DEMETER

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This chapter describes the main features of the long-term dynamic top-down economy-energy-environment (E^3) model DEMETER, which has been used for the analysis of a number of climate change issues (see van der Zwaan *et al.*, 2002; Gerlagh and van der Zwaan, 2003; Gerlagh and van der Zwaan, 2004; Gerlagh *et al.*, 2004; van der Zwaan and Gerlagh, 2006). The DEMETER version described here simulates fossil fuels and non-fossil energy, as well as a decarbonization option through CCS, in addition to a simple climate module and generic production and consumption behavior. DEMETER connects to both models of endogenous growth (such as Bovenberg and Smulders, 1996, and Chakravorty *et al.*, 1997) and to (top-down) models particularly focusing on energy and climate change (e.g. Buonanno *et al.*, 2003, and Goulder and Mathai, 2000). While DEMETER fits in the tradition of models like DICE (Nordhaus, 2002), it is clearly much richer in technological detail than Nordhaus' pioneering top-down model. It shares the endogenization of technical change through learning curves with bottom-up models as first developed by Messner (1997) and reported in Nakicenovic *et al.* (2001). In this sense, DEMETER is hybrid and especially useful for deriving insight for policy making (Jaccard *et al.*, 2003). Below, after an introduction, brief descriptions are given of how DEMETER models the representative consumer, the final good producer, energy producers, technological change, climate change, and carbon dioxide capture and storage (CCS).

1. Introduction

DEMETER models distinct time periods of five years, each denoted by $t=1,\ldots,8$. The model distinguishes one representative consumer, three representative producers (also referred to as sectors), and a public agent that can set emission taxes to reduce carbon dioxide emissions. Producers are denoted by superscripts $j=C,F,N$, for the producer of the final good or consumption good, the producer of energy based on fossil-fuel technology, and the producer of energy based on carbon-free technology. There are four goods for which an equilibrium price is determined that brings supply and demand in equilibrium: the final good with price $?_t$ normalized to unity, $?_t=1$, fossil fuel energy, with price μ_t^F, carbon-free energy with price μ_t^N, and labour with price w_t. We use β_t^τ as the price deflator for the final good from period t to period t. So, $\beta_t^\tau=1/[(1+r_t)(1+r_{t+1})\ldots(1+r_{t-1})]$, where r_t is the real interest rate. By definition, $\beta_t^t \equiv 1$ and $\beta_t^\tau = 1/\beta_\tau^t$. When convenient, we also use $\beta_t = \beta_t^{t+1} = 1/(1+r_t)$. Figure 1 presents a schematic overview of the model flows. The time lag between investments and capital used as a production factor is represented through an "L" on top of the flow arrows.[1]

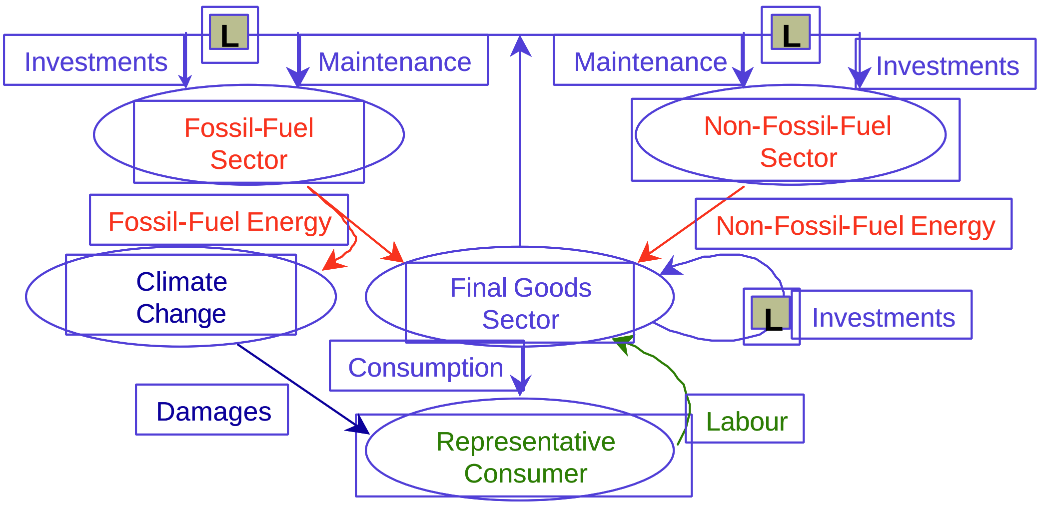

FIGURE 1. *DEMETER schematic overview of flows*

The final good is produced by sector $j=C$, where output is denoted by Y^C. The same good is used for consumption, investments I in all three sectors and for operating and maintenance M (as usually distinguished in energy models) in both energy sectors $j=F,N$:

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

[1] The complete GAMS code is available through the internet, via the web-page of the first author: www.vu.nl/ivm/organisation/staff/reyer_gerlagh.html.

We distinguish operating & maintenance costs, on the one hand, and investments costs, on the other hand, in the energy sector chiefly since the empirical data on learning rates often pertain to investment costs (cf. McDonald and Schrattenholzer, 2001) and we want to avoid overestimating learning rates. Fossil fuel energy is demanded by the final goods sector $j=C$ and supplied by the fossil-fuel sector $j=F$. Carbon-free energy is demanded by the final goods sector $j=C$ and supplied by the carbon-free energy sector $j=N$. Labour L_t is demanded by the final goods sector $j=C$ and supplied inelastically by the consumers. Finally, the public agent may levy a tax t_t on emissions Em_t produced by the final good sector when using fossil-fuel energy sources.

2. The representative consumer

We assume there is one representative consumer who maximises welfare subject to a budget constraint:

$$W = \sum_{t=1}^{\infty} (1+\rho)^{-t} L_t \ln(C_t / L_t) , \qquad (2)$$

where W is total welfare, ? is the pure time preference, and C_t / L_t is consumption per capita. Welfare optimisation gives the Ramsey rule as a first-order-condition for consumption,

$$ß_t = (C_t / L_t)/((1+?)(C_{t+1}/L_{t+1})) . \qquad (3)$$

3. The final good producer

The representative producer maximizes the net present value of the cash flows:

$$\text{Max} \sum_{t=1}^{\infty} b_0^t (Y_t^C - I_t^C - w_t L_t - m_t^F Y_t^F - m_t^N Y_t^N - t_t Em_t) , \qquad (4)$$

subject to the production constraints (5)-(12), given below. Revenues consist of output Y_t^C, expenditures consist of investments, I_t^C (one period ahead), labour L_t at wage w_t, fossil-fuel energy Y_t^F at price μ_t^F, and carbon-free energy, Y_t^N at price μ_t^N, and the public agency levies a tax t_t on emissions. First order conditions are given in the appendix.

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

$$\tilde{Y}_t^C = ((A_t^1 \tilde{Z}_t)^{(\gamma-1)/\gamma} + (A_t^2 \tilde{E}_t)^{(\gamma-1)/\gamma})^{\gamma/(\gamma-1)}, \qquad (\tilde{\lambda}_t) \tag{5}$$

where A_t^1 and A_t^2 are technology coefficients, and ? is the substitution elasticity between $\tilde{Z}_t$ and $\tilde{E}_t$. Notice that the Lagrange variable for the profit maximization program is given between brackets. The capital-labour composite $\tilde{Z}_t$ is defined as:

$$\tilde{Z}_t = (I_{t-1}^C)^{\alpha} (\tilde{L}_t)^{1-\alpha}, \qquad (\tilde{\theta}_t) \tag{6}$$

which says that the capital/labour composite has fixed value share a for capital. Note that new capital is by definition equal to the investments of one period ahead, $\tilde{K}_t^j = I_{t-1}^j$.

We model energy services $\tilde{E}_t$ as consisting of a CES aggregate of energy produced by the sectors *F* and *N*:

$$\tilde{E}_t = ((\tilde{Y}_t^F)^{(\sigma-1)/\sigma} + (\tilde{Y}_t^N)^{(\sigma-1)/\sigma})^{\sigma/(\sigma-1)}, \qquad (\tilde{\chi}_t) \tag{7}$$

where s is the elasticity of substitution between *F* and *N*. The CES aggregation allows for a strictly positive demand for the new technology *N*, if the price of the carbon-free energy exceeds the price of the fossil-fuel energy *F* even by an order of magnitude. By assuming the elasticity of substitution σ to have a (bounded) value larger than one, 1<s<8 , it is ensured that the (expensive) new technology has at least a small but positive value share. In this way, the CES aggregation effectively represents a niche market and enables the economic system to take advantage of a diversified energy production, e.g. because different technologies exist, each having their own markets for which they possess a relative advantage. In DEMETER, niche markets are represented on the macro level, while gradual substitution of one technology for the other technology takes place when prices change. Though one could argue that the competition between energy sources will intensify (and thus the elasticity of substitution will increase) once the market share of carbon free technologies rises as a result of a carbon tax, we assume s to be constant both for reasons of simplicity and for reasons of lack of empirical data. As we will argue in section 3, there is not much empirical evidence on the value of s.

Carbon dioxide emissions, Em_t, are linked to the production of the newest vintage through an emission intensity parameter ε_t^F (where $\varepsilon_t^N=0$ for the carbon-free energy technology) that describes the level of emissions per unit of fossil-fuel energy use:

$$\tilde{Em}_t = e_t^F \tilde{Y}_t^F , \qquad (\tilde{\tau}_t) \qquad (8)$$

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

$$Y_t^C = (1-\delta)Y_{t-1}^C + \tilde{Y}_t^C , \qquad (\tilde{\lambda}_t) \qquad (9)$$

$$Y_t^j = (1-\delta)Y_{t-1}^j + \tilde{Y}_t^j , \qquad (\tilde{\mu}_t^j ;\ j=F,N) \qquad (10)$$

$$L_t^j = (1-\delta)L_{t-1}^j + \tilde{L}_t \,, \qquad (\tilde{w}_t) \qquad (11)$$

$$Em_t = (1-\delta)Em_{t-1} + \tilde{E}m_t \,. \qquad (\tilde{\tau}_t) \qquad (12)$$

where the last equation (12) presents the relation between total emissions Em_t and emissions of the new vintage $\tilde{E}m_t$. Note that the equations should not be read as describing accumulation over time, and related thereto, the variables Y_t^C, Y_t^F, Y_t^N, L_t^C, Em_t, do not represent stock variables. Instead, the equations more-or-less describe the slow adjustment of production characteristics over time, as the capital stock slowly adjusts with new vintages in every period.

4. Energy producers

Both energy producers, the fossil fuel sector j=F and the non-fossil fuel sector j=N are treated symmetrically. Production of energy, $\tilde{Y}_t^j$ (j=F,N), requires investments I_{t-1}^j (in the previous period) and maintenance costs, M_t^j. Energy producers maximize the net present value of cash flows:

$$\text{Max} \quad \sum_{t=1}^{\infty} \beta_0^t (\mu_t^j Y_t^j - I_t^j - M_t^j) \,. \qquad (13)$$

Each new vintage with output $\tilde{Y}_t^j$ requires proportional investments one period ahead, I_{t-1}^j, and maintenance costs $\tilde{M}_t^j$ according to:

$$\tilde{Y}_t^j = a_t^j I_{t-1}^j \,, \qquad (?_{j,t};\ j=F,N) \qquad (14)$$

$$\tilde{Y}_t^j = b_t^j \tilde{M}_t^j \,, \qquad (?_{j,t};\ j=F,N) \qquad (15)$$

where we maintain subscripts t for the technology parameters a_t^j and b_t^j to describe decreasing costs of energy production (increasing levels for a_t^j and b_t^j) resulting from learning-by-doing. We assume that knowledge gained is public, that is non-rival and non-exclusive. Thus firms will not internalise the positive spill-overs from their investments in their prices. Hence, production parameters a_t^j and b_t^j are treated as exogenous by the firms, and the individual firms are confronted with constant returns to scale.[2] In a similar way as expressed in the production of consumer goods (9), energy output is distinguished by vintage (10), and the same vintage approach applies to maintenance costs, M_t^j:

$$M_t^j = (1-\delta)M_{t-1}^j + \tilde{M}_t^j . \qquad (?_{j,t};\ j=F,N) \qquad (16)$$

Profit maximisation of (13) subject to (10), (16), (14), and (15) gives zero profits. First order conditions are listed in the appendix.

In this formulation we have not explicitly modelled resource exhaustion. One may argue that resource depletion implies in principle increasing extraction costs that, in practice, however, is usually counter-balanced by continuous technological development that tend to reduce extraction costs over time. Looking at the expected future price trajectories for fossil fuels (e.g., Nakicenovic et al., 1998, p 111, medium scenario B), we see that the shadow-prices for all fossil fuels increase over time. We thus may underestimate the costs of supplying fossil fuels, but not too much, since expected increases in fossil fuel prices are small.

5. Technological change

The DEMETER model incorporates various insights from the bottom-up literature that stresses the importance of internalising learning-by-doing effects in climate change analyses. Energy production costs decrease as the experience increases through the installation of new energy vintages. In this version of DEMETER, the endogenous modelling of learning by doing is limited to the energy sectors; we have not included learning effects for overall productivity and energy efficiency. Thus, A_t^1 and A_t^2 as employed in (5) are exogenously determined by a benchmark (business as usual) growth path.

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[2] An extended version of DEMETER 1.0 also includes subsidies for new technologies, as presented in van der Zwaan *et al*. (2002). These can be used to internalise learning-by-doing in order to reach a dynamically efficient allocation. In this paper, however, we abstract from such subsidies.

For the energy sector, the model describes the learning process through a scaling variable h_t^j the inverse of which measures the relative productivity a_t^j and b_t^j relative to long-term productivity levels, a_∞^j and b_∞^j.

$$h_t^j \; a_t^j = a_\infty^j , \qquad (j=F,N) \qquad (17)$$

$$h_t^j \; b_t^j = b_\infty^j . \qquad (j=F,N) \qquad (18)$$

Stated in other terms, the variable h_t^j measures the costs of one unit of output $\tilde{Y}_t^j$ as compared to potential long-term costs. For example, h_t^j =2 means that one unit of energy output of sector *j* costs twice as much investments and maintenance costs as compared to the situation in the far future when the learning effect has reached its maximum value.

To capture the process of gaining experience and a decreasing value of h_t^j, we introduce the variable X_t that represents experience; it counts accumulated installed new capacity (vintage) at the beginning of period *t*:

$$X_{t+1}^j = X_t^j + \tilde{Y}_t^j . \qquad (j=F,N) \qquad (19)$$

Furthermore, we use a scaling function g^j(*X*)? [1,8) that returns the value for h_t^j as dependent on cumulative experience X_t^j. Employing discrete time steps, the value of h_t^j is given by the average value of g^j(*X*) over a period:

$$h_t^j = \int_{X_t^j}^{X_{t+1}^j} \mathrm{g}^j(x)\,\mathrm{d}x \,/(X_{t+1}^j - X_t^j), \qquad (j=F,N) \qquad (20)$$

We assume g?(.)=0, that is, production costs decrease as experience increases, and we assume g^j(8)=1, that is, production costs converge to a strictly positive floor price (minimum amount of input associated with maximum learning effect) given by the levels of a_∞^j and b_∞^j. Finally, we assume a constant learning rate *lr*>0 for technologies at the beginning of the learning curve (that is, for small values of *X*). This means that, initially, production costs decrease by a factor (1–*lr*), for every doubling of installed capacity.

Such decreases have been observed empirically for a large range of different technologies (IEA/OECD, 2000).

A function $g^j(.)$ that supports all these assumptions is given by:

$$g^j(X) = c^j(1-d^j)X^{-d^j} + 1. \tag{21}$$

where we omitted subscripts t and superscript j for the variable X, and $0<d^j<1$ measures the speed of learning, and c^j measures the size of the learning costs relative to the long-term production costs.[3] Finally, we notice that, in a model without learning-by-doing, we would have $g^j(.)=1$.

6. Climate change

Emissions are included in the equilibrium through equations (12) and (8). Environmental dynamics are included by linking emissions to atmospheric CO_2 concentrations, Atm_t, and, in turn, to temperature change, $Temp_t$:

$$Atm_{t+1} = (1-\delta^M)Atm_t + \pi(Em_t + \overline{\overline{Em}}_t), \tag{22}$$

$$Temp_{t+1} = (1-\delta^T)Temp_t + \delta^T \overline{T}\ {}^2\ln(Atm_t / Atm_0), \tag{23}$$

where δ^M is the atmospheric CO_2 depreciation rate, p is the retention rate, $\overline{\overline{Em}}_t$ are emissions not linked to energy production, δ^T is the temperature adjustment rate due to the atmospheric warmth capacity, and $\overline{T}$ is the long-term equilibrium temperature change associated with a doubling of atmospheric CO_2 concentrations. The climate change sub-model is based on Nordhaus (1994).

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[3] The learning rate lr and the parameter d used in (21) and **Fehler! Verweisquelle konnte nicht gefunden werden.** are approximately related by the equation $d = -\ln(1-lr)/\ln 2$. For small learning rates lr, we make the approximation $d=lr/\ln 2$.

7. DEMETER 2.0 with CCS

DEMETER's public agent can set carbon taxes, fossil fuel taxes, and non-carbon energy subsidies. These three policy instruments may all serve to reduce the emissions of carbon dioxide. When the agent imposes a carbon tax, levied on carbon dioxide emissions, one of the possible reactions is a reduction in overall energy consumption (as modelled in DEMETER 1.0). Producers can also shift from fossil energy to carbon-free energy (DEMETER 1.0), or, alternatively (as included as additional carbon abatement option in DEMETER 2.0), decarbonize fossil-based energy production through the application of Carbon dioxide Capture and Storage (CCS). Carbon dioxide emissions, Em_t, are proportional to the carbon content of fossil fuels, denoted by ε_t^F, while $CCSR_t$ represents the share of the emissions captured through CCS. The relation between emissions and fossil fuel energy production (and use) thus becomes:

$$Em_t = e_t^F (1 - CCSR_t) Y_t^F . \qquad (24)$$

Today, there is no scientific guarantee that carbon dioxide stored underground will not once start leaking back into the atmosphere. In that case, naturally, this leakage should be accounted for as a future additional source of CO_2 emissions. The central scenarios adopted in this study abstract from such carbon leakage phenomena. As part of our sensitivity analysis, however, we do include carbon leakage in our model.

The variable $CCSR_t$ can be understood as the carbon dioxide capture and storage ratio: it is the share of the total amount of CO_2 emissions from the combustion of fossil fuels that is prevented through the application of CCS. Alternatively, we can interpret $CCSR_t$ in a broader sense, that is, as a generic endogenous decarbonization measure, in which ε_t^F is the carbon intensity of a benchmark fuel mix that is optimal without carbon tax, and $CCSR_t$ represents an aggregation of all activities that reduce carbon dioxide emissions as a result of directed policies, not only through CCS implementation but also e.g. fuel-switching options. The parameter ε_t^F decreases over time exogenously and describes *inter alia* the 'autonomous' substitution of e.g. gas for oil and coal. In principle, we do not simulate a carbon-tax-induced substitution between fossil fuels, in any case not through the parameter ε_t^F. In practice, however, a broad interpretation of $CCSR_t$ implies that we do account for an endogenous simulation of fossil-fuel substitution effects. Thus, while the thrust of this article's findings relates to the nature of *endogenous* energy decarbonization, with the parameter ε_t^F DEMETER also possesses a feature describing a particular kind of *exogenous* energy decarbonization (as reported in Gerlagh and van der Zwaan 2004).[4]

The carbon dioxide capture and storage process is described through an 'effort variable' Q_t^{CCS}, which is assumed to be a second-order polynomial function depending on the share of carbon dioxide that is captured and stored (25). In DEMETER all activities are described per vintage. Tildes on top of variables refer to the most recent vintage installed, as for the fossil fuel use Y_t^F in this equation. The parameter ? describes the increase in marginal costs when a higher share of fossil fuels is decarbonized. For ?=0, in one period, costs of CCS are linear and marginal costs are constant. For ?=1, marginal costs double when the share of fossil fuels to which CCS is applied increases from almost nothing to all fossil fuels being combusted. This specification constitutes an important extension in comparison to the work by Ha-Duong and Keith (2003) and Keller *et al.* (2003). In our case, the low-cost CCS options are used first, when carbon taxes are low, while more expensive CCS alternatives are added to the set of applied CCS technologies under higher carbon taxes: these higher taxes justify the more elevated expenses and effort per unit of reduced emissions. CCS technology is only implemented in response to carbon taxes. Under constant investment and maintenance prices, the share of fossil fuel energy from which carbon dioxide is captured and stored is assumed to be linear in the carbon tax..

The variable h_t^{CCS} is an inverse measure for the level of learning in CCS application. The higher its value, the lower the cumulative learning, the more effort is required to implement CCS. When CCS deployment accumulates and thus the amount of emissions avoided increases (26), the resulting (installation and operation) experience, X_t^{CCS}, leads to an enhancement of related knowledge, and a corresponding decrease in the cost parameter

[4] This exogenous decarbonization of fossil fuels amounts to 0.2% per year.

h_t^{CCS} (27). In eq. (27), c^{CCS} and d^{CCS} are constant technology parameters describing the experience (or learning) curve for CCS.[5] When experience X_t^{CCS} accumulates, CCS options become cheaper, and, for constant carbon taxes, more CCS technology is applied. Investments, one period before, are proportional to the effort Q_t^{CCS} (28), and so are maintenance costs (29). The parameters a^{CCS} and b^{CCS} define the investments and maintenance flows required for one unit of the effort Q_t^{CCS}. In every period, total CCS maintenance costs are summed over all vintages, through (30). The parameter d denotes the share of vintage capital that is depreciated per period. Summarizing, we have:

$$Q_t^{CCS} = h_t^{CCS} (CCSR_t + \tfrac{1}{2} k \; CCSR_t^2) e_t^F \tilde{Y}_t , \tag{25}$$

$$X_{t+1}^{CCS} = X_t^{CCS} + CCSR_t e_t^F \tilde{Y}_t . \tag{26}$$

$$h_t^{ccs} = 1 + c^{ccs} (1 - d^{ccs}) (X_t^{ccs})^{-d^{ccs}} . \tag{27}$$

$$I_{t-1}^{CCS} = Q_t^{CCS} / a^{CCS} , \tag{28}$$

$$\tilde{M}_t^{CCS} = Q_t^{CCS} / b^{CCS} . \tag{29}$$

$$M_t^{CCS} = (1-d) M_{t-1}^{CCS} + \tilde{M}_t^{CCS} . \tag{30}$$

The climate change dynamics used are as in DICE99 (Nordhaus and Boyer 2000). They describe a multi-stratum system, including an atmosphere, an upper-ocean stratum, and a lower-ocean stratum.[6]

References

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.

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

[5] For low values of X_t^{CCS}, the learning rate is given by $(1 - 2^{-d^{ccs}})$.

[6] As DICE99 uses periods of 10 years, we recalibrated the DICE99 climate module parameters to fit our five-year period structure.

Gerlagh, R., and B.C.C. 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.

Gerlagh, R. and B.C.C. van der Zwaan (2004), "A sensitivity analysis of timing and costs of greenhouse gas emission reductions under learning effects and niche markets", *Climatic Change*, 65: 39-71.

Gerlagh, R., B.C.C. van der Zwaan, M.W. Hofkes, and G. Klaassen (2004), 'Impacts of CO2-taxes in an economy with niche markets and learning-by-doing', *Environmental and Resource Economics*, 28, 367-394.

Goulder L.H. and K. Mathai (2000), "Optimal CO_2 abatement in the presence of induced technological change." *Journal of Environmental Economics and Management* 39: 1-38.

Ha-Duong, M. and D.W. Keith (2003). "Carbon storage: the economic efficiency of storing CO_2 in leaky reservoirs." *Clean Techn Environ Policy* 5:181-189.

Jaccard M., J.Nyboer, C.Bataille *et al.* (2003), "Modeling the cost of climate policy: distinguishing between alternative cost definitions and long-run cost dynamics" *The Energy Journal* 24: 49-73.

Keller K., Z.Yang, M. Hall, and D.F. Bradford (2003), "Carbon dioxide sequestration: when and how much?", CEPS working paper 94, Princeton University.

McDonald, A. and L. Schrattenholzer (2001). "Learning rates for energy technologies." *Energy Policy* 29: 255-261.

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

Nakicenovic, N. A. Grübler and A. McDonald, eds. (1998). *Global energy perspectives*. IIASA-WEC. Cambridge, UK: Cambridge University Press.

Nakicenovic, N. *et al*., eds. (2001), *Special Report on Emission Scenarios*. Published for the Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK: Cambridge University Press.

Nordhaus W.D. (1994). *Managing the global commons*. Cambridge, MA: MIT Press.

Nordhaus, W.D. and J. Boyer (2000), "Warming the world, economic models of global warming", MIT Press, Cambridge, MA.

Nordhaus, W.D. (2002), "Modeling induced innovation in climate change policy." Ch. 9 in *Modeling induced innovation in climate change policy*, A. Grübler, N. Nakicenovic, and W.D. Nordhaus (eds), Resources for the Future Press, Washington D.C.

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.

van der Zwaan, B.C.C. and R. Gerlagh (2006), "Climate Sensitivity Uncertainty and the Necessity to Transform Global Energy Supply", *Energy*, forthcoming.