Time Profile of Climate Change Stabilization Policy

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Summary

We develop an economic model for fossil-fuel and carbon-free energy supply and demand with capital and labor as production factors, and endogenous technological change through learning by research and learning by doing. We use the model to study inter-temporally efficient carbon taxes for climate stabilization targets. Calculations show an inverted U-curve with an initial rise of carbon-taxes that sets in motion the transition from fossil-fuels to carbon-free energy sources, followed by a drop in carbon taxes when the carbon-free energy sources have grown mature.

Keywords: Induced technological change, Environmental taxes, Partial equilibrium, Learning by doing

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

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1. Introduction

Since Working Group I of the Intergovernmental Panel on Climate Change (IPCC-WGI) developed a set of possible pathways for stabilizing the atmospheric CO2 concentration at 350, 450, 550, 650 and 750 p.p.m.v. over the next few hundred years, a debate has been going on in the literature as to the optimal timing of emission reductions that are required to reach these stabilization targets. Especially the paper by Wigley, Richels and Edmonds (WRE, 1996), who argue that it is better to postpone substantial emission reduction as long as possible, was influential and gave rise to much discussion. Gruebler and Messner (1998), for example, confirmed the pattern of emissions computed by WRE (1996), but nonetheless arrived at different policy conclusions. In their view, emission reductions in the short term, though small, are essential to give the economy the opportunity to learn from experience in abatement technologies. They concluded that the objective of long-term emission reduction requires an immediate shift away from 'business as usual' policies, irrespective of the size of early emission reductions. Other articles that discuss arguments in favour and/or against early action are, among many others, Azar (1999), Grubb (1997, 1998), Goulder and Mathai (1998) and Tol (1999).

Analytical approaches that are followed to calculate emission reduction paths consistent with stabilization are different in many respects. Most complex models with a deep level of physical detail use a recursive dynamic approach, and calculate a window of tolerable emission paths consistent with stabilization targets. At the same time, most economic models use reduced forms and apply an inter-temporal optimisation framework to calculate cost-effective emission paths. Some analyses treat technology as a static variable, others as an exogenously dynamic variable, and still others include feed back relations from policies to technology, treating the latter as an dynamic and endogenous variable. Some analyses apply (high) market discount rates before aggregation of costs and benefits, while other apply a (lower) 'fair' discount rate. Other arguments that play a role are uncertainties and irreversibilities of investments, sunk costs of existing capital stock, characteristics of the modelled carbon cycle, international institution building, issues of intergenerational equity, first-mover advantages, and the modelling of impacts of climate change.

In this paper, we focus on the feed back of emission reduction policies on energy technologies, and its implications for a cost-effective path that ensures a stabilization of atmospheric CO2 concentration at 450 or 550 ppmv. We pay due attention to technological change in energy production, both through R&D and learning by doing as in the models by Nordhaus (2002) and Buonanno *et al*. (2003). As regards most of the other modelling issues mentioned above, we follow a relatively simple approach without uncertainty and without regional differentiation, and with a simple carbon cycle model. We develop a global partial energy model, DEMETER-2E,[1] with the following features. Total energy demand follows an exogenous path. There are two energy sources (fossil fuels and carbon-free) that compete for their market shares. The model describes two channels for technological innovations, through research and development (R&D) and through learning by doing (LbD). The level of R&D is driven by economic incentives, that is, by the value of an innovation to the innovator. The modelling of innovations follows the tradition of the endogenous growth models with natural resources that have been specified to study growth and sustainability (Gradus and Smulders 1993; Bovenberg and Smulders 1995; den Butter and Hofkes 1995; Verdier 1995; Bovenberg and Smulders 1995, 1996; Beltratti 1997; Smulders 1999, Smulders and de Nooij 2003). In contrast to innovations through R&D, learning by doing requires no additional effort. It is a direct spillover effect of production.

Within this model, the only option to reduce emissions is to shift energy demand and supply from fossil fuels to carbon-free energy sources. One might object that, in practice, energy savings will also constitute an essential part of emission reductions, but for the longer term in which we are mostly interested, to constrain climate change, the substitution between various energy sources is indispensable, since energy is an essential production factor. A shift away from fossil fuel based energy sources towards carbon-free energy sources is unavoidable (Chakravorty *et al*. 1997, Caldeira *et al*. 2003). And because of this, it is particularly important to study the effect of induced technological change on the relative contribution of various competing technologies used for energy production (Weyant and Olavson 1999).[2]

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[1] 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 (van der Zwaan *et al*; 2002, and Gerlagh *et al*. 2004), 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.

[2] 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).

Our focus on the transition in energy sources, together with the focus on induced technological change, may produce results that are substantially different from results of earlier integrated assessment models that lacked these features. These earlier results indicate that atmospheric carbon stabilization requires an ever-increasing effort to reduce emissions, and carbon taxes to continuously increase over time. As a case in point, we present results of our own calculations with DICE99 (Nordhaus and Boyer, 2000).[3] Figure 1 presents atmospheric carbon dioxide concentrations for the benchmark or Business as Usual (BAU) scenario, which increase from 355 ppmv in 2000, to 590 ppmv in 2100 and 855 ppmv in 2200. The figure also presents results for two stabilization scenarios for 550 ppmv and 450 ppmv, respectively. Figure 2 shows the associated carbon taxes, required to reduce emissions for the stabilization scenarios. It is clear that carbon taxes steeply increase once the atmospheric carbon dioxide concentrations hit their stabilization target levels, approximately in 2100 and 2050, respectively, for the 550 and 450 ppmv stabilization scenario. It is also apparent from the figure that carbon taxes are monotonically increasing, also after stabilization has been reached. This finding signifies the conventional hypothesis that reduction efforts and the economic burden of the stabilization policy continuously increase over time.

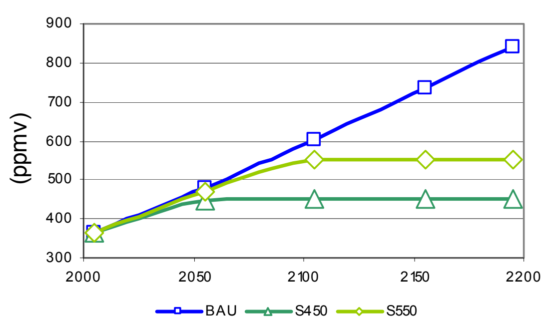

FIGURE 1. *Atmospheric carbon concentration under benchmark (BAU) and two stabilization scenarios. Own calculations with DICE99.*[4]

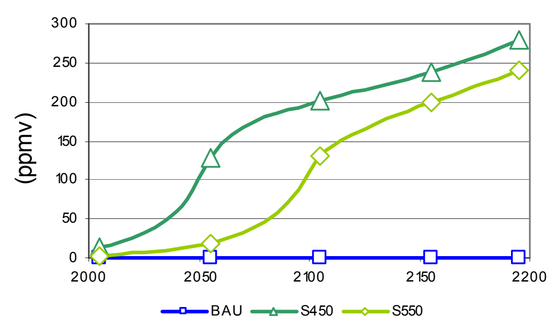

FIGURE 2. *Carbon tax under benchmark (BAU) and two stabilization scenarios. Own calculations with DICE99.*[4]

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[3] See Chapter 5 of the book, or http://www.econ.yale.edu/~nordhaus/homepage/Dice020899.gms for the GAMS source code.

[4] As these calculations do not aim at a cost-benefit analysis, but at a cost-effective stabilization policy, we omitted the climate change damage function from the DICE99 model.

In the model employed in this paper, we expect a different timing profile for the carbon tax. In a first stage, to set in motion the transition from fossil fuels to carbon-free energy sources, an increasing carbon tax is needed. Once the transition is accomplished, a second phase begins and the need for a carbon dioxide tax may lessen. When the carbon tax has established a carbon-poor or carbon-free energy system, the scale of the carbon-poor energy system may induce sufficiently research to become competitive with fossil fuels without the need for continued carbon taxes, and carbon taxes may fall after a while. Overall, the carbon tax path might follow an inverted U-curve, with an initial rise, followed by a peak and fall. The inverted U-curve offers an optimistic picture in sharp contrast with the results of earlier integrated assessment models shown above.

The paper is organized as follows. Section 2 describes the basic features of energy production for each energy source, fossil fuels and carbon-free. Section 3 connects energy production to carbon emissions and to changes in the global average temperature. It also describes the causal chain from population growth to growth of aggregate energy demand and the split of energy demand in two energy sources. Section 4 describes the calibration of the model. Section 5 provides the results of the benchmark, 550 ppmv, and 450 ppmv stabilization simulations. The final section concludes. 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. Energy production under endogenous technology

This section presents the basic elements of our model for energy production and innovation, for one energy source. Figure 3 gives an overview of the production structure. We model energy as a produced good, as depicted in the middle column of the figure, using capital and labor as production factors. Overall productivity of capital and labor depends on knowledge gained through experience, so-called learning by doing labeled with symbol b, pictured through the lower 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 its use producers have to pay a license fee – from a freely available public knowledge stock. Both private and public research-based technology stocks are 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 enter into a license contract with innovators and pay a running royalty for use of innovations. The revenues from the license contracts are sufficient for the innovators to cover the research expenditures. Producers of energy take wages and energy prices as given. The royalty rate for innovations is determined in the market for innovation contracts.

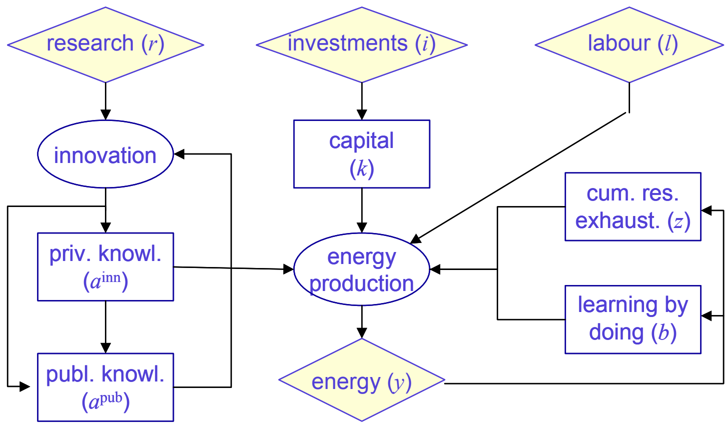

FIGURE 3. *Schematic overview of innovation and energy production in the model. The innovation and energy production processes are presented in an ellipse. Stocks are presented in rectangles. Commodity flows are presented in diamonds.*

Our model assumes a continuum of infinitely small firms, indexed j, that produce energy labeled $y_{j,t}$ according to

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

where ς is a constant 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. The parameters α, η_a, η_b, represent the elasticity of output with respect to capital, knowledge gained through R&D, and knowledge gained through learning by doing, respectively. The parameter μ measures the decrease in productivity due to resource exhaustion.

Modeling an aggregate energy source for all fossil fuels, we have to make a distinction between aggregate resource exhaustion and a decrease in the quality of remaining resource stocks. With the ongoing extraction of fossil fuels, reserves decrease in quality and require an increasing effort for exploitation. The model focuses on the decrease in reserves' quality, driving the transition towards alternative energy sources. In the very long term, physically, some fossil fuel reserves may remain, but these will not be economically exploitable. That is, for economic exploitation, it is not only the quantity of the physical stock of reserves that matters, but also the quality of the remaining reserves, in relation to the state of technology. An advanced technology may extend the economic reserves, while physically, the reserves are not affected by technology. To capture this phenomenon, we do not model an initial resource stock that is exhausted, with an associated Hotelling rent for the resource exhaustion equation, but instead, we assume a continuous exhaustion of reserves that are easily accessible. The decrease in quality drives up the effort that is required to extract the resource and to produce a certain amount of energy. The effort is measured by $(z_t)^\mu$; it increases because of decreasing quality of, say, oil wells when the reserves decrease as a function of cumulative production.[5] The increased effort is related to the cumulative exploitation levels as described through 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 ($=\Sigma_j y_{j,t}$). The continuous exhaustion of easily accessible reserves creates a shadow-price or resource rent, comparable with the Hotelling resource rent. Whereas the Hotelling rent is increasing exponentially with the interest rate, the resource rent associated with the decreasing quality is approximately constant over time. In our benchmark simulations, it accounts for about five per cent of total energy production costs.[6]

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, instead there are well-defined property rights.

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[5] The argument presented here on increasing efforts is known as the folk theorem, which as a general rule says that cheap (easily accessible) resource reserves are exhausted before expensive resources will be exploited. In a recent stream of literature, the folk theorem has been shown to fail when energy prices sharply increase. Cheap energy sources can then be preserved for later use to smoothen over time energy prices. (see Favard 2002 for an analysis and overview). In our benchmark scenario, fossil fuel energy prices do not increase sharply, and thus, we may assume the folk theorem to hold.

[6] We notice that, for convenience, we assume physical resource use as measured by the increase of z and output as measured by y proportional. For fossil fuels, we can think of the resource as coal, oil, and gas, whereas gasoline or electricity would be a typical output product. Both variables can be measured in Exa Joules (EJ). The state of technology is supposed to measure the productivity of capital and labor in resource extraction and energy output production; it does not measure the efficiency in preventing losses in refining and conversion. These are assumed exogenous to the model.

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.[7]

To describe the use of innovations as an input to production, let us consider the number of patented innovations, $a^{inn}{}_t$ at time t, for which an innovator holds the property rights, and for which a license contract can be entered. Similarly, denote the number of 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 royalty payments as $a^{pub}{}_t$. Let the number of innovations that are employed by the *j-th* firm, at date t be denoted as $a_{j,t}$, with a subscript j for the firm. For convenience, we omit the subscript t from the remainder of this paragraph. Let $h \in [0, a^{inn}]$ denote the (continuous) index for patented innovations. For each innovation, the innovator offers firm j a license contract based on running royalties. When the firm enters into the contract, it has to pay a license fee that is a fixed percentage $\theta_{h,t}$ of net revenues. For use of innovation h, expenditures thus amount to $\theta_{h,t} q_t y_{j,t}$, where q_t is the output price minus taxes and subsidies. Let $a^{inn}_{j,h} \in \{0,1\}$ be the (dummy) variable that states whether the firm j has entered the license contract for innovation h. The amount of innovations in use by firm j, a_j, is now given by[8]

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

For the firm j, the returns to scale on the number of innovations it employs are decreasing (1). Though there is no difference in the contribution to the productivity between an innovation with a high or a low index number, each additional innovation for which a license contract is signed contributes less to the productivity. A firm will enter a license contract for innovation h, if and only if the royalty rate θ_h does not exceed its value, that is, the marginal value of the knowledge

[7] By this assumption, we abstract from decreasing returns to scale for carbon-free energy production that comes from scarcity of sites for windmills and photovoltaic cells. In some other studies, it is assumed that costs for carbon-free energy sources increase sharply with respect to the level of energy supply (e.g. Fisher and Newell 2004). Alternatively, one may consider fossil fuels with carbon capturing and sequestration as a carbon-free energy source. In that case, we should employ the same variable z and parameter μ for both energy sources.

[8] We note that this equation does not state perfect substitution among innovations, but merely it states that the contribution of various innovations to productivity can be added, while the sum has decreasing returns to productivity in equation (1). A firm cannot substitute a more intensive use of one innovation for a less intensive use of another innovation. In this sense, there is no (continuous) substitution. For each innovation, the firm has to decide to use that innovation, and to fully pay for its use, or not to use that innovation.

stock a_j in production. Since all firms have the same production technology (1), all firms will enter the license contract for innovation h when the royalty rate falls short of its marginal value, while no firm will enter a license contract when the royalty rate exceeds its marginal value. Demand for a license contract for an innovation h is a step-function of the royalty rate θ_h. An innovator holding the patent for innovation h will maximize revenues when the royalty rate is set to the maximal level for which all firms enter the license contract. Consequently, all innovators will set the same royalty rate, at the marginal value in production of knowledge a. Since the royalty rate θ_h is the same for all innovators, we drop the subscript h, and since $a^{inn}_{j,h}=1$ for all j,h, equation (3) becomes

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

We return to the production of innovations at the end of this section.[9]

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 from 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 $i_{j,t} + w_t l_{j,t} + \theta_t a^{inn}{}_{j,t} q_t y_{j,t}$, while revenues amount to $q_t y_{j,t}$. The firms, that are forward looking, maximize the net present value of their cash flows:

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[9] A difference with the main body of endogenous growth literature is that we do not consider product variety and price setting under monopolistic competition (see Barro and Sala-i-Martin 1995 for an overview). The reason for this distinction is that we do not model innovations as embodied in intermediate goods, but instead, we model innovations as intangible knowledge that can be applied in production generically. The dissemination of knowledge through license contracts based on running royalties is a common finding in the micro-literature, see the discussion in Baumol (2002), p79, p84, footnote 2, and McGavock, Haas and Patin (1992). IBM and Philips are two outstanding examples. IBM's profit from licensing its inventions has been $1.7 billion in 2000, contributing to slightly more than 20 percent of the firm's total profit (Feder, 2001). Philips is a major player on the innovation market for compact discs. Every cd-player worldwide contains a number of Philips patents. License revenues for optical data storage alone raised 268 million euro in 2002 (Dekker 2003).

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

where $(1/\beta)-1$ is the real interest rate, subject to the production identity (1), the dynamics of resource depletion (2), and to the (standard) capital depreciation-investments relation, for capital $k_{j,t}$ of firm j at time t,

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

where δ_k is the depreciation rate, and i_t is the investment flow. For 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, following from the firm's maximizing behavior.

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. We denote the innovators by index $\tilde{h}$. The number of innovations for which patents are held by innovator $\tilde{h}$, is denoted by $a_{\tilde{h}}$. The flow of new ideas that are invented by an individual innovator $\tilde{h}$, $\Delta a_{\tilde{h}}$, is linearly proportional to its research expenditures $r_{\tilde{h}}$, but is decreasing in the aggregate research flow r, the so-called fishing-out effect (Caballero and Jaffe 1993; Kortum 1993). Finally, the set of innovations for which patents are held by innovator $\tilde{h}$ also decreases by a fraction δ_{inn} as these innovations leak to the public domain because of patents that expire:

$$\Delta a^{inn}{}_{\tilde{h}} = \zeta\, r^{\pi-1}\, a^{1-\pi}\, r_{\tilde{h}} - \delta_{inn} a^{inn}{}_{\tilde{h}}. \tag{8}$$

where ζ is a scaling constant and π measures the rate of fishing out. On an aggregate level, π 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 $\tilde{h}$ gives

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

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 these innovations enter the public domain. Second, public knowledge is also produced as a direct spin-off of research, $\chi\zeta\ r_t^{\pi}\ a_t^{1-\pi}$, where the parameter $\chi>0$ describes the leakage of research activities to public knowledge:

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

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

3. Climate change and energy aggregation

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:

$$E_t = \varepsilon_t\, y_{f,t}\ , \qquad (11)$$

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).[10]

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

[10] Obviously, the substitution of technology for capital and labor, or vice versa, will imply a change in conversion efficiency from resources to energy output, and thus, the emission intensity will depend on endogenous variables. For convenience, we assumed the emission intensity to follow an exogenous path, and we think that, on the time scale we consider, the error in simulated emissions implied by this simplification is insubstantial compared to changes in emissions implied by the transition from fossil fuels to carbon-free energy sources.

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”:

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

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

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_t at the basis of its carbon content, and thus, the tax is expressed in $/tC and it adds a constant mark up to the energy system towards alternative(uc)6.7(t)-5.3(i energy sources. The model includes subsidies for the renewable energy sources, so that market prices become

$$p_{n,t} = (1-s_t)q_{n,t}. \tag{15}$$

The model has thus two instruments available, a carbon tax and a carbon-free energy subsidy, to enhance the transition from fossil fuel energy sources towards carbon-free energy sources.

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 isset equal to the population growth rate plus an assumed 1.5 per cent growth per year, g_{ypc},

$$\hat{y}_{t+1} = (\text{Pop}_{t+1}/\text{Pop}_t)(1+g_{ypc})\hat{y}_t \tag{16}$$

Population (Pop_t) is assumed to grow logistically:

$$\text{Pop}_{t+1} = \text{Pop}_t\left(1 + g_{\text{Pop}}\left(1 - \frac{\text{Pop}_t}{\text{PopLT}}\right)\right), \tag{17}$$

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.

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. Under this assumption, carbon-free technologies will not reach a substantial market share, irrespective of future decreases in production costs.

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_f and y_n 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, $\sigma(y_f/y_n)$. In the literature, various VES-aggregation functions have been specified, see Nadiri (1982, Section 3.1.2) for an overview.[11] Our aggregation function is based on the symmetric VES aggregator function proposed in Kadiyala (1972).[12] We have specified a linearly homogeneous aggregator function,

$$y_{f,t}^{\vartheta} y_{n,t}^{\vartheta} (y_{f,t}^{(\sigma-1)/\sigma} + y_{n,t}^{(\sigma-1)/\sigma})^{(1-2\vartheta)\sigma/(\sigma-1)} = \hat{y}_t \,, \tag{18}$$

such that it satisfies the following features. The elasticity of substitution is unity if one technology is dominant, $\sigma \to 1$ for $y_f/y_n \to 0$, or $y_f/y_n \to \infty$. 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.

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 (BAU) 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 is estimated to be 320 EJ.[13] 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. Because of the variability and volatility

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[11] The authors are grateful to Marzio Galeotti for his help on this topic.

[12] 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 $\sigma(y_f/y_n)=\sigma(y_n/y_f)$.

[13] 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.

of these prices, this is not straightforward. Prices for fossil fuels are assumed to reach 2.5 $/GJ in the model-start-off year 2000 (Gerlagh and van der Zwaan 2004), and to remain constant during the first decades and slowly increase thereafter (Figure 4).

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. The average price of final energy by the carbon-free energy is taken to be 7.0 $/GJ, in the year 2000 (Gerlagh and van der Zwaan 2004). This value is merely taken as a realistic figure of the current cost of a particular carbon-free energy alternative, generically speaking. Parameters are chosen such that during the 21st century, the development of production costs for the carbon-free energy source slowly decrease (Figure 4), with a speed that is consistent with a learning rate of 20%.[14] Figure 5 presents the implicit experience curves for both fossil fuels and the carbon-free energy source under the benchmark scenario.[15] Due to the decreasing price for carbon-free energy and slowly increasing price for fossil fuels, the equilibrium shifts to a carbon-free energy dominated situation.

These features of the benchmark scenario are reached under the assumption 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. Parameters have been calculated such that in equilibrium research expenditures amount to about 2 per cent of the value of energy output (Figure 6), and social returns on research exceed the private returns by factor 4. The research intensity of carbon-free energy is slightly above 2%, because the value of an innovation anticipates the value of future sales, and due to the increasing market share for carbon-free energy sources, there is a slightly larger incentive to invest in research, compared to fossil fuels, which has a decreasing market share.

The substitution elasticity between the two energy sources and other parameters have been chosen such that, in the benchmark (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 7 and Figure 10). This is an optimistic benchmark scenario, compared to many other analyses, but it is not incredible (Chakravorty *et al*. 1997). Consistent with this transition, total reserves of fossil fuels, measured in energy content, which can be exploited under economically profitable

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[14] We recall that there is no explicit learning rate in the model. The learning rate can be calculated ex post.

[15] We notice from Figure 5 that the experience curve for the carbon-free energy source is above the historic experience curve for fossil fuels.

conditions amount to about 160 ZJ (Figure 11). When cumulative fossil fuel energy supply reaches this level, prices go up and carbon-free energy sources take over.

Finally, we notice that we choose to assume a benchmark subsidy on carbon-free energy sources, to make sure that the BAU scenario is close to a cost-minimization scenario (Figure 7). This assumption requires some explanation. Due to knowledge spillover effects, energy production has increasing returns to scale for both energy sources. In turn, average cost pricing that pays a return on capital equal to the market interest rate plus the capital depreciation rate, implies energy prices that exceed marginal costs per unit of energy output. But, for the fossil-fuels, resource exhaustion decreases the returns to scale, and thus, the gap between average costs and marginal costs is larger for the carbon-free energy sources when compared to the fossil fuel energy sources. It is efficient to subsidize carbon-free energy sources compared to fossil fuel energy sources, or the other way around, to tax fossil fuel energy sources relative to carbon-free energy sources, thereby correcting the ratio of average cost prices such that these better reflect the ratio in marginal costs. When we abstract from taxes and subsidies under BAU, a carbon tax would shift the energy system towards a more efficient allocation, and a double dividend would arise: lower carbon dioxide emissions and lower energy production costs. The existing energy taxes and subsidies are rather complex, however, and we would jump to premature conclusion when our model would suggest a double dividend on the basis of these model features. We have chosen to explicitly assume an almost efficient pre-existing tax structure through modeling a constant subsidy on carbon-free energy sources that more or less captures the difference in the returns to scale. Figure 7 shows that, indeed, the BAU scenario closely resembles a scenario that minimizes total energy production costs. Table 1, Appendix 2, presents a detailed list of parameter values.

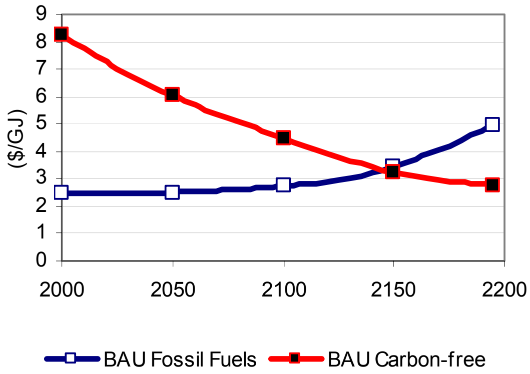

FIGURE 4. *Energy production costs for fossil fuels and carbon-free energy benchmark, BAU scenario.*

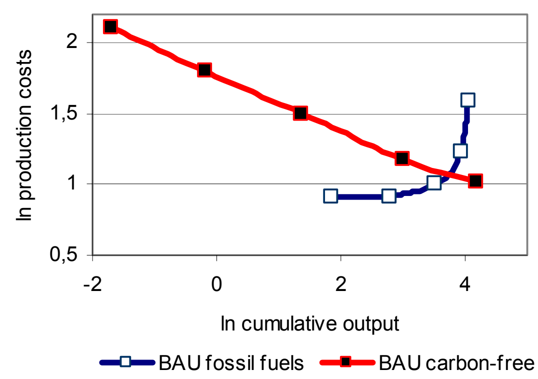

FIGURE 5. *Experience curves for fossil fuels and carbon-free energy sources, BAU scenario.*[16]

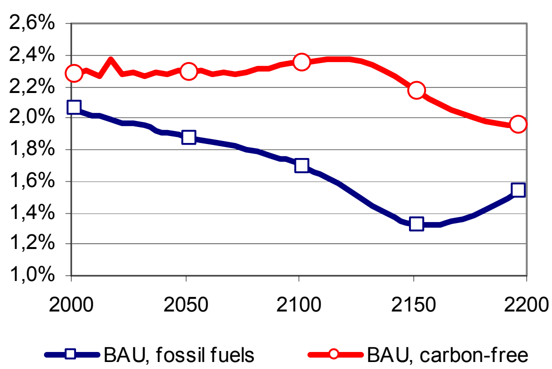

FIGURE 6. *R&D expenditures for fossil fuels and carbon-free energy sources, relative to value of energy output, BAU scenarios.*

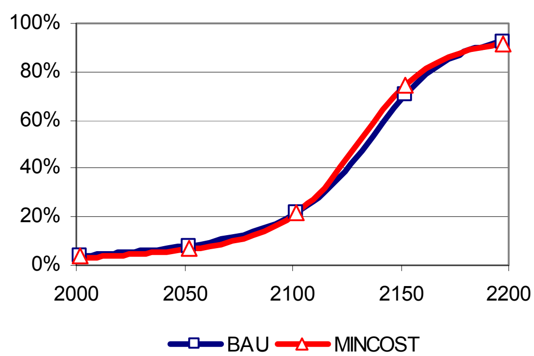

FIGURE 7. *Share of carbon-free energy sources over time, in BAU compared with a cost-minimizing scenario.*

5. Simulation of BAU and stabilization policies

This section presents and discusses the results with the calibrated model. We have simulated three scenarios. The first BAU scenario assumes the absence of carbon taxes. Emission levels steadily increase throughout the 21st century and peak at 2100 at a level of about 18.4 GtC/yr, as shown in Figure 8. During the 22nd century, carbon-free energy sources take over as dominant energy suppliers (Figure 10) and emission levels fall. Atmospheric carbon dioxide concentrations lag behind emissions (12), and parts per million volume peak at 2150 at a level of about 740, shown in Figure 9. Comparing our benchmark with the DICE99 benchmark (Figure 1), we find in our

[16] The experience curve draws the production costs (ln) as a function of cumulative output (ln).

model higher emissions and atmospheric concentration levels up to 2100, due to an assumed steeper increase in energy demand. After 2100, we find lower emissions and atmospheric concentration levels due to the assumed transition towards carbon-free energy sources (Figure 7).

The second scenario constrains the atmospheric carbon dioxide levels to 550 ppmv and it calculates the inter-temporal cost-efficient tax levels to reach this target. The third scenario constrains the atmospheric carbon dioxide levels to 450 ppmv.

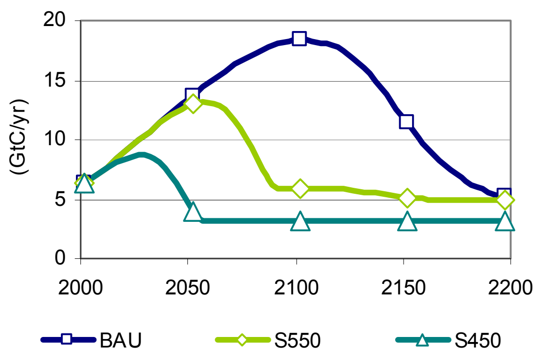

FIGURE 8. *Emissions for benchmark BAU scenario, the S550 ppmv and S450 scenario*

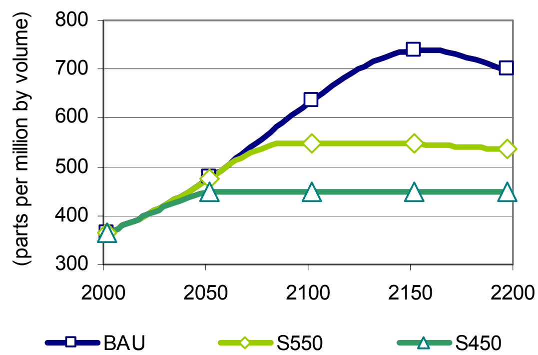

FIGURE 9. *Atmospheric carbon concentration for benchmark BAU scenario, the S550 ppmv and S450 scenario*

Figure 10 shows how the share of carbon-free energy changes over time in the three scenarios. Under BAU, the carbon-free energy source slowly matures over the two centuries, until by 2200 carbon-free energy sources are dominant. The S550 and S450 scenarios set in motion an early transition towards carbon-free energy sources, advancing the shift by about 60 years for the S550 scenario, and by about 100 years for the S450 scenario. Over the first century, under BAU, cumulative mining of fossil-fuels, measured in energy contents ZJ, rises from 16 ZJ in 2000 to 86 ZJ in 2100. The energy content of fossil fuel reserves exploited over the next century exceeds historic cumulative energy content by about factor 4. As Figure 11 also shows, fossil fuel extraction continues throughout the 22nd century, after which it levels off. The S550 and S450 scenarios leave large parts of fossil fuel reserves unexploited.

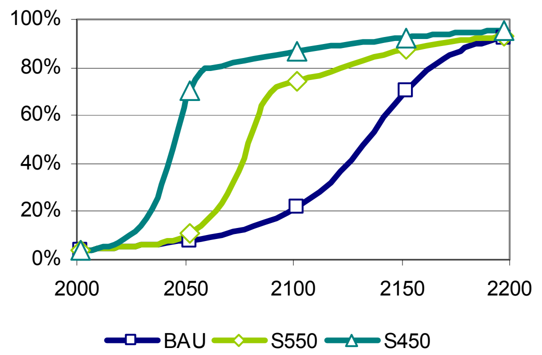

FIGURE 10. *Share of carbon-free energy sources for benchmark BAU scenario, the S550 and the S450 scenario*

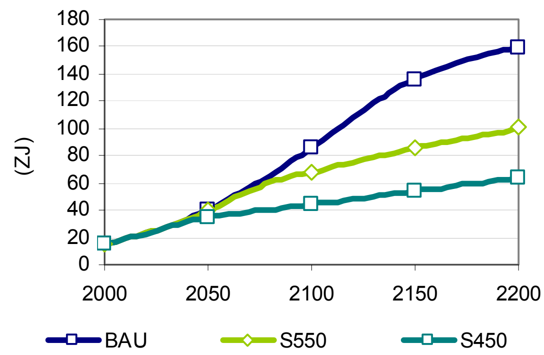

FIGURE 11. *Cumulative fossil fuel exploitation for benchmark BAU scenario, the S550 and the S450 scenario*

Figure 12 presents carbon taxes for the scenarios. Carbon taxes measure the effort that is required to reach the climate change targets. The figure is central to our results, as it shows that a stabilization of climate change may require a policy impulse, rather than a continuously increasing effort. Carbon taxes follow an inverse U-curve. To stabilize carbon dioxide concentrations, fossil-fuel energy sources need to be taxed to start a rapid transition towards the carbon-free energy source, and the more stringent the stabilization target, the earlier the transition is to be made and the more pronounced the carbon tax required. When the energy system is, however, successfully transformed, carbon taxes can be relaxed. Once the carbon-free energy source has become dominant, it raises sufficiently research to become self-supporting and it does not require a continuous carbon tax to be maintained. For the S550 scenario, carbon taxes even drop to zero by the end of the 22nd century. For the S450 scenario, carbon taxes drop after their peak around 2050, but increase again after 2100, showing an ‘N-curve’. The reason for this second rise is that fossil fuels do not vanish after the transition, and under growing output levels, emissions still tend to increase in the long term. A 450 ppmv stabilization requires rather strict emission levels, and to counter the relatively low but increasing trend, a carbon tax remains necessary.

Figure 13 presents the increase in total costs for energy supply. This variable also measures the effort, but not from the policy perspective as in case of the carbon tax, but in terms of what society has to spend additionally to its benchmark energy production costs to reach it stabilization targets. The figure looks similar to Figure 12. The major difference is that, once the transition has been carried through, additional knowledge gains enable energy costs to fall below the benchmark level for the 22nd century.

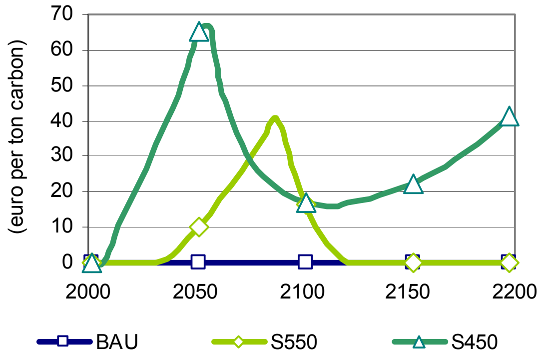

FIGURE 12. *Carbon tax for S550 and S450 scenario*

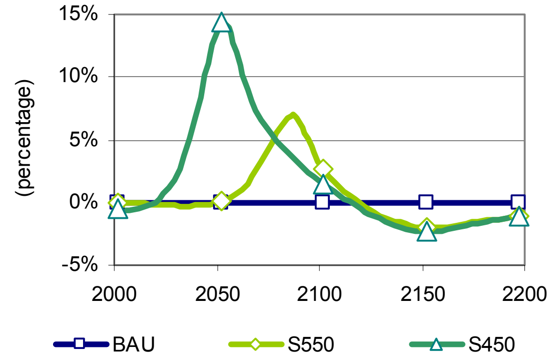

FIGURE 13. *Increase in energy system costs for S550 and S450 scenario relative to BAU*

To better understand the fall in carbon taxes after the transition has been carried through (around 2100 under S550 and 2050 under S450), we present the costs of energy production for both energy sources as an (inverse) measure of the endogenous level of technology. Figure 4 plots the energy production costs for fossil fuels and carbon-free energy under BAU, while Figure 15 shows these costs for the other two scenarios. We draw the following conclusions from the figures. Under BAU (Figure 4), production costs for carbon-free energy steadily decrease, until, around 2150, they equal production costs of fossil fuels. From that time on, fossil fuels their loose market share; 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 S550 and S450 scenarios (Figure 15), the same mechanism causes the production costs for fossil fuels to increase after 2080 and 2040, respectively, 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 for these energy sources innovation and learning by doing are stimulated. This leads to an earlier decrease in production costs for the carbon-free energy source. Thus, the endogenous adjustment of knowledge acts as a multiplier for the energy transformation policy.

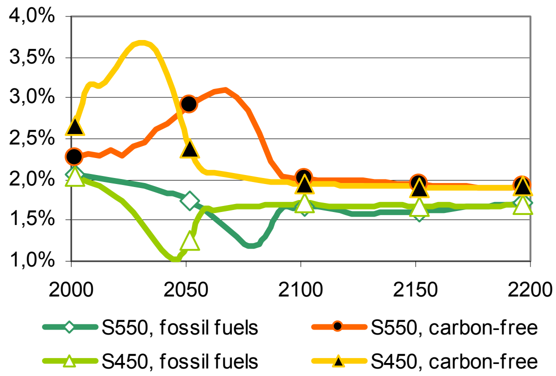

FIGURE 14. *R&D expenditures under stabilization scenarios for fossil fuels and carbon-free energy sources, relative to value of energy output.*

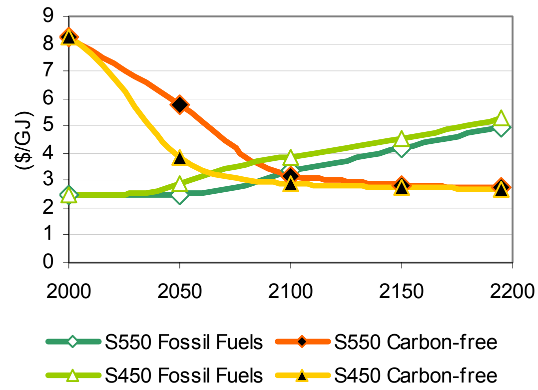

FIGURE 15. *Energy production costs for fossil fuels and carbon-free energy, S550 and S450 scenario.*

6. Discussion

In this paper we presented a partial-equilibrium energy model that incorporates various features of endogenous growth models. In line with the endogenous growth literature, our model is a cartoon model that plays up certain features while neglecting most of the other mechanisms through which climate change policies affect the economy. The model's main purpose is to explore the possible connection from carbon taxes to research expenditures, knowledge build up, and production costs for alternative energy sources. It describes the value of an innovation as the incentive for R&D driving productivity growth. The model also describes the channel of learning by doing, but different from energy system models that also describe learning by doing, in our model, production costs do not autonomously decrease with increasing cumulative output, but tend to increase because of increasing wages and decreasing resource quality, and production costs can only decrease insofar as the increase in productivity exceeds the increase in wages and the increase in effort due to resource scarcity. Nonetheless, the model has been calibrated such that under the benchmark scenario, for the carbon-free energy sources, it produces an implicit learning rate of about 20%.

We have used the model to study the time profile of carbon taxes under stabilization scenarios. The results indicate that a climate change stabilization target does not need to be perceived as an ever-lasting and increasing burden, associated with monotonically increasing carbon taxes. Taking induced technological change into consideration, an optimistic perspective may arise, where a carbon tax's main purpose is to direct the energy system towards carbon-free energy sources, after which the carbon tax can slowly be removed.

We make two qualifications to this result. First, to be sure, even though a required carbon tax might be impermanent, in our analysis, the carbon tax has been assumed broad both in the spatial and temporal dimension. We assumed global coordinated action, on a time scale of more than hundred years. The results thus have no direct implications for the effort required to meet the targets of the Kyoto Protocol, where a much smaller group of countries attempts to reduce its greenhouse gas emission levels in a much shorter time span. In all likelihood, carbon taxes supporting the Kyoto Protocol targets will reach much higher levels then those calculated here.

Second, the results crucially depend on the assumption that carbon-free energy sources are physically not inferior to fossil fuels. We thereby abstract from problems typical for wind and solar energy such as space requirements for sites, and their intermittent nature. A carbon-free energy supply to come through requires that for most of the practical problems low-cost solutions must be found. The optimist's perspective is that, when these resources are sufficiently scaled up, large flows of research and innovations will follow that, indeed, will enable us to solve most of the problems effectively and at modest costs.

Acknowledgments

The research has been funded by the Dutch National Science Foundation (NWO) under contract nr. 016.005.040, and by the EU under contract number ENG2-CT2001-00538. The author thanks the participants of the annual meeting of the *International Energy Workshop*, Laxenbourg, Austria, 24-26 June, 2003, and the participants of the *IAEE European Conference*, Zurich, September 1-3, 2004 for their comments.

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:

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

$$\left. - \psi k + \beta\psi_{+1}(i + (1-\delta_k)k) + \kappa z - \beta\kappa_{+1}(z + y)\right) \quad (19)$$

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,

$$q = \theta q a^{inn} + \lambda + \beta\kappa_{+1}, \quad (20)$$

$$\theta q y = \eta_a \lambda y/a, \quad (21)$$

$$w = (1-\alpha)\lambda\, y/l\ , \quad (22)$$

$$1 = \beta\ \psi_{+1}\ , \quad (23)$$

$$\psi = \beta(1-\delta)\psi_{+1} + \alpha\lambda y/k, \quad (24)$$

$$\kappa = \beta\kappa_{+1} + \mu\lambda y/z. \quad (25)$$

We can substitute equations (23) in (24) to derive a capital cost equation that shows capital costs to consist of interest and depreciation:

$$\delta_k + 1/\beta - 1 = \alpha\lambda y/k\ . \quad (26)$$

The price of the output good, q, consists of three parts (20), the running royalty rate $\theta q a^{inn}$, the immediate production costs λ, and the resource scarcity rent $\beta\kappa_{t+1}$. From (20) and (21), 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,

$$\theta q a = \eta_a\lambda\ . \quad (27)$$

Substitution of (27) in (20) gives us output prices q as

$$q = (1+\eta_a\, a^{inn}/a)\lambda + \beta\kappa_{+1}. \quad (28)$$

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

$$\lambda = \min\ \{(\delta_k+1/\beta-1)k+wl \mid 1\leq\varsigma\ z^{-\mu}a^{\eta_a}b^{\eta_b}k^{\alpha}l^{1-\alpha}\} = \xi\ z^{\mu}\ a^{-\eta_a}\ b^{-\eta_b}\ , \quad (29)$$

with ξ the price of the factor composite $(k_j)^{\alpha}(l_j)^{1-\alpha}$, dependent on capital costs, $\delta_k+1/\beta-1$, and wages, w

$$\xi = \varsigma^{-1}\alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)}(\delta_k+1/\beta-1)^{\alpha}\, w^{1-\alpha}, \quad (30)$$

which is exogenous to the firm. The term $\beta\kappa_{+1}$ describes the resource rent for the future increase in resource exploitation efforts due to present exploitation levels. Equations (28) and (29) 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 $\Delta a_{\tilde{h}}$ to its owner $\tilde{h}$. An equilibrium on the market for innovations requires that the costs of developing a new technology, that is, the costs of an increase $\Delta a_{\tilde{h}}$, equal the revenues the innovator can obtain by selling the license contract. 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, $r_{\tilde{h}}/\Delta a_{\tilde{h}}$, given by (8),

$$\beta\varphi^{inn}_{+1} = \zeta^{-1}\ r^{1-\pi}\ a^{\pi-1}. \tag{31}$$

We obtain the overall research effort r,

$$r = (\zeta\beta\varphi^{inn}_{+1})^{1/(1-\pi)}\ a. \tag{32}$$

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

$$\varphi^{inn}_t = \sum_{s=t}^{\infty}(\beta(1-\delta_{inn}))^{(s-t)}\theta_s q_s y_s\ , \tag{33}$$

In terms of a recursive equation, we write

$$\varphi^{inn} = \theta q y + (1-\delta_{inn})\beta\varphi^{inn}_{+1}. \tag{34}$$

Private and social returns on research do not match. The social returns of an innovation held by the innovator can be understood as the (social) shadow-price of equation (9). The social value of public knowledge can, similarly, be understood as the shadow-price of equation (10). The social value of privately held innovations is based on their contribution to output production, (1), private knowledge production (9), and public knowledge production (10), either directly or indirectly through the overall knowledge stock aggregation as in equation (4). The marginal value of overall knowledge in output production (1) is captured by $\theta q y$. The marginal value of overall knowledge in private knowledge production (9) is captured by $(1-\pi)\zeta(r_t/a_t)^{\pi}\ \beta\varphi^{soc}_{+1}$. The direct marginal value of privately held innovations in private knowledge production (9) is captured by $(1-\delta_{inn})\beta\varphi^{soc}_{+1}$. The marginal value of overall knowledge in public knowledge production (10) is captured by $\chi(1-\pi)\zeta(r_t/a_t)^{\pi}\ \beta\varphi^{pub}{}_{+1}$. The direct marginal value of privately held innovations in public knowledge production (10) is captured by innovations that leak from the private sector to the public domain, as measured by $\delta_{inn}\beta\varphi^{pub}{}_{+1}$. Together, this gives for the social value of a privately held innovation:

$$\varphi^{soc} = \theta qy + (1-\delta_{inn} + (1-\pi)\zeta(r_t/a_t)^{\pi})\beta\varphi^{soc}{}_{+1} + (\delta_{inn} + \chi(1-\pi)\zeta(r_t/a_t)^{\pi})\beta\varphi^{pub}{}_{+1}. \tag{35}$$

In turn, the social value of knowledge in the public domain, in terms of a recursive equation, is given by

$$\varphi^{pub} = \theta qy + (1-\pi)\zeta(r_t/a_t)^{\pi})\beta\varphi^{soc}{}_{+1} + (1-\delta_{pub} + \chi(1-\pi)\zeta(r_t/a_t)^{\pi})\beta\varphi^{pub}{}_{+1}. \tag{36}$$

Given these three values for innovations, we can calculate the social 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 (31). 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 (31). For this factor, we find

$$(\mathrm{d}a^{inn}/\mathrm{d}r)(r_h/\Delta a^{inn}{}_h) = \pi. \tag{37}$$

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 SRR is now given by

$$SRR = \pi(\varphi^{soc}{}_{+1}+\chi\varphi^{pub}{}_{+1})/\ \varphi^{inn}{}_{+1}. \tag{38}$$

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, $SRR\approx 4$. Baumol (2002, page 135), for instance, in citing Wolff (1997), argues that the estimated social rate of return is about 50%, while the private rate of return is between 10 and 12.5 percent. Nadiri (1993) presents a survey of the literature and shows that the social rate of return on R&D typically varies from 20% to over 100% with an average close to 50%.

Energy aggregation

From equalizing prices and marginal productivity in (18), $p_1/p_2 = \partial\hat{y}/\partial y_1/\partial\hat{y}/\partial y_2$, and we have

$$\left(1-\vartheta\right)\left(y_n p_n y_f^{(\sigma-1)/\sigma} - y_f p_f y_n^{(\sigma-1)/\sigma}\right) = \vartheta\left(y_f p_f y_f^{(\sigma-1)/\sigma} - y_n p_n y_n^{(\sigma-1)/\sigma}\right), \tag{39}$$

Total model

The dynamic two-technology model consists of equations (1), (2), (4), (5), (7), (9), (10), (14), (20), (22), (23), (25), (26), (27), (30), (32), (34), (35), (36), (38), both for fossil fuels and carbon-free energy; equations (18) and (39) are used for aggregation. The impact of energy production on the global carbon cycle is calculated ex post via equations: (11), (12) and (13).

Transversality conditions

For prices that follow a dynamic relation, κ, φ^{inn}, φ^{pub}, and φ^{soc} as in (25), (34), (35), (36) we rule out Ponzi schemes, as we demand that these prices are bounded from above. For our simulations, calculations are based on a truncated period t=1,…,T, and we use the steady state equivalent equations of (25), (34), (35), and (36), to calculate the levels for κ, φ^{inn}, φ^{pub}, and φ^{soc} in the last period T.

In the last period, investments i_T are calculated on basis of the growth equation

$$i = (g_{\hat{y}} + \delta_k)k. \tag{40}$$

Similarly, in the last period, research expenditures are based on

$$r = (\zeta\beta\varphi^{inn})^{1/(1-\pi)}\ a. \tag{41}$$

which is, for constant φ^{inn}, the steady state equivalent of equation (32).

Appendix 2. Model parameters and variable values in calibration procedure

TABLE 1. *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	6.890	0.635
δ_{inn}	0.350		a^{inn}	1.000*	0.093
δ_b	0.350		a^{pub}	5.890	0.542
δ_{pub}	0.350		b	3.343	0.116
χ	5.128*		z	14.027	0.319
μ	0.135*	0.000	q	2.500	7.000
η_a	0.203*		λ	2.307	6.796
η_b	0.100		l	2.482	0.304
π	0.300		i	0.780	0.107
ζ	0.257*		k	1.698	0.208
ς	0.594*	0.320*	ξ	2.697	4.997
σ	5.000		r [trillion $]	0.0768*	0.0106
ϑ	0.026*		κ	0.158	0.00
s	0.100		ψ	1.276	1.276
			φ^{inn}	0.213	0.284
Exogenous. Variables			φ^{pub}	0.425	0.649
w	1.000		φ^{soc}	0.663	1.012
$\hat{y}$	1.548*		θ	0.068	2.175
			SRR	4.000*	4.593
Exogenous variables growth rates			*Variables growth rates*		
$g_{\hat{y}}$	0.1095*		g_p	0*	-0.0311
g_w	0.0252		g_φ	0	0
			g_y	0.1095*	0.2005
			g_a	0.1095	0.1633
			g_l	0.0822	0.1346

* 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 for fossil fuels, and growth rates g_p=0, g_y=0.1095 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. The variable values in the dynamic model can slightly differ from values reported here, since to keep the calibration process tractable, some one-period approximations have been used.

TABLE 2. *Population and climate change parameters*

Parameters and variables	(unit of measurement)	value in model	per year
ε_1	(gC/MJ)	0.0205	
Atm_0	(ppmv)	590	
δ_M	(.)	0.0408	0.0083
δ_E	(.)	0.36	
$\bar{E}$	(GtC/yr)	6.65	1.33
δ_T	(.)	0.096	0.02
$\overline{T}$	(K)	3.0	
g_{ypc}	(.)	0.051	0.01
g_{Pop}	(.)	0.149	0.0282
Pop_1	(billion people)	5.89	
PopLT	(billion people)	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", *Resource and Energy Economics* 25:11-34.

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. (2003), "Induced technological change under technology competition", *Nota di Lavoro* 5.2003, Fondazione Eni Enrico Mattei, Milan, Italy.

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.

Grübler A. and S.Messner (1998) "Technological change and the timing of mitigation measures" in *Energy Economics* 20: 495-512.

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. and J. Boyer. (2000), "Warming the World: Economic Models of Global Warming", MIT Press, 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.

Wigley T.M.L., R.Richels, and J.A.Edmonds (1996) "Economic and environmental choices in the stabilization of atmospheric CO2 concentrations" in *Nature* 379: 240-379.

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

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