The Economics of Geological CO_2 Storage and Leakage

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Keywords: climate change, carbon dioxide emission reduction, technological innovation, CO_2 capture and storage (CCS), geological leakage

JEL classification: H21, D58, C61, O33, Q40

26 January 2007

Abstract

The economics of CO_2 capture and storage in relation to the possibility of significant 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 %/yr, 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, however, for not now analysing the potential climatic and economic implications of CO_2 leakage. Do values exist for the CO_2 leakage rate that are acceptable from a cost or carbon-cycle point of view? 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 concise 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, top-down versus bottom-up energy-economy-environment models. 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 like 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%/yr. 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%/yr or even 1%/yr 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 section 4, we thus investigate three scenarios with (time-independent) leakage of CO_2 from geological storage, in which the leakage rate amounts to 0.5%/yr, 1%/yr and 2%/yr, respectively.

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%/yr CO_2 leakage rate is probably not acceptable from a global climate point of view, while a 0.1%/yr rate may perhaps be. For a storage option with a 1%/yr 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%/yr leakage rate. Given that climate change is a problem stretching over the forthcoming couple of centuries, one may conclude that in the 1%/yr leakage case CCS becomes a clearly ineffective emissions abatement option. If a 0.1%/yr 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. A few observations can be made about the long-term evolution of the mean leakage rate. First, one may assume that injection occurs arbitrarily distributed across a large collection of heterogeneous reservoirs, about which we know virtually nothing, in terms of possible CO_2 leakage, before actually operating them as storage sites. In other words, we start employing storage reservoirs more or less randomly, 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 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. Given this latter argument, as well as the large range of leakage rate values we study in this paper (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, we abstract from CO_2 leakage time-variability.

CO_2 leakage lowers the value of CCS as climate mitigation option below the level of the CO_2 tax. If we store one unit of CO_2 at t=0 and the leakage rate is λ, an amount equal to $\lambda e^{-\lambda t}$ leaks back to the atmosphere at any given time t. Given a real interest rate r and CO_2 tax τ_t – the shadow price for atmospheric CO_2 emissions – the net present value (NPV) of cumulative future CO_2 leakage is:

$$NPV_{leakage} = \tau_\lambda = \int_0^\infty \lambda e^{-(r+\lambda)t} \tau_t dt \,. \tag{1}$$

If, for convenience, we assume that CO_2 taxes increase exponentially at rate g, we find:

$$\tau_\lambda = \tau_0 \int_0^\infty \lambda e^{(-r+g-\lambda)t} dt = \frac{\lambda}{\lambda + r - g} \tau_0 \,. \tag{2}$$

Alternatively, the integrated carbon-mitigation NPV represented by the implementation of CCS, τ_{CCS}, equals $\tau - \tau_{\lambda}$, with τ the NPV of the CO_2 tax. For zero leakage, equation (2) implies that fossil fuel combustion combined with CCS deployment (assuming 100% capture efficiency) should be fully exempt from the CO_2 tax, while, hypothetically, for infinite leakage the application of CCS does not imply a reduction of the imposed CO_2 tax (and consequently, as CCS is a costly technology, it will not be used). Another special case is when atmospheric CO_2 uptake is modelled as an exhaustible resource, e.g. when a ceiling is set to the total cumulative amount of emitted CO_2. In this case, the CO_2 tax will follow the Hotelling rule, and its growth rate will equal the real interest rate, such that $\tau_{\lambda}=\tau_0$ (Hotelling, 1931). That is, for any positive CO_2 leakage, $\lambda>0$, CCS has no net benefit.

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; Gerlagh and van der Zwaan, 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.* (2001) 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 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), but that only few top-down models are available that incorporate CCS opportunities. 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 general description of the model and to Gerlagh and van der Zwaan (2006) for more details on the specification of CCS.[2]

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.

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

There is a public agent that sets taxes to CO_2 emissions and subsidies to non-carbon energy, both serving to reduce CO_2 emissions. When the agent imposes a CO_2 tax, one of the possible reactions is a reduction in overall energy consumption. Producers can also shift from fossil-fuel to carbon-free energy, or, alternatively, decarbonize fossil-based energy production through the application of CCS. CO_2 emissions Em_t are proportional to the carbon content ε_t^F of fossil fuels. The variable $CCSR_t$ represents the share of CO_2 emissions captured through CCS technology application. The relation between CO_2 emissions and fossil-fuel energy use thus becomes:

$$Em_t = \varepsilon_t^F (1 - CCSR_t) Y_t^F . \tag{3}$$

Since there is today no scientific guarantee that CO_2 stored underground will not once start leaking back into the atmosphere, we have expanded DEMETER to account for possible CO_2 leakage phenomena, implying the simulation of an additional future source of CO_2 emissions as fraction of the geologically stored stock of CO_2 at any give point in time.

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 equation 4). 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 κ=0, in one period, costs of CCS are linear and marginal costs are constant. For κ=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 (equation 5), the resulting (installation and operation) experience, X_t^{CCS}, leads to an enhancement of related knowledge, and a corresponding decrease in the cost parameter h_t^{CCS} (equation 6). 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} (equation 7), and so are maintenance costs (equation 8). 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 (equation 9). Parameter δ denotes the share of vintage capital depreciated per period.

$$Q_t^{CCS} = h_t^{CCS}(CCSR_t + \tfrac{1}{2}\kappa\ CCSR_t^2)\varepsilon_t^F \tilde{Y}_t^F , \tag{4}$$

$$X_{t+1}^{CCS} = X_t^{CCS} + CCSR_t\varepsilon_t^F \tilde{Y}_t^F . \tag{5}$$

$$h_t^{ccs} = 1 + c^{ccs}(1-d^{ccs})(X_t^{ccs})^{-d^{ccs}} . \tag{6}$$

$$I_{t-1}^{CCS} = Q_t^{CCS} / a^{CCS} , \tag{7}$$

$$\tilde{M}_t^{CCS} = Q_t^{CCS} / b^{CCS} . \tag{8}$$

$$M_t^{CCS} = (1-\delta)M_{t-1}^{CCS} + \tilde{M}_t^{CCS} . \tag{9}$$

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; Gerlagh and van der Zwaan, 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^{CCS} =20 MtC/yr.

4. Simulation results

We define 6 scenarios allowing us to analyse the significance of CO_2 leakage for climate change policy making. The first of these is a benchmark (business-as-usual) scenario that involves no constraint on CO_2 emissions. The other 5 scenarios reflect cases in which a CO_2 stabilization target is reached through the introduction of a climate policy instrument. In each of these 5 scenarios we have opted for imposing a stringent climate control target, that is, of 450 ppmv atmospheric CO_2 concentration, while they differ in the assumed CO_2 leakage rate. In all 5 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.

BAU: ***No climate change policy*** is implemented, and hence no tax on CO_2 emissions is applied. Energy consumption and CO_2 emissions thus increase steadily over the entire 21st century.

S00: A climate stabilization target of 450 ppmv is reached through a tax on CO_2 emissions, while geological CCS is characterized by a **0 % leakage rate**.

S05: A climate stabilization target of 450 ppmv is reached through a tax on CO_2 emissions, while geological CCS is characterized by a **0.5 % leakage rate**.

S10: A climate stabilization target of 450 ppmv is reached through a tax on CO_2 emissions, while geological CCS is characterized by a **1.0 % leakage rate**.

S20: A climate stabilization target of 450 ppmv is reached through a tax on CO_2 emissions, while geological CCS is characterized by a **2.0 % leakage rate**.

S99: A climate stabilization target of 450 ppmv is reached through a tax on CO_2 emissions, but **no CCS option** is available, e.g. as a result of an unacceptably high leakage rate.

To cross-check the consistency of our model we first define 5 different climate stabilization scenarios, of 450, 475, 500, 525 and 550 ppmv respectively, and inspect the CO_2 emission profiles corresponding to these atmospheric CO_2 concentration targets. Indeed, as can be seen from Figure 1, DEMETER generates for each of these targets the CO_2 emission profiles as reported in the scientific climate policy and carbon cycle literature (see e.g. Wigley *et al.*, 1996). Figure 2 shows the CO_2 emission profile when a climate stabilization target of 450 ppmv only is adopted. As expected, the emission profile is essentially the same irrespective of the leakage rate by which the CCS mitigation option is characterised, as demonstrated by the S00, S05, S10, S20 and S99 curves. Only small emission differences occur by the end of the century between scenarios with different leakage rates, as a result of timing issues, programming horizon cut-off effects, and the economic trade-off between reaching a given stringent climate goal and implementing costly but climate-friendly energy technologies.

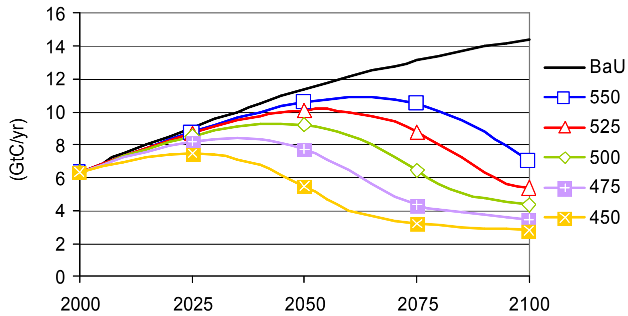

FIGURE 1. *CO_2 emissions (GtC/yr) for various concentration stabilization targets.*

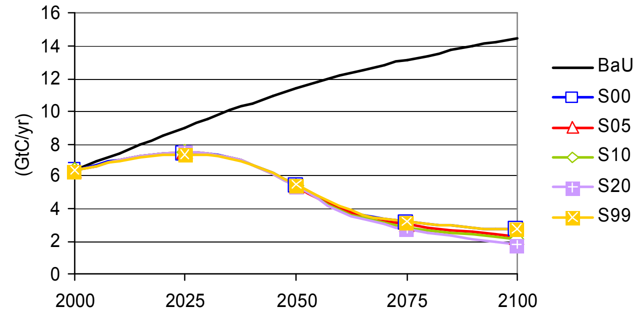

FIGURE 2. *CO_2 emissions (GtC/yr) for various leakage scenarios (450 ppmv target).*

Figure 3 depicts the cumulative amount of geologically stored CO_2 resulting from CCS activities as a function of time, under the 450 ppmv climate stabilization target and the different CO_2 leakage rates in the scenarios as defined above. Clearly, if geological CCS is not subject to undesirable leakage effects, as is simulated for the 21st century in scenario S00, the cumulative quantity of geologically stored CO_2 increases steadily, and monotonically, reaching globally an integrated amount of over 120 GtC in 2100. On the other hand, if no CCS option is applied, as a result of the absence of the necessary incentives (as in BAU) or since CCS proves to generate unacceptably high leakage rates (like in S99), DEMETER model-runs correctly generate the zero-storage line shown in Figure 3. When geological CO_2 storage is imperfect and provokes a non-negligible but limited level of average leakage, predefined in DEMETER as a constant rate with a value below some threshold (above which CO_2 leakage is judged to become unacceptably high), the cumulative geological CO_2 storage curve lowers with respect to that of scenario S00: the amount of CO_2 stored underground during this century reaches approximately 80, 60 and 50 GtC for leakage rates of 0.5, 1.0 and 2.0 %/yr (in scenarios S05, S10 and S20) respectively. In Figure 4 the geological CO_2 seepage process is plotted against time for the different leakage scenarios with the 450 ppmv climate stabilization target. Naturally, the S20 scenario, with a leakage rate increasing to almost 1 GtC/yr in 2100, tops the S10 and S05 scenarios that simulate leakage rates reaching about 0.6 and 0.4 GtC/yr respectively by the end of the century. The other three scenarios, as can be seen in Figure 4, involve no CO_2 seepage: S00 since the CO_2 leakage rate of installed CCS capacity is zero, S99 and BAU because no CCS technology is deployed.

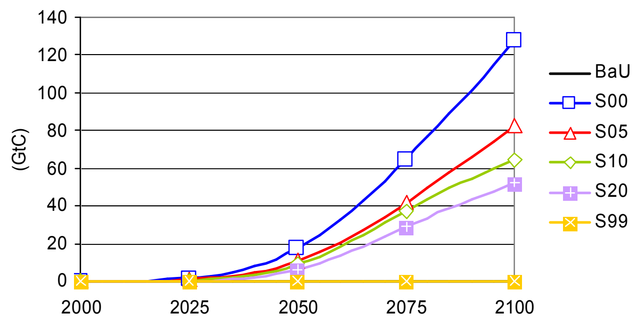

FIGURE 3. *Cumulative geological CO_2 storage (GtC) for various leakage scenarios (450 ppmv target).*

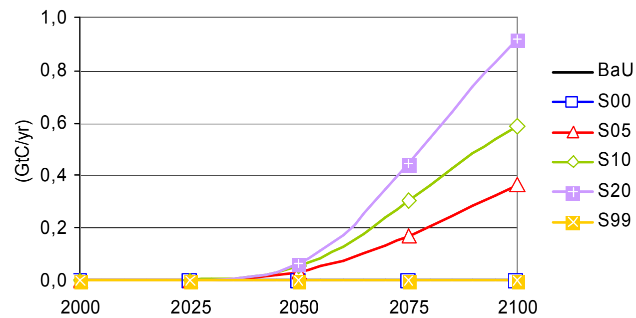

FIGURE 4. *Annual geological CO_2 seepage (GtC/yr) for various leakage scenarios (450 ppmv target).*

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, and CO_2 taxation proves to be both particularly effective and efficient (Gerlagh and van der Zwaan, 2006). Figure 5 shows the time-dependence of the CO_2 tax that DEMETER calculates to be the optimal path to achieve a 450 ppmv climate stabilization target under varying assumptions regarding the CO_2 leakage rate associated with CCS technology application. In all 5 climate management scenarios, the CO_2 tax increases almost exponentially during the first half of the 21st century, but levels off after about 2050 to hover around a plateau between 100 and 250 US$/tC depending on the leakage scenario under consideration. The ranking between S00, S05, S10 and S20, in order of increasing tax levels, can be understood by realizing that higher taxation is required when CCS is characterised by more leakage of CO_2, since under accrued seepage less climate mitigation potential is available through CCS, necessitating stronger policy incentives. It proves that when CCS is excluded from the set of climate mitigation options as a result of exorbitantly large leakage phenomena, the long-term tax level, now destined to stimulate the deployment of non-carbon energy resources other than CCS, falls in the middle of the calculated range at a little over 150 US$/tC.

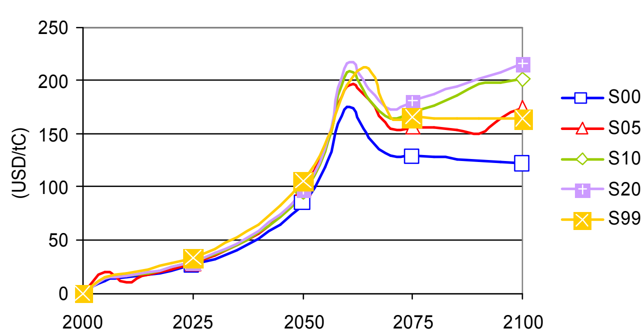

FIGURE 5. *CO_2 tax (US$/tC) for various leakage scenarios (450 ppmv target).*

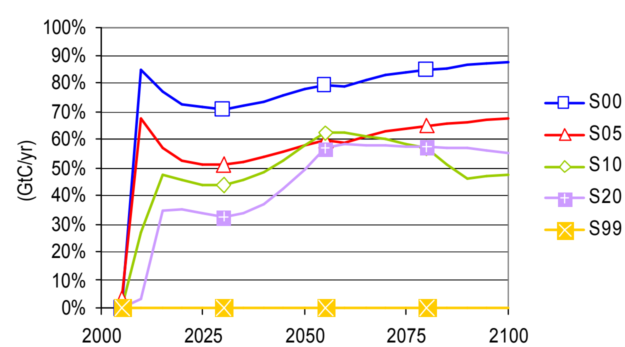

FIGURE 6. *Share of CO_2 tax to CCS (%) for various leakage scenarios (450 ppmv target).*

DEMETER internalizes energy technology learning-by-doing by assigning additional investments to those (essentially non-carbon) energy resources that possess potential for significant future cost reductions through learning processes, and it employs the CO_2 tax to bring in line the private objective of profit maximization and the social objective of minimizing dynamic costs. Because both CCS technologies and renewables are assumed to possess cost reduction potential, simulated in DEMETER via learning curves, for each the marginal social costs of deployment fall short of the marginal private costs. Figure 6 shows the time-dependence of the share of the CO_2 tax that can be claimed back for avoided CO_2 emissions after an investment in CCS application. This Figure shows that DEMETER generates the expected outcome, in that the internal ranking between S00, S05, S10 and S20 corresponds to, respectively, a decreasing share of the total CO_2 tax given back after CCS investments. This is understandable, as the social value of CCS decreases when the leakage rate becomes higher. Apart from modelling initiation phenomena – DEMETER generates a zero tax-to-CCS share in 2005 as a result of simulation start-off assumptions – when there is no CO_2 leakage, DEMETER calculates that CCS receives an average of 80% exemption of the CO_2 tax, while a substitution of renewables for fossil fuels would generate a full 100% CO_2 tax reduction. Even if CCS is characterised by zero CO_2 leakage, renewables still receive a higher share of the CO_2 tax revenues, as their costs are expected to decrease faster through learning processes. Typically, for the simulated CO_2 leakage rates, we find that the tax-to-CCS share remains between 30% and 70% for most of the century with an average of some 50%. Through equation (2) these numbers can be understood by realizing that in DEMETER the interest rate is about 5%/yr and the CO_2 tax growth rate about 3%/yr: in the long run a leakage rate of 2%/yr then still results in τ_λ being approximately 50%, as confirmed by Figure 6. As depicted in this Figure, only during the 2nd half of the century a small deviation of the expected tax-to-CCS share is found for scenario S10: apparently the balancing of investment capital (derived from the recycling of CO_2 tax revenues) between CCS and renewable energy technology is more delicate when the leakage rate amounts to approximately 1.0%/yr. But otherwise the results described in this section *grosso modo* confirm what we expected beforehand from our initial CCS analysis.

5. Top-down versus bottom-up modelling

The question addressed above with a top-down energy-economy-environment model can also be analysed with a bottom-up energy system model. It proves that results obtained with these two complementary approaches 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 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 (2006). With both DEMETER and MARKAL we find that, even under a CO_2 leakage rate of 0.5%/yr (or lower), CCS develops significantly during the 21st century and as such contributes substantially to mitigating global climate change. If the CO_2 leakage rate is as high as 1%/yr, however, with MARKAL CCS disappears almost entirely from the fossil-based power sector except for a small contribution by 2100 (see Figure 1 in van der Zwaan and Smekens, 2006). With DEMETER, on the other hand, 40-50% of all 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%/yr (or even more). In a DEMETER–MARKAL comparison, 0.5%/yr CO_2 leakage proves to be the breaking-point beyond which modelling results start to fundamentally differ from each other. Similarly, 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 our simulations a leakage rate of 1%/yr instead of 0.5%/yr (typically to about a quarter of the original quantity stored), while for DEMETER this amount is only reduced by a fraction (of around 20%). As we saw above, with DEMETER even under a leakage rate of up to 2%/yr 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 found between these DEMETER and MARKAL findings. First, of course, the differences are most profound if with MARKAL we only inspect the fossil-based power sector: the resulting order-of-magnitude discrepancy can at least partly be understood because DEMETER by principle simulates the entire energy economy rather than only part of it. But even when we view MARKAL's entire energy system, a sizeable discrepancy remains. A second reason therefore is that in DEMETER the cost difference between CCS technology applied to the use of fossil fuels, on the one hand, and the generic renewable energy resource, on the other hand, is relatively large, at least during the first part of the century when learning has not yet yielded significant technology cost reductions. This implies that even as the climate mitigation potential of CCS is somewhat reduced as a result of non-negligible CO_2 leakage, economic interest still exists to deploy CCS, since renewables remain still a relatively costly alternative. In MARKAL, on the contrary, this cost-dichotomy between CCS and renewables is smaller, rendering model outcomes more sensitive to CO_2 leakage phenomena, so that under significant leakage CCS may even vanish from the calculated scenarios altogether. As third reason, related to the previous point, we observe that MARKAL simulates a very large range of different energy technologies (unlike the three stylistic ones modelled in DEMETER) that taken together imply a relatively smooth ranking in terms of costs between different non-carbon energy technologies. In other words, if the unit cost of avoiding CO_2 emissions through CCS increases as a result of CO_2 leakage, readily another technology is available that avoids these emissions at competitive prices, thereby obviating the need for CCS application. In MARKAL apparently at leakage rates above 0.5%/yr CCS decidedly loses economic competitiveness in comparison to other CO_2 mitigation options.

There is yet a fourth explanation that connects to the theory as described in Section 2. Our intuition is 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 equations (1) and (2) this would imply that the NPV of CO_2 leakage, τ_λ (or, alternatively, $\tau - \tau_{CCS}$, i.e. the NPV of the CO_2 tax minus the integrated carbon-mitigation value represented by CCS), is larger for MARKAL than it is for DEMETER, and the NPV of CO_2 leakage more sensitive to the leakage rate λ. The reason for $r-g$ being smaller in the former is that MARKAL treats the atmospheric CO_2 uptake as an exhaustible resource, and thus sets a ceiling to the total cumulative amount of CO_2 that can be emitted during the 21st century. Consequently, the CO_2 tax in MARKAL follows more closely the Hotelling rule.[3] On the other hand, MARKAL plans over a finite horizon and there is no leakage considered for the stored CO_2 at the end of the simulation period. This feature helps explaining why CCS becomes relatively more profitable in later periods. In general, however, for any substantial positive leakage, $\lambda>0$, CCS in MARKAL more quickly looses its net benefit. Indeed, Figure 7 shows that the CO_2 tax as calculated by MARKAL and DEMETER under a stringent climate constraint behaves pretty much the same until the middle of the century. From around 2050 differences in these tax paths start to occur: while CO_2 taxes in DEMETER level off during the 2nd half of the century to values close to 200\$/tC, in MARKAL they continue to increase exponentially to reach values about four times higher by the end of the simulation horizon. *Quod erat demonstrandum.*

The explanation for the relatively low CO_2 taxes in DEMETER is that, as a result of optimistic assumptions regarding the learning potential of renewables, these new technologies fall below the competitive (fossil-fuel based) break-even price during the 2nd half of the century. In combination with the assumed natural uptake of part of the atmospheric CO_2, this leads to a lowering of the shadow price of CO_2 emissions and thus it controls the rise of CO_2 taxes in the second half of the century. In MARKAL, on the other hand, 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 (although smaller than simulated in early modelling periods in DEMETER) remains. In combination with the ceiling on total cumulative allowed emissions, this necessitates an increase of CO_2 taxes as time proceeds under tighter emission reduction requirements.

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

Figure 7 also shows that for each of the two models slightly higher taxes are needed when CO_2 leakage amounts to 1%/yr, rather than 0.5%/yr, for the reasons explained earlier.

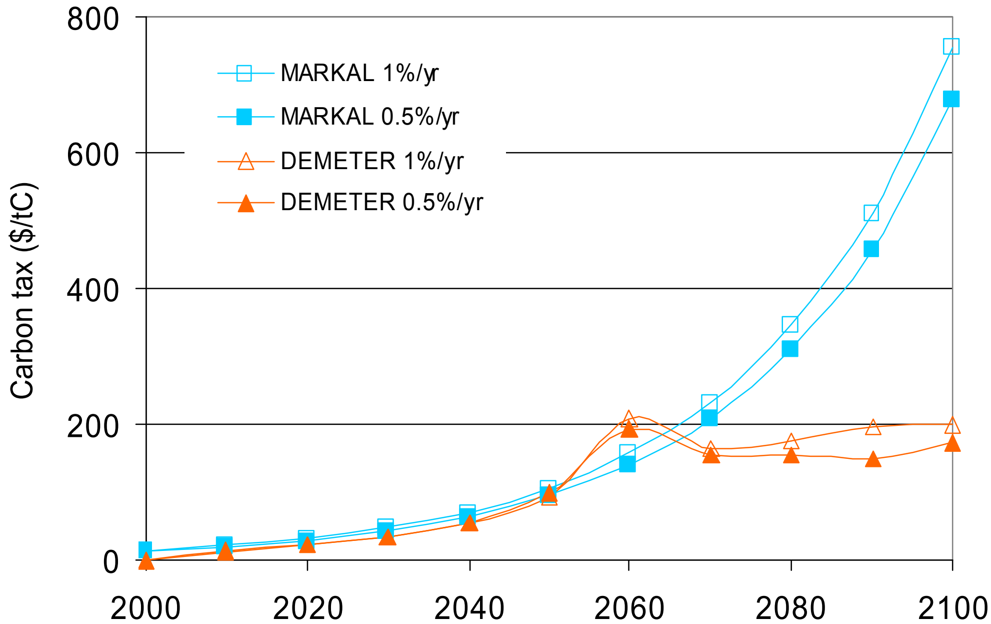

FIGURE 7. *Optimal CO_2 tax (in US$/tC) as calculated by MARKAL and DEMETER under a stringent climate constraint for two values of the leakage rate (1 and 0.5%/yr).*

6. Conclusions

In the version used for this paper, DEMETER simulates three main endogenous mechanisms for achieving reductions in the total level of CO_2 emissions:

- **saving** energy;
- **decarbonizing** fossil fuel energy supply by either a transition from carbon-intensive to carbon-poor fossil fuels or an application of CCS technology;
- **switching** to the use of non-carbon energy sources such as renewables.

Like in our previous work, we confirm that the fear that allowing for the deployment of CCS might preclude the development of renewables is unjustified. According to our calculations, in order to reach a stringent climate stabilization target, at least half of the energy system should consist of renewables by 2100, even if CCS will be extensively promoted. But CCS technology might 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, in terms of climate change control, be consistent with the growing expectation that fossil fuels, and in particular coal, will continue to be a dominant form of energy supply during the 21st century (see, for example, Stephens and van der Zwaan, 2005; van der Zwaan, 2005). 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 prospects for the use of fossil fuels complemented with CCS technology.

The economics of CO_2 capture and storage in relation to the possibility of significant 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 soon significantly contribute to realizing the necessary deep cut in global CO_2 emissions. The economic implications of CO_2 leakage associated with large-scale deployment of CCS have so far only been studied marginally. 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. The fact that the natural scientific uncertainties regarding the 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.

This article studies the economic and climatic aspects of CO_2 leakage from geological storage media when CCS is applied on a global scale, through a qualitative description, a concise analytical inspection and more detailed integrated assessment modelling. With a stylistic top-down energy-environment-economy model representing three main CO_2 emission reduction options we find that costly CCS with CO_2 leakage of even a few %/yr possesses non-negligible economic and climate control value. We hereby find a higher allowable upper limit than the 0.5%/yr reported recently with results from detailed bottom-up energy systems modelling, 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. If one discards the other possible drawbacks of CO_2 seepage, among which notably safety risks, 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. At least from the perspective as investigated in this study, our results thereby seem to somewhat downgrade the need for careful CO_2 storage site selection. One of our other main conclusions is that when significant learning-by-doing cost reduction potential is available for energy technology deployment, and for CCS and renewables in particular, CO_2 taxes may not need to exceed a level of approximately 200$/tC, even if there is relatively large CO_2 leakage.

Acknowledgements

The authors acknowledge funding from the EU TranSust.Scan project (no. 022773 under Sixth Framework Programme priority FP6-2004-SSP-4, and its predecessor TranSust under contract EVG3-2002-00507, see: www.transust.org) that allowed this analysis of the economics of geological CO_2 storage and leakage, as well as the simulation of the climate change mitigation potential of CCS, with the top-down integrated assessment model DEMETER. Reyer Gerlagh thanks the Centre for Advanced Study (CAS) at the Norwegian Academy of Science and Letters in Oslo for financial, administrative and professional support, and the CAS researchers of the 2005-2006 academic year, amongst whom especially Michael Hoel. Valuable feedback from many colleagues is much appreciated, especially that of Koen Smekens who provided the model runs with MARKAL. This paper has also benefited from comments by the participants of the TranSust.Scan meeting held in Vienna on 9-10 October 2006. All remaining errors are ours.

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