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

NOTA DI LAVORO 128.2004

OCTOBER 2004
CCMP – Climate Change Modelling and Policy

Reyer Gerlagh, *IVM, Institute for Environmental Studies, Vrije Universiteit*

This paper can be downloaded without charge at:
The Fondazione Eni Enrico Mattei Note di Lavoro Series Index:
http://www.feem.it/Feem/Pub/Publications/WPapers/default.htm

Social Science Research Network Electronic Paper Collection:
http://ssrn.com/abstract=609763

The opinions expressed in this paper do not necessarily reflect the position of Fondazione Eni Enrico Mattei
Corso Magenta, 63, 20123 Milano (I), web site: www.feem.it, e-mail: working.papers@feem.it
A Climate-Change Policy Induced Shift from Innovations in Energy Production to Energy Savings

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

The research has been funded by the Dutch National Science Foundation (NWO) under contract nr. 016.005.040.

Address for correspondence:
Reyer Gerlagh
Institute for Environmental Studies
IVM/FALW/VU
Vrije Universiteit
De Boelelaan 1087
1081HV Amsterdam
The Netherlands
E-mail: reyer.gerlagh@ivm.vu.nl
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 (Newell 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 \( t = 1, \ldots, 60 \), 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:

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

where \( W \) is total welfare, \( \rho \) 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 \( E \)

\[
Y_t = (A_{Y,M} Y, M)^{(\sigma-1)/\sigma} + (A_{Y,E} Y, E)^{(\sigma-1)/\sigma} Y, E^\sigma/\sigma, \]

(2)
where $\sigma$ is the elasticity of substitution between $M$ and $E$, and $A_{YM}$ and $A_{YE}$ are the technology variables that control the productivity of $M$ and $E$, respectively. The parameters $\pi_{YM}$ and $\pi_{YE}$ 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,

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

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

$$Z_{M,t} + Z_{E,t} = (K_t)^\mu (L_t)^{1-\mu} \ (\bar{\varsigma})$$ (5)

where $A_{YM}$ and $A_{YE}$ 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, $\mu$, $q$, and $\bar{\varsigma}$, 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 $\delta_K$, and accumulates through investments $I$,

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

Knowledge is produced on basis of research. All knowledge stocks, $A_{YM}$, $A_{YE}$, $A_{YM}$, and $A_{YE}$ 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).

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

where $\delta_A$ 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 $R$.

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

where $R$ is the aggregate research level,

$$R = R_{Y,M} + R_{Y,E} + R_{M,Z} + R_{E,Z}$$ (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:

$$P_{t+1} = (1 + \chi(1 - P_t / PLT))P_t,$$

(10)

where $\gamma$ is the population growth rate for low population levels and $PLT$ 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 $\omega$ (Baumol 2002, p135). For $\omega=1$, the model would calculate a first-best allocation. For $\omega>1$, 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 $\varepsilon_t$ that describes the level of emissions per unit of energy use:

$$Em_t = \varepsilon_t E_t.$$

(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”:

$$ATM_{t+1} = (1-\delta_M)(ATM_{t-1} - ATM_0) + (1-\delta_E)(Em_{t-1} - \dot{Em}_t),$$

(12)

$$TEMP_{t+1} = (1-\delta_T) TEMP_t + \delta_T TEMP_0 \ln(ATM_t / ATM_0) / \ln(2),$$

(13)
where $\delta_M$ is the atmospheric CO$_2$ depreciation rate, $ATM_o$ is the pre-industrial atmospheric CO$_2$ concentration, $1-\delta_E$ is the retention rate, $Em_t$ are emissions not linked to energy production, $\delta_T$ is the temperature adjustment rate resulting from 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 $\tau_t$ 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,

$$q^\tau_t = q_t + \tau_{E,t}\varepsilon_t,$$

(14)

where $q^\tau_t$ is the price of energy including the carbon tax, $q_t$ is the production costs of energy, and $\varepsilon_t$ 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. $\tau_t > 0$, the generic intermediate $M$ is subsidized with a rate $s_{M,t}$

$$\mu^\tau_t = (1-s_{M,t})\mu_t,$$

(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:

$$\tau_{E,t}\varepsilon_tE_t = s_{M,t}\mu_tM_t.$$

(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 \((g_e)\), overall research expenditures \((R)\), and the real interest rate. These 15 data points are used to calibrate the 17 parameters \(PLT, \gamma, \chi, \zeta_{Y,E}, \zeta_{M,Z}, \zeta_{E,Z}, \pi_{Y,E}, \pi_{M,Z}, \pi_{E,Z}, \zeta_M, \zeta_Z, \delta_K, \delta_A, \rho, \alpha, \epsilon, \) and the growth rate of \(\epsilon\). We notice that there is freedom for the choice of the unit of measurement for knowledge, \(A_{M,Z}\) and \(A_{E,Z}\). 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 \(\sigma\), for which we following Manne (1999), \(\sigma=0.4\). The social returns on research are assumed to exceed the private returns by factor 4 (Baumol 2002, p135), thus, \(\omega=4\). The elasticity of knowledge accumulation to research is set to half, \(\eta=0.5\). 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. \(\gamma=0.48\), 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 \(\zeta_M\) 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 \(\zeta_{M}\), and between \(A_{E,Z}\) and \(\zeta_{E}\). Practically, we set \(A_{M,Z}\) to 100, and demand that \(\zeta_M=\zeta_{E}\).
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](image1)

![Figure 2. Atmospheric CO2 concentration levels](image2)

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.
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.

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.

![R&D in Energy Saving Knowledge](image1.png)

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

![Energy Saving Knowledge](image2.png)

**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.

![R&D in Energy Production Knowledge](image3.png)

**FIGURE 9. R&D expenditures for Energy Production Knowledge**

![Energy Production Knowledge](image4.png)

**FIGURE 10. Development of Energy Production Knowledge**
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 $\beta_t$ 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,

$$\beta_t = (C_t / P_t) / ((1 + p)(C_{t+1} / P_{t+1}))$$  \hspace{1cm} (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,

$$\mu_M = (A_{Y, M}^{\pi_{Y, M}} M)^{(\sigma-1)/\sigma} \ Y^{1/\sigma},$$  \hspace{1cm} (18)

$$q_E = (A_{Y, E}^{\pi_{Y, E}} E)^{(\sigma-1)/\sigma} \ Y^{1/\sigma},$$  \hspace{1cm} (19)

$$\xi Z_M = \mu M,$$  \hspace{1cm} (20)

$$\xi Z_E = q E,$$  \hspace{1cm} (21)

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

$$\theta_{Y, M} = \lambda \ A_{Y, M}^{\pi_{Y, M}} M^{(\sigma-1)/\sigma} \ Y^{1/\sigma},$$  \hspace{1cm} (23)

$$\theta_{Y, E} = \lambda \ A_{Y, E}^{\pi_{Y, E}} E^{(\sigma-1)/\sigma} \ Y^{1/\sigma},$$  \hspace{1cm} (24)
\[ \theta_{M,Z} = \pi_{M,Z} \mu M/A_{M,Z} + \beta \theta_{M,Z,+1} [(1-\delta_A) + (1-\eta_{M,Z})\zeta_{M,Z}(R_{M,Z}/A_{M,Z})^{\eta_{Y,Z}}], \] (25)

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

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

\[ \psi_{+1} = 1/\beta, \] (28)

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

Carbon tax scenario

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

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

\[ (q+\tau_c \epsilon_t)E = (A_E E)^{(\sigma-1)/\sigma} Y^{1/\sigma}. \] (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 \( \mu, q, \zeta, \psi, \theta_{Y,M}, \theta_{Y,E}, \theta_{M,Z}, \theta_{E.Z} \), and 1 price deflator \( \beta \). The model has 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, \( \rho, \sigma, \zeta_M, \zeta_E, \alpha, \delta_K, \delta_A, 4x\zeta_j, 4x\eta_j, \omega \) and 5 climate change parameters, \( \epsilon_t, \delta_M, \delta_E, \delta_T, TEMP \). There are two policy instruments \( \tau_M \) and \( \tau_c \), that are linked through (16).
## APPENDIX 2. Calibration results

### Table 1. Variable and parameter values in first period (2000)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Per period</th>
<th>Endogenous variables</th>
<th>Per period</th>
<th>per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>0.186$^#$</td>
<td>$Y$</td>
<td>217.300*</td>
<td>44.025</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.252$^#$</td>
<td>$C$</td>
<td>161.220</td>
<td>33.031</td>
</tr>
<tr>
<td>$\delta_K$</td>
<td>0.351$^#$</td>
<td>$I$</td>
<td>43.500*</td>
<td>8.819</td>
</tr>
<tr>
<td>$\delta_A$</td>
<td>0.229$^#$</td>
<td>$M$</td>
<td>224.120*</td>
<td>44.824</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.400</td>
<td>$E$</td>
<td>21.320*</td>
<td>4.284</td>
</tr>
<tr>
<td>$\zeta_M$</td>
<td>2.092$^#$</td>
<td>$K$</td>
<td>86.900*</td>
<td></td>
</tr>
<tr>
<td>$\zeta_E$</td>
<td>2.092$^#$</td>
<td>$R$</td>
<td>10.856</td>
<td>2.186</td>
</tr>
<tr>
<td>$\omega$</td>
<td>4.000</td>
<td>$R_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.500</td>
<td>$R_{YE}$</td>
<td>0.520</td>
<td>0.104</td>
</tr>
<tr>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td>$R_{MZ}$</td>
<td>10.000*</td>
<td>2.014</td>
</tr>
<tr>
<td>$\zeta_{YE}$</td>
<td>10.611$^#$</td>
<td>$R_{EZ}$</td>
<td>0.336</td>
<td>0.067</td>
</tr>
<tr>
<td>$\zeta_{MZ}$</td>
<td>1.278$^#$</td>
<td>$A_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\zeta_{EZ}$</td>
<td>9.522$^#$</td>
<td>$A_{YZ}$</td>
<td>503.004</td>
<td></td>
</tr>
<tr>
<td>$\pi_{YM}$</td>
<td>0.000</td>
<td>$A_{MZ}$</td>
<td>100.000*</td>
<td></td>
</tr>
<tr>
<td>$\pi_{YE}$</td>
<td>0.765$^#$</td>
<td>$A_{EZ}$</td>
<td>262.062</td>
<td></td>
</tr>
<tr>
<td>$\pi_{MZ}$</td>
<td>0.321$^#$</td>
<td>$M$</td>
<td>24.129</td>
<td>4.826</td>
</tr>
<tr>
<td>$\pi_{EZ}$</td>
<td>0.495$^#$</td>
<td>$E$</td>
<td>0.651</td>
<td>0.130</td>
</tr>
<tr>
<td>$\psi$</td>
<td>1.280</td>
<td>$\zeta$</td>
<td>8.885</td>
<td></td>
</tr>
<tr>
<td>$q$</td>
<td>0.270$^*$</td>
<td>$\mu$</td>
<td>0.957</td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.957</td>
<td>$\zeta$</td>
<td>8.885</td>
<td></td>
</tr>
<tr>
<td>$\zeta$</td>
<td>8.885</td>
<td>$\theta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{YM}$</td>
<td>n.a.</td>
<td>$\theta_{YZ}$</td>
<td>0.032</td>
<td></td>
</tr>
<tr>
<td>$\theta_{YE}$</td>
<td>2.561</td>
<td>$\theta_{EZ}$</td>
<td>0.039</td>
<td></td>
</tr>
<tr>
<td>$\theta_{MZ}$</td>
<td>2.561</td>
<td>$\theta_{EZ}$</td>
<td>0.039</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>$\theta_{EZ}$</td>
<td>0.970</td>
<td>$\zeta_{YM}$</td>
<td>n.a.</td>
<td></td>
</tr>
</tbody>
</table>

* 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.
REFERENCES

Azar, C., Schneider, H.S., 2002. Are the economic costs of stabilising the atmosphere prohibitive? Ecological Economics 42, 73-80


Our Note di Lavoro are available on the Internet at the following addresses:
http://www.feem.it/Feem/Pub/Publications/WPapers/default.html

NOTE DI LAVORO PUBLISHED IN 2003

PRIV 2.2003 Iibolya SCHINDELE: Theory of Privatization in Eastern Europe: Literature Review
PRIV 3.2003 Witze LISE, Claudia KEMFERT and Richard S.J. TOL: Strategic Action in the Liberalised German Electricity Market
KNOW 5.2003 Reyer GERLAGH: Induced Technological Change under Technological Competition
ETA 6.2003 Efrem CASTELNUOVO: Squeezing the Interest Rate Smoothing Weight with a Hybrid Expectations Model
SIEV 7.2003 Anna ALBERINI, Alberto LONGO, Stefania TONIN, Francesco TROMBETTA and Margherita TURVANI: The Role of Liability, Regulation and Economic Incentives in Brownfield Remediation and Redevelopment: Evidence from Surveys of Developers
NRM 8.2003 Eliasios PAPYRakis and Reyer GERLAGH: Natural Resources: A Blessing or a Curse?
CLIM 9.2003 A. CAPARROS, J.-C. PEREAU and T. TAZDAIT: North-South Climate Change Negotiations: a Sequential Game with Asymmetric Information
KNOW 10.2003 Giorgio BRUNELLO and Daniele CHECCHI: School Quality and Family Background in Italy
CLIM 11.2003 Efrem CASTELNUOVO and Marzo GALEOTTI: Learning By Doing vs Learning By Researching in a Model of Climate Change Policy Analysis
KNOW 12.2003 Carole MAIGNAN, Gianmarco OTTAVIANO and Dino PINELLI (eds.): Economic Growth, Innovation, Cultural Diversity: What are we all talking about? A critical survey of the state-of-the-art
KNOW 14.2003 Maddy JANSSENS and Chris STEYAERT (lix): Theories of Diversity within Organisation Studies: Debates and Future Trajectories
KNOW 15.2003 Tuzin BAYCAN LEVENT, Enso MASEMEL and Peter NILKAMP (lix): Diversity in Entrepreneurship: Ethnic and Female Roles in Urban Economic Life
KNOW 16.2003 Alexandra BITUSIKOVA (lix): Post-Communist City on its Way from Grey to Colourful: The Case Study from Slovakia
KNOW 17.2003 Billy E. VAUGHN and Katarina MLEKOV (lix): A Stage Model of Developing an Inclusive Community
KNOW 18.2003 Selma van LONDON and Arie de RUIJTER (lix): Managing Diversity in a Glocalizing World
PRIV 20.2003 Claudio CALZOARI and Alessandro PAVAN (lix): Monopoly with Resale
PRIV 22.2003 Marco LiCalzi and Alessandro PAVAN (lix): Tilting the Supply Schedule to Enhance Competition in Uniform-Price Auctions
PRIV 23.2003 David ETTINGER (lix): Bidding among Friends and Enemies
PRIV 24.2003 Hannu VARTIAINEN (lix): Auction Design without Commitment
PRIV 26.2003 Christine A. PARLOUR and Uday RAJAN (lix): Rationing in IPOs
PRIV 27.2003 Kjell G. NYBORG and Ilya A. STREBULAEV (lix): Multiple Unit Auctions and Short Squeezes
PRIV 28.2003 Anders LUNANDER and Jan-Eric NILSSON (lix): Taking the Lab to the Field: Experimental Tests of Alternative Mechanisms to Procure Multiple Contracts
PRIV 30.2003 Eniel MAASLAND and Sander ONDERSTAL (lix): Auctions with Financial Externalities
ETA 31.2003 Michael FINUS and Bianca RUNDSHJAGEN: A Non-cooperative Foundation of Core-Stability in Positive Externality NTU-Coalition Games
KNOW 32.2003 Michele MORETTO: Competition and Irreversible Investments under Uncertainty
PRIV 33.2003 Philippe QUIRION: Relative Quotas: Correct Answer to Uncertainty or Case of Regulatory Capture?
KNOW 34.2003 Giuseppe MEDA, Claudio PIGA and Donald SIEGEL: On the Relationship between R&D and Productivity: A Treatment Effect Analysis
ETA 35.2003 Alessandra DEL BOCA, Marzo GALEOTTI and Paolo ROTA: Non-convexities in the Adjustment of Different Capital Inputs: A Firm-level Investigation
One Thousand Working Papers

IEM 81.2003  
Alessandro LANZA, Matteo MANERA and Massimo GIOVANNINI: Oil and Product Dynamics in International Petroleum Markets

CLIM 82.2003  
Y. Hossein FARZIN and Jinhua ZHAO: Pollution Abatement Investment When Firms Lobby Against Environmental Regulation

CLIM 83.2003  
Giuseppe DI VITA: Is the Discount Rate Relevant in Explaining the Environmental Kuznets Curve?

CLIM 84.2003  
Reyer GERLAGH and Wietze LISE: Induced Technological Change Under Carbon Taxes

NRM 85.2003  
Rinaldo BRAU, Alessandro LANZA and Francesco PIOLIARI: How Fast are the Tourism Countries Growing?

KNOW 86.2003  
Elena BELLINI, Gianmarco I.P. OTTAVIANO and Dino PINELLI: The ICT Revolution: opportunities and risks for the Mezzogiorno

SIEV 87.2003  
Lucas BRETSCGHER and Sjak SMULDERS: Sustainability and Substitution of Exhaustible Natural Resources. How resource prices affect long-term R&D investments

CLIM 88.2003  
Johan EYCKMANS and Michael FINUS: New Roads to International Environmental Agreements: The Case of Global Warming

CLIM 89.2003  
Marzio GALEOTTI: Economic Development and Environmental Protection

CLIM 90.2003  
Marzio GALEOTTI: Environment and Economic Growth: Is Technical Change the Key to Decoupling?

CLIM 91.2003  
Marzio GALEOTTI and Barbara BUCHNER: Climate Policy and Economic Growth in Developing Countries

IEM 92.2003  
A. MARKANDYA, A. GOLUB and E. STRUKOVA: The Influence of Climate Change Considerations on Energy Policy: The Case of Russia

ETA 93.2003  
Andrea BELTRATTI: Socially Responsible Investment in General Equilibrium

CTN 94.2003  
Parkash CHANDER: The r-Core and Coalition Formation

IEM 95.2003  
Matteo MANERA and Angelo MARZULLO: Modelling the Load Curve of Aggregate Electricity Consumption Using Principal Components

IEM 96.2003  
Alessandro LANZA, Matteo MANERA, Margherita GRASSO and Massimo GIOVANNINI: Long-run Models of Oil Stock Prices

CTN 97.2003  

KNOW 98.2003  
John CROWLEY, Marie-Cecile NAVES (ixiii): Anti-Racist Policies in France. From Ideological and Historical Schemes to Socio-Political Realities

KNOW 99.2003  
Richard THOMPSON FORD (ixiii): Cultural Rights and Civic Virtue

KNOW 100.2003  
Alaknanda PATEL (ixiii): Cultural Diversity and Conflict in Multicultural Cities

KNOW 101.2003  
David MAY (ixiii): The Struggle of Becoming Established in a Deprived Inner-City Neighbourhood

KNOW 102.2003  
Sébastien ARCAND, Danielle JUTEAU, Sirma BILGE, and Francine LEMIRE (ixiii): Municipal Reform on the Island of Montreal: Tensions Between Two Majority Groups in a Multicultural City

CLIM 103.2003  
Barbara BUCHNER and Carlo CARRARO: China and the Evolution of the Present Climate Regime

IEM 104.2003  
Barbara BUCHNER and Carlo CARRARO: Emissions Trading Regimes and Incentives to Participate in International Climate Agreements

CLIM 105.2003  
Anil MARKANDYA and Dirk T.G. RÜBBELKE: Ancillary Benefits of Climate Policy

NRM 106.2003  
Anne Sophie CRÉPIN (lxiv): Management Challenges for Multiple-Species Boreal Forests

NRM 107.2003  
Anne Sophie CRÉPIN (lxiv): Threshold Effects in Coral Reef Fisheries

SIEV 108.2003  
Sara ANIYAR (lxv): Estimating the Value of Oil Capital in a Small Open Economy: The Venezuela’s Example

SIEV 109.2003  
Kenneth ARROW, Partha DASGUPTA and Karl-Göran MÄLER(lxv): Evaluating Projects and Assessing Sustainable Development in Imperfect Economies

NRM 110.2003  
Anastasios XEPAPADEAS and Catarina ROSETA-PALMA(Axix): Instabilities and Robust Control in Fisheries

NRM 111.2003  
Charles PERRINGS and Brian WALKER (lxv): Conservation and Optimal Use of Rangelands

ETA 112.2003  
Jack GOODY (lxv): Globalisation, Population and Ecology

CTN 113.2003  
Carlo CARRARO, Carmen MARCHIORI and Sonia OREFFICE: Endogenous Minimum Participation in International Environmental Treaties

CTN 114.2003  
Guillaume HAERRINGER and Myrna WOODERS: Decentralized Job Matching

CTN 115.2003  
Hideo KONISHI and M. Utku UNVER: Credible Group Stability in Multi-Partner Matching Problems

CTN 116.2003  
Somdeb LAHIRI: Stable Matchings for the Room-Mates Problem

CTN 117.2003  
Somdeb LAHIRI: Stable Matchings for a Generalized Marriage Problem

CTN 118.2003  
Marita LAUKKANEN: Transboundary Fisheries Management under Implementation Uncertainty

CTN 119.2003  
Edward CARTWRIGHT and Myrna WOODERS: Social Conformity and Bounded Rationality in Arbitrary Games with Incomplete Information: Some First Results

CTN 120.2003  
Gianluigi VERNASCA: Dynamic Price Competition with Price Adjustment Costs and Product Differentiation

CTN 121.2003  
Myrna WOODERS, Edward CARTWRIGHT and Reinhard SELTEN: Social Conformity in Games with Many Players

CTN 122.2003  
Edward CARTWRIGHT and Myrna WOODERS: On Equilibrium in Pure Strategies in Games with Many Players

CTN 123.2003  
Edward CARTWRIGHT and Myrna WOODERS: Conformity and Bounded Rationality in Games with Many Players

1000  
Carlo CARRARO, Alessandro LANZA and Valeria PAPPONETTI: One Thousand Working Papers
NOTE DI LAVORO PUBLISHED IN 2004

IEM 1.2004 Anil MARKANDYA, Suzette PEDROSO and Alexander GOLUB: Empirical Analysis of National Income and So2 Emissions in Selected European Countries
ETA 2.2004 Masahisa FUJITA and Shlomo WEBER: Strategic Immigration Policies and Welfare in Heterogeneous Countries
PRA 3.2004 Adolfo DI CARLUCCIO, Giovanni FERRI, Cecilia FRALE and Otavio RICCHI: Do Privatizations Boost Household Shareholding? Evidence from Italy
ETA 4.2004 Victor GINSBURGH and Shlomo WEBER: Languages Disenfranchisement in the European Union
ETA 5.2004 Romano PIRAS: Growth, Composition of Public Goods, and Second-Best Optimal Policy
PRA 7.2004 Sandro BRUSCO, Giuseppe LOPOMO and S. VISHWANATHAN (lxv): Merger Mechanisms
PRA 8.2004 Wolfgang AUSSENEG, Pegaret PICHLER and Alex STOMPER (lxv): IPO Pricing with Bookbuilding, and a When-Issued Market
PRA 9.2004 Pegaret PICHLER and Alex STOMPER (lxv): Primary Market Design: Direct Mechanisms and Markets
PRA 11.2004 Bjarni BREDSTRUP and Harry J. PAARSH (lxv): Nonparametric Identification and Estimation of Multi-Unit, Sequential, Oral, Ascending-Price Auctions With Asymmetric Bidders
PRA 12.2004 Ohad KADAN (lxv): Equilibrium in the Two Player, k-Double Auction with Affiliated Private Values
PRA 13.2004 Maarten C.W. JANSEN (lxv): Auctions as Coordination Devices
PRA 14.2004 Gadi FIBICH, Arieh GAVIOUS and Aner SELA (lxv): All-Pay Auctions with Weakly Risk-Averse Buyers
PRA 15.2004 Orly SADE, Charles SCHNITZLEIN and Jaime F. ZENDER (lxv): Competition and Cooperation in Divisible Good Auctions: An Experimental Examination
PRA 16.2004 María STRYSZOWSKA (lxv): Late and Multiple Bidding in Competing Second Price Internet Auctions
CCMP 17.2004 Slim Ben YOUSSEF: R&D and Cleaner Technology and International Trade
NRM 18.2004 Angelo ANTICI, Simone BORGHESI and Paolo RUSSU (lxvi): Biodiversity and Economic Growth: Stabilization Versus Preservation of the Ecological Dynamics
SIEV 19.2004 Anna ALBERINI, Paolo ROSATO, Alberto LONGO and Valentina ZANATTA: Information and Willingness to Pay in a Contingent Valuation Study: The Value of S. Erasmo in the Lagoon of Venice
NRM 21.2004 Jacqueline M. HAMILTON (lxvi): Climate and the Destination Choice of German Tourists
NRM 23.2004 Pius ODUNGA and Henk FOLMER (lxvi): Profiling Tourists for Balanced Utilization of Tourism-Based Resources in Kenya
NRM 24.2004 Jean-Jacques NOWAK, Monther SAHLI and Pasquale M. SGRO (lxvii): Tourism, Trade and Domestic Welfare
NRM 26.2004 Juan Luis EUGENIO-MARTÍN, Noelia MARTÍN MORALES and Riccardo SCARPA (lxvii): Tourism and Economic Growth in Latin American Countries: A Panel Data Approach
NRM 27.2004 Raúl Hernández MARTÍN (lxvii): Impact of Tourism Consumption on GDP. The Role of Imports
NRM 29.2004 Marian WEBER (lxvii): Assessing the Effectiveness of Tradable Landuse Rights for Biodiversity Conservation: an Application to Canada's Boreal Mixedwood Forest
NRM 30.2004 Trond BJØRNDAL, Phoebe KOUNDOURI and Sean PASCOE (lxvii): Output Substitution in Multi-Species Trawl Fisheries: Implications for Quota Setting
CTN 33.2004 Wilson PEREZ: Divide and Conquer: Noisy Communication in Networks, Power, and Wealth Distribution
ETA 39.2004 Alberto CAVALIERE: Price Competition with Information Disparities in a Vertically Differentiated Duopoly
PRA 40.2004 Andrea BIGANO and Stef PROOST: The Opening of the European Electricity Market and Environmental Policy: Does the Degree of Competition Matter?
CCMP 41.2004 Micheal FINUS (lxix): International Cooperation to Resolve International Pollution Problems
KTHC 42.2004 Francesco CRESPI: Notes on the Determinants of Innovation: A Multi-Perspective Analysis
Rod GARRATT, James E. PARCO, Cheng-ZHONG QIN and Amnon RAPOPORT (lxx): Potential Maximization and Coalition Government Formation

Kfir ELIAZ, Debraj RAY and Ronny RAZIN (lxx): Group Decision-Making in the Shadow of Disagreement

Sanjeev GOYAL, Marco van der LEIJ and José Luis MORAGA-GONZALEZ (lxx): Economics: An Emerging Small World?

Edward CARTWRIGHT (lxx): Learning to Play Approximate Nash Equilibria in Games with Many Players

Finn R. FORSUND and Michael HOEL: Properties of a Non-Competitive Electricity Market Dominated by Hydroelectric Power

Eliyahu PAPPYRAKIS and Reyer GERLAGH: Natural Resources, Investment and Long-Term Income

Marzio GALEOTTI and Claudia KEMFERT: Interactions between Climate and Trade Policies: A Survey

A. MARKANDYA, S. PEDROSO and D. STREIMIKIENĖ: Energy Efficiency in Transition Economies: Is There Convergence Towards the EU Average?

Rolf GOLOMBEK and Michael HOEL: Climate Agreements and Technology Policy

Sergei IZMALKOV (lxx): Multi-Unit Open Ascending Price Efficient Auction

Gianmarco I.P. OTTAVIANO and Giovanni PERI: The Political Economy of Privatization: Why Do Governments Want Reforms?

Chiara M. TRAVISI and Peter NIJKAMP: Economic Evaluation of Climate Change Impacts and Adaptability in Italy

Valeria COSTANTINI, Francesco GRACCEVA, Anil MARKANDYA and Giorgio VICINI: Comparison between Artisanal Fishery and Manila Clam Harvesting in the Venice Lagoon by

Pierre-André JOUVEY, Philippe MICHEL, and Gilles ROTILLON: Equilibrium with a Market of Permits

Bob van der ZWAAN and Reyer GERLAGH: Climate Uncertainty and the Necessity to Transform Global Energy Supply

Francesco BOSELLO, Marco LAZZARIN, Roberto ROSON and Richard S.J. TOL: Economy-Wide Estimates of the Implications of Climate Change: Sea Level Rise

Siddhartha BANDYOPADHYAY and Mandar OAK: Party Formation and Coalitional Bargaining in a Model of Proportional Representation

Hans-Peter WEIZARD, Michael FINUS and Juan-Carlos ALTAMIRANO-CABRERA: The Impact of Surplus Sharing on the Stability of International Climate Agreements

Chiara M. TRAVISI and Raymond J. G. M. FLORAX and Peter NIJKAMP: A Meta-Analysis of the Willingness to Pay for Agricultural Environmental Safety: Evidence from a Survey of Milan, Italy, Residents

Chiara M. TRAVISI, Raymond J. G. M. FLORAX and Peter NIJKAMP: Willingness to Pay: The Question of Generation Adequacy in Liberalised Electricity Markets

Valentina BOSETTI and David TOMBERLIN: Economic Evaluation of Climate Change Impacts and Adaptability in Italy

Massimo DEL GATTO: Agglomerated Integration, and Territorial Authority Scale in a System of Trading Cities, Centralisation versus devolution

Bob van der ZWAAN and Reyer GERLAGH: Climate Uncertainty and the Necessity to Transform Global Energy Supply

Francesco BOSELLO, Marco LAZZARIN, Roberto ROSON and Richard S.J. TOL: Economy-Wide Estimates of the Implications of Climate Change: Sea Level Rise

Siddhartha BANDYOPADHYAY and Mandar OAK: Party Formation and Coalitional Bargaining in a Model of Proportional Representation

Hans-Peter WEIZARD, Michael FINUS and Juan-Carlos ALTAMIRANO-CABRERA: The Impact of Surplus Sharing on the Stability of International Climate Agreements

Chiara M. TRAVISI and Raymond J. G. M. FLORAX and Peter NIJKAMP: A Meta-Analysis of the Willingness to Pay for Agricultural Environmental Safety: Evidence from a Survey of Milan, Italy, Residents

Chiara M. TRAVISI, Raymond J. G. M. FLORAX and Peter NIJKAMP: A Meta-Analysis of the Willingness to Pay for Agricultural Environmental Safety

Valentina BOSETTI and David TOMBERLIN: Real Options Analysis of Fishing Fleet Dynamics: A Test

Alessandra GORIA e GAMBARELLI: Economic Evaluation of Climate Change Impacts and Adaptability in Italy

Massimo FLORIO and Mara GRASSENI: The Missing Shock: The Macroeconomic Impact of British Privatisation

John BENNETT, Saul ESTRIN, James MAW and Giovanni URGA: Privatisation Methods and Economic Growth in Transition Economies

Kira BÖRNER: The Political Economy of Privatisation: Why Do Governments Want Reforms?

Pehr-Johan NORBACK and Lars PERSSON: Privatisation and Restructuring in Concentrated Markets

Angela GRANZOTTO, Fabio PRANOVI, Simone LIBRALATO, Patrizia TORRICELLI and Danilo MAINARI: Comparison between Artisanal Fishery and Manila Clam Harvesting in the Venice Lagoon by

Using Ecosystem Indicators: An Ecological Economics Perspective

Somdeb LAHIRI: The Cooperative Theory of Two Sided Matching Problems: A Re-examination of Some Results

Giuseppe DI VITA: Natural Resources Dynamics: Another Look

Anna ALBERINI, Alistair HUNT and Anil MARKANDYA: Willingness to Pay to Reduce Mortality Risks: Evidence from a Three-Country Contingent Valuation Study

Valeria PAPPONETTI and Dino PINELLI: Scientific Advice to Public Policy-Making

Paulo A.L.D. Nunes and Laura ONOFRI: The Economics of Warm Glow: A Note on Consumer’s Behavior and Public Policy Implications

Patrick CAYRAGE: Investments in Gas Pipelines and Liquefied Natural Gas Infrastructure What is the Impact on the Security of Supply?

Valeria COSTANTINI and Francesco GRACCEVA: Oil Security: Short- and Long-Term Policies

Valeria COSTANTINI and Francesco GRACCEVA: Social Costs of Energy Disruptions

Christian EGENHOFER, Kyriakos GIALLOGLOU, Giacomo LUCIANI, Maroeska BOOTS, Martin SCHEEPERS, Valeria COSTANTINI, Francesco GRACCEVA, Anil MARKANDYA and Giorgio VICINI: Market-Based Options for Security of Energy Supply

David FISK: Transport Energy Security. The Unseen Risk?

Giacomo LUCIANI: Security of Supply for Natural Gas Markets. What is it and What is it not?

L.J. de VRIES and R.A. HAKVOORT: The Question of Generation Adequacy in Liberalised Electricity Markets

Alberto PETRUCCI: Asset Accumulation, Fertility Choice and Nondegenerate Dynamics in a Small Open Economy

Carlo GIUPPONI, Jaroslaw MYSIAK and Anita FASSIO: An Integrated Assessment Framework for Water Resources Management: A DSS Tool and a Pilot Study Application

Margaretha BREIL, Anita FASSIO, Carlo GIUPPONI and Paolo ROSATO: Evaluation of Urban Improvement

on the Islands of the Venice Lagoon: A Spatially-Distributed Hedonic-Hierarchical Approach
Paul MENSINK: Instant Efficient Pollution Abatement Under Non-Linear Taxation and Asymmetric Information: The Differential Tax Revisited

Mauro FABIANO, Gabriella CAMARSA, Rosanna DURSI, Roberta IVALDI, Valentina MARIN and Francesca PALMISANI: Integrated Environmental Study for Beach Management: A Methodological Approach

Irena GROSFELD and Iraj HASHI: The Emergence of Large Shareholders in Mass Privatized Firms: Evidence from Poland and the Czech Republic

Maria BERRITTELLA, Andrea BIGANO, Roberto ROSON and Richard S.J. TOL: A General Equilibrium Analysis of Climate Change Impacts on Tourism

Reyer GERLAGH: A Climate-Change Policy Induced Shift from Innovations in Energy Production to Energy Savings
This paper was presented at the ENGIME Workshop on “Mapping Diversity”, Leuven, May 16-17, 2002

This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications”, organised by the Fondazione Eni Enrico Mattei, Milan, September 26-28, 2002

This paper was presented at the Eighth Meeting of the Coalition Theory Network organised by the GREQAM, Aix-en-Provence, France, January 24-25, 2003

This paper was presented at the ENGIME Workshop on “Communication across Cultures in Multicultural Cities”, The Hague, November 7-8, 2002

This paper was presented at the ENGIME Workshop on “Social dynamics and conflicts in multicultural cities”, Milan, March 20-21, 2003

This paper was presented at the International Conference on “Theoretical Topics in Ecological Economics”, organised by the Abdus Salam International Centre for Theoretical Physics - ICTP, the Beijer International Institute of Ecological Economics, and Fondazione Eni Enrico Mattei – FEEM Trieste, February 10-21, 2003

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

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

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

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

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

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
### 2003 SERIES

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Title</th>
<th>Editor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLIM</td>
<td><em>Climate Change Modelling and Policy</em></td>
<td>Marzio Galeotti</td>
</tr>
<tr>
<td>GG</td>
<td><em>Global Governance</em></td>
<td>Carlo Carraro</td>
</tr>
<tr>
<td>SIEV</td>
<td><em>Sustainability Indicators and Environmental Valuation</em></td>
<td>Anna Alberini</td>
</tr>
<tr>
<td>NRM</td>
<td><em>Natural Resources Management</em></td>
<td>Carlo Giupponi</td>
</tr>
<tr>
<td>KNOW</td>
<td><em>Knowledge, Technology, Human Capital</em></td>
<td>Gianmarco Ottaviano</td>
</tr>
<tr>
<td>IEM</td>
<td><em>International Energy Markets</em></td>
<td>Anil Markandya</td>
</tr>
<tr>
<td>CSRM</td>
<td><em>Corporate Social Responsibility and Management</em></td>
<td>Sabina Ratti</td>
</tr>
<tr>
<td>PRIV</td>
<td><em>Privatisation, Regulation, Antitrust</em></td>
<td>Bernardo Bortolotti</td>
</tr>
<tr>
<td>ETA</td>
<td><em>Economic Theory and Applications</em></td>
<td>Carlo Carraro</td>
</tr>
<tr>
<td>CTN</td>
<td><em>Coalition Theory Network</em></td>
<td>Carlo Carraro</td>
</tr>
</tbody>
</table>

### 2004 SERIES

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Title</th>
<th>Editor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCMP</td>
<td><em>Climate Change Modelling and Policy</em></td>
<td>Marzio Galeotti</td>
</tr>
<tr>
<td>GG</td>
<td><em>Global Governance</em></td>
<td>Carlo Carraro</td>
</tr>
<tr>
<td>SIEV</td>
<td><em>Sustainability Indicators and Environmental Valuation</em></td>
<td>Anna Alberini</td>
</tr>
<tr>
<td>NRM</td>
<td><em>Natural Resources Management</em></td>
<td>Carlo Giupponi</td>
</tr>
<tr>
<td>KTHC</td>
<td><em>Knowledge, Technology, Human Capital</em></td>
<td>Gianmarco Ottaviano</td>
</tr>
<tr>
<td>IEM</td>
<td><em>International Energy Markets</em></td>
<td>Anil Markandya</td>
</tr>
<tr>
<td>CSRM</td>
<td><em>Corporate Social Responsibility and Management</em></td>
<td>Sabina Ratti</td>
</tr>
<tr>
<td>PRA</td>
<td><em>Privatisation, Regulation, Antitrust</em></td>
<td>Bernardo Bortolotti</td>
</tr>
<tr>
<td>ETA</td>
<td><em>Economic Theory and Applications</em></td>
<td>Carlo Carraro</td>
</tr>
<tr>
<td>CTN</td>
<td><em>Coalition Theory Network</em></td>
<td>Carlo Carraro</td>
</tr>
</tbody>
</table>