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The Path to Net Zero Emissions

Abstract

To reach the goals of the Paris agreement, net carbon emissions must be reduced to zero by the second half of this century. To achieve this, some kind of carbon dioxide removal (CDR) is needed. The paper gives an analysis of the interaction between extraction of fossil energy resources and CDR. If there is sufficient capacity for storing captured carbon, it will be optimal to have a period of negative net emissions. In this case cumulative extraction will not depend on climate costs, but will be higher the lower is the cost of CDR at low levels of CDR.

JEL-Codes: Q350, Q400, Q540.

Keywords: net zero emissions, negative emissions, carbon removal, CDR, CCS, stranded assets.

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1 Introduction

To reach the ambitious goals of the Paris agreement, the world needs to reduce net carbon emissions to zero by the second half of this century. Reducing *gross* emissions this fast seems highly unrealistic, hence there is a need for some kind of carbon removal, also called carbon dioxide removal, or CDR for short. With CDR, it is in principle possible to achieve zero *net* emissions even if gross emissions are positive. In several of the IPCC scenarios that are consistent with temperatures not exceeding 1.5 or 2 degrees Celsius, it is assumed that CDR by the middle of this century is so large that we have *negative* net emissions.[1]

The feasibility and limitations of various methods of CDR are discussed in Section 2. For the formal analysis in this paper, I do not distinguish between different types of CDR. Moreover, in the main part of the analysis it is assumed that there is no binding limit on the accumulated carbon that is removed and stored. This assumption is relaxed in Section 8.

The paper gives an analysis of the interaction between extraction of fossil energy resources and CDR. The general model is presented in Section 3, and results derived from this model are given in Sections 4-7. One important result is that as long as there is no binding constraint on accumulated carbon storage, it is will always be optimal to have a period of negative net emissions. In this case total accumulated resource extraction is independent of the size of the climate costs (as long as these costs are high enough to justify CDR).

In Section 8 I show that if there is a sufficiently strict limit to accumulated carbon storage, net emissions will always be non-negative in the optimal outcome. Moreover, accumulated resource extraction will in this case be lower the higher are the climate costs.

[1] See for example IPCC (2023); in particular Section B.6. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

2 Carbon dioxide removal and the feasibility of negative net emissions.

Negative emissions are only possible if the sum of CDR activities are sufficiently large. There are three main types of CDR:

- Biological CDR, such as reforestation, soil management, and the restoration of coastal wetlands and peatlands.
- Use of bioenergy in combination with Carbon Capture and Storage (CCS) from power plants and other industrial processes.
- Direct air capture, i.e. a technological similar to CCS, but capturing CO_2 directly from the atmosphere.

The first of these is the most low-tech, and is clearly feasible. However, most of the CDR of this type needs land that could have alternative uses. This is captured in our model by marginal costs being higher the higher is the CDR. This type of CDR also has a limited time duration: With e.g. reforestation on a plot of land carbon will be removed from the atmosphere as long as the forest grows. Once the forest reaches a mature age, there is no further removal of carbon from the atmosphere. This limitation of biological CDR does not necessarily jeopardize its use, since it will in Section 5 will be shown that optimal CDR should eventually approach zero.

If there is no CCS connected to use of bioenergy, the removal of carbon with CCS must be lower than the gross emissions. This is because even with CCS, there will be some remaining emissions from the industrial processes that use CCS. Moreover, not all fossil energy use is suitable for CCS, e.g. fossil fuel used for transportation. With bioenergy use at a rate y, CCS can be applied to immediate emissions equal to $x+y$. If it is possible to capture a fraction α of these emissions with CCS, denoted z, this type of CDR will be limited by the constraint

$$z \leq \alpha(x+y)$$

For negative emissions, i.e. $z > x$, to be possible with the use of only CCS, it follows that we must have $\alpha(x + y) > x$, i.e.

$$y > \frac{1-a}{\alpha}x \tag{1}$$

The lower is x, and hence the higher is the price of fossil energy, the higher is the supply of bioenergy likely to be. It therefore seems reasonable that this inequality holds for small values of x. For larger values of x the inequality (1) may not hold unless bioenergy production is encouraged by subsidies or other policies. Encouraging the production of bioenergy in order to make it easier to obtain negative emissions is, however, not necessarily a good idea: Unlike fossil energy, bioenergy is climate neutral in the sense that it is possible to have a constant positive use of bioenergy without this giving any change over time in the carbon concentration in the atmosphere. Bioenergy may nevertheless have a negative climate effect due to land use changes. As long as bioenergy production is constant, the balance of carbon in the atmosphere and in biomass and soils will remain constant: The yearly release of carbon from using bioenergy will be exactly matched by regrowth of biomass. However, an *increase* in the production of bioenergy will change this balance. As pointed out by e. g. Fargione et al. (2008), converting forests, peatlands, savannas, or grasslands to increase the production of crop-based bioenergy will give a large immediate release of carbon from plant biomass and soils to the atmosphere. Similarly, a more intensive use of forests to increase bioenergy production will reduce the carbon content stored in the forests, see e. Hoel et al. (2014) and Hoel and Sletten (2016). These effects are in other words exactly the opposite of what we might want to achieve through biological CDR.

With direct air capture there is in principle no limit to the magnitude or duration of CDR, so that net negative emissions are in principle feasible. However, the technology for this type of CDR is presently very immature, and future costs are highly uncertain.[2]

[2] See Vista Analyse (2023) for a recent survey of technologies and costs for direct air capture. https://www.vista-analyse.no/no/publikasjoner/direct-air-capture-of-co2-a-review/

To conclude: Negative emissions are definitely feasible. However, due to the limitations discussed above the total amount of cumulative negative emissions may be restricted to a level that is lower than the optimization problem without any limitations on CDR suggests.

3 The General Model

I use a partial equilibrium model of fossil energy use in combination with some type of carbon removal technology (henceforth CDR). Fossil energy is modeled as a homogeneous non-renewable resource where the unit cost of extraction, $b(A)$, are increasing in accumulated extraction A. This is a specification frequently used in the resource literature, see e.g. Heal (1976). Notice that a special case of this is what sometimes is called the pure Hotelling case, where unit extraction costs are constant and there is a fixed amount of resources. In this case the cost function $b(A)$ has an inverse L shape, with the vertical part of the function being at the corresponding to the exogenously fixed amount of the resource.

The gross benefit of using fossil energy x is $u(x)$, which is strictly increasing and concave. The price p of using energy is equal to the marginal utility $u'(x)$. I assume that $u'(0) \equiv p^*$ is finite. The interpretation is that if the price of fossil energy exceeds p^*, demand will be zero, with other energy sources covering all energy demand.

Using carbon energy gives an immediate release of carbon to the atmosphere. Over time, some of this carbon is transferred to the ocean and other sinks. However, a significant portion (about 25% according to e.g. Archer, 2005) remains in the atmosphere for ever (or at least for thousands of years). Farzin and Tahvonen (1996) showed how this can be modeled by splitting the carbon emissions in two, with a standard decay rate for the first but zero decay for the second. In the present paper I only consider the carbon released that remains in the atmosphere for ever. This is thus a special case of the model just mentioned, with immediate decay of the first part of the emissions.[3]

[3]This simplification is of no importance for the long-run steady state, but the details

In my model, $x(t)$ measures the yearly production of fossil energy, and $S(t)$ measures the stock of carbon in the atmosphere caused by the production of fossil energy. I measure units of fossil fuel and carbon in the atmosphere in the same units, e.g. tons of carbon, so that in the absence of CDR we would have $\dot{S}(t) = x(t)$. With CDR removing $z(t)$ of carbon from the atmosphere, this is modified to $\dot{S}(t) = x(t) - z(t)$. The cost of the CDR activity is given by a strictly convex cost function $c(z)$. I also include a potential limit $\bar{R}$ on the accumulated removed carbon, denoted R.

Climate costs are given by an increasing and strictly convex function of the total amount of carbon in the atmosphere, $D(S)$.

The objective function in the social optimization problem is standard:

$$W = \int_0^\infty e^{-rt} \left[u(x(t)) - xb(A) - c(z(t)) - D(S(t)) \right] dt \tag{2}$$

where r is the discount rate. In addition to the non-negativity constraints on x and z, we have the following constraints:

$$\dot{A}(t) = x(t) \tag{3}$$

$$\dot{S}(t) = x(t) - z(t) \tag{4}$$

$$\dot{R}(t) = z(t) \qquad R(t) \leq \bar{R} \tag{5}$$

The current value Hamiltonian corresponding to the maximization of W subject to (3)-(5) is (ignoring the time references and writing the Hamiltonian so that all shadow prices are non-negative)

$$H = u(x) - c(z) - D(S) + (-\lambda)x + (-\gamma)(x - z) + (-\mu)z + \alpha(\bar{R} - R) \tag{6}$$

of the dynamics towards the steady state would be slightly different if I had taken the partial depreciation into account.

The necessary conditions for the optimum are

$$
\begin{aligned}
u'(x) - b(A) - (\lambda + \gamma) &\leq 0 \; [= 0 \text{ for } x > 0] && (7)\\
\gamma - \mu - c'(z) &\leq 0 \; [= 0 \text{ for } z > 0] && (8)\\
\dot{\lambda} &= r\lambda - xb'(A) && (9)\\
\dot{\gamma} &= r\gamma - D'(S) && (10)\\
\dot{\mu} &= r\mu - \alpha && (11)
\end{aligned}
$$

The tranversality conditions for this problem imply that

$$
\begin{aligned}
Lim_{t\to\infty} e^{-rt}\lambda(t) &= 0\\
Lim_{t\to\infty} e^{-rt}\gamma(t) &= 0
\end{aligned}
$$

Using these conditions, the equations (9) and (10) can be solved to give

$$\lambda(t) = \int_0^\infty e^{-r\tau} x(t+\tau) b'(A(t+\tau)) d\tau \tag{12}$$

and

$$\gamma(t) = \int_0^\infty e^{-r\tau} D'(S(t+\tau)) d\tau \tag{13}$$

which I will make use of later.

4 The outcome without CDR

Without CDR we can set $\mu = \alpha = 0$. Hence it follows from (7) that for $x > 0$ we have

$$\dot{p}(t) = b'(A)\dot{A} + \dot{\lambda} + \dot{\gamma}$$

which together with (9) and $\dot{A} = x$ gives

$$\dot{p}(t) = r\lambda + \dot{\gamma} \tag{14}$$

Without CDR $S(t) = A(t)$ is rising and we therefore have $\dot{\gamma} > 0$ (from (13)) so that (14) implies that $p(t)$ is also rising over time, so that $x(t)$ is declining. The long-run steady state, reached asymptotically, follows from (7)-(10):

$$x^* = 0 \quad (15)$$
$$\lambda^* = 0 \quad (16)$$
$$\gamma^* = \frac{1}{r} D'(S^*) \quad (17)$$
$$b(A^*) + \gamma^* = p^* \quad (18)$$
$$S^* = A^* \quad (19)$$

We immediately see that the total fossil resource extraction A^* is lower with a climate cost than without, and more generally:

Proposition 1 *Without CDR, total resource extraction is lower the higher is the level of the marginal climate cost function $D'(S)$.*

The difference between cumulative resource extraction without and with climate costs may be interpreted as stranded assets. The proposition above hence implies that there will be more stranded assets the higher is the level of the marginal climate cost function $D'(S)$.

5 Unlimited cumulative CDR

We now consider the case of CDR, but where the constraint on $\bar{R}$ on cumulative CDR is so large that it is non-binding. As above, we can set $\mu = \alpha = 0$ for this case.

The outcome will obviously depend on the cost of CDR. For CDR to be at all relevant, it must be assumed that

$$c'(0) < p^* \quad (20)$$

If this condition does not hold, it will never be optimal to use CDR, since the cost of removing carbon in this case would be higher than the maximal marginal benefit of using carbon.

I also assume that marginal damage costs of carbon are zero for sufficiently low levels of carbon in the atmosphere, as it otherwise could be optimal to remove carbon for ever.

When the condition (20) holds, we will always have some CDR in the optimal outcome. Hence, the steady state following from (7)-(10) is given by

$$x^* = 0 \tag{21}$$

$$z^* = 0 \tag{22}$$

$$\lambda^* = 0 \tag{23}$$

$$\gamma^* = \frac{1}{r} D'(S^*) \tag{24}$$

$$b(A^*) + \gamma^* = p^* \tag{25}$$

$$\gamma^* = c'(0) \tag{26}$$

The following proposition follows immediately:

Proposition 2 *With unlimited cumulative CDR , total resource extraction is independent of the level of the marginal climate cost function $D'(S)$, but lower the higher are the marginal costs of CDR at low levels of CDR.*

The detailed development towards the steady state will of course depend on all of the functions and parameters of the model. Some key properties can however be given. If $D'(S)$ is sufficiently small for small values of S, $\gamma(0)$ may be so small that $z(0) = 0$. The rising $\gamma(t)$ (from (13)) will eventually at some date τ_1 make $\gamma(t) = c'(0)$. After this date $\gamma(t)$ will continue to rise, so that $z(t)$ now will be positive and rising. From the steady state we know that $z(t)$ eventually must start to decline; this must occur at a date τ_2 when $\gamma(t)$ reaches its maximum and starts to decline. From (13) it is clear that for $\gamma(t)$ to decline from date τ_2, $S(t)$ must go from rising to declining at some date $\tau_3 > \tau_2$. For all $t > \tau_3$ we hence must have $z(t) > x(t)$, with $z(t)$ and

$x(t)$ both declining and reaching zero asymptotically. The last property is sufficiently interesting to justify a proposition:

Proposition 3 *The existence of CDR with costs satisfying (20) implies that it will always be optimal to have a phase of negative net emissions of carbon.*

The time paths for $x(t)$ and $z(t)$ are illustrated in Figure 1. For all $t > \tau_3$ we have negative net emissions, so that $S(t)$ is declining towards its steady-state value S^*.[4]

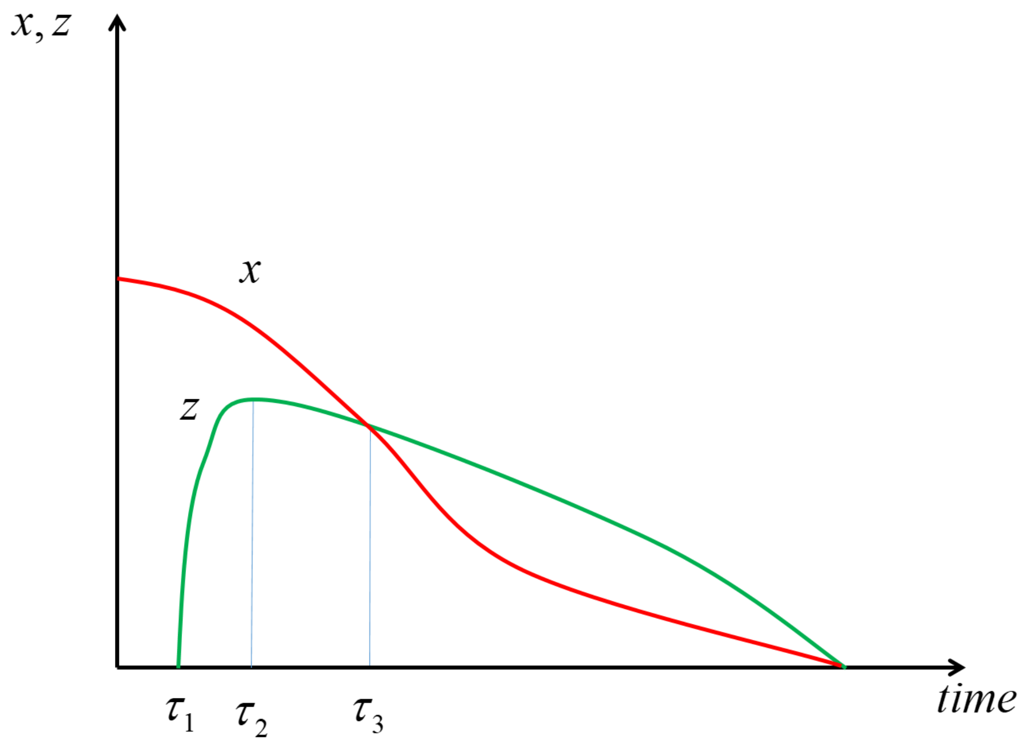

Figure 1: Time paths of extraction and CDR

[4] The Figure is "wrong" in the sense that it seems that $x = z = 0$ is reached in finite time.

6 The pure Hotelling model

I now consider the special case of the pure Hotelling model, where extraction costs are zero, and there is a finite amount of the resource available.

Without CDR, there are now two possible long-run outcomes: Either all of the resource will be extracted, or there will be some unextracted resource, i.e. stranded assets. The first case will occur for "low" climate costs. More specifically, this case will occur for

$$\frac{1}{r}D'(\bar{A}) \leq p^* \tag{27}$$

where $\bar{A}$ is the total amount of the resource available. When this condition holds, the marginal value of the final resource available is higher than the social cost of carbon, and should hence be depleted. In this case the climate cost affects the time profile of resource extraction, but not the total cumulative extraction.

If (27) does *not* hold, we get the second of the two possible long-run outcomes: Since the social cost of carbon eventually will exceed the marginal value of resource extraction in this case, some of the resource should remain unextracted.

When CDR with a cost function satisfying (20) is available, we will always have some CDR in the optimal outcome. We saw above that without CDR a possible outcome was one with stranded assets, i.e. some of the resource stock $\bar{A}$ left unextracted. For such an outcome to be valid, we must have $\lambda(t) = 0$ for all t. Moreover, for resource extraction to stop, $p(t) = \gamma(t)$ must reach p^* either in finite time or asymptotically. But the inequality (20) implies that $z(t) > 0$ for $p(t)$ sufficiently close to p^*, so that $S(t)$ must be declining (from (4)) This in turn gives, from (13), that $p(t) = \gamma(t)$ must be declining, implying a rising value of $x(t)$, which contradicts the assumption of stranded assets. Hence, we have the following proposition:

Proposition 4 *There will be no stranded assets in the optimal outcome of the pure Hotelling model if we have the possibility of CDR with costs satisfying (20).*

The long-run steady state follows from equations (7)-(10):

$$
\begin{aligned}
x^* &= z^* = 0 \\
\gamma^* &= \frac{1}{r} D'(S^*) \\
\gamma^* &= c'(0) < p^*
\end{aligned}
$$

Notice in particular that the long-run amount of carbon in the atmosphere is independent of the stock of extractable fossil resources ($\bar{A}$), but is larger the larger is the marginal cost of CDR at low CDR levels.

The time path of resource extraction and carbon removal is similar to what we found for the general case. One minor difference is that when there is a binding resource constraint, the long-run steady is reached in finite time.

7 Inverse L climate costs

The goals of the Paris agreement might be interpreted as what we might call an "inverse L" cost function, with negligible costs for a temperature increase below some threshold, and "infinitely" high costs above the threshold. Assume first there is a direct link between temperature and the stock of carbon in the atmosphere. An inverse L climate cost could then be modeled as $D' = 0$ for $S < S^*$ and $D' =$ "∞" for $S \geq S^*$. (Our results would not be changed much if we instead assumed a small and constant marginal cost for values of S below the threshold S^*.). The interpretation of D' for this case is that it is an endogenous shadow price associated with the constraint $S \leq S^*$. The simplest way to analyze such a situation is to use an approximation like e.g. $D'(S) = k/(S^* - S)$ with k being positive and arbitrarily small. With this approximation, all of the previous analysis and results remain valid. However, the magnitude of cumulative negative emissions approaches zero as k approaches zero. The reason for this follows from the reasoning leading to Proposition 2: For a very small k, a very small reduction in S will bring γ down to $c'(0)$. In the limit, we hence have the following result: As long as $S(t) < S^*$, $z(t)$ will be rising if it is positive, while $x(t)$ is declining and higher than $z(t)$. At some date $\tau_2 = \tau_3$, $S(t)$ will reach S^* while $z(t)$ at the same time reaches $x(t)$. After this date, $x(t)$ continues to decline, with $z(t) = x(t)$ and hence net zero emissions.

The reasoning above was based on a direct link from S to temperature increase. In reality, there is a time lag between the two. Denoting temperature increase by T, we can model such a lag by $\dot{T} = \sigma(F(S) - T)$, where σ is a positive parameter and $F' > 0$. If the inverse climate cost is represented by a constraint $T(t) \leq T^*$, we clearly must have $S(t) \leq F^{-1}(T^*) \equiv S^*$ in the long run. However, if the constraint $T(t) \leq T^*$ is binding, it immediately follows from $\dot{T} = \sigma(F(S) - T)$ that we must have a period of $F(S) > T$ for T^* to be reached, i.e. a period of $S(t) > S^*$. But since $S(t) = S^*$ once $T(t) = T^*$ has been reached, we must have a period of negative emissions bringing $S(t)$ down to S^* as $T(t)$ approaches T^*. Hence, we can conclude that Proposition 3 remains valid also for the case of an absolute limit to acceptable temperature increase.

8 A binding limit to cumulative CDR

The steady state defined by (21)-(26) gives a steady-state value $R^* = A^* - S^*$ of cumulative CDR. If the limit $\bar{R}$ on cumulative CDR is lower than the value R^*, the outcome described in section 5 is not feasible. Instead, the outcome must imply that $R(t)$ reaches its limit $\bar{R}$ in finite time. Let $\bar{\tau}$ denote the time when $R(t)$ reaches $\bar{R}$. Define $\beta = \gamma + \mu$. Prior to $\bar{\tau}$ we have $\alpha = 0$. It therefore follows from (10) and (11) that

$$\dot{\beta} = r\beta - D'(S)$$

Equations (7)-(11) therefore remain valid, with γ replaced by β.

Will the steady state described by (21)-(26) (and γ^* replaced by β^*) be reached at $\bar{\tau}$? The answer is no. If this steady state was valid at $\bar{\tau}$, using equations (21)-(26) to go backwards in time would give $x(t) = \lambda(t) = 0$ for all $t < \bar{\tau}$, which is inconsistent with the steady state (21)-(26) being reached.

Since the steady state is not reached at $\bar{\tau}$, the dynamics after $\bar{\tau}$ are exactly the same as we found in Section 4, i.e. with no CDR. The steady state is as described in Section 4, except that (19) is replaced by

$$S^* = A^* - \bar{R} \tag{28}$$

It is straightforward to verify that the following proposition follows from the equation above combined with (18) and (17):

Proposition 5 *With a binding limit $\bar{R}$ on cumulative CDR, total resource extraction is higher and the long-run carbon in the atmosphere is lower the higher is the limit $\bar{R}$. Total resource extraction and long-run carbon in the atmosphere are both lower the higher is the level of the marginal climate cost function $D'(S)$.*

We now turn to the dynamics prior to the date $\bar{\tau}$. We know that $x(t)$ is positive and bounded away from zero for all $\tau \leq \bar{\tau}$. Moreover, $z(t)$ is continuous, and hence approaches zero as τ approaches $\bar{\tau}$. There must therefore exist a period prior to $\bar{\tau}$ where $z(t) < x(t)$. This gives us the following proposition:

Proposition 6 *With a binding limit $\bar{R}$ on cumulative CDR, net emissions will be positive after some date prior to the date when the limit $\bar{R}$ is reached.*

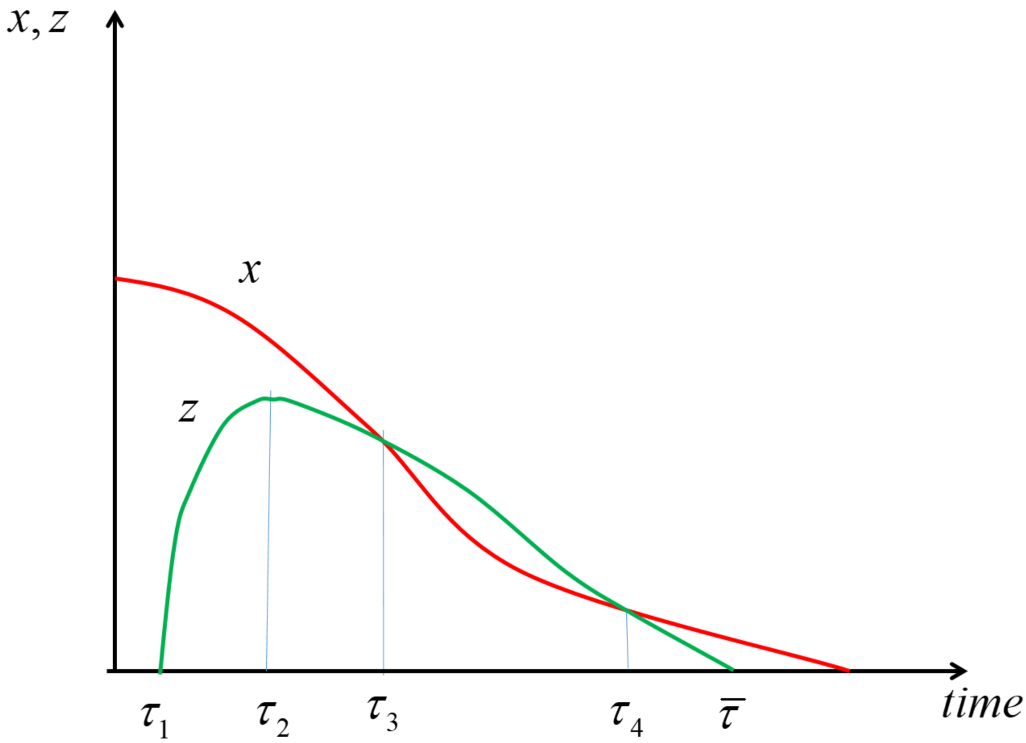

Figure 2 : Extraction and CDR with a limit on storage capacity

Figure 2 illustrates the case where $\bar{R}$ is "large". This figure is almost identical to Figure 1. The difference is that instead of net emissions being negative for all $\tau > \tau_3$, net emissions turn positive again at a date $\tau_4 < \bar{\tau}$.

If instead $\bar{R}$ is sufficiently small, $z(t) < x(t)$ for all t. This follows from the fact that $z(t) < \varepsilon$ for all t with ε approaching zero as $\bar{R}$ approaches zero. Combining this with the fact that $x(t)$ is positive and bounded away from zero for all $\tau \leq \bar{\tau}$ gives us the following proposition:

Proposition 7 *When the limit $\bar{R}$ on cumulative CDR is sufficiently small, net emissions will always be positive.*

9 Concluding remarks

If the goals from the Paris agreement are to be reached, it seems reasonable to expect CDR to play a significant role in future climate policies. The analysis above reveals that CDR should be used at least to some extent. Moreover, if the availability of storage sites for captured carbon is sufficiently large, it will be optimal to have a period of negative net emissions.

With rising extractions costs for fossil energy resources, the cumulative extraction of these resources will depend either on the cost of CDR or on the limit of available storage sites for captured carbon: Cumulative extraction will be lower the higher are the costs of CDR at low levels of CDR or the less storage possibilities are available. For a more general cost function for CDR that is increasing in cumulative storage, we should therefore expect cumulative extraction of fossil energy resources to be lower the higher are these costs. The optimal long-run amount of carbon in the atmosphere will also depend on the cost function for CDR.

The specification of the climate cost function is of course crucial for the optimal long-run amount of carbon in the atmosphere. Somewhat surprisingly, the climate cost function does not affect long-run cumulative resource extraction in the main model specification used in this analysis (see in particular Proposition 2). However, Proposition 5 indicates that this result will no longer hold for a more general cost function for CDR, with costs rising in cumulative storage.

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