A REGULATORY FRAMEWORK FOR CARBON CAPTURING AND SEQUESTRATION WITHIN THE POST-KYOTO PROCESS.

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Abstract

The option of capturing CO_2 at large power stations and storing it in geological formations allows for the use of fossil energy resources without further destabilization of the climate system. From an economic point of view, the efficiency of Carbon Capturing and Sequestration (CCS) depends mainly on leakage rates, marginal costs of CCS (including the energy penalty) and the volume of available depositories. We show that if CCS is to become an option to buy time, a regulatory framework is needed. In particular, a framework has to be designed that creates incentives for profit-oriented firms and investors to reduce leakage rates as well as energy penalties, and to deposit carbon in safe depositories only. A generic model is presented in order to clarify the economics of CCS. The paper proposes a new instrument called Carbon Sequestration Bonds (CSB). It is shown that CBS must be combined with a CO_2 tax or a tradable permit scheme in order to encourage firms to sequester the optimal amount of carbon. We discuss two version of this instrument: In the first version, a firm which intends to store carbon dioxide in geological formations has to buy a bond. The bond will be devalued by some kind of environmental authority after a fixed transmission time of the bond according to the fraction of leaked CO_2. Proportional to the stored fraction of CO_2, however, the company would obtain interest for the bond. A company can sell its bonds already during the transmission time if other agents on the market are ready to bear the risk of devaluation of the bond. It is argued that this system creates an incentive for firms to undertake CCS investments and at the same time to use relatively safe geological formations. In the second version of our proposal, emission permits have to be bought as long as it is not clear to which degree the geological formation is leaking. The permit can be traded on the market by CCS firms. If market agents trust in low leakage-rates, firms can sell their permits immediately. However, the value of the permit is uncertain as long as it is not proven which fraction of the carbon will stay underground. Over time, uncertainty on leakage rate can be expected to shrink for each individual formation. Based on this information the environmental authority decides sequentially how much carbon is accepted to be indefinitely stored in geological formations. Thus the second proposal reduces the ecological risks of CCS and increases the economic risks because investors may be discouraged to invest in CCS.

Introduction

The option of capturing CO_2 at large power stations and storing it in geological formations (CCS) allows for the use of fossil energy resources without further destabilization of the climate system. If backstop-technologies such as renewable energy sources are high-cost options it be may reasonable to temporarily use end-of-pipe technologies if technological change will reduce the costs of the backstop-technology.

However, CCS is a risky option for three reasons: First, greenhouse gases may outgas from geological deposits and therefore may harm the climate system further. Second, underground CO_2-migration may cause undesirable side-effects. Third, CCS may induce economic risks because it postpones investments in backstop-technologies like renewable energy sources and hence may prevent the reduction of costs of the backstop-technologies by technological change. If it turns out that the leakage rate or the energy penalty are relatively high, the postponement of investments in the backstop-technology increases the mitigation costs.

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There is an ongoing debate within economics about how to design regulatory frameworks aimed at enhancing innovative activities in order to reduce environmental risks by defining safe-minimum-standards. Recently, economists have proposed environmental performance bonds [3], [6]. In contrast to direct charges for known environmental damages, environmental performance bonds are issued by a regulatory authority and must be bought by firms undertaking environmentally risky investments. According to the literature, the bond price is set equal to the current best estimate of the largest potential future environmental damage. If the damage event occurs the bond will be devaluated by the regulatory authority. If the damage does not occur, the bond is kept in an interest-bearing escrow account. In this paper we will apply environmental bonds to CCS taking explicitly into account the transient nature of the CCS option. We also will offer a roadmap towards a coherent framework allowing for an assessment of different institutional options. This paper is organized as follows. In part 2 we describe a simple intertemporal model deriving the conditions under which CCS can be regarded as an option to buy time. Moreover, we proof that taxes, emissions caps and environmental performance bonds are equivalent in a deterministic world. The equivalence principle between price and quantity regulation is already well-established in environmental economics. Up to now, the equivalence between environmental performance bonds on the one hand and taxes, and emission caps on the other hand has not been proofed. The existing literature has evaluated the idea of environmental bonds in a non-formal way. Therefore, the implications of time and uncertainty on the design of a bond system were hidden. In this article, we have embedded the idea of environmental bonds explicitly within an intertemporal framework which allows us to derive a formula for the bond price which avoids the ambiguity within the existing literature. In part 3 we present a more sophisticated social planner model – called MIND – in order to identify the crucial determinants for an optimal use of CCS. We have identified four crucial determinants: the learning rate of the renewable energy technologies, their initial investment costs, the leakage rate and the investment costs for CCS. We use this model as a heuristic to present two versions of Carbon Sequestration bonds as a corner stone to regulate agents in real-world markets supporting the transformation to a sustainable energy system. It will turn out that a classification of environmental risks is needed in order to apply the idea of environmental bonds to CCS properly. We will also present a sensitivity analysis from the MIND model identifying the energy penalty, the learning-rate of the backstop-technology and the leakage rate on the optimal amount of carbon to be sequestered.

Carbon Capturing and Sequestration as an option to buy time?

In this section we analyze CCS within the framework of an aggregate stock pollution model combined with a model of waste disposal. The intertemporal aspects of CCS are also analyzed by [4] which confirms that this framework is appropriate for analyzing the economics of CCS. From an economic point of view, a social planner has to decide to what extent the atmosphere and to what extent geological formations should be used over time. The social planner is a metaphor for an agent who is willing to internalize all relevant social costs of economic activities. According to conventional wisdom in economics, social planner models are compared with decentralized market models. If it turns out that not all components of social costs are internalized by agents on decentralized markets, then policy intervention is needed and justified. First, we present the social planner version of the model. In a second step, we formulate a decentralized market model. In the final step we discuss three policy instruments internalizing social costs: taxes, permits and CCS-Bonds.

The Social Planner Solution

Using the following notation one can begin to formulate an optimization problem of a social planner deriving an intertemporal optimum:

C	flow of consumption
Q	net domestic product
E	environmental pressure
$U(C)$	utility function
S	stock of fossil fuels

K	stock of total physical capital
A	stock of pollution within the atmosphere
D	volume of the geological deposit
R^A	rate of carbon release into the atmosphere
R^S	rate of CCS
$R:=R^A+R^S$	total rate of carbon use
κ	costs of capturing and sequestration
ρ	discount rate
α	air pollution stock decay rate
β	leakage rate of geological formation

The social planner strives to steer the system by the three control paths $x(t):=\{C(t), R^A(t), R^S(t)\}$ in such a way that the following expression, representing the global welfare, is optimized

$$\int_0^\infty U(C(t), E(A(t), D(t))\, \mathrm{e}^{-\rho t} dt\ .$$

The utility function U comprises consumption and environmental pressure. The latter has a negative effect upon utility and depends on the accumulated stock of carbon in both environmental media.

K, A, D, S make up the state of the system. They are linked to the control variables by four deterministic relations:

$$\frac{dK}{dt} = Q(R^A + R^S, K, E(A, D)) - \kappa(R^S) - C, \tag{1}$$

whereby the macro-economic production function fulfils the usual neoclassical assumptions. We norm labor to quantity one and assume that it is not changed in our model. Damages operate also through the production function: emissions released into the atmosphere do not only increase the global mean temperature but may also harm global productivity. The sequestration of carbon may induce additional groundwater pollution or scarcity on land use.

The remaining three equations simply describe the exchange of carbon through the various media:

$$\frac{dA}{dt} = R^A - \alpha A + \beta D, \qquad \frac{dD}{dt} = R^S - \beta D, \qquad \frac{dS}{dt} = -R^A - R^S \tag{2}$$

The optimization is to be performed under the initial conditions for $y:=(K, A, D, S)$, and the boundary condition $S(\infty)=0$.

While most standard economic optimization problems can be conveniently discussed in terms of an equilibrium situation, we note that CCS must be analyzed as an inherently transient phenomenon: the crucial question to be answered is, under which circumstances it was optimal to *build up* a stock D over time. As an analysis in terms of transient dynamics will not allow for transparent solutions in general, we ask the simpler question: "Is there a situation where the social planner has an interest in the *slightest amount* of CCS?" We give now an illustrative answer by comparing the following two situations:

- Case I: Nothing is sequestered, i.e., $R^A{}_0(t)=R(t)$, leading to a path which we call "business as usual" or "master" trajectory.

- Case II: a very small amount δR^S is constantly sequestered in time, and the same amount is avoided in terms of R^A, i.e. $R^S(t)= \delta R^S$, $R^A(t)=R^A{}_0(t)-\delta R^S$. Furthermore, the consumption level is reduced in such a way, that the evolution of capital is identical in both cases. By $R^S(t)=\delta R^S$, we implicitly assume that the initial resource is so large that its future scarcity is not important under the time horizon set by ρ.

When comparing the two cases, we assume $\partial Q/\partial E=0$, and also that Case II induces a reduction in environmental pressure for each t. (If a shift from R^A to R^S had no environmental benefits, it would be meaningless to trade them off against the CCS-costs κ.) As shown in the Appendix, then a sufficient condition for case II to be preferred over case I is given by

$$\frac{\partial E}{\partial A} > (1+\frac{\alpha}{\rho})\,(\frac{\partial E}{\partial D} + (\beta+\rho)\ \kappa'(0)\ \frac{\partial U/\partial C}{-\partial U/\partial E}) \tag{3}$$

For $\partial U/\partial C$, $\partial E/\partial D$, we have to insert the maximum, and for $|\partial U/\partial E|$, $\partial E/\partial A$, the minimum over time following the master trajectory. The message of the formula is clear: The social planner will sequester if the environmental effects of atmospheric accumulation on utility are high, and also when the leakage and the decay rate, furthermore the environmental effects of CCS deposits, costs of CCS, and importance of consumption for the global welfare are low.

Comparison of the social planner solution with the behavior of a decentralized market

In order to discuss the need for regulatory instruments, we first introduce the optimization problem of the private enterprise which has the control paths R^A, R^S, and investment $I=dK/dt$ at its disposal. For the expression to be optimized we assume

$$\int_0^\infty (Q(R^A + R^S, K, E(A,D)) - I - \kappa(R^S))\, e^{-rt}\ dt$$

Q is a generic good which can be used for consumption and investment. The firm discounts its profits with the market interest rate r which is a parameter for the firm and cannot be chosen arbitrarily. The rationale behind this assumption is that the firms are embedded in a world of well-functioning markets in which agents are pricetakers. The interest rate is determined on the capital market where households supply their savings for firms' investments and firms supply their goods for households' good demand. We assume here that the interest rate is determined at a level where capital and the generic good market is in an equilibrium characterized by $\rho=r$.

For the special case of large $S(0)$ and $\partial Q/\partial E=0$ already discussed above, it becomes clear that the private enterprise will act very differently from the social planner. As the utility function does not contain E beyond Q, there is no negative feedback for building up a carbon deposit in the atmosphere. Hence, when repeating the Cases I and II intercomparison, a shift in deposition of δR^S would simply result in a welfare loss of $\kappa'(0)\delta R^S/\rho$. In general, without intervention of the state, the private enterprise would emit 100% of used carbon to the atmosphere.

Regulatory instruments within a market economy

Since it is now obvious that without intervention of the state the private enterprise will not emulate the social planner solution and hence will produce a net welfare loss from the viewpoint of the social planner, the question is how the social planner could set up a policy instrument which lets the social planner solution emerge under the selfish behavior of the private enterprise. We argue that if the state adequately adjusts individual, time-dependent taxes on both types of carbon emissions and on investment then the private household will optimize with respect to the new welfare

$$\int_0^\infty (Q(R^A + R^S, K, E(A,D)) - I - \kappa(R^S) - t^A R^A - t^S R^S - t^I I + L)\, e^{-rt}\, dt \qquad \textbf{(4)}$$

$L(t)$:=$t^A(t)$ R^A*(t) + $t^S(t)$ R^S*(t) + t^I I*(t) denotes a lump-sum transfer which re-distributes the acquired tax of the optimal paths (*) independent of the enterprise's behavior. Without such a transfer, the total tax paid would be missing in the balance equation (1) for consumption. The state has to stimulate in total 7 desired paths: R^A, R^S, C, K, A, D, S. However, only *three* instruments influencing the control paths of the enterprise are needed: As social planner and enterprise share the identical constraints (1) and (2), a successful emergence of R^A, R^S, K will imply the desired paths for C, A, D, S. In the Appendix B we derive the three taxes necessary under the simplifying assumption $S(0)=\infty$ and $\partial Q/\partial E=0$

$$t^A = \frac{\partial Q}{\partial R}, \quad t^S = \frac{\partial Q}{\partial R} - \kappa', \quad t^I = (t^I(0) + 1 - \int_0^t e^{-r\tau}\ \frac{\partial Q}{\partial K}\, d\tau)\, e^{rt} - 1, \qquad \textbf{(5)}$$

the right-hand sides to be evaluated at the optimal path according to the social planner's solution. Plausibly, the atmospheric emission tax is positive, and the CCS-tax shrinks with CCS-costs. By these taxes, the social costs for using the environmental deposits will be internalized in the enterprise's planning horizon.

Equivalence of Carbon Sequestration bonds with other instruments

An emission cap would probably be utilized up to its limit; hence it would serve as a quantity control scheme. Therefore, instead of setting up an emission tax, the social planner could directly prescribe the emissions, just reducing the number of taxes and the number of independent paths to be induced by one, compared to the above pure tax-scheme. Then, also, the social optimum would emerge, with the same arguments as given above.

It can also be shown that a bond system is equivalent with the tax and the quantity control scheme. It turns out that imposing a tax, a quantity limit implemented by a tradable permit or a bond system scheme can be equalized if the social planner has the deterministic information as presupposed until now. The bond system works as follows. For every quantity of $R^S(t)$ the firm has to buy a bond bR^S. After a fixed time T, the firm will return the bond with interest for that fraction exp($-\beta T$) which has not leaked out yet, i.e. $b\ R^S$ exp(rT) exp($-\beta T$). One can show that in a *deterministic* world with only one CCS-site, the bond system has a steering effect identical to the tax $t^S R^S$ if the following time-dependent bond-price is used: $b(t)$:=$t^S(t)$/(1-exp($-\beta T$)).

A realistic regulatory framework for CCS under hard uncertainty

The social planner solution and the regulatory framework in section 2 are too simple in order to be used as a guide for policy makers. In particular, the model takes only CCS into account as a mitigation option. The economics of CCS are already analyzed in [4] in which the trade-offs between discounting, leakage rate, the costs of sequestration are explored. However, as we will argue *all* relevant mitigation options have to be assessed within an integrated framework: First, improving the energy efficiency of fossil-fuel use, second, the substitution of fossil fuels by renewable energy technologies or nuclear power, and third CCS. Therefore, CCS must be evaluated within a framework allowing to calculate the benefits and the costs of all these options. Based on such an assessment, a realistic regulatory framework can be designed.

The social planner solution

MIND [2] is a social planer model which derives an optimal investment path for all relevant mitigation options subject to the so-called climate window ensuring that the Global Mean Temperature (GMT) is limited to 2.0°C until the end of the century and to 0.2°C per decade. According to conventional wisdom within economics, such an ambitious climate protection goal is seen as relatively costly option. The reason for this is that many Integrated Assessment models have not incorporated endogenous technological change. MIND considers technological change mainly driven by investment decisions of firms and not as "manna from the heaven". It has turned out that if investors and firms can react flexibly to new emerging scarcities induced by an ambitious climate policy, the losses on the GDP can be reduced substantially. It has also been turned out that CCS can reduce the macro-economic mitigation costs. Due to a sensitivity analysis four crucial factors determine the costs and benefits of CCS: the leakage rate, the investment costs of CCS, the learning rate of the renewables, and their respective investment costs. Within the MIND model we only consider renewable energy technologies as backstop-technologies. A backstop-technology is a technological option that uses only reproducible input factors for production like wind, biomass, sun, labor or capital. According to this definition the current nuclear power technology is not a backstop-technology at least for two reasons: First, uranium is an exhaustible input factor and second, depositing nuclear waste is an unresolved question. Because of these reasons nuclear power can only be considered as an option to buy time but not as a sustainable way to use energy. Figure 1a shows that the higher the learning rate and the lower the initial investments, the lower is the optimal amount of carbon to be captured and to be sequestered. The economic rationale behind this result of the sensitivity studies is quite simple: CCS as an end-of-pipe option is a temporary solution which is only preferable if the costs are relatively low compare to the backstop-technologies. The costs of the renewable energy option depend on two factors: the learning rate and the initial investment costs. For every doubling of cumulative capacity, the costs fall by a constant fraction of the initial investment costs. This rate is called the *learning rate*. Therefore, CCS can be considered as joker if it will turn out that the renewable energy option is more costly than it is expected. Moreover, Figure 1a also shows that there are "regions" where the optimal amount of carbon reacts more sensitive on the variation of these two factors. In Figure 1b, the amount of CCS is dependent on the on the efficiency of investment in CCS and the leakage rate. The higher the efficiency of investments in CCS, the higher is the optimal amount of carbon to be stored in geological formations. A high leakage rate makes it impossible to achieve the climate window. Therefore, it reduces the optimal amount of CCS. Similar to Figure 1a in Figure 1b there are also regions of high and low sensitivity because the opportunity costs of CCS influence other mitigation options in a non-linear way.

[Please, Insert figure 1a and 1b here]

To conclude, both figures clearly show that the optimal amount of sequestered carbon reacts sensitively to changes in the learning rate, the investment costs of the renewable energy sources, the leakage rate and CCS costs. This sensitivity study can be considered as guide for designing a regulatory framework because we have identified key parameters which are on the one hand unknown and on the other crucial for the determination of CCS. Unfortunately this parameter uncertainty can only be reduced further by a better validation on empirical data if investments are undertaken in CCS and in the renewable energy sector.

For this, it would be reasonable to start with small-scale experiments under an appropriated designed regulatory framework. In the next section, we present two proposals dealing with one crucial parameter – the leakage rate. In the light of the discussion above, it is obvious that Carbon Sequestration Bonds are only one element within a broader regulatory framework [1], [5] for the transformation of the world-wide energy system. Nevertheless, it seems worthwhile to discuss these two versions of regulating CCS as a first step. However, these two proposals are not contradictory but can be used in a combined way.

Proposal #1: Carbon Sequestration as a joker if other mitigation options fail

Leaking carbon dioxide would not be a catastrophic event, as long as no large amounts of carbon dioxide leak from all formations simultaneously. The following considerations always presuppose that global unexpected leakage does not occur.

Although the probabilities of such damage are not (yet) known, some safe-minimum standards could be defined which are the basis for the calculation of the bond price. The parameters derived in our model could be used as a reasonable heuristic. As carbon dioxide leaks from a geological formation, the atmosphere is used for its storage without a price having previously been paid. Therefore, the company has to buy a permit for the use of the atmosphere in case carbon dioxide should leak. As the amount of permits is not increased, their price will rise. This solution alone will not prevent mismanagement in carbon dioxide sequestration. The management of a company could count on decreasing permit prices in the long run, or just assume that another management will have to deal with the damage later. Whenever the time frame of investors is shorter than the time assumed for carbon dioxide to leak, and whenever they are willing to take high risks, the storage of carbon dioxide in geological formations will always be the preferred option of investors because the risks can be shifted upon later generations. It is therefore crucial to create incentives for companies to store carbon dioxide in formations as safely as possible in the first place, and for them to do so in their own self-interest.

Every company that plans to store carbon dioxide in geological formations has to buy bonds that equal the disutility induced by CCS (which are the not internalized costs of private enterprise). From the point of view of the firm this bond is an asset. For the transmission time of the bond, the company guarantees that all carbon dioxide will remain within the geological formations. If this really happens to be the case, the company will receive interests on the bond – equal to a long-term security. The company is allowed to sell the bond on the market during the transmission time. After the transmission time the owner of the bond has to prove to some kind of environmental authority how much dioxide has remained underground. For the leaked fraction of carbon dioxide, the bond is partially devalued, the owner has to partially depreciate the claims to the environmental authority, and in addition, the owner or the company has to issue a CO_2 emission certificate. The net amount paid to the environmental agency has to be used for subsidizing renewable energies. These subsidies are paid as a compensation for the competitive disadvantage of the renewable energies. Without carbon sequestration in geological formations, the renewables would become profitable much sooner. When carbon dioxide leaks from geological formations, precious time for a cost-efficient transformation of the energy system is wasted. Carbon sequestration bonds have to be tradable on markets. However, companies will only be able to sell their bonds when they can offer buyers better interest rates than a non-risky security. Therefore, an incentive is created for the entire energy sector not to undermine trust in the bonds. The threat of a devaluation of bonds makes the safety of geological formations a marketable good.

Proposal #2: CCS-bonds as special emission permits

Our second proposal mimics the market character of the first proposal in several ways. However, it imposes an emission cap and therefore makes the CCS-bonds part of the emission certificate scheme.

For carbon to be sequestered, also atmospheric emission permits have to be bought, as it is not clear yet to which degree the geological formation is leaking. However, this certificate is not devalued as in the atmospheric emission case, but it is just “blocked” as long as it is not proven which fraction of the carbon will stay underground.

Once the worst cases of leakage rate have been excluded by experience over time, for that amount accumulated over time that seems to be safely deposited, a fraction of the initial emission certificate becomes unblocked by the state and can be sold again. As the CCS-company can expect an increasing emission certificate price, it has an incentive to eventually perform CCS, particularly into those formations which have a high chance to be dense. For later sequestration into the same formation, the CCS-company would have to buy a smaller amount of emission permits right from the beginning, because the highest leakage rates have already been excluded. Over time, uncertainty on leakage rate can be expected to shrink for each individual formation. In addition, the CCS-company is free to sell the blocked permits whenever it wants – so there is a market based on trust in low leakage even before the state is willing to unblock the bond.

To conclude, in proposal 2 the guardrail on emissions is set to first priority. The effects of the uncertainties are shifted onto global welfare (apart from potential damages underground), in case leakage cannot be excluded quickly enough or the price for emission permits becomes too high for a well-functioning economy.

Conclusion

For high environmental damages by atmospheric carbon, it is worthwhile to include CCS in the portfolio of carbon treatment even if backstop-technology options like renewable energy technologies are available. We find that a regulatory framework is needed in order to internalize all relevant social costs such that a private enterprise would follow the desired emission- and sequestration path. We argue that in case of low uncertainty, taxes on both options would give the desired equivalence of social planner and private enterprise solution. In the deterministic case, these taxes can also be substituted by quantity limits or a bond system.

However, environmental authorities have to deal with situations of "hard uncertainty" where probability density functions about leakage rates and other crucial parameters like the learning rate or the investment costs are not known. We have argued that this type of uncertainty demands the start of a learning process about new emerging ecological and economic risks. Therefore, we have proposed two different permit schemes which are designed in such a way that safe deposits are preferred and uncertainty about leakage is actively reduced by CCS-companies. In proposal #1 CCS is considered as a joker if other mitigation options fail from an economic point of view. Proposal #2 is designed in order to avoid the ecological worst-case scenario that the leakage rate of geological formations is much higher than expected. However, these two proposals should not be seen as contradictory because both have the potential to merge to a hybrid version. The risk of violating the climate window and therefore increasing the probability of dangerous climate change must only be considered seriously, if CCS is used at large-scale. In the very beginning, only mall-scale experiments will be launched with relatively low environmental risks on a global scale. Therefore, for small-scale experiments proposal #1 could be appropriate because it encourages investors to undertake CCS-investments. If CCS become a large-scale option proposal #1 could be transformed to proposal #2 which set the guardrail on emission to first priority. Both permit schemes would have to be extended in order to internalize environmental risks of CCS beyond CO_2 leakage as well.

Appendix A: Derivation of a sufficient condition to perform CCS

Here we search for a sufficient condition under which the social planner can improve global welfare by including CCS compared to a path without CCS (which we call "master path"). As we do not strive for the optimum CCS-path here, but rather would like to demonstrate that there *are* cases where CCS is meaningful, we make the following simplifying assumption: a constant, infinitesimal amount δR^S is shifted from R^A into R^S, without touching $K(t)$, in order to make up case II. We want to derive when this shift would increase global welfare, for which we will not have to assume that the master path is optimal in any sense.

From (2) we derive $\delta D(t)=D(t)=(1-\exp(-\beta t))\,\delta R^S/\beta$, $\delta A(t)=\delta R^S(\exp(-\alpha t)-\exp(-\beta t))/(\alpha-\beta)<0$ and $\delta C\approx-\kappa'(0)\,\delta R^S$ in 1st order Taylor expansion of κ. From now on, we silently assume such first order expansions for all other functional dependencies. Then $\delta E\approx E_A\,\delta A+E_D\,\delta D$, and $\delta U\approx U_C\,\delta C+U_D\,\delta E$, with subscripts denoting partial derivatives. The partial derivatives need to be evaluated arguments taken from the master path. Hence, they are time-dependent. If they were time-independent, the shift in welfare could be calculated analytically, as only exponential would have to be integrated. Therefore, we substitute the time-dependent partial derivatives by those extreme values which would minimize the shift in welfare, δW. Which derivates should take their minimum and which their maximum value, is readily inspected, noting that $\delta A(t)<0$ and $\delta D(t)>0$, furthermore that $\delta E<0$ was assumed. The shift in welfare then reads

$$\delta W_{\min}=\frac{\delta R^S}{(\alpha+\rho)(\beta+\rho)\rho}\left(\alpha(E_D U_E-\gamma)-\rho((E_A-E_D)U_E+\gamma)\right)\quad\text{with }\gamma:=(\beta+\gamma)\kappa'(0)U_C$$

If we require that this expression is larger than zero, we derive the inequality given in the main text and ensure that the gain δW due to CCS is positive, according to $\delta W\geq\delta W_{\min}>0$.

Appendix B: Equivalence of the social planner and tax solution

We first derive the paths the private enterprise would choose under a given tax for the special case $\partial Q/\partial E$=0 and infinite carbon reserves. This implies that for the private enterprise, A and D do not enter the optimization. According to control theory (e.g., [7]) then the firm's optimal path is given by

$$\frac{dK}{dt} = I, \quad \frac{d\phi_1}{dt} = r\phi_1 - \frac{\partial Q}{\partial K}, \quad \frac{\partial h}{\partial I} = -1 + \phi_1 - t^I = 0, \quad \frac{\partial h}{\partial R^A} = \frac{\partial Q}{\partial R} - t^A = 0, \quad \frac{\partial h}{\partial R^S} = \frac{\partial Q}{\partial R} - \kappa' - t^S = 0$$

with $h{:}=Q-I-\kappa-R^A t^A-R^S t^S-I t^I+L+\phi_1 I$. The conditions for the taxes follow readily. Furthermore, ϕ_1=1-s, leading to the first-order ordinary differential equation in t^I: $dt^I/dt = rt^I+r-Q_k$. The standard solution of this linear differential equation was given in one of the main sections.

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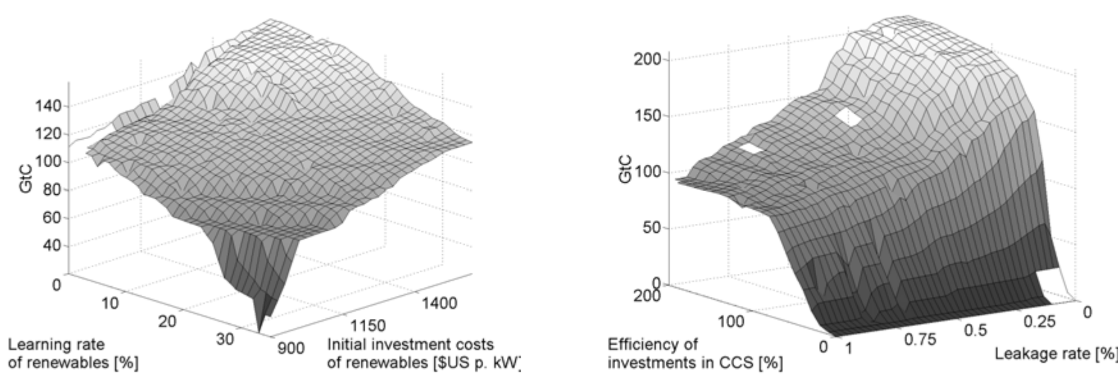

Figure 1: The influence of learning rate and initial investment costs (left) or leakage rate and the efficiency of investment in CCS (right) on the (social) optimal amount of carbon to be sequestered.