The Value of ITC under Climate Stabilization

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NOTA DI LAVORO 126.2005

OCTOBER 2005

CCMP – Climate Change Modelling and Policy

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This paper is one of a series published by FEEM on the theme of innovation modeling in the context of the challenge of stabilising atmospheric concentrations of greenhouse gases, as part of the Innovation Modeling Comparison Project. This is an international project launched and overseen by the Steering Committee of the informal International Programme on the Economics of Atmospheric Stabilisation. The broad aim of the collaboration is to advance understanding of the economic issues surrounding atmospheric stabilisation, and the specific aims of the IMCP are to provide insights into the "state of the art" and implications of endogenous modeling of technical change in global energy-environment models when applied to various levels of atmospheric stabilisation.

Members of the Steering Committee provided review comments on earlier drafts and the paper has been forwarded to external review, the final results will be published as a Special Issue of the Energy Journal. The papers have all been encouraged to draw on a common baseline (the "Common Poles-Image baseline") and to report results in comparable formats, so as to facilitate intercomparison of the different modeling results. All the results and judgements expressed here remain the responsibility of the authors.

The work presented in this paper was supported by the Netherlands Organization for Scientific Research (NWO) under contract nr. 016.005.040. FEEM fund the working papers series, and seed money for the coordination work of the Innovation Modeling Comparison Project was provided by UK Department of Environment, Food and Rural Affairs and the German Ministry of Environment.

The author is grateful to Ottmar Edenhofer and Claudia Kemfert for organizing the IMCP (Innovation Modelling Comparison Project) workshop, 23th-24th February 2005, Berlin, where this paper was presented, and to the participants for their comments.

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Summary

We assess the effect of ITC in a global growth model, DEMETER-1CCS, with learning by doing where energy savings, an energy transition, and carbon capturing and sequestration (CCS) are the main options for emissions reductions. The model accounts for technology based on learning by doing embodied in capital installed in previous periods. We have run five scenarios, one baseline scenario in which climate change policy is assumed absent, and four stabilization scenarios in which atmospheric CO2 concentrations are stabilized at 550, 500, 450, and 400 ppmv. We find that the timing of emission reductions and the investment strategy is relatively independent of the endogeneity of technological change. The vintages structure of production is more important. But ITC reduces costs by about factor 2, though these benefits only materialize after some decades.

Keywords: Energy, Carbon taxes, Endogenous technological change, Niche markets

JEL Classification: Q43, Q54, Q55

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1. Introduction

Until recently, most economic assessments of climate-change policies neglected policy's effects on economic performance through technological development. This omission is not surprising, as there is a substantial gap in our understanding of the determinants for both the level and the direction of technological change. Though already in the 1960s there were a few studies that looked into the theory for technological change induced by prices changes in factors of demand (e.g. Kennedy 1964), the topic did not receive much attention until the 1990s. In these years, a stream of so-called endogenous-growth models were developed, describing cumulating knowledge as a major determinant of long-term economic growth (Aghion and Howitt 1992, Mankiw 1995). Following the macro-economic literature on aggregate growth, environmental economics started to apply the insights and to build theoretic models of innovation in relation to environmental policy (Gradus and Smulders 1993; Bovenberg and Smulders 1995, 1996; Verdier 1995; Beltratti 1997; Smulders 1999, Goulder and Mathai 2000; Smulders and de Nooij 2003, Nakada 2004). Subsequently, these insights are now applied to an increasing number of economic models that assess the interplay between energy use, climate change, climate policy and technological change (Carraro and Galeotti 1997, Goulder and Schneider 1999, Nordhaus 2002, Manne and Richels 2002, van der Zwaan *et al.* 2002, Gerlagh and van der Zwaan 2003, 2004, Buonanno *et al.* 2003, Popp 2004, Gerlagh 2004, Gerlagh *et al.* 2004, Gerlagh and Lise 2005). A common finding in these studies is that the inclusion of technical change in the analysis decreases the costs of emission reductions, but whether the cost reduction is substantial, compared to an analysis without induced technological change (ITC), remains subject of debate (Fischer and Morgenstern 2003, Goulder 2004). While some authors suggest that ITC substantially cuts the costs (Manne and Richels 2002, Gerlagh and van der Zwaan 2003), or even renders a double dividend possible (Carraro and Galeotti 1997), others are more pessimistic and claim that ITC will have a relatively small impact compared to the contribution of factor substitution for given technology (Goulder and Schneider 1999, Nordhaus 2002). This paper contributes to that literature, assessing the effect of ITC in a global growth model with learning by doing where energy savings, an energy transition, and carbon capturing and sequestration (CCS) are the main options for emissions reductions. We specifically assess the required investments portfolio in fossil fuel and non-carbon energy sources and in CCS to reach various stabilization targets, and its relation to enhanced learning.

The outlay of the paper is as follows. In Section 2, we present our model, DEMETER-1CCS. It is a growth model with learning by doing for fossil fuels, non-carbon energy, and it contains a decarbonisation option through CCS, and a simple climate module. The model is an extension of the DEMETER model that has been used for various climate change policy analysis (van der Zwaan *et al.* 2002, Gerlagh and van der Zwaan 2003, 2004, Gerlagh *et al.* 2004). This section presents the primal equations. Welfare and profit functions, and first order conditions are given in the appendix. In Section 3, we briefly elaborate on the calibration issues. In Section 4, we present and discuss calculations for a benchmark and various stabilization scenarios. In Section 5, we conclude.

2. DEMETER-1CCS

The DEMETER model has been used in a few papers already (van der Zwaan *et al.*, 2002, Gerlagh and van der Zwaan, 2003, Gerlagh and van der Zwaan 2004, Gerlagh *et al.* 2004). The model presented here extends the DEMETER-1 model with a description of carbon capturing and sequestration. The model has 30 distinct time periods of five years, each denoted by t=1,…,30. The model distinguishes one representative consumer, three representative producers (also referred to as sectors), and a public agent that can set emission taxes to reduce carbon dioxide emissions. Producers are denoted by superscripts j=C,F,N, for the producer of the final good or consumption good, the producer of energy based on fossil-fuel technology, and the producer of energy based on carbon-free technology. The final good is produced by sector j=C, where output is denoted by Y^C. The same good is used for consumption, investments I in all three sectors and for operating and maintenance M (as usually distinguished in energy models, cf. McDonald and Schrattenholzer, 2001) in both energy sectors j=F,N (1). We also distinguish a separate carbon capture and storage (CCS) activity for which investments and maintenance are required. We assume there is one representative consumer who maximizes welfare (18) subject to a budget constraint, and for the three sectors, we assume a representative producer who maximizes profits, which is equal to the net present value of the cash flows (19) and (20), subject to the production constraints (2)-(8), given below.

To describe production, DEMETER accounts for technology that is embodied in capital installed in previous periods. It therefore distinguishes between production that uses the vintages of previous periods, and production that uses the newest vintage for which the capital stock has been installed in the directly preceding period. The input and output variables, as well as prices, associated with the most recent vintages are denoted by tildes (~). For every vintage, the production of the final good is based on a nested CES-function, using a capital-labour composite, $\tilde{Z}_t$, and a composite measure for energy services, $\tilde{E}_t$, as intermediates (2), where A_t^1 and A_t^2 are technology coefficients, and γ is the substitution elasticity between $\tilde{Z}_t$ and $\tilde{E}_t$. Notice that the

Lagrange variable for the profit maximization program is given between brackets. The capital-labour composite $\widetilde{Z}_t$ has fixed value share α for capital (3). Note that new capital is by definition equal to the investments of one period ahead, $\widetilde{K}_t^j = I_{t-1}^j$. We model energy services $\widetilde{E}_t$ as consisting of a CES aggregate of energy produced by the sectors *F* and *N* (4), where σ is the elasticity of substitution between *F* and *N*.

One part of production employs the new vintage, the other part employs the old capital stock that carries over from the previous period. All flows, output, use of energy, labour, and the output of emissions are differentiated between the old and the new vintages. The input/output flow in period *t* is equal to the corresponding flow for the new vintage, plus the corresponding flow for the old capital stock of the previous period, times a depreciation factor (1–δ), (5), (6), (7), and (8).

$$C_t + I_t^C + I_t^F + I_t^{CCS} + I_t^N + M_t^F + M_t^{CCS} + M_t^N = Y_t^C . \tag{1}$$

$$\widetilde{Y}_t^C = ((A_t^1 \widetilde{Z}_t)^{(\gamma-1)/\gamma} + (A_t^2 \widetilde{E}_t)^{(\gamma-1)/\gamma})^{\gamma/(\gamma-1)}, \qquad (\tilde{\lambda}_t^2) \tag{2}$$

$$\widetilde{Z}_t = (I_{t-1}^C)^{\alpha} (\widetilde{L}_t)^{1-\alpha}, \qquad (\widetilde{\theta}_t) \tag{3}$$

$$\widetilde{E}_t = ((\widetilde{Y}_t^F)^{(\sigma-1)/\sigma} + (\widetilde{Y}_t^N)^{(\sigma-1)/\sigma})^{\sigma/(\sigma-1)}, \qquad (\widetilde{\chi}_t) \tag{4}$$

$$Y_t^C = (1-\delta) Y_{t-1}^C + \widetilde{Y}_t^C , \qquad (\tilde{\lambda}_t^1) \tag{5}$$

$$Y_t^j = (1-\delta) Y_{t-1}^j + \widetilde{Y}_t^j , \qquad (\widetilde{\mu}_t^j ;\ j=F,N) \tag{6}$$

$$L_t^j = (1-\delta) L_{t-1}^j + \widetilde{L}_t , \qquad (\widetilde{w}_t) \tag{7}$$

$$Em_t = (1-\delta) Em_{t-1} + \widetilde{E}m_t . \qquad (\widetilde{\tau}_t) \tag{8}$$

.

Both energy producers, the fossil fuel sector *j=F* and the non-fossil fuel sector *j=N* are treated almost symmetrically. The only difference is in the costs and in the option for fossil-fuel energy producers to decarbonize through carbon capturing and storage. We first describe the production process for the non-fossil fuel sector. Production of energy, $\widetilde{Y}_t^j$ (*j=F,N*), requires investments I_{t-1}^j (in the previous period) and maintenance costs, M_t^j, see (6), (9), (10), (11), and (12). Each new vintage with output $\widetilde{Y}_t^j$ requires a certain effort, measured through the variable *Q*, which is proportional to investments (one period ahead) and maintenance costs (9), where the variable h_t^j is a measure of technology variable over time, and a^j and b^j measure the constant investment and maintenance share in production costs.

$$Q_t^j = h_t^j \tilde{Y}_t^j , \qquad (\varphi_{j,t};\ j=F,N) \tag{9}$$

$$I_{t-1}^j = Q_t^j / a^j , \qquad (\zeta_{j,t};\ j=F,N) \tag{10}$$

$$\widetilde{M}_t^j = Q_t^j / b^j . \qquad (\eta_{j,t};\ j=F,N) \tag{11}$$

$$M_t^j = (1-\delta) M_{t-1}^j + \widetilde{M}_t^j . \qquad (\xi_{j,t};\ j=F,N) \tag{12}$$

We assume that knowledge is a public good that is non-rival and non-exclusive. Thus firms will not internalize the positive spill-over effects from their investments in their prices. Hence, the productivity parameter h_t^j is treated as exogenous by the firms, and the individual firms are confronted with constant returns to scale. Profit maximization of (20) subject to (6), (9), (10), (11), and (12) gives zero profits. First order conditions are listed in the appendix.

Energy production based on fossil fuels can be confronted with a carbon tax levied on carbon dioxide emissions, and producers can choose to decarbonize energy through carbon capturing and sequestration (CCS). Carbon dioxide emissions, Em_t, are proportional to the carbon content of fossil fuels, denoted by ε_t^F, but part of emissions, *CCSR*, is captured through a carbon capturing and storage activity (13). The variable *CCSR* can be understood as the carbon capturing and sequestration ratio. When convenient, we use the acronym *CCS* for the carbon capturing and storage activity, measured in metric tons of carbon, and *CCSR* for the ratio of emissions prevented through this activity. The tildes on top of the variable denote that emission intensities are vintage specific. Alternatively, we can interpret the *CCSR* variable in a broader perspective as a broad decarbonization measure, where ε_t^F is the carbon intensity of a benchmark fuel mix that is optimal without carbon tax, and *CCSR* includes all activities that reduce carbon dioxide emissions, including fuel-switching options.

Similar to the production of energy described above, the carbon capturing and sequestration process is described through an effort variable Q_t^{CCS}, which is assumed a second order polynomial function of the share of carbon that is captured and sequestered:

$$\tilde{E}m_t = \varepsilon_t^F(1-CCSR)\tilde{Y}_t^F. \qquad (\tilde{\tau}_t) \qquad (13)$$

$$Q_t^{CCS} = h_t^{CCS}(CCSR_t + \tfrac{1}{2}\kappa\, CCSR_t^2)\varepsilon\tilde{Y}_t^F, \qquad (\varphi_{j,t};\ j{=}CCS) \qquad (14)$$

Investments and maintenance costs are described through the same equations as for the production process: (10), (11), and (12). The quadratic cost curve implies that the amount of carbon that is captured and not emitted is linear in the carbon tax.

Technological change

The DEMETER model incorporates various insights from the bottom-up literature that stress the importance of internalizing learning-by-doing effects in climate change analyses. Energy production costs decrease as the experience increases through the installation of new energy vintages. In this version of DEMETER, the endogenous modelling of learning by doing is limited to the energy sectors; we have not included learning effects for overall productivity and energy efficiency. Thus, A_t^1 and A_t^2 as employed in (2) are exogenously determined by a benchmark (business as usual) growth path.

For energy production and CCS, the variable h_t^j measures the state of technology. More specific, it defines the costs of one unit of output $\widetilde{Y}_t^j$ as compared to potential long-term costs. For example, $h_t^j=2$ means that one unit of energy output of sector j costs twice as much investments and maintenance as compared to the situation in the far future when the learning effect has reached its maximum value.

To capture the process of gaining experience and a decreasing value of h_t^j, we introduce the variable X_t that represents experience; it counts accumulated installed new capacity (vintage) at the beginning of period t. For energy production, the new capacity is equal to the output of the new vintage (15). For carbon capturing and sequestration, the new capacity is the amount of emissions prevented (16). Furthermore, we use a scaling function that returns the value for h_t^j as dependent on cumulative experience at the beginning of the period, X_t^j (17). Our scaling function satisfies $\partial h_t^j / \partial X_t^j \leq 0$, that is, production costs decrease as experience increases, and we assume $h_t^j=1$ for $X_t^j \rightarrow \infty$ that is, production costs converge to a strictly positive floor price (minimum amount of input associated with maximum learning effect) given by the levels of a_∞^j and b_∞^j. Finally, we assume a constant learning rate for technologies at the beginning of the learning curve (that is, for small values of X), captured by the power d^j. This means that, initially, production costs decrease by a factor $2^{-d^j}=(1-lr)$, where lr is the so-called learning rate, for every doubling of installed capacity. Such decreases have been observed empirically for a large range of different technologies (IEA/OECD, 2000).

$$X_{t+1}^j = X_t^j + \widetilde{Y}_t^j \,. \qquad (j=F,N) \qquad (15)$$

$$X_{t+1}^{CCS} = X_t^{CCS} + CCSR_t \varepsilon_t \tilde{Y}_t^F \,. \qquad (16)$$

$$h_t^j = c^j (1-d^j)(X_t^j)^{-d^j} + 1, \qquad (j=F,N,CCS) \qquad (17)$$

Climate change

Emissions are included in the model through equations (8) and (13). The carbon cycle and climate change dynamics are included by linking emissions to atmospheric, upper ocean, and lower ocean CO_2 storage, and ocean and global average surface temperature, following the RICE model (Nordhaus and Boyer 2000).

3. Calibration and data for numerical analysis

For all parameters but for CCS, an extensive discussion on calibration issues can be found in earlier papers on the DEMETER 1 model (van der Zwaan *et al.*, 2002, Gerlagh and van der Zwaan, 2003, Gerlagh and van der Zwaan 2004, Gerlagh *et al.* 2004). Here we confine ourselves to the parameters that affect CCS. CCS costs consist of three parts: capturing of carbon, that is the separation and compression, its transport, and its storage. For a fossil fuel fired electricity plant, capturing carbon makes the major share in total costs. For this process, only limited commercial experience is available and the cost ranges quoted in the literature are large, dependent on specific capture technology and the power plant in case. But the capture technology part in CCS systems is similar to more common technologies used for sulphur and nitrous oxides removal from flue gases. Worldwide, the costs of applying these technologies have decreased considerably over the past decades (Rubin *et al.*, 2004a and 2004b) and learning rates for capital costs of 11% and 12% were found. We assume that CCS will follow the same route of technological progress, and we take a learning rate of 10%. As DEMETER does not distinguish between the capture and storage parts of CCS technologies, it is supposed that this 10% learning rate is applicable to the employment of CCS at large. Still, application of the learning rate requires an estimation of the initial level of cumulative experience and the initial costs per ton of carbon. To estimate initial cumulative experience, we consider existing carbon dioxide storage e.g. the Sleipner project (0.2-0.3 MtC/yr), in the Weyburn project (1-2 MtC/yr) and West Texas (5-10 MtC/yr), and assume that experience has cumulated to about 20 MtC/yr of CCS capacity installed.

In the first period, we assume that some CCS is economic feasible at costs of around 10 $/tC (avoided, that is, 3 $/tCO$_2$ avoided). This relatively low figure is justified by the assumption that, in some cases, CCS can increase the output of oil fields. At the high-cost end, it is assumed that if one nears the point of applying CCS to the use of all fossil fuel electricity generation, or about one third of total energy demand in primary energy equivalents, costs will be as high as 150 $/tC.[2] For the intermediate range, we assume that the amount of CCS applied is linear in the carbon tax. We note that these values imply that the application of a full-cost CCS system would typically add some 2-5 cent/kWh to the costs of electricity.

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[2] The IPCC (Intergovernmental Panel on Climate Change, Working Group III), in an envisaged Special Report on Carbon Dioxide Capture and Storage, is currently in the process of assembling a comprehensive overview of CCS technologies, including an assessment of their prospective costs.

4. Simulation Results

In this section, we will report on the model results of the emission stabilisation scenarios and how they vary with and without endogenous technological change. The overall objective of this part is to analyse the impact of technological change on crucial economic variables like gross world product (GWP), consumption, and investment strategies, that is the composition of the portfolio of technologies subject to emission stabilisation scenarios. Due to limited space, we cannot elaborate on a full sensitivity analysis or parameter study. We refer to Gerlagh and van der Zwaan (2004) and Gerlagh *et al.* (2004) for a discussion on sensitivity of results with respect to various parameters, including the elasticity of substitution between the fossil fuel and non-carbon energy source and the learning rates.

We have run five scenarios, one baseline or ‘business as usual’ (BAU) scenario in which climate change policy is assumed absent, and four stabilization scenarios in which atmospheric CO_2 concentrations are stabilized at 550, 500, 450, and 400 ppmv (Figure 1). Given the inertia of the energy system, e.g. due to past investments in capital for fossil fuel production and fossil fuel combustion, even a very stringent climate change policy cannot let emissions drop to zero immediately. Even when emissions immediately fall (Figure 2), the inertia of the climate system makes it impossible not to overshoot the 400 ppmv target. Therefore, for the 400 ppmv scenario, we demanded the atmospheric stabilization target to be binding from 2100 onwards. Consequently, in the last decades of the 21st century, emissions fall short of the steady state level that is consistent with a stable 400 ppmv concentrations, and can increase somewhat from 2100 onwards. From Figure 2, we also notice that the timing of emission reductions is relatively independent of the endogeneity of technological change. It turns out that the vintages structure of production is more important from the timing perspective. One has to wait for new vintages of capital that are either less energy intensive or are based on carbon-poor energy sources before emissions can drop. Consequently, emission reductions are somewhat delayed. Also, as we know from the literature, the discount rate employed will have a certain effect on timing.

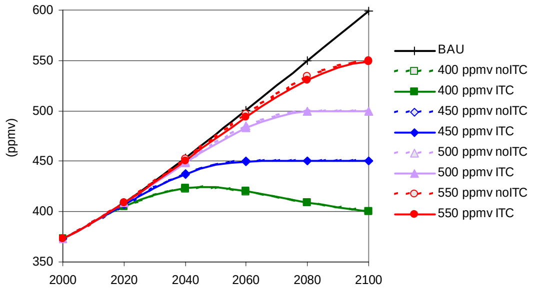

FIGURE 1. *Atmospheric CO_2 concentration*

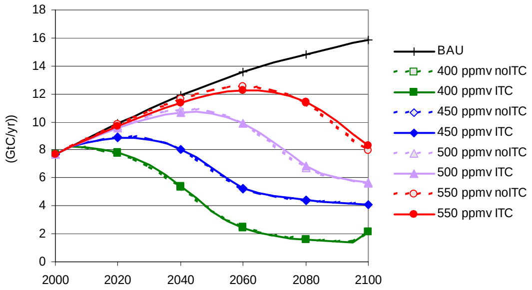

FIGURE 2. *Global CO_2 emissions*

The model recognizes three basic mechanisms for emission reduction: energy savings, a transition towards renewables, and carbon capturing and sequestration of fossil fuels. The latter two options both contribute to a decarbonisation of the energy system. Figure 3 compares energy savings and decarbonisation of energy in one chart. The figure shows that, for the first decades (one marker per 20 years), both options are equally important. But over time, the curve bends to the left, signifying that energy decarbonisation becomes a more important mechanism.

Figure 4 zooms in on the contribution of CCS on emission reductions; it portrays the annual amount of carbon captured and sequestered. After comparison of this figure with the emissions in Figure 2, we see that CCS substantially contributes to the emission reduction effort.

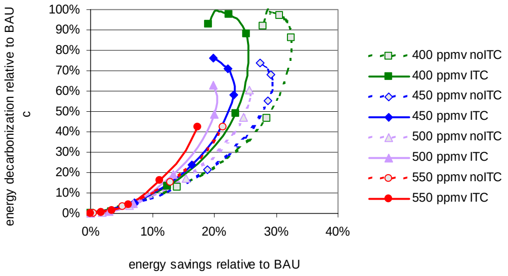

FIGURE 3. *Mechanisms for emission reductions*

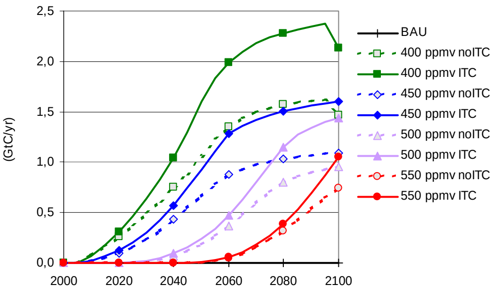

FIGURE 4. *Carbon capture and sequestration*

Figure 5 presents the costs of stabilization in terms of loss of Gross World Product (GWP) relative to the baseline scenario, while Figure 6 shows the costs in terms of loss of consumption. Comparing the two figures, an outstanding result is that consumption losses exceed GWP losses by about factor 2. The reason for this is that a stabilization policy substitutes investments for consumption (Figure 7). Carbon capturing and sequestration requires substantial investments (Figure 9), which counts as part of production so that it does not lead to a decrease in output, but it goes at the cost of consumption. Investments in fossil fuel energy supply decrease under a stabilization policy (Figure 8), but this is more than offset by increased investments in non-carbon energy sources (Figure 10). Not only are non-carbon energy sources more expensive then fossil fuels, but they also require a larger share of investments compared to maintenance costs.

Another conclusion we can draw from Figure 5 and Figure 6 is that, first, ITC reduces costs by about factor 2, but these benefits only materialize after some decades. The first twenty years, from 2000 to 2020, ITC has almost no effect on costs, but thereafter, the extra investments in CCS and non-carbon energy sources start to pay off, when they have contributed to an increase in knowledge, and consequently, to lower energy costs. By 2100, in all four stabilization scenarios, under ITC, GWP is almost unaffected or is even increased compared to the baseline. In the two most-stringent stabilization scenarios, investments in technological change clearly start to pay off as consumption losses decrease during the second half of the 21^{st} century.

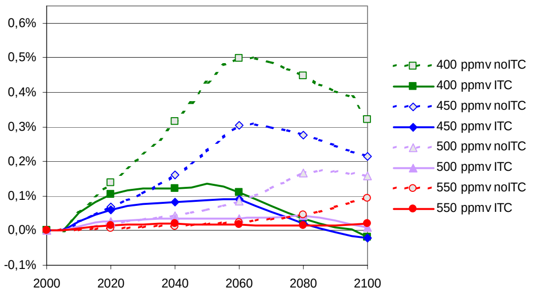

FIGURE 5. *Loss of Gross World Product*

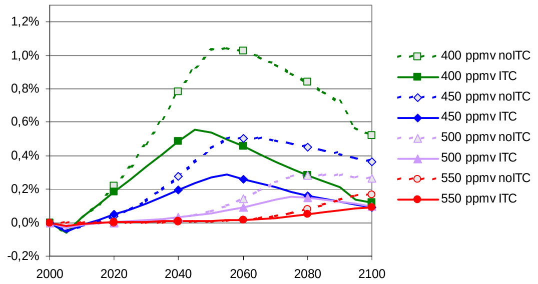

FIGURE 6. *Loss of Consumption*

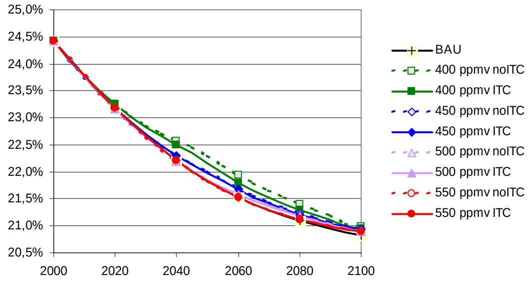

FIGURE 7. *Total Investments per GWP*

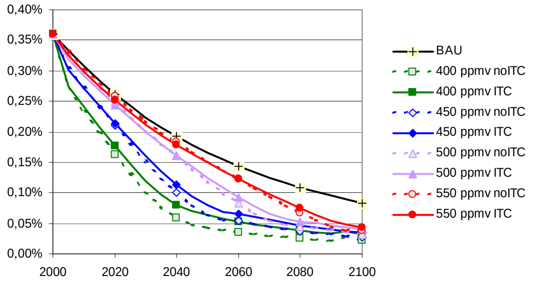

FIGURE 8. *Investments in fossil fuels energy*

When we specifically look at the implications of ITC on the investment strategy, we find limited effects only. Basically, investments in fossil fuels under ITC exceed the levels without ITC (Figure 8). The obvious reason is that ITC leads to an increase in costs of fossil fuels because of the foregone learning when the economy substitutes away from fossil fuels. On the other hand, because ITC reduces the costs of CCS and non-carbon energy sources, investments can slightly fall (Figure 9 and Figure 10). The changes brought about by ITC are, however, insubstantial compared to the significance of the stabilization target, especially in the first decades.

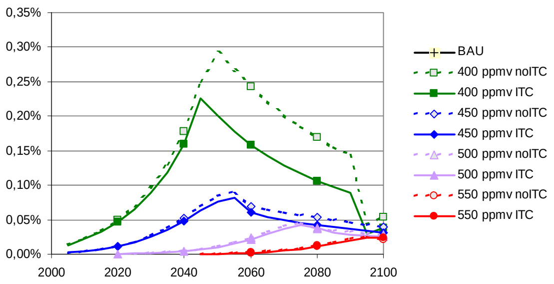

FIGURE 9. *Investments in CCS*

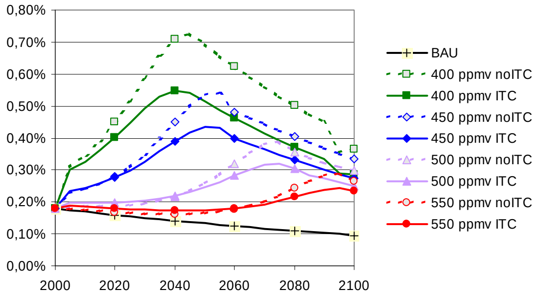

FIGURE 10. *Investments in non-carbon energy technology*

5. Conclusion

In this paper, we developed a global growth model with learning by doing for fossil fuel energy supply, non-fossil fuel energy supply, and CCS. We used the model to assess the implications of ITC on output, consumption, and investments. Basically, the results suggest that ITC does not affect too much the strategy to follow when we strive for climate stabilization. Whether or not technology adjusts, for carbon dioxide emissions to come down, we will have to save on energy first, and apply CCS to fossil fuels, and finally move away from fossil fuels to alternative energy sources. But the recognition of ITC drastically changes our view on the costs of such policies. When acknowledging that technologies adjust to policy's demand through economic incentives, long-term costs of emission reductions can come down substantially. When we see climate stabilization as one part of a trajectory towards sustainable development, we can understand that such a transition is costly, but need not be a lasting burden.

Appendix. Further model conditions

Welfare maximization is given by (18), where W is total welfare, ρ is the pure time preference, and C_t / L_t is consumption per capita. Intertemporal profits are equal to intertemporal revenues, which, for the consumer good producer, consist of output Y_t^C, expenditures consist of investments, I_t^C (one period ahead), labour L_t at wage w_t, fossil-fuel energy Y_t^F at price μ_t^F, and carbon-free energy, Y_t^N at price μ_t^N (19). For the non-carbon energy producers, profits are equal to the value of output minus investments and maintenance costs (20). For the fossil fuel energy producer, the cash flows equation (20) is adjusted to account for additional costs of investments and maintenance for *CCS*, and for the carbon tax levied on emissions (21).

$$\text{Max } W = \sum_{t=1}^{\infty} (1+\rho)^{1-t} L_t \ln(C_t / L_t)\,, \tag{18}$$

$$\text{Max } \sum_{t=1}^{\infty} \beta_0^t (Y_t^C - I_t^C - w_t L_t - \mu_t^F Y_t^F - \mu_t^N Y_t^N)\,, \tag{19}$$

$$\text{Max } \sum_{t=1}^{\infty} \beta_0^t (\mu_t^N Y_t^N - I_t^N - M_t^N)\,. \tag{20}$$

$$\text{Max } \sum_{t=1}^{\infty} \beta_0^t (\mu_t^F Y_t^F - I_t^F - M_t^F - I_t^{CSS} - M_t^{CCS} - \tau_t\, Em_t^F)\,. \tag{21}$$

First order conditions

Welfare optimization gives the Ramsey rule as a first-order-condition for consumption, (22), where β_t is the price deprecation factor from period t to t+1. Maximizing net profits (19), subject to the constraints (2)-(8) yields the following first order conditions for Y_t^C, Y_t^j (j=F,N), L_t, , Em_t, $\tilde{Z}_t$, I_t^C, $\tilde{L}_t$, $\tilde{E}_t$, $\tilde{Y}_t^j$:

$$\beta_t = (C_t / L_t)/((1+\rho)(C_{t+1}/L_{t+1}))\,. \tag{22}$$

$$\tilde{\lambda}_t = (1-\delta)\beta_t \tilde{\lambda}_{t+1} + 1\,, \qquad (Y_t^C), \tag{23}$$

$$\tilde{\mu}_t^j = (1-\delta)\beta_t \tilde{\mu}_{t+1}^j + \mu_t^j\,. \qquad (Y_t^j, j{=}F,N), \tag{24}$$

$$\tilde{w}_t^j = (1-\delta)\beta_t \tilde{w}_{t+1}^j + w_t^j\,. \qquad (L_t), \tag{25}$$

$$\tau_t = \tilde{\tau}_t - (1-\delta)\beta_t \tilde{\tau}_{t+1}\,. \qquad (Em_t), \tag{26}$$

$$\tilde{\theta}_t = \tilde{\lambda}_t^2 (A_t^1)^{(\gamma-1)/\gamma} (\tilde{Z}_t / \tilde{Y}_t^C)^{-1/\gamma} \qquad (\tilde{Z}_t), \tag{27}$$

$$1 = \beta_t \tilde{\theta}_{t+1} \alpha \tilde{Z}_{t+1} / I_t^C \qquad (I_t^C), \tag{28}$$

$$\tilde{w}_t \tilde{L}_t = (1-\alpha)\tilde{\theta}_t \tilde{Z}_{t+1} \qquad (\tilde{L}_t), \tag{29}$$

$$\tilde{\chi}_t = \tilde{\lambda}_t^2 (A_t^2)^{(\gamma-1)/\gamma} (\tilde{E}_t / \tilde{Y}_t^C)^{-1/\gamma} \qquad (\tilde{E}_t), \tag{30}$$

$$\tilde{\mu}_t^j = \tilde{\chi}_t (\tilde{Y}_t^j / \tilde{E}_t)^{-1/\sigma}\,. \qquad (\tilde{Y}_t^j; j{=},N,F) \tag{31}$$

where the variables associated with the first order conditions are given between brackets, $\tilde{\lambda}_t$ is the shadow price for $\tilde{Y}_t^C$, that is the Lagrange variable for (5) which is the same as the Lagrange variable for (2), $\tilde{\mu}_t^j$ is the shadow price for $\tilde{Y}_t^j$, and the Lagrange variable for (6), $\tilde{w}_t$ is the shadow price for $\tilde{L}_t$, and the Lagrange variable for (7), $\tilde{\theta}_t$ is the shadow price for the labour/capital composite $\tilde{Z}_t$ and the Lagrange variable for (3), $\tilde{\chi}_t$ is the shadow price for the energy composite $\tilde{E}_t$ and the Lagrange variable for (4).

The non-carbon energy producers maximize net profits (20) subject to (6), (9), (10), (11), and (12). Calculating the first order conditions for Y_t^j, $\tilde{Y}_t^j$, Q_t^j, $\tilde{M}_t^j$, I_{t-1}^j, and M_t^j, we find (24) and

$$\tilde{\mu}_t^N = h_t^N \varphi_t^N \ , \qquad (\tilde{Y}_t^N) \qquad (32)$$

$$\varphi_t^j = \zeta_t^j + \eta_t^j \ , \qquad (Q_t^j, j=F,N,CCS) \qquad (33)$$

$$\tilde{\xi}_t^j = b^j \eta_t^j \ , \qquad (\tilde{M}_t^j, j=F,N,CCS) \qquad (34)$$

$$1 = a^j \beta_t \zeta_{t+1}^j \ , \qquad (I_{t-1}^j, j=F,N,CCS) \qquad (35)$$

$$\tilde{\xi}_t^j = (1-\delta)\beta_t \tilde{\xi}_{t+1}^j + 1 \ , \qquad (M_t^j, j=F,N,CCS) \qquad (36)$$

where $\tilde{\mu}_t^j$ is the shadow price for $\tilde{Y}_t^j$, and the Lagrange variable for (6), φ_t^j is the shadow price of Q_t^j and the Lagrange variable of (9), ζ_t^j and η_t^j are the Lagrange variables of (10), and (11), and $\tilde{\xi}_t^j$ is the shadow price of $\tilde{M}_t^j$.

The fossil fuel energy producers maximize net profits (21) subject to (6), (8), (9), (10), (11), (12), (13), and (14). Calculating the first order conditions for Y_t^j, Q_t^j, $\tilde{M}_t^j$, I_{t-1}^j, M_t^j, $\tilde{Y}_t^j$, and $CCSR_t$, we find (24) for $j=F$, (33), (34), (35), and (36) for $j=F,CCS$, and

$$\tilde{\mu}_t^F = h_t^F \varphi_t^F + (1 - CCSR_t)\tilde{\tau}_t \varepsilon_t^F + h_t^{CCS} \varphi_t^{CSS} \varepsilon_t^F (CCSR_t + \tfrac{1}{2}\kappa CCSR_t^2) \ , \ (\tilde{Y}_t^F) \qquad (37)$$

$$(1 + \kappa\, CCSR_t)\varphi_t^{CCS} h_t^{CCS} \geq \tau_t \perp CCSR_t \geq 0, \qquad (CCSR_t) \qquad (38)$$

respectively, where the Lagrange variable of (12), $\tilde{\tau}_t$ is the shadow price for $\tilde{Em}_t$ and the Lagrange variable for (8), which has the same value as the Lagrange variable for (13).

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(lxv) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications” organised by Fondazione Eni Enrico Mattei and sponsored by the EU, Milan, September 25-27, 2003

(lxvi) This paper has been presented at the 4th BioEcon Workshop on “Economic Analysis of Policies for Biodiversity Conservation” organised on behalf of the BIOECON Network by Fondazione Eni Enrico Mattei, Venice International University (VIU) and University College London (UCL) , Venice, August 28-29, 2003

(lxvii) This paper has been presented at the international conference on “Tourism and Sustainable Economic Development – Macro and Micro Economic Issues” jointly organised by CRENoS (Università di Cagliari e Sassari, Italy) and Fondazione Eni Enrico Mattei, and supported by the World Bank, Sardinia, September 19-20, 2003

(lxviii) This paper was presented at the ENGIME Workshop on “Governance and Policies in Multicultural Cities”, Rome, June 5-6, 2003

(lxix) This paper was presented at the Fourth EEP Plenary Workshop and EEP Conference “The Future of Climate Policy”, Cagliari, Italy, 27-28 March 2003

(lxx) This paper was presented at the 9th Coalition Theory Workshop on "Collective Decisions and Institutional Design" organised by the Universitat Autònoma de Barcelona and held in Barcelona, Spain, January 30-31, 2004

(lxxi) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications”, organised by Fondazione Eni Enrico Mattei and Consip and sponsored by the EU, Rome, September 23-25, 2004

(lxxii) This paper was presented at the 10th Coalition Theory Network Workshop held in Paris, France on 28-29 January 2005 and organised by EUREQua.

(lxxiii) This paper was presented at the 2nd Workshop on "Inclusive Wealth and Accounting Prices" held in Trieste, Italy on 13-15 April 2005 and organised by the Ecological and Environmental Economics - EEE Programme, a joint three-year programme of ICTP - The Abdus Salam International Centre for Theoretical Physics, FEEM - Fondazione Eni Enrico Mattei, and The Beijer International Institute of Ecological Economics

(lxxiv) This paper was presented at the ENGIME Workshop on “Trust and social capital in multicultural cities” Athens, January 19-20, 2004

(lxxv) This paper was presented at the ENGIME Workshop on “Diversity as a source of growth” Rome November 18-19, 2004

(lxxvi) This paper was presented at the 3rd Workshop on Spatial-Dynamic Models of Economics and Ecosystems held in Trieste on 11-13 April 2005 and organised by the Ecological and Environmental Economics - EEE Programme, a joint three-year programme of ICTP - The Abdus Salam International Centre for Theoretical Physics, FEEM - Fondazione Eni Enrico Mattei, and The Beijer International Institute of Ecological Economics

(lxxvii) This paper was presented at the Workshop on Infectious Diseases: Ecological and Economic Approaches held in Trieste on 13-15 April 2005 and organised by the Ecological and Environmental Economics - EEE Programme, a joint three-year programme of ICTP - The Abdus Salam International Centre for Theoretical Physics, FEEM - Fondazione Eni Enrico Mattei, and The Beijer International Institute of Ecological Economics.

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CSRM	*Corporate Social Responsibility and Sustainable Management* (Editor: Sabina Ratti)
PRCG	*Privatisation Regulation Corporate Governance* (Editor: Bernardo Bortolotti)
ETA	*Economic Theory and Applications* (Editor: Carlo Carraro)
CTN	*Coalition Theory Network*