Induced technological change under carbon taxes

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Abstract

We develop a partial energy equilibrium model with capital and labor as production factors, and endogenous technological change through learning by doing and learning through research. Our model reproduces the learning curve typical for (bottom-up) energy system models. The model also produces an endogenous S-curved transition from fossil fuel energy sources to carbon-free energy sources over the coming two centuries. We use the model to study changes in fossil fuel and carbon-free energy use and carbon dioxide emissions induced by carbon taxes. It is shown that, (i) induced technological change accelerates the substitution of carbon-free energy for fossil fuels substantially. Also, (ii) a transient carbon tax has a permanent effect on the state of technology of the carbon-free energy and advances the transition of the energy system.

Induced technological change under carbon taxes

1. Introduction

Environmental taxes and regulation reduce pollution by shifting behavior away from polluting activities, but they also encourage the development of new technologies that make pollution control less costly in the long run (Newel *et al.* 1999; Popp 2002). Understanding of the response of technology to economic incentives – dubbed induced innovation or induced technological change (ITC) – will prove crucial for designing appropriate environmental policies (Jaffe *et al.* 2002). In the literature, the subject of ITC has been studied mostly in the context of one representative aggregate technology (e.g. Verdier 1995, Beltratti 1997, Newell *et al.* 1999, Goulder and Matthai 2000, Nordhaus 2002). In that context, technology is treated as a production factor, and ITC stands for a substitution of the factor technology for other production factors. This paper extends the literature as it addresses ITC in the context of two competing technologies (energy sources).

Induced technological change is receiving considerable attention in the climate change related literature where the potential contribution of ITC to policies aiming at greenhouse gas emission reductions is subject of a yet undecided debate. Some studies try to estimate empirically the impact of ITC relative to the factor substitution effects without technological change (Carraro and Galeotti 1997, Goulder and Schneider 1999, Nordhaus 2002, van der Zwaan *et al.* 2002, Buonanno *et al.* 2003, Gerlagh and van der Zwaan 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. 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. The somewhat disappointing result of these two studies may, however, be explained by the set up of the analyses. Nordhaus'(2002) study is based on one representative technology, and assumes that the reduction of carbon dioxide emissions requires the substitution of knowledge for energy. It abstracts from changes in energy composition, that is, the substitution of carbon poor energy sources for carbon rich energy sources. The substitution between energy sources is included in the other study by Goulder and Schneider (1999), who consider fossil fuels versus renewable energy sources. These two energy sources are, however, treated as complements (elasticity of substitution below unity), so that substitution and competition is limited. Such an approach may be quite realistic in the short run, as global energy demand is ever increasing and renewables are, not yet, substitutes. They may become so in the long run, which is the focus of our analysis.

ITC is a more prominent factor in a context with multiple competing energy sources (van der Zwaan *et al*. 2002, Gerlagh and van der Zwaan 2003) and such a context would also be in line with many so-called Integrated Assessment Models (e.g. Peck and Teisberg 1992; Manne *et al*. 1995). To constrain climate change, the substitution between various energy sources is essential. In the long term, energy savings will be insufficient to reach substantial abatement levels of carbon dioxide emissions, since energy is an essential production factor. Instead, if a substantial emission abatement strategy is aimed for, a shift away from fossil fuel based energy sources towards carbon-free energy sources is unavoidable (Chakravorty *et al*. 1997, Caldeira *et al*. 2003). For this reason, in studying the added value of ITC, we have to take into account the effect of ITC on the relative contribution of various competing technologies used for energy production (Weyant and Olavson 1999).[1]

The objective of this paper is twofold. First, our methodological objective is to bridge the gap between an energy-system (bottom-up) and a neo-classical economic (top-down) approach. Second, we carry out policy analyses to verify the role of ITC in climate change policy, and to verify whether as a transient carbon tax can have a long-term impact on emission levels.

To study these questions, we develop a partial energy model, DEMETER-2E;[2] the first DEMETER model has been described and used in van der Zwaan et al (2002) and Gerlagh and van der Zwaan (2003). When used for policy analyses, the model assesses the potential contribution of ITC to carbon dioxide emissions reduction, and to compare this contribution of ITC with the contribution of substitution between carbon dioxide emitting and carbon free energy sources for a given technological state. It has the following features. Total energy demand is fixed. There are two energy sources (carbon and carbon-free) that compete for their market shares. The model describes technological innovations through learning by doing and research and development (R&D). The level of R&D is driven by economic incentives, that is, by the value of an innovation to the innovator in the tradition of the endogenous growth models with natural resources that have been specified to study growth and sustainability (Gradus and Smulders 1993;

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[1] More in general, a representative aggregate technology does not perform well when there are increasing returns to scale at the disaggregate level, e.g. because of endogenous technological change (Basu and Fernald 1997).

[2] DEMETER is an acronym for DE-carbonization Model with Endogenous Technologies for Emission Reduction. For this paper, we apply a part of version 2, in which only the Energy sector is considered (DEMETER-2E). As DEMETER-2E only describes the energy sector, it is limited when compared with DEMETER-1, but on the other hand it extends DEMETER-1 by including learning by research and distinguishing between private and public innovations. In the future, we intend to extend DEMETER-2E with the production of non-energy consumer goods as well.

Bovenberg and Smulders 1995; den Butter and Hofkes 1995; Verdier 1995; Bovenberg and Smulders 1996; Beltratti 1997; Smulders 1999, Smulders and de Nooij 2003).

For this model, we can calculate *ex-post* the learning curves for both energy sources, and compare their characteristics, such as the learning rates, with those found in the energy system literature. We also compare the transition simulated from carbon to carbon-free energy sources with the features described in the energy-system literature. When both learning curves and transition dynamics simulated by our model satisfy the features described in the energy-system literature, we think we have contributed to bridging the gap between bottom-up and top-down models.

In carrying out policy analyses, we study the response of CO_2 emissions on a carbon tax, when taking account of technological change. Most applied numerical studies so far assumed a technological state that dynamically developed over time, but that was independent of emission policies. We assess by how much these results may change if we include induced technological change (ITC), following emission policies. We have two specific sub-questions.

First, what is the significance of ITC for the responsiveness of cumulative emissions to constant carbon dioxide taxes? To measure this response, we take the reduction in cumulative carbon dioxide emissions over the period 2000-2100 following a constant carbon tax of 25 $/tC. We compare the reduction in cumulative emissions without ITC, and with ITC. The ratio between the two is a good measure for the relative impact and significance of ITC. This number is important, since most analyses with applied general equilibrium models assume given technology, and this may be realistic when the ITC impact factor is minor, but it may be too pessimistic when the ITC impact factor is large.

Second, we want to study the implications of transient taxes on the present carbon dioxide emission intensity of production and its future paths. Will a carbon tax direct technological innovations towards ‘cleaner’ production of energy, that is, towards carbon-free energy, so that after the tax is dropped, emissions remain below their levels that would appear without tax (the so-called Business as Usual)? That is, is the change in technology persistent?

We are aware of the limitations of the modeling approach we follow, which is an abstraction of reality. Producers are assumed to maximize profits, we neglect taxes, and other market distortions. Still we think our analysis can provide valuable qualitative insights on technological innovation as induced by carbon taxes, and on the differences between the neo-classical economics approach and energy-system approaches. We calibrate the model to generate a benchmark scenario that is in line with other studies, and then we study the effect of a permanent tax of 25 $/tC for which the situation with and without ITC is considered, and a transient tax of 25 $/tC for 20 years (2005-2025) and 40 years (2005-2045), respectively.

Section 2 describes the basic features of the model for one energy source. Section 3 extends the model so that it describes two competing energy sources, one fossil fuel, the other carbon-free.

There, we also describe the assumptions that link population growth to energy demand, and energy production to carbon emissions and to changes in the global average temperature. Section 4 describes the calibration of the model. Section 5 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 first order conditions of the model. The numerical parameter values, as found in the calibration procedure, are presented in Appendix 2.

2. Endogenous technology for energy production

This section presents the basic elements of our model for energy production and innovation, for one energy source. Figure 1 presents an overview of the model. We model energy as a produced good, as depicted in the central column of the figure, using capital and labor as production factors. Overall productivity depends on knowledge gained through experience, so-called learning by doing labeled with symbol *b*, pictured through the feed-back loop on the right, and knowledge produced through research carried out by innovators, depicted at the left side of the figure and labeled with symbol *a*. We distinguish a privately owned research-based knowledge stock, for which use producers have to pay a license fee, from a freely available public knowledge stock. The research-based technology is described as an expanding library of ideas that can be used in the production process. Innovation is a cumulative process; each innovation builds on the stock of existing knowledge. Energy producers can make use of all past and present innovations, that is the total stock of knowledge, and pay a license fee to all innovators that have developed and own the innovations that are currently in use. In turn, the innovators receive the license fees from all present and future energy producers that use their innovations. Both innovators and producers of final goods take prices as given. We do not consider product variety and price setting under monopolistic competition as in many other endogenous-growth models (see Barro and Sala-i-Martin 1995 for an overview). For the carbon energy source, we assume that current production exhausts the resource and this, in turn, decreases future factor productivity. Stated in other words, through resource exhaustion, current production increases the future effort required to maintain a certain output level.

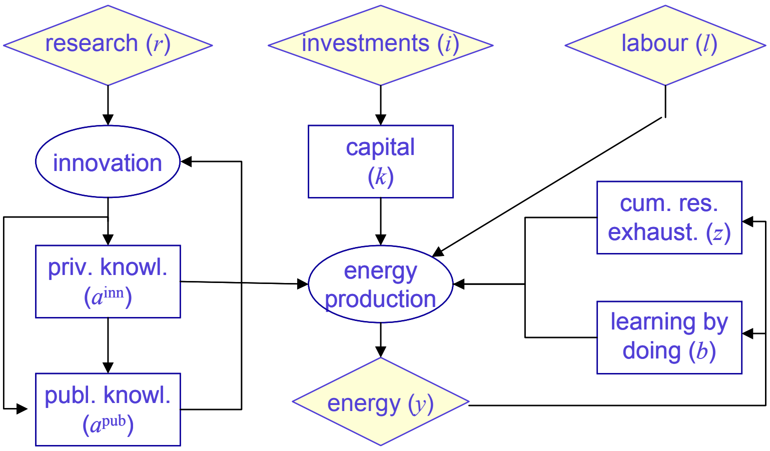

FIGURE 1. *Schematic overview of innovation and energy production in the model. The innovation and energy production processes are presented in an ellipse. Stocks are presented in rectangles. Commodity flows are presented in diamonds.*

Our model assumes a continuum of infinitely small firms, indexed j, that produce energy according to

$$y_{j,t} = \varsigma\,(z_t)^{-\mu}(a_{j,t})^{\eta_a}(b_t)^{\eta_b}(k_{j,t})^{\alpha}(l_{j,t})^{1-\alpha}, \tag{1}$$

where ς is an overall productivity parameter, z_t is the cumulative energy production, which, for fossil fuels, we consider an inverse measure of resource exhaustion. For fossil fuels, the value of $(z_t)^{\mu}$ reflects the effort required to exploit, say, oil wells. The variable $a_{j,t}$ denotes the total knowledge stock gained through research, b_t denotes the non-rival knowledge stock gained through learning by doing publicly available to all firms, $k_{j,t}$ is the capital stock, and $l_{j,t}$, is labor use in efficient labor units. Human capital increasing labor productivity is not specified explicitly, as it is considered embodied in the labor good, exogenous to the individual firm.

For fossil fuels, the effort $(z_t)^{\mu}$ increases because of decreasing quality of oil wells when the reserves decrease as a function of cumulative production. The increased effort is measured by the increase in the variable z_t,

$$z_{t+1} = z_t + y_t. \tag{2}$$

where we omitted the subscript j for the output variable y_t $(=\Sigma_j y_{j,t})$. In the continuation of this paper, we also omit time subscripts when convenient. Equation (1) states that the effort required for energy production, $(z_t)^{\mu}$, increases by 2^{μ} for every doubling of the cumulative resource exploitation level. We assume that the energy sources are owned by the firms that exploit these, hence there is no open access, but there are well-defined property rights. This also implies that the impact on future efforts of current energy production is internalized, as resource depletion influences the energy price in our model. For carbon-free energy sources, there is no exhaustion and we assume μ=0, so that the variable z_t can be interpreted as a measure of cumulative production or experience.

The knowledge variable $a_{j,t}$ is a measure of the number of innovations that are employed by the *j-th* firm, at date *t*. Let $h\in[0,1]$ denote the innovators, and $a^{inn}_{j,h}$ the (continuous) number of innovations in use by firm *j* owned by innovator *h*. Furthermore, let a^{pub} denote the innovations in public domain, for which no patents have been granted, or for which the patents are expired so that their use is free from license payments. We assume that innovations are perfect substitutes so that the total stock of knowledge through R&D is given by

$$a_j = \int_0^1 a^{inn}_{j,h}\,\mathrm{d}h + a^{pub}. \tag{3}$$

Also, we assume that the firms have to pay a license fee $\theta_{h,t}$ for the innovations employed, for every innovation that is not in the public domain $a^{inn}_{j,h,t}$, for every unit of output $y_{j,t}$, so that for the firm *j*, expenditures on innovations amount to $\int_0^1 \theta_{h,t} a^{inn}_{j,h,t} y_{j,t}\,\mathrm{d}h$. Due to the assumed perfect substitutability between innovations (3), innovators face perfect competition and cannot earn monopoly rents, and the license fee $\theta_t y_{j,t}$ clears the market of innovations. The license fee is the same for all innovators, we drop the subscript *h*, and use the aggregate stock of innovations held by innovators so that (3) becomes

$$a_j = a^{inn}{}_j + a^{pub}. \tag{4}$$

We return to the production of innovations at the end of this section.

The learning-by-doing knowledge stock b_t is based on cumulative experience, that is, the cumulative output level, with some depreciation δ_b,

$$b_{t+1} = (1-\delta_b)b_t + y_t, \tag{5}$$

where we omitted the subscript *j* for the output variable y_t, as in equation (2). Knowledge through *a* and *b* increases productivity, while the resource externality *z* decreases productivity, and when the former two effects exceed the latter, $\mu<\eta_a+\eta_b$, productivity increases over time, whereas in the other case, $\mu>\eta_a+\eta_b$, productivity decreases over time.

In addition to the license fees, firms pay for investment expenditures, $i_{j,t}$, and wages, $w_t l_{j,t}$. At time *t*, total expenditures thus amount to $i_{j,t} + w_t l_{j,t} + \theta_t a^{inn}{}_{j,t} y_{j,t}$, while revenues amount to $q_t y_{j,t}$. The firms maximize the net present value of their cash flows:

$$\max \sum_{t=1}^{\infty} \beta^t ((q_{j,t} - \theta_t a^{inn}_{j,t}) y_{j,t} - w_t l_{j,t} - i_{j,t}), \tag{6}$$

where $(1/\beta)-1$ is the real interest rate, subject to the production identity (1), the dynamics of resource depletion (2), and to the capital depreciation-investments relation,

$$k_{j,t+1} = (1-\delta_k)k_{j,t} + i_{j,t}. \tag{7}$$

where δ_k is the depreciation rate, and i_t is the investment flow. Fore each individual firm, expenditures on licenses are proportional to output and production has constant returns to scale with respect to the production factors capital and labor. The firms thus operate in a competitive market pricing the output at marginal cost. This holds for all firms and we can (as for h) omit firms' subscripts j. Appendix 1 presents the full set of first order conditions.

Next we turn to the supply of innovations. There are two externalities working in opposite direction. As a positive externality, knowledge about past innovations is public, that is, knowledge is non-rival when it is used to produce new knowledge. Research innovators use the 'library' of past inventions to produce new innovations, and an increase in the knowledge stock a also increases the flow of new innovations. As a negative externality, research efforts r by one innovator negatively affects the finding of new innovations by other innovators, because a limited number of new innovations are attainable from the current state of knowledge. The flow of new innovations for an individual innovator h is thus decreasing in the aggregate research flow r, the so-called fishing-out effect (Caballero and Jaffe 1993; Kortum 1993). Finally, the number of new innovations produced by an innovator h, Δa_h, is proportional to its research expenditures r_h, and a fraction δ_{inn} of innovations owned by the innovator leaks to the public domain because of patents that expire:

$$\Delta {a^{inn}}_h = \zeta\, r^{\pi-1}\, a^{1-\pi}\, r_h - \delta_{inn} {a^{inn}}_h. \tag{8}$$

where ζ is a scaling constant and π measures the rate of fishing out. On an aggregate level, it measures the elasticity of the aggregate flow of new innovations Δa^{inn} with respect to the aggregate research expenditures r. An increase in the research expenditures leads to a less-then-proportional increase in new inventions. The aggregation of innovations (8) over the innovators h gives

$$a^{inn}_{t+1} = \zeta\, r_t^{\pi}\, a_t^{1-\pi} + (1-\delta_{inn}) a^{inn}_t. \tag{9}$$

Public knowledge is fed through two channels. First, part of the property rights for innovations held privately by the innovators expires, $\delta_{inn} a^{inn}$, and public knowledge is also produced as a direct spinn-of of research, $\chi\zeta\, r_t^{\pi}\, a_t^{1-\pi}$, where the parameter $\chi \in (0,\infty)$ describes the leakage of research activities to public knowledge:

$$a^{pub}_{t+1} = (1-\delta_{pub}) a^{pub}_t + \delta_{inn}\, a^{inn}_t + \chi\zeta\, r_t^{\pi}\, a_t^{1-\pi}. \tag{10}$$

Also, a small fraction δ_{pub} of knowledge becomes obsolete. Appendix 1 presents the full set of first-order conditions characterizing the market for innovations.

3. Energy aggregation and climate change

In this section, first we extend the model with emissions and a simple representation of the carbon cycle, and then we specify competition between fossil-fuel technologies and carbon-free technologies.

Carbon emissions, expressed as a function of time by E_t, are proportional to the use of fossil-fuel-based energy, $y_{f,t}$, through the carbon intensity factor ε_t:

$$E_t = \varepsilon_t \, y_t \ , \qquad (11)$$

where ε_t is assumed to be time-dependent to account for a gradual de-carbonization process; it declines by 0.2% per year until it reaches 80% of the intensity at 2000, $\varepsilon_t = \max(0.8,\ 0.998^t)\varepsilon_1$. Fossil-fuel consumption has been subject to such a process since the early times of industrialization, by a transition –in chronological order– from the use of wood to coal, from coal to oil, and most recently from coal and oil to natural gas (Nakicenovic *et al.*, 1998, Fig 4.16).

Carbon emissions are linked to the atmospheric carbon dioxide concentration, which in turn determines the global average surface temperature. The carbon cycle dynamics assumed here are simple, and follow the approximations supposed in DICE (Nordhaus, 1994). Carbon emissions are linked to the atmospheric carbon-dioxide concentration, Atm_t, which in turn determines the global average surface temperature, Temp_t, using a "1-box representation":

$$\text{Atm}_{t+1} = \text{Atm}_0 + (1-\delta_M)(\text{Atm}_t - \text{Atm}_0) + (1-\delta_E)(E_t + \bar{E}), \qquad (12)$$

$$\text{Temp}_{t+1} = (1-\delta_T)\text{Temp}_t + {}^2\log\left(\frac{\text{Atm}_{t+1}}{\text{Atm}_0}\right)\overline{T}\ \delta_T, \qquad (13)$$

where δ_M is the atmospheric CO_2 depreciation rate, $1-\delta_E$ the retention rate of emissions, $\bar{E}$ are emissions linked to deforestation, agricultural production, and other non-energy greenhouse gas sources, δ_T the temperature adjustment rate resulting from the atmospheric warmth capacity, and $\overline{T}$ is the long-term equilibrium temperature change associated with a doubling of the atmospheric CO_2 concentration.

In various scenarios, energy is taxed at a fee τ at the basis of its carbon content, and thus, the tax is expressed in \$/tC and it adds a constant markup value to the production costs,[3]

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[3] Alternatively, taxes can be specified as a constant markup ratio: $p_t = (1+\tau_t)q_t$.

$$p_t = q_t + \tau_t \varepsilon_t, \tag{14}$$

where q_t is the production cost and ε_t the energy efficiency as defined in equation (11).

Fossil fuels compete with a generic carbon-free energy source. Energy produced by both technologies has its own characteristics but they are substitutes. For convenience, we assume inelastic demand on the aggregate level, $\hat{y}_t$, which growth-rate is set equal to the population growth rate plus an assumed 1.5 per cent growth per year, g_{ypc},

$$\hat{y}_{t+1} = (\mathrm{Pop}_{t+1}/\mathrm{Pop}_t)(1+g_{ypc})\hat{y}_t \tag{15}$$

Population (Pop_t) is assumed to grow logistically:

$$\mathrm{Pop}_{t+1} = \mathrm{Pop}_t\left(1 + g_{\mathrm{Pop}}\left(1 - \frac{\mathrm{Pop}_t}{\mathrm{PopLT}}\right)\right), \tag{16}$$

where g_{Pop} is the population growth rate for low population levels and PopLT is the population level in the long term to which Pop_t converges.

The two energy technologies are denoted by g=1,2. We do not assume that energy produced by both technologies has constant elasticity of substitution, but we assume a linearly homogeneous and variable elasticity of substitution (VES) aggregation function. Energy system models (e.g. Peck and Teisberg 1992) typically assume that carbon-free technologies are perfect substitutes for fossil fuel technologies but have limited maximum supply and relatively high production costs that slowly decrease over time. Such a set of assumptions does not facilitate an explanatory description of a continuous diffusion over time of carbon-free technologies, since under perfect substitution demand is zero for all but the cheapest technology, unless positive demand is explicitly included as a volume constraint. More generally, perfect substitution between different technologies cannot explain that relatively expensive new technologies can develop before they become fully competitive with mature technologies. In contrast, models with a neo-classical point of reference typically assume complementarity between energy technologies. In Stephan *et al* (1997) and Goulder and Schneider (1999), carbon-free technologies and fossil fuel based technologies are relatively poor substitutes, that is, they have substitution elasticity of unity, or less[4]. Under this assumption, carbon-free technologies will not reach a substantial market share, irrespective of future decreases in production costs.

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[4] Note that the elasticity of substitution measures the inverse of the curvature of the production isoquant. It divides the percentage change in the factor ratio (that is the change in the angle of the input vector) by the percentage change in the prices (the change in the slope of the isoquant). See, for example, Varian, 1992.

In this paper, we specify an aggregator function that bridges the two views on substitutability. We use the variable σ to denote the elasticity of substitution between the technologies. We assume that σ is constant along an expansion path, that is when both y_1 and y_2 increase by the same factor, but σ varies along an isoquant for constant $\hat{y}_t$. Specifically, the two technologies are considered moderate substitutes, $\sigma \approx 1$, when one technology is dominant and demand for the other technology is best described through niche markets. The two technologies are considered good substitutes, $\sigma > 1$, when both technologies have substantial market share. Finally, as in the energy system literature, we assume that no energy source has an absolute comparative advantage in use, that is, we treat demand for both technologies symmetrically. We can thus write the elasticity of substitution as a function of the relative inputs of both technologies, $\sigma(y_1/y_2)$. In the literature, various VES-aggregation functions have been specified, see Nadiri (1982, Section 3.1.2) for an overview. Our aggregation function is based on the symmetric VES aggregator function proposed in Kadiyala (1972).[5] We have specified the aggregator function that is linearly homogeneous,

$$y_{1,t}^{\vartheta} y_{2,t}^{\vartheta} \left(y_{1,t}^{(\sigma-1)/\sigma} + y_{2,t}^{(\sigma-1)/\sigma}\right)^{(1-2\vartheta)\sigma/(\sigma-1)} = \hat{y}_t, \tag{17}$$

such that it satisfies the following features. The elasticity of substitution is unity if one technology is dominant, $\sigma \to 1$ for $y_1/y_2 \to 0$, or $y_1/y_2 \to \infty$. Thus, when one technology is in its infancy with high production costs, its elasticity of demand is about minus unity, and it has an almost constant value share. This lower bound on the value share for infant technologies is denoted by the parameter ϑ. Also, the elasticity of substitution exceeds unity, signifying more intense competition, when both technologies are comparable in size. Appendix 1 presents the condition when prices are equalized to marginal productivity. Figure 2 shows the elasticity of substitution, σ, for the aggregator function (17), as a function of the share of both energy sources.

4. Calibration and methodology

We used the model outlined above to carry out a numerical simulation based on approximate real-world data. As a benchmark scenario, we constructed a business-as-usual path that follows common assumptions on future energy consumption and prices. The model runs for 45 time steps of 5 years each, representing the period 2000-2250, though the presentation of data and figures will be restricted to the first two centuries 2000-2200. On the basis of the database developed for the IIASA-WEC study (Nakicenovic *et al.*, 1998), final commercial energy consumption in 2000

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[5] Most other VES functions assume that the elasticity of substitution is monotonically increasing in the share of one of the production factors, while we treat both technologies symmetrically, that is, we assume $\sigma(y_1/y_2)=\sigma(y_2/y_1)$.

is estimated to be 320 EJ.[6] From the same database, the share of fossil fuel technologies in energy production (in 2000) is estimated at 96 %. This corresponds to 307 EJ. The remaining share of 13 EJ is carbon-free energy. Future energy consumption is assumed to increase by 1 per cent per capita (=g_{ypc}). In 2000, the population (Pop_t) is estimated to be 5.89 billion (Pop_1) and its growth rate 1.45% (World Bank, 1999). The population is assumed to converge to the level of 11.4 billion people (PopLT), as in the IIASA-WEC study (Nakicenovic *et al*, 1998).

Since our model represents the two energy resources in an aggregate way, we have to make reasonable estimates for the average initial energy prices required. Because of the variability and volatility of these prices, this is not straightforward. Prices for final energy derived from natural gas technologies vary in a range from 2 to 3 \$(1990)/GJ.[7] Since coal, oil and natural gas are, *grosso modo*, competitive, a good reference price in our calculations for the average fossil fuel energy resource is 2.5 \$/GJ, in the model-start-off year 2000.

A large spread exists in production costs for energy from wind, solar and biomass options. Prices for commercial final electricity from wind turbines varied in 1995 between 5 and 20 \$(1990)/GJ, in the highest-cost and lowest-cost production cases, respectively.[8] Whereas electricity production costs for photovoltaics are still significantly higher than that for wind energy, costs of electricity derived from biomass are comparable to that of wind energy.[9] The average price of final energy by the carbon-free energy is taken to be 7.0 \$/GJ, in the year 2000. This value is merely taken as an example from the range of current feasible wind electricity prices; it represents a realistic figure of the current cost of a particular carbon-free energy alternative, generically speaking.

We furthermore assume that both the fossil fuel and carbon-free energy have the same technology parameters, except for the productivity parameter ς and the resource exhaustion parameter μ, which is set to zero for the carbon-free technology. Since we assume that only for the fossil-fuel energy source, energy production requires an ever-increasing effort due to exhaustion of the fossil-fuel wells, the equilibrium will converge to a carbon-free energy dominated situation. Figure 3 presents the cumulative production paths for the fossil-fuel and carbon-free energy sources. It shows that in the benchmark scenario (Business as Usual, abbreviated to BAU), in

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[6] This figure is expressed in primary energy source equivalents, and excludes non-commercial biomass use, as well as traditional carbon-free sources such as nuclear and hydropower.

[7] See, for example, IEA/OECD 1999, p.41.

[8] See, for example, IEA/OECD 2000, p.54. In fig.3.3 in this publication, one sees that in 1995 (in the EU) wind energy production costs varied from about 0.02 to 0.08 ECU(1990)/kWh. Assuming an approximate equivalence between the ECU and \$, as well as the conversion factor of 3.6 in going from GWh to TJ (that is, 0.0036 from kWh to GJ), one obtains the range quoted here.

[9] See, for example, IEA/OECD, 2000, p.21.

2100, fossil-fuel production has accumulated to about 100 ZJ, five times the cumulative output level at 2000. In the 22nd century, cumulative fossil-fuel production doubles again. At the end of the 22nd century, cumulative fossil-fuel energy production levels off. We notice that, in our model, the end of the fossil-fuel era is not implied by physical upper bound on the fossil-fuel reserves, but the economic reserves endogenously decrease when the carbon-free energy source becomes competitive.

The substitution elasticity between the two energy sources (Figure 2) and other parameters have been chosen such that, in the benchmark scenario, also referred to at the Business as Usual (BAU) scenario, the share for the carbon-free energy takes an S-shaped curve and increases from 4% in 2000 to 22% in 2100 and 93% in 2200 (Figure 5). Related to the carbon-free energy gain in market share, the carbon-free energy benefits from economies of scale more than the fossil fuel energy source and its price decreases over time, while the price for the fossil fuel energy technology slightly increases (Figure 6).

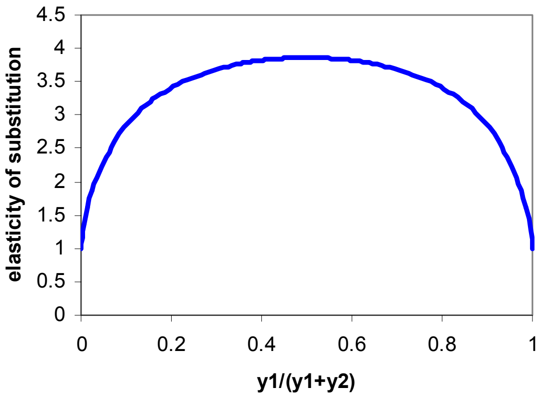

FIGURE 2. *Elasticity of substitution between fossil fuel and carbon-free energy sources, using simulation parameter values σ=5, ϑ=0.037.*

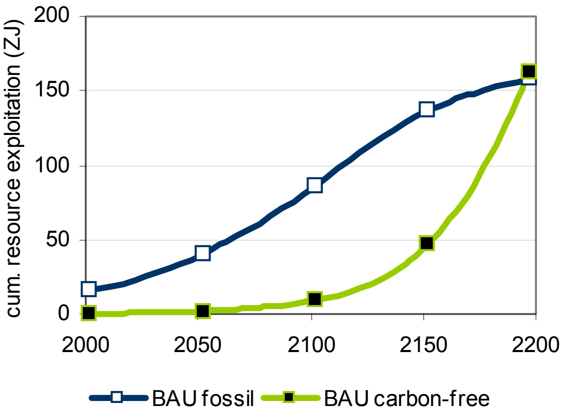

FIGURE 3. *Development of cumulative energy production over time, for fossil fuel and carbon-free energy in BAU.*

5. Simulation of carbon-tax policies

This section presents and discusses the results with the calibrated model. We have simulated five scenarios. The first BAU scenario assumes the absence of carbon taxes. The second scenario, labeled TAX25_NOITC, assumes a constant carbon tax of 25 $/tC, but it abstracts from technological change induced by the carbon tax. The third scenario is based on the same permanent 25 $/tC tax and includes the full model with endogenous technological change. Comparison of the second and third scenario can show us the importance of induced technological relative to factor substitution. The fourth and fifth scenario both assume endogenously adjusting technical change, and assume a transient 25 $/tC tax of 20 years and 40 years, respectively. Comparison of the third, fourth, and fifth scenario gives information on the persistence of technological change induced by a transient carbon tax.

Figure 4 shows the level of emissions in the period 2000–2200 for the first three scenarios, BAU, a steady 25 $/tC tax without ITC and with ITC. Figure 5 shows how the share of carbon-free changes over time in the same three cases.

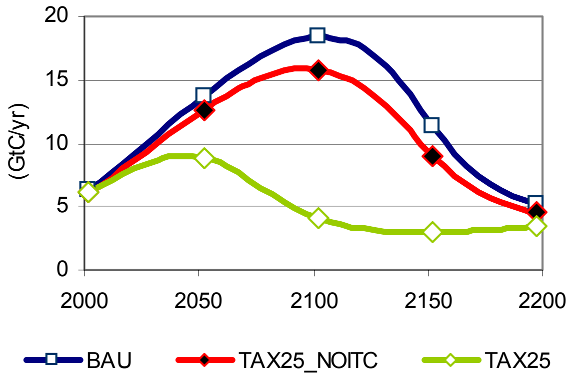

FIGURE 4. *Emissions for benchmark BAU scenario, a 25 $/tC tax without technological adjustment, and a 25 $/tC tax with endogenous technological change*

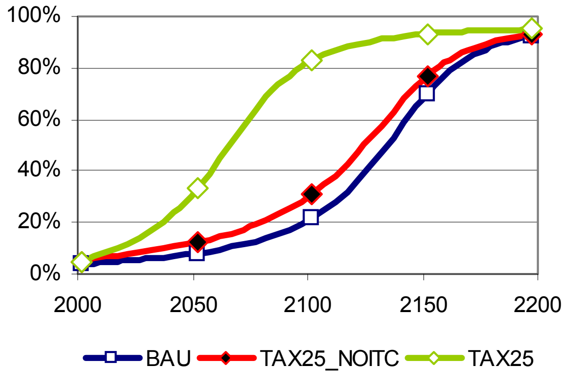

FIGURE 5. *Share for carbon-free energy for benchmark BAU scenario, a 25 $/tC tax without technological adjustment, and a 25 $/tC tax with endogenous technological change*

We can derive the following conclusions from Figure 4 and Figure 5. Our model appears to produce a reasonably common BAU scenario as a benchmark. After 2100, the energy system makes an endogenous transition towards the carbon-free energy technology, and emissions drop. This is an optimistic perspective, when compared to benchmark scenarios developed by other scenarios, but it is not incredible (Chakravorty *et al.* 1997).

When we abstract from the impact of carbon taxes on technology,[10] a carbon tax of 25 $/tC advances the shift towards the carbon-free energy modestly by about 10 years, and thus reduces emissions modestly. This finding is not surprising, as it is in line with most other studies. In contrast, when we allow the technology variables $a_{g,t}$ and $b_{g,t}$ to endogenously adjust to the carbon tax scenarios, so that there is ITC in our calculations, the effect of a carbon tax is amplified by a magnitude. The transition towards the carbon-free energy source is advanced by about 70 years; it takes off at around 2020, and emissions drop substantially during the second half of the 21st

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[10] That is, we fix the paths for the variables a and b on their BAU paths, and omit the equations that otherwise determine their dynamics.

century. The next figures present some insights in the cause for this advance in transition. Figure 6 plots the energy production costs for fossil fuels and carbon-free energy, while Figure 7 shows these costs for the case with a steady 25 $/tC tax and ITC.

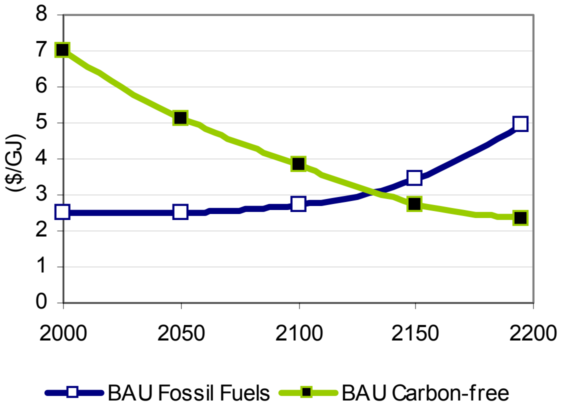

FIGURE 6. *Energy production costs for fossil fuels and carbon-free energy benchmark BAU scenario.*

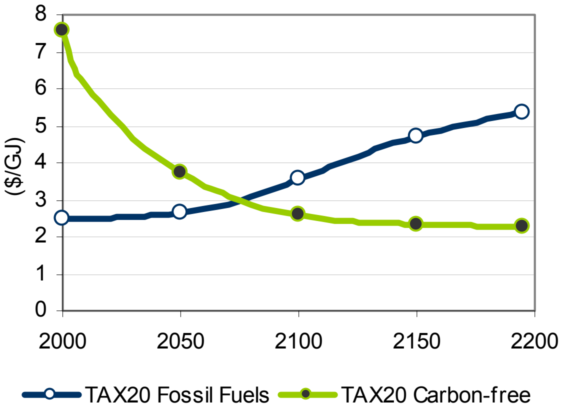

FIGURE 7. *Energy production costs for fossil fuels and carbon-free energy, 25 $/tC tax scenario with ITC.*

We draw the following conclusions from Figure 6 and Figure 7.[11] Under BAU (Figure 6), production costs for carbon-free energy steadily decrease, until, by 2130, they equal production costs of fossil fuels. From that point on, the loss of market shares faced by fossil fuels accelerates; output levels for fossil fuels decreases, the R&D effort and learning by doing decreases and the growth of innovations slows down. Technological development becomes insufficient to compensate for resource exhaustion and the increase in wages and fossil fuel prices increase. In the 25 $/tC tax scenario (Figure 7), the same mechanism causes the production costs for fossil fuels to increase after 2070, when carbon-free energy sources take over as the dominant energy source. At the same time, the carbon tax increases the market share for carbon-free energy and stimulates innovation and learning by doing, and this leads to an earlier decrease in production costs for the carbon-free energy source. Thus, ITC acts as a multiplier for a policy that aims at a transformation from carbon-based to carbon-free energy sources.

In the energy system literature, the phenomenon of decreasing production costs when experience increases for new technologies is typically described through a learning curve. In models that describe learning by doing through learning curves (e.g. MESSAGE, Messner 1997; DEMETER-1, van der Zwaan *et al.* 2002, Gerlagh and van der Zwaan 2003), typically a constant

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[11] While it is not presented in the figures, the energy production costs under the TAX20_NOITC scenario match the BAU levels.

learning rate (*lr*) is assumed of approximately 20% for new technologies, at which the cost of investments or the costs of production per output unit declines for each doubling of cumulative production. This corresponds to

$$q_t = q_1 \, (z_t/z_1)^{\alpha-1}, \tag{18}$$

where z_t is the cumulative experience at period t, and $0<\alpha<1$ defines the learning rate as

$$lr = 1 - 2^{\alpha-1}. \tag{19}$$

While in our model, there is no exogenous learning rate, we can reproduce *ex post* the learning curves and the learning rate that comes out of our simulations.

Thereupon, we plot the logarithm of production cost per unit of output against the logarithm of cumulative output for fossil fuels and carbon-free in Figure 8 and Figure 9, respectively. For the carbon-free energy sources, under BAU, over the period 2000-2200, we find an average learning rate of about 20% (Figure 9). Thus, our model reasonably captures the main insight from the energy system learning-by-doing literature.

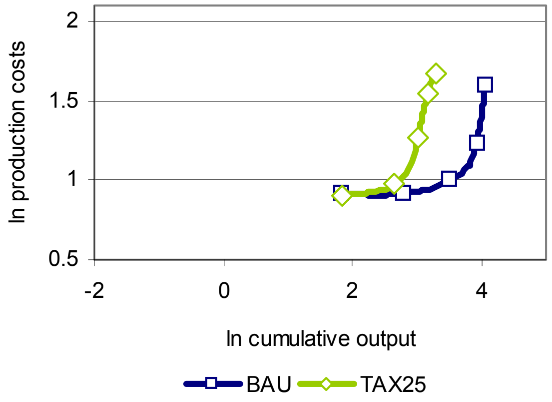

FIGURE 8. *Simulated learning curve for fossil fuels, BAU scenario and 25 \$/tC tax scenario with ITC.*

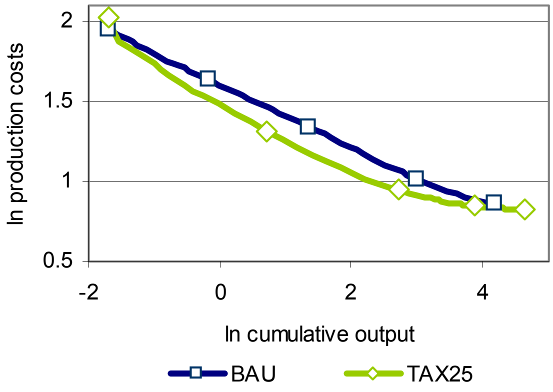

FIGURE 9. *Simulated learning curve for carbon-free energy, BAU scenario and 25 \$/tC tax scenario with ITC.*

In the steady 25 \$/tC tax case, initially the learning curve becomes steeper. Obviously, in our model, the learning curve is not assumed ex ante, but it merely gives a reduced presentation of the complex interplay between increasing wages, extraction efforts, innovations, and learning by doing. In our model, the mechanisms underlying the curve differ from the energy system models in an important way. First, for both energy sources, technology advances through two channels, R&D and learning by doing, but at the same time, technological growth has to offset increasing wages for both energy sources, and increasing resource scarcity for the fossil fuels as well. Thus, production costs only decrease when technological advances are sufficient to offset the two forces that tend to increase prices. For fossil fuels, as has become clear from Figure 6 and Figure 8, in the early decades of the 21st century, technological progress is just sufficient to compensate increasing wages and increasing scarcity. After the break-through of carbon-free energy sources, prices increase, even though the stock of technology keeps growing.

Second, in our model, while technological progress through learning by doing is based on past cumulative experience, technological progress through R&D is based on expected revenues from innovations. Thus, an anticipated increase in the market share for carbon-free energy sources increases current R&D effort and decreases production costs, in advance of the rise in carbon-free energy. This explains why in Figure 9 the learning curve for the 25 $/tC scenario lies below the learning curve for the BAU scenario.

Finally, we turn to the policy question expressed in the introduction whether transient carbon taxes can have permanent effects on emissions when they direct technological change. Figure 10 and Figure 11 show the effect of a transient tax of 25 $/tC for 20 years (2005–2025) (TAX25A), a transient tax of 25 $/tC for 40 years (2005–2045) (TAX25B), and the permanent tax over the whole period (TAX25) as used for the graphs above, and compare this to the BAU.

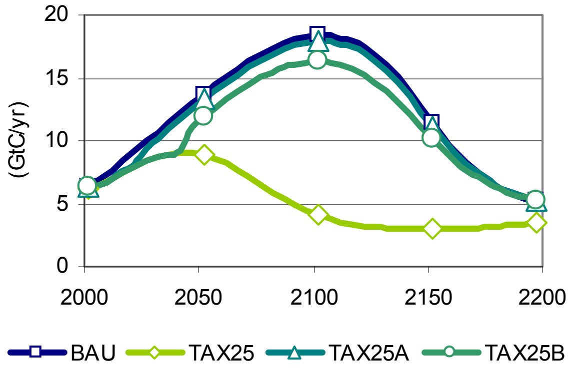

FIGURE 10. *Emissions for benchmark BAU scenario, a permanent 25 $/tC tax, and two transient 25 $/tC tax scenarios with endogenous technological change*

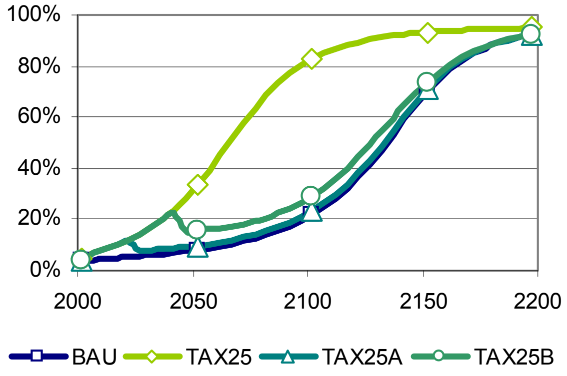

FIGURE 11. *Share for carbon-free energy for benchmark BAU scenario, a permanent 25 $/tC tax, and two transient 25 $/tC tax scenarios with endogenous technological change*

From Figure 10 we derive the ITC impact factor, to find the significance of ITC for the responsiveness of cumulative emissions to constant carbon dioxide taxes. We measure this response as the reduction in cumulative carbon dioxide emissions over the period 2000-2100 following the steady carbon tax of 25 $/tC. We compare the reduction in cumulative emissions without ITC, and with ITC. This leads to an ITC impact factor of 5.0 (=560/110, see TABLE 1), which is substantially above the factor 2 found by Carraro and Galeotti (1997). They, however, only included learning by research and left out learning by doing. By this number, our model clearly indicates that it is too pessimistic to assume technology as given in the long run.

TABLE 1. *Cumulative emissions and reduction (2000-2100).*

	Cumulative emissions	Reduction*		ITC factor
	(GtC)	(GtC)	(%)	
BAU	1300			
TAX25_NOITC	1180	110	(9%)	
TAX25	730	560	(44%)	5.0
TAX25A	1250	50	(4%)	
TAX25B	1130	160	(13%)	

* Differences may not precisely match with numbers in the first column entry due to rounding off errors.

Figure 11 shows that a transient carbon tax of 25 $/tC for 20 years (2005-2025) advances the transition by about 5 years compared to BAU and decreases cumulative emissions over the period 2000–2100 by 4% (see also TABLE 1). A transient tax of about 40 years advances the transition by about 80 years and reduces cumulative emissions by 13%, while a permanent tax advances the transition by about 70 years and reduces cumulative emissions by 44%. This remarkable sensitivity of the results with respect to carbon taxes also indicates that the BAU is covered with uncertainty regarding the date when carbon-free energy overtakes fossil fuels. Small perturbations in the early decades can have a large and lasting impact on the structure of the future energy system. This may be considered a weakness of the model, but it may as well be as a fundamental property of the energy system, which in the long term may not be as stable as often assumed in model analyses.

With the help of Equations (12) and (13) the atmospheric carbon concentration and the global average temperature can be calculated. This is presented in Figure 12 and Figure 13.

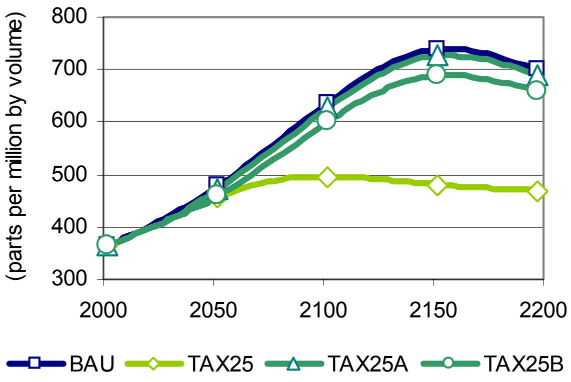

FIGURE 12. *Atmospheric carbon concentration for benchmark BAU scenario, a permanent 25*

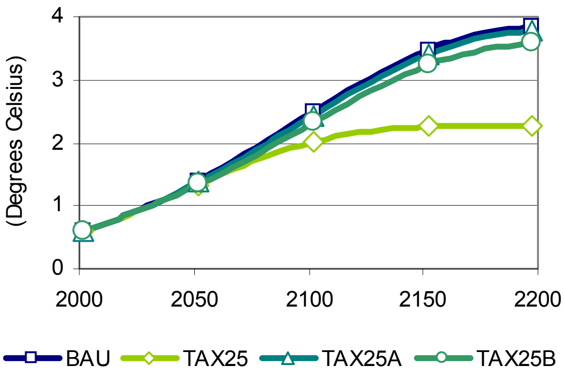

FIGURE 13. *Temperature for benchmark BAU scenario, a permanent 25 $/tC tax, and two*

$/tC tax, and two transient 25 $/tC tax scenarios with endogenous technological change.

transient 25 $/tC tax scenarios with endogenous technological change.

Figure 12 and Figure 13 show the impact of a (transient) tax of 25$/tC and ITC on the atmospheric carbon concentration and the global temperature. Figure 13 shows that only a transient tax can keep the global warming impact below the mark of 2.5°C. In that case the atmospheric carbon concentration stabilizes reaches its peak of about 500 ppmv in the year 2100.

6. Discussion

In this paper we presented a model of neo-classical nature, that successfully reproduced some of the results known from the energy-system models, notably (i) the learning curve, and (ii) the S-curved transition towards new (carbon-free) technologies.

As for (i), this paper may contribute to bridge the gap between the neo-classical economic literature that focuses on incentives for R&D as the driving force for productivity growth, and the energy systems models that more or less mechanically describe productivity as dependent on cumulative historic experience. Also, in our model, in contrast to energy system models, production costs tend to increase because of increasing wages. Production costs can only decrease insofar as the increase in productivity exceeds the increase in wages. When, in the long term, fossil fuels are slowly replaced by carbon-free energy sources, research levels will fall for fossil fuels, and production costs will increase due to increasing wages. Fossil fuels will follow an inverted learning curve when fading out.

As for (ii), from energy system analysis, it is known that the process from invention, to demonstration projects, to significant market shares typically takes between five and seven decades (Nakicenovic *et al.* 1998). Energy system models incorporate these insights by explicitly setting constraints on the increase in market shares for new technologies. Our model does not have such market penetration constraints, but it still generates the same S-curve for the market share of carbon-free energy sources. Also, when climate change policy stimulates the transition towards non-carbon emitting energy sources, the transition is enhanced, but it becomes not unrealistically high. Our model describes how economic incentives enhance the penetration rate of new technologies, for a discussion on these issues, see Caldeira *et al.* (2003), O'Neill *et al.* (2003), Swart *et al.* (2003), Hoffert *et al.* (2003).

Besides the methodological insights, we have used the model to carry out some policy analyses, to verify whether as a transient carbon tax can have a lasting impact on emission levels. The results found indicate that endogenous technological change has a very large impact on the responsiveness of emissions to carbon dioxide taxes. As a measure of this response, we have taken the reduction in cumulative carbon dioxide emissions over the period 2000-2100 following a constant carbon tax of 25 \$/tC. Endogenous technological change enhances cumulative emissions reductions by factor 5. This is in strong contrast with previous studies, which found that either the impact of ITC is as important as factor substitution (Carraro and Galeotti 1997; van der Zwaan *et al* 2002; Gerlagh and van der Zwaan 2003) or less important (Goulder and Schneider, 1999; Nordhaus, 2001). We may conclude that taking induced technological change into consideration, a more optimistic perspective arises on the possibilities of emission reductions than without it.

Acknowledgments

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Appendix 1. First order conditions for firms' profit maximization

The energy producers

In this appendix, we derive all first order conditions for the representative energy producer.

The Lagrangean for profit maximization (6) subject to (1), (2), and (7) reads:

$$\mathbf{L} = \Sigma_t\, \beta^t\, (qy - \theta a^{inn} y - wl - i + \lambda(\varsigma z^{-\mu} a^{\eta_a} b^{\eta_b} k^{\alpha} l^{(1-\alpha)} - y)$$

$$- \psi k + \beta\psi_{+1}(i + (1-\delta_k)k) + \kappa z - \beta\kappa_{+1}(z + y)) \qquad (20)$$

Where $\beta^t\lambda_t > 0$ is the dual variable for (1), $\beta^{t+1}\psi_{t+1} > 0$ is the dual variable for (7), and $\beta^{t+1}\kappa_{t+1} > 0$ is the reversed dual variable for (2). For convenience, we omitted time subscripts for the variables in the Lagrangean, and used shorthand notation ψ_{+1} to denote the forward time lap ψ_{t+1}. The first order conditions for y, a, l, i, k, and z are, respectively,

$$q = \theta a^{inn} + \lambda + \beta\kappa_{+1}, \qquad (21)$$

$$\theta y = \eta_a \lambda y/a, \qquad (22)$$

$$w = (1-\alpha)\lambda\, y/l\ , \qquad (23)$$

$$1 = \beta\ \psi_{+1}\ , \qquad (24)$$

$$\psi = \beta(1-\delta)\psi_{+1} + \alpha\lambda y/k, \qquad (25)$$

$$\kappa = \beta\kappa_{+1} + \mu\lambda y/z. \qquad (26)$$

We can substitute equations (24) in (25) to derive a capital cost equation that shows capital costs to consist of interest and depreciation:

$$\delta_k + 1/\beta - 1 = \alpha\lambda y/k \ . \qquad (27)$$

The price of the output good, q, consists of three parts (21), the license fee θa^{inn}, the immediate production costs λ, and the resource scarcity rent $\beta\kappa_{t+1}$. From (21) and (22), we see that innovation costs make a constant mark up η_a on top of the immediate production costs net of the license fee, λ,

$$\theta a = \eta_a\lambda \ . \qquad (28)$$

which enables us to give the price of innovations θ as:

$$\theta = \eta_a \ \xi \ z^{\mu} \ a^{-1-\eta_a} \ b^{-\eta_b}. \qquad (29)$$

Substitution of (28) in (21) gives us output prices q as

$$q_t = (1+\eta_a \ a^{inn}/a)\lambda_t + \beta\kappa_{t+1}. \qquad (30)$$

where λ_t is the marginal production costs per unit of output,

$$\lambda_t = \min \{(\delta_k+1/\beta-1)k+wl \mid 1\leq\varsigma \ z^{-\mu}a^{\eta_a}b^{\eta_b}k^{\alpha}l^{1-\alpha} \} = \xi_t \ z_t^{\mu} \ a_t^{-\eta_a} \ b_t^{-\eta_b} \ , \qquad (31)$$

with ξ the price of the factor composite $(k_{j,t})^{\alpha}(l_{j,t})^{1-\alpha}$, dependent on capital costs, $\delta_k+1/\beta-1$, and wages, w_t

$$\xi = \varsigma^{-1}\alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)}(\delta_k+1/\beta-1)^{\alpha} \ w^{1-\alpha}, \qquad (32)$$

which is exogenous to the firm. The term $\beta\kappa_{t+1}$ describes the resource rent for the future increase in resource exploitation efforts due to present exploitation levels. Equations (30) and (31) display that output prices are proportional to factor costs, as expressed in ξ, inversely proportional to the technological productivity, a^{η_a} and b^{η_b}, that there is a mark up $\eta_a a^{inn}/a$ for the costs of technology and for the resource rent.

For the carbon-free energy resource sector, we assume that there is no exhaustion and we assume μ=0; this does not change the first order conditions.

Innovators

Let φ^{inn}_t denote the asset price of an innovation, that is, the value of an increased innovation level Δa_h to its owner. An equilibrium on the market for innovations requires that the costs of developing a new technology, that is, the costs of an increase Δa_h, equals the revenues the innovator can obtain by selling the license fees. That is, the asset price of an innovation, one period ahead, $\beta\varphi^{inn}_{+1}$, has to be equal to the production costs per unit of innovation, $r_h/\Delta a_h$, given by (8),

$$\beta\varphi^{inn}_{+1} = \zeta^{-1}\, r^{1-\pi}\, a^{\pi-1}. \tag{33}$$

We obtain the overall research effort r,

$$r = (\zeta\beta\varphi^{inn}_{+1})^{1/(1-\pi)}\, a. \tag{34}$$

The revenues from an innovation are equal to the net present value of future license fees:

$$\varphi^{inn}_{t} = \sum_{s=t}^{\infty} (\beta(1-\delta_{inn}))^{(s-t)}\theta_s y_s\,, \tag{35}$$

In terms of a recursive equation, we write

$$\varphi^{inn}_{t} = \theta_t y_t + (1-\delta_{inn})\beta\varphi^{inn}_{t+1}. \tag{36}$$

Private and social returns on research do not match. The social returns of an innovation held by the innovator are given by

$$\varphi^{soc}_{t} = \theta_t y_t + (1-\delta_{inn})\beta\varphi^{soc}_{t+1} + \delta_{inn}\beta\varphi^{pub}_{t+1} \tag{37}$$

where the first two terms on the right-hand-side are the same as for the private returns, but the third term reflects the fact that those innovations that leak from the private sector to the public domain also contribute to the social value of the privately held innovations. In turn, the social value of knowledge in the public domain, in terms of a recursive equation, is given by

$$\varphi^{pub}_{t} = \theta_t y_t + (1-\delta_{pub})\beta\varphi^{pub}_{t+1}. \tag{38}$$

Given these three values for innovations, we can calculate the social rate of return on research in period t (SRR_t). For the individual firm, the private value of an innovation is equal to the production costs per unit of innovation, $\beta\varphi^{inn}_{+1}=r_h/\Delta a_h$, as described in (33). Public returns, however, fall short of private returns because of the fishing out of innovations. The factor is given by the ratio between marginal productivity of research, $\mathrm{d}a^{inn}/\mathrm{d}r$, as described by (9), and the private productivity of research, $(\Delta a^{inn}{}_h/r_h)$, given by (33). For this factor, we find

$$(\mathrm{d}a^{inn}/\mathrm{d}r)(r_h/\Delta a^{inn}{}_h) = \pi. \tag{39}$$

At the same time, public returns exceed private returns because of the spill-over from privately held knowledge to publicly available knowledge. First, the social value of privately held innovations exceeds the private value, $\varphi^{soc}{}_{t+1}/\ \varphi^{inn}_{t+1}>1$, and second, research leads to a direct spin of on public knowledge, $\chi\varphi^{pub}{}_{t+1}/\ \varphi^{inn}_{t+1}$. The *SSR* is now given by

$$SRR_t = \pi(\varphi^{soc}{}_{t+1}+\chi\varphi^{pub}{}_{t+1})/\ \varphi^{inn}_{t+1}. \tag{40}$$

When the *SRR* exceeds unity, $SRR>1$, the social returns on research exceed the costs, and policies are warranted that stimulate research above its equilibrium level. Typically, from empirical studies, the *SRR* is found to be in the order of four, $SRR\approx 4$.

Energy aggregation

From equalizing prices and marginal productivity in (17), $p_1/p_2 = \partial\hat{y}/\partial y_1/\partial\hat{y}/\partial y_2$, and we have

$$(1-\vartheta)\left(y_2 p_2 y_1^{(\sigma-1)/\sigma} - y_1 p_1 y_2^{(\sigma-1)/\sigma}\right) = \vartheta\left(y_1 p_1 y_1^{(\sigma-1)/\sigma} - y_2 p_2 y_2^{(\sigma-1)/\sigma}\right), \tag{41}$$

Total model

The dynamic two-technology model consists of equations (1), (2), (4), (5), (7), (9), (10), (14), (21), (23), (24), (26), (27), (28), (32), (34), (36), (37), (38), (40), both for fossil fuels and carbon-free energy; equations (17) and (41) are used for aggregation. The impact of energy production on the global carbon cycle is calculated ex post via equations: (11), (12) and (13).

Appendix 2. Model parameters and variable values in calibration procedure

Table 2. *Calibration parameters and variable values in first period (2000-2004) for fossil fuels*

Parameters	Fossil fuels	Carbon-free	*Endogenous variables*	Fossil fuels	Carbon-free
α	0.300		y [ZJ]	1.536*	0.064*
β	0.784		p [$/GJ]	2.500*	7.000*
δ_k	0.350		a	8.221	0.942
δ_{inn}	0.350		a^{inn}	1.000*	0.115
δ_b	0.350		a^{pub}	7.221	0.826
δ_{pub}	0.350		b	3.423	0.125
χ	6.441*		z	15.566	0.394
μ	0.164*	0.000	q	2.500	7.000
η_a	0.250*		λ	2.295	6.792
η_b	0.100		l	2.468	0.304
π	0.500		i	0.758	0.100
ζ	0.565*		k	1.689	0.208
ς	0.572*	0.295*	ξ	2.798	5.435
σ	5.000		r [trillion $]	0.0768*	0.010
ϑ	0.037*		κ	0.172	0.000
			ψ	1.276	1.276
			φ^{inn}	0.218	0.235
Exogenous. Variables			φ^{pub}	0.218	0.235
w	1.000		φ^{soc}	0.341	0.367
$\hat{y}$	1.491*		θ	0.070	1.803
			SRR	4.000*	4.000
Exogenous variables growth rates			*Variables growth rates*		
$g_{\hat{y}}$	0.0987*		g_p	0*	-0.0278
g_w	0.0252		g_φ	0	0
			g_y	0.0987*	0.1623
			g_a	0.0987	0.1301
			g_l	0.0199	0.1022

* For fossil fuels, empirical data for y and p, a normalization for $a=1$, research expenditures that make 2 per cent of total value of output, and a social rate of return on research of SRR=4, and growth rates $g_p=0$, $g_y=0.0987$ are used to calibrate the parameters χ, η_a, ς, ζ, μ, and the variable $\hat{y}$. For carbon-free energy, empirical data for y and p are used to calibrate the parameters ς and ϑ. Other parameters are based on literature and guesses.

TABLE 3. *Population and climate change parameters*

Parameters and variables	per period	per year
ε_1	0.0205	
Atm_0	0.590	
δ_M	0.0408	0.0083
δ_E	0.36	
$\bar{E}$	0.00665	0.00133
δ_T	0.096	0.02
$\overline{T}$	3.0	
g_{ypc}	0.051	0.01
g_{Pop}	0.149	0.0282
Pop_1	5.89	
PopLT	11.36	

References

Barro R.J. and X.X.Sala-i-Martin (1995) *Economic growth.* McGraw-Hill, Inc., New York.

Basu S., J.G. Fernald (1997), Returns to scale in US production: Estimates and implications, *Journal Of Political Economy* 105 (2): 249-283.

Beltratti, A. (1997) "Growth with Natural and Environmental Resources", in C. Carraro and D. Siniscalco, eds., *New Directions in the Economic Theory of the Environment*, Cambridge University Press, Cambrige.

Bovenberg A.L. and S.A. Smulders (1995) "Environmental quality and pollution-augmenting technological change in a two-sector endogenous growth model" in *Journal of Public Economics* 57: 369-391.

Bovenberg, A.L., and S.A. Smulders (1996) "Transitional Impacts of Environmental Policy in an Endogenous Growth Model", *International Economic Review* 37: 861-893.

Buonanno, P., C. Carraro, and M. Galeotti (2003) "Endogenous induced technical change and the costs of Kyoto", forthcoming in *Resource and Energy Economics*.

Caballero, R.J., and A.B. Jaffe, (1993), How High Are The Giant's Shoulders: Empirical Assessment of Knowledge Spillover and Creative Destruction in a Model of Economic Growth, *NBER Macroeconomic Annual*.

Caldeira, K., A.K. Jain, and M.I. Hoffert (2003), "Climate sensitivity uncertainty and the need for energy without CO_2 emission", *Science* 299: 2052-2054.

Carraro C. and M.Galeotti (1997) "Economic growth, international competitiveness and environmental protection: R&D innovation strategies with the WARM model", *Energy Economics* 19: 2-28.

Chakravorty U., J.Roumasset, and K.Tse (1997) "Endogenous substitution among energy resources and global warming" in *Journal of Political Economy* **105**: 1201-1234.

Den Butter F.A.G. and M.W. Hofkes (1995) "Sustainable development with extractive and non-extractive use of the environment in production" in *Environmental and Resource Economics* 6: 341-358.

IEA/OECD (1999). Key World Energy Statistics. International Energy Agency, OECD, Paris.

IEA/OECD (2000). Experience Curves for Energy Technology Policy. International Energy Agency, OECD, Paris.

Gerlagh, R. and B. van der Zwaan, 2003, “Gross world product and consumption in a global warming model with endogenous technological change”, Resource and Energy Economics 25:35–57.

Goulder L.H. and K.Mathai (2000) "Optimal CO2 abatement in the presence of induced technological change" in *Journal of Environmental Economics and Management* **39**: 1-38.

Goulder L.H. and S.H.Schneider (1999) "Induced technological change and the attractiveness of CO2 abatement policies" in *Resource and Energy Economics* **21**: 211-253.

Gradus R.H.J.M. and S.A.Smulders (1993) "The trade-off between environmental care and long-term growth; pollution in three prototype growth models" in *Journal of Economics* 58: 25-51.

Hoffert, M.I., K. Caldeira, G. Benford, T. Volk, D.R. Criswell, C. Green, H. Herzog, A.K. Jain, H.S. Kheshgi, K.S. Lackner, J.S. Lewis, H.D. Lightfoot, W. Manheimer, J.C. Mankins, M.E. Mauel, L.J. Perkins, M.E. Schlesinger, T.M.L. Wigley (2003), “Response”, *Science* 300: 582-583.

Jaffe A.B., R.G. Newell, and R.N. Stavins (2002), “Environmental Policy and Technological Change”, in *Environmental and Resource Economics* 22:41-70.

Kadiyala, K.R. (1972), “Production functions and elasticity of substitution”, in *Southern Economic Journal* 38:281-284.

Kortum, S.S., (1993), Equilibrium R&D and the Patent-R&D Ratio: U.S Evidence, *American Economic Review*, 81, 450-457.

Manne A.S., R.Mendelsohn, and R.Richels (1995) "MERGE, A model for evaluating regional and global effects of GHG reduction policies" in *Energy Policy* **23**: 17-34.

Messner, S., (1997). Endogenized technological learning in an energy systems model. Journal of Evolutionary Economics 7, 291–313.

Nadiri, M.I., (1982), “Producers Theory”, Ch. 10 in *Handbook of Mathematical Economics, Vol II*, K.J. Arrow and M.D. Intriligator (eds), North Holland, Amsterdam.

Nakicenovic, N., A. Grübler, A. McDonald, (1998). Global Energy Perspectives. IIASA-WEC. Cambridge University Press, Cambridge, UK.

Newell R.G., A.B. Jaffe and R.N. Stavins (1999), “The induced innovation hypothesis and energy-saving technological change”, *Quarterly Journal of Economics* 114: 941-975.

Nordhaus,W., (1994), Managing the Global Commons, the Economics of Climate Change. MIT Press, Cambridge, Massachusetts.

Nordhaus W.D. (2002), “Modeling induced innovation in climate change policy”, Ch 9 in *Modeling induced innovation in climate change policy*, A. Grubler, N. Nakićenović, and W.D. Nordhaus (eds), Resources for the Future Press.

O’Neill, BG., A. Grübler, N. Nakicenovic, M. Obersteiner, K. Riahi, L. Schrattenholzer, F. Toth (2003), “Planning for future energy resources”, *Science* 300: 581.

Peck, S.C., T.J. Teisberg, (1992). CETA: a model for carbon emission trajectory assessment. The Energy Journal 13 (1), 55–77.

Popp, D. (2000), “Induced innovation and energy prices”, *American Economic Review* 92: 160-180.

Smulders S.A. (1999) "Endogenous growth theory and the environment" in *Handbook of environmenal and resource economics*, Ch. 42, edited by J.C.J.M.v.d.Bergh. Edward Elgar,

Smulders S.A., and M. de Nooij (2003), “The impact of energy conservation on technology and economic growth”, in *Resource and Energy Economics* 25(1): 59-79.

Stephan, G., G. Müller-Fürstenberger, P. Previdoli (1997), “Overlapping Generations Or Infinitely-Lived Agents: Intergenerational Altruism And The Economics Of Global Warming”, Environmental and Resource Economics, 10:27-40.

Swart, R., J.R. Moreira, T. Morita, N. Nakicenovic, H. Pitcher, H-H. Rogner (2003), “We disagree with Hoffert *et al.*”, *Science* 300: 582.

Van der Zwaan B.C.C., R. Gerlagh, G. Klaassen, and L. Schrattenholzer (2002), “Endogenous technological change in climate change modelling”, *Energy Economics* 24:1-19.

Varian, Hal R. (1992), Microeconomic analysis, W.W. Norton & Company; 3rd edition.

Verdier, T. (1995) “Environmental Pollution and Endogenous Growth”, in C. Carraro and J. Filar, eds., *Control and Game-Theoretic Models of the Environment*, Birckauser, Boston.

Weyant, J.P. and T. Olavson (1999), “Issues in modeling induced technological change in energy, environment, and climate policy”, in *Environmental Modeling and Assessment* 4: 67-85.

World Bank, (1999). World Development Indicators, 1999. World Bank, Washington, DC.