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GROSS WORLD PRODUCT AND CONSUMPTION IN A GLOBAL WARMING MODEL WITH ENDOGENOUS TECHNOLOGICAL CHANGE

A Study with DEMETER

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Abstract
This paper analyzes the macro-economic costs and effects on consumption and energy demand of limiting the global average atmospheric temperature increase to 2 degrees Celsius. We use a macro-economic model in which there are two competing energy technologies (carbon and non-carbon, respectively), technological change is represented endogenously, and energy is aggregated through a CES function implying positive demand for the relatively expensive non-carbon technology. Technological change is represented through a learning curve describing decreasing energy production costs as a function of cumulative experience. We compare scenarios that (I) allow for energy savings, versus scenarios that assume energy demand following an exogenous path, and scenarios that (II) allow for enhanced learning effects resulting from increased experience obtained with the carbon and non-carbon technologies, versus scenarios that assume production costs following an exogenous path. We find that energy savings constitutes an important mechanism for decreasing abatement costs in the short and medium term, while the acquisition of additional learning experience substantially decreases abatement costs in the longer term.

CONTENTS

1. INTRODUCTION

Models of energy-economy-climate interactions have so far nearly always regarded progress in carbon mitigation technologies as an exogenous process, rather than as endogenous technological change. This is true for both so-called bottom-up and top-down models. Bottom-up models, that analyze the economics of global warming from an energy systems point of view, have included technological progress predominantly as an exogenous process of cost and efficiency improvements for the set of technologies considered (as is done, for example, for a relatively rich set of energy alternatives in Nakicenovic et al., 1998). Top-down models, that take a macroeconomic approach towards questions concerning climate change, usually include technological change as an augmenting exogenous coefficient in the production function. The autonomous energy efficiency improvement, or AEEI, is a well-known example (see, for example, Manne et al., 1995; Manne and Richels, 1997; Peck and Teisberg, 1992; Nordhaus, 1994). Yet treating technological improvements as 'manna from heaven' provides no entry for policies that aim at directing innovation towards technologies with lower or zero carbon emission levels. Only recently, the literature has started to include technological progress as an endogenous process. Representing technological change endogenously, e.g. by letting it depend on up-front investments in non-carbon emitting energy technologies, may help us to find policies that implement substantial emission reduction measures at relatively low costs.

An early attempt to address technological progress in a bottom-up model of carbon accumulations has been undertaken by Anderson and Bird (1992). Whereas their accounting for technological change in a dynamic energy systems model cannot be considered endogenous in the common sense of the word, Anderson and Bird rightly point out the relevance of technical progress and its relation to public and private R&D. The first to really include technological progress endogenously in a bottom-up model of energy systems optimization has been Messner (1995). Messner uses the model MESSAGE to minimize the discounted costs of supplying energy, subject to a given exogenous level of final energy demand and exogenous assumptions on costs, efficiencies and market penetration constraints. New in her approach (see also Messner, 1997) is the inclusion of learning curves, referring to the phenomenon that costs of employing specific energy technologies decrease as commercial investments and installed capacities accumulate. Wright (1936), in his seminal paper on the airplane industry, was the first to publish on the observation that experience improves performance in production processes. He analyzed the relationship between cost and quantity when factory processes are subject to learning. Subsequently, Arrow (1962) generalized the formulation of the experience effect, and pioneered the economics of what became known as 'learning-by-doing'. Recently, in the field of energy and global warming economics, others have followed the example of Messner to incorporate learning-by-doing effects that reflect experience phenomena, amongst whom Barreto and Kypreos (1999) and Seebregts et al. (2000). Energy modelers seem to agree that, unsurprisingly, with the inclusion of endogenous technological progress via learning curves, a more favorable development of innovative non-carbon energy technologies is obtained (see, for example, Kram et al., 2000). Grübler and Messner (1998) extend Messner's earlier approach by analyzing the optimality of carbon emission abatement. They suggest that the endogenous treatment of technological progress implies (somewhat) stronger emission reductions in the near term.

In top-down models, attempts to implement endogenous technological change have been more recent, and their focus has been rather on investments in R&D, as opposed to learning by accumulation of experience. Nordhaus (1999) incorporates what he entitles 'induced innovation' in a new version of DICE: R&DICE. In DICE, capital and labor can substitute for carbon energy. In R&DICE, emissions are controlled, in addition to this substitution effect, by some form of 'induced technological change'. However, energy conservation -and not emission reduction- still is the driving force for research activity.[1] The main extension of the DICE model to R&DICE, realized through the inclusion of an R&D variable, is that it allows for the choice between *immediate* substitution of capital and labor for energy and *delayed* substitution through technological change. There is no channel, such as the development of a carbon-free energy source, through which research can exclusively be used to reduce carbon emissions, independently of modifications in the evolution of total energy consumption. This set-up of R&DICE may explain why Nordhaus finds that endogenous technological change is a factor that influences climate change policy much less than direct substitution of energy by capital and labor. Goulder and Schneider (1999) investigate the impact on climate and economy of including induced technological progress in the form of expanded R&D efforts. Their main finding is that increased climate R&D efforts might 'crowd out' R&D in non-energy sectors and carbon-based energy sectors; the overall effect might therefore be a slowdown in output and GWP. Goulder and Mathai (1998) incorporate induced technological progress both via R&D expenditures and by a form of learning-by-doing. They find that if knowledge is gained through R&D, carbon abatement can be postponed to the future, but if knowledge is gained through learning-by-doing, the cost-effective choice could be to (slightly) advance the timing of carbon emission abatement. For a (non-exhaustive) review of the recent work on endogenous technological change and global warming, among which Nordhaus (1999), Goulder and Schneider (1999) and Goulder and Mathai (1998), as well as Jorgenson and Wilcoxen (1993) and, to a lesser extent, some other references in the area, see Weyant and Olavson (1999).

Both bottom-up and top-down energy modeling with endogenous technological change, although fundamentally different, have merits. In this paper, we follow Gerlagh *et al*. (2000) and van der Zwaan et al. (2002), who designed a macroeconomic (top-down) model including learning curves for energy technologies that were previously used in energy systems (bottom-up) models. This model, called DEMETER[2], possesses three important characteristics. First, two different energy technologies -carbon and carbon-free- are explicitly distinguished as primary factors in the production function. This feature makes that our approach is significantly different from the R&DICE model (Nordhaus, 1999) and that of Goulder and Mathai (1998). Carbon emissions are supposed to relate directly to the use of fossil fuels, rather than assuming that emissions are proportional to overall production. A transition to the carbon-free technology offers one opportunity for carbon emission reduction. The costs associated with the use of the non-carbon energy resource decrease over time, as it has a relatively large learning potential. Since DEMETER allows for analyzing the feasibility of realizing a transition from a carbon-based to a carbon-free technology, our model is comparable to the model designed by Goulder and Schneider (1999). As will be pointed out, there are also a number of significant differences, one of which is the fact that in DEMETER a substantially higher elasticity of substitution is assumed between the two energy technologies. Second, the model includes energy demand as an endogenous rather than an exogenous variable. This feature extends the model as compared to the bottom-up models by Messner (1997), Grübler and Messner (1998), and Barreto and Kypreos (1999). It enables us to explicitly examine the different effects of mitigation measures and endogenous technological progress on energy demand, as well as their interaction with the dynamics of different energy technologies. Third, the model assumes a positive demand for the non-carbon energy source, despite its substantially higher costs. One can think of niche markets that provide the opportunity for new energy technologies to gain rather easily a modest share of the energy market, irrespective of their elevated prices. This feature is new compared to many bottom-up models, where often a positive demand for new expensive energy sources can only result from imposed lower bounds to the capacity of these new technologies.

[1] This becomes clear from the discussion of the results of R&DICE, in which Nordhaus (1999) presents a back-of-the-envelope calculation that supports the argument that research is not of much help for the abatement of carbon emissions.

[2] The DE-carbonisation Model with Endogenous Technologies for Emission Reductions.

This paper addresses the impact of stringent temperature targets on gross world product, aggregate consumption and energy use, under the assumption of endogenous technological change. We attempt to provide policy makers with information along the lines of the recommendations brought forward by the 1999 Workshop on Experience Curves for Policy Making of the International Energy Agency (IEA). There, it was recommended "that experience curves are used to analyze costs and benefits of programs to promote environment friendly technologies…" (IEA/OECD, 2000). We use the same model as in van der Zwaan et al. (2002), but we use different scenarios[3], while attempting to answer three new specific questions. First, what happens under the assumed scenarios to gross world product (GWP), that is, will GWP decrease as much as in other energy models under a tight temperature constraint, or will learning effects provide channels through which emission reductions are possible without slowing down gross output? Second, what is, under the same conditions, the effect on welfare and consumer demand for the final (homogeneous) generic consumption good? Third, what is the effect on the consumption of energy?

Whereas the model has been described both in van der Zwaan et al. (2002) and, more extensively, in Gerlagh et al. (2000), its theoretical form is briefly recapitulated in Section 2. Section 3 reviews the most important calibration parameters and describes the four scenarios that allow analyzing different simulation methods in relation to business-as-usual. Section 4 analyzes and compares the various results of the different scenarios, and discusses our findings. In Section 5, our main conclusions are drawn.

[3] A difference occurs first in that we have calibrated DEMETER to new input data. As a result of this, numerical results presented here may show differences relative to the findings reported in van der Zwaan *et al*. (2002). More importantly, we now employ a market failure in all our scenarios, and adopt the same long-term energy costs for the fossil and non-fossil technologies (that both learn). Still, the induced differences do not affect the dynamics of the energy system and do not alter our previous conclusions reported in van der Zwaan *et al*. (2002).

2. MODEL DESCRIPTION

DEMETER is a computable general equilibrium (CGE) model for the integrated assessment of global warming with some characteristics of the models that are developed in the endogenous growth literature (see, for example, the seminal paper of Romer, 1990). The model is presented first in its basic form without endogenous technological change, then in its complete form including learning-by-doing. For an elaborate description of the model, we refer to Gerlagh et al. (2000).

2.1 DEMETER without learning-by-doing

One representative firm produces all final consumer goods, investment goods, and intermediate goods used for the maintenance of energy plants. This assumption allows us to use one aggregate production function, like in most macroeconomic models of climate change. In DEMETER, it is expressed by a nested CES function:

$$Q(t) = [\, A(t)\,(K_C(t)^{\alpha}\, L(t)^{1-\alpha}\,)^{\gamma} + B(t)\,((F(t)^{\chi} + N(t)^{\chi}\,)^{1/\chi}\,)^{\gamma}\,]^{1/\gamma}, \tag{1}$$

in which $Q(t)$ is the aggregate production or gross output of the final good, $A(t)$ is the level of technological progress for the capital/labor composite, $K_C(t)$ is the capital stock required for the production of the consumer good, $L(t)$ is labor input, $B(t)$ is the specific level of energy technological progress or energy technology stock, $F(t)$ is the fossil energy input, and $N(t)$ is the non-fossil energy input, all dependent on time t.[4] The parameters α, χ and γ are time-independent: α expresses the value share of capital in the Cobb-Douglas capital/labor composite, χ represents the elasticity of substitution between fossil and non-fossil energy use, and γ represents the elasticity of substitution between the capital/labor composite, on the one hand, and the fossil/non-fossil energy composite, on the other hand.[5]

The explicit use of different (energy) technologies for the production of final goods and the use of CES aggregations (notably for F and N) are common features of general equilibrium modelling, and it is shared with other macro-economic models such as CETA (Peck and Teisberg, 1992), MERGE (Manne et al., 1995; Manne and Richels, 1997), and the model by Goulder and Schneider (1999).[6] Our choice for the elasticity parameter between zero and unity, $0<\chi<1$, in equation, (1) marks, however, an important deviation from these three models. CETA and MERGE assume perfect substitution, that is, they aggregate linearly, so that $\chi=1$, in line with bottom-up models such as MESSAGE (Messner, 1995). The model by Goulder and Schneider assumes that there is a significant level of complementarity between different energy options, rather than these alternatives being perfect substitutes, that is, they assume $\chi<0$.[7] DEMETER avoids these perfect substitution and complementarity assumptions, via the use of positive elasticities of substitution between the fossil and non-fossil energy alternatives, that is, by supposing

[4] The model employs discrete time steps of five years each.

[5] The elasticity of substitution parameter χ is related to the elasticity of substitution ε between F and N by the relation $\varepsilon = 1/(1-\chi)$. Similarly, the elasticity of substitution parameter γ is related to the elasticity of substitution σ between the K-L composite and the F-N composite by the relation $\sigma = 1/(1-\gamma)$. Under the assumption that the FN composite expenditures constitute a small share of total expenditures, σ can be considered as equalling approximately the (negative) demand elasticity for energy, i.e. the elasticity of energy consumption to energy prices.

[6] Note that these models have a more complex production structure, as compared to DEMETER. For example, CETA and MERGE distinguish between electric and non-electric energy, before further dis-aggregation into a variety of energy production technologies. The model by Goulder and Schneider, in addition to having a more extensive production function, is different notably since it includes an accumulated stock of knowledge through R&D, instead of employing learning curves as used in DEMETER.

[7] Goulder and Schneider assume an elasticity of substitution between energy options of 0.90, equivalent to $\chi = -0.11$.

$0<\chi<1$. The elasticities as introduced in DEMETER ensure that it is always efficient to use at least a certain minimum amount of a given fuel, irrespective of its potentially high price (at present, this holds for non-fossil energy). Technically, we assume that $F(t)$ and $N(t)$ are good substitutes by employing an elasticity of substitution equal to 3, that is $\chi=2/3$. In the first modelling periods, when total energy production costs of $N(t)$ exceed the production costs of $F(t)$ by almost a factor of three, the CES aggregation ensures that there is a small -but still positive- demand for $N(t)$.

Both the assumptions of perfect substitutability ($\chi=1$, following models such as CETA and MESSAGE) and poor substitutability ($\chi<0$, following the model of Goulder and Schneider, 1999) lead to substantially higher calculated costs of policies that aim at substituting non-fossil energy sources for current fossil-fuel based energy systems, than when parameter values of $0<\chi<1$ are taken. The following numerical example makes this apparent. Consider the case in which one unit of energy is produced. The fossil-fuel energy technology produces energy at unit production costs, while the corresponding costs with the non-fossil energy technology reach three times that level. Furthermore, assume that the non-fossil fuels have some initial, relatively low, share in the output of energy production, say 10%, and that this share has to be increased to 50% to meet a given carbon reduction target. We will calculate the increase in energy costs per unit of efficient energy output, comparing three elasticity levels: $\chi=0$, $\chi=½$, and $\chi=1$. Assuming a Cobb-Douglas aggregation of F and N, that is $\chi=0$, it follows from the initial prices that the fossil-fuel energy source has a share parameter in total energy output of 0.75, whereas the non-fossil-fuel energy source has a share parameter of 0.25.[8] The substitution of the non-fossil energy source for 40 per cent point of the fossil energy source decreases the efficient output of energy by 3.8%,[9] while costs increase with 67%.[10] Thus, energy costs per unit of efficient energy output increase by 73%. Assuming good but imperfect substitution, $\chi=½$, is consistent with identical weight parameters in the CES aggregation for F and N,[11] and the substitution of non-fossil-fuel energy for 40 per cent point of fossil-fuel energy increases output by 25%.[12] Given that costs increase by 67%, energy costs per unit of output increase by 33.3%. Under perfect substitutability, $\chi=1$, output does not change after substitution, and the costs of energy production increase with 67%. The costs per efficient energy output thus increase by 67% as well. To summarise, assuming a Cobb-Douglas type of substitution (rather poor substitutability), energy costs are raised by 73%, assuming perfect substitutability, energy costs are raised by 67%, and assuming good but imperfect substitutability, energy costs are raised by 33%. Our assumption in DEMETER of good but imperfect substitution thus potentially involves the least possible cost increase of a policy that aims at a substitution of non-fossil fuel energy sources for fossil-fuel energy sources to a level of 50% of non-fossil energy to total energy supply.

Both the general and energy-specific technology stocks are assumed to increase exogenously. Increases of $A(t)$ represent economic growth that is neutral in the use of production factors, whereas the growth of $B(t)$ is chosen such as to reproduce an exogenous path for the AEEI. The labor force, proportional to population and to labor productivity, is assumed to grow according to an exogenous time-dependent growth rate, $g_L(t)$. The production of fossil-fuel energy, $F(t)$, requires a capital stock, $K_F(t)$, as well as maintenance and operation (M&O) efforts, expressed by $M_F(t)$. The required expenses in M&O are assumed to include those for fuel acquisition. We use the expression:

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[8] Under a Cobb-Douglas production function, the share parameters are proportional to expenditures on inputs (prices multiplied by input volumes). Since the expenditure ratio between F and N is (1x0.9):(3x0.1), the share parameter ratio is 3:1, resulting in the share parameters as quoted.

[9] Calculating the Cobb-Douglas output level, and comparing the new allocation with the old allocation, we find $(5^{0.}75\text{x}.5^{0.25})/(0.9^{0.75}\text{x}0.1^{0.25})=0.962$, corresponding to a 3.8% energy output decrease.

[10] Multiplying prices by output levels, and comparing the new allocation with the old allocation, we find (1x0.5+3x0.5)/(1x0.9+3x0.1)=1.67, corresponding to a 67% increase of costs.

[11] For $\chi=½$, the elasticity of substitution between F and N is equal to $\sigma=2$. With equal weight parameters, the ratio of energy volumes must be equal to the inverse ratio of prices, to the power σ. Indeed, $(0.9:0.1)=(3:1)^2$.

[12] Calculating the CES output level, and comparing the new allocation with the old allocation, we find $(0.5^{0.5}+0.5^{0.5})^2/(0.9^{0.5}+0.1^{0.5})^2=1.25$.

$F(t) = \min\{ a_F(t)K_F(t) , b_F(t)M_F(t) \}$, (2)

in which a_F expresses the capital productivity for the fossil-fuel technology and b_F the corresponding productivity of required M&O efforts. In a similar way, the model provides for non-fossil energy, $N(t)$, production (with corresponding variables $K_N(t)$, $M_N(t)$, $a_N(t)$ and $b_N(t)$).

The capital stocks, $K_C(t)$, $K_F(t)$ and $K_N(t)$, are assumed to depreciate at a fixed rate δ. Periodical gross investments are made in these capital stocks, denoted by $I_C(t)$, $I_F(t)$ and $I_N(t)$. Gross output of the final good, $Q(t)$, is used for consumption, $C(t)$, investments in non-energy capital, $I_C(t)$, investments in both fossil and non-fossil energy capacity, $I_F(t)$ and $I_N(t)$, and maintenance costs for both energy production alternatives, $M_F(t)$ and $M_N(t)$:

$$Q(t) = C(t) + I_C(t) + I_F(t) + I_N(t) + M_F(t) + M_N(t) . \tag{3}$$

Carbon emissions, expressed as a function of time by $E(t)$, are proportional to the use of fossil-fuel-based energy, $F(t)$, via the aggregate carbon emission factor $\varepsilon(t)$:

$$E(t) = \varepsilon(t) F(t) . \tag{4}$$

The factor $\varepsilon(t)$ is assumed to be time-dependent, to be able to account for a gradual de-carbonization process. Fossil fuel consumption has been subject to such a process since the early times of industrialisation, 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. Carbon emissions are linked to the atmospheric carbon dioxide concentration, which in turn determines the global average surface temperature. The carbon cycle dynamics assumed in DEMETER 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':

$$Atm(t+1) = (1-\delta^M) Atm(t) + \varphi(E(t) + \overline{E}(t)) , \tag{5}$$

$$Temp(t+1) = (1-\delta^T) Temp(t) + \delta^T \overline{T}\ ^2 \ln(Atm(t) / Atm(0)) , \tag{6}$$

in which δ^M is the atmospheric CO_2 depreciation rate, φ is the retention rate, $\overline{E}(t)$ are emissions not linked to energy production, δ^T is 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.

Similar to other welfare maximising integrated assessment models, the inclusion of a temperature constraint in the model results in a positive shadow price for carbon emissions. This shadow price can be interpreted as the tax required on carbon emissions to meet the temperature constraint.

If technological change is exogenous to the model, that is, if $A(t)$, $B(t)$, $a_F(t)$, $b_F(t)$, $a_N(t)$, and $b_N(t)$ are treated as (time-dependent) parameters rather than as variables, then the competitive equilibrium results in a social welfare optimum. The welfare optimisation program that is used to calculate the competitive equilibrium maximises the total discounted sum of utility derived from consumption:

$$Max \sum_{t=1}^{\infty} (1+\rho)^{-t} Pop(t) \ln(C(t) / Pop(t)) , \tag{7}$$

subject to a set of equations, the essential ones of which are given above. In equation, (7), $Pop(t)$ denotes population and ρ stands for a pure discount rate of 3.5% per year.[13] The model is solved for 40 periods corresponding to the interval 2000-2200. Results are presented for the time interval 2000-2100.

2.2 DEMETER with learning-by-doing

Yet, the purpose of our analysis is to study the effects of endogenous technological change on the costs of CO_2 reduction targets, that is, we want to link, dynamically, energy supply and demand for the two energy sources to the development of the productivity variables $a_F(t)$, $b_F(t)$, $a_N(t)$, and $b_N(t)$. To simulate energy production costs that decrease as experience accumulates, the model distinguishes 'vintages'. The most recent vintage is designated with a tilde. For example, part of the current fossil-fuel energy production, $F(t)$, uses the vintages built up previously (that is, up to period t–1), while the remaining part of production, $\widetilde{F}(t)$, uses the most recent vintage, based on the latest production technologies:

$$F(t) = (1-\delta)\, F(t-1) + \widetilde{F}(t), \tag{8}$$

where (1–δ) is the depreciation factor of the vintage that was new in the previous period. For each separate vintage, the production functions and identities, (1)-(4) apply.

Both energy sources are treated symmetrically, in that the same learning curves and same learning rates are used. To describe the learning curve for both energy resources, experience variables $X_F(t)$ and $X_N(t)$ are introduced. In every period, the new energy capacities installed, $\widetilde{F}(t)$ and $\widetilde{N}(t)$, add to these cumulative experience variables:

$$X_F(t+1) = X_F(t) + \widetilde{F}(t). \tag{9}$$

The same equation applies for the non-fossil-fuel technology.

Learning-by-doing is incorporated in the model by a scaling function g(X) depending on the cumulative experience X. This scaling function expresses that with little cumulative experience, energy-specific investment and M&O efforts have lower productivity levels compared to the situation where a high level of experience has been accumulated. We determine the learning-by-doing parameters for any period t, $a_F(t)$, $b_F(t)$, $a_N(t)$, and $b_N(t)$, by dividing constant values for the productivity parameters, $\overline{a}_F, \overline{b}_F, \overline{a}_N, \overline{b}_N$, by the average value of the scaling function $g_j(.)$ (with j being either F or N) over period t:

$$a_F(t) = \overline{a}_F\,(X_F(t+1) - X_F(t)) \Big/ \int_{X_F(t)}^{X_F(t+1)} g_F(x)\,\mathrm{d}x\,, \tag{10}$$

$$b_F(t) = \overline{b}_F\,(X_F(t+1) - X_F(t)) \Big/ \int_{X_F(t)}^{X_F(t+1)} g_F(x)\,\mathrm{d}x\,. \tag{11}$$

Again, the same equations apply for the non-fossil-fuel technology.

[13] This corresponds to a real interest rate of 5% per year, given an average per capita consumption growth of 1.5% per year.

The usual functional form for g(.) assumes a constant learning rate (*lr*), which is the rate at which production costs decline for each doubling of cumulative experience. This is expressed by:

$$g(x) = g_0 x^{\alpha-1}, \tag{12}$$

where $0<\alpha<1$ and $g_0>0$ are parameters that specify the learning features. The value of the exponent $\alpha-1$ is the basis of the process of learning-by-doing and defines the speed of learning for the technology considered (which in our simulation is taken equal for the two technologies). The learning rate is given by

$$lr = 1 - 2^{\alpha-1}. \tag{13}$$

Equation (12) represents the standard formalization of a learning curve, and implies ever-decreasing production costs, $g(x)\to 0$, so that $a_F(t)\to\infty$, $b_F(t)\to\infty$, $a_N(t)\to\infty$, and $b_N(t)\to\infty$, for $t\to\infty$, if experience continually accumulates. But since energy production uses no labor as production factor, but only the final good as input for investments and maintenance, the above functional form implies that (labor) productivity in the energy technologies increases at a speed faster than in the sector that produces the final good (where no learning is available), and continues to do so for the indefinite future. This we consider unrealistic. In DEMETER, we therefore slightly adjust this functional form and assume that, in the long run, the productivity growth for the energy technologies is approximately equal to the productivity growth in the final goods sector. That is, we assume that the productivity parameters $a_F(t)$, $b_F(t)$, $a_N(t)$, and $b_N(t)$ converge to the constant levels $\overline{a}_F, \overline{b}_F, \overline{a}_N, \overline{b}_N$. Technically, this assumption implies a floor to the production costs and $g(.)\to 1$ for large values of the argument x:

$$g(x) = g_o x^{\alpha-1} + 1. \tag{14}$$

Having now described technological change in relation to cumulative experience, we should be aware of the implications endogenous technologies may have for market failures in a competitive equilibrium. Since in the competitive equilibrium no positive spill-over effects of investments (in fossil or non-fossil energy technologies) are taken into account, investments will not reach their dynamically efficient level, from the social point of view. The competitive equilibrium underlying all scenarios presented in this paper possesses this market failure. It is for this reason that these scenarios do not represent real welfare optima.[14]

[14] We use a complete description of the first order conditions of the competitive equilibrium for its calculation.

3. CALIBRATION AND SCENARIOS

3.1 Calibration

In order to render DEMETER's simulations as realistic as possible, in particular its reproduction of a likely business-as-usual scenario, the evolution of the variables that are exogenous to the model has been carefully chosen, and its various parameters, as well as the start values of the endogenous variables, carefully calibrated. The world population is assumed to increase by 1.0 % per year today and to stabilize in 2100, so that an approximate stable population is reached of somewhat over 11 billion by the end of the century (as in World Bank, 1999, and Nakicenovic et al., 1998). Gross World Product (GWP) in 1997 is assumed to have amounted 25.1 trillion US$1990 (World Bank, 1999) and its current and future annual per capita growth rate 1.5 % in the business-as-usual scenario. Final commercial energy consumption in 1997 is estimated to have been some 265 EJ per year.[15] We assume that the share of fossil fuel technologies in this total energy consumption level is initially 96 %, the remaining 4 % coming from non-fossil renewable energy.[16] The initial average price of final energy from fossil fuels is assumed to be 2.5 $/GJ (IEA/OECD, 1999, p.41)[17], and that from our stylized non-fossil technology 7.2 $/GJ.[18] The price ratio between the fossil and non-fossil technology of 2.9, and the assumed elasticity of substitution between fossil and non-fossil energy of 3, indeed provide the non-fossil energy share of 4 %. Energy production accounts for about 2.7 % of GWP.

The AEEI in our business-as-usual scenario is about 1.0 % per year (see the IIASA-WEC scenarios in Nakicenovic et al., 1998). From our combined assumptions on population growth, GWP growth and the value of the AEEI follows that the energy consumption growth rate is about 1.5 % per year initially and decreases to about 0.5 % per year in 2100. In 1997, energy-related carbon emissions are assumed to be some 6.3 GtC/yr and carbon emissions related to land-use changes and industrial processes are around 1.3 GtC. In the remainder of this article, the latter is assumed constant over time. It follows that the carbon emission intensity of the fossil technology is 0.0248 gC/MJ in 1997. The fossil technology is supposed to be subject to ‘decarbonization’. The decarbonization of fossil fuels is assumed to be 0.2 % per year initially. This rate decreases to 0 % by 2100, so that then a floor carbon emission intensity level is reached of 0.020 gC/MJ. Our business-as-usual scenario incorporates learning-by-doing for both technologies. As a result, and given non-fossil’s elevated current prices, non-fossil energy prices decrease relatively rapidly. Hence, as a result of the CES aggregation of fossil and non-fossil energy, their relative shares change, such that non-fossil's energy share evolves from 4 % in 1997 to 12 % in 2100. The corresponding fossil to non-fossil energy substitution occurs at a rate of about 0.5 % per year initially, increasing to 1.3 % per year in 2020, and thereafter slowing down to a rate of some 0.8 % per year by the end of the century. The energy consumption growth rate, the decarbonization rate and energy substitution rate combined make that carbon emissions increase by about 1.5 % per year initially, and some 0.3 % per year by the end of the century. From this follows that total (i.e. energy and non-energy origins combined) busi-

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[15] This figure excludes the shares of nuclear energy and hydropower that are omitted in DEMETER.

[16] These values correspond only roughly to actual fossil and renewable energy shares, partly because DEMETER abstracts from any further energy diversification (among which a specification of nuclear energy and hydropower).

[17] Prices for final energy derived from natural gas technologies vary in a range from 2 to 3 $(1990)/GJ (IEA/OECD, 1999, p.41). Since coal, oil and natural gas are, more or less, competitive, a good reference price in our calculations for the average fossil-fuel energy resource is 2.5 $/GJ.

[18] 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 5-20 $/GJ. Whereas electricity production costs for photo-voltaic systems are still significantly higher than that for wind energy, costs of electricity derived from biomass are comparable to that of wind energy (IEA/OECD, 2000, p.19).

ness-as-usual carbon emissions in 2100 amount to some 15 GtC/yr. The corresponding business-as-usual carbon emission path, as simulated in DEMETER, is depicted in Figure 4.1.

Fossil-fuel and non-fossil-fuel energy production technologies are treated symmetrically, that is, they are assumed to have in principle the same learning potential. In both energy sectors, production costs continue to decrease as a result of learning-by-doing, in both cases reaching a floor of 1.25 $/GJ in the long run. The learning rate for both the fossil and non-fossil energy resources is assumed to be 20 % per doubling of cumulative experience.[19] Since fossil fuels have currently a large share in energy production, the technology has gained already from substantial past experience, reflected in the relatively low production costs of 2.5 $/GJ. But the extent to which past experience has been obtained leaves reduced scope for many doublings of cumulative experience in the 21st century. In our model, with endogenous learning, fossil energy production costs appear to decrease by about 20% to 2.0 $/GJ in 2100. On the other hand, non-fossil fuels presently occupy a minor share in energy production only, as a result of (and resulting in) limited past experience, implying the currently relatively high production costs of 7.2 $/GJ. Thus, unlike the fossil case, there is scope for many doublings of cumulative non-fossil experience in the 21st century. The production costs for the non-fossil-fuel technology show in our model a sharp decrease of about 50% to 3.9 $/MJ in 2100.

The energy production costs are assumed to be distributed over capital (investment) and M&O+fuel costs in the stylized -but realistic- ratio of 20:80 for the fossil and 80:20 for the non-fossil energy technology (van der Zwaan et al., 2002). It follows from our assumptions that investment costs for non-fossil energy are currently about 10 times those for fossil energy, and that this reduces to about a factor of 4 in the long run. The long-term elasticity of energy consumption to energy prices σ is assumed to be 0.4, as is commonly done in similar macro-economic models (e.g. Manne et al., 1995).

3.2 Scenarios

In the business-as-usual scenario (from here on, BAU), we assume that the economy does not internalize climate change. Cumulative emissions related to energy and non-energy origins combined, from 2000 to 2100, amount to about 1200 GtC. In this BAU scenario, the atmospheric CO_2 content in 2100 is approximately 600 ppmv, more than a doubling of the pre-industrial value of 280 ppmv, compared to about 365 ppmv in 2000. The corresponding temperature increase in 2100 is about 2.3 °C, relative to pre-industrial times, corresponding to about 1.7 °C increase relative to 2000. Moreover, we assume that in the competitive equilibrium the returns from learning are not captured, and, therefore, there is a market failure.

The BAU benchmark scenario is compared with scenarios in which a constraint is set on the average global surface temperature increase. This atmospheric temperature increase, with respect to the pre-industrial level, is (by us) not allowed to exceed a level of 2 °C. Four methodologically different cases are investigated, each based on this same temperature constraint. The BAU scenario is labeled S0, where convenient, and the four analyzed scenario variants, characterized by having the temperature constraint imposed, are labeled S1, S2, S3 and S4. Table 3.1 summarises the main characteristics of these scenarios. The scenarios reflect the different methods employed in the literature as to the modeling of energy demand and technological progress. Energy demand can be modeled as an endogenous variable, or as an exogenous parameter. Future decreasing energy production costs can be accounted for endogenously, e.g. via learning-by-doing, or they can be assumed to follow an exogenous path. We emphasize that the scenarios S1-S4 are

[19] For a justification of this value, see for example McDonald and Schrattenholzer (2001), who present a range of 8 to 30% for a large set of energy technologies at large.

designed in such a way that the scenario outputs only differ from BAU as a result of the imposed temperature constraint and the levying of emission taxes.[20]

Table 3.1 *Typology of scenarios*

Scenario	Temperature Constraint	Endogenous Technologies	Endogenous Energy Demand
S0 (BAU)	No	Yes	Yes
S1 (EXT-FXE)	2 °C	No	No
S2 (EXT-FLE)	2 °C	No	Yes
S3 (LBD-FXE)	2 °C	Yes	No
S4 (LBD-FLE)	2 °C	Yes	Yes

Scenario S1 supposes a fixed energy demand (abbreviated to FXE), that is, energy demand follows the same path as in the BAU scenario.[21] Learning for the energy technologies is assumed to be exogenous and energy production costs follow exactly the same path as in the BAU scenario (abbreviated to EXT for 'exogenous technology'). Because of the rigid exogenous energy demand, the scenario resembles more a cost minimizing than a welfare maximizing program.

Scenario S2 incorporates a flexible energy demand (abbreviated to FLE) through the full exploitation of the macroeconomic part of DEMETER. Thus, the model allows for a decrease in energy demand when energy prices increase. Technological progress is exogenous and leads to decreasing energy production costs along the same path as in the BAU scenario and in S1.

Scenario S3 employs a fixed (BAU) energy demand. It includes, however, more pronounced learning-by-doing (abbreviated to LBD), since this scenario takes full account of the experience gained through augmented investments in the fossil and non-fossil technologies. This scenario allows especially prices for the non-fossil energy to decrease faster than in the scenarios with exogenous technological change. Thus, emission reduction costs can reach lower values in S3 than under S1.

Scenario S4 combines the flexible energy demand, as in S2, with an endogenous price decrease through enhanced learning-by-doing, as in S3. Thus, scenario S4 fully employs the various characteristics of DEMETER. [1]

[20] Stated in more precise modelling terms, all parameters for the scenarios S1-S4 are chosen such that the scenarios exactly replicate the same BAU scenario in case no temperature constraint is set and no carbon taxes are implemented. In other words, energy production costs decrease over time in all scenarios. They decrease with the same speed in the BAU, S1, and S2 scenarios. The other two scenarios, S3 and S4, have different paths for the energy production costs only if the energy demand for the two energy technologies follows a different path as well

[21] Since gross world output appears to vary within narrow bounds between the various scenarios, this assumption is almost identical to assuming a zero elasticity of substitution between the K-L composite and the F-N composite.

4. RESULTS

Below, we discuss our major findings. We first present the main implications of using our different modeling assumptions on energy savings and investment behavior. We report on the achievable levels of carbon emission abatement, as well as on the levels of energy reduction and investments in the non-fossil energy technology, required to reach these levels of abatement, all as a function of time.[22] We then present our main results regarding the costs of limiting the temperature increase to two degrees Celsius, by reporting on the calculated production costs for the non-fossil technology, overall consumption levels and gross world product, again as a function of time.

4.1 Emission abatement, energy reduction and non-fossil investments

Figure 1 shows the evolution of carbon emissions, expressed in gigaton carbon per year (GtC/yr). In the four temperature-constrained scenarios, emissions reach values lower than 8 GtC/yr around the middle of the century and values below 2 GtC/yr by the end of the century. The figure demonstrates that including technology as an endogenous process leads to an earlier abatement of carbon emissions (compare S3 with S1 and S4 with S2). Furthermore, by including both technological progress and energy demand in an endogenized fashion (S4), it appears that earlier reductions in emissions can be reached than suggested by previous research. Our results demonstrate that it might be cost-effective to keep global CO_2 emissions at levels below 9 GtC/yr during the first half of the 21st century. Emissions would, of course, still need to decrease significantly below that level during the second half of this century.

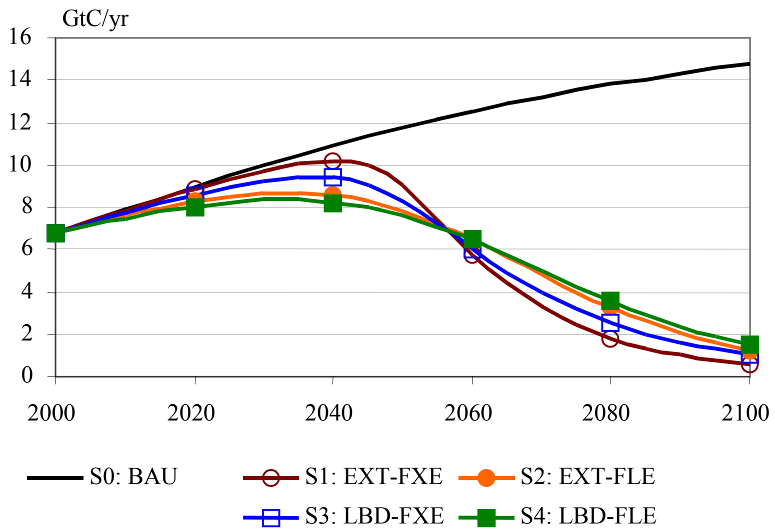

Figure 4.1 *Total Carbon Emissions (in GtC/yr)*

The next two figures portray the underlying mechanism for emission reductions, which differs considerably among the scenarios. Two options are available for realizing the carbon emission mitigation depicted in Figure 1. First, it is possible to reduce energy consumption by the substitution of capital and labor for energy. This direction of action is followed in S2 and S4: see Figure 4.2. Note that, as stated in Table 3.1, in S1 and S3 this option is not available. Yet, en-

[22] Note that in van der Zwaan (2002) we have also reported on carbon emissions abatement and energy reduction achievements. In that article, however, the scenarios employed were different from the ones presented here (in that, e.g., in that paper not all scenarios simulated a market failure, and the long-term floor prices for fossil and non-fossil energy were assumed to be unequal).

ergy is a necessary input for production, and it is assumed to have a long-term demand-price elasticity of 'only' 0.4, so that this option is rather limited in its use. Under S2, energy use is cut by 5 % in 2020, and by 20 % around 2050. Scenario S4 presents similar figures. Yet, after around 2070 (when the lowest energy demand is reached, compared to BAU), energy savings become less important in both S2 and S4, the origin of which is that, as a result of increased learning, the price of the non-fossil 'backstop' technology has substantially decreased. It becomes then more attractive to switch between the energy technologies, than to reduce total energy consumption.

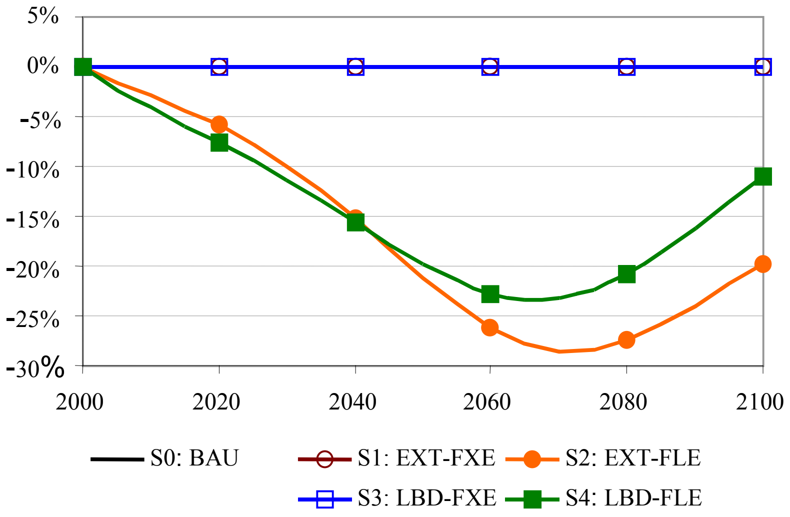

Figure 4.2 *Total Energy Consumption (as the difference relative to BAU)*

Indeed, the economy has a second option to reduce emissions: a transition towards the use of non-fossil energy. In the BAU scenario the share of the non-fossil technology increases slowly over the 21st century, and reaches a little over 12 % in 2100. If the allowed temperature increase is constrained, however, shares of at least 90 % are needed by the end of the century. Thus, a radical transition from fossil to non-fossil fuels needs to take place. Figure 4.3 shows the investments in the non-fossil energy capacity, as a percentage of GWP, that are required to set this transformation of the energy system in motion. Under S1, when there is no learning-by-doing and when energy demand is fixed, the transition towards the carbon-free technology is delayed as long as possible in order to postpone the associated costs. Consequently, once instigated, the transition needs a strong impulse. In Figure 4.3, we thus find a sharp increase in investments in the non-fossil technology after about 2030. The pattern resembles a rapid transition of the energy system, comparable with (but smoother than) the typical bang-bang solution found in linear models, that is, a sudden shift from one corner to another corner solution of the energy system optimization.[23]

[23] Note that, whereas in linear models the speed of the transition is usually limited by an assumed upper bound for the penetration rate of new technologies, in our model no such constraint is present. On the contrary, the CES function allows for a smooth energy switch from *F* to *N*, and the particular properties of the CES aggregation of *F* and *N* imply that the otherwise bang-bang solution is avoided.

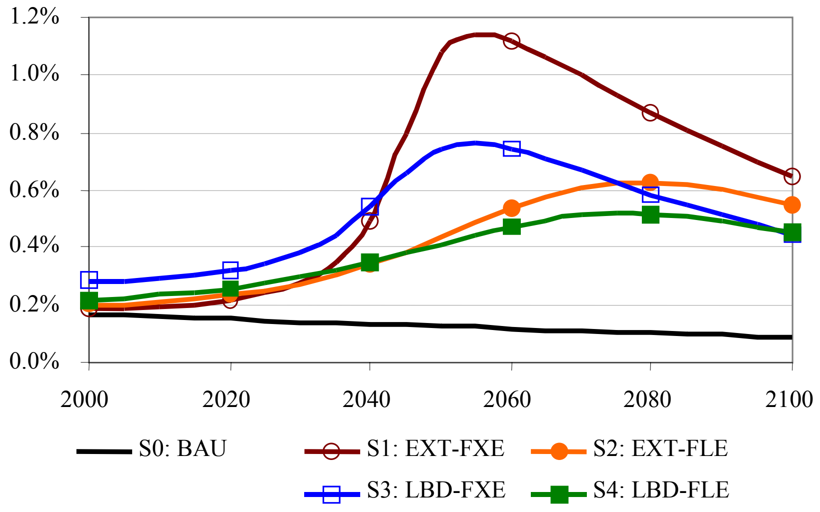

Figure 4.3 *Investments in the non-fossil energy capacity (as a percentage of GWP)*

Figure 4.3 shows that learning-by-doing warrants the advancement of investments in the non-fossil technology (compare S3 with S1 and S4 with S2, over the first decades of the 21st century). These investment advancements smoothen both the emission and investment curves with respect to the case that technological change is modeled exogenously. We also find that allowing for an energy cutback, as an alternative option for achieving emission reduction, levels off the investment curve (compare S2 with S1 and S4 with S2). The explanation is that the presence of this mechanism diminishes the need for a rapid transition towards the carbon-free technology. From Figure 4.3 one concludes that investments in the non-fossil-fuel technology should not be delayed. If we had not assumed that a market failure exists with respect to utilizing learning benefits, even higher levels of immediate additional investments in the non-fossil energy technology would have been appropriate.

Associated, and in addition, to the two options for meeting the desired emission reduction evolutions, a policy measure is available. Taxes can be levied on carbon fuels to reduce their use, a measure sometimes referred to as technology 'push'. The levels of required taxes were extensively reported in van der Zwaan et al. (2002). In the scenarios developed for this article, we find that (for all scenarios) taxes of about 10 $/tC are required in 2000, while the required taxes in 2100 range from 400 $/tC (in S4) to 600 $/tC (in S1).24

4.2 Costs of a stringent global warming policy

Considerable costs are involved in implementing a stringent greenhouse gas policy. The energy reduction option requires augmented inputs of capital and labor, in order to maintain the same level of overall output in the economy, and therefore implies paying a certain price. The energy system transformation option, that is, a transition from fossil towards non-fossil energy technologies, requires substantial investments (as shown in Figure 4.3), and hence also results in making certain expenditures. The environmental desiderata justifying these expenditures are benefits in terms of global warming. There is also an economic payback, however: the increased learning of the non-fossil technology leads to decreasing average energy production costs, and therefore benefits society as a whole. This benefit from a stringent emission reduction policy is presented in Figure 4.4. Under BAU, and under the scenarios with exogenous technological change, production costs for non-fossil energy supply decrease by nearly 50% from 7.2 $/GJ in

[24] Note that DEMETER also allows for providing subsidies on non-carbon fuels (as was done in van der Zwaan et al., 2002), to promote their employment (technology 'pull"). In this paper, we assume that a market failure exists in all scenarios, that is, no subsidies are provided that internalise the positive spill-over from learning-by-doing through investments in new technologies.

2000 to 3.9 $/GJ in 2100. If our model accounts for the fact that increased investments in the non-fossil energy technology enhance the learning effect, as in S3 and S4, production costs show a sharper decrease to about 2.8 $/GJ in 2100, thereby reducing the costs of the greenhouse gas policy.

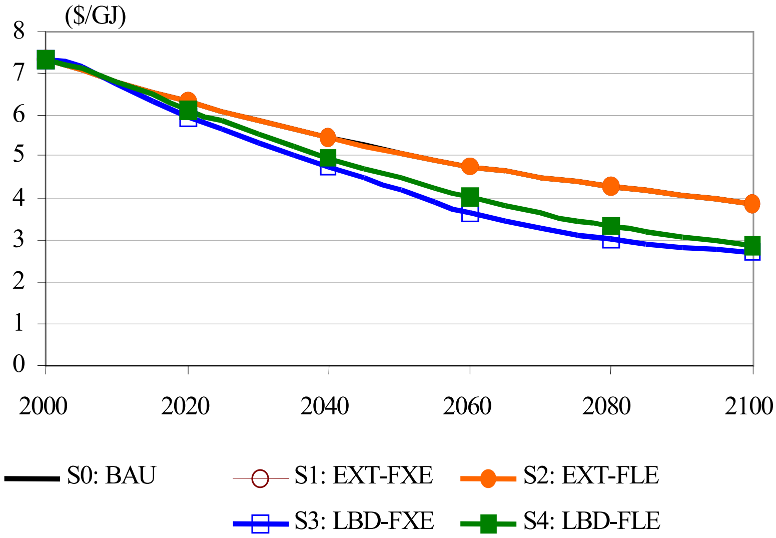

Figure 4.4 *Production costs for non-fossil energy (in $/GJ)*[25]

The results presented above also emerge in the evolution of the consumption of final goods. This evolution is presented in Figure 4.5 as the difference in consumption between a given scenario and the BAU scenario (expressed as a fraction with respect to BAU). If energy demand is fixed and production costs for the carbon-free technology develop according to an exogenous path (as in S1), emission reductions are brought about by a costly transition towards the carbon-free technology. While the transformation of the energy system takes place, the required investments diminish the opportunities available for consumption of the final good. For S1, Figure 4.5 approximately mirrors the investment curve of Figure 4.3, in that consumption is low when non-fossil investments are large. This explains why, in our model, aggregate consumption has an overall decreasing tendency over the entire 21st century with a temporary steep decrease around 2040 (when investments in the carbon-free technology accelerate rapidly). The S1 consumption curve stays below that in BAU, over the whole simulation period, since the required investments remain high, even at the end of the century, with respect to those needed in BAU. Whereas total consumption decreases overall, and even steeply in the first half of the century, S1 GWP evolves quite differently. Investments in new non-fossil energy plants contribute positively to GWP, and thus we encounter an inverse evolution pattern for GWP, as opposed to that of total consumption: see Figure 4.6. Initially, GWP increases rather rapidly for a few of decades. Meanwhile, however, investments in the carbon-free technology replace some of the investments necessary for the production of final goods, so that the economy is slowed down. This explains why the GWP increase curbs, and subsequently GWP decreases, reaching about the BAU level by the end of the 21st century.

[25] BAU, S1 and S2 coincide, and S3 and S4 nearly coincide.

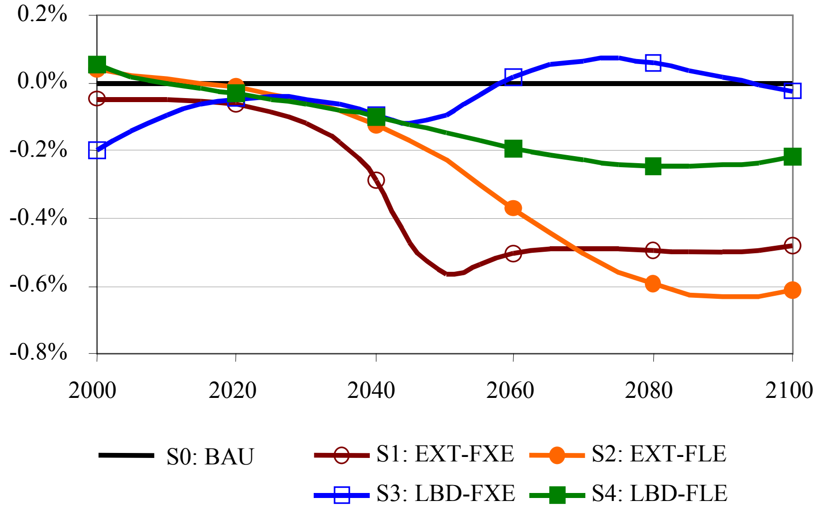

Figure 4.5 *Consumption of Final Good (as the difference with respect to BAU)*

If we allow for energy consumption reduction as a channel for emissions mitigation, like is simulated in S2, flexibility is added to the system. An opportunity is opened for a relative decrease in investments in the non-fossil technology, and thus an increase in the use of the generic consumption good (in comparison to S1). Yet, compared to BAU, energy reduction remains a costly measure, and we find both consumption and GWP levels falling with respect to BAU. In Figure 4.5 and Figure 4.6, the results for S2 more or less present a pattern common to many top-down models that do not focus on transition dynamics.

If we include endogenous technological change, as in S3, investments in the carbon-free technology are brought forward in time. Initially, investments go at the cost of consumption. After about 2060, consumers and society can profit from the experience and cost reduction phenomenon brought about by the early investments in the initially relatively expensive carbon-free technology. Consumption levels then exceed the BAU reference levels. Since investments contribute positively to current GWP and increase future production levels, GWP levels under S3 exceed GWP levels under both BAU and S1 over the entire century (see Figure 4.6).

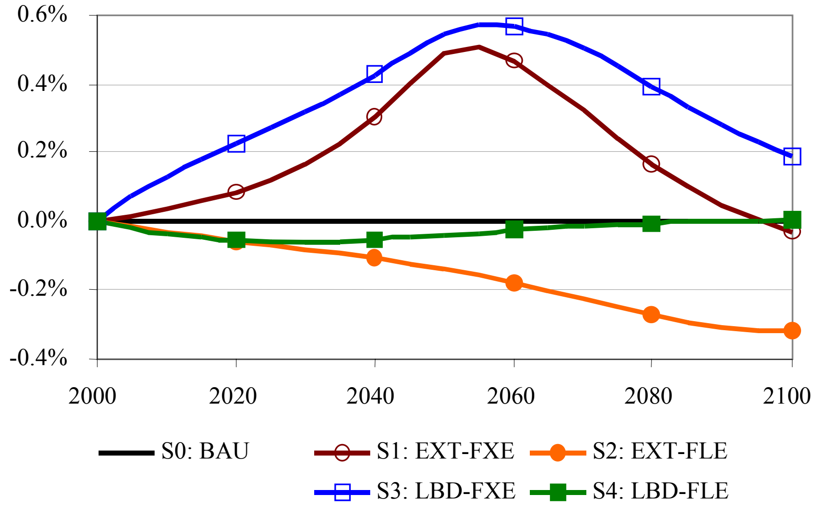

Figure 4.6 *Gross World Product (as the difference with respect to BAU)*

Finally, S4 includes both flexible mechanisms to realize the emission reduction aimed at. Not only production costs decrease endogenously for the carbon-free technology, but also energy use adjusts endogenously to the energy price. During the first few decades, energy savings decrease gross output, but since investments in the fossil-fuel energy are decreased, consumption can maintain approximately its BAU level. Thereafter, investments in the non-fossil fuel technology have to increase, at the cost of consumption. Since investments count positively in gross product, the GWP level recovers to the BAU reference level. Meanwhile, the decrease in consumption levels remains relatively modest. Throughout the 21st century, consumption does not decrease by more than 0.25% compared to the BAU consumption level.

To produce one further aggregate result, we calculate and compare the Net Present Value (NPV) of the future stream of consumption in the 21st century plus the equivalent variation (EV) values (together referred to as NPV+EV) in the different scenarios, relative to the NPV of consumption in the BAU reference scenario and expressed in trillion US$. Table 4.1 presents our findings. The BAU NPV of consumption (EV=0 in BAU) throughout the 21st century is about 30 times the current GWP level. When reducing emissions to constrain the temperature increase, and not accounting for energy savings options or enhanced learning effects, consumption levels decrease, such that a total discounted loss is incurred of 1.69 trillion US$(1990). This loss corresponds to a 0.19% decrease with respect to the NPV of consumption in BAU. Taking energy reduction into account as a mechanism to reach our environmental objective reduces the costs by 0.67 trillion US$(1990). Also taking into account an enhanced learning-by-doing reduces the costs by 1.16 trillion US$(1990), so that total costs amount to only 0.53 trillion US$(1990). From both policy scenario comparisons (compare S3 with S1, and S4 with S2) it can be seen that the enhanced learning is valued in the range of half a trillion to one trillion US$(1990). With both energy conservation and enhanced learning-by-doing, the stringent greenhouse policy costs only 0.06% of the BAU NPV of consumption of the final good. This is a remarkably low level. Most studies report considerably (or even much) higher costs of stringent greenhouse gas policies. Without the endogenization of technological change, these studies typically arrive at costs, in terms of the discounted value of cumulative consumption, at the percentage level (see, for example, Nordhaus, 1994, Chapter 5). We find costs that are one to two orders of magnitude lower, depending on the extent to which energy demand and technological change are accounted for endogenously. Insofar we know, until now, only some econometric models, as opposed to general equilibrium models, have come up with low -or even negative- net costs of stringent environmental policies (see e.g. Carraro and Galeotti, 1997; Dowlatabadi, 1998).

We have carried out a brief sensitivity analysis, in which we found that different assumptions affecting the steepness of the learning curve have the largest effect on our calculated cumulative costs. A variation in the learning rate affects our results on costs mostly since it modifies the potential for the non-fossil energy technology to be deployed at a large scale. For example, when the learning curve is assumed to be steeper than the one we currently employ, the production costs for the non-fossil-fuel energy source decrease faster in all four scenarios S1-S4 (while the relative ordering of the four scenarios S1-S4 is affected to a lesser extent).[26]

Table 4.1 *Net present value of consumption plus money equivalent effects* (*equivalent variation*) *of the temperature constraint.*

	NPV+EV [trillion US$]	Costs [EV in trillion US$]	Percentage
BAU	887.00	0.00	0.00
S1: EXT-FXE	885.31	1.69	0.19
S2: EXT-FLE	885.98	1.02	0.11
S3: LBD-FXE	886.33	0.67	0.08
S4: LBD-FLE	886.47	0.53	0.06

[26] When varying the learning rate from its central value of 20% to values of 10% and 30%, it is found that the cost of meeting the temperature constraint in S4, expressed as a change of 0.06% (see Table 2) with respect to the BAU NPV of consumption, is modified by some 0.2%. A more elaborate sensitivity analysis is currently under progress.

In the literature on endogenous technological change and global warming, the closest to our analysis comes the work by Goulder and Schneider (1999), who also study an economy with one carbon-based and one carbon-free energy sector. Their analysis still differs in quite a number of important details, however. Goulder and Schneider study predominantly R&D as channel through which technological change is endogenized, while we take the learning-by-doing option. They assume complementarity between the different energy sectors, whereas we assume substitutability. They assume constant carbon taxes over time, while DEMETER introduces taxes that vary over time. They calculate GWP costs and benefits that include the costs to mankind caused by climate damages (or the benefits by avoiding them), while we abstract from these damages in DEMETER.[27] Notwithstanding all these differences, however, we confirm one of their main conclusions: endogenous technological change (or ITC, *induced* technological change, in the words of Goulder and Schneider) makes CO_2 abatement policies generally more attractive.[28]

[27] Although we abstracted from the damages resulting from global warming in the current analysis, DEMETER allows for incorporating them rather easily.

[28] Goulder and Schneider point out that the *net benefits* from a given carbon tax are higher in the presence of ITC, even though the *gross costs* of the tax are raised as well.

5. DISCUSSION AND CONCLUSIONS

The novelty of DEMETER is that it combines several different features of a variety of bottom-up and top-down models of climate change. The model has a macroeconomic basis with endogenous energy demand, while specifying two explicit energy technologies, carbon and carbon-free. Both technologies follow the same learning curve, and both exhibit substantial learning-by-doing. The second technology, however, is able to better profit from its learning potential, because it is at present used to only a relatively modest extent (similarly, fossil technologies have profited largely from significant learning effects in the past). The modeling of a positive demand for the relative expensive non-fossil energy source ensures a smooth transition from the fossil-fuel technology towards the fossil-free technology.

Our first finding with DEMETER is that including endogenous innovation in a macroeconomic model implies earlier emission reductions to meet carbon concentration constraints than in a model with exogenous technological progress (cf. Wigley et al., 1996). We find that the effect is stronger than suggested so far in the literature. The support and development of carbon-free energy technologies turns out to be a more important emission reduction option than considered to date. We find that, when one includes technological progress endogenously, early investments in the non-fossil technology are warranted. These investments ought to be realized earlier than traditional models suggest. In terms of climate change policy-making, we conclude that if a maximum temperature increase of 2 °C is the objective, it is optimal to reduce (compared to the expected BAU carbon emission pattern) global energy related CO_2 emissions to a maximum allowed level of around 9 GtC. This maximum can be reached by about 2030 and ought to be followed by substantial decreases afterwards.

A policy aiming at constraining the temperature increase to 2 °C is ambitious, and it requires incentives to reduce the use of fossil-fuel based energy resources, e.g. through a tax on carbon dioxide emissions, together with incentives to develop new carbon-free technologies, e.g. through subsidies. Subsidies could be used to internalize the learning effect, though, in our analysis, we abstracted from this opportunity. The reduction of total energy demand is a valuable option for emission reduction during the first coming decades. For the long term, however, carbon-free technologies will be needed to reach the desirable low emission levels.

Some policy-makers, and scientists the like, consider constraining the temperature increase to 2 °C practically unfeasible, because of the expected high economic costs associated with this target. Our calculations, however, show that it is possible to reach such an objective with investments in the carbon-free technology that are ‘only’ about twice as high as those currently realized, that is, as those in BAU. It is true that such investments will decrease total future consumption opportunities. In the end, however, the corresponding cumulative costs only amount to 0.06% of the BAU net present value of consumption. In our opinion, this low cost level justifies putting more efforts in constraining the temperature increase to 2°C. Note that since investments contribute positively to GWP, the scenarios that involve enhanced levels of investments in the non-fossil energy technology display higher GWP levels. This is apparent in scenarios in which energy demand is modeled exogenously, since in these scenarios a transition from fossil to non-fossil energy is the only available option for reducing carbon emissions, and thus increased non-fossil investments are called for to meet the temperature constraint.

These encouraging results on abatement costs crucially depend on four assumptions, regarding energy demand, learning effects, the magnitude of substitutability between several energy sources, and the use of environmental policies to moderate existing market failures.

I. A decrease in energy demand is an important option -especially in the short and medium term- to bring down emission reduction costs. In a climate change analysis of the energy economy with the assumption of a fixed path for energy demand, as is common practice in most bottom-up models, one leaves out an important mechanism to reduce carbon emissions. By omitting this flexibility, substantially higher costs of climate change policies can be expected (as we demonstrate by a comparison between scenarios S1 and S2, and S3 and S4).

II. We assume that additional investments in the carbon-free energy technology, necessary to meet the emission reduction policy, amplify the process in which production costs for these technologies decrease. In other words, there is a positive spill-over obtained (through learning-by-doing) from the experience gained by current emission reduction efforts, in the form of accumulated deployment of carbon-free energy. The importance of this assumption is shown notably in Figure 4.4, and can be quantified by an inspection and comparison of scenarios S1 and S2 with S3 and S4.

III. Stimulating the use of new technologies is an essential part of a successful transition policy. Assuming good but imperfect substitution implies that expensive energy sources have a certain share in the market and are relevant to users to whom new relatively expensive technologies have a comparative advantage. Market segments exist for certain energy users to whom it proves profitable, even at actual prices, to use the more expensive non-fossil energy technology. Policies should aim at increasing such market segments. Thereby, the final overall costs of the required energy transition can be substantially reduced. We have modeled this understanding through the CES aggregation of the F and N technologies, choosing an elasticity of substitution between unity and infinity.

IV. A stringent greenhouse gas policy (e.g. through the levying of carbon taxes) can help reducing existing market distortions. In other words, the costs of environmental regulation may be less if they, while benefiting the environment, reduce an existing market failure, compared to the situation in which this regulation does not reduce existing distortions in the economy. In our analysis, we followed Arrow's seminal paper (1962) by adopting the learning-by-doing phenomenon. We assumed that learning-by-doing spill-over effects are not internalized (in none of our scenarios, hence the market failure), and thus, that investments in both energy technologies fall short of their socially optimal level. When taxing the fossil-fuel technology to decrease emissions, we stimulate the non-fossil fuel technology. The non-fossil technology is presently at the steeper part of the learning curve (while the learning curve itself is equal for both fossil and non-fossil technologies), in comparison to the fossil technology. The carbon taxes thus create an incentive that partly corrects the market failure of the learning spill-overs not being fully internalized.

Taken together, we recognize that these four assumptions combined are perhaps rather optimistic. We claim, however, that they are not fundamentally biased. Greenhouse gas emissions are not an essential production factor, and the transition towards zero-carbon emitting energy technologies does not need to involve an incremental process where marginal costs of each next step substantially exceed the costs of the previous step. Through the simulation of the four assumptions listed above, DEMETER deviates substantially from the (general equilibrium) integrated assessment models that have so far been designed in the field of climate change studies. With the results of DEMETER presented above, we back the statement that "induced (technological) change … may be much more significant if extensions from the conventional economic frameworks are considered" (Weyant and Olavson, 1999).

Among one of the main windows for future research is an extensive analysis of the sensitivity of our results to various assumptions on input parameters and start-off values of both exogenous and endogenous variables. Given the considerable effects on our modeling results of incorporating learning-by-doing for fossil and non-fossil energy production, we want to extend our sensitivity analysis with respect to learning rates to a robustness analysis vis-à-vis other modeling parameters and variables in our learning-by-doing context. For example, we could also analyze how our results would modify if different values were assumed for our elasticities of substitution, long-term energy costs, and future (autonomous) energy efficiency improvements. Another topic for future study would be the extension of DEMETER from learning-by-doing to learning-by-learning (that is, learning through R&D), by which potentially more explanatory value can be added to the learning curve phenomenon.

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