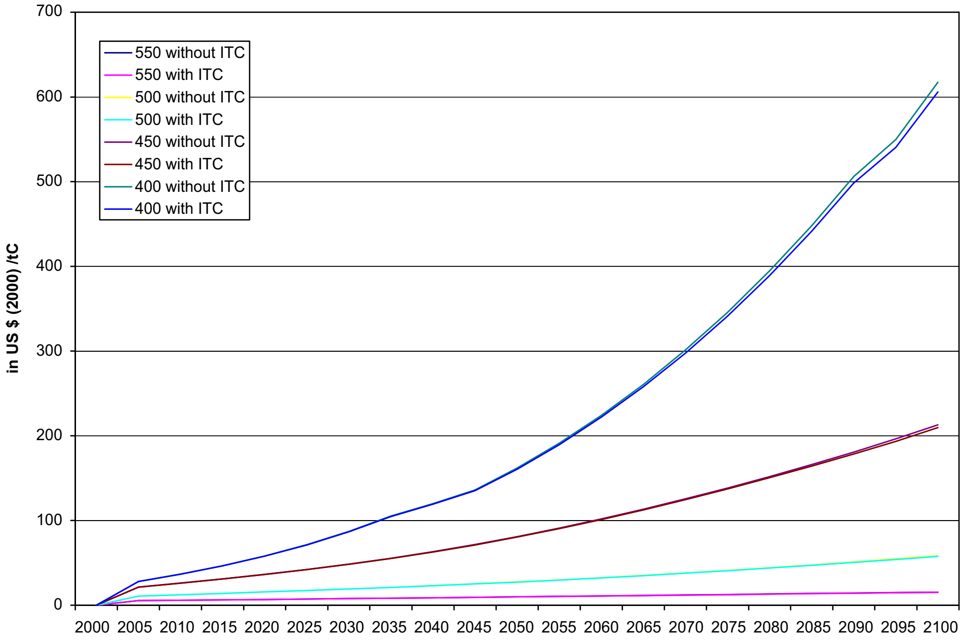

Fig. 4. Permit prices under different emissions stabilization scenarios.

spend more on R&D the higher the emissions mitigation target is. As investment in R&D improves energy efficiency, emissions abatement targets can be met with less economic decline. Emissions reduction targets can be achieved either through an increase in energy efficiency (substituting emissions-intensive technologies) or through a decline in production.[7] The latter would be more cost-intensive. For example, in the 400 ppm scenario, very drastic emissions abatement would be necessary, especially in the first 50 years. In the model, this could be reached either by a complete substitution of emissions-intensive technologies, i.e. an increase in energy efficiency, or by a decline in production. With ITC, countries react with the former; without ITC, countries react primarily with the latter. In the emissions reduction scenario of 450 ppm, R&D investment shares reach 35% of total investments (Fig. 2). This can primarily be explained by the higher emissions reduction target, as the higher the climate protection goals, the more the amount spent on R&D investments and the less the amount spent on adaptation. In the 400 ppm stabilization scenario, R&D investment

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[7] We also assume that a so-called carbon-free technology is available at a high fossil fuel price; see Edenhofer et al. (forthcoming).

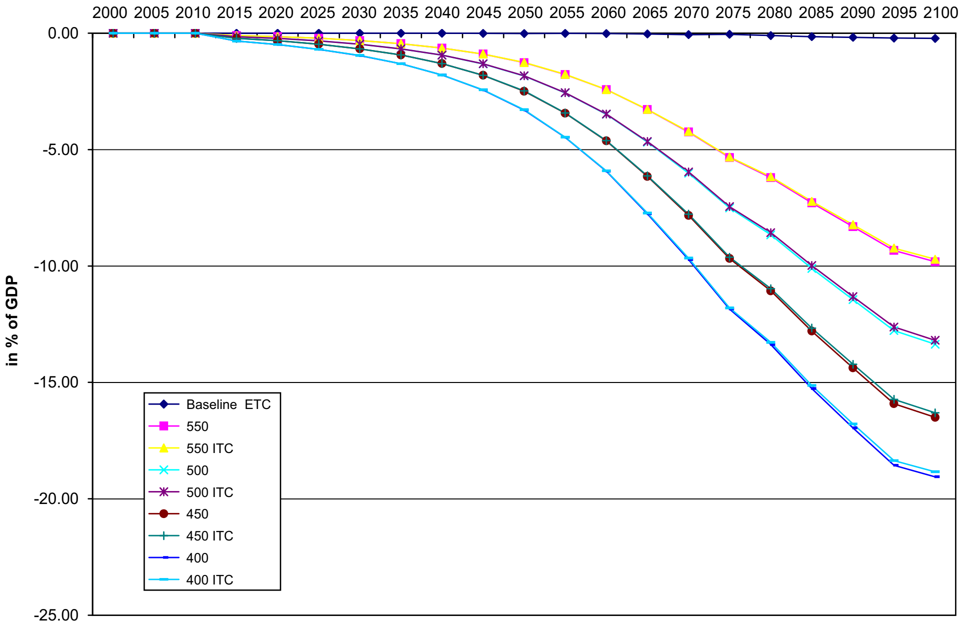

Fig. 5. Avoided damage compared with baseline.

reaches up to 90% of total investments if we assume an R&D sensitivity parameter, β, of 1.5.[8] With a lower sensitivity parameter ($\beta = 0.5$), R&D investments are lower, especially in the early time periods when climate change impacts are minor. With rising climate impacts and less expenditure on R&D (with $\beta = 0.5$) in earlier periods, output is more negatively affected both by climate change and by fewer mitigation options through technological change. Both effects lead to a greater disparity within the earlier time periods but to a convergence of R&D expenditures in the long run. The highest share of R&D expenditure comes from industrialized regions.

5. Conclusion

This paper investigates the economic impacts of emissions stabilization scenarios with or without induced technological change (ITC). Model calculations demonstrate that with the incorporation of ITC, emissions stabilization targets can be met with lower compliance costs. ITC leads to an increased share of R&D expenditures, which lowers the costs of innovative and energy-efficient technologies.

Strong emissions mitigation targets can only be met if countries start to implement climate policy as early as possible. Without the inclusion of ITC, countries react basically with declines in production rather than increases in R&D expenditures.

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Appendix A. Mathematical description

In order to include ITC in WIAGEM, we assume that the energy output ratio, i.e. the energy productivity, is influenced by knowledge improvements that are determined by the accumulation of R&D investments. Investment in R&D and knowledge stock only takes place if countries implement climate control measures. If countries are affected by the negative impacts of climate change, they increase investment in protection as well as investment in R&D. Furthermore, sectors invest in R&D if they have to meet binding emissions reduction targets. New knowledge produces new processes and products, which lower the energy intensity of output. This methodology is different from other approaches such as those of Nordhaus (2002), Popp (2004) and Goulder and Schneider (1999). As we do not assume that there is a specific R&D sector to find the optimal spending on R&D, and as we assume that R&D spending leads to a substantial reduction in energy intensity, emissions abatement becomes less costly.

The representative producer of region i and sector j ascertains the CES *profit function*. In this description, we stick to the dual approach in order to be consistent with

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[8] The stabilization scenario of 400 ppm is very special: because there are no longer any climate impacts, R&D investments increase drastically and crowd out other investments. Because of very drastic emissions reductions in the early time periods, economic costs are higher in the first 50 years than in the last 50 years.

previous publications of WIAGEM and because of better comparison to other CGE modeling approaches.[9]

$$\begin{aligned}\Pi_{i,j}^{Y}(p) =& A[a_{i,j}^{\mathrm{d}x}(p_{i,j})^{1-\sigma_{\mathrm{d}x}} + (1-a_{i,j}^{\mathrm{d}x})(p^{fx})^{1-\sigma_{\mathrm{d}x}}]^{1/1-\sigma_{\mathrm{d}x}} \\ & -(a_{i,j}^{m}(p_{i,j}^{m})^{1-\sigma_{klem}} + (1-a_{i,j}^{m})(EP_{i}^{E}(p_{i,j}^{e})^{1-\sigma_{kle}} \\ & + (1-EP_{i}^{E})[a_{i,j}^{k}(p_{i,j}^{rk})^{1-\sigma_{kl}} \\ & + (1-a_{i,j}^{k})(p_{i,j}^{l})^{1-\sigma_{kl}}]^{1-\sigma_{kle}/1-\sigma_{kl}})^{1-\sigma_{klem}/1-\sigma_{kle}})^{1/1-\sigma_{klem}}\end{aligned}$$

with $\Pi_{i,j}^{Y}$ is the profit function of region i and sector j[10], $Y_{i,j}$ the activity level of region i and sector j, A the productivity factor, $a_{i,j}^{\mathrm{d}x}$ the regional domestic production share of total production by sector j, $a_{i,j}^{k}$ the regional value share of capital within capital–energy composite, $a_{i,j}^{m}$ the value share of material within capital–energy–labor–material composite, $p_{i,j}$ the regional price of domestic good j, p^{fx} the price of foreign exchange (exchange rate), $p_{i,j}^{rk}$ the regional price of capital for sector j, $p_{i,j}^{e}$ the regional price of energy of sector j, $p_{i,j}^{m}$ the regional price of material/land of sector j, $p_{i,j}^{l}$ the regional price of labor of sector j, $\sigma_{\mathrm{d}x}$ the elasticity of transformation between production for the domestic market and production for the export market, σ_{ke} the substitution elasticity between capital and energy, σ_{kle} the substitution elasticity between labor, capital and energy composite, σ_{klem} the substitution elasticity between material and labor, capital and energy composite, $EP_{i,t}^{E}$ the regional energy productivity[11] with $EP_{i,t}^{E} = \kappa_{i,t}^{E} KR\&D_{i,t}^{\theta}$ regional R&D expenditures in energy ($KR\&D$) stimulate innovations in more energy-efficient technologies. κ parameterizes the efficiency of R&D. θ is the elasticity parameter (with $0 \leqslant \theta \leqslant 1$).

The stock of R&D investments ($KR\&D_{i,t}$) increases over time by $KR\&D_{i,t+1} = R\&D_{i,t} + (1{-}\lambda) KR\&D_{i,t}$ which determines the accumulation of knowledge stock due to R&D expenditures ($R\&D_{i,t}$) with a depreciation rate of λ.

The reaction function of R&D investments is as follows:

$$I_{i,t}^{R\&D} = [\delta_{i,t}^{E} \times I_{i,t}]^{\vartheta},$$

with

$$\delta_{i,t}^{E} = \phi_{i,t}\left(\frac{Y_{i,t}}{CI_{i,t}}\right)^{\beta} \forall \quad 0 \leqslant \delta_{i,t}^{E} \leqslant 1, 0 \leqslant \phi_{i,t} \leqslant 1$$

and $\phi = 0.01$ in the baseline, where $CI_{i,t}$ is the impact of climate change, β $(0 \leqslant \beta \leqslant 1.5)$ and ϑ are sensitivity parameters and $\phi_{i,t}$ is the percentage of regional emissions abatement (coefficient). The total emissions abatement target, Φ, is defined by the individual scenarios:

$$\Phi_{t}^{TARGET} = \frac{E_{TOT,t}^{TARGET}}{E_{TOT,t}^{BASE}},$$

with $E_{TOT,t}^{TARGET}$ as the emissions for concentration targets of 550, 500, 450, and 400 ppm and $E_{TOT,0}^{BASE}$ the baseline emissions.

Table 2
Parameter assumptions of different scenarios

Emissions stabilization target	Technological change	No technological change
Baseline Target = 550, 500, 450, 400	ETC: $\phi = 0.01$ ITC: $\Phi_{t}^{TARGET} = \frac{E_{t}^{TARGET}}{E_{0}^{TOT}}$ $\delta_{i,t}^{E} = \phi_{i,t}\left(\frac{Y_{i,t}}{CI_{i,t}}\right)^{\beta} \forall \quad 0 \leqslant \delta_{i,t}^{E} \leqslant 1$	No ETC: $\phi = 0$ No ITC: $\Phi_{t}^{TARGET} = \frac{E_{t}^{TARGET}}{E_{0}^{TOT}}$ $\delta_{i,t}^{E} = 0$

Regional emissions abatement (measured in %) is defined as follows:

$$\phi_{i,t} = \frac{E_{TOT,0}^{BASE}}{E_{i,0}^{BASE}} \Phi_{t}^{TARGET},$$

with $E_{i,0}^{BASE}$ as baseline emissions in region i.

We cover various impacts of climate change. Total climate impacts are determined by the following equation[12]:

$$CI_{t}^{r} = \alpha_{t}^{r}\left(PT_{t}^{\beta} \cdot \frac{y_{t}^{r}}{y_{0}^{r}}\right) - I_{t}^{PC}$$

with PT as potential temperature change, α and β as parameters (varying from 0.5 to 1.5), and y_0 as base-year regional GDP.

We assume that with increasing energy R&D, energy productivity increases with higher investment. R&D investment competes with investment in protection measures, $I_{i,t}^{PC}$, i.e. adaptation:

$$I_{i,t}^{PC} = [\varepsilon_{i,t} \times I_{i,t}]^{\vartheta}, \text{ with } \varepsilon_{i,t} = 1 - \delta_{i,t}^{E}.$$

Adaptation costs increase with increasing impacts of climate change and are additional investments that a country has to spend if climate change takes place. We distinguish between conventional investments, investments in R&D, and investment in adaptation. The following equation illustrates that the three investments compete against each other. The higher the investments are for adaptation or R&D, the less can be spent on conventional investment.

$$\begin{aligned}\Pi_{t+1}^{I}(p) &= p_{t+1}^{k} - \sum_{j} a_{j}^{i} p_{j,t}^{a} - \varepsilon_{i,t} p_{i,t}^{pc} - \delta_{i,t}^{E} p_{i,t}^{R\&D}, \\ \varepsilon_{i,t} &= 1 - \delta_{i,t}^{E},\end{aligned}$$

where Π_{t}^{I} is the profit function for investment activity I in time period t, a_{j}^{i} the value share of investment in good j, p_{t}^{k} the price of capital in period t, $p_{j,t}^{a}$ the price of Armington good j in time period t, $p_{i,t}^{pc}$ the price of investment in

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[9] A full description of the model, including all equations and interlinkages, is provided in Kemfert (2002b).

[10] The notation Π with the superscript Y is used to consider the activity subset, which is represented by production Y. Because of the zero profit condition, this equation needs to be equal to zero.

[11] As we incorporate variations in energy productivity in a CGE modeling framework, energy productivity changes must be profit-neutral.

[12] The impacts of climate change cover ecological, health, energy, and mortality impacts; see Kemfert (2002a).

protection (adaptation) in time period t, and $p_{i,t}^{R\&D}$ the price of investment in R&D in time period t (Table 2).

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