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Analysis of Climate Damage Abatement Costs Using a Dynamic Economic Model

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Summary: Future costs arising from climate change and the transformation of the energy system are investigated using a modified version of the Multi-Actor Dynamic Integrated Assessment Model (MADIAM). A cost-benefit analysis is applied to compute optimal business investment scenarios. The economic core of MADIAM describes an economy driven by business striving to maximise profits by investing in physical and human capital. Profits are continually eroded by wage pressures and competition and can be maintained only by investing in human capital (i.e. productivity), which is thus the main driver of economic growth. Future costs accrue from climate damages and the higher expense of non-fossil fuels, which are used either to mitigate climate change or because of declining fossil resources. The impact of various taxation scenarios on the absolute costs, the cost structure and climate change is examined.

Zusamenfassung: Mit einer modifizierten Version des *Multi-Actor Dynamic Integrated Assessment Model* (MADIAM) werden die zukünftigen Kosten des Klimawandels und der Transformation des Energiesektors untersucht. Mittels einer Kosten-Nutzen-Analyse werden optimale Investitionsszenarien der Unternehmen berechnet. Im ökonomischen Kernmodell von MADIAM wird die Wirtschaft von der Profitmaximierung der Unternehmen angetrieben, die dazu in physisches und Humankapital investieren. Profite schrumpfen ständig durch Lohndruck und Wettbewerb und können nur durch Investitionen in Humankapital (d.h. Produktivität) auf Dauer erhalten werden. Diese Investitionen sind daher der wesentliche Wachstumsmotor. Zukünftige Kosten entstehen durch Klimaschäden und die höheren Kosten für nichtfossile Energien, die sowohl zur Vermeidung des Klimawandels als auch zum Ausgleich abnehmender fossiler Ressourcen benutzt werden. Wir untersuchen den Einfluss verschiedener Steuerszenarien auf absolute Kosten, auf deren Zusammensetzung und auf die Klimaänderung.

1 Introduction

Integrated assessment (IA) studies of the socio-economic impacts of climate change are typically based on models of the coupled physical-climate and socio-economic systems. The models are used for academic research, but also for policy advice (for overviews see e.g. Parson and Fisher-Vanden 1998, Rotmans and Dowlatabadi 1998, Weyant 2000, IPCC 2001a). However, the interactions between the different components of the system are highly nonlinear and depend on processes and parameters which are often very uncertain or poorly understood. Moreover, the complexity of the different sub-systems implies that the models are necessarily based on a large number of simplifying assumptions and are able to focus only on certain aspects of the complete system. Despite their wide use,

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and although the individual (sub-)models often belong to the mainstream of the respective disciplines, these assumptions are often not laid open to the user. This tends to limit their usefulness for policy advice. Additional problems arise from the fact that IA models usually employ and couple models from incompatible modelling traditions, e.g. dynamic models from the natural sciences and the essentially static equilibrium models of economics.

The Multi-Actor Dynamic Integrated Assessment Model (Weber et al. 2005) used in this study is based on a novel systems dynamic approach to describe the evolution of the coupled climate-socio-economic system. It avoids the problem of coupling incompatible models by applying a uniform modelling strategy to all modules of the integrated model. Applying such a framework to economics is non-standard and requires some explanation.

MADIAM consists of the economic module MADEM (Multi-actor Dynamic Economic Model) coupled to the climate module NICCS (Hooss et al. 2001). The NICCS module is an impulse-response representation of a fully coupled state-of-the-art 3D model of the carbon cycle and the general ocean-atmosphere circulation system. This approach reproduces the results of the complex model with high accuracy and at a greatly reduced computational cost.

The MADEM module focuses on the interactions between the main economic actors, which are characterised by different roles and motivations. These result jointly in the growth of productivity, which is the main source for economic growth. In contrast to the study of Weber et al. (2005), where the roles of different actors were described by prescribed control algorithms, we focus here on the investment strategy of business, which is determined now by an inter-temporal cost-benefit optimisation. This is applied to determine the impact of climate change, declining fossil resources and government tax policies on the evolution of macroeconomic costs.

In the following section we describe the core of the economic model in more detail. Section 3 covers extensions to include climate damages, finite fossil resources, business investments in mitigation and exogenous taxes. Section 4 illustrates the model behaviour in some simulation examples. Section 5 summarises the principal conclusions.

2 MADEM-Core

The core model of MADEM has been described in detail by Barth (2003) and Weber et al. (2005), so we give here just a brief overview. The model describes an economy with only one region and one sector. Thus we ignore in this study important processes such as international trade, technology transfer, policy coordination, etc. and focus on an idealized aggregated global economy. Economic growth is driven by the efforts of business to increase profits by investing in physical and human capital (productivity). Investments in capital increase profits by production expansion, while investments in productivity counteract the erosion of profits through competition and the wage demands of labour. In contrast to neoclassical growth models (e.g. Solow 1956, Romer 1986), this results in a system out of general equilibrium with well-observed real-world features like (structural) unemployment and positive profits.

Annual output y depends on three primary production factors: physical capital k, human capital h and employed labour l. Since human capital h is regarded as a proxy for all factors that contribute to labour productivity $\hat{y} = y/l$ (like training, education, R&D) we shall use instead labour productivity $\hat{y}$ as equivalent state variable (equation (8) below). We distinguish *per capita* variables, e.g. $\hat{y}$, from the associated integral variables, y, by a circumflex. The appendix contains an overview over the model variables.

We assume that the technological level associated with a given level of labour productivity also uniquely determines the physical capital requirement per work-place, $\hat{k} = k/l = f(\hat{y})$. Thus, in contrast to the usual neo-classical approach, physical capital and labour are not regarded as instantaneously substitutable, but are coupled as in input/output (IO) models (Leontief 1941). However, we do not assume a constant *k/l* ratio as in IO models, but assume this to be a function $f(\hat{y})$ of labour productivity, which can be changed through investments in human capital. Our three primary production factors are thereby reduced to only two independent factors.

Specifically, we assume that the capital requirement per workplace is proportional to labour productivity, $\hat{k} = \hat{y}/\nu$, with constant ν. This is in accordance with the empirical findings from long time series of a constant production-to-capital ratio $\nu = y/k$ for industrialised countries (Maddison 1982, 1995). Thus the annual production rate can be expressed in two alternative forms:

$$y = \nu k = \hat{y} l, \tag{1}$$

where the factors $\nu = const.$ and $\hat{y}$ represent the mean output/input productivity ratios of production with respect to the primary production factors physical capital and labour, respectively. From now on we use the term productivity only in the sense of mean labour productivity.

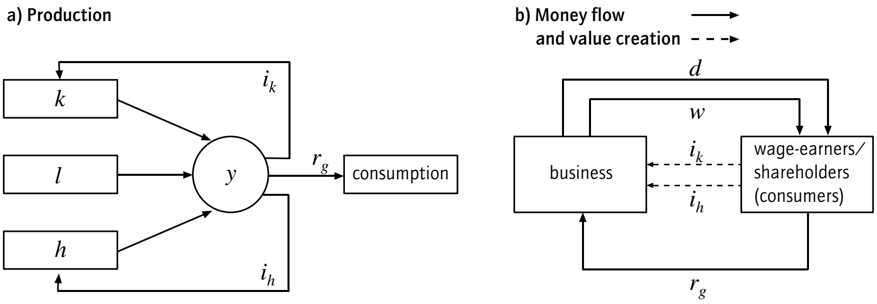
Given the available labour pool $l_{\max} = l^0_{\max} \exp(\lambda_l t)$, productivity and physical capital determine the employment rate

$$q = \frac{l}{l_{\max}} = \frac{\nu k}{\hat{y}\, l_{max}} < 1. \tag{2}$$

A variable employment rate q, depending on investments in physical and human capital, distinguishes our model from traditional AK models (Barro and Sala-i-Martin 1995). These are also characterised by a constant production-to-capital ratio ν, but have a constant level of employed labour, arising from the assumption of constant labour productivity. In our model, productivity grows through investments in human capital, which reduces the number of employed labour unless accompanied by investments in physical capital. Thus, structural unemployment arises under conditions in which it is more profitable for business to invest in productivity than in physical capital. The complementary case of idle capital is presently not considered in our model.

Figure 1

Production Factors and Products (panel a, left, equation (3)) and Money Flows and Value Creation (panel b, right, equation (6)) for the MADEM-Core Model



The full arrows represent the closed money flow via consumption in panel b, while the dashed arrows represent added value created through investments.

Source: Authors.

Total annual production y can be used either for annual investments i_k, i_h in physical and human capital, respectively, or annual production r_g of consumer goods and services (cf. Figure 1a),

$$y = i_k + i_h + r_g . \tag{3}$$

The expenses of production are simply payments to the owners of the production factors, because in our aggregate economy intermediate goods are not considered. Workers receive wages w for the provision of labour and the associated productivity/human capital. The resulting net profit x' goes to the owners of physical capital, who can decide whether and how to split it between investments and dividends d:

$$x' = y - w = i_k + i_h + d, \tag{4}$$

so that $$y = i_k + i_h + w + d. \tag{5}$$

Comparing equations (3) and (5), dividends and wages are seen to be used entirely for consumption,

$$w + d = r_g . \tag{6}$$

In this concept, economic growth depends solely on the splitting of profits between dividends and investments and is thus controlled by the capital owners.

The evolution of the core-model economy over time is determined by three state variables: physical capital k, productivity $\hat{y}$ and the labour wage rate $\hat{w}$:

$$\dot{k} = i_k - \lambda_k k, \tag{7}$$

$$\dot{\hat{y}} = \mu_h \frac{i_h}{l}, \tag{8}$$

$$\hat{w} = \lambda_w (\hat{w}^0 - \hat{w}). \tag{9}$$

Equation (7) is the usual growth equation for physical capital, determined by the balance between investments i_k and depreciation, with a constant depreciation rate λ_k.

Productivity growth, equation (8), is governed by investments i_h in productivity. In usual national accounts these will show up mainly as R&D expenditures and wages of teachers rather than investments. The parameter μ_h describes the effectiveness of the investments, while the factor $1/l$ enters because the investments refer to productivity, a *per capita* variable; it ensures that the economy is scale independent. We have not attempted to describe the spreading of new technology by distinguishing between different vintage streams of capital, but have simply assumed that new technology, associated with enhanced productivity and reduced labour requirements, is immediately available and used. This is an acceptable approximation if the rate of productivity growth does not significantly exceed the turn-over rate of capital.

The evolution of the wage rate, $\hat{w}$, equation (9), expresses the profit-eroding impact of increasing wage demands of labour and falling market prices due to business competition. Within an aggregated macro-economic model, the two effects cannot be distinguished and are thus modelled here simply as an increase of wages.

It is assumed in equation (9) that the net effect of profit-erosion is to drive the wage rate towards a target wage rate $\hat{w}^0$ proportional to productivity,

$$\hat{w}^0 = a_w \hat{y}, \tag{10}$$

at the adjustment rate $\lambda_w (\hat{w}^0 - \hat{w})$. As neither the wage demands of labour nor business competition drive the economy to a stagnation point, the target wage factor a_w will lie below a limiting level a_w^{max} which suffices only to replace depreciated capital, while the profits and the production growth are zero:

$$a_w^{max} = 1 - \frac{\lambda_k}{\nu}. \tag{11}$$

In summary, the model's control variables are the investments in human and physical capital, which are controlled by business, and the target-wage coefficient a_w and wage-rate adjustment parameter λ_w, which are determined by business competition and wage earners. Investments will be chosen later to maximise the inter-temporal cost-benefit ratio for business (equation (27)). The control strategies of wage-earners and business can be outlined as follows:

Wage-earners wish to maximise wages, and to maintain a high employment level and a steady growth of the economy. While a higher target-wage coefficient a_w would lead to higher wage rates, it would also motivate business to invest more in human than physical capital to reduce the employment level (and total wages) through rationalisation (equation (2)). To counter this tendency, wage earners will lower the target wage if the employment level drops.[1] Thus, the wage earners' control variable $a_w < a_w^{max}$ is a function of the employment level. We assume the simple power law relation

$$a_w = a_w^{min} + \left(a_w^{max} - a_w^{min}\right) q^{\alpha_q} \tag{12}$$

where a_w^{min}, α_q are constant parameters. The parameter λ_w in equation (9) is kept constant.

The goal of business is to maximize share-holder value, expressed in our model by the dividends *d* issued to shareholders. Profits are regarded only as a means to this end. Business has the choice of spending its profits *x'* directly on dividends, on investments in physical capital or on investments in productivity. The first option rewards shareholders in the short term at the cost of economic growth. The second option, investments in physical capital, increases production. However, increased physical capital translates into significantly increased profits only when the level of the current wage rate is sufficiently depressed below the zero-profit wage-rate limit. Furthermore, investments in physical capital increase production only if full employment has not yet been attained; otherwise, capital investments must be accompanied by investments in human capital to free workers for new jobs. The third option, investments in productivity for a fixed stock of physical capital, leads immediately to an increase in the profit rate through a reduction of employment and thus wages (cf. Figure 2), while the production itself remains unchanged ($y = k\nu$, $\nu =$ const, equation (1)). In general, continuing investments in productivity (human capital), leading to a depressed employment level, are needed to enhance profits and counter the erosion of profits, but parallel investments in physical capital are also necessary to increase profits by expanding production, thereby also relieving pressure on the labour market.

3 The Cost-Benefit Version of MADIAM

To represent climate-related effects, the MADEM core model needs to be extended to include carbon emissions and taxes, energy costs, finite fossil fuel resources and climate damages. We introduce also the optimality criterion for determining business investments.

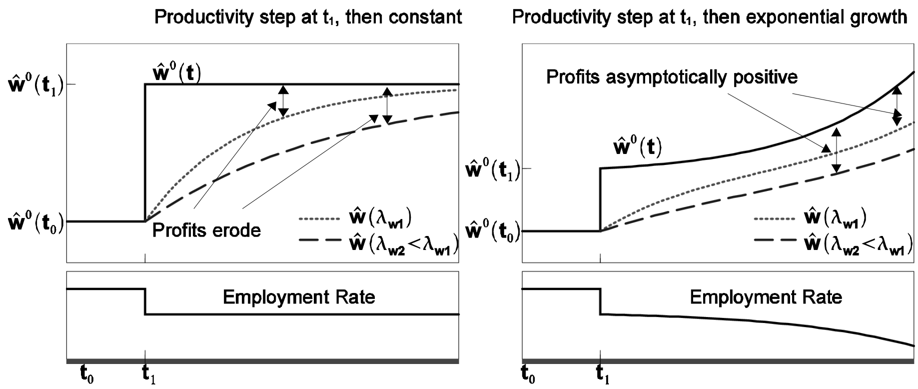
These extensions require minor changes to the core model, without affecting the basic model structure, however. Additional cost terms appear in equation (5), so that dividends are now calculated as

$$d = y - w - i_k - i_h - \gamma E - \delta - \tau, \tag{13}$$

1 This mechanism resembles a Phillips curve-like pattern, although the rationale is different as MADIAM does not take inflation into account. Rather, it describes real wage decline as the result of reduced bargaining power of workers when unemployment is large, and vice versa.

Figure 2

Dynamic Adjustment of Wage Rates, Profits and Employment Level



Left: A step-function increase in productivity immediately raises the target wage $\hat{w}^0$ (proportional to $\hat{y}$) and depresses the employment level $q = l/l_{max}$. The wage rate $\hat{w}$ then adjusts with a time lag determined by the time constant λ_w , so that the profit rate (determined by the difference $\hat{w}^0 - \hat{w}$) gradually erodes. The employment rate remains at its depressed level (assuming physical capital investments are fixed at a rate balancing depreciation).

Right: If productivity grows at a constant rate, the difference $\hat{w}^0 - \hat{w}$ no longer tends to zero, allowing a positive profit rate to be maintained. Increasing productivity lowers the demand for labour, and the employment level declines. Note that y-axes are scaled arbitrarily.

Source: Authors.

where γE denotes the average energy costs, δ represents (tangible) climate damages, and τ the imposed carbon taxes (see below). The limiting target-wage coefficient at zero profits and zero growth from equation (11) also needs to be modified to reflect these additional terms:

$$a_w^{max} = 1 - \frac{\lambda_k}{\nu} - \frac{1}{y}\left(\gamma E + \delta + \tau\right). \tag{14}$$

3.1 Carbon Taxes and Emissions

Taxes on CO_2 emissions are set proportional to the emissions and total production

$$\tau = c_\tau \frac{y}{y^0} e, \tag{15}$$

where c_τ is a constant tax coefficient and y^0 the initial production. The proportionality to y corresponds to the assumption that the non-market "value of climate", expressed in terms of willingness-to-pay, can be represented as a time-independent constant fraction of total production. This is based on the assumption (Hasselmann et al. 1997) that the effort an individual is willing to expend on the preservation of climate represents a time-independent fraction of the individual's total economic effort. Thus the value of climate, and accordingly the tax levied to preserve its value, is not discounted at normal business rates, but represents a fixed fraction of GDP. Tax revenues can be spent either as a lump-sum reward to consumers, or specifically to accelerate the transition from fossil to non-fossil energy supply (see end of section).

Carbon emissions e are related to energy use E through the energy-carbon (for short: *carbon*) efficiency f_c, while energy use E is related to production y through the production-energy (*energy*) efficiency f_e,

$$e = \frac{E}{f_c} \quad \text{and} \quad E = \frac{y}{f_e}. \tag{16}$$

The net output-carbon (*net carbon*) efficiency $f = y/e$ relating output to emissions is then

$$f = f_e f_c. \tag{17}$$

Increased energy efficiency depends on technological change. Since productivity is our proxy for technological change, we assume that $f_e(\hat{y})$ is a function of productivity.[2] The energy efficiency of machines is limited thermodynamically. Assuming that the use of physical energy cannot be completely replaced by the processing of information, we limit therefore the future growth of f_e in accordance with the logistic relation

$$f_e = f_e^{max}\left(1 - \frac{\Phi_1}{\Phi_2 + \hat{y}}\right). \tag{18}$$

The constants $f_e^{max}, \Phi_1, \Phi_2$ are estimated empirically (Barth 2003).

For simplicity, we neglect improvements in the energy-per-carbon ratio by fossil-fuel switching or advances in fossil-fuel technology and assume that the carbon efficiency is determined directly by the share of non-fossil (emission-free) energy plants in the overall energy system. This is determined by the share k_n of physical capital in non-fossil plants relative to the total capital k_e in energy plants,

$$f_c = \frac{k_e}{k_e - k_n}, \tag{19}$$

where it is assumed that the capital required to generate a certain amount of energy $E = y/f_e$ is proportional to that amount, $E \sim k_e$, and that k_e is already contained in the overall physical stock k. Thus, investments i_e in the energy system cannot be freely chosen but are determined by the growth of energy demand,

2 f_e follows the technological state-of-the-art, which depends on R&D and innovation and is best described in our model by human capital. Once available, new technologies require physical capital investments to spread. As discussed in section 2, this is not represented explicitly in our model, but is absorbed in the normal turn-over rate of capital.

$$i_e = k_e + \lambda_k k_e - \sigma\tau, \tag{20}$$

where λ_k denotes the capital depreciation rate. The term $\sigma\tau$, where σ can take the values 0 or 1, expresses the two options that the tax revenues τ can be cycled back into the economy either to increase the investments in non-fossil energy systems ($\sigma = 1$) or to increase consumption ($\sigma = 0$).

Business controls the fraction $0 \le z \le 1$ of i_e that is used to build non-fossil energy plants, so that the set of business control variables is extended by z. The associated non-fossil energy capital stock grows as

$$\dot{k}_n = z i_e - \lambda_k k_n + \sigma\tau. \tag{21}$$

3.2 Energy Costs

The average energy cost, γ, depends on the relative shares and unit costs of fossil and non-fossil generated energy. The unit costs of fossil fuels, γ_f, are assumed to increase with the inverse square of the available resources, $\gamma_f \sim c^{-2}$ (Barth (2003), on the basis of Rogner's (1997) extraction-cost estimates and the fossil-resource estimates by IPCC (2001b) and Rogner (1997)). For simplicity, non-fossil unit energy costs, γ_n, are assumed to be constant. This ignores important learning mechanisms and should be regarded only as a preliminary device to avoid distracting from the other processes which are the main focus of this study.

$$\gamma_f = \gamma_f^0 \left(\frac{c^0}{c} \right)^2, \tag{22}$$

$$\gamma_n = \text{const.} \tag{23}$$

$$\gamma = \gamma_f \frac{k_e - k_n}{k_e} + \gamma_n \frac{k_n}{k_e} \tag{24}$$

$$\dot{c} = -e, \tag{25}$$

where the upper index 0 refers to the initial value at time $t = 0$. The last equation describes the decline of fossil fuel resources through CO_2 emissions.

3.3 Climate-Related Costs

Climate-related costs consist of damages from extreme events and costs of adaptation measures. These impacts are poorly known, thus we follow Hasselmann et al. (1997) and represent them as a simple quadratic function of the changes ΔT and rates of change

$d\Delta T/dt$ of global mean temperature, as computed from the CO_2 emissions using the NICCS model:

$$\delta = D\ y\left\{\left(\frac{\Delta T}{T_b}\right)^2 + \left(\frac{d\Delta T/dt}{dT_b/dt}\right)^2\right\}, \tag{26}$$

where T_b is a benchmark temperature, dT_b/dt a benchmark rate of change of temperature and D a benchmark coefficient relating mean (tangible) climate damages to GDP.

3.4 Optimisation

We assume that businesses determine their optimal investment strategy by maximising the net present value U of dividends in a risky world according to:

$$\max. U = \int_0^\infty \frac{d^{1-k} - 1}{1-k} e^{-\lambda_d t} dt \xrightarrow[k \to 1]{} \int_0^\infty \ln(d) e^{-\lambda_d t} dt \tag{27}$$

Business is risk averse when splitting net profits *x'* between investments and dividends *d*. As investments do not pay off for certain (as increased future dividends) and losing an investment is usually considered more harmful than the respective enjoyment from the additional dividends when the same investment is successful, businesses will apply a concave utility function with respect to dividends. We choose here a constant inter-temporal elasticity of substitution (CIES) function, where k is a measure for risk aversion (e. g. Barro and Sala-i-Martin 1995). We set $k \to 1$, yielding a logarithmic utility function, with the discount factor λ_d.

4 **Simulation Results**

The following simulations illustrate the general behaviour of our model and the impact of different taxation schemes on the cost structure. Each model run optimises with a 5 years time step over a time horizon of 600 years to capture long-term climate change effects in the computations, but only the first 300 years will be shown to avoid contamination by terminal effects. The model is calibrated to reproduce historical growth rates of GDP, productivity and unemployment from 1915-2000 (Maddison 1982, 1995). The model is therefore initialised in 1915. All economic variables are normalised to the values of capital and labour of that year.

Constrained World Baseline

The reference scenario of our analysis, the Constrained World Baseline (CWB, see Figure 3a), represents a business optimisation in a model world constrained by $c^0 = 10^4$ GtC available resources and a climate damage of 1.6% of GDP at the benchmark temperature change (T_b) (Barth 2003). No taxes have yet been applied. The CWB parameters are listed in the Appendix.

The top panel of Figure 3a shows the evolution of production *y*, productivity $\hat{y}$ and the net carbon efficiency f. Production and productivity grow at constant annual rates of

2.8% and 1.6%, respectively. Net carbon efficiency f grows slightly over the first 120 years (i.e. the period 1915–2030) through improvements in energy efficiency f_e. The rapid growth of f after 2035 results from business starting to invest actively in non-fossil energies ($z > 0$ in equation (2)), thereby raising carbon efficiency f_c.

The center panel shows the resulting CO_2 emissions and climate change. The growth of f decouples emissions from GDP growth, so that emissions peak at 18 GtC/yr in 2055, falling to zero around 2150. This results in a peak global average temperature of ΔT = 3°C in 2020 and slowly decreasing temperature afterwards.

Economic costs are shown as fractions of production in the bottom panel. Damage costs (dashed line) peak at 2.7% of GDP in 2055. The cost share for total energy (solid line with squares) decreases initially due to the gradual increase in energy efficiency. The switch to more expensive non-fossil fuels after 2035 increases the energy costs up to a maximum of 9% of GDP in 2100, when the energy system has completely changed to non-fossil supply. The declining costs after 2100 result again from the continuing increase in energy efficiency. The sum c_c of damages and energy costs (dotted line) peaks at 10.5% of GDP in 2100.

Climate-related costs clearly contribute less to the overall costs than the increase in energy costs due to the switch to the more expensive non-fossil fuels. Since fossil fuel resources are finite, this changeover must necessarily occur at some time. The exact timing, however, is determined by the trade-off of the anticipated damage costs against the increase in energy costs. It depends on the available fossil resources, the difference in fossil and non-fossil unit energy costs, and the expected magnitude and timing of climate damages. In a scenario without climate damages the switch to non-fossil fuels started 60 years later than in the CWB (Barth 2003).

Tax Rate 100 $/tC

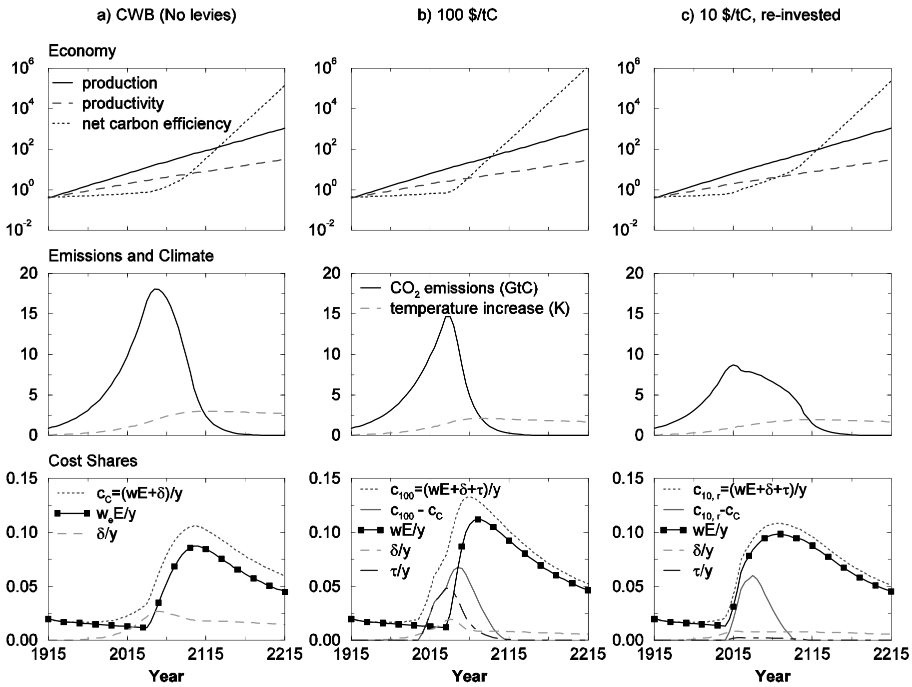
The rather high global warming in the CWB scenario suggests imposing taxes on energy use to provide an incentive to business to change to non-fossil fuels earlier and/or more rapidly. In the following we denote any kind of monetary tool that increases energy costs as “taxes”; the details of its specific implementation are beyond the scope of this study.

We first examine the effect of applying a tax rate that grows linearly from zero in 2000 to 100 $/tC in 2020, corresponding to $c_\tau = 0.00132$ GtC^{-1} (Figure 3b). This is at the upper end of recent estimates for marginal abatement costs under a global trading scheme (Hourcade et al. 2001). The revenues are recycled to increase consumption ($\sigma = 0$ in equations (20), (21)). Thus, taxes simply increase the cost of using fossil fuels (dash-dotted line in bottom panel of Figure 3b). This provides the expected incentive to invest in carbon efficiency and thereby leads to a faster increase in net carbon efficiency (top panel, dotted line). Carbon emissions are significantly reduced after 2035, and global mean temperature increases by only 2°C in 2080.

This positive effect for climate, however, requires a greater demand for expensive non-fossil fuels, so that energy costs reach 11% of GDP in 2075. Although damages are significantly reduced (max. 1.9% in 2040), total costs (c_{100}) peak at 13.2% of GDP in 2055. Before 2035, the additional total costs compared to those of the CWB scenario (solid line,

Figure 3

Business Optimisation Results for Economic (top panel), Climate-Related (center) and Cost-Related (bottom) Variables from Three Scenarios



a) the Constrained World Baseline (CWB), b) the CWB settings plus a 100 $/tC tax, and c) the CWB settings plus a 10 $/tC tax which is re-invested in non-fossil energy supply.
Legend: c_c, c_{100}, $c_{10,r}$: total cost in the respective scenario; w_eE: energy cost; δ: damage cost; τ: tax revenues; y: total production.

Source: Authors.

bottom panel) consist entirely of taxes (dash-dotted line, bottom panel), and reach 6.5% of GDP in 2055.

Surprisingly, investments appear unaffected by these costs, so that production and productivity remain almost unchanged (Figure 3b, top panel). This is because increased energy costs, damages, or taxes reduce the target wage coefficient a_w^{max} (equation (14)), leading to reduced wage demands. However, as tax revenues are redistributed to consumers, these reductions are compensated completely before 2035, when the enhanced costs are due entirely to taxes. In the following 80 years, however, the energy costs lie above those of the CWB. These additional costs are not compensated, so that the income of wage earners (wages plus recycled taxes) is reduced by the switch to non-fossil energy.

Tax Rate 10 $/tC with Invested Revenues

We now consider the case where tax revenues are used specifically to enhance investments in non-fossil energy supply ($\sigma = 1$ in equations (20), (21)). The tax rate again increases linearly from zero to its final level between 2000 and 2020.

In this case even a small tax rate of 10 $/tC (c_τ = 0.000132 GtC^{-1}) yields significant effects (Figure 3c). Carbon emissions decline shortly after the tax is imposed, resulting in a maximum increase of global mean temperature of only ΔT = 1.9°C in 2110. This is because the carbon efficiency now starts to increase as soon as the first taxes are collected (the "kink" around the year 2005 in the dotted line in the top panel of Figure 3c). Business starts investing in 2030 at a slower rate than in the previous case, which causes the second "kink".

The cost structure also changes. Since emissions are strongly reduced and the tax rate is rather low, tax revenues are very small (max. 0.25% of GDP). But as tax revenues directly increase the carbon efficiency, even this small contribution leads to the observed strong emissions reduction. Climate damages are also small (max. 0.8% of GDP). However, the beneficial effects for consumers from these saved costs are outweighed by the increased energy costs caused by the early transition to more expensive non-fossil fuels. As taxes are now no longer used to refund the wage cuts, the consumption of workers is now reduced by the full additional costs of up to 5.5% of GDP.

5 Conclusions

In our computations we have examined the impact on climate change and the additional costs incurred when carbon taxes are imposed to reduce climate change. Taxes are an effective tool for reducing climate change. The added costs give an incentive to reduce emissions and thus climate change and the associated damages. The effect on climate is strongest when taxes directly support the investments in non-fossil energy supply.

Taxes have three effects on the cost structure: first, direct tax payments, second, reduced damage costs, and third, increased energy costs through the use of more expensive non-fossil fuels. If taxes are redistributed to consumers, the first effect is neutral for wage earners: wage cuts through tax payments are balanced by the recycled revenues. The second effect is positive for wage earners: less damage costs allow higher wages. The third effect, however, forces wage cuts if the economy is to keep growing at an unchanged rate. These reductions amount to 2–3% of GDP for a 100 $/tC tax, while climate change is reduced by 1°C (33%) relative to the CWB.

When the taxes are reduced to 10$/tC but the revenues are used instead to accelerate the energy system transition directly via investments in non-fossil energy, the additional costs to consumers are not compensated by tax revenues, so that the full costs of 5.5% of GDP have to be paid in this case by consumers. The resulting reduction in climate change of 1.1°C (37%) is only slightly better than in the case of a 100 $/tC tax returned to consumers. The lower-tax case is therefore less attractive from the point of view of the consumers. However, it should be noted that an income reduction of 5% over a hundred years in an economy that grows by more than one order of magnitude in the same period represents a net delay of only two or three years. This might be an acceptable price to pay for a significant reduction of the risks of climate change.

We emphasize that the details of the model response depend on a number of calibration parameters and the assumed actor control algorithms, which are partly not well established or had to be derived *ad hoc* due to lack of data. However, the purpose of this model study was not to provide reliable predictions, but rather to identify the critical processes and their interactions that need to be more closely studied in future investigations.

Several issues have not been addressed. For example, the extent to which consumers or society in general are willing to trade reduced consumption against improved climate protection was not considered. This requires the use of a societal welfare function, in addition to the business utility function on which the present analysis is based (see Barth 2003 for an application, and the treatment of consumer preferences in Weber et al. 2005). By regarding the prices of non-fossil fuels as constant, we have furthermore ignored the important price dynamics of non-fossil fuels. These are governed by learning curves, leading to reduced unit costs for non-fossil energies and thus to smaller overall energy costs. The mitigation costs of climate change presented here should therefore be seen as conservative upper estimates.

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Appendix

CWB Calibration

The CWB scenario is initialised with the settings listed below. Capital-related dimensions are normalised by initial physical capital ($k(t_0) = 1$), labour related dimensions by initial labour ($l(t_0) = 1$).

Table A1

Model Variables

	Variable	Initial Value	Description
	k	1	Physical capital
	y	0.4	Annual production
	$\hat{w}$	0.22	Wage rate
	k_e	0.1	Physical capital for energy supply
A	k_n	0.001	Physical capital for non-fossil energy supply
	l	1.0	Labour
	c	10^4	Fossil resources in GtC
	e	0.9	Emissions in GtC
	v	0.4	Capital productivity
	μ_h	0.1	Efficiency of investment in human capital
	λ_k	0.05 1/yr	Depreciation rate
	λ_d	0.01 1/yr	Intertemporal discount rate
	D	0.008	Damage fraction of GDP
	T_b	2°C	Benchmark climate change
B	dT_b/dt	0.02°C/yr	Benchmark change rate of T_b
	γ_f	0.007	Fossil fuel unit cost
	γ_n	0.1	Non-fossil energy unit cost
	f_e^{max}	0.7	Maximum energy efficiency
	$l_{\max}^0$	1.05	Initial value labour pool
	λ_l	0.012 1/yr	Growth rate of labour pool (UN 1999)
	α_q	60	Wage coefficient exponent
	Φ_1	25 1/yr	Scale parameter for f_e
	Φ_2	27.5 1/yr	Scale parameter for f_e
	i_k		Investment in physical capital
	i_h		Investment in human capital
C	z		Share of energy investment used for k_n
	a_w^{min}	0.66	Minimum wage coefficient
	λ_w	0.15 1/yr	Rate of wage adaptation

A = Endogenous state and derived variables.
B = Exogenous constants.
C = Control variables (either exogenous or determined by optimisation).

Source: Authors.