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Research or Carbon Capture and Storage - How to limit climate change?

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Abstract

The consequences of the 2°C climate target and the implicitly imposed ceiling on CO_2 have been analyzed in several studies. We use an endogenous growth model with a ceiling and a carbon capture and storage (CCS) technology to study the effect of the ceiling on the allocation of limited funds for R&D, CCS and capital accumulation. It turns out that the advantagenousness of CCS investments rise with the CO_2 stock. If the gains of CCS, in terms of lower energy costs, outweigh the gains of R&D and capital accumulation, investments are reallocated towards CCS. On the one hand, this reduces the investments into R&D and/or capital. On the other hand, lower energy costs may increase research and/or capital investments. Positive CCS investments allow a higher extraction of fossil fuel, which implies lower backstop utilization. Consequently, CCS investments lower the advantageousness of R&D ceteris paribus. Furthermore, we show that the gains of CCS can be high enough to justify an investment reallocation even before the ceiling is binding, which contrast with existing literature.

Keywords: Climate Change, Research and Development, Carbon Capture and Storage, Endogenous Growth, Fossil Fuel, Renewable Resource

JEL classification: O13; O44; Q54

1. Introduction

In the last few decades the concerns about climate change have risen to level that a considerable number of nations agreed in the Kyoto Protocol to limit the global temperature increase. The probably best known political project in this regard is the 2°C

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climate target which was finally endorsed by The United Nation Conference of the Parties in Cancun (UNFCCC (2010)). The basic assumption of the climate target is that the consequences of climate change are manageable as long as the target is not violated. Otherwise, climate costs may increase sharply to unaffordable levels. To keep the global temperature increase below the 2°C target, several technologies can be deployed. Maybe the best known ones are renewable energies like solar, wind, biomass and water power. These energy sources can substitute fossil fuel driven energy generation, which is the main source of CO_2 emissions and the driving force of global warming.[1] Recently, with carbon capture and storage (CCS) another technology has been developed that can tackle climate change. The CCS technology separates CO_2 from conventional power plants and stores it in exploited fossil fuel deposits. Thereby, it allows the utilization of fossil fuel while avoiding the discharge of CO_2 emissions.

The literature has dealt with climate change in two different ways. On the one hand, a large number of authors explicitly consider the damages of CO_2 by assuming a damage function or a negative effect of CO_2 on utility or production. Farzin (1996), Hoel and Kverndokk (1996), Tahvonen (1997), Hoel (2011) and Van der Ploeg and Withagen (2012) are following this approach. On the other hand, Amigues et al. (2012), Chakravorty et al. (2006a), Chakravorty et al. (2006b), Chakravorty et al. (2008), Chakravorty et al. (2012), Coulomb and Henriet (2011), Eichner (2013), Henriet (2012), Kollenbach (2013) and Lafforgue et al. (2008) impose an exogenous ceiling on the stock of CO_2 in the atmosphere.[2] Since a maximal concentration of CO_2 is proportional to a maximal temperature rise, the ceiling reflects the 2°C target.[3] Other international agreements, like the Montreal Protocol on Substances that Deplete the Ozone Layer, are also imposing a ceiling on specific concentrations. Therefore, it seems likely or at least hopefully that a Kyoto follow up agreement will implicitly or explicitly include a CO_2 ceiling.

As the ceiling is exogenously given, the two approaches are answering two different questions. While the first approach determines the first best solution to deal with climate change or more generally pollution, the second approach asks for the second best solution

[1] 75% of CO_2 emissions stem from burning fossil fuel. Cf. Hoel (2011) and Van der Ploeg and Withagen (2012).

[2] A more general pollution ceiling has been considered by Smulders and Gradus (1996).

[3] According to Graßl et al. (2003) the maximal concentration lies between 400 and 450ppm, whereas Hansen et al. (2008) advocates a value of 350ppm to keep the planet as it was during the development of human civilization.

given the ceiling. Until recently, the effects of a ceiling were only analyzed in Hotelling type models.[4] Therefore, neither capital nor R&D have been considered, which are both important determinants for economic development and may serve as substitutes for exhaustible fossil fuel. Chakravorty et al. (2012) allows for technological development by assuming a learning-by-doing effect, while Henriet (2012) explicitly considers research. However, Henriet (2012) assumes that research determines the time until a backstop is available. Thus, long term growth cannot be explained by her model. To our knowledge only Kollenbach (2013) considers capital and a research driven steadily technological progress, which reduces the costs of a backstop.[5] By integrating an emission ceiling in the endogenous growth model of Tsur and Zemel (2005) he shows that in the short run the ceiling increases the scarcity of fossil fuel and is therefore boosting the attractiveness of research in the short run. Consequently, more final goods may be invested into R&D and less into the capital stock. However, CCS is not considered by Kollenbach (2013).

CCS, or in a more general sense abatement, is well known in the environmental literature. It has been discussed by Keeler et al. (1972), d'Arge (1971), Smulders and Gradus (1996), Amigues et al. (2012), Chakravorty et al. (2006a), Coulomb and Henriet (2011), Lafforgue et al. (2008), Le Kama et al. (2013) and Hoel and Jensen (2012). All studies use the realistic assumption that abatement is costly. Therefore, it competes with costly research and capital accumulation for limited funds in an endogenous growth model in the vein of Tsur and Zemel (2005) and Kollenbach (2013).[6] This aspect is neither covered by Tsur and Zemel (2005) and Kollenbach (2013) nor by the mentioned studies related to abatement, which do not consider capital and R&D. To investigate the trade off between R&D, capital accumulation and CCS and analyze the effect of a ceiling on the optimal allocation of funds, we integrate CCS into the model of Tsur and Zemel (2005) and Kollenbach (2013), respectively.

As CCS allows the extraction of cheap fossil fuels without emitting CO_2, positive CCS investments imply lower energy costs. If these lower costs outweigh the gains of R&D and

[4] This model type goes back to the seminal work of Hotelling (1931).

[5] The literature concerning the substitution of fossil fuel by capital and/or technology goes back at least to Stiglitz (1974), Solow (1974), Dasgupta and Heal (1974) and Hartwick (1977). Several endogenous growth studies have also analyzed this question. Cf. for example Barbier (1999) and Schou (2000). A comprehensive review of the endogenous growth theory covering environmental concerns is given by Pittel (2002).

[6] Another R&D approach, which is used by Acemoglu et al. (2012), assumes a given number of scientists which have to be allocated among R&D sectors or firms.

capital accumulation, positive CCS investments are optimal. CCS investments affect the economic development in three ways. Firstly, the reallocation of investments from R&D and/or capital accumulation towards CCS implies a lower rate of technological progress and/or capital accumulation. Secondly, the CCS implied lower energy costs increase available production which may boosts R&D and/or capital investments. Thus, the net effect of CCS investments on R&D and capital investments is unclear. In a particular case, it may be optimal to reallocate all available production to CCS implying a decreasing capital stock and a constant technology level. The economic development process found by Tsur and Zemel (2005) is overruled in this case. The third effect of the CCS investments is its impact on the R&D advantageousness. If CCS investments are positive, they allow for a higher fossil fuel use and therefore ceteris paribus lower backstop utilization. Consequently, the advantageousness of R&D is depressed. If the ceiling is binding, increasing (decreasing) CCS investments directly imply a lower (higher) advantageousness of R&D. Furthermore, we study the cause of the divergence between Chakravorty et al. (2006a), Lafforgue et al. (2008) and Amigues et al. (2012), Coulomb and Henriet (2011) in more detail. According to the former two studies abatement is only optimal, if the emission stock is at the ceiling. In contrast Amigues et al. (2012) and Coulomb and Henriet (2011) find that abatement may be optimal before the ceiling is binding. Amigues et al. (2012) argue that the heterogeneity of abatement costs causes the different result, while Coulomb and Henriet (2011) refers to limited application fields of abatement. Our results support Amigues et al. (2012) and Coulomb and Henriet (2011). In other words, they show that CCS may be optimal before the ceiling is binding. In view of the results of Amigues et al. (2012) and Coulomb and Henriet (2011) we argue that the divergence to Chakravorty et al. (2006a) and Lafforgue et al. (2008) is caused by an upper limit for abated emissions. An upper limit is assumed by Amigues et al. (2012), Coulomb and Henriet (2011) and us but not by Chakravorty et al. (2006a) and Lafforgue et al. (2008). Our result is explained by the decreasing effect of CCS investments on energy costs. If the gains of lower energy costs outweigh the gains of R&D and capital accumulation, CCS investments are positive regardless whether the ceiling is binding or not yet binding.

The outline of the paper is as follows. In section 2 we describe the model. The (constraint) social optimum is determined in section 3. Section 4 concludes.

2. Model

We use the framework developed by Tsur and Zemel (2005) which is augmented by a ceiling on CO_2 emissions and a carbon capture and storage (CCS) possibility.[7] In the following the assumptions of the model are briefly discussed. A composite good $Y = F(K, x)$ is produced by means of capital K and energy x according to the well-behaved and concave production function $F(K, x)$, i.e. $F_x > 0$, $F_K > 0$, $F_{xx} < 0$, $F_{KK} < 0$, $F_{Kx} = F_{xK} > 0$ and $J = F_{xx}F_{KK} - F_{Kx}^2 > 0$. Both inputs are necessary for production so that $F(0, x) = F(K, 0) = 0$. While capital is accumulated by saving the composite good, energy is generated by using exhaustible and polluting fossil fuel R or a clean backstop b (e.g. solar energy or fusion power). The utilization of every fossil fuel unit causes one emission (CO_2) unit E.[8] Therefore, R and E are used synonymously in the following. The extraction costs of fossil fuel are given by the increasing and strictly convex function $M(R)$, i.e. $M'(R) > 0$ and $M''(R) > 0$. We assume that no fixed costs exists and that the marginal costs of the first used fossil fuel unit are zero. Thus, $M(0) = 0$ and $M'(0) = 0$. The supply costs of the backstop $M_b B(A) b$ are linear in the backstop. $M_b > 0$ is a constant cost parameter and the function $B(A) > 0$ reflects the influence of the technology level A on the backstop costs. A higher technology level decreases backstop costs, i.e. $B'(A) < 0$. However, the effect diminishes for large A so that $B''(A) > 0$, $\lim_{A\to\infty} B(A) = \bar{B} > 0$ and $\lim_{A\to\infty} B'(A) = 0$. Furthermore, we assume a positive technology endowment A_0. The technology level is increased by R&D investments I according to

$$\dot{A} = I. \tag{1}$$

We assume $I \in [0, \bar{I}]$. The lower limit reflects that there cannot be negative investments. The upper limit $\bar{I}$ is given by net production

$$Y^n := F(K, x) - M(R) - M_b B(A) b, \tag{2}$$

i.e. by production net of energy costs. Net production can also be used for consumption C, capital accumulation $\dot{K}$ and CCS investments N. Thus, the capital stock develops according to

$$\dot{K} = F(K, x) - M(R) - M_b B(A) b - C - I - M_N N, \tag{3}$$

[7] For a more detailed discussion of the assumption we refer to Tsur and Zemel (2005). The ceiling has already been introduced into the model of Tsur and Zemel (2005) by Kollenbach (2013). For the sake of simplicity the time index t is suppressed as long as it is not necessary for understanding.

[8] This can be realized by a appropriate unit choice.

where M_N denotes the unit cost of CCS. Investing into one CCS unit N eliminates one emission unit E. We assume that CCS possibilities are constrained from above either by $\bar{I}$ or $\bar{N} > 0$, i.e. $N \in \left[0, \min\left(\bar{N}, \frac{\bar{I}}{M_N}\right)\right]$. The first upper bound $\bar{I}$ implies that it is not possible to capture and store one additional emission unit, if the complete net production is already used for CCS and research. The second upper bound $\bar{N}$ reflects the limited technological possibilities to capture and store CO_2. Firstly, CCS is only an option for industrial complexes but not for mobile use of fossil fuel, like in cars or planes. Secondly, the CCS processes generally allow only a sequestration rate of 85% to 90%.[9] Thus, CCS does not eliminate CO_2 completely but only partly. Therefore, $\bar{N} \leq E(t)$, $\forall t$. The development of the fossil fuel resource stock S_R and the emissions S_E is determined by

$$\dot{S}_R = -R, \tag{4}$$

$$\dot{S}_E = R - N - \gamma S_E. \tag{5}$$

With every used fossil fuel unit the fossil fuel stock decreases. The emission stock increases in fossil fuel utilization net of CCS investments and decreases due to the natural regeneration rate γ.[10] A ceiling $\bar{S}_E$ on the emissions stock S_E is imposed exogenously. As mentioned above, the ceiling can be the result of an international agreement.[11] The ceiling implies that

$$\bar{S}_E - S_E \geq 0 \tag{6}$$

must hold at every point in time. We distinguish three different conditions of the ceiling. If the ceiling is non-binding for a limited time period so that it binds in the future, we refer to this time period as phase 1. The limited time period characterized by a binding ceiling is called phase 2. Phase 3 is an unlimited time period with a non-binding ceiling

[9]Cf. Blohm et al. (2006), section 2. A similar assumption is used by Coulomb and Henriet (2011).

[10]The equation of motion of the emission stock is widely used in the literature. Cf. Guruswamy Babu et al. (1997), Chakravorty et al. (2006a) and Tsur and Zemel (2009).

[11]Cf. Chakravorty et al. (2006a), Chakravorty et al. (2008) and Chakravorty et al. (2012). The ceiling can also reflect a damage function with negligible damages below the ceiling and prohibitive high damages above it. Chakravorty et al. (2008) and Lafforgue et al. (2008) refer to this point. According to Chakravorty et al. (2006a) and Chakravorty et al. (2008) the ceiling can be imposed by some regulatory authority. Eichner (2013) argue that the ongoing international climate negotiations refer mainly to the 2° climate target and therefore to an implicit ceiling.
To concentrate on the effects of the exogenous ceiling we abstain from a specific damage function. This procedure is in line with Chakravorty et al. (2006a), Chakravorty et al. (2006b), Chakravorty et al. (2008), Lafforgue et al. (2008) and Chakravorty et al. (2012). Therefore, we are not going to analyze whether the ceiling is optimal or not. Furthermore, this implies that there are no marginal costs of CO_2 emissions.

that remains non-binding for all following points in time.

Utility U depends only on consumption C according to the increasing and strictly concave function $U(C)$, i.e. $U'(C) > 0$ and $U''(C) < 0$. Furthermore, we assume $\lim\limits_{C\to 0} U(C) = \infty$, $U(0) = -\infty$ and $\lim\limits_{K\to 0} F_K = \lim\limits_{x\to 0} F_x = \infty$.[12] Thus, utility is given by

$$U(C) \begin{cases} \geq 0, & \text{for } C > 0, \\ = -\infty, & \text{for } C = 0. \end{cases} \tag{7}$$

3. The constrained social optimum

To deduce the constrained social optimum we consider a constrained social planer, who maximizes intertemporal utility $\int\limits_0^\infty e^{-\rho t} U(C(t))dt$, with ρ denoting the time preference rate, given the initial state $(K_0, A_0, S_{R_0}, S_{E_0})$ and subject to (1), (3), (4), (5), (6), $K \geq 0$, $S_R \geq 0$, $0 \leq I + M_N N \leq \bar{I}$, $0 \leq N \leq \bar{N}$ and $R, b, C \in [0, \infty[$.[13] The costate variables associated with the capital stock, technology level, resource stock and emission stock are denoted λ, κ, τ and θ. Obviously, an exogenous increase of the capital stock, the technology level or the resource stock has a positive value for the social planer. Consequently, the related costate variables λ, κ and τ are positive, since they can be interpreted as shadow prices. On the other hand, an exogenous increase (decrease) of the emission stock tightens (relax) the optimization problem of the social planer in phase 1 and phase 2. Therefore, $\theta < 0$ during these phases. In phase 3 the ceiling has lost its relevance so that $\theta = 0$ holds. The Lagrange multiplier associated with the ceiling is μ. Hence, the current-value Lagrangian

[12] The assumptions are not made by Tsur and Zemel (2005), which implies that Tsur and Zemel (2005) allow the collapse of production and therefore of consumption, i.e. a doomsday scenario. However, the corresponding setting is an extreme case that is generally not necessary for our analysis. Therefore, we use the extended assumptions of Kollenbach (2013)

[13] We refer to the social planer as a constrained one, since the ceiling is imposed exogenously. Thus, we are going to analyze the optimal solution given the ceiling, which can be interpreted as a second best solution. Cf. Chakravorty et al. (2008) and Chakravorty et al. (2012).

reads[14]

$$
\begin{aligned}
L = U(C) + \lambda\left[F(K, b+R) - M(R) - M_b B(A) b - M_N N - I - C\right] \\
+ \kappa I - \tau R + \theta[R - N - \gamma S_E] + \mu[\bar{S}_E - S_E] + \zeta_I I \\
+ \zeta_{\bar{I}}[\bar{I} - I - M_N N] + \zeta_N N + \zeta_{\bar{N}}[\bar{N} - N] \qquad (8)
\end{aligned}
$$

An interior optimum is given by the following necessary conditions:

$$\frac{\partial L}{\partial C} = U' - \lambda = 0, \qquad (9)$$

$$\frac{\partial L}{\partial R} = \lambda[F_x - M'] - \tau + \theta = 0, \qquad (10)$$

$$\frac{\partial L}{\partial b} = \lambda[F_x - M_b B(A)] = 0, \qquad (11)$$

$$\frac{\partial L}{\partial I} = -\lambda + \kappa + \zeta_I - \zeta_{\bar{I}} = 0, \qquad (12)$$

$$\frac{\partial L}{\partial N} = -\lambda M_N - \theta - \zeta_{\bar{I}} M_N + \zeta_N - \zeta_{\bar{N}} = 0. \qquad (13)$$

(10) and (11) determine both total energy input and the energy mix. The marginal productivity of energy is given by $F_x(K, x)$, while $M_b B(A)$ represents the marginal costs of the backstop. The supply of fossil fuel is determined by $M'(R) + \frac{\tau-\theta}{\lambda} = F_x(K, x)$, i.e. by the marginal product of energy, the sum of the marginal fossil fuel costs and a term $m^q = \frac{\tau-\theta}{\lambda}$ that is called the relative scarcity index by Kollenbach (2013). The latter sets the shadow prices related to fossil fuel into relation to the shadow price of capital. Provided that both energy sources are used, Fig. 1 shows that the total energy input is determined by $F_x = M_b B(A)$. The fossil fuel input is given by $M'(R) + m^q = M_b B(A)$, since it is not optimal to use fossil, if their costs exceeds the backstop unit costs. Thus, only backstop is used, if $M_b B(A)$ falls short of $M'(0) + m^q$. On the other hand, energy generation relies completely on fossil fuel, if the backstop unit costs exceed $M'(R^{\#}) + m^q$. Following Tsur and Zemel (2005), we assume that both energy sources are used simultaneously, which requires $M'(0) + m^q < M_b B(A) < M'(R^{\#}) + m^q$.

[14] We have omitted the constraints concerning $b \geq 0$, $R \geq 0$ and $C \geq 0$. As stated above the optimality of $C = 0$ is ruled out by the assumption $U(0) = -\infty$. Concerning the energy sources we follow Tsur and Zemel (2005) and assume an interior solution, i.e. the simultaneous utilization of both resources. Note that this is possible due to the fossil fuel cost function. If the marginal fossil fuel costs are independent from R, a simultaneous use is not possible. Cf. Chakravorty et al. (2006a) and Hoel (2011).
In contrast to Kollenbach (2013) we use here the "direct approach" of Feichtinger and Hartl (1986), section 6.2 to solve the optimization problem with a state space constraint instead of the "indirect approach". However, both approaches give similar results.

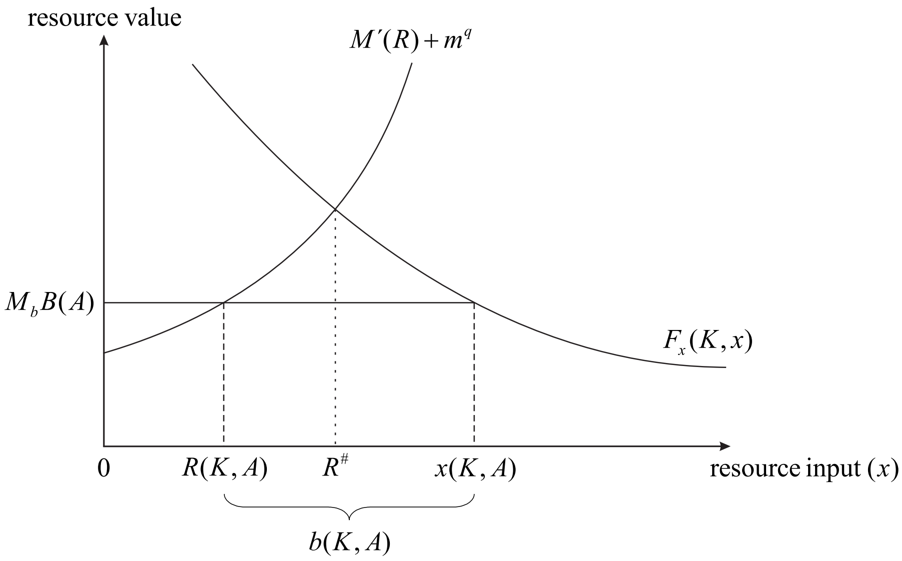

Figure 1: Usage of exhaustible resource and backstop

The complementary slackness conditions concerning the R&D and CCS investments are

$$\begin{aligned} &\zeta_N N = 0,\ \zeta_N \geq 0\ (a), && \zeta_{\bar{N}}(\bar{N} - N) = 0,\ \zeta_{\bar{N}} \geq 0\ (b), \\ &\zeta_I I = 0,\ \zeta_I \geq 0\ (d), && \zeta_{\bar{I}}(\bar{I} - I - M_N N) = 0,\ \zeta_{\bar{I}} \geq 0\ (d). \end{aligned} \tag{14}$$

Since the Lagrangian (8) is linear in N and I we get a so-called bang bang solution concerning CCS and R&D investments. This solution is given by the maximization of the Hamiltonian $H = U(C) + \lambda[F(K, b + R) - M(R) - M_b B(A)b - M_N N - I - C] + \kappa I - \tau R + \theta[R - N - \gamma S_E]$ with respect to I and N. With * denoting optimal values, we get

$$\begin{array}{llll} I^* = 0 & \&\quad N^* = 0, & \text{if } \lambda > \kappa \text{ and } \lambda > \dfrac{|\theta|}{M_N}, & (i) \\ 0 \leq I^* \leq \bar{I} & \&\quad N^* = 0, & \text{if } \lambda = \kappa \text{ and } \lambda > \dfrac{|\theta|}{M_N}, & (ii) \\ I^* = 0 & \&\quad 0 \leq N^* \leq \min\left[\bar{N}, \dfrac{\bar{I}}{M_N}\right], & \text{if } \lambda > \kappa \text{ and } \lambda = \dfrac{|\theta|}{M_N}, & (iii) \\ 0 \leq I^* + M_N N^* \leq \bar{I} & \&\quad 0 \leq N^* \leq \min\left[\bar{N}, \dfrac{\bar{I}}{M_N}\right], & \text{if } \lambda = \kappa \text{ and } \lambda = \dfrac{|\theta|}{M_N}, & (iv) \\ 0 \leq I^* \leq \bar{I} - M_N \bar{N} & \&\quad N^* = \min\left[\bar{N}, \dfrac{\bar{I}}{M_N}\right], & \text{if } \lambda = \kappa \text{ and } \lambda < \dfrac{|\theta|}{M_N}, & (v) \\ I^* = 0 & \&\quad N^* = \min\left[\bar{N}, \dfrac{\bar{I}}{M_N}\right], & \text{if } \lambda > \kappa \text{ and } \lambda < \dfrac{|\theta|}{M_N}, & (vi) \\ I^* = \bar{I} - M_N N & \&\quad N^* = \min\left[\bar{N}, \dfrac{\bar{I}}{M_N}\right], & \text{if } \lambda < \kappa \text{ and } \kappa < \dfrac{|\theta|}{M_N}, & (vii) \end{array} \tag{15}$$

$$I^* = \bar{I} \qquad \& \qquad N^* = 0, \qquad \text{if } \lambda < \kappa \text{ and } \kappa > \frac{|\theta|}{M_N}, \qquad (viii)$$

$$I^* + M_N N^* = \bar{I} \qquad \& \qquad N^* \leq \min\left[\bar{N}, \frac{\bar{I}}{M_N}\right], \qquad \text{if } \lambda < \kappa \text{ and } \kappa = \frac{|\theta|}{M_N}. \qquad (ix)$$

The conditions of (15) compare the advantageousness of capital accumulation, R&D and CCS investments with each other. The gains of investments into the capital stock and R&D are obviously. A higher capital stock increases production and therefore the possibility to consume, while a higher technology level decreases the backstop costs which boosts net production ceteris paribus. The gain of CCS investments is the possibility to use more fossil fuel, as the related emissions are captured and stored. Since the utilization of fossil fuel is only favorable, if the marginal fossil fuel costs do not exceed the marginal backstop costs, positive CCS investments imply lower energy costs and therefore a higher net production.

Together with (12), (13) and (14) the conditions of (15) determine the optimal R&D and CCS investments. According to (15) both R&D and CCS investments are minimal, singular or maximal. If the CCS investments are maximal and technologically bounded by $\bar{N}$, R&D and CCS can occur simultaneously even though the social planer is not indifferent between the two options, like in case (vii). Suppose $N > 0$ and $I > 0$ hold for this case, then $\zeta_N = \zeta_I = 0$ as well as $\zeta_{\bar{I}} = \kappa - \lambda > 0$ and $\frac{\zeta_{\bar{N}}}{M_N} = \frac{|\theta|}{M_N} - \kappa > 0$ so that (12) and (13) are fulfilled. However, if CCS investments are bounded by net production $\bar{I}$, no R&D occurs and $\zeta_N = \zeta_{\bar{N}} = 0$. Then (12) and (13) imply $\zeta_{\bar{I}} = \frac{|\theta|}{M_N} - \lambda > 0$ and $\zeta_I = \frac{|\theta|}{M_N} - \kappa > 0$. In a similar way it can be shown that the other cases of (15) together with (12) and (13) always give $\zeta_i \geq 0$, $i = I, N, \bar{I}, \bar{N}$, which is in line with the complementary slackness conditions of (14).[15]

[15] Neither Chakravorty et al. (2006a) nor Lafforgue et al. (2008) consider an upper limit of abatement. However, without an upper limit $\kappa \leq -\lambda M_N < |\theta|$ imply infinitely high CCS investments, which are rather unrealistic. In fact, at every point in time no more emission units can be abated than are currently in the atmosphere. As we will see below, the upper limit has fierce consequences for optimal CCS investments.

The costate variables develop according to

$$\frac{\partial L}{\partial K} = \lambda F_K = \rho\lambda - \dot{\lambda}, \tag{16}$$

$$\frac{\partial L}{\partial S_E} = -\gamma\theta - \mu = \rho\theta - \dot{\theta}, \tag{17}$$

$$\frac{\partial L}{\partial S_R} = 0 = \rho\tau - \dot{\tau}, \tag{18}$$

$$\frac{\partial L}{\partial A} = -\lambda M_b B'(A) b = \rho\kappa - \dot{\kappa}. \tag{19}$$

Substituting the derivation of (9) with respect to time into (16) gives the well-known Ramsey-rule

$$\hat{C} = \frac{F_K - \rho}{\eta}. \tag{20}$$

According to the rule consumption increases (decreases), if the marginal product of capital exceeds (falls short of) the time preference rate. The reaction of consumption to the difference is the stronger the smaller is the positive elasticity of marginal utility η.
The complementary slackness condition related to the ceiling $\bar{S}_E$ reads

$$\mu(\bar{S}_E - S_E) = 0,\ \ \mu \geq 0. \tag{21}$$

The equation system is completed by the transversality conditions

$$\begin{aligned} &(a)\ \lim_{t\to\infty} e^{-\rho t}\lambda(t)[K(t) - K^*(t)] \geq 0, \qquad &&(b)\ \lim_{t\to\infty} e^{-\rho t}\tau(t)[S_R(t) - S_R^*(t)] \geq 0, \\ &(c)\ \lim_{t\to\infty} e^{-\rho t}\theta(t)[S_E(t) - S_E^*(t)] \geq 0, \qquad &&(d)\ \lim_{t\to\infty} e^{-\rho t}\kappa(t)[A(t) - A^*(t)] \geq 0. \end{aligned} \tag{22}$$

Before we turn to the question when and how much to invest into CCS and R&D, we describe the mechanism that determines the development of the economy. This mechanism was described by Tsur and Zemel (2005) for an economy without a ceiling, which is equivalent with an economy in phase 3. Kollenbach (2013) shows that a ceiling affects but not completely altered the mechanism.
An economy in phase 3 is characterized by $\theta = \mu = 0$. Thus, the scarcity index m^q reduces to its natural level $\frac{\tau}{\lambda}$. The scarcity index increases constantly with the growth rate $\hat{m}^q = F_K > 0$, as the utilization of fossil fuel implies a shrinking fossil fuel stock. Due the to constantly increase of m^q, we get a direct conjunction of m^q and time t. As can be seen in Fig. 1 a higher scarcity index reduces fossil fuel and boosts backstop utilization ceteris paribus. This observation is important for the following description of the development mechanism.

Tsur and Zemel (2005) show that the economic development can be analyzed graphically by means of two characteristic manifolds (planes) in the three-dimensional capital-technology-time (K, A, t) space. The first plane describes all points which allow a steady state. That is why it is called the steady state plane (SSP) in the following. It is given by $F_K(K, x) = \rho$ and depends on total energy input but not on the energy mix. Therefore, the plane is independent form the development of the scarcity or time, respectively. However, it is increasing in technology. Above (below) the plane consumption decreases (increases). The second plane is called the singular plane (SiP), as it describes all points where singular research is optimal. The area above the SiP is the only section of the (K, A, t) space where maximal R&D can be optimal. Below the SiP only minimal R&D is possible. The SiP is given by $-M_b B'(A)b = F_K(K, x)$. Thus, it depends on backstop utilization, which ceteris paribus increases with the scarcity index. As R&D becomes more advantageous if more backstop is used, the SiP is decreasing in time so that more points in the (K, A, t) space allow for R&D. If no fossil fuel is used, the SiP is also independent from t. Similar to the SSP the SiP increases in technology. Fig. 2 illustrates the two planes for an arbitrary point in time t in the (K, A) space. While the SSP remains at its position, the SiP shifts downwards as fossil fuels become scarcer until it reaches its position for an exhausted resource stock denoted with SiP(T_R).

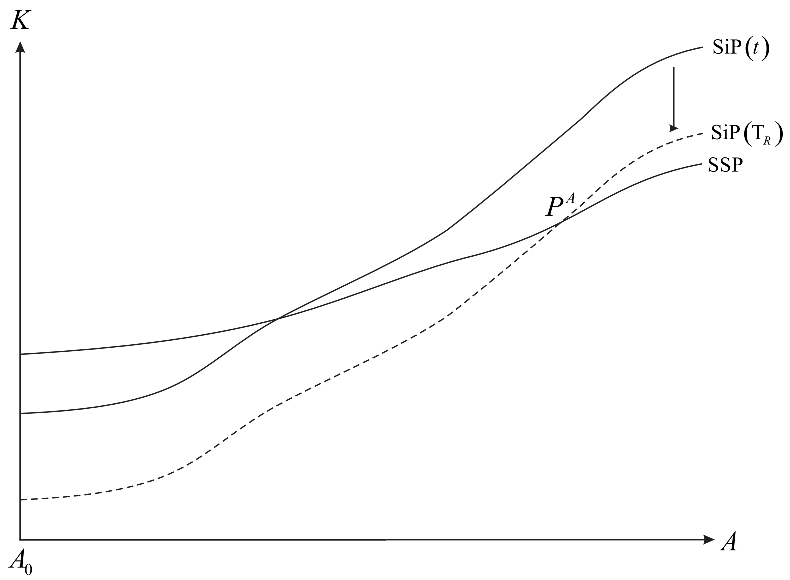

Figure 2: Singular and steady state plane in the capital technology space

At every point in time the economy can be described by its capital stock and its technology level, i.e. by a point in the (K, A, t) space. Tsur and Zemel (2005) show that

depending on the position of this point in relation to the two planes, the development path can be determined. Basically, an economy located below the SiP approaches the SiP on a most rapid approach path (MRAP), i.e. by capital accumulation but minimal R&D. Above the SiP the MRAP consists of maximal R&D and consequently a capital stock reduction. Once reached, the SiP binds the development path so that the economy conducts singular R&D for ever or switches into a steady state at the intersection of SiP and SSP for an exhausted fossil fuel stock (point P^A in Fig. 2). The latter is only optimal, if the SiP lies above the SSP for large technology level.
There are two additional development possibilities. In the first exceptional case, the economy is too poor, i.e. its capital endowment is too small, to reach the SiP so that the capital stock is reduced until the SSP is reached. Thus, this case is a poverty trap. The second exceptional case is characterized by a high capital endowment and a SiP located above the SSP for large A. It is then possible that the intersection of SiP and SSP cannot be reached and the economy switches from maximal to minimal R&D above the SiP.

For the determination of the optimal CCS investment it is important to notice that the described regular development implies $\kappa > (<, =) \lambda$ above (below, on) the SiP. Only in case of the second exception $\lambda > \kappa$ holds above the SiP.

Kollenbach (2013) shows that the ceiling adds the additional scarcity $\frac{|\theta|}{\lambda}$ to the natural one. This additional scarcity reflects the necessary adaption of resource utilization to adhere to the ceiling. During phase 1 the additional scarcity increases constantly, as $\hat{\theta} - \hat{\lambda} = \gamma + F_K$. In phase 2 the ceiling is binding, which implies a positive μ so that $\hat{\theta} = \rho + \gamma + \frac{\mu}{\theta}$ can be negative, yielding an decreasing $|\theta|$. Thus, the development of the additional scarcity depends on the phase. By modifying the proof of Kollenbach (2013) Appendix A.1 it can be shown that the only sequence containing all three phases reads phase 1, phase 2, phase 3 and that the switch from one phase to the next as well as the development during the phases is smooth.[16] Thus, the sequence starts with a non-binding ceiling that becomes binding later on. During that time (phase 1) the additional scarcity increases constantly, since the emission stock is converging against the ceiling. Consequently, the maximal amount of usable fossil fuel shrinks. Since a higher scarcity index implies a substitution of fossil fuel by backstop ceteris paribus and a higher backstop utilization implies a higher advantageousness of R&D, the SiP is lowered by

[16]The proof of Kollenbach (2013) has to be adapted to the "direct" optimization approach.

the additional scarcity. Thus, the advantageousness of R&D is boosted, while the one of capital accumulation is depressed. In the moment the ceiling becomes binding, the economy switches into phase 2. Since the natural scarcity increases constantly and fossil fuel utilization cannot fall below a specific level given by $\gamma\bar{S}_E$, the additional scarcity decreases in the long run and vanishes at the end of the phase.[17] This implies, that the energy mix is converging against the one without a ceiling. Consequently, the boost of R&D advantageousness becomes smaller. Thus, R&D advantageousness is still higher in phase 2 than without a ceiling but the difference is decreasing. At the end of phase 2 the economy switches into phase 3 and the ceiling will never be reached again. Hence, there is no additional scarcity and the R&D advantageousness is at its natural level.

The ceiling increases the R&D advantageousness in the short- and middle-run, which, depending on the capital endowment, may lead to earlier and more R&D investments. Furthermore, the stated sequence of phases imply that it is not optimal to increase CCS investments to a level that prevents the attainment of the ceiling. Otherwise the economy switch from phase 1 into phase 3, which is neither compatible with the phase sequence nor with a continuous development, as θ is negative in phase 1 but zero in phase 3.

Lemma 1 *It is not optimal to increase CCS investments to a level that prevents a binding ceiling.*

Based on these observations we analyze in the following when CCS, R&D or capital stock investments are optimal and how the development path of the economy is affected by the CCS option. Obviously, CCS is not conducted during phase 3. In this phase the economy develops according to the program described above.[18] To emphasize the differences between the other two phases, both phases will be analyzed individually, starting with phase 1.

3.1. Phase 1

During phase 1 the ceiling is not binding implying $\mu = 0$. However, the economy approaches the ceiling. Consequently, a higher emission stock has a negative value for the constraint social planer, i.e. $\theta < 0$. To analyze how the CCS option affects the development path we assume at first that the economy is located below the singular

[17] From a technical point of view this follows from $\theta = 0$ in phase 3 and the continuous development of the economy.

[18] Cf. Tsur and Zemel (2005) for more details.

plane. In this case capital accumulation is more advantageous than R&D ($\lambda > \kappa$) so that (15) $(ii), (iv), (v), (vii), (viii), (ix)$ are ruled out. The remaining cases give the three known possibilities on CCS investment: minimal, singular and maximal. Furthermore, we have to notice that (17) and (16) can be rewritten as $\hat{\theta} = \rho + \gamma$ and $\hat{\lambda} = \rho - F_K$, respectively. Since $F_K > 0$, the growth rate of λ is lower than the rate of θ. Thus, if (15) (vi) holds at the first point in time of phase 1, i.e. if CCS is more advantageous than capital accumulation at $t = 0$, it will stay so during the whole phase. Even if this is not the case, which implies that either (15) (i) or (iii) hold, CCS may become more advantageous than capital accumulation over time and stays so. It is also noteworthy that singular CCS is only possible for one point in time, since (15) (iii) cannot hold for a longer time period due to the different growth rates of λ and θ. Furthermore, a switch from minimal over singular to maximal CCS does not imply that the fossil fuel utilization path exhibits jumps, since all elements of equations (10) and (11), determining the energy mix, are continuous in time. This is clarified by Fig 1. All depicted functions can move in time but only in a continuous way, implying a steady development of fossil fuel utilization. However, an increase of CCS investments will lower the emission stock growth rate.

The development path is not affected by the CCS option provided that no CCS occurs. In case of maximal CCS the capital stock can both increase or decrease. The former occurs, if the upper bound of CCS is given by $\bar{N}$, i.e. by the technological constraint. Net production can be positive so that the capital stock increases provided that consumption is sufficiently low. If the development path approaches the SiP faster or slower depends on two opposed effects. On the one hand, the CCS costs decreases the capital accumulation rate. On the other hand, CCS allows a higher utilization of fossil fuels and therefore lower energy costs, which boosts capital accumulation ceteris paribus. If the upper bound of CCS investment is given by net production, the capital stock has to decrease, as $C > 0$ must hold. The analysis of maximal CCS holds also for singular CCS, if CCS investments are sufficiently high. Otherwise, both CCS and capital investments are positive. However, the case of singular CCS is negligible, as it maximally appears at one point in time. Thus, the CCS option can slow down the development or even invert the direction of the development path. Although, the latter is only possible, if the capital endowment is sufficiently large. Otherwise, maximal CCS investments may completely consume the capital stock implying zero consumption, which is ruled out by assumption as a part of an optimal solution. However, maximal CCS may reduce the capital stock to a level that does not allow a later approach of the singular plane, i.e. CCS may lead into the poverty trap. Such a development path can be only optimal, if the gains from CCS, i.e. higher early consumption due to more fossil fuel utilization and therefore lower energy costs, outweigh the gains of a higher capital stock and R&D at later points in time, i.e. higher consumption due to a higher production and lower energy costs. Obviously, the higher the time preference rate the likelier is the optimality of such a development path.

After having discussed the case of an economy located below the singular plane, we turn to the opposite, an economy above the SiP. As stated above, in the standard case $\lambda < \kappa$ holds in this region of the (K, A, t) space implying maximal R&D. Optimal CCS investments are given by (15) $(vii), (viii)$ and (ix). Thus, if (15) $(viii)$ holds, CCS investments are minimal and the development path of the economy is not affected by the CCS option. However, from (19) we get $\hat{\kappa} = \rho + \frac{\lambda}{\kappa} M_b B'(A) b$. Since $B'(A) < 0$, the growth rate of κ is smaller than the one of θ. Thus, even if R&D is more advantageous than CCS at early points of time, this may change later on leading to a switch from maximal R&D to maximal CCS investments. As in the case of an economy below the singular plane, the advantageousness of CSS exceeds the one of R&D from the point in time CCS has become more advantageous. Furthermore, (15) (ix) can only hold for one point in time, due to the different growth rates of κ and θ. If CCS is more advantageous than R&D the amount of R&D investments depend on the upper bound for CCS. If the upper bound is given by net production, no production is left for R&D. So CCS investments completely drive out R&D investments in this case implying that the development path is described by a decreasing capital stock and a constant technological level. On the other hand, R&D investments may be positive, if the upper bound of CCS investments is given by the technological constraint $\bar{N}$. The effect of the CCS option on the amount of R&D investments is determined by two opposite effects in this case. According to (15) (vii), the first effect decreases R&D investments, as the costs of CCS lower the available net production. The second effect is given by the higher fossil fuel utilization which increases net production due to lower energy costs.

The type of the upper CCS bound is important for the reaction of the development path when it reaches the singular plane. Recall that the SiP bounds the development path, i.e. it is not optimal to leave the singular plane. Without the CCS option, an economy which approaches the SiP from above switches from maximal to singular R&D to follow the plane. However, with maximal CCS this is only possible, if the upper CCS bound is the technological one, as only this allows positive R&D investments and therefore a development along the SiP. Thus, if the whole net production is used for CCS, the development path breaks through the singular plane so that the economy is located below the SiP afterwards while still performing maximal CCS. If the economy approaches the SiP from below, CCS investments are either minimal or the upper CCS bound is $\bar{N}$. Otherwise, the capital stock is decreasing, which implies an economy located below the SiP during the whole phase 1.

In an exceptional case R&D investments are minimal above the singular plane, i.e. $\lambda > \kappa$ holds. Consequently, optimal CCS investments are determined by (15) $(i), (iii)$ and (vi), similar to the case of an economy located below the SiP. However, the capital stock decreases in the exceptional case, whether or not CCS investments are positive. Furthermore, a possible switch from maximal to minimal R&D above the singular plane does not affect CCS investments, since the relation of κ to λ does not affect the relation of θ to κ and λ. Thus, if positive CCS investments are (not) optimal before the switch, they are also (not) optimal after it.

The above results contrast sharply with the ones of Chakravorty et al. (2006a) and Lafforgue et al. (2008), which both found that CCS does not occur as long as the ceiling is not binding. However, our results are in line with Amigues et al. (2012) and Coulomb and Henriet (2011). From a technical point of view our results are caused by our consideration of upper limits for CCS investments. The technological limit $\bar{N}$ is used in a similar form by Coulomb and Henriet (2011), while Amigues et al. (2012) links abatement to the consumption of a specific fossil fuel type. Our results are robust to the type of the upper limit, as they hold also for the economic limit of net production $\frac{\bar{I}}{M_N}$.
The economic interpretation is straightforward. By imposing a constraint on the economy the ceiling forces a reduction (increase) of fossil fuel (backstop) utilization. The strictness of the constraint, i.e. the deviation from the optimal energy mix without the ceiling, is measured by the shadow price θ. The stricter the constraint the higher is $|\theta|$. However, CCS investments work in a similar way as a reduction of the emission stock. They enable the economy to increase fossil fuel utilization without violating the ceiling, i.e. CCS investments reduce the strictness of the ceiling. If the gains from an additional fossil

fuel unit, in form of more available production due to lower energy costs, are higher than the costs of capture and store the additional emission unit, i.e. if $\frac{|\theta|}{M_N} > \lambda$, CCS can be optimal. If the gains of CCS also outweigh the gains of R&D, i.e. if the CCS induced limited energy cost reduction outweighs the everlasting one of R&D, positive CCS investments are optimal. Thus, there can be a gain from CCS even if the ceiling is not yet binding.

Proposition 1 *Positive CCS investments are possible during phase 1, if the gains of CCS outweigh the ones of capital accumulation and R&D, i.e. if the ceiling is sufficiently tight and therefore its shadow price sufficiently high. If CCS investments are maximal and the investments are limited by net production, the capital stock declines monotonically. If CCS investments are technologically limited or minimal, also investments into the capital stock and/or R&D occur.*

The CCS induced higher use of fossil fuel has a further indirect effect on economic development. Ceteris paribus more fossil fuel can be only used, if the relative scarcity index is lower implying less backstop utilization and therefore a higher position of the singular plane in the (A, K) space. Thus, compared with an economy without the CCS option positive CCS investments decrease the advantageousness of R&D. However, this affects the development only, if the economy reaches the singular plane.

Proposition 2 *Positive CCS investments cause a ceteris paribus reduction of R&D advantageousness.*

3.2. Phase 2

Phase 2 is characterized by a binding ceiling so that the shadow price θ is negative and $\mu > 0$. The latter implies that the growth rate

$$\hat{\theta} = \rho + \gamma + \frac{\mu}{\theta} \tag{23}$$

can be both positive or negative. Furthermore, it can be equal to the growth rates of λ or κ for some time. The relevance of this fact is explained below. From (5) and $S_E = \bar{S}_E$ we get

$$R = N + \gamma \bar{S}_E. \tag{24}$$

The equation establishes a link between the development of the relative scarcity index $m^q = \frac{\tau - \theta}{\lambda}$ and investments into CCS and R&D. Suppose CCS is constant, then (24) implies a fixed fossil fuel utilization. If also no R&D is conducted, the technology level A and therefore the backstop unit costs are constant. Fig. 1 shows that the scarcity index needs to be constant in this case to guarantee a constant fossil fuel amount. If R&D are positive, the technology level increases implying lower backstop unit costs and therefore a lower scarcity index.[19] The effects of changes in CCS investments can be analyzed in a similar manner. If CCS investments increase (decrease), e.g. due to more (less) available net production, (24) implies that fossil fuel utilization rises (shrinks). Thus, the relative scarcity index needs to decrease (increase). As higher (lower) fossil fuel utilization lowers (boosts) the use of the backstop, increasing (decreasing) CCS investments cause a decline (rise) of R&D advantageousness, i.e. an increase (decrease) of the singular plane in time. Thus, the mechanism is the one which is causing the indirect effect of proposition 2. However, the mechanism is here more visible, as changes of CCS investments directly affect the R&D advantageousness.

It has to be noticed that (10) and (11) do not allow jumps in the fossil fuel utilization, which is of some importance for the following analysis of the optimal development. Basically, the analysis is similar to the one of section 3.1. Therefore, we refrain from repeating the whole analysis and concentrate on the differences. For this we have to notice that the advantageousness of CCS (the additional scarcity) does not steadily increase but decrease in the long run and vanishes at the end of the phase. Thus, the CCS advantageousness reaches its peak either at the junction point between phase 1 and 2 or at some point in time during phase 2. This implies that both capital accumulation and R&D become more advantageous than CCS, provided that CCS is or becomes more advantageous at early points in time of phase 2.

At first, we assume again that the economy is located below the singular plane, and conducts maximal CCS. If the CCS investments are technically constrained, the fossil fuel utilization and therefore also the singular plane are constant in time. The economy may also accumulate capital so that it is approaching the SiP. Is the CCS constraint given by net production, fossil fuel utilization and the SiP vary with net production in time. I.e. a higher (lower) net production implies more (less) CCS and therefore an increase (decrease) of the SiP in time. However, the vanishing advantageousness of CCS during phase 2 implies that the economy needs to switch from maximal to minimal CCS. As jumps of fossil fuel utilization are ruled out, a discontinuous switch is not possible. Instead, (15) (iv) needs to hold for a limited time interval, which is called the transition period in the

[19] Cf. Kollenbach (2013).

following. The time interval exits, since (23) allows an identical development of $|\theta|$ and λ. Thus, investments can be reallocated from CCS to capital accumulation in a steady way while the economy is indifferent between both investment options. Since lower CCS investments imply a higher scarcity index, the singular plane decreases in time during the transition period.
If the economy is located above the SiP and conducts maximal CCS, there needs to be a similar transition period during which (15) (ix) holds to steadily reallocate investments from CCS to R&D. During this period the development of the scarcity index and therefore of the SiP in time is subject to two opposing effects. On the one hand, R&D implies an increase of the SiP. On the other hand, decreasing CCS investments together with (24) connote a decrease of the SiP. Before the transition period, the development of the SiP depends on the upper CCS bound. If CCS investments are technically bounded, R&D investments are positive and the SiP increases in time. Otherwise, net production is completely used for CCS so that no research is conducted. The SiP decreases (increases) in time, if net production and therefore CCS investments decrease (increase).
The transition period is also of relevance for an economy close to or on the singular plane. In section 3.1 it was shown that the development path cannot reach the SiP or switch to singular R&D, respectively, if the CCS investments are constrained by net production. This also holds for phase 2 provided that the economy has not yet entered the transition period. If this is not the case, CCS investments are lower than net production implying the possibility of capital and R&D investments so that the economy can follow the singular plane. As R&D is conducted while CCS investments are decreasing, the development of the SiP in time is ambiguous.

If the scarcity index reaches its peak during phase 2, it is possible that the economy conducts no CCS at the beginning of the phase but switches to maximal CCS later on. In this case, the development path is similar to the one described in section 3.1. However, there also needs to be an entrance transition period to reallocate net production from either capital accumulation or R&D to CCS.

Generally, our result concerning CCS investments during phase 2 is in line with Chakravorty et al. (2006a) and Lafforgue et al. (2008). However, as they do not consider an upper limit of CCS, their results reflect only what we have called the transition period. Constant CCS investments, which we get if maximal CCS is technically constrained, are not obtained by them. The economic interpretation of positive CCS investments is same as already given in section 3.1 and proposition 1. Thus, CCS investments are maximal, if the gains of CCS outweigh the ones of capital accumulation and R&D. The available net production is split among CCS and capital accumulation and/or R&D, if the gains of CCS and at least one other investments possibility are equal while outweighing the gains of the other investment possibility.

Proposition 3 *Positive CCS investments are possible during phase 2, if the gains of CCS outweigh or at least equal the ones of capital accumulation and R&D. If CCS investments are maximal at some point in time during phase 2, there needs to be a transition period with indifference between the gains of CCS and either capital accumulation or R&D.*

3.3. Optimal Development

Similar to the procedure of Kollenbach (2013) we have to join the analysis of the three phases to describe the development process over the whole planning period $[0, \infty[$. This is done by using the relative scarcity index and taking notice of the smooth transition from one phase to the next. Since an increasing (decreasing) scarcity index implies a decline (rise) of the singular plane in time, we get that the singular plane decreases constantly during phase 1 and switches smoothly into phase 2. The development of the SiP in phase 2 depends on R&D and CCS investments. If neither R&D nor CCS is conducted, the SiP is independent from time. It increases in time, if either R&D is conducted or CCS investments decline. In the case that CCS investments increase and outweigh the effect of possibly positive R&D investments, the SiP decreases. After the smooth transition to phase 3, the SiP decreases in time until the fossil fuel stock is exhausted. The development of the singular plane is visualized by the numbered arrows on the right side of Fig. 3. The arrows are located between the singular plane of $t = 0$ and the one of $t = T_R$, i.e. between SiP(0) and SiP(T_R). The directions of the arrows indicate the possible movements during phase 1,2 and 3, while a dash betokens that the SiP can also be independent of time. Furthermore, Fig. 3 depicts the time independent steady state plane (SSP) and three possible development paths with the capital endowment K^1, K^2 and K^3, respectively. The arrows indicate how the economy develops along a path.

The development of the SiP during phase 1 and 3 is caused by the increasing natural, and in case of phase 1 also additional, scarcity. This result is in line with the one of Kollenbach (2013). As proposition 2 shows, the additional scarcity is ceteris paribus lower, if CCS investments are positive. Furthermore, the possibility of a decreasing SiP, caused

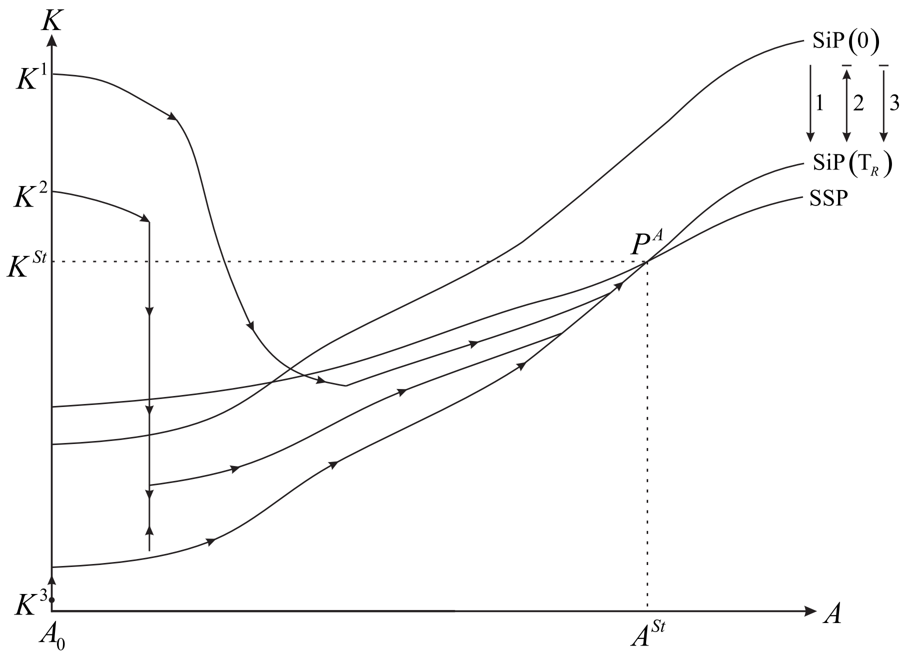

Figure 3: The development path

by diminishing CCS investments, during phase 2 is not obtained by Kollenbach (2013). As a lower (higher) SiP increases (decreases) the advantageousness of R&D, an economy located above the SiP may conduct more (less) maximal R&D, while an economy below the SiP can switch to singular R&D on the SiP at a lower (higher) capital stock level. Thus, the CCS option causes here the first important disparity to the literature. The second disparity is the direct effect of positive CCS on the development path, caused by the reallocation of investments from capital accumulation and/or R&D to CCS. Provided that the upper limit of maximal CCS investments is given by the technological constraint N, the direction of the development path may be the same as without the CCS option. In other words, an economy below (above, on) the singular plane may approach the SiP via capital accumulation (maximal, singular R&D). Examples are given by the development paths, which start at the capital level K^1 and K^3, respectively. The rich economy with the capital endowment K^1 conducts CCS but at a level that allows also R&D investments implying an increasing technology level A. From the point in time the development path reaches the singular plane the economy switches to singular R&D so that the development path does not decrease but increase in the capital stock. The final steady state P^A is characterized by the intersection of the SSP and the singular plane for an exhausted resource stock SiP(T_R). Provided that the energy cost reduction effect of CCS investments on net production and consumption is not too large, the decreasing section of the development

path is stepper than without CCS, as less net production is available for R&D while the capital stock is consumed at a similar rate.
In a poor economy with the capital endowment K^3 R&D is not possible as long as the singular plane is not reached. In the depicted case, no R&D is conducted before the exhaustion of the fossil fuel stock. Provided again a sufficiently small energy cost reduction effect of CCS on net production and consumption, the time period until the economy reaches the singular plane is extended, since net production is partly used for CCS and not for capital accumulation.
An example for an economy whose maximal CCS investments are limited by net production is illustrated by the development path starting with the capital endowment K^2. At the beginning CCS investments are either zero or limited by technology. After the limit is given by net production, the path decreases parallel to the capital axis no matter if the economy is located above or below the SiP, since no net production is available for consumption, capital accumulation or R&D. This implies that the economy cannot follow the SiP. Consequently, the singular plane is irrelevant for the development of the economy. As CCS is not considered by Tsur and Zemel (2005) and Kollenbach (2013), this overruling of the SiP cannot be obtained in their models. In the illustrated case, the capital stock decreases below the singular plane so that the economy approaches the SiP by capital accumulation after maximal CCS is no longer limited by net production or the economy has entered the transition period. After it has reached the SiP, the economy switches to singular R&D to approach the final steady state P^A.[20]

Closely related to the development of the singular plane in time is the development of the relative scarcity index. The index is of special interest, since it translates directly into the fossil fuel price in a Hotelling model with constant marginal extraction costs, as used by Chakravorty et al. (2006a). Fig. 4 illustrates two possibilities which are in line with the economic development paths starting with the capital endowment K^2 and K^1, respectively, referred to as path 2 and path 1 in the following. In phase 1 total scarcity $\frac{\tau-\theta}{\lambda}$ grows constantly as the economy is approaching the ceiling and the resource stock is declining. The latter is illustrated by the increasing natural scarcity $\frac{\tau}{\lambda}$. Total scarcity is affected by both R&D and CCS investments during phase 2. While R&D and increasing

[20]Notice that in all discussed cases the optimality of a steady state is implied by a SiP(T_R) which is located above the SSP for large technology levels. If the SSP is located above the SiP(T_R), the economy would grow forever, provided a sufficiently high capital endowment to avoid the poverty trap.

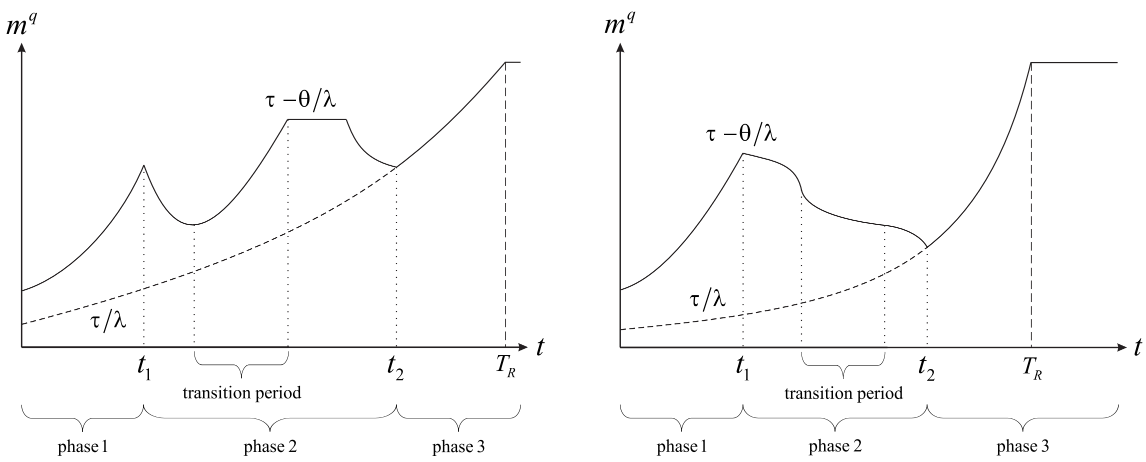

Figure 4: The relative scarcity index

CCS imply a scarcity reduction, decreasing CCS investments cause a boost of scarcity. The total scarcity development depicted on the left hand side of Fig. 4 can then be explained by path 2, provided that the economy exhibits an increasing net production at the beginning of phase 2. We assume that the economy is located at the lower end of the vertical section of path 2 when entering the transition period. Then, no R&D can outweigh the decline of CCS investments, implying a scarcity increase. At the end of the transition period the economy may still be located below the singular plane so that scarcity remains constant. It decreases again with the switch of the economy to singular R&D on the singular plane. In a similar way the total scarcity development on the right hand side of Fig. 4 can be explained by path 1, whereby the decreasing CCS investments during the transition period counter the decreasing effect of R&D on scarcity.

The gap between total and natural scarcity equals the additional scarcity. During phase 1 the gap increases, as the economy approaches the ceiling. At the end of phase 2 the gap vanishes, basically due to the constantly increasing natural scarcity. However, if R&D is conducted or CCS investments increase, the additional scarcity is further reduced, as on the right hand side of Fig. 4. On the other hand, decreasing CCS investments imply an increasing total scarcity so that the gap can even temporary widen, as illustrated on the left hand side of the figure. To understand the effect of the CCS option on total scarcity during phase 2 recall that CCS has the same effect as an exogenous reduction of the emission stock, it extends the amount of fossil fuel that can be used without violating the ceiling. Thus, if CCS investments increase (decrease), the additional scarcity needs to be lower (higher) to adapt fossil fuel utilization to the extended (reduced) usable amount.

Our results show that a rising or diminishing total scarcity at the ceiling can be completely explained by changing CCS investments. While R&D can also explain a decrease of total scarcity, changes of the energy demand, as used by Chakravorty et al. (2006a) for an explanation, does not affect total scarcity, provided that both energy sources are used.[21]

4. Conclusion

By integrating carbon capture and store technology in the endogenous growth model of Tsur and Zemel (2005) and Kollenbach (2013) we have analyzed when investments into the capital stock, R&D or CCS should be used to attain a climate target, like the well known 2°C target. It has turned out that the tighter the climate target and therefore the ceiling on the emission stock the higher is the advantageousness of CCS investments. If the gains of CCS investments outweigh the ones of both capital accumulation and R&D, investments are reallocated towards CCS. This affects the development of the economy in three ways. The two direct effects are given by the investment reallocation. On the one hand, the reallocation decreases the rate of capital accumulation and/or research driven technological progress ceteris paribus. On the other hand, CCS investments allow a higher utilization of fossil fuel, which implies lower energy costs. This counter the first effect, as it boosts net production and therefore it may also increase investments into capital and/or R&D. If net production is sufficiently low and positive CCS optimal, net production is exclusively used for CCS implying a complete drive out of capital stock and R&D investments. In this case, the development mechanism, as described by Tsur and Zemel (2005), is overruled. The third effect of CCS on the economic development is given by its impact on the advantageousness of R&D. As positive CCS investments allow a higher utilization of fossil fuel, it decreases backstop use ceteris paribus and therefore the advantageousness of R&D. If the emission ceiling is binding, it establishes a direct link between R&D advantageousness and changes of CCS investments. Increasing (Decreasing) CSS investments lower (boost) the utilization of the backstop implying a lower (higher) R&D advantageousness.

Furthermore, we have shown that positive CCS investments can be optimal before the ceiling is binding. This result contrast with Chakravorty et al. (2006a) and Lafforgue et al. (2008) but is in line with Coulomb and Henriet (2011) and Amigues et al. (2012).

[21] Cf. Kollenbach (2013).

From a technical point of view, our result is caused by the upper limits we impose on CCS investments. Economically, there are indeed gains form CCS even with a not yet binding ceiling. CCS investments work in a similar way as a reduction of the emission stock. As stated above, they allow a higher utilization of fossil fuel which implies temporary lower energy costs. Consequently, net production is higher without violating the climate target. If the gains from the temporary lower energy costs outweigh the gains from lower backstop costs and a higher capital stock, CCS investments are more advantageous then the other two investments possibilities, no matter if the ceiling is binding or binds at a later point in time.

The comparison between the temporary gains of CCS and the gains of R&D and capital accumulation is also important to rationalize the case where CCS leads the economy in a poverty trap, i.e. to such a low capital stock that the research option cannot be realized. This development is only optimal, if the gains of CCS in terms of higher consumption in the short run outweigh the gains of lower backstop costs and/or a higher capital stock at later points in time. Obviously, such a development path is fostered by a high time preference rate.

The level of CCS investments depends on whether the ceiling is not yet binding, binding or never again binding. In the first case, CCS investments are either zero or maximal, i.e. constrained by technology or available net production. If the ceiling binds, CCS investments can also be singular, i.e. lie between these two extreme cases. In fact, there needs to be a transition period with singular CCS investments, if maximal investments are optimal at least at one point in time. Is the ceiling never binding, there is no need for CCS investments. Notice that it is not optimal to increase CCS investments to levels which prevent an approach of the ceiling.

We use several simplifying assumption whose relaxation may affect our results. While we consider extraction costs that progressively increase in resource use, we have ignored a stock dependence like used by Farzin (1996), Grafton et al. (2012) and Van der Ploeg and Withagen (2012). By introducing non-homogeneous fossil fuels like Chakravorty et al. (2008), it would be possible to study the effect of CCS on the utilization order of energy sources. It seems also promising to extend the model by a second technology to analyze the effect of CCS on the direction of technical change.

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