A Climate-Change Policy Induced Shift from Innovations in Energy Production to Energy Savings

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Summary

We develop an endogenous growth model with capital, labor and energy as production factors and three productivity variables that measure accumulated innovations for energy production, energy savings, and neutral growth. All markets are complete and perfect, except for research, for which we assume that the marginal social value exceeds marginal costs by factor four. The model constants are calibrated so that the model reproduces the relevant trends over the 1970-2000 period. The model contains a simple climate module, and is used to assess the impact of Induced Technological Change (ITC) for a policy that aims at a maximum level of atmospheric CO2 concentration (450 ppmv). ITC is shown to reduce the required carbon tax by about a factor 2, and to reduce costs of such a policy by about factor 10. Numerical simulations show that knowledge accumulation shifts from energy production to energy saving technology.

Keywords: Induced technological change, Environmental taxes, Partial equilibrium

JEL Classification: H23, O31, O41, Q42, Q43

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1. INTRODUCTION

Environmental taxes and regulation reduce pollution by shifting behavior away from polluting activities, but they also encourage the development of new technologies that make pollution control less costly in the long run (Newel *et al*. 1999; Popp 2002). Understanding of the response of technology to economic incentives – dubbed induced innovation or induced technological change (ITC) – will prove crucial for designing appropriate environmental policies (Jaffe *et al*. 2002). In the literature, the subject of ITC has explicitly been studied in various theoretic models (e.g. Verdier 1995, Beltratti 1997, Newell *et al*. 1999, Goulder and Matthai 2000). In a slightly different strand of literature, a more general approach is followed when adapted endogenous growth models are used to investigate the effect of reduced resource use on growth (Gradus and Smulders 1993; Bovenberg and Smulders 1995; den Butter and Hofkes 1995; Bovenberg and Smulders 1996; Smulders 1999, Smulders and de Nooij 2003). Many of these studies develop endogenous growth models with capital and/or labour, and a natural resource, most often energy, as factors of production, in which economic growth is generated through the accumulation of knowledge. Such models are advantageous when one aims to study the effect on growth of resource conservation rules. One conclusion emerging from these studies is that abatement measures can increase growth when they reduce pollution and pollution harms the production of knowledge. In most other cases, resource use reduction harms growth.

In this paper, we build an endogenous growth model, comparable with those used in the second strand of literature, with three sectors; the first sector produces the final good, the second a generic intermediate, and the third produces energy. The final good uses the generic intermediate and energy as production factors, and productivity of both inputs is endogenous through technology driven by research. Both the intermediate and energy sector use a capital-labor composite as production factor, and also for these sectors, productivity of the input depends on a technology variable that measures accumulated (and depreciated) research. A major difference with the average endogenous growth model that includes a resource, though, is that we model energy as an intermediate good. The energy production technology, and thus the energy production costs, is endogenous to the model. A second major difference is that our model is calibrated to reproduce the trends of the past decades in overall growth and energy efficiency improvement.

The model is used to carry out policy analyses that verify the role of ITC in climate change policy. It thereby contributes to the literature on induced technological change in the context of climate change, which is a yet undecided debate (Carraro *et al*. 2003). Various studies try to estimate the impact of ITC relative to the factor substitution effects without technological change through scenario analyses (Carraro and Galeotti 1997, Grübler and Messner 1998, Goulder and Schneider 1999, Nordhaus 2002, van der Zwaan *et al*. 2002, Buonanno *et al*. 2003, Gerlagh and van der Zwaan 2003, Gerlagh and Lise, 2003). But the estimated contribution of ITC varies considerably between the studies. Carraro and Galeotti (1997) employ an econometric model for the EU and come to an optimistic conclusion. ITC can bring about a double dividend when proper R&D incentives will reduce emissions without the need for decreasing consumption. Grübler and Messner (1998) use an energy-system model and conclude that ITC substantially decrease costs and warrant early emission reduction efforts. Goulder and Schneider (1999) and Nordhaus (2002) are more pessimistic and conclude that, though ITC is not negligible, its contribution to greenhouse gas emission abatement is small when compared to the contribution of factor substitution for given technology. Gerlagh and Lise (2003) consider two competing energy sources (i.e. renewables and carbon-rich energy sources). They show that induced technology change accelerates the substitution of carbon-free energy for fossil fuels substantially, and that in this setting, induced technological change is a powerful contributor to emission reductions.

One specific issue that we address in this paper is the question whether endogenous technological change (ETC) is beneficial to climate change policies. From the outset, such is not obvious. While ETC increases flexibility and thereby reduces costs, it can also increase costs when lower output levels lead to lower investments in learning. It is not unreasonable to assume that economic output will decrease more with endogenous technology, compared to a situation with an exogenous technological path. In this paper, we will verify whether costs of energy reductions increase or decrease when we account for endogenous technological change, and by how much. The approach is as follows. As in many other studies, we define scenarios in which policy sets an environmental target (i.e. atmospheric carbon emission concentration) with endogenous carbon taxes to reach the target. ITC is beneficial when costs of reaching this target decrease when modeling endogenous technological change, compared to a scenario in which technology follows a benchmark path set by the benchmark (or 'business as usual') scenario without environmental target. Our finding is important since most costs estimates for climate change policies assume given technology, and their estimates may be realistic when the ITC impact factor is minor, but it may be too pessimistic or too optimistic when the ITC impact factor is large.

When carrying out numerical scenario analyses, caution is warranted. We are aware of the limitations of the modeling approach we follow. In a certain way, we develop a cartoon model in the tradition of the highly stylized models developed in endogenous growth theory. The model explores some specific mechanisms, while abstracting from other mechanisms. Just to mention one feature, we neglect all taxes and other market distortions apart from carbon taxes. Still we think our analysis can provide valuable qualitative insights on technological innovation as induced by climate change policy. Also, we attempt to reduce the sensitivity of our results with respect to specific model features as we calibrate the model such that it reproduces the recent past and produces a benchmark scenario that is in line with other studies.

Section 2 describes the basic features of the model. It describes the accumulation of knowledge and the linkage from energy use to climate change. Section 3 describes the calibration of the model. Section 4 provides the results of the simulations. The final section discusses the implications of our analysis for climate change policies. Two Appendices are added to the paper. Appendix 1 presents the full list of model equations, including the first order conditions for the energy producers and innovators. The numerical parameter values, as found in the calibration procedure, are presented in Appendix 2.

2. MODEL SET UP

The model has 60 distinct time periods of five years, each denoted by t=1,…,60, covering the period 2000-2300. The model distinguishes one representative consumer, a representative production technology, and a public agent that can set emission taxes to reduce carbon dioxide emissions. There is one final good, or consumer good, for which prices are normalized to unity. All other prices are measured relative to this good.

The representative consumer

We assume there is one representative consumer who maximises welfare subject to a budget constraint:

$$W = \sum_{t=1}^{\infty} (1+\rho)^{-t} P_t \ln(C_t / P_t)\,, \tag{1}$$

where W is total welfare, ρ is the pure time preference, and C_t / P_t is consumption per capita.

Production

Output of the final good is denoted by Y. The final good is made of a generic intermediate M and energy E

$$Y_t = \{(A_{Y,M}{}^{\pi_{Y,M}}\ M)^{(\sigma-1)/\sigma} + (A_{Y,E}{}^{\pi_{Y,E}}\ E)^{(\sigma-1)/\sigma}\}^{\sigma/(\sigma-1)}, \tag{2}$$

where σ is the elasticity of substitution between M and E, and $A_{Y,M}$ and $A_{Y,E}$ are the technology variables that control the productivity of M and E, respectively. The parameters $\pi_{Y,M}$ and $\pi_{Y,E}$ describe the elasticity of productivity to knowledge accumulation.

Both the generic intermediate M and energy E are produced using a capital-labor composite Z as production factor,

$$M_t = \varsigma_M A_{M,Z}^{\pi_{M,Z}} Z_M \qquad (\mu) \qquad (3)$$

$$E_t = \varsigma_E A_{E,Z}^{\pi_{E,Z}} Z_E \qquad (q) \qquad (4)$$

$$Z_{M,t} + Z_{E,t} = (K_t)^{\alpha}(L_t)^{1-\alpha} \qquad (\xi) \qquad (5)$$

where $A_{Y,M}$ and $A_{Y,E}$ are technology variables that control the productivity of the capital-labor composite in producing M and E, respectively. The parameters $\pi_{M,Z}$ and $\pi_{E,Z}$ describe the elasticity of productivity to knowledge accumulation. The variables between brackets, μ, q, and ξ, denote the Lagrange dual variables of the welfare maximization program, or stated otherwise, denote the shadow price for M, E, and Z, respectively.

Capital depreciates at rate δ_K, and accumulates through investments I,

$$K_{t+1} = (1-\delta_k)K_t + I_t. \qquad (\psi) \qquad (6)$$

Knowledge is produced on basis of research. All knowledge stocks, $A_{Y,M}$, $A_{Y,E}$, $A_{Y,M}$, and $A_{Y,E}$ are treated equally, and we use subscript $j=(Y,M),\ (Y,E),\ (M,Z),\ (E,Z)$ when convenient. The accumulation of knowledge depends on both the current stock of knowledge, A_j, and the level of research expenditures, R_j. The flow of new ideas has decreasing returns to scale in the research flow R_j, the so-called fishing-out effect (Caballero and Jaffe 1993; Kortum 1993).

$$A_{j,+1t} = (1-\delta_A)A_{j,t} + \zeta_j R_{j,t}^{\eta} A_{j,t}^{1-\eta} \qquad (\theta_j,\ j=(Y,M),\ (Y,E),\ (M,Z),\ (E,Z)) \qquad (7)$$

where δ_A is the share of knowledge that becomes obsolete in each period.

The model is closed by the commodity balance for the final good; output Y is used for consumption C, investments I, and research expenditures R.

$$C_t + I_t + R_t = Y_t, \qquad (\lambda) \qquad (8)$$

where R is the aggregate research level,

$$R = R_{Y,M} + R_{Y,E} + R_{M,Z} + R_{E,Z} \qquad (9)$$

Labour L_t is supplied inelastically. We assume it is a fixed ratio of population, i.e. $L_t = \gamma\ P_t$ with $0< \gamma <1$ and P_t is the total population. In turn, population is assumed to grow logistically:

$$P_{t+1} = (1+\chi(1-P_t/P^{LT}))P_t, \tag{10}$$

where γ is the population growth rate for low population levels and P^{LT} is the population level in the long term to which P_t converges.

The model assumes complete and perfect markets for all goods, except for research. That is, the model imposes the first order conditions that follow from the welfare maximization program, presented in the appendix. For research, it is assumed that the marginal social value of research exceeds the marginal social costs by factor ω (Baumol 2002, p135). For ω=1, the model would calculate a first-best allocation. For ω>1, the social benefits of research exceed the costs. Thus, there is a research externality in the model. This is important for climate change policies for the following reason. A policy measure that will increase the total research effort will tend to increase welfare, whereas a policy measure that decreases the overall research effort will tend to decrease welfare. It is not obvious, from the outset, whether climate change policy will increase or decrease total research.

Climate Change

Carbon dioxide emissions, Em_t, are linked to the use of energy through an emission intensity parameter ε_t that describes the level of emissions per unit of energy use:

$$Em_t = \varepsilon_t\ E_t. \tag{11}$$

We assume that emission intensity of energy use and energy efficiency of production improves (so-called energy-efficiency improvement or EEI) autonomously over time. Carbon emissions are linked to the atmospheric carbon concentration, which in turn determines the global average surface temperature. The carbon cycle dynamics assumed in our model are simple and follow the approximations supposed in DICE (Nordhaus, 1994) and DEMETER (Gerlagh and Van der Zwaan, 2003). The link between carbon emissions, atmospheric carbon concentration ATM_t and the global surface temperature, $TEMP_t$, is a “1-box representation”:

$$ATM_{t+1} = (1-\delta_M)(ATM_t-ATM_o) + (1-\delta_E)(Em_t-\bar{E}m_t), \tag{12}$$

$$TEMP_{t+1} = (1-\delta_T)\ TEMP_t + \delta_T\ TEMP_o \ln(ATM_t/ATM_o)/\ln(2), \tag{13}$$

where δ_M is the atmospheric CO_2 depreciation rate, ATM_o is the pre-industrial atmospheric CO_2 concentration, $1–\delta_E$ is the retention rate, $\bar{E}m_t$ are emissions not linked to energy production , δ_T is the temperature adjustment rate resulting form the atmospheric warmth capacity, and $TEMP_o$ is the long-run equilibrium temperature change associated with a doubling of the atmospheric CO_2 concentration. The model version used for this paper does not specify a damage function, though such an equation can simply be added. The reason is that damage estimates are subject to normative debates on the valuation of environmental losses, and we attempt to keep away from these discussions. Instead, we will run cost-effective analyses that assume a certain climate change target.

To reach climate change targets, the public agent may levy a tax τ_t on emissions Em_t produced by the final good sector when using energy. The public agent may levy a tax on emissions produced by the final good producer when using energy in production. This carbon tax is a fee expressed in \$/tC, $\tau_{E,t}$, and it adds a constant markup value to the energy users costs,

$$q^{\tau}{}_t = q_t + \tau_{E,t}\varepsilon_t, \tag{14}$$

where $q^{\tau}{}_t$ is the price of energy including the carbon tax, q_t is the production costs of energy, and ε_t the emission intensity as defined in equation (11). We assume that the public agent is budget neutral in the case of a tax policy, so that, on the other hand, if a carbon tax is levied, i.e. τ_t>0, the generic intermediate M is subsidized with a rate $s_{M,t}$

$$\mu^{\tau}{}_t = (1-s_{M,t})\mu_t, \tag{15}$$

where $\mu^{\tau}{}_t$ is the intermediate price of M including the subsidy. The carbon tax revenues and the total amount of subsidies are in balance:

$$\tau_{E,t}\varepsilon_t E_t = s_{M,t}\mu_t M_t. \tag{16}$$

Alternatively, we could assume that carbon tax revenues are recycled by research subsidies, but this would produce a bias in our results in favor of carbon taxes. Under our central assumption of research externality $\omega>1$, even without carbon taxes, a subsidy on research would increase total welfare. Selling an innovation subsidy as a natural by-product of carbon taxes mixes up climate change policies and generic research policies.

3. Calibration

We use the model outlined above to carry out a numerical simulation where model parameters are based on historical trends derived from the World Development Indicator (WDI) set for the period 1960 to 2000. Based on the WDI data, we estimate levels and growth rates for the main variables for the period 2000-2005. In the second calibration stage, the model starts in 1900 and runs to 2300, and we calculate parameters such that simulated variable levels and growth rates in the period 2000-2005 match the empirical data. This scenario is the benchmark, and is also referred to as Business as Usual (BAU).

Variables that are used as an input in the calibration process are population (P), labor (L) population growth (g_L), output or GDP (Y), GDP growth rate (g_Y), gross investments (I), the capital stock (K), total primary energy supply and total primary energy use measured in Exa Joules (E), the energy price in \$/GJ (q) and its growth rate (g_q), the energy-efficiency improvement (EEI), CO_2 emissions (Em), the decline in the emission intensity of energy (g_ε), overall research expenditures (R), and the real interest rate. These 15 data points are used to calibrate the 17 parameters P^{LT}, γ, χ, $\zeta_{Y,E}$, $\zeta_{M,Z}$, $\zeta_{E,Z}$, $\pi_{Y,E}$, $\pi_{M,Z}$, $\pi_{E,Z}$, ς_M, ς_Z, δ_K, δ_A, ρ, α, ε, and the growth rate of ε. We notice that there is freedom for the choice of the unit of measurement for knowledge, $A_{M,Z}$ and $A_{E,Z}$.[1] Thus, there are two degrees of freedom in the calibration process, which is used to compensate for the difference between the 15 data points and the 17 parameters calculated. Furthermore, there are some parameters chosen on basis of the literature. The elasticity of substitution between energy and the generic intermediate M is described by the parameter σ, for which we following Manne (1999), σ=0.4. The social returns on research are assumed to exceed the private returns by factor 4 (Baumol 2002, p135), thus, ω=4. The elasticity of knowledge accumulation to research is set to half, η=0.5. Finally, we take $\pi_{Y,M}$=0, so that $A_{Y,M}$ and $\zeta_{Y,M}$, drop out of the model. We can do so without loss of generality since all energy-neutral innovation is already captured through the variables $R_{M,Z}$ and $A_{M,Z}$.

In 2000, the world population (P_{2007}) is 6.1 billion people, and its growth rate is 1.2%. In the long run, the world population is assumed to stabilize at a level of 11.4 billion people (as in World Bank, 1999; and Nakicenovic et al. 1998; and Gerlagh and Van der Zwaan, 2003). We assume that labor force is a fixed rate of population, i.e. γ=0.48, as indicated by the most recent WDI data. We calculated per capita GWP in 2000 at 5.800 US\$(1995), and the trend of the per capita GWP growth rate at 1.7% per year. In 2000, total energy use is estimated at 326 EJ per year. The energy intensity (ratio of energy use over GDP) is approximately 10.5 GJ/\$, and on basis of the 1971–1991 WDI sample, we estimate the Energy Efficiency Improvement (EEI) at 1% per year. The initial average price of energy (q) is assumed to be 2.7 US\$(1995)/GJ, and almost constant. The autonomous improvement of the emission intensity is 0.2% per year, and for the year 2000, the emission intensity is estimated at 0.0155 kgC/GJ. The CO_2 emissions (Em_{2000}) amount to almost 6 Gigaton carbon (GtC) per year.

[1] We can increase $A_{M,Z}$ by any factor and decrease ς_M by the same factor (raised to the power $\pi_{M,Z}$) and represent the same equilibrium with the same flows M and E. Thus, in the calibration, there is arbitrage between $A_{M,Z}$, and ς_M, and between $A_{E,Z}$ and ς_E. Practically, we set $A_{M,Z}$, to 100, and demand that $\varsigma_M=\varsigma_E$.

4. SIMULATION RESULTS

Policy Scenarios

This section presents and discusses the results with the calibrated model. After the calibration stage, we use the model for simulations. The simulation model runs for 60 time steps of 5 years each, representing the period 2000-2300, though the presentation of data and figures will be restricted to the first two centuries 2000-2200. State variables (knowledge and capital stocks) are fixed at the beginning of this period. We have simulated four scenarios. First, the BAU scenario assumes the absence of carbon taxes.

In the second scenario, policy makers are supposed to employ the carbon tax instrument such that total research expenditures are maximized. That is, the carbon tax is not used to combat emissions, but to increase welfare derived from the consumption of final goods. The background to this policy is the understanding that a carbon tax supported by a subsidy on the intermediate M might increase the overall research effort, or decrease the overall research effort, and it is not known in advance which of the two possibilities holds. In case the overall research level is increased, this will increase welfare since the marginal social benefits of research exceed the marginal social costs by factor $\omega > 1$. Whether a carbon tax will increase or decrease the overall research levels cannot be concluded in advance, it depends on parameter values that follow from the calibration process. The second scenario is labeled MAXW.

Then, we consider two stabilization scenarios, labeled 450_ITC and 450_NOITC that target the atmospheric carbon concentration level at 450 ppmv. In the BAU scenario, this carbon concentration level will be reached around 2050. In both stabilization scenarios, there is a variable carbon tax (in $/tC) levied on energy use to achieve the target. Figure 1 plots the emission levels and Figure 2 plots the associated carbon concentration levels. Figure 1 shows that, for our simple 1-box atmospheric model, the 450 ppmv target is consistent with long-term constant annual emissions of about 3.2 GtC. Comparison of the third and fourth scenario can show us the importance of induced technological change relative to factor substitution that happens with the benchmark technological change path.

Scenario Results

From the comparison of the four scenarios, we will draw conclusions with respect to the relation between ETC and (i) the timing of emission reductions, (ii) the carbon tax levels required to reach climate stabilization targets, (iii) the costs of meeting the climate change constraints, and (iv) the direction of technological change.

From Figure 1, the first outstanding conclusion is that the endogenous growth model suggests a win-win policy exists. The second scenario, which maximizes welfare abstracting from climate change costs, results in lower emission levels compared to the benchmark. A modest carbon tax (Figure 3 and Figure 4) raises expenditures in energy savings R&D (Figure 7) and lowers expenditures for energy production R&D (Figure 9). The overall R&D expenditures are lifted by 0.04% of GDP. Given that the social benefits of R&D exceed the costs, consumption increases, by 0.19% in 2050 and by 0.26% in 2100 (Figure 6).

The second conclusion we draw from Figure 1 and Figure 2 is that ITC (the third scenario) implies a slight advancement of emission reductions, compared to the fourth scenario without ITC. In Figure 2, the two graphs for the two scenarios are almost on top of one another, but in Figure 1, a difference is visible. This finding is consistent with Grübler and Messner (1998) and van der Zwaan *et al.* (2002). The result, however, should be interpreted with care, given the findings for the second scenario. A substantial part of the advancement of emission reductions is due to the carbon-tax induced welfare gain that is independent of the climate change constraint, as presented in the second scenario.

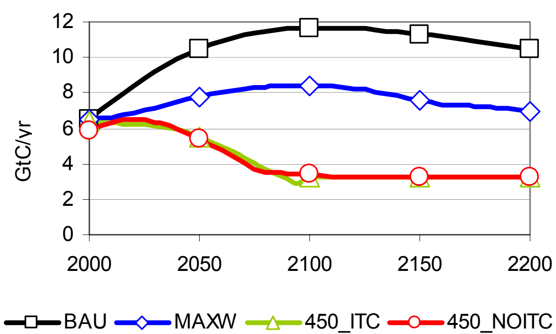

FIGURE 1. *Annual emission levels*

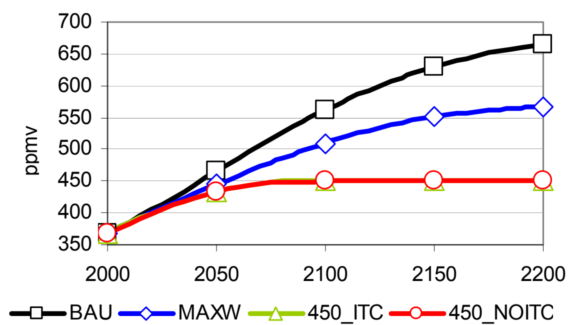

FIGURE 2. *Atmospheric CO2 concentration levels*

Next, we turn to the implications of ITC for the level of the carbon tax. It is obvious that an economy with endogenous technology is more flexible and in the long-term, technological change increases the elasticity of emissions. Figure 3 and Figure 4 present the tax on carbon dioxide emissions that supports the energy reductions. They show that ITC cuts the required carbon tax by approximately half. Stated the other way around, ITC doubles the elasticity of emissions with respect to a carbon tax. The tax levels shown for the end of the 21st and the whole 22nd century do not seem realistic from a political perspective. In the longer term, however, we can expect the substitution between carbon rich and carbon poor energy sources to contribute substantially to emission reductions (Gerlagh and van der Zwaan 2004) and long-term carbon taxes required to meet the climate change constraints will substantially be cut.

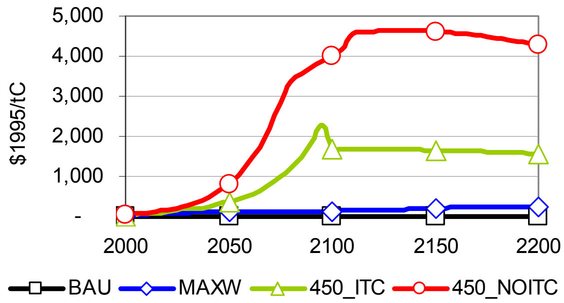

FIGURE 3. *Carbon tax*

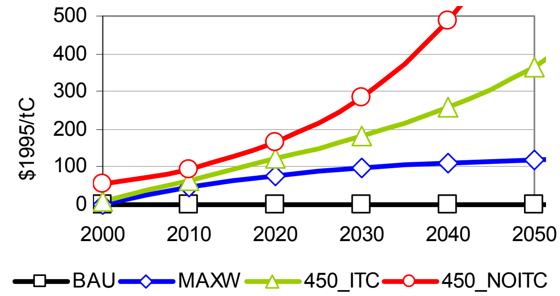

FIGURE 4. *Carbon tax for first five decades*

The effect of ITC on the costs of climate change targets is even stronger than its effect on the elasticity of emissions. Figure 5 shows the development of consumption per capita, and Figure 6 shows the same path, but now relative to the benchmark BAU scenario. The first figure shows that, on the scale of long-term income growth, costs of meeting climate change targets are almost negligible. Azar and Schneider (2003) and Gerlagh and Papyrakis (2003) discuss the relevance of this finding, which is a common feature found in many analyses with IAMs. Figure 6 shows that, notwithstanding the small size of the costs compared to the overall income growth, costs are still substantial and significantly different between the two scenarios with and without ITC. Abstracting from ITC, the emission reduction by about two-third, in the 22nd century, decreases output and consumption by about 5%. When technology adjusts, costs decrease to below 1% of GDP. When calculating the costs in terms of the welfare measure as defined in (1), we find that ITC decreases the costs by factor 11.8. Thus, studies based on inflexible technology may vastly overestimate long-term costs of energy savings.

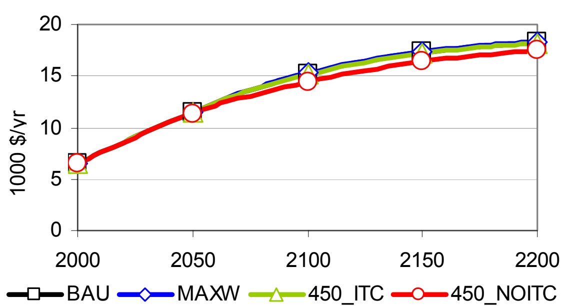

FIGURE 5. *Output per capita*

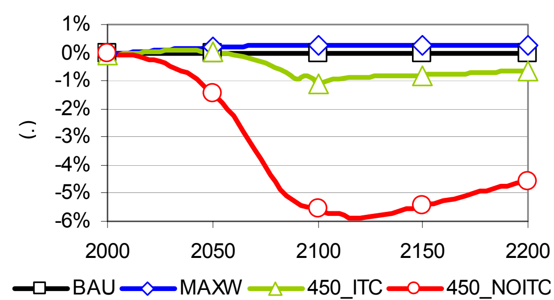

FIGURE 6. *Development of consumption relative to BAU scenario.*

The next figures present R&D expenditures and the paths of technology, that is, how technology accumulation adjusts to climate change policy. Figure 7 presents the share of R&D in GDP that is used to increase the productivity of energy in the production of the final good. Comparing the third (450_ITC) and the first (benchmark) scenario, we see that the climate change policy increases energy saving R&D by about factor 4/3 in the short-term, and by about factor 2 in the long term. The carbon tax peaks at the end of the 21st century, and so the energy savings R&D expenditures peak around the same period. Figure 8 presents the implications for the development of the stock of energy savings knowledge, A_{YE}. In the benchmark scenario, energy savings knowledge increases by almost factor 4 over the current century. The increased R&D expenditures induced by the carbon tax enhance the accumulation of energy savings knowledge by another factor 2.

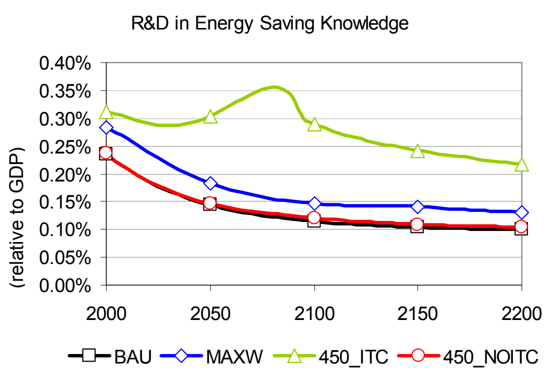

FIGURE 7. *R&D expenditures for Energy Savings as share of GDP*

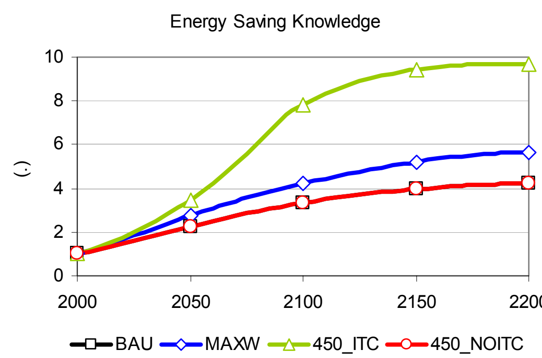

FIGURE 8. *Development of Energy Savings Knowledge, A_{YE}, relative to level in 2000*

Figure 9 presents the effect of the carbon-tax on the energy production technology. The effect is opposite to the energy savings technology. A carbon tax captures part of the value of energy supply, and thereby reduces the revenues that can be invested in research increasing the efficiency of energy production. The R&D expenditures are about halved, and consequently, the knowledge stock is halved, compared to the benchmark, as well, as shown in Figure 10.

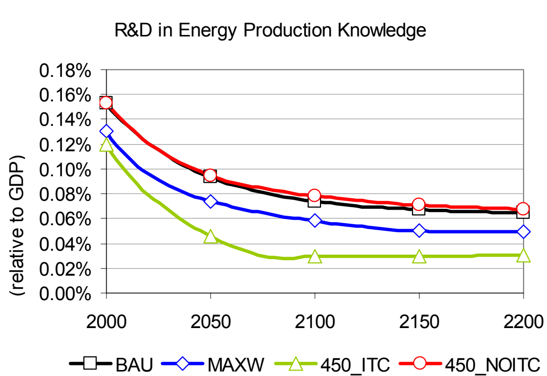

FIGURE 9. *R&D expenditures for Energy*

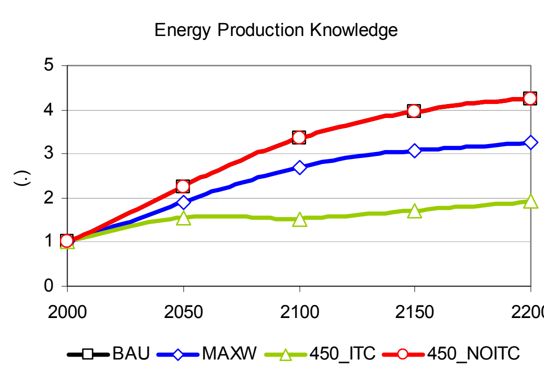

FIGURE 10. *Development of Energy Production*

Production as share of GDP *Knowledge, A_{EZ}, relative to level in 2000*

Comparing the two knowledge stocks, we see that the carbon tax shifts knowledge from efficient energy production to efficient energy use. We also mention that the R&D levels for the generic productivity of *M* is almost unaffected (not shown in a graph). In the climate change constrained scenario, energy production is less efficient than in the benchmark scenario, but energy use is more efficient. Costs involved in this shift of knowledge are small, compared to costs involved in factor substitution.

5. CONCLUSION

In this paper, we have built an endogenous growth model with three sectors, and with endogenous technology for each of the sectors. The first sector produces the final good, the second a generic intermediate, and the third produces energy. Energy production and use lead to emissions of carbon dioxide, and the model contains a simple climate change module that links emissions to atmospheric carbon dioxide concentration levels and temperature change. This module can also be used inversely to define a window of emission paths that are consistent with an exogenous climate change target, such as an atmospheric 450 ppmv ceiling.

We have used numerical simulations to study the potential for a double dividend, that is, a reduction in emissions and increase in output, at the same time. Climate change policy can bring about a double dividend when an energy savings policy increases the R&D level in certain sectors more than it decreases the R&D level in other sectors, assuming that social returns to R&D are the same in both sectors. Indeed, when parameter values where calibrated to match the 1970-2000 growth levels for output and energy use, we found a double dividend for modest energy savings. Yet when energy savings were more stringent to be consistent with a 450 ppmv stabilization target economic growth fell.

The model is also used to carry out policy analyses that verify the specific role of ITC in climate change policy. We conclude from the results that ITC's contribution to greenhouse gas emission abatement can be substantial. In our calculations, the elasticity of emissions to a carbon tax doubles, and the costs of emission reductions drop by approximately factor 10. In this setting, induced technological change proves a powerful contributor to emission reductions.

Our finding is important since most cost estimates for climate change policies assume given technology, and their estimates may be too pessimistic. There are two apparent qualifications to be made. First, results crucially depend on parameter values, which do not only depend on growth rates over the period on which the model is calibrated for output and energy use, but which also depend on various assumptions such as on the relative value of research expenditures and the social rate of return on research. For future work, it is essential to gather more data that allow us a more robust calibration procedure. Second, the model assumes a long-term planning and cooperation on a global scale. When climate change targets are set on a shorter horizon and cooperation is incomplete, such as under the Kyoto Protocol, technology will be less adaptive and climate change policy costs increase.

Having said this, we want to emphasize that not all results are sensitive. It seems intuitive that a carbon tax will shift innovations between sectors, from sectors that are responsible for fossil fuel energy production to sectors that are responsible for energy savings and carbon-free energy production. It is this shift in research that will drive most of the long-term cost reductions for climate change mitigation policies. This also points to an important caveat in the current study. Inclusion of carbon capturing and sequestration and carbon-free energy sources is an apparent subject for further work.

APPENDIX 1. FIRST ORDER CONDITIONS FOR FIRMS' PROFIT MAXIMIZATION

We use β_t as the price deflator for the final good from period t to period t+1. So, $\beta_t = 1/(1+r_t)$, where r_t is the real interest rate. Welfare optimisation gives the Ramsey rule as a first-order-condition for consumption,

$$\beta_t = (C_t / P_t)/((1+\rho)(C_{t+1}/P_{t+1})) \tag{17}$$

The first order conditions for M, E, Z_M, Z_E, K, $A_{Y,M}$, $A_{Y,E}$, $A_{M,Z}$, $A_{E,Z}$, $R_{Y,M}$, $R_{Y,E}$, $R_{M,Z}$, $R_{E,Z}$, and I are, respectively,

$$\mu M = (A_{Y,M}{}^{\pi_{Y,M}} M)^{(\sigma-1)/\sigma}\ Y^{1/\sigma}, \tag{18}$$

$$qE = (A_{Y,E}{}^{\pi_{Y,E}} E)^{(\sigma-1)/\sigma}\ Y^{1/\sigma}, \tag{19}$$

$$\xi Z_M = \mu M, \tag{20}$$

$$\xi Z_E = qE, \tag{21}$$

$$\alpha\, \xi(Z_M + Z_E) = (\delta_k + \psi - 1)K, \tag{22}$$

$$\theta_{Y,M} = \lambda\ \pi_{Y,M}\ A_{Y,M}{}^{\pi_{Y,M}(\sigma-1)/\sigma-1}\ M^{(\sigma-1)/\sigma}\ Y^{1/\sigma}$$

$$+ \beta\theta_{Y,M,+1}\ [(1-\delta_A) + (1-\eta_{Y,M})\zeta_{Y,M}(R_{Y,M}/A_{Y,M})^{\eta_{Y,M}}], \tag{23}$$

$$\theta_{Y,E} = \lambda\ \pi_{Y,E}\ A_{Y,E}{}^{\pi_{Y,E}(\sigma-1)/\sigma-1}\ E^{(\sigma-1)/\sigma}\ Y^{1/\sigma}$$

$$+ \beta\theta_{Y,E,+1}\ [(1-\delta_A) + (1-\eta_{Y,E})\zeta_{Y,E}(R_{Y,E}/A_{Y,E})^{\eta_{Y,E}}], \tag{24}$$

$$\theta_{M,Z} = \pi_{M,Z}\ \mu M/A_{M,Z} + \beta\theta_{M,Z,+1}\ [(1-\delta_A) + (1-\eta_{M,Z})\zeta_{M,Z}(R_{M,Z}/A_{M,Z})^{\eta_{Y,Z}}], \tag{25}$$

$$\theta_{E,Z} = \pi_{E,Z}\ qE/A_{E,Z} + \beta\theta_{E,Z,+1}\ [(1-\delta_A) + (1-\eta_{E,Z})\zeta_{E,Z}(R_{E,Z}/A_{E,Z})^{\eta_{E,Z}}], \tag{26}$$

$$\omega = \beta\theta_{j,+1}\ [\eta_j\ \zeta_j(A_j/R_j)^{1-\eta_j}]. \qquad j=(Y,M),\ (Y,E),\ (M,Z),\ (E,Z) \tag{27}$$

$$\psi_{+1} = 1/\beta, \tag{28}$$

In a first-best optimum, we would have ω=1. As explained in the main text, however, it is assumed that in market equilibrium, ω=4.

Carbon tax scenario

In the case of a carbon tax scenario, equations (18) and (19)become

$$(1-s_M)\mu M = (A_M\ M)^{(\sigma-1)/\sigma}\ Y^{1/\sigma}, \tag{29}$$

$$(q+\tau_c\varepsilon_t)E = (A_E\ E)^{(\sigma-1)/\sigma}\ Y^{1/\sigma}. \tag{30}$$

Complete model

The complete model consists of the 21 endogenous variables: for W, Y, R, C, M, E, Z_M, Z_E, K, $A_{Y,M}$, $A_{Y,E}$, $A_{M,Z}$, $A_{E,Z}$, $R_{Y,M}$, $R_{Y,E}$, $R_{M,Z}$, $R_{E,Z}$, I, Em, Atm, $Temp$, 8 shadow prices μ, q, ξ, ψ, $\theta_{Y,M}$, $\theta_{Y,E}$, $\theta_{M,Z}$, $\theta_{E,Z}$, and 1 price deflator β. The model has and 30 equations: (1)-(6), 4x(7), (9)-(8), (11)-(13), (17), (18)-(26), 4x(27), (28). The model has 2 exogenous variables, P, L, and 16 economic parameters, ρ, σ, ς_M, ς_E, α, δ_K, δ_A, 4xζ_j, 4xη_j, ω and 5 climate change parameters, ε_t, δ_M, δ_E, δ_T, $TEMP_o$. There are two policy instruments τ_M and τ_c, that are linked through (16)

APPENDIX 2. CALIBRATION RESULTS

TABLE 1. *Variable and parameter values in first period (2000)*

Parameters	Per period	*Endogenous variables*	Per period	per year
ρ	0.186#	Y	217.300*	44.025
α	0.252#	C	161.220	33.031
δ_K	0.351#	I	43.500*	8.819
δ_A	0.229#	M	224.120	44.824
σ	0.400	E	21.320*	4.284
ς_M	2.092#	K	86.900*	
ς_E	2.092#	R	10.856	2.186
ω	4.000	$R_{Y,M}$	n.a.	
η	0.500	$R_{Y,E}$	0.520	0.104
$\zeta_{Y,M}$	n.a.	$R_{M,Z}$	10.000*	2.014
$\zeta_{Y,E}$	10.611#	$R_{E,Z}$	0.336	0.067
$\zeta_{M,Z}$	1.278#	$A_{Y,M}$	n.a.	
$\zeta_{E,Z}$	9.522#	$A_{Y,E}$	503.004	
$\pi_{Y,M}$	0.000	$A_{M,Z}$	100.000*	
$\pi_{Y,E}$	0.765#	$A_{E,Z}$	262.062	
$\pi_{M,Z}$	0.321#	Z_M	24.129	4.826
$\pi_{E,Z}$	0.495#	Z_E	0.651	0.130
		ψ	1.280	
		q	0.270*	
		μ	0.957	
Environmental variables		ξ	8.885	
		$\theta_{Y,M}$	n.a.	
		$\theta_{Y,E}$	0.032	
Exogenous Variables		$\theta_{M,Z}$	2.561	
P (billion)	6.730	$\theta_{E,Z}$	0.039	
		$\chi_{Y,M}$	n.a.	
L (manyr)	16.152	$\chi_{Y,E}$	0.941	
		$\chi_{M,Z}$	0.970	
P_{max}	11.360	$\chi_{E,Z}$	0.941	
Exogenous variables growth rates		*Variables growth rates*		
		β	0.784*	
g_L	0.061	g_Y	0.141*	0.027
g_{Pop}	0.061	g_M	0.087	0.027
		$g_E = g_Y - EEI$	0.087*	0.017
		g_K	0.150	0.028
		g_q	0.000*	0.002
		g_μ	0.002	0.000
		g_ξ	0.054	
		$g_{A,Y,M}$	n.a.	
		$g_{A,Y,E}$	0.112	
		$g_{A,M,Z}$	0.170	
		$g_{A,E,Z}$	0.112	
		$g_{Z,M}$	0.084	
		$g_{Z,E}$	0.031	

* The variables with an * have been based on empirical data, and are used as input in the calibration process.

The parameters with an # have been calculated as part of the calibration process

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