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Economics of geological CO_2 storage and leakage

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Abstract The economics of CO_2 capture and storage in relation to the possibility of leakage of CO_2 from geological reservoirs once this greenhouse gas has been stored artificially underground will be among the main determinants of whether CCS can significantly contribute to a deep cut in global CO_2 emissions. This paper presents an analysis of the economic and climatic implications of the large-scale use of CCS for reaching a stringent climate change control target, when geological CO_2 leakage is accounted for. The natural scientific uncertainties regarding the rates of possible leakage of CO_2 from geological reservoirs are likely to remain large for a long time to come. We present a qualitative description, a concise analytical inspection, as well as a more detailed integrated assessment model, proffering insight into the economics of geological CO_2 storage and leakage. Our model represents three main CO_2 emission reduction options: energy savings, a carbon to non-carbon energy transition and the use of CCS. We find CCS to remain a valuable option even with CO_2 leakage of a few percent per year, well above the maximum seepage rates that we think are likely from a geo-scientific point of view.

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1 Introduction

A range of options exists suitable for significantly reducing this century current CO_2 emissions. Atmospheric concentrations of this greenhouse gas (GHG) well above pre-industrial levels constitute the main cause for the predicted rise in average surface temperature on Earth and the corresponding change of the global climate system. Among the many technologies capable of contributing to stabilizing atmospheric CO_2 concentrations, thereby mitigating global climatic change, CO_2 capture and storage (CCS) has recently received particular attention. The capture of CO_2 before or after the combustion of fossil fuels, and its subsequent storage in either geological formations or the ocean, or its industrial re-use and/or chemical fixation, is today considered as one of the promising means to start addressing the problem of climate change in the near term.

Still, much is left to be understood about the technical, economic and political dimensions of CCS. Important questions remain in particular regarding possible environmental externalities and safety risks associated with the storage of CO_2 underground (see e.g. Wilson et al. 2003, and IPCC 2005). The hazard associated with gradual CO_2 leakage ranks high among the potential risks of geological CO_2 storage, since it could reduce or eliminate the suitability of CCS as climate change mitigation option, and is therefore the main subject of this article. The Intergovernmental Panel on Climate Change (IPCC) concludes that observations from engineered and natural analogues as well as preliminary modelling efforts suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and likely to exceed 99% over 1,000 years (IPCC 2005). Solid scientific support for these types of statements, however, is until today very limited. This constitutes no reason, though, for not now analysing the potential climatic and economic implications of CO_2 leakage. Are there values for the CO_2 leakage rate that are acceptable from a cost and carbon-cycle point of view? How is the efficiency of CCS affected, and what is the economic penalty incurred from geologically stored CO_2 leakage? What is the CO_2 tax required to stimulate CCS deployment under various leakage scenarios? This article attempts to answer these kinds of questions.

Below, Section 2 concisely introduces the basic economic implications for the wide-spread use of CCS and climate change mitigation efforts of CO_2 leakage after this GHG has been stored in geological reservoirs for emission reduction purposes. Section 3 describes the methodology we use for our analysis: after a brief recollection of some of the essential features of DEMETER, it is explained how this top-down integrated assessment model is expanded to reflect both the application of CCS technology and physical leakage of geologically stored CO_2, and subsequently employed to address the above research questions. Section 4 gives a description of our modelling scenarios and reports our findings in terms of the importance for climate change control efforts of CO_2 leakage phenomena. In Section 5 we investigate what the origins may be of what seems to be a discrepancy in research results regarding the implications of geological CO_2 leakage obtained with, respectively, our top-down energy–economy–environment (EEE) model and a selected model with similar generic EEE features but belonging to the bottom-up family. In Section 6 we draw our conclusions and discuss some of the main lessons for policy-making that follow from our analysis.

2 Climate change, CCS and CO_2 leakage

The presence of oil, natural gas, and CO_2 trapped in geological formations implies that in sedimentary basins impermeable cap-rocks are available with sufficient quality to confine fluids and gases for long periods of time. Evidence from natural systems demonstrates that reservoir seals exist that are able to contain fossil fuels and CO_2 underground over time scales of millions of years. Still, it is imaginable that CO_2 artificially stored underground slowly leaks from its geological medium and gradually migrates to the aboveground environment. Especially for storage options other than depleted oil and gas fields, such as aquifers and coal seams, aspects of long-term storage effectiveness are uncertain. Also, a large number of sites exist where one might have expected to find oil or natural gas, but where no such resources proved available, potentially as a result of an insufficient quality of geological cap-rock material. At many places on Earth large quantities of oil and natural gas may once have been stored underground, but that, in the absence of appropriate containment layers, eventually seeped away to be absorbed in the aboveground biosphere or atmosphere. Hence, it may not be guaranteed that the formations employed for artificial CO_2 storage retain integrity forever, possibly for depleted oil and natural gas fields, but especially for other geological reservoirs.

Examples abound showing that not only fossil fuels such as oil and natural gas but also CO_2 can remain trapped in underground reservoirs for very long periods of times. Currently exploited oil and natural gas fields, often 'polluted' with CO_2, are known to be millions of years old, during which period these pockets of sequestered fossil fuels have retained their storage integrity. The CO_2 used in Texas for enhanced oil recovery originates from large naturally stored volumes of CO_2 that have been present in the local terrestrial crust for at least millennia. The large volume of CO_2 trapped underground in the Pisgah Anticline (Mississippi) is thought to have been created in Late Cretaceous times, more than 65 million years ago. Given these examples, and since oil and natural gas fields have a proven containment integrity record for millions of years, there is good reason to believe that CO_2 can also be stored artificially without noteworthy leakage, at least in depleted oil and natural gas fields, for time frames compatible with the natural CO_2 cycle. This would render CCS with geological CO_2 storage fit for contributing to controlling global climate change. While there seems thus little doubt that the long-term secure storage underground of a gas like CO_2 is feasible in many locations and geological formations, no full certainty exists, as there are also plenty examples of natural CO_2 leakage from the geological underground, notably around volcanic activity. Fossil fuels, however abundant in comparison to some other natural resources, are still relatively rare and certainly limited from a broader resource perspective. They are only found at sites with specific geological features, including the presence of an appropriate cap-rock that prevents the confined oil or natural gas from dissipating. Most likely, during the Earth's history, in many more places fossil fuels once accumulated, but seeped away and dissolved in oceans and the atmosphere as a result of unfavourable geologic containment conditions. Many fossil-fuel-retaining reservoirs that existed long ago, or past oil and natural gas fields *in statu nascendi*, have probably disappeared over time (Deffeyes 2005). This observation confirms that leakage back into the atmosphere of artificially stored CO_2 is a phenomenon that deserves attention and should be studied when contemplating the storage of CO_2 underground for climate change reduction purposes (see e.g. also Kharaka et al. 2006).

The indicative figures for possible CO_2 leakage from the IPCC (2005) suggest that for carefully selected CO_2 storage sites annual leakage rates are very likely to remain below 0.1%/year. It could prove difficult, however, to select CO_2 storage sites guaranteed characterised by such low leakage rates, let alone by 100% storage efficiency. Even while the geosciences leave most of the large physical CO_2 leakage rate uncertainties for the moment unresolved, one may ask already now what the leakage rates are that can still be considered acceptable from at least an economic or climate control point of view. It may well be that in terms of the relative costs of CCS implementation or the lead times involved with the carbon cycle and global climate change, CO_2 leakage rates are allowed that are considerably higher. Also, if more severe limitations exist than expected with respect to our CO_2 storage site selection capabilities, or management proves insufficient during storage operation, leakage rates of 0.1%/year or even 1%/year cannot be totally excluded. The relevance of such high rates for energy scenario analysis and the economics of climate change assessments should therefore be researched. Also for other reasons, as will be clarified in Sections 3 and 4, we thus investigate five scenarios with leakage of CO_2 from geological storage: two scenarios with a time-dependent leakage rate corresponding to (expected) CO_2 storage lifetimes of 100 and 200 years, and three scenarios with time-independent leakage, in which the leakage rate amounts to constant values of 0.5%, 1% and 2%/year.[1]

Under imperfect storage conditions, CO_2 migration times are likely to vary significantly according to the storage option considered, and depend on the characteristics of the formation of the site specified (see, for example, NITG 2007). The leakage time frame that characterises each option, and the compatibility of that time frame with climate change policy targets as well as features of the natural carbon cycle, is determinant for the option's suitability to mitigate, postpone, or preclude climate change. A back-of-the-envelope calculation readily demonstrates that a 1%/year CO_2 leakage rate is probably not acceptable from a global climate point of view, while a 0.1%/year rate may perhaps be. For a storage option with a 1%/year leakage rate, a given quantity of geologically stored CO_2 will have reduced to 37% of that amount after 100 years, whereas 90% of that quantity is still stored underground after a century for a storage medium characterised by a 0.1%/year leakage rate. Given that climate change is a problem stretching over the forthcoming couple of centuries, one may conclude that in the 1%/year leakage case CCS becomes a clearly ineffective emissions abatement option. If a 0.1%/year leakage rate applies, however, a large share of the geologically stored CO_2 remains sequestered even after the time frame of several centuries, so that CCS retains much of its value as climate change management technology. This simple observation is confirmed by more refined economic analyses of climate change, as in Ha-Duong and Keith (2003).

Leakage of CO_2 from underground storage may be subject to change over time. Much depends on whether one considers leakage on a global scale or locally per individual storage site. A few observations can be made about the long-term evolution of the mean leakage rate, that is, if such a rate exists, since much in this

[1]These leakage rates correspond to (expected) CO_2 storage lifetimes of 200, 100 and 50 years, respectively.

domain remains speculative. First, when considering the global scale as we do in this paper, one may assume that injection occurs arbitrarily distributed across a large collection of heterogeneous reservoirs, about which we know very little, in terms of possible CO_2 leakage, before actually operating them as storage sites (the 'no knowledge' case). In other words, we start employing storage reservoirs more or less randomly over a series of options, without precise prior knowledge about the potential range of their associated CO_2 leakage rate (as in Pacala 2002). In this case, in the long run the average leakage rate decreases, because the fraction of CO_2 remaining in less leaky reservoirs increases. Second, at some point it may be possible to develop prior understanding of what the approximate leakage rate values are of specific potential geological storage sites, e.g. through detailed modelling exercises of the behaviour and interaction of CO_2 with its surrounding geological material (as in Hepple and Benson 2002). If the quantity of CO_2 we plan to store underground becomes large, and the limited capacity of each single reservoir necessitates the use of a growing number of storage formations, gradually the probability of selecting less favourable sites (i.e. with higher leakage rate) will increase, as the best sites are used first. In this (so-called 'perfect knowledge') case the overall mean CO_2 leakage rate is likely to progressively augment over time. Third, the reality may be somewhere in between these two outer cases, and both phenomena may be at work simultaneously, so that decreasing and increasing average leakage rate tendencies (partly or completely) level out. Otherwise, however, at a global scale the CO_2 leakage rate may increase or decrease over time, depending on the knowledge we acquire about physical leakage processes of individual storage sites. In all likelihood we will eventually acquire the scientific knowledge so as to carefully select the most suitable storage sites, e.g. those characterised by a cap rock that sufficiently seals the CO_2 stored beneath. Since for the moment uncertainties regarding potential global leakage processes remain large around what are most probably small central values[2], we judge that constant leakage ought to be one of the cases subjected to analysis.

As for individual storage sites, today our natural scientific understanding of geological CO_2 migration and leakage processes is limited, and values of possible leakage rates are only speculative. It is therefore difficult to claim anything conclusive about the nature of leakage phenomena at the local level for single storage locations. Rather than assuming that CO_2 leaks exponentially according to a constant rate over time, however, it seems increasingly plausible that the leakage rate is time-dependent, with e.g. a bell- or S-shape. The current state-of-the-art understanding of realistic leakage functions seems to suggest that it is most likely that there is first a long induction period with no leakage, then a period in which leakage starts and its rate potentially increases, followed by a period during which the leakage rate decreases again. Given these arguments, in this study we not only investigate constant leakage rates (as we did in van der Zwaan and Gerlagh 2008) but also time-dependent ones according to a bell-shape. In this paper we thus study both time-variability and time-constancy of CO_2 leakage rates, as well as a large range of possible leakage rate and storage lifetime values (including, in addition to the above, 0 and ∞ CO_2 leakage rates), most of which are considered pessimistic by the IPCC (2005) from a natural scientific viewpoint.

[2]Private communications with David Keith and John Gale, amongst others.

CO_2 leakage lowers the value of CCS as climate mitigation option below the prevailing level of the CO_2 tax. Herzog et al. (2003, Eq. 3) define the effectiveness of temporary carbon storage as the net present value of the total stream of avoided emissions. Taking their definition, but slightly adjusting their notation and considering the storage at time t of one unit of CO_2 in a leaky reservoir, in our case as applied to CCS with geological storage, we express the effectiveness η_t as:

$$\eta_t = \frac{\tau_t - \int\limits_0^\infty e^{-rs} a_{t+s} \tau_{t+s} \mathrm{d}s}{\tau_t}, \tag{1}$$

in which a_{t+s} is the amount of CO_2 (relative to the emissions prevented, that is, captured and stored) leaking back to the atmosphere after s years, τ_{t+s} the atmospheric CO_2 shadow price (i.e. carbon tax) at which these emissions are valued at time $t + s$, and r the constant real interest rate.

In principle $\int_0^\infty a_s ds \leq 1$, with equality when all stored CO_2 eventually leaks back to the atmosphere. We have to distinguish, however, between the amount of avoided CO_2 emissions and the amount of stored CO_2, since the process of capturing and storing CO_2 through CCS technology application requires energy itself. Hence, when CCS is employed more primary fuel is needed to deliver a given level of secondary energy service, in comparison to the situation in which no CCS is applied. That is, in order to generate an amount of usable energy that would otherwise emit one unit of CO_2, more fossil fuels are needed when the process is complemented with CCS, which intrinsically involves the production of more than one unit of CO_2. When one accounts in terms of units of final energy use, the energy penalty incurred by CCS implementation implies that one has to store more than one unit of CO_2, as a result of which we may find $\int_0^\infty a_s ds > 1$. With this in mind, we see with Eq. 1 that η_t may obtain a negative value (even when the discounted carbon tax decreases over time).

Equation 1 shows that the effectiveness of CCS strongly depends on the value of discounting. This was also pointed out by Herzog et al. (2003), who calculate η_t for various stylized carbon tax and CO_2 storage scenarios. In particular, they investigate three carbon price evolution cases—(1) constant prices, (2) prices increasing at the discount rate, and (3) a two-stage mixture between these two with first (2) and then (1)—and employ a detailed model of a leaky ocean with storage depth as one of the main determinants. In the current paper we take their analysis a step further and apply their effectiveness formulation to another setting. First, we assume an expression for the storage effectiveness that is time-dependent, as given in Eq. 1, rather than the time-independent version adopted in Herzog et al. (2003). Second, we investigate the case of geological CCS, rather than ocean storage of CO_2. Third, rather than merely determining values for η_t under different conditions, as in Herzog et al. (2003), we calculate these within an integrated assessment model that we subsequently use to simulate the optimal response to climate change stabilization scenarios. Fourth, rather than investigating leakage based on different injection depths (as is appropriate for the case of ocean storage), we analyze different values for the geological leakage rate, both constant and time-dependent. Fifth, rather than imposing carbon prices exogenously as in cases (1), (2) and (3) of Herzog et al. (2003), we calculate these prices endogenously in DEMETER, which prove to become closest to their case (3). Unlike their study, we calculate the most efficient level of CCS deployment, based on and consistent with our effectiveness measure η_t. Our analysis has thereby elements in common with van't Veld and Plantinga (2005), who determine the optimal share of carbon sequestration through forestry in a context of increasing carbon prices.

Let us first consider the special case of exponential leakage, that is, when the leakage rate is assumed constant at value λ. We also suppose that CCS technology is characterised by an energy penalty $1 - c$, so that a share of $1 - c$ of the energy content of the primary fuel is required to operate the CCS process. Hence, in order to avoid one unit of CO_2 through CCS implementation, we need to capture and store $1/c$ units of CO_2 ($0 < c < 1$). The moment of storage is referred to as period $s = 0$, and at every future point in time, given the constant leakage rate, an amount equal to $(\lambda/c)\, e^{-\lambda s}$ will leak back to the atmosphere. When carbon taxes increase exponentially at rate g, so that $\tau_{t+s} = e^{gs}\tau_t$, we find:

$$\eta_t = \frac{\tau_t - \int_0^\infty e^{(g-r-\lambda)s}\frac{\lambda}{c}\tau_t ds}{\tau_t} = 1 - \frac{\lambda/c}{\lambda + r - g}. \tag{2}$$

This relation expresses correctly that for zero leakage, $\lambda = 0$, the storage effectiveness is 100%. In this case, fossil fuel combustion combined with CCS technology should thus be fully exempt from the carbon tax. In the hypothetical extreme case of infinite leakage, $\lambda \to \infty$, the CCS effectiveness becomes negative. Consequently, since CCS is a costly technology, it will not be deployed at all. An additional important special case is when the atmospheric CO_2 uptake is modelled as an exhaustible resource, that is, when a ceiling is set to the total cumulative amount of CO_2 that can be emitted into the atmosphere. In this case the carbon tax follows the Hotelling rule, i.e. its growth rate equals the real interest rate, $g = r$ (Hotelling 1931). Equation 2 then shows, for any positive leakage, $\lambda > 0$, that the CCS effectiveness is negative, $\eta < 0$ (when $c < 1$; $\eta = 0$ when $c = 1$), so that CCS deployment is senseless. In reality, however, we know that substantial part of the atmospheric CO_2 is absorbed by the ocean and biosphere through a series of natural feedback mechanisms, so that no absolute ceiling exists on the cumulative allowable amount of CO_2 emissions. Let us assume that the atmospheric CO_2 decays at a rate ε associated with this natural feedback system, so that for a given climate stabilization scenario the carbon tax typically increases at a reduced rate of $g = r - \varepsilon$. According to relation (2), the CCS effectiveness then becomes $\eta_t = (\varepsilon - (c^{-1} - 1)\lambda)/(\lambda + \varepsilon)$. If one takes an energy penalty of 30%, i.e. $c = 0.7$, while $\varepsilon = 1\%$/year (a typical figure found in the climate science literature) and $\lambda = 1\%$/year (i.e. a storage lifetime of 100 years, considered by most geo-scientists as a conservative upper limit for well-chosen storage sites), the CCS effectiveness becomes $\eta = 29\%$. When $\lambda = 0.5\%$/year (i.e. a storage lifetime of 200 years), we get $\eta = 52\%$. When the climate is stabilized in terms of the atmospheric CO_2 content and carbon taxes can thus remain constant, so that $g = 0$, we similarly obtain an effectiveness $\eta_t = \left(r - \left(c^{-1} - 1\right)\lambda\right)/(\lambda + r)$. For a 5%/year real interest rate and $\lambda = 1\%$/year we then have $\eta = 76\%$, while for $\lambda = 0.5\%$/year we find $\eta = 87\%$. These results are listed in Table 1.

Let us now contemplate the case in which leakage does not follow an exponential decay, i.e. the leakage rate is not constant, like in Herzog et al. (2003). They analyse a more complex model (as applicable to CO_2 storage in the ocean) that can be interpreted as CO_2 being stored in a medium in which it passes through multiple layers before it leaks back to the atmosphere. The cumulative fraction leaked to the atmosphere, expressed as a ratio with respect to the CO_2 initially stored, then

Table 1 CCS effectiveness under two leakage models and different assumptions regarding (1) the carbon tax growth rate relative to the interest rate and (2) the average storage life-time ($c = 0.7$)

Interest rate—carbon tax growth rate ($r - g$; %/ year)	Average storage life-time of total system (1/ λ; year)	Effectiveness exponential model (η; %)	Effectiveness two-layer model (η; %)
1	100	29	37
1	200	52	64
5	100	76	88
5	200	87	96

The case of $r - g = \varepsilon \approx 1\%$/year can be understood as representing the early phase of a global CO_2 stabilization program. Similarly, the case of $r - g = r = \varepsilon \approx 5\%$/year strongly resembles the long-term phase of such a program with constant carbon tax levels (g=0). This interpretation we confirm later when numerically calculating time paths for η (see Fig. 8) and compare these with the values reported in Table 1

follows an S-shape. In addition to investigating exponential leakage, in this paper we also make an approximation leakage model of Herzog et al., which we do through a two-layer simulation. Figures 1 and 2 depict three different seepage models that we use in our analysis, in terms of annual leakage and cumulative leakage respectively. The first model assumes an exponential leakage curve, for which CO_2 on average takes 100 years to seep back to the atmosphere. The second model is a two-layer system, in which CO_2 on average takes 50 years to pass through each of the two layers. In the Appendix we show that the average time of residence of CO_2 in the totality of this two-layer system is thus 100 years, like in the exponential seepage case. Figure 1 shows that the two layers in sequence produce a hump-shaped annual leakage curve with maximum leakage after about 50 years. This figure also graphically demonstrates that the average storage lifetime of CO_2 before it leaks back to the atmosphere is approximately equal for these two models (amounting indeed to precisely 100 years in each case). The third model is also a two-layer system, but with each of the layers characterized by an average CO_2 lifetime of 100 years, so that the overall time of residence in the total system is on average 200 years. Each of these three models represents a relatively high leakage rate in comparison to the series considered in Herzog et al. (2003), which explains that our calculations prove to be relatively more conservative with respect to the extent of use of CO_2 storage (*in case geological* CCS).

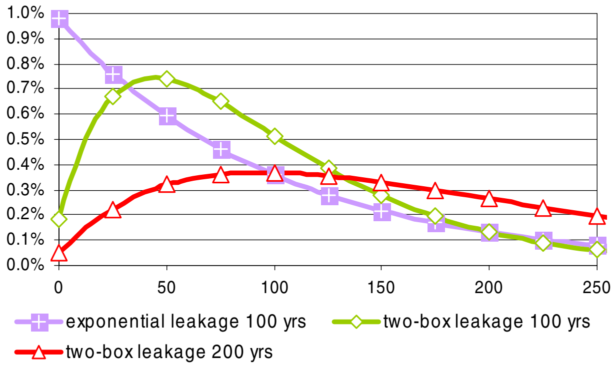
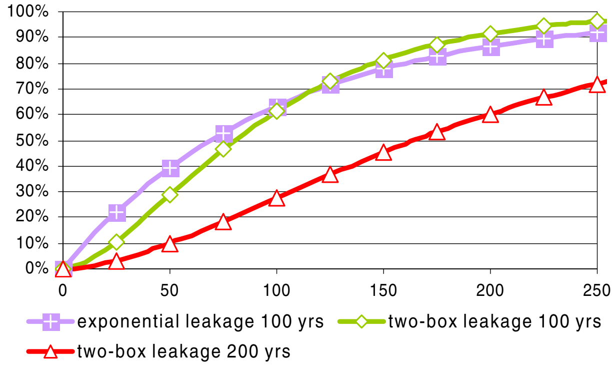


Fig. 1 Annual leakage as percentage of the initially stored CO_2 in an exponential model and two two-layer models (lifetime specified)

Fig. 2 Cumulative fraction leaked as percentage of the initially stored CO_2 in an exponential model and two two-layer models (lifetime specified)



Of course, the economic effectiveness of CCS, as described through η_t in Eq. 1, does not only depend on the average time that CO_2 is stored away from the atmosphere, but also on the precise path of leakage back to it. For an exponential decay at rate λ, the expected storage time is 1/λ years and the corresponding CCS effectiveness is described by relation 2. If we use the two-layer model, with leakage rate 2λ from layer 1 to layer 2, and the same leakage rate 2λ from layer 2 to the atmosphere, the expected storage time is also 1/λ years, but the effectiveness of CCS is given by (see the Appendix for a derivation):

$$\eta_t = 1 - c^{-1}\left(\frac{2\lambda}{2\lambda + r - g}\right)^2. \tag{3}$$

By comparing Eqs. 2 and 3, both derived under the assumption of an exponentially growing carbon tax, one can easily show that CO_2 storage with exponential leakage has a lower effectiveness than a two-layer leakage system when both have the same expected storage time 1/λ (see again the Appendix for a proof of the corresponding inequality). Table 1 points this out by presenting the results of CCS effectiveness calculations for both the exponential and the two-layer model, for carbon taxes rising with 1%/year less than the interest rate and for constant carbon taxes with a 5%/year interest rate, under the assumption that the energy penalty is 30%.

3 DEMETER with CCS and leakage

To perform our analysis we use a top-down energy–economy–environment model. We recently developed a long-term dynamic top-down model of the global economy that simulates the use of fossil fuels, non-fossil energy, and an energy technology decarbonising fossil fuels through CCS (Gerlagh and van der Zwaan 2006). This model, including a basic climate module and generic production and consumption behavior, is an extension of DEMETER that previously has been instrumental in our study of several climate policy queries (see van der Zwaan et al. 2002; Gerlagh and van der Zwaan 2003, 2004; Gerlagh et al. 2004; van der Zwaan and Gerlagh 2006). DEMETER contributes to bridging research of endogenous growth (such as Bovenberg and Smulders 1996, and Chakravorty et al. 1997) with top-down integrated assessment analyses of the economics of 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 more elaborate especially in technological detail than this reduced-form top-down formulation of the problem of climate change. DEMETER shares the endogenization of technical change through learning curves with bottom-up models as developed by Messner (1997), reported in e.g. Nakićenović et al. (2000) and used in a series of engineering energy systems models (such as in Smekens and van der Zwaan 2006). In this sense, DEMETER is fundamentally hybrid and, because of its endogenous cost definition, fit for analysing long-term energy technology cost dynamics and deriving practical insight for climate policy making (Jaccard et al. 2003).

In a preceding article with DEMETER (Gerlagh and van der Zwaan 2006) we analysed the types of economic instruments that can be used to address the problem of climate change, as well as the incentives available to induce technical change towards physical emission reduction options like CCS, in a way similar to the work by Fischer and Newell (2004). We observed that an increasing number of existing (especially but not solely bottom-up) models are today able to simulate the deployment of CCS technologies (see e.g. Riahi et al. 2004, and Smekens and van der Zwaan 2006). Models abound, however, that still need to be expanded to include CCS technology, and especially only few top-down models are available that incorporate CCS opportunities.[3] The novelty of our analysis was to present a top-down model that includes CCS and a rich endogenous technological cost reduction representation through the simulation of learning curves. Because we modelled a more detailed specification of energy supply—in the new version of DEMETER we distinguish between energy savings, a switch from fossil fuels to non-carbon energy sources, and the decarbonisation of fossil fuels e.g. through CCS—our work extended that by Ha-Duong and Keith (2003), who incorporated CCS in their top-down DIAM model, and Keller et al. (2003), who included CCS in the top-down RICE model. We included a CCS supply curve with non-constant marginal costs, whereas Ha-Duong and Keith (2003) and Keller et al. (2003) mainly focus on the economic value of CCS, including CO_2 leakage, as an additional abatement option with fixed marginal costs, in an inter-temporal emission reduction scheme. In this paper we again use our updated version of DEMETER, and further expand it to reflect the phenomenon of CO_2 leakage.

DEMETER models a representative infinitely-living consumer who maximizes welfare under a set of equilibrium conditions and a range of (*inter alia* climate change) constraints. Solving the program involves the quantification of a combination of policy instruments and calculation of dynamic time-paths for a series of economic and energy-specific variables that lead to an optimal aggregated and discounted overall welfare. The climate change dynamics used are as in DICE, involving a multi-layer system with an atmosphere and upper- and lower-ocean stratum (Nordhaus and Boyer 2000). As DEMETER has been used in a few papers already, that include extensive accounts of the adopted simulation characteristics, we restrict ourselves here to a concise presentation of its main features only, mostly as related to CCS. We refer in particular to Gerlagh et al. (2004) for an extensive

[3]In a recent overview by Edenhofer et al. (2006) of ten models, five proved to simulate CCS in some form or another, while only two of these five were top-down (the other three being bottom-up).

general description of the model and to Gerlagh and van der Zwaan (2006) for more details on the specification of CCS.[4]

To summarize briefly, there are four representative producers and corresponding sectors, denoted by superscripts $j = C, F, N$, CCS, for the producer of the final good, the producer of energy based on fossil-fuel technology, respectively carbon-free technology, and the producer of CCS technology. Output of the final good sector is denoted by Y^C. This good is used for consumption C, investments I in all four sectors, operation & maintenance M in both energy sectors and the application of CCS technology to the fossil energy sector. Our distinction between investments costs and operation & maintenance costs is in line with most bottom-up energy system models. Fossil-fuel energy is demanded by the final good sector and supplied by the fossil-fuel energy sector. Likewise, carbon-free energy is demanded by the final good sector and supplied by the carbon-free energy sector. The fossil-fuel sector demands CCS technology from the CCS sector when CO_2 taxes are levied. The price of fossil-fuel energy consists of three parts: energy production costs (I and M), costs of applying CCS and CO_2 taxes. The representative producer maximizes the NPV of its cash flow.

There is a public agent that sets taxes to CO_2 emissions and provides subsidies to the use of non-carbon energy. Both these policy instruments serve to reduce CO_2 emissions. When this central agent imposes a carbon tax, one of the possible reactions of the entire economic system is a reduction in overall energy consumption. Producers can also shift from fossil fuels to carbon-free energy, or, alternatively, decarbonize fossil-based energy production through the application of CCS. The level of CO_2 emissions, Em_t, is proportional to the use of fossil fuel energy, Y_t^F. Equation 4 expresses how Em_t is obtained through a multiplication of Y_t^F by the carbon content of fossil fuels, ε_t^F, and $1 - \mathrm{CCSR}_t$, in which CCSR_t represents the share of CO_2 emissions captured and stored through CCS technology application. Like in van der Zwaan and Gerlagh (2008), CO_2 emissions from current fossil fuel use (Em_t) are complemented by additional emissions generated from geological leakage of previously stored CO_2 (Lk_t). Unlike in van der Zwaan and Gerlagh (2008), however, where we assumed a constant leakage rate, we here adopt both a one-layer and two-layer storage model as specified in the previous section. The way we implement the two-layer model in DEMETER is described here. The case of constant seepage, associated with a one-layer or exponential leakage model, is a straightforward simplification of this two-layer model.

The stock of CO_2 in layer 1 as a result of CCS activity is indicated by S^1. Likewise, the stock of CO_2 in layer 2 as a result of CO_2 flowing from layer 1 to layer 2 is indicated by S^2. From storage layer 1, every period a share λ_1 leaks to layer 2, while from layer 2 a share λ_2 leaks into the atmosphere. Given the energy penalty incurred of $1 - c$, the effective energy content of fossil fuels is reduced by a factor $1/c$. In other words, when we want to produce a certain amount of energy Y_t^F complemented with CCS, the amount of CO_2 captured and stored is larger than the emissions would have been without CCS. These assumptions explain Eqs. 4 to 6. We now formulate our expression for the effectiveness of CCS, as reported in Eq. 1, in terms of shadow prices as indicated in Eq. 9. Indeed, the CCS effectiveness η_t can be calculated on the

[4]A full description of the model is also available from the authors.

basis of the ratio between the shadow price of storing CO_2 in the first layer, τ_t^1, and the shadow price of storing CO_2 in the atmosphere, τ_t (the carbon tax), corrected for the energy penalty coefficient c. Given the carbon tax, we can calculate the shadow prices for the two storage layers backwards (see Eqs. 7 and 8). Equation 7 expresses that the shadow price for CO_2 in layer 2, τ_t^2, is equal to the next period shadow price for CO_2 in the atmosphere multiplied by the leakage rate from layer 2 to the atmosphere plus the next period shadow price of CO_2 in layer 2 multiplied by the share of CO_2 that remains in this layer. Equation 8 similarly expresses that the shadow price in layer 1 equals the next period shadow price in layer 1 multiplied by the CO_2 share that remains in this layer plus the shadow price for layer 2 multiplied by the leakage rate from layer 1 to layer 2. Both Eqs. 7 and 8 use the time-dependent depreciation factor between period t and $t+1$, $\beta_t = 1/(1+r_t)$, in which r_t is the real interest rate. The real interest rate is linked to consumption growth on the basis of the Ramsey rule (see notably Gerlagh et al. 2004).

$$\mathrm{Em}_t + \mathrm{Lk}_t = \varepsilon_t^F \left(1 - \mathrm{CCSR}_t\right) Y_t^F + \lambda_2 S_t^2, \tag{4}$$

$$S_{t+1}^1 = \left(1 - \lambda_1\right) S_t^1 + \frac{\mathrm{CCSR}_t \varepsilon_t^F Y_t^F}{c}, \tag{5}$$

$$S_{t+1}^2 = \left(1 - \lambda_2\right) S_t^2 + \lambda_1 S_t^1, \tag{6}$$

$$\tau_t^2 = \beta_t \left(\left(1 - \lambda_2\right) \tau_{t+1}^2 + \lambda_2 \tau_{t+1}\right), \tag{7}$$

$$\tau_t^1 = \beta_t \left(\left(1 - \lambda_1\right) \tau_{t+1}^1 + \lambda_1 \tau_{t+1}^2\right), \tag{8}$$

$$\eta_t = 1 - \frac{\tau_t^1}{c\tau_t}. \tag{9}$$

The CO_2 capture and storage process is described through an effort variable Q_t^{CCS}, assumed to be a second-order polynomial function depending on the share of CO_2 captured and stored (see Eq. 10). As all economic activity is described per vintage, we distinguish between latest and older vintages: tildes on top of variables refer to the most recent vintage installed (see e.g. for the fossil-fuel use Y_t^F). The parameter κ describes the increase in marginal costs when a higher share of fossil fuels is decarbonized. For $\kappa = 0$, in one period, costs of CCS are linear and marginal costs are constant. For $\kappa = 1$, marginal costs double when the share of fossil fuels to which CCS is applied increases from almost nothing to all fossil fuels being used. This specification constitutes an important extension of the work by Ha-Duong and Keith (2003) and Keller et al. (2003). In DEMETER, the low-cost CCS options are used first, when CO_2 taxes are low, while more expensive CCS alternatives are added to the set of applied CCS technologies under higher CO_2 taxes: these higher taxes justify the more elevated expenses and effort per unit of reduced CO_2 emissions. CCS technology is only implemented in response to CO_2 taxes. Under constant investment and maintenance prices, the share of fossil-fuel energy from which CO_2 is captured and stored is assumed to be linear in the CO_2 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 (Eq. 10), the resulting (installation and operation) experience, X_t^{CCS} (Eq. 11), leads to an enhancement of related knowledge, and a corresponding decrease in the cost parameter h_t^{CCS} (Eq. 12). In this equation, c^{CCS} and d^{CCS} are constant technology parameters describing the learning curve for CCS. When experience X_t^{CCS} accumulates, CCS options become cheaper, and, for constant CO_2 taxes, more CCS technology is applied. Investments, one period before, are proportional to effort Q_t^{CCS} (Eq. 13), and so are maintenance costs (Eq. 14). Parameters a^{CCS} and b^{CCS} define investment and maintenance flows required for one unit of effort Q_t^{CCS}. In every period, CCS maintenance costs are summed over all vintages (Eq. 15). Parameter δ denotes the share of vintage capital depreciated per period.

$$Q_t^{\text{CCS}} = h_t^{\text{CCS}} \left(\text{CCSR}_t + \frac{1}{2} \kappa \text{CCSR}_t^2 \right) \varepsilon_t^F \tilde{Y}_t^F, \tag{10}$$

$$X_{t+1}^{\text{CCS}} = X_t^{\text{CCS}} + \text{CCSR}_t \varepsilon_t^F \tilde{Y}_t^F. \tag{11}$$

$$h_t^{\text{ccs}} = 1 + c^{\text{ccs}} \left(1 - d^{\text{ccs}}\right) \left(X_t^{\text{ccs}}\right)^{-d^{\text{ccs}}}. \tag{12}$$

$$I_{t-1}^{\text{CCS}} = Q_t^{\text{CCS}} / a^{\text{CCS}}, \tag{13}$$

$$\tilde{M}_t^{\text{CCS}} = Q_t^{\text{CCS}} / b^{\text{CCS}}. \tag{14}$$

$$M_t^{\text{CCS}} = (1 - \delta)\, M_{t-1}^{\text{CCS}} + \tilde{M}_t^{\text{CCS}}. \tag{15}$$

Like with its previous versions, DEMETER has been calibrated extensively to reflect as closely as possible the global economy and energy system. For more details about the calibration procedure we refer to our earlier publications (van der Zwaan et al. 2002; Gerlagh and van der Zwaan 2003, 2004; Gerlagh et al. 2004). The extent to which CCS technology can contribute to GHG emission control and atmospheric CO_2 concentration stabilization will, to a large extent, be determined by its cost. Our assumptions regarding the cost ranges of CCS are described in Gerlagh and van der Zwaan (2006). In brief, we suppose a series of different CCS options is available, with prices from low to relatively high levels. In the first modelling period we assume that the initial installation of CCS technology can be economically feasible at marginal costs of around 10 \$/tC avoided. At the high-cost end, when one nears the point of equipping all fossil-fuel electricity generation with CCS, we presume that marginal costs are as high as 150 \$/tC avoided. This high-cost value corresponds to the average of the typical cost ranges as provided by the IPCC (2005). For comparison, Ha-Duong and Keith (2003) assume constant initial marginal CCS costs of 75 \$/tC, while Keller et al. (2003) assume constant initial costs of 100 \$/tC. As for the prospected cost reduction potential of CCS technology we follow the current learning curve literature and adopt a value of 10% for the corresponding learning rate (IEA/OECD 2000; McDonald and Schrattenholzer 2001; Rubin et al. 2004). We assume that the above CCS cost estimates and cost reduction potential are applicable for an initial level of cumulative experience with installed CCS capacity of $X_t^{\text{CCS}} = 20$ MtC/year. Furthermore, we assume that at most 50% of total fossil fuel consumption can be complemented with CCS technology, which reflects that, in contrast to the electricity sector, the transport sector remains little susceptible to CCS application during the foreseeable future, and that, while developed countries can today in principle readily afford CCS technology, many developing countries for the moment still can probably not.[5]

4 Simulation results

Unlike in van der Zwaan and Gerlagh (2008), the results of which we do not wish to unnecessarily repeat here, we abstain from presenting our business-as-usual scenario. We refer to our previous paper also for the cross-check we performed regarding the internal consistency of our model under different climate stabilization scenarios. In that paper we investigated the 450, 475, 500, 525 and 550 ppmv stabilization scenarios, and confirmed that DEMETER generates for each of these atmospheric CO_2 concentration targets the CO_2 emission profiles as reported in the scientific climate policy and carbon cycle literature (see e.g. Wigley et al. 1996). We here define seven scenarios that allow us to analyse the significance of CO_2 leakage for climate change policy making. These seven scenarios reflect cases in which a CO_2 stabilization target is reached through the imposition of a carbon tax. In each of the seven scenarios we have opted for imposing a stringent climate control target, that is, of 450 ppmv atmospheric CO_2 concentration[6], while they differ in the assumed CO_2 leakage rate. In all seven climate-constrained scenarios the timing and extent of the implementation of new energy technologies, as well as those of the corresponding CO_2 emission reductions, are calculated through the welfare maximization program as described in Section 3.

No_CCS: Climate stabilization is reached without the use of geological CCS, e.g. since it is characterized by *unacceptably high leakage*.

No_leakage: Climate stabilization is reached partly through CCS, as there is *no leakage* associated with geological CO_2 storage.

2L_200 yrs: Climate stabilization is reached partly through CCS, but geologically stored CO_2 seeps to the atmosphere according to a *two-layer model* with an expected lifetime of *200 years*.

2L_100 yrs: Climate stabilization is reached partly through CCS, but geologically stored CO_2 seeps to the atmosphere according to a *two-layer model* with an expected lifetime of *100 years*.

1L_200 yrs: Climate stabilization is reached partly through CCS, but geologically stored CO_2 seeps to the atmosphere according to a *one-layer model* with an expected lifetime of *200 years*.

[5] Also for programmatic reasons the introduction of this upper limit proves desirable, since otherwise DEMETER generates unrealistically high carbon taxes when CO_2 leakage is simulated as it leads to the need for almost zero additional emissions and no further leaking options in later periods.

[6] Non-energy-related CO_2 emissions are exogenously included in the ceiling. Greenhouse gas emissions other than CO_2 are not simulated and thus excluded from the ceiling. The overall CO_2-equivalent greenhouse gas concentration will thus considerably exceed the imposed constraint of 450 ppmv.

1L_100 yrs: Climate stabilization is reached partly through CCS, but geologically stored CO_2 seeps to the atmosphere according to a *one-layer model* with an expected lifetime of *100 years*.

1L_50 yrs: Climate stabilization is reached partly through CCS, but geologically stored CO_2 seeps to the atmosphere according to a *one-layer model* with an expected lifetime of *50 Years*.

Figure 3 shows the CO_2 emission profile (Em_t in Eq. 4) when a climate stabilization target of 450 ppmv is adopted for the five scenarios with leakage of CO_2 plus the scenario in which no CCS is available. Given the timeframe over which leakage takes place, it is not justified to analyse our findings over the twenty-first century only, as we did in our previous work with DEMETER. We have thus extended the presentation of our results up to 2200 (while we run the model until 2400), as can be seen from Fig. 3. As expected, the emission profile during the first half of this century is essentially the same irrespective of the leakage rate by which the CCS mitigation option is characterised. The six curves also demonstrate, however, that differences start to occur between the scenarios around the second half of the century, and that their divergence becomes fairly significant during the twenty-second century. Clearly, when CCS is characterised by leakage significantly less emissions are allowed from the energy system than when no CCS is used (and thus only renewables), because stored CO_2 constitutes an additional source of emissions in the former case. Between the five leakage scenarios differences occur as a result of the different underground CO_2 storage lifetimes and the different profiles of this CO_2 leaking to the atmosphere, which results in different economic trade-offs between reaching the stringent climate goal and implementing costly but climate-friendly energy technologies. Figure 4 depicts the annual amounts of CO_2 that are stored underground in the five scenarios with leakage of CO_2 plus the scenario in which CCS is not affected by leakage. Clearly, among these scenarios the no-leakage case leads in the amounts of CO_2 yearly stored away from the atmosphere. The amounts stored level off between 3.5 and 4.0 GtC/year during the second half of this century, mainly because non-carbon energy resources are sufficiently competitive by then to substitute for CCS-complemented fossil fuels. For each of the two leakage models (one-layer and two-layer) we also see that the longer the expected time that CO_2 remains geologically stored, the more CO_2 is calculated optimal to avoid through CCS. Furthermore, the two-layer model is preferred above the one-layer model in terms of the amount of CCS it allows (at least during the twenty-first century), even

Fig. 3 CO_2 emissions (GtC per year) for various leakage scenarios

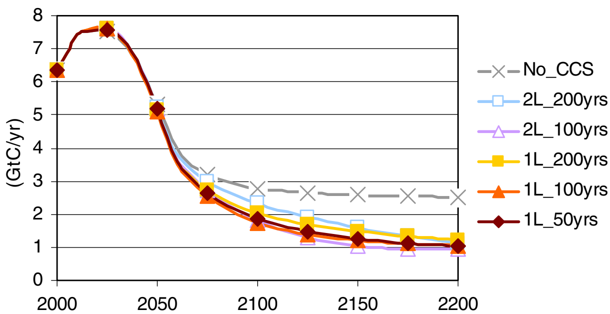
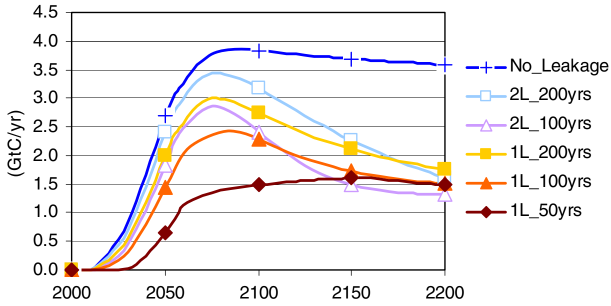


Fig. 4 CO_2 stored underground (GtC per year) for various leakage scenarios



when they yield the same CO_2 storage time, because the former initially postpones seepage further to the future (which is correspondingly discounted).

Figure 5 depicts the cumulative amount of geologically stored CO_2 resulting from CCS activity as a function of time, under the 450 ppmv climate stabilization target and for the six CO_2 leakage scenarios of Fig. 4. Clearly, if geological CCS is not subject to undesirable leakage effects, the integrated quantity of geologically stored CO_2 increases steadily, and monotonically, reaching globally an amount of well over 200 GtC in 2100 and 600 GtC in 2200 (upper curve in Fig. 5). When geological CO_2 storage is imperfect and provokes a non-negligible but limited leakage profile, with either a constant rate (as in the one-layer model) or a bell-shaped rate (as in the two-layer model), the cumulative geological CO_2 storage curve lowers with respect to that of the first scenario: in 2100 the integrated amount of CO_2 stored underground during this century reaches approximately 200, 160, 140, 110 and 50 GtC for the leakage scenarios 2L_200 yrs, 1L_200 yrs, 2L_100 yrs, 1L_100 yrs and 1L_50 yrs, respectively. After 2100, the stock further builds up but not as steeply as during this century. The ordering between the curves in Fig. 5 can be explained in the same way as for those in Fig. 4.

In Fig. 6 the geological CO_2 seepage process is plotted per annum. The curves in Fig. 6 together with those of Figs. 3, 4 and 5 constitute a complete set describing the dynamics of CCS activity and associated CO_2 flows for each of the different scenarios and underlying leakage profiles. We see from Fig. 6 that the scenarios represent widely diverging leakage rates in 2100, between 0.4 and 1.0 GtC/year, while in 2200, with levels that are much higher, the range significantly narrows, to values between 1.2 and 1.6 GtC/year. This finding is consistent with the results depicted in

Fig. 5 Cumulative geological CO_2 storage (GtC) for various leakage scenarios

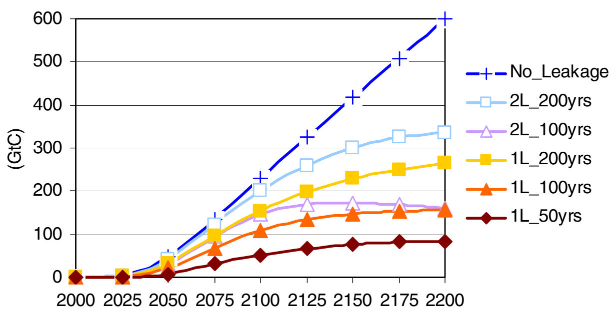
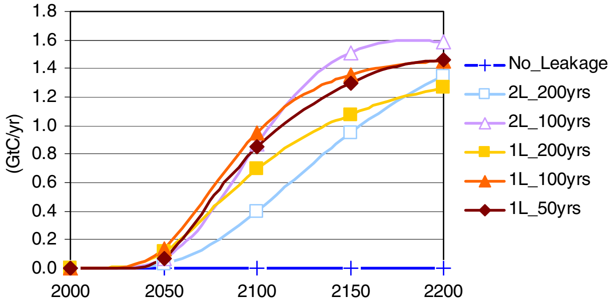


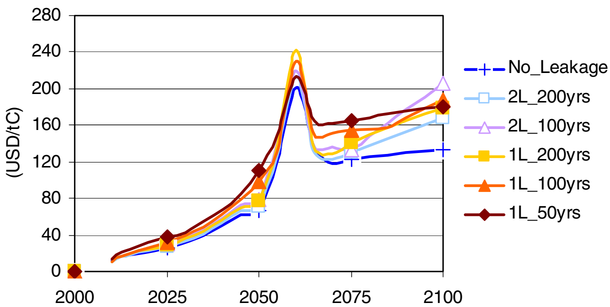
Fig. 6 Annual geological CO_2 seepage (GtC per year) for various leakage scenarios



the previous figures. The results of Figs. 5 and 6 match in the sense that the prevailing leakage rates applied to the cumulated amounts of CO_2 stored underground e.g. in 2200 (Fig. 5) yield, of course, the annual amounts of seepage in that year (Fig. 6). We also see that, when there is substantial leakage on the time scale of centuries (with leakage rates of about 0.5%/year and higher as in our case), the long-term CO_2 storage level per annum will be about equal to the long-term annual amount of CO_2 leakage (cf. Figs. 4 and 6), with in our case a value of typically about 1.5 GtC/year. Under a climate constraint this value cannot in any case exceed the uptake potential of CO_2 by the Earth's biogeochemical system, of about 2.5 GtC/year. We find that in the longer term leakage is responsible for slightly above half of the amount of CO_2 that this system (essentially the oceans and land biomass) is capable of absorbing and depreciating. This interpretation has two main implications. First, a higher leakage rate does not so much render CCS economically unattractive. Rather, leakage puts a limit to the cumulative amount of CO_2 that can be stored underground. The leakage rate thus determines the magnitude of the contribution of CCS to the goal of globally reducing CO_2 emissions. The horizontally bending curves of Fig. 5 demonstrate this neatly. Second, even whereas CCS characterized by CO_2 leakage proves still to be very profitable, the need for non-carbon energy resources to mitigate climate change is not diminished. CCS plus leakage only delays their introduction.

As demonstrated in our previous analyses with DEMETER, the adoption of an appropriate policy instrument is indispensable for reaching any climate stabilization target and the realization of the geological storage of CO_2—carbon taxation proves to be both particularly effective and efficient (Gerlagh and van der Zwaan 2006). Figure 7 shows the carbon tax path that DEMETER calculates to be optimal to

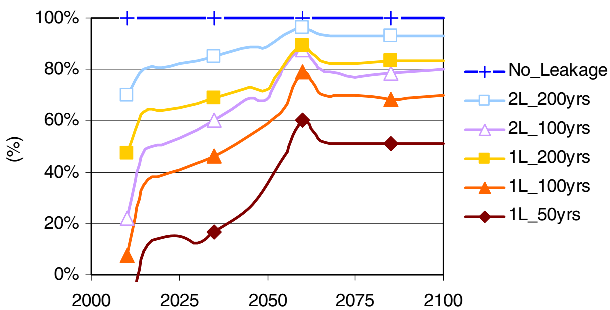
Fig. 7 CO_2 tax (US$ per tC) for various leakage scenarios



achieve a 450 ppmv climate stabilization target under varying assumptions regarding the CO_2 leakage profile associated with CCS technology application. In all six scenarios, the carbon tax increases almost exponentially during the first half of the twenty-first century, but then, after a rebound peak (when the emissions ceiling becomes binding), levels off after about 2060 to remain within a bandwidth of 120 and 200 US$/tC depending on the leakage scenario under consideration. The overall ranking between the scenarios can be understood by the rule of thumb that higher taxation is required when CCS is characterised by more leakage of CO_2, since under accrued seepage less climate mitigation potential is available through CCS, which necessitates stronger policy incentives to stimulate the other non-carbon resource renewables. Also, with CCS being deployed with a higher leakage rate during early stages, there is a higher level of unavoidable emissions from geological seepage in later periods (that then start constituting a kind of background source), which implies a stronger reliance on renewables and hence higher tax levels to stimulate these carbon-free energy resources. The tax profile depicted in Fig. 7 resembles closely that of Case 3 in Herzog et al. (2003), which helps us to explain that the CCS effectiveness values we calculate are similar to their Case 3 figures (with $t^* \approx 50$ year).

Figure 8 depicts the CCS effectiveness calculated by DEMETER in each of the six scenarios as a function of time. Of course, when there is no leakage, CCS is 100% effective as carbon mitigation option, as shown by the horizontal line in this figure. We reported in Table 1 values for the CCS effectiveness parameter, purely based on calculations with our analytical expressions (2) and (3). We can now confirm these values with numerical simulations with our integrated assessment model DEMETER, as shown in Fig. 8. With an interest rate $r \approx 5\%$/year, and the tax values as in Fig. 7 (with a growth rate $g \approx 4\%$/year before 2060 and $g \approx 0\%$/year after 2060), it proves that we reproduce closely the cases presented in Table 1 (corresponding to, respectively, the rows with $r - g \approx 1\%$/year and $r - g \approx 5\%$/year for each of the cases with 100 and 200 year storage lifetime and the one- and two-layer model). As Fig. 8 demonstrates, when the carbon tax growth rate is high (as is the case during the first half of the century), the CCS effectiveness is relatively low, typically between about 20% and 70% (when considering the 100 and 200 year lifetime cases), with higher values when the storage lifetime is higher or when leakage resembles more closely a two-layer rather than a one-layer model. Figure 8 also points out that when the carbon tax growth rate is reduced to values close to zero (as is the case during the second half of the century), the CCS effectiveness becomes significantly higher, typically with values between about 70% and close to 100%,

Fig. 8 CCS effectiveness (percent) for various leakage scenarios



again with higher values when the storage lifetime is elevated or when leakage can be better described by a two-layer than a one-layer model.

5 Top-down versus bottom-up modelling

The issues addressed above with a top-down energy–economy–environment model can also be analysed with a bottom-up energy system model. While it is difficult to draw any general conclusion, it proves that results obtained with these two complementary approaches may at least in some cases differ non-negligibly. As an example we here compare the top-down model DEMETER with the bottom-up model MARKAL, demonstrate that we obtain diverging results with these two models in terms of the economics of CO_2 storage and leakage, and investigate how these different findings should be interpreted and can be understood.

Like DEMETER, MARKAL was recently expanded to account for the simulation of CCS technology. The new MARKAL version not only includes a representation of a range of CO_2 capture technologies and storage options, but also reflects environmental externalities induced by geological CO_2 storage and leakage of CO_2 from underground storage formations, as described in, respectively, Smekens and van der Zwaan (2006) and van der Zwaan and Smekens (2008). With both DEMETER and MARKAL we find that, even under a CO_2 leakage rate of 0.5%/year (or lower), CCS develops significantly during the twenty-first century and as such contributes substantially to mitigating global climate change. If the CO_2 leakage rate is as high as 1%/year, however, with MARKAL CCS disappears almost entirely from the fossil-based power sector except for a small contribution by 2100 (see Fig. 1 in van der Zwaan and Smekens 2008). With DEMETER, on the other hand, lots of new capacity of fossil fuel energy production is equipped with CCS during the latter half of this century irrespective of a CO_2 leakage rate as high as 1%/year (or even more). Indeed, Fig. 5 shows that when the expected CO_2 storage lifetime is 100 to 200 years (which in the one-layer case corresponds to a constant leakage rate of 1% and 0.5%/year, respectively) still large amounts of CO_2 are stored underground (and even with a 2%/year leakage rate the cumulative amount of CO_2 geologically stored is still some 50 GtC in 2100). In a DEMETER–MARKAL comparison, 0.5%/year CO_2 leakage proves to be the breaking-point beyond which modelling results start to fundamentally differ from each other. For MARKAL the amount of geologically stored CO_2 integrated over all sectors (that is, fossil-based power production, biomass-based power production, hydrogen production and industry) is decimated when adopting in scenario simulations a leakage rate of 1%/year instead of 0.5%/year (typically to about a quarter of the original quantity stored), while for DEMETER this amount is only reduced by a fraction (of around 30%). With DEMETER even under a leakage rate of up to 2%/year still significant economic interest exists to invest in CCS. For MARKAL, on the other hand, under such a high leakage rate CCS technology fully disappears from the modelling solution.

There are several reasons for the differences in results found with DEMETER and MARKAL. Fundamental disparities exist between these two models, since with MARKAL we mostly inspect the power sector and focus on Western Europe, while with DEMETER we simulate the entire world energy economy, rather than only part of it, and assume global cooperation. Between these two models, CO_2 emission

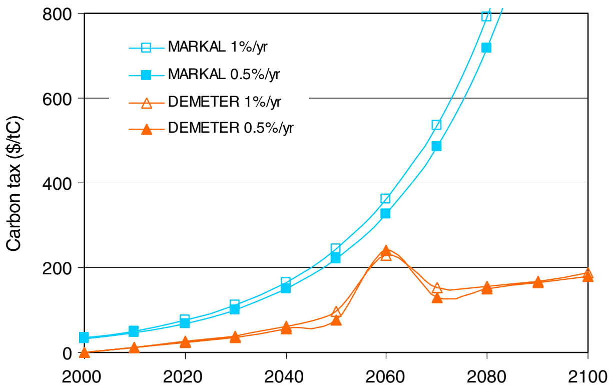


Fig. 9 Optimal CO_2 tax (in US$ per tC) as calculated by MARKAL and DEMETER under a stringent climate constraint of 450 ppmv for two values of a constant leakage rate (1% and 0.5%/year)

and tax levels can thus also expected to be different. Naturally, in particular their different regional focus implies diverging CO_2 tax paths, since the fulfilment of part of a global climate target strongly depends on local conditions. Whereas DEMETER simulates a rudimentary carbon-cycle, which allows calculating the approximate climatic consistency between a CO_2 emission path and a CO_2 concentration target, MARKAL simply sets a ceiling to the total cumulative amount of CO_2 that can be emitted (in Western Europe) during the twenty-first century. In MARKAL, the atmosphere is thus an exhaustible resource and CO_2 can be emitted through the use of an allowance, the price of which can be interpreted as the carbon tax. The allowance is valid for any year in the century, and, consequently, the net present value of the allowance must be about the same in 2010 as in 2100. In other words, CO_2 taxes in MARKAL must more-or-less follow the Hotelling rule, and hence grow exponentially with the interest rate.[7] On the other hand, MARKAL plans over a finite horizon and there is no leakage considered for the CO_2 stored at the end of the simulation period.[8] Indeed, Fig. 9 shows that the CO_2 tax as calculated by MARKAL and DEMETER under a stringent climate constraint of 450 ppmv behaves pretty much the same until the middle of the century. From around 2050, however, strong differences in these tax paths start to occur: while CO_2 taxes in DEMETER level off during the second half of the century to values close to 200 $/tC, in MARKAL they continue to increase exponentially to reach much higher values by the end of the simulation horizon. The explanation for the relatively low CO_2 taxes in DEMETER at the end of the century is that, as a result of optimistic assumptions regarding the learning potential of renewables, these new technologies eventually fall below the competitive (fossil-fuel based) break-even price (for an extensive description of these features see van der Zwaan et al. 2002, and Gerlagh et al. 2004). In combination with the assumed natural uptake of part of the atmospheric CO_2, these features lead to a lowering of the shadow price of CO_2 emissions, so that the rise of CO_2 taxes in the second half of the century remains controlled. In MARKAL, on the other hand,

[7]Note that MARKAL does not model a unique interest rate, but uses different ones for each end-use sector.

[8]In terms of the way future tax levels affect current decisions, i.e. according to Eq. 1, this can be interpreted as a drop to zero of the carbon tax after 2100.

while some (often modest) cost reductions are achieved for nearly all competing energy technologies, a sizeable cost cap between most of the available renewables and fossil-based energy production remains. In combination with the ceiling on total cumulative allowed emissions, this necessitates an increase of CO_2 taxes as time proceeds under ever tighter emission reduction requirements. Figure 9 also shows that for each of the two models slightly higher taxes are needed when CO_2 leakage amounts to 1%/year, rather than 0.5%/year, for the reasons explained earlier.

To understand the implications of different tax paths for the effectiveness of CCS, we employ the theory as described in Section 2. For convenience, one can summarize the observed tax level evolutions in Fig. 9 by stating that the difference between the interest rate and the CO_2 tax growth rate, $r - g$, is smaller in MARKAL than it is in DEMETER. According to Eqs. 2 and 3 this implies that the effectiveness of a given CCS option (characterised by a certain leakage profile and energy penalty) is smaller for MARKAL than it is for DEMETER. This, in turn, implies that any selected CCS technique is generally a more attractive mitigation option in DEMETER than in MARKAL. Consequently, DEMETER also allows for higher leakage rates associated with CCS deployment than MARKAL. Indeed, we find that a smaller gap between r and g (that is, a smaller value for $r - g$) renders the CCS effectiveness, and so the realized deployment of CCS, more sensitive to the CO_2 leakage rate.

Another important aspect in this context is that, while DEMETER describes a smooth substitution between CCS-supplemented fossil fuels, one the one hand, and renewable energy resources, on the other hand, MARKAL describes a long series of energy technologies with large mutual substitution potential on the basis of only small relative cost changes. MARKAL simulates many separate technologies in the power sector with often small cost differentials between them. When an alternative technology gains a slight edge over an incumbent technology, e.g. because the incumbent technology becomes slightly more costly, it may be optimal to (slowly but) completely substitute the new technology for the existing one. This feature is not present in DEMETER. In our case, if CCS is competitive with some relatively low leakage rate, a small decrease in the economic effectiveness of CCS (e.g. because the leakage rate moderately increases) may make it slightly more costly in comparison to an alternative and thereby induce, in MARKAL, a completely different set of technologies that appear in the end-solution.

6 Conclusions

As in Gerlagh and van der Zwaan (2006), we confirm that allowing for the deployment of CCS does most likely not preclude the necessity to stimulate the large-scale development of renewables. According to our calculations, in order to reach a stringent climate stabilization target of e.g. 450 ppmv, at least half of the energy system should consist of renewables by 2100, even if CCS will be extensively promoted during this century as well. CCS technology, however, may be a welcome option to relax the requirements on renewable energy sources and, as it proves in this study, even so if CCS is characterized by significant leakage of geologically stored CO_2. The large-scale application of CCS needed for a significantly lower contribution of renewables would be consistent, in terms of climate change control, with the growing expectation that fossil fuels, and in particular coal, will continue to be a dominant form of energy supply during the twenty-first century (see, for example, Stephens and van der Zwaan 2005; van der Zwaan 2005). Current expectations from at least the geo-sciences are that possible CO_2 leakage from underground storage sites is low enough as to not harm the climate-mitigation prospects for the CCS-complemented use of fossil fuels.

The economics of CO_2 capture and storage in relation to the possibility of leakage of CO_2 from geological reservoirs once this GHG has been stored artificially underground will be among the main determinants of whether CCS can significantly contribute to realizing the necessary deep cut in global CO_2 emissions. The economic implications of potential CO_2 leakage associated with the large-scale deployment of CCS have so far only been researched in a few studies. This paper presents an analysis of the economic and climatic implications of the wide-spread use of CCS for reaching stringent climate change control targets, when geological CO_2 leakage is accounted for. We complement previous work in this field by presenting a qualitative description, a concise analytical inspection, as well as a more detailed integrated climate assessment, all three proffering insight into the economics of geological CO_2 storage and leakage. The fact that the natural scientific uncertainties regarding the nature and rates of possible leakage of CO_2 from geological reservoirs are likely to remain large for some time to come does not imply that the corresponding economics cannot be investigated already today.

With our stylistic top-down energy–environment–economy model DEMETER, that involves three main CO_2 emission reduction options, we find that costly CCS with CO_2 leakage of even a few percent per year, irrespective of whether modelled as a constant rate or in a bell-shaped form, possesses non-negligible economic and climate control value. We hereby find a higher allowable upper limit than the 0.5%/year reported recently on the basis of findings with the detailed bottom-up energy systems model MARKAL. Still, exercises with both types of models confirm that economically and climatically acceptable leakage rates are probably well above the maximum seepage rates that we think are likely from a geo-scientific point of view. One may conclude that our finding takes away some of the urgency of attempts to natural-scientifically research the precise levels of possible CO_2 seepage rates: the geo-sciences may not need to resolve this in order for CCS to be adopted on a large scale for the mitigation of climate change.

Of course, there may be other reasons to be concerned over possible CO_2 seepage than arguments related to economics and climatics only. Political and sociological aspects may turn out more critical in practice for the deployability of CCS. The social choice aspect of the subject notably relates to the possibility that the population in the vicinity of CCS activity may be exposed to CO_2 safety risks involved with the capture, transportation or injection process. Also engineering and legal aspects matter, as there are currently no technologies or regulations to monitor CO_2 once it has been stored underground. Indeed, one cannot discard these other possible drawbacks of CO_2 seepage, as they may finally be most determinant for the feasibility of large-scale CCS deployment.

From the perspective as investigated in this study, our results seem to somewhat downgrade the need for careful CO_2 storage site selection, as long as one can say with a high level of confidence that potential storage sites involve leakage below a rate of about 1%/year as determined in this article. Of course, leakage in DEMETER is modelled as a system-wide process with an average certain rate, but our findings still bear relevance for specific site selection and could function as targets for probabilistic failure simulations or risk analyses for the assessment of individual storage locations.

Subjects for future research also include questions like how one could detect leakage during site validation and operation, how one could credibly model the migration of CO_2 in a variety of geological formations, and how one may act upon leaks when discovered, or e.g. “re-plug” them when the site under consideration is an abandoned fossil fuel well.

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Appendix

The two-layer model In the two-layer model we suppose that CO_2 is stored in a geological depository that leaks to another formation characterized by seepage to the atmosphere. Flows of CO_2 are assumed to be mono-directional only. While in principle the two layers may be abstract constructs, for ease of visualization we interpret them as distinct physical layers on top of each other, i.e. the second layer above the first one with the flow of CO_2 upwards. Storage of captured CO_2 takes place in the first layer. Given the energy penalty incurred by the capture process, we assume that initially $1/c$ units of CO_2 are stored in the first leaky reservoir. A constant fraction, or rate, 2λ of the remaining stock of CO_2 in layer 1 seeps into layer 2. Thus, when x is defined as the remaining stock in the first layer, $x = c^{-1}e^{-2\lambda t}$. The second layer leaks its stock with the same rate 2λ to the atmosphere. The remaining level of CO_2 in the second layer, defined as y, must then satisfy $\mathrm{d}y/\mathrm{d}t = -\mathrm{d}x/\mathrm{d}t - 2\lambda y$. It is straightforward to see that:

$$y = t\,2c^{-1}\lambda e^{-2\lambda t}, \text{ since} \tag{16}$$

$$\mathrm{d}y/\mathrm{d}t = 2c^{-1}\lambda e^{-2\lambda t} - t4c^{-1}\lambda^2 e^{-2\lambda t} = -\mathrm{d}x/\mathrm{d}t - 2\lambda y. \tag{17}$$

The average (or expected) lifetime of CO_2 residing underground in this two-layer model is:

$$\begin{aligned}\int_0^\infty (t2c\lambda y)\,\mathrm{d}t &= \int_0^\infty t^2 4\lambda^2 e^{-2\lambda t}\mathrm{d}t \\ &= \left[-t^2 2\lambda e^{-2\lambda t} - 2te^{-2\lambda t} - (1/\lambda)\,e^{-2\lambda t}\right]_0^\infty \\ &= (1/\lambda)\,. \end{aligned} \tag{18}$$

This proves our claim that a two-layer model with twice an exponential leakage rate of 2λ possesses the same average storage time as a one-layer exponential model with leakage rate λ. When taxes are assumed to increase exponentially at rate g, the storage effectiveness, according to Eq. 1, takes the form:

$$\begin{aligned} 1-\int_0^\infty (2\lambda y)\, e^{(g-r)t}\mathrm{d}t &= 1-\int_0^\infty t4c^{-1}\lambda^2 e^{-(2\lambda+r-g)t}\mathrm{d}t \\ &= 1-\Big[-\big(t4c^{-1}\lambda^2/(2\lambda+r-g)e^{-(2\lambda+r-g)t} \\ &\qquad -\big(4c^{-1}\lambda^2/(2\lambda+r-g)^2\; e^{-(2\lambda+r-g)t}\Big]_0^\infty \\ &= 1-4c^{-1}\lambda^2/(2\lambda+r-g)^2. \end{aligned} \tag{19}$$

We now prove the inequality:

$$1-c^{-1}\left(\frac{2\lambda}{r+2\lambda-g}\right)^2 > 1-\frac{\lambda/c}{r+\lambda-g}, \text{ i.e. } \left(\frac{2\lambda}{r+2\lambda-g}\right)^2 < \frac{\lambda}{r+\lambda-g}. \tag{20}$$

This inequality is equivalent to $4\lambda\,(r+\lambda-g) < (r+2\lambda-g)^2$. Its validity can easily be checked by realizing that the right-hand-side minus the left-hand-side is equal to $(r-g)^2$, which is always larger than zero. Hence, one-layer CO_2 storage with exponential leakage has a lower effectiveness than similar two-layer CO_2 storage (i.e. with each of the two layers also leaking exponentially, but with twice the rate of that in the one-layer case), even when these two types of repositories are characterized by the same average storage time.

References

Bovenberg AL, Smulders SA (1996) Transitional impacts of environmental policy in an endogenous growth model. Int Econ Rev 37:861–893

Buonanno P, Carraro C, Galeotti M (2003) Endogenous induced technical change and the costs of Kyoto. Resource Energy Econ 25:11–34

Chakravorty U, Roumasset J, Tse K (1997) Endogenous substitution among energy resources and global warming. J Politic Econ 105:1201–1234

Deffeyes KS (2005) Beyond oil: the view from Hubbert's peak. Farrar, Straus & Giroux

Edenhofer O, Lessmann K, Kemfert C, Grubb M, Kohler J (2006) Synthesis report from the innovation modelling comparison project. Special issue on induced technological change and the economics of atmospheric stabilization. Energy J 57–109

Fischer C, Newell R (2004) Environmental and technology policies for climate change and renewable energy. Discussion Paper 04-05 (Rev), Resources for the Future, Washington DC

Gerlagh R, van der Zwaan BCC (2003) Gross world product and consumption in a global warming model with endogenous technological change. Resource Energy Econ 25:35–57

Gerlagh R, van der Zwaan BCC (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, van der Zwaan BCC (2006) Options and instruments for a deep cut in CO_2 emissions: carbon capture or renewables, taxes or subsidies? Energy J 27(3):25–48

Gerlagh R, van der Zwaan BCC, Hofkes MW, Klaassen G (2004) Impacts of CO_2-taxes in an economy with niche markets and learning-by-doing. Environ Resource Econ 28:367–394

Goulder LH, Mathai K (2000) Optimal CO_2 abatement in the presence of induced technological change. J Environ Econ Manage 39:1–38

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

Hepple RP, Benson SM (2002) Implications of surface seepage on the effectiveness of geologic storage of carbon dioxide as a climate change mitigation strategy. In: Kaya Y, Ohyama K, Gale J, Suzuki Y (eds) GHGT-6: sixth international conference on greenhouse gas control technologies. Kyoto, Japan, 30 September–4 October

Herzog H, Caldeira K, Reilly J (2003) An issue of permanence: assessing the effectiveness of temporary carbon storage. Climatic Change 59:293–310

Hotelling H (1931) The economics of exhaustible resources. J Politic Econ 34:137–175

IEA/OECD (2000) Experience curves for energy technology policy. International Energy Agency, Organisation for Economic Co-operation and Development, Paris, France

IPCC (2001) Special report on emission scenarios. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge UK

IPCC (2005) Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change, Working Group III, Cambridge University Press, Cambridge UK

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

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

Kharaka YK, Cole DR, Hovorka SD, Gunter WD, Knauss KG, Freifeld BM (2006) Gas–water–rock interactions in Frio Formation following CO_2 injection: implications for the storage of greenhouse gases in sedimentary basins. Geology 34:7

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

Messner S (1997) Endogenized technological learning in an energy systems model. J Evolution Econ 7:291–313

Nakićenović N, et al (2000) Special Report on Emissions Scenarios (SRES), IPCC, Working Group III, Cambridge University Press.

NITG (2007) Netherlands institute of applied geoscience, TNO. www.nitg.tno.nl /eng /projects / 6_stor /index.shtml

Nordhaus WD (2002) Modeling induced innovation in climate change policy, Ch. 9. In: Grübler A, Nakiæenoviæ N, Nordhaus WD (eds) Modeling induced innovation in climate change policy. Resources for the Future Press, Washington DC

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

Pacala SW (2002) Global constraints on reservoir leakage. In: Kaya Y, Ohyama K, Gale J, Suzuki Y (eds), GHGT-6: sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September–4 October

Papathanasiou D, Anderson D (2001) Uncertainties in responding to climate change: on the economic value of technology policies for reducing costs and creating options. Energy J 22:79–114

Riahi K, Rubin ES, Taylor MR, Schrattenholzer L, Hounshell DA (2004) Technological learning for carbon capture and sequestration technologies. Energy Econ 26(4):539–564

Rubin ES, Taylor MR, Yeh S, Hounshell DA (2004) Learning curves for environmental technologies and their importance for climate policy analysis. Energy 29:1551–1559

Smekens K, van der Zwaan BCC (2006) Atmospheric and geological CO_2 damage costs in energy scenarios. Environ Sci Policy 9:3

Stephens JC, van der Zwaan BCC (2005) The case for carbon capture and storage. Issues in Science and Technology, Fall, 69–76

van der Zwaan BCC (2005) Will coal depart or will it continue to dominate global power production during the 21st century? Climate Policy 5(4):445–453

van der Zwaan BCC, Gerlagh R (2006) Climate sensitivity uncertainty and the necessity to transform global energy supply. Energy 31:2571–2587

van der Zwaan BCC, Gerlagh R (2008) The economics of geological CO_2 storage and leakage. FEEM, Nota di Lavoro, Milan

van der Zwaan BCC, Smekens K (2008) CO_2 capture and storage with leakage in an energy-climate model. Environ Model Assess (in press)

van der Zwaan BCC, Gerlagh R, Klaassen G, Schrattenholzer L (2002) Endogenous technological change in climate change modeling. Energy Econ 24:1–19

van't Veld K, Plantinga A (2005) Carbon sequestration or abatement? The effect of rising carbon prices on the optimal portfolio of greenhouse-gas mitigation strategies. J Environ Econ Manage 50:59–81

Wigley TML, Richels RG, Edmonds JA (1996) Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. Nature 379(6562):240–243

Wilson EJ, Johnson TL, Keith DW (2003) "Regulating the Ultimate Sink: Managing the Risks of Geologic CO_2 Storage". Environ Sci Technol 37:16.