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# CCS-Bonds as a superior instrument to incentivize secure carbon sequestration

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**Abstract**

Geological sequestration of CO2 on a massive scale implies that large area fractions of the underground could become flooded by CO2, imposing a unprecedented regulatory challenge to environmental authorities. Therefore we propose carbon sequestration bonds as complementary, market-based instruments that should further help to manage the risk of decadal-scale CO2 leakage. Such bond schemes address market failures that could occur if the investment behavior of operators under uncertainty differed from society's preference. For a stylized setup we demonstrate that our bond system has the potential to simultaneously address regulatory challenges stemming from information asymmetries and diverging orders of preference.



Keywords: Carbon Sequestration, Leakage, Observational systems, bond schemes, investment under uncertainty, information asymmetry, detection limit

## 1. Introduction

According to IPCC-AR4, Carbon Capturing and Sequestration (CCS) represents one of the key technologies to mitigate further global warming. Under a 450ppm CO2 target, our welfare-maximizing analyses derive an amount of up to ≈2000 GtCO2 to be sequestered as desirable from a purely economic, globally aggregated point of view [1]. This information alone does not establish CCS as a necessary mitigation option. However the following additional aspects lead us to the conclusion that it appears as highly rational to develop CCS at least up to a demonstration stage, both in terms of engineering as well as in regulatory terms.

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First, the welfare-loss from disregarding under a 450ppm target is ~0.5%GDP according to Edenhofer et al. [2]. While this does not appear a large number, it is one of several effects that may add up to a total of mitigation costs then potentially being viewed as unacceptable. Second, if mitigation targets are anticipated that are even more ambitious than 450ppm CO2, such as observing the EU's 2° target with high certainty, then it may become unavoidable to include a negative emissions option in the mitigation folder, such as biomass+CCS. Third, non-CCS-options may surprise society with non-anticipated technological difficulty, side-effects or simply high floor costs. Then it would be wise, under a precautionary perspective, to co-develop CCS while also pushing those alternative options. Finally, countries with abundant cheap coal and little potential for renewable energy may view CCS as their preferred mitigation option.

Any of those arguments may lead us into a future with massive-scale deployment of CCS, imposing a challenge to environmental authorities on an unprecedented scale. The following example may serve as an illustration. The German environmental protection agency published numbers [3] according to which sequestration of CO2 emissions from German point sources could in fact be accommodated over decades in the national reservoirs, however resulting (after being extrapolated by us) in a net 'underground-fill' of 1%-5% of German area. For environmental cases on such order of magnitude (for the time being by sheer geographical dimension) we regard it as attractive to complement supervision through the state by market-based incentive schemes for secure sequestration.

At GHGT-7 we suggested two CCS-bond schemes as market-based instruments that should manage the risk of decadal-scale CO2 leakage [4]. According to a first scheme, for each unit of CO2 to be sequestered, the operator does not have to buy an emission certificate, but must buy a CCS-bond instead, to be held by the state authority and handed back after 30 years or so with high interest, if leakage has been proven below a certain limit. If the operator can convince the capital market of safe operation, the operator can sell the option on that bond early-on, hence in case of convincing operation, providing high chance for early re-capitalization of the operator. A second version of the bond scheme [5] acknowledges the fact that a major fraction of operated sequestration sites may display unexpected leakage due to a systematic serial defect. For that reason the second scheme requests to buy an emission certificate at first, as if the CO2 was directly released into the atmosphere. Under continued observation, worst cases of leakage rates would then be excluded in successful cases, and those portions of the certificate could be sold as unblocked emission rights on a CO2 market. Apart from that feature, both versions are alike, for what reason we generically speak of 'the bond scheme' in the following. Our bond scheme is mainly designed for the case of massive-scale underground injection of CO2 and assumes that a phase with demonstration plants has successfully been operated such that capital markets are already oriented to a certain extent.

The bond scheme has witnessed positive resonance from most of the German parliamentarian parties on the federal level and a CCS-critical NGO, while we were confronted with considerable skepticism from both entrepreneurs and some government advisors on CCS. The proponents of our bond scheme subscribed to our arguments condensed above, while the counterarguments we have received over the last years may be listed as follows (termed 'C1', ..., 'C4' – 'C' for 'counterargument' – hereafter):

**C1** A CO2 cap (or tax) alone provides enough incentive for CCS; no additional instrument is necessary if an operator can spare emission rights when injecting CO2 underground and in addition the operator has to purchase emission certificates in case of leakage.

**C2** (Alternative to 1.:) Best-practice of geological survey and injection, supervised by an governmental authority alone is sufficient to guarantee leakage rates well below 1%/10kyrs. Geo-technologies are suitable to establish such orders of magnitude as standard cases. No market-based instruments are necessary.

**C3** Either the bond's interest rate will be so low that the company will not sequester or it will be so high that in case of successful operation, the state may go bankrupt.

**C4** Volatility in the bond's option value will prevent investment into CCS.

In this article, we address most of those counterarguments. The article is organized as follows. In the next section we introduce an illustrative example on how to incentivize optimal CCS paths when CCS is operated by a myopic entrepreneur. In the subsequent section we condense the insights from that example in view of CCS bonds in general, while also addressing above four critical remarks C1, ..., C4. Finally we conclude with our main findings and an outlook on further research needs.

## 2. A stylized model for the design of CCS incentives under multiple discount rates

In previous work displayed at GHGT7+8 we introduced CCS bonds as instruments to manage the uncertainty on site-dependent leakage rates. When asking for the specific *economic* benefits of a bond scheme as against other incentive schemes we note that *even under uncertainty* there is no difference between a bond scheme or any other scheme to incentivize the socially optimal CCS, if (1) there is no information asymmetry between society and operator, and (2) both sorts of actors likewise discount the future and display the same kind of risk aversion. This section is devoted to the latter issue.

We start out by the question: why are investments into low-carbon technologies not already flowing, although the climate problem has been formulated already decades ago? One of the reason for this imperfection of the global market, in our view, – and in addition to mitigation involving a free rider problem – lies in the fact that *investment behavior of energy companies is generically governed by a significantly larger discount rate than that of the society as a whole or at least take higher risks on the future*. This represents a central working hypothesis of our article. For reasons of compactness, in the following we lump both aspects into the term 'discount rate', that therefore should not be understood in its most literal sense (thereby we somewhat mimic climate economists' debate on the correct pure rate of time preference). Accordingly CO2 targets would require either a cap system or a CO2 tax that encapsulates that higher discount rate as well. The latter discussion is beyond the scope of this article. Instead we would like to tackle the issue as much focussed on CCS as possible.

The model we would like to introduce now, is designed to address the following question. By what incentives would a company match a society's economically optimal path in terms of the following variables:

1. amount of sequestered CO2,
2. investment into pre-sequestration geological surveys,
3. investment into post-injection observational networks.

For the sake of transparency, we now assume the most parsimonious causal relations possible.

*<u>Modeling society's investment paths:</u>*

The society as a whole may be characterized by the 2-period welfare function

$$W_S(I, R) = 2\,c\,R^{1/2} - I - d\,b(I)\,R \quad ,$$

whereby $R$ denotes the amount of sequestered CO2 in period #1, ($2\,c\,R^{1/2}$) the additional production from the usage of fossil fuels, the CO2 of which is now allowed to be sequestered, leading here to a linear increase in global welfare for simplicity, ($b(I)\,R$) the amount of CO2 that has leaked out until period #2, ($d\,b(I)\,R$) the damage induced by that leakage, and $I$ the cumulative investment into pre-sequestration geological surveys and post-injection observational networks (Friedmann et al. [6] regarded those costs as minor. However that may be a question of detection limit. 0.1%/yr seems to be regarded as very ambitious if leakage location is apriori unknown). Note that the second period matters only insofar as long-term damage ($d\ b(I)\ R$) occurs from CO2 leakage and is – for simplicity – not discounted at all.

Hereby we interpret the society as pessimistic in the sense that it focuses on the worst case of leakage, given a certain amount of investment in observational systems. This is synonymous with saying that such investment would tighten the *detection limit* on the leakage rate – the real leakage rate may in fact be much smaller, closer to the expectations of geologists. However in our model, society wants to be on the safe side and sequester only as much CO2 as it were compatible with the proven worst case possible, given a particular observational certain network density. In that sense our model rests on a 'performance-based' rather than a 'procedural' approach [7, p. 3482]. Furthermore we assume that the investment $I$ also covers the costs of pre-injection surveys such that the maximum non-detectible leakage fraction $b(I)$ is not transgressed. Thereby we allow to cover both pre- and post-injection observational aspects by one single variable $b(I)$.

In order to be more specific, we now assume the simplest possible functional relationship for $b(I)$ – see also Figure 1:

$$b(I) := 1 - k\, I \ \text{ for } I < I_{\max} := (1 - b_{\min}) / k, \text{ and}$$
$$b(I) := b_{\min} \text{ otherwise.}$$

For any $I$, society assumes its welfare maximum at

$$R_S^*(I) = c^2 / (d\, b(I))^2$$

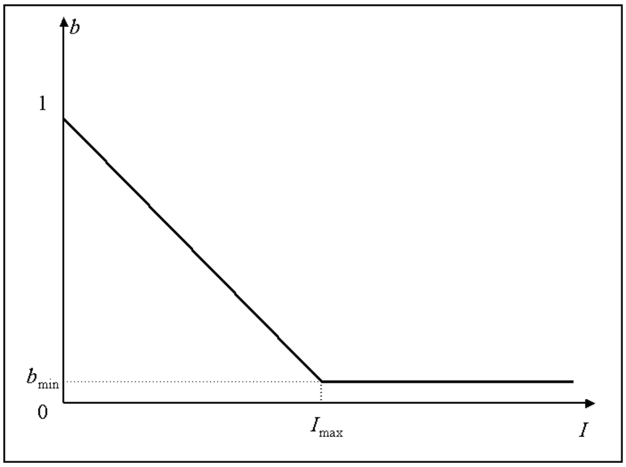


**Figure 1:** Leakage fraction $b$ vs. investment into pre-injection surveys and post-injection observation $I$. Without such investment, our risk-averse society does not assume that any portion of injected CO2 stays underground in period #2, hence $b(0)=1$. Investment can reduce worst-case leakage down to a *technology limit* $b_{\min}$.

Given that functional relation, welfare is linear in $I$, hence, for given $R$, society would either choose $I=0$ or $I=I_{\max}$. This binary investment behavior simplifies subsequent analysis considerably. The related investment threshold turns out to be

$$R_S^I = 1/(k\, d)\ ,$$

hence, for low amount of sequestration, investment does not pay off, for high amount it does. Over joint $(I,R)$ control space, even this simple model displays multiple (two) optima, depending on the 'return-to-investment' parameter $k$ in relation to $d/(c^2)$ and $b_{min}$. As in the context of the present article we are interested in a situation where society would like to invest in CCS including observational systems, from now on we assume k such that (1) society in fact would invest and (2) for simplicity, there are no multiple optima. Both can be achieved at once in assuming that low-$R$-optimum ceases to exist, i.e. the 0-investment $R_S^* > R_S^b$. The latter is the case if and only if

$$k >! \, d / c^2$$

what we assume from now on. Under these circumstances, society chooses the high-$I$-high-$R$ optimum

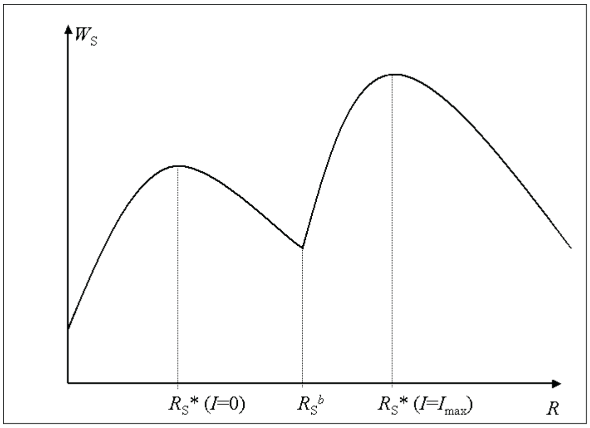


**Figure 2**: Society's welfare function vs. sequestration volume. In general, our model displays two local optima, representing the zero-investment and the high-investment branch of solutions.

$$R_S^* = c^2/(d\, b_{min})^2 \;\text{ with }\; I(R_S^*)=I_{max} \,,$$

and our question is now *how to make an entrepreneur choose that high-investment path,* i.e. $R_E^* =! R_S^*$.

<u>*Modeling an entrepreneur's investment paths:*</u>

A company materializes the very production function and investment losses that we assumed for the society as a whole, hereby following the ansatz of our former contribution at GHGT-7 [4]. Damages from CO2 leakage are external to the entrepreneur and need to be internalized by fiscal instruments. We introduce a *sequestration tax* ($t^S R$) to be paid in period #1, an atmosphere pollution tax ($t^A R\, b$) to be paid in period #2, and an incentive for successful sequestration ($x\, R\, (1\text{-}b)$), to be received in period #2. In this article we deviate from our previous work by explicitly allowing the company to discount future more than society as a whole does; accordingly we assume a discount factor $q$<1 for period #2 in the entrepreneur's production function (for period #2 being realized after 30 years or so, $q \ll 1$ ):

$$W_E(I, R) = 2\, c\, R^{1/2} - I - t^S R + q\, ((1\text{-}b(I))\, x - b(I)\, t^A)\, R \,.$$

The company's investment switch then occurs at

$$R_E^{\,b} = 1 \,/\, (q\, k\, (x + t^A)) \,.$$

From this one can show that $R_E^* =! R_S^*$ is obtained if the following 4 conditions are simultaneously fulfilled as joint sufficient condition:

$$t^S = d\, b_{min}$$
$$t^A = t^S / q$$
$$x = t^A / (1-b_{min})$$
$$\text{subject to}$$
$$k > 4\, d\, b_{min} / c^2 .$$

(The latter inequality ensures – in analogy to the society's solution – that the company does not experience a low-investment optimum.) The fact that these incentives and taxes scale with $b_{min}$ may give the misleading impression that under perfect sequestration, no incentives were necessary. However here it is crucial to discuss the terms that enter the welfare function as a whole, as our model displays singular behavior in the limit $b_{min} \rightarrow 0$: the optimal $R$ scales with $1/b_{min}$, hence $b_{min} \rightarrow 0$ results in a finite welfare loss, i.e. still in a finite steering from inadequate choice of $R$. Therefore it is improper to discuss the analytic behavior of taxes decoupled from that of $R$; in fact there will always be incentives necessary to internalize damages from leakage.

Furthermore one sees that the larger the company's discounting, the stronger the period #2 fiscal instruments needs to be. This implies that for above quadruple of conditions to be effective, society would have to know the company's discount rate in advance. In particular, assuming $q$=1, i.e. (in the framework of our modeling world) equal discounting for company and society, leads to sub-optimal investment behavior accounting to society's metric. We regard this effect of fundamental importance way beyond the scope of this article.

On a more particular level, dependence of a policy tool on a company's discount rate represents a major drawback of that instrument. First, it may be rather intricate to figure out a company's discounting behavior. Second, different companies may be characterized by different discount rates (in reality: in particular risk aversions) while for the design of a fiscal instrument it would be highly desirable that all companies could be treated equally. For that reason we suggest to utilize one degree of freedom our model has, that was suppressed by above most compact solution. In fact the more general solution for $R_E^* =! R_S^*$ reads

$$t^S = d\, b_{min}$$
$$t^A = t^S / \langle q \rangle$$
$$x = t^A / (1-b_{min})$$
$$\text{subject to}$$
$$k > (t^S + q\, t^A)^2 / (q\, t^A\, c^2) ,$$

hereby $\langle q \rangle$ denoting some 'intermediate' value for $q$, and $t^A$ is chosen as to minimize the lower bound for $k$ if $q$ equaled $\langle q \rangle$. The latter makes it easiest for $k$ to fulfill above inequality and therefore expands applicability of the above framework. While $q$ is not known in general, we find it highly plausible that it might be known within certain bounds. Due to the quadratic nature of above inequality in $q$, both bounds will lead to a stricter requirement for the return to investment parameter $k$, that might be fulfilled nevertheless if a successful CCS demo phase had lowered implementation costs for observational networks through learning by doing.

We would like to close this section by noting that the key idea behind this discount rate-independent solution (within certain bounds) was to neutralize the term in the entrepreneur's welfare function in which her or his discount factor appears, i.e. we have tuned the fiscal instrument such that we achieved $\{(1-b_{min})\, x - b_{min}\, t^A =! 0\}$ (while ensuring at the same time that the high-investment path stays more attractive than the low-investment path).

## 3. The specific benefits of CCS bonds

The preceding section has shown that even if companies were more myopic than society as a whole, and their discounting preferences were diverse and largely unknown, still optimal underground injection and observational network investment paths could be induced by the adequate mix of a present-day injection tax, a future penalty on leakage and a future incentive on safely sequestered CO2. Quite the contrary, when not anticipating myopic behavior, standard incentive schemes would generically fail. Our model comprises the limiting case 'q=1' (no difference in discounting). Then the two welfare functions become alike with $t^A:=d$, being equivalent in saying that the company would have to pay the (atmospheric) carbon tax in case of future leakage. It that sense, we suspect that C1 (see end of introduction) silently assumes non-myopic entrepreneurs. Our model can be interpreted as to reflect an aspect of the bond system, version #1: ($t^S$ $R$) would be the bond price, and ((1-$b_{min}$) $R$ $x$) the return with high interest.

Furthermore, both C1&C2 silently assume that information asymmetry between operator (of an injection site) and society is not an issue. While over the past decades we have seen quite successful management of environmental sites by state authorities, it has to be noted that this was operated on quite a smaller scale in terms of area and/or number of sites. According to common economic reasoning, the state becomes increasingly inefficient when it comes to managing the plans and desires of a large number of competing actors, for what reason we suggest that the capital market should complement the state in stimulating, absorbing and weighing maximum information on numerous sites.

Still on the same topic, there seem to be vastly differing expert opinions about the maximum leakage rate, that can be controlled, on the 'market of opinions'. E.g., a recent survey [8, p. 162] reports quite a divergence in opinion between ZEP (zero emission platform – http://www.zero-emissionplatform.eu/website/) and other groups of stakeholders. The authors of this article themselves have received expert opinions that revealed a clash of orders of magnitude on leakage rates that one would expect from geo-scientific reasoning vs. a detection limit according to a combined, yet more direct observation of leakage. Also for that reason, for society it would be interesting to see whether the capital market went more for the optimistic or the pessimistic case. We do not find it implausible to link expert judgment also to financial consequences for that very judgment if massive scale deployment of technologies is involved. If operators believe in the quality of their site, it should be possible to convince the capital market as well, in which case there is no difference between a bond and a more traditional scheme.

C3 makes clear why the bond scheme not only includes the benefits of the model we analyzed in the previous section, but significantly goes beyond it. Although bankruptcy of the state could be avoided through lump-sum transfers from all operating companies such that there were no transfer of capital and operators on average [4], still taxes and incentives that scale with $1/\langle q \rangle$ (as in our example) appear likely to become ill-posed – if not fiscally unstable – in a world with imperfect knowledge. Quite the contrary, the bond scheme transforms future issues into present-day accounting in assuming that long-term investors (e.g. like pension funds) would find an interest rate attractive even if it were only mildly larger than the standard interest rate for long-term investment on the capital market. In our tax model, the state would have to refund $\sim 1/\langle q \rangle \gg 1$, while in case of the bond scheme the loss for the state may be on the order of magnitude of the unavoidable costs for enforcing observation of massive-scale sequestered CO2. Note that otherwise the state would have to pay an army of bureaucrats and directly-employed technicians. In fact, for the society as a whole, the costs for observing CO2 are unavoidable in either scheme.

C3 further states that the bond price may prevent investment into CCS. In our framework, this might be in part due to the fact that the operator has doubts about the site or thinks the volatility of the options price for the bond cannot be handled (hence, also absorbing criticism C4). For the latter, the same arguments must be put in place as for all instruments at the capital market (as in particular for a potentially volatile atmospheric CO2 certificate price): secondary instruments need to be implemented to insure against such volatility. The more fundamental issue whether the accumulated knowledge from a successful demonstration phase on CCS until 2020 or 2030 suffices to build long-term investor's trust in CCS operation, is beyond the scope of this article; however we hope to stimulate a discussion accordingly.

## Conclusion

We have presented the third in a series of articles suggesting CCS-bonds as a market-based incentive scheme for secure large-scale geological sequestration of CO2. Our scheme assumes that capital markets have already been informed on the feasibility and quantitative properties of CCS in a demo phase, that nevertheless could be designed to already test our instruments smaller scale. In this article we reflect certain counterarguments from stakeholders against our bond scheme. We address most of those issues in a positive way and can point out that CCS bonds, as against any other instrument we are aware of at the moment, simultaneously address, (1) myopic or (2) overly risk-taking operators and (3) information asymmetry of operator vs. society. In particular we argue that CCS bonds do not put an extraordinary fiscal burden on the state or would be superfluous by a standard CO2 tax that would have to be paid after leakage. We have to leave for further investigation whether our expectations on the long-term investment behavior of capital markets into semi-proven new technologies is realistic and whether a cap-and-trade system if designed to anticipate myopic behavior as well, would already encapsulate the desired benefits of our bond system. In more general terms, here we have studied a particular fiscal instrument focusing on CCS, that in future work should be analyzed in the context of further potential and closely related market failures.

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