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Carbon storage: the economic efficiency of storing CO_2 in leaky reservoirs

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Abstract Fossil fuels can be used with minimal atmospheric emissions of carbon dioxide by capturing and storing the CO_2 away in geologic structures. However, stored CO_2 can leak back to the atmosphere reducing the utility of this technology. To explore the trade-offs between discounting, leakage, the cost of sequestration and the energy penalty (the energy necessary to capture, transport and inject carbon underground), we derive analytic expressions for the value of leaky CO_2 storage compared to perfect storage when storage is a marginal component of the energy system. If the annual leak rate is 1% and the discount rate is 4%, for example, then CO_2 mitigation using leaky storage is worth 80% of mitigation with perfect storage. Using an integrated assessment numerical model (DIAM) to explore the role of leakage when CO_2 storage is non-marginal, we find that a leakage rate of 0.1% is nearly the same as perfect storage while a leakage rate of 0.5% renders storage unattractive. The possibility of capturing CO_2 from the air, not only from flue gases, makes storage with higher leakage rates interesting. Finally, we speculate about the role of imperfect carbon storage in carbon accounting and trading.

Carbon storage

Introduction

Geologic carbon storage is a means of storing carbon dioxide (CO_2) away from the atmosphere by injecting it at depths greater than about 1 km into porous sedimentary formations using technologies derived from the oil and gas industry (Holloway 2001; Herzog 2001; Bachu 2001). Natural underground reservoirs have held natural CO_2 in place for thousands of years, but leakage does and will occur. Each year a fraction of the gas stored underground can be expected to return to the atmosphere. The purpose of this work is to discuss economic implications of leakage.

Geologic CO_2 storage might enable the use of fossil fuels without contributing to climate change. Doing so requires a set of technologies for capture, transportation and injection of CO_2. While much is uncertain about future technology and its costs, the multiplicity of technical options and the fact that most if not all of the component technologies have already been demonstrated at commercial scale strongly suggests that capture and storage is a viable near-term option for managing CO_2 emissions. The cost of capture generally dominates the cost of transport and injection. In the electric sector, previous studies suggest that the cost of avoiding CO_2 emissions using these methods is in order of 50 to 150 U.S.$/tC (Johnson and Keith 2003; Herzog 1999).

The long-range transportation of CO_2 and its injection into deep underground reservoirs is comparatively well understood: The upstream oil and gas industry routinely injects CO_2 underground to enhance oil recovery (CO_2-EOR). A bit more than 2,000 km of CO_2 pipelines have been laid in Texas to provide for CO_2-EOR. In these operations the goal is to maximize oil return and minimize the carbon left underground so that it can be re-used, since operators must pay for the CO_2. Yet at the end of an EOR operation a major fraction of CO_2 purchased remains underground.

Industrial experience with CO_2-EOR and with the disposal of CO_2-rich acid gas streams, as well as related experience with natural gas storage and the underground disposal of other wastes, suggests that this technology can be implemented with acceptable local risk and that it could therefore play a significant role as a response to the challenge of global warming. This is why geologic carbon storage has become more and more relevant as a climate policy option during these last 5 years. The section "Discussions about leakage" extends this introduction with a short review of the literature on leakage.

We assess the economic implications of CO_2 storage in leaky reservoirs from two perspectives. First, in the section "Microeconomics of leakage", we take consider the cost effectiveness of mitigation options while assuming that storage is a marginal component of the energy system. We assess the relative value of perfect and imperfect storage,

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or equivalently of imperfect storage and a non-carbon alternative energy source that is adopted to mitigate CO_2 emissions. An efficiency ratio involving the leakage rate, the discount rate, and the energy intensity of storage is derived to compare the two technologies.

Second, in the section "Numerical results in a long run cost–benefit model" we address the economics of leakage when CO_2 storage plays a significant (non-marginal) role in the energy system so that the flux of leaking CO_2 can be large compared to emissions from other sources. This analysis adopts the perspective of optimal climate policy in which trade-offs between costs and benefits play out over time. The problem of finding the efficient mix of two abatement technologies (one being carbon capture and storage) is solved using a numeric optimization model: DIAM. Simulations of optimal long-term global CO_2 trajectories confirm the orders of magnitude previously found: a leak rate of 0.1%/year is roughly equivalent to perfect storage. For higher leak rates, the availability of air capture can make a significant difference.

The last section discusses policy implications for regulating storage activities.

Discussions about leakage

Natural analogues show that carbon dioxide can remain trapped underground for very long periods, but they also show that releases can lead to serious local environmental consequences. Excess local concentration of CO_2, for example, can lead to acidification of ground-water, and elevated carbon dioxide concentration in soils can kill plants. While local environmental issues are certainly important they will be ignored here, as this paper is concerned about the global implications of leakage.

Current research can be organized into two categories: descriptive and normative. The descriptive research tries to predict the magnitude of leakage, studying for example rock formations, existing wells, or natural and artificial analogues. The normative approach asks "how small is small enough", framing the problem as a question of resource management over time. Our focus is on the normative problem, but we first review some of the descriptive literature.

Describing leakage

Both Jimenez and Chalaturnyk (2002) and Celia and Bachu (2002) explore the mechanisms of leakage. They stress that leakage is possible through or along existing wells, stating for example that in the state of Texas in the United States, more than 1,500,000 oil and gas wells have been drilled. Precisely assessing the status of these wells is difficult since more than one-third have been abandoned, some more than a century ago. The authors conclude that transport models for leakage analysis must include proper representation of existing wells.

Saripalli et al. (2002) present a risk assessment pointing out that cap-rock integrity, leading to slow leakage, is a greater cause of concern than the risk of catastrophic failure at the well head during the injection process. This does not contradict the previous point that existing wells are an important factor that compromise cap-rock integrity.

The comparative study by Benson et al. (2002) confirms both these ideas: "Long industrial experience with CO_2 and gases in general shows that the risks from industrial sequestration facilities are manageable using standard engineering controls and procedures. [...] On the other hand, our understanding of and ability to predict CO_2 releases and their characteristics in any given geologic and geographic setting is far more challenging". They also state that in natural gas storage projects, "in the vast majority of cases, leakage is caused by defective wells (poorly constructed or improperly plugged abandoned wells)".

How small is small enough? Geophysical aspects.

On the normative point of view, Hepple and Benson (2002) and Pacala (2002) assessed the maximum leakage (or seepage) rates that would be compatible with stabilization of the atmospheric carbon dioxide concentration. Both studies find that residence times greater than 1,000 years (in other words, seepage rates less than 0.1%/year) allow for an effective storage policy. But the latter study finds that mean residence time as low as a 100 years could still allow one to meet a stringent environmental target, whereas the former states that with few exceptions, a 1%/year leakage rate is unacceptably high.

This difference can be traced to different assumptions on the long-term evolution of the mean leakage rate. Pacala assumes that injection is randomly distributed across a collection of heterogeneous unlimited reservoirs. Consequently in the long run the fraction of carbon remaining in the less leaky reservoirs increases, so the average leak rate decreases. On the contrary, Hepple and Benson assume that reservoirs have limited capacity, so as very large quantities of CO_2 are sequestered underground, the probability of selecting less favorable sites with higher leak rates will increase.

How small is small enough? Economic aspects

Herzog et al. (2003) calculate the storage effectiveness for injecting CO_2 at various depths in the ocean. Their analysis can be transposed directly to geological storage, since deeper oceanic injection is equivalent to less leaky reservoirs. They use a Hotelling model, in which the critical parameter is the long-term evolution of the marginal damages from climate change, assumed to be equal to the carbon price. If this rises at or near the discount rate, then temporary storage is not interesting. If on the contrary marginal damages are constant, or there is a backstop technology that caps abatement cost, then temporary storage is nearly equivalent to permanent storage.

Hawkins (2002) notes that, considering the world's fossil fuel reserves as underground stored carbon, the present global emissions from energy use represent an annual leak rate of about 0.1% per year, which is unsustainable. He also points out that the leak rate of the current carbon storage sites is unknown: we can not be sure it is less than one per thousandth per year. The conclusion is that, while carbon storage should not be ignored, it should not crowd out other mitigation options, and the upper bound on leak rates should be on below a level of concern given the amount stored.

Dooley and Wise (2002) used the MiniCAM 2001 integrated assessment model to examine two leak rates: 1%/year and 0.1%/year. They conclude that the smaller leak rate does not lead to a substantial impact on required net annual emissions reductions, in line with the findings of Hepple and Benson (2002) and Pacala (2002). They also find that 1% leakage per year is likely intolerable, as it represents an unacceptably costly financial burden moved to future generations. The implication is that monitoring technology should progress to the point where it can resolve the fate of injected CO_2 with this level of specificity.

Keller et al. (2002) analyze leakage in an optimal economic growth framework using both a simple analytic model and a numerical integrated assessment model. They conclude that CO_2 storage (at a constant marginal cost of U.S.$100 per ton of C, with a reservoir half-life of 200 years) could reduce mitigation costs and climate damages considerably, and that a subsidy for the initial non-competitive storage is sound economic policy.

They also introduce the notion of an efficiency factor of storage: for example, 100 tons of sequestered CO_2 would be worth 50 tons of avoided CO_2 emissions at an efficiency factor 50%. This factor decreases when the leakage rate increases or when the energy needed for storage increases. On the other hand, increasing the discount rate tend to increase the storage efficiency.

Microeconomics of leakage

This short review of the literature shows that the leakage rates over 1%/year tend to be on the high side, while leakage rates less than 0.1%/year tend to be acceptable. This section uses a simple microeconomic model to discuss the relation between leakage, the discount rate and the relative cost of carbon capture and storage. The argument is based on the equality of marginal costs across substitutable technologies, and will also discuss the energy penalty of capture and storage. This leads to an estimation of a maximal acceptable leakage rate that depends of a plausible estimate of the ratio between the cost of perfect storage—or equivalently non-fossil energy—and that of leaky storage.

Permanent storage by re-capturing leaks

Consider two technological options to deliver energy without CO_2 emissions:

- The first is to use a non-fossil primary energy source so that paying some incremental cost a above the conventional energy price results in 1 ton of carbon being not emitted in the atmosphere.
- The second option achieves the same result by producing energy burning 1 ton of carbon from fossil fuels, and then—instead of exhausting it in the atmosphere—capturing and injecting it underground. For the sake of simplicity we start by neglecting the energy needed for capture and storage; we will come back on this assumption later.

Alternatively, one may view the first option as being perfect storage where the second is imperfect.

To achieve the same environmental result as the first, the second option has to offset any carbon that leaks out of underground storage, for example by capturing and storing additional CO_2. If c is the marginal cost to capture 1 ton of carbon and inject it underground, the net present cost of this technological option will be c plus the cost of offsetting future leaks. The standard way to assess net present value NPV of a flow of costs $x(t)$ occurring over time in the future is to use a parameter called the discount rate δ (similar to an interest rate) and sum up the discounted costs over time (see Portney and Weyant (1999) for a recent discussion of this standard methodology's limitations in the context of climate change):

$$NPV = \int_{t=0}^{\infty} x(t)\mathrm{e}^{-\delta t}\mathrm{d}t$$

Assume that leakage is proportional to the amount of carbon stored, and denote λ the annual leakage rate of the underground carbon reservoir. The storage option entails an initial cost of c and a subsequent annual cost of $x(t)=\lambda c$ forever. The total net present cost of the storage option is thus $NPV = c + \lambda c/\delta$, where $\lambda c/\delta$ is the geometric sum of the cost to keep the same total amount of carbon underground by injecting additional CO_2 to make up for leaks.

The question is not to determine which of these two options is cheaper than the other. Both have cost curves with increasing marginal costs. Basic economic reasoning suggests that to minimize the cost of meeting any emission constraint, it is best to spread the effort across the two technologies so that their marginal cost is the same. The economic efficiency condition is thus $NPV=a$, assuming of course the absence of other strategic, environmental or political externalities.

This is why, to compare the two technologies, we determine the ratio $r=c/a$ that corresponds to the economic efficiency condition. This ratio corresponds to the "efficiency factor" recently derived in a similar way by Keller et al. (2002). Economic efficiency implies:

$$r = \frac{\delta}{\lambda + \delta} \tag{1}$$

Intuitively, the ratio is less than unity because leaks make capture and storage less environmentally efficient than abatement. This is why it has to be cheaper by a factor of r in order to be as interesting.

This result shows that, as long as the leak rate λ is an order of magnitude lower than the discount rate, then the penalty for leakage is very small (r is close to one). A public discount rate of a few percent per year is usually recognized as a sensible order of magnitude, in line with observed population and macro-economic growth rates in the long term. This implies that storage with leak rates of a few thousandths per year is economically very close to perfect avoided emissions.

If the leak rate is a few percent per year, then sensitivity to the discount rate becomes important. Consider for example a discount rate of 4%/year and a leakage rate of 1%/year. Then $r=0.8$. Carbon storage should be pushed to the point when its marginal cost is 80% of marginal abatement cost. Supposing for example that the value of non-emitted carbon is U.S.$10 per ton, this leads to a value of temporarily stored carbon of U.S.$8 per ton of carbon[1]. The penalty is not overwhelming.

Another assumption in Eq. (1) that needs discussion is that the leakage rate λ is constant. Actually, even assuming that carbon capture and storage operates at a small scale in front of the energy system, one can expect the storage conditions to change in the long run as different geologic reservoirs and new technologies are used. Supposing for example that $\lambda(t)=\lambda e^{-\tau t}$, that is a constant decrease at exponential rate τ, then the leakage efficiency ratio becomes:

$$r = \frac{\delta + r}{\lambda + \delta + r} \qquad (2)$$

Intuitively the faster the sinks improve (larger τ), the closer is r to unity. We ignore whether λ can be expected to increase or decrease in the long run.

The energy penalty

Carbon capture and storage has another disadvantage compared to abatement: it needs energy. For example, a coal-fired power plant would take an efficiency penalty when fitted with a system to capture the carbon dioxide from flue gases. Herzog's (1999) studies show an energy penalty in the 14–20% range using existing technology, and 7–17% using 2012 assumptions. The numbers depend largely on the existing energy market conditions, since the penalty is relative to the reference technology for electricity production.

Define the energy penalty μ as follows. To produce the same amount of energy services that would have emitted 1 ton of carbon in the air, one has to capture and store $1/(1-\mu)$ tons of carbon underground. Another way to see μ is to say that the carbon capture and storage process uses fossil energy, and thus emits μ tons of carbon in the air per ton of carbon stored underground, so that the net removal from the atmosphere is therefore $1-\mu$ ton per ton of carbon processed.

The energy penalty makes air capture less interesting than previously. Offsetting leaks by storing more carbon underground would result in the underground stock growing exponentially. But future leaks can also be compensated by abatement instead of storage.

Consider a one-time atmospheric removal of one net ton of carbon, for a storage of $1/(1-\mu)$ ton underground. The initial cost to do this is $c/(1-\mu)$. Assume that this store of carbon in the ground declines at a rate λ without being replenished. Leaks get smaller and smaller with time, since the stored carbon depletes at an exponential rate λ, and at date t leakage is

$$\frac{\lambda}{1-\mu} e^{-\lambda t}$$

The cost to compensate for this leakage through abatement is

$$x(t) = a\frac{\lambda}{1-\mu} e^{-\lambda t}$$

Assuming a constant discount rate, leakage rate and energy penalty, the efficiency condition $NPV=a$ leads to:

$$r = \frac{\delta}{\lambda - \delta} - \mu \qquad (3)$$

This formula makes explicit the trade-off between the leak rate and the energy penalty of carbon capture. This kind of trade-off is likely to be important when comparing different storage options, which would differ both in energy requirements and in leak rates. If the energy penalty is too large, then carbon storage does not make economic sense unless $c<0$, that is there is a joint benefit to storage (as in CO_2-EOR).

Application

For a given a and c, the ratio r can be used to determine up to what leakage rate λ the storage option is environmentally as efficient as the abatement option. However, it is necessary to remember that for each technology there is a portfolio of actions that can be ordered by increasing marginal costs along a cost curve.

Freund (2001) published explicit estimates of storage costs curves. Some storage has been achieved at negative costs as an ancillary benefit of enhanced oil recovery. Another way to sequester carbon dioxide, less explored but maybe also profitable, is injection into deep, unminable coal seams because this allows the recovery of the natural gas that was adsorbed at the surface of the coal (Reeves 2002, Wong and Gunter 2000). Injection in depleted gas fields is also possible, with maybe the option of CO_2-enhanced gas recovery. Beyond those, the economics of injection into saline aquifers or into the sea are presently even more uncertain. Of course, the curve depends on how the portfolio of actions is delimited, and for each specific technology costs vary at each particular potential underground reservoir with geometry, geology, location and market forces.

There is also a cost curve for producing CO_2 streams, as discussed for example by Johnson and Keith (2003). Opportunities at very low cost come as by-products of hydrogen and natural gas production, but quantities are limited. Higher up on the curve, the majority of today's market production comes from natural resources: CO_2 is mined from underground reservoirs such as the Mac Elmo Dome in Colorado. Presently the average delivered price is U.S.$10–20 per ton. Herzog (1999) studied the cost of existing carbon capture systems from power plant flue gas, which uses an amine-based absorption technology. He reports mitigation cost in the range U.S.$20–60 per ton of CO_2 using present-day technologies (the price per ton of carbon is 44/12=3.7 times higher). Beyond that, Ha-Duong and Keith (2002) discussed how carbon could be captured directly from the air at over U.S.$150 per ton of carbon, for example as a joint product of bio-ethanol energy.

The cost curves show that the acceptability of a leakage rate depends on values of c that may differ between

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[1] The net effect of δ on the dollar value of storage is ambiguous, because the carbon value decreases but r increases with the discount rate.

specific applications, and that our example with plausible and significant numbers is just that (an example). For a discount rate of 4%/year and a leakage rate of 1%/year and an energy penalty of 20%, then r=0.6. With a 5% discount rate, a 2% leak rate and a 15% energy penalty, the efficiency ratio is still over 50% (0.56).

Since there is evidence that some carbon capture and storage options are substantially less expensive than alternatives, this suggests that 1% leakage may be acceptable in some cases. In the electric sector, for example, when large reductions in emissions are requested (greater than 50%), then mitigation using CO_2 capture and storage may be half the cost of mitigation achieved using non-fossil alternatives (Biggs et al. 2001; Johnson and Keith 2003).

Numerical results in a long run cost–benefit model

We now turn to the long-term implications of leakage. This section explores the consequences for climate policy of leaks in the artificial carbon store, complementing the previous section by taking a more macro-economic perspective on two key issues: non-marginal storage and cost–benefit analysis.

Concerns about possibly large amounts of carbon stored underground in the long run can be quantified using the following orders of magnitude. At the global scale, if industrial carbon management plays a big role in mitigating emissions, then as much as 500 GtC could be stored by 2100. If the average leak rate is only 0.2% annually, there would be a 1 GtC per year source undermining CO_2 stabilization. However, storing that much carbon underground by the end of the century means storing 5 GtC per year on average, which is several times larger than the annual leakage in the end.

In order to keep all these numbers and other long-term assumptions consistent, we resort to a numerical model. That model also allows us to explore the implications of a potentially important technology: capturing CO_2 directly from the air. One air capture technology for example could be to use biomass as a fuel for a power plant, capturing and storing the CO_2 in this plant's flue gases.

In this study a simple integrated assessment model, DIAM (Dynamics of Inertia and Adaptability Model), is used to compare optimal global CO_2 strategy with and without air capture, and with or without leaks. The model maximizes the expected discounted inter-temporal sum of inter-temporal utility. DIAM does not represent explicit individual technologies or capital turnover, but does include a representation of the inertia related to induced technical change. The inertia of the worldwide energy system induces adjustment costs, related to the rate of change of abatement.

The DIAM version 2.5 used here[2] is derived from the version described by Ha-Duong and Keith (2002). This numerical experiment is comparable to the previous section's micro-economic model in that carbon stored underground leaks at a constant annual rate, and two reduction technologies are available: a generic abatement technology; and capture with storage. However, the cost curve for carbon capture and storage is flat because we are interested in costs for non-marginal quantities. As Ha-Duong and Keith (2002) discussed, carbon capture and storage can be modeled as a backstop technology, that is available at a constant marginal cost of around U.S.$150 per ton of carbon (about half of this is adjustment costs).

This section briefly describes the model, focusing first on the damage function, and then on the mitigation cost functions, before reporting the sensitivity of optimal CO_2 trajectories to variations in the leakage rate and to the possibility of capturing carbon directly from the air.

The model

The benefits of avoiding climate change, or alternatively the cost of climate impact, is represented using a nonlinear damage function (Fig. 1). This frames optimal climate policy as a problem of action facing a known threshold of abrupt climate change. While other versions of DIAM represent uncertainty regarding climate and ecosystems sensitivity, DIAM 2.5 was run here in deterministic mode to better focus on the role of leakage.

The impact is a function of atmospheric carbon dioxide concentration lagged 20 years. While it is measured in monetary units, it represents a global willingness to pay to avoid the given level of climate change, including nonmarket values. The impact at any date is defined as a fraction of wealth at this date. Therefore it scales over time with the size of the economy. The assumption is that, even though a richer economy is structurally better insulated against climate variations than an poorer economy, the overall desire to limit interference with the biosphere increases linearly with wealth.

The model represents emissions abatement occurring by two activities X and Z, each with its own cost function. Activity X represents emissions abatement through conventional existing energy technologies, its marginal cost increases with mitigation, and X is constrained below 1.

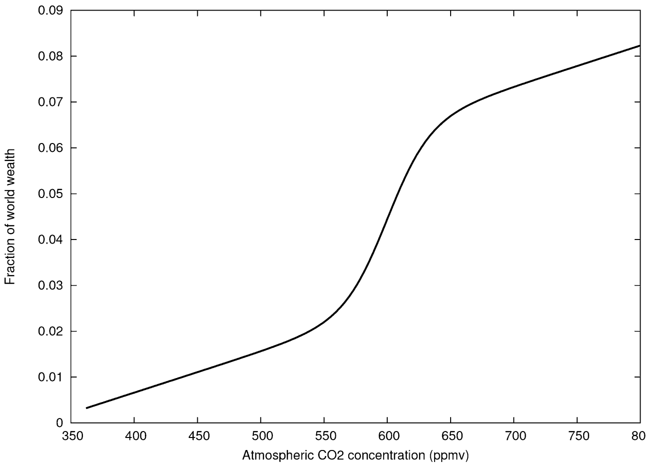

Fig. 1. The impact of climate change. Fraction of global wealth lost each year as a function of carbon dioxide concentration, as used in the cost-benefit model DIAM version 2.5. Damage depends on concentration 20 years before and is assumed to be zero in 2000

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[2] The GAMS source code is available at http://www.andrew.cmu.edu/user/mduong

Activity Z represents carbon capture and storage at constant marginal cost. The unavailability of air capture is represented as the constraint $X+Z<1$, stating that the total abatement cannot exceed the overall demand for energy in the baseline. This constraint can be relaxed to represent the possibility that Z captures the CO_2 directly from the air, as discussed by Ha-Duong and Keith (2002).

Before leaks, anthropogenic carbon emissions at any given time are $E^{\text{landuse}}+(1-X-Z)E^{\text{ref}}$. Land use emissions are exogenous and considered irreducible. In addition, the underground reservoir S leaks at annual rate λ into the atmosphere. The energy penalty on carbon capture and storage is $\mu=15\%$, so an activity level Z corresponds to an increase of the underground stock by $[Z/(1-\mu)]E^{\text{ref}}$.

Table 1 displays the cost of achieving mitigation activities X and Z. The cost of each activity depends both on its scale X or Z, and on the rate at which it is being increased.

Calibration of cost functions were unchanged from the previous version, and are comparable to the DICE-98 model by Nordhaus and Boyer (2002). Ignoring adjustment costs, activity X incurs quadratic abatement costs up to full abatement. This leads to a marginal carbon price increasing linearly. In marginal terms, the order of magnitude is a U.S.$100 carbon tax for a 20% abatement of world emissions, a common ballpark number.

Table 1. The cost of reducing carbon emissions in DIAM 2.5 for each activity. Gross World Production (GWP) was about U.S.$$18\times10^{12}$ for the base year. All base costs decline at an autonomous technical progress rate of 1% per year. The r=30-year inertia parameter in adjustment costs is the characteristic time of the world's energy system

Activity (Unit)	Total cost= U.S.$	Base cost U.S.$/tC	× Scale tC	× Multiplier (dimensionless)
Conventional abatement	$C_X=$	2.45% GWP (t_0)	$\frac{E^{\text{ref}}}{E^{\text{ref}}(t_0)}$	$\dot{X}^2+\left(r\dot{X}\right)^2$
Backstop Carbon capture +storage	$C_Z=$	75 U.S.$/tC	$\dot{Z}E^{\text{ref}}$	$1+(r\dot{Z})^2$

Results

Results are displayed numerically in Table 2 and graphically in Fig. 2. Figure 2 shows two variables: global anthropogenic carbon emissions (excluding leakage) on the top panel, and carbon dioxide atmospheric concentration on the bottom panel. The top dashed curve corresponds to a business as usual reference scenario. The continuous line corresponds to Table 2's first row (no leak, no air capture) while the dashed line next to it corresponds to Table 2's next to the last row (leak rate 0.5%/year, air capture available).

The results displayed in Fig. 2 illustrate the model calibration. The overall shape of the optimal trajectories tells the following plausible story. During the next few decades, there will be a slow departure from current trends, because of the considerable inertia in the world's energy system. Late in this century, the atmospheric carbon dioxide concentration stabilizes below what constitutes in this model a soft ceiling at around 550 parts per million. In the next century, the atmospheric carbon dioxide concentration will decline.

Our point is not to discuss the desirability of this storyline in itself. Rather, the model is used to study the sensitivity of optimal trajectories to two parameters: the leak rate and whether the backstop technology can capture carbon from the atmosphere. Results, presented in Table 2, were remarkably insensitive to the value of the energy penalty parameter μ so this parameter is kept constant in the simulations.

The table's rows correspond to various leak rates with and without the availability of air capture. The columns show (in 2050 and 2150) three variables: the percentage of abatement using conventional technologies X; the percentage of abatement using the backstop Z and the atmospheric CO_2 concentration M.

First consider the effect of leakage in the absence of air capture. This corresponds to the top half of Table 2, or technically the constraint that $X+Z$ cannot go over 100% of reference emissions. We explored leakage rates ranging from zero to 1%/year. In 2050 the backstop technology Z is not used in any scenario. It is because at this date, the marginal cost of X has not risen to the backstop's cost. The fact that X differs across rows for this date reminds us that the model is finding a global

Table 2. Results and sensitivity analysis. Optimal levels of emissions abatement X are given as a percentage of baseline emissions. The atmospheric CO_2concentration M is in parts per million. The annual amount of carbon capture and storage Z is given as a percentage of baseline emissions, and is zero in 2050 for all scenarios. The possibility of capturing carbon directly from the air (lower part of the table) is represented by relaxing the constraint $X+Z<100\%$ in the optimization program

Air capture?	Leak rate	Optimum in 2050		Optimum in 2150		
	λ (%/year)	Abatement X (%)	$[CO_2]$ M (ppmv)	Abatement X (%)	Storage Z (%)	$[CO_2]$ M (ppmv)
No	0	17	496	52	47	512
No	0.1	18	494	61	38	525
No	0.5	23	491	93	6	533
No	1	23	490	100	0	529
Yes	0	17	496	58	57	494
Yes	0.1	17	495	61	54	507
Yes	0.5	20	492	86	57	521
Yes	1	23	490	100	0	529

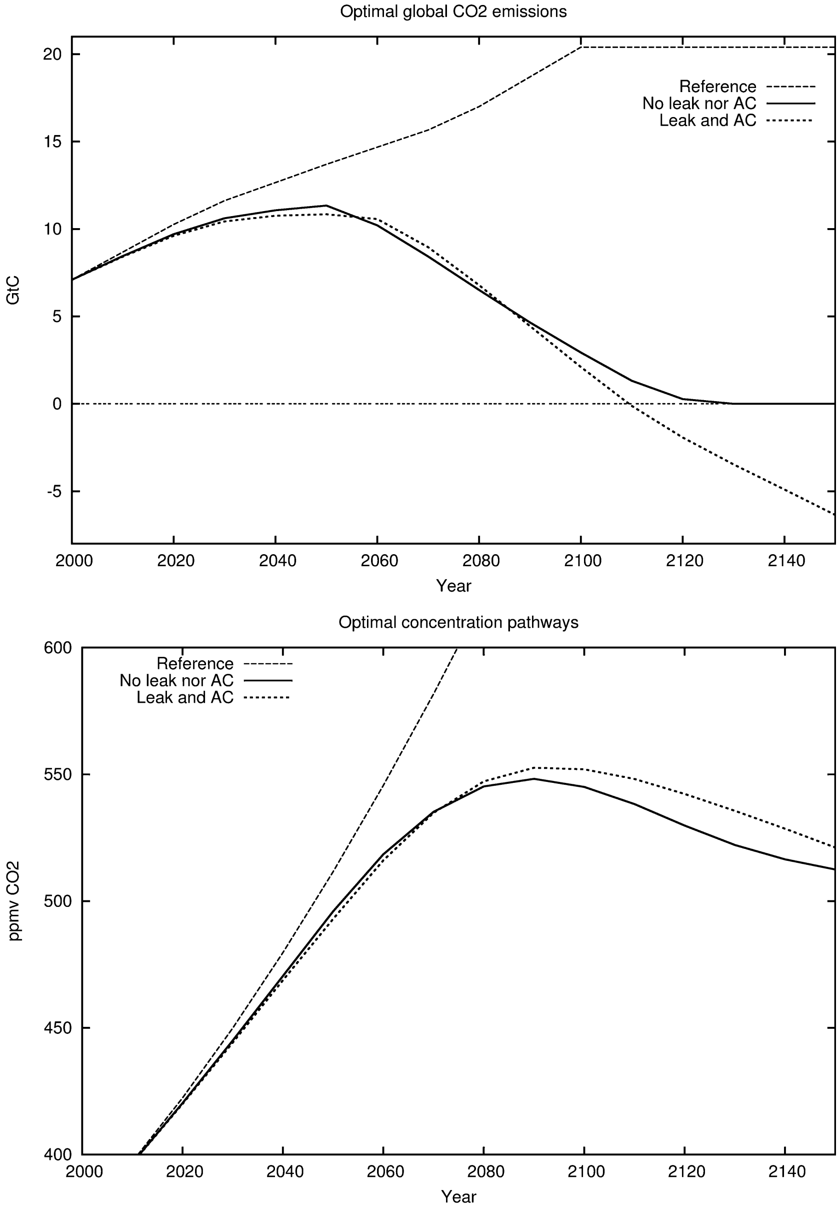

Fig. 2. Optimal CO_2 trajectories. *Upper panel*, global carbon emissions, not including emissions from leaks due to underground storage. *Lower panel*, atmospheric CO_2 concentration in parts per million

optimum and is thus forward looking. Since it optimizes intertemporally, Z=0 does not imply that X should be the same across all four rows.

The model sensibly finds that the larger the leakage rate, the smaller the carbon capture Z, and the larger the abatement X should be. This applies at all periods. We find that with perfect storage, the amount of carbon capture is lower than, but comparable to, the amount of abatement. This remains true with a 0.1% leakage rate. Carbon capture plays a marginal role at 0.5% leak rate, and does not enter the optimal technology mix at all at any date with a 1%/year leak.

Consider now the atmospheric concentration M. Table 2 suggests that optimal M in 2050 and in 2150 varies in opposite directions when increasing the leak rate. The intuitions behind this result is that a zero leak rate implies the availability of a perfect long term pollution sink. This in turn makes it cheaper to control CO_2 emissions. That has two effects on the optimal trajectories. In the long run the optimal balance of costs and benefits is tilted toward a cleaner environment. At the same time, the optimal burden sharing is also tilted toward future generations: abatement effort in the first periods is comparatively lower.

How does this change when allowing for air capture? The lower half of Table 2 presents results where the constraint X+Z<100% is relaxed. As the top panel in Figure 2 shows, net emissions indeed become negative around 2110 on the optimal path. As the table shows, in 2150 this (X+Z greater than 100%) remains true for the lower three leakage rates. Overall, the qualitative results presented above remain the same: more leakage implies less reliance on carbon capture and storage.

Compared to the no-air capture scenarios, there is more carbon storage everywhere along the way, and ultimately in 2150 the atmospheric concentration is lower. Air capture also pushes up the acceptable leak rate to 0.5%/year. This next-to-the-last row illustrates a scenario where CO_2 stored underground contributes significantly to the emissions, about 10 GtC/year, but that source is actively offset by capturing carbon from the air even through most (86%) of the energy system is carbon free.

Concluding remarks

Policy implications for the value of carbon

Assuming that market-based instruments will be used implementing a carbon emissions reduction policy, how would carbon storage fit within the environmental regulatory framework?

The IPCC defined emission trading as "a market-based approach to achieving environmental objectives that allows those reducing greenhouse gas emissions below what is required to use or trade the excess reductions to offset emissions at another source inside or outside the country". Imagine for example an operator owning two power plants. In the first plant A the operator can reduce emissions easily, but the other plant B uses a different technology and it is more expensive to reduce emissions there. Under a flexible regulation regime, if the operator was ordered to reduce its plants' overall emissions by 10%, then he would be allowed to concentrate his efforts on A, go way above 10%, and assign the excess reduction to the plant B. Emission trading extends this flexibility to situations where plants A and B are not owned by the same firm.

Firms engaged in carbon capture and storage clearly have a role to play in this market for certificates of emissions reduction or, in less diplomatic language, pollution permits. We assert that because of leakage and the energy penalty, 1 ton stored underground should correspond to less than 1 ton of carbon permanently removed from the atmosphere. With the usual caveats about the efficient markets assumption, about the absence of externalities and about discounting, the ratio *r* derived in this paper can be interpreted as the socially desirable ratio for discounting carbon storage.

The energy penalty should not be left out of the picture, or one risks creating the opportunity to make money by simply moving carbon up and down. In an economy where carbon already has a price reflecting the climate externality, then storage projects already internalize the energy penalty. In this situation they should be regulated using Eq. (1). It is conceivable, however, that a firm involved in carbon storage faces a carbon price not reflecting the climate change externality. For example, energy intensive industries have obtained a differential treatment in some countries. In this situation or for a carbon storage project that occurs in a country not controlling emissions at all, for example as a Clean Development Mechanism/Joint Implementation project, Eq. (3) should be used instead.

Conclusion

This paper examined leakage of artificially stored CO_2 from an economic perspective, using first a cost–efficiency microeconomic model, and then a global cost–benefit integrated assessment model.

Leakage of stored carbon is at heart a problem of intertemporal distribution of abatement costs and benefits. Having decided to mitigate global warming for the benefit of future generations, the present generation should allocate its efforts as efficiently as possible across the various technological options. This is why in a normative economics analysis the discount rate plays the central role, and gives the numeric anchor needed to assess what is an acceptable leakage rate.

The simplest interpretation of our results is that leakage rates one order of magnitude below the discount rate are negligible. In line with previous findings from the literature reviewed, the numerical simulations presented in this paper found that longer than 1,000 years is practically as good as infinity. Storage with residence time as short as a few hundred years may still be valuable.

The microeconomic analysis provides a more detailed answer for higher leakage rates in term of storage efficiency ratio *r*. We use this ratio for projects that remove carbon only temporarily from the atmosphere, to adjust the credit they can claim and be free from further liabilities from leakage. Assuming a public discount rate δ, a leakage rate λ then a project should be credited only the fraction $\delta/(\delta + \lambda)$ of the carbon value initially injected. If the project does not internalize the climate externality in its energy prices, then the energy penalty term μ should be subtracted from this ratio.

These results hold even for one-time storage opportunities, such as enhanced oil recovery. With a 1% annual leak rate and a 1–4% discount rate, the economic efficiency ratio is between 50% and 80%. This is not overwhelming.

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