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Abstract

This paper takes the 'policy failure' in establishing a global carbon price for efficient emissions reduction as a starting point and analyzes to what extent technology policies can be a reasonable second-best approach. From a supply-side perspective, carbon capture and storage (CCS) policies differ substantially from renewable energy policies: they increase fossil resource demand and simultaneously lower emissions. We show in a theoretical model that, under idealized conditions, a pure CCS subsidy can be as efficient as a carbon tax. Within a numerical dynamic general equilibrium model, we analyze CCS and renewable energy policies under more realistic parameter settings for imperfect or missing carbon prices. We find that in contrast to renewable energy policies, CCS policies are not always capable of reducing emissions in the long run. If feasible, CCS policies carry often lower social costs compared to renewable energy policies. In case fossil resources are abundant and renewable energy costs low, renewable energy policies perform better. Our results indicate that a pure CCS policy or a pure renewable energy policy carry specific risks of missing the environmental target. A smart combination of both, however, can be a robust and low-cost temporary second-best policy.

JEL-Code: Q310, Q380, Q400, Q540, Q580.

Keywords: renewable energy subsidy, supply-side dynamics, green paradox, carbon pricing, global warming, CCS.

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1 Introduction

While a global carbon price is the economist's textbook advice for reducing emissions efficiently, governments struggle with the introduction of substantial domestic or even global carbon prices. Until now, states could neither agree upon a global emissions trading scheme, nor on a globally harmonized carbon tax. The reasons are numerous: Besides free-rider incentives, carbon pricing policies re-distribute disposable income, rents and wealth through several channels on a domestic as well as a global scale (Fullerton, 2011). These redistributions can be regressive, e.g. increased energy prices due to cleaner energy provision reduce the disposable income of low-income households more than for high-income households (e.g. Parry, 2004; Parry and Williams III, 2010). Climate policy can also have a progressive effect if scarcity rents associated to fossil resource ownership are reduced and revenues from carbon pricing transferred to low-income households.

In any case, the transformation of income and rents creates a bargaining and rent-seeking process about compensation schemes that impedes the implementation of efficient policies: Internationally, negotiating explicit transfers between countries is a difficult task. Every party insists on an advantageous burden sharing rule and fears to be hoodwinked regarding the sharing of costs and benefits. Domestically, compensation policies for higher energy prices may imply high transaction costs, in particular in developing countries with insufficient public institutions.

Despite the difficulties to establish significant carbon prices, many governments euphorically promote renewable energy by targeted technology policies. There are at least 118 countries with explicit renewable energy targets or policies (REN21, 2011). Global investments into new renewable energy capacities are higher than into fossil energy capacities in the electricity sector (IPCC, 2011, Ch. 11, p. 878). Public support for these measures is high because renewable energy is associated with several local and national benefits, ranging from improved air quality over technological first-mover advantages to greater energy security and higher energy access in remote rural areas (IPCC, 2011, Ch. 11.3). [1]

This paper takes the global policy failure in establishing a carbon price as a starting point. It analyzes the extend to which second-best[2] energy policies can replace carbon pricing policies. We provide an extensive discussion for the specific case of renewable energy policies to reduce emissions if carbon prices are missing in Kalkuhl et al. (2011): Despite the political appeal, a naive up-scaling of renewable energy deployment is very costly and the resulting emissions are highly sensitive to the level of subsidies undermining environmental effectiveness. This study adds technology policies for carbon

[1] This corresponds to the suggestion of Victor (2011) that support for policies is greatest if costs are widely spread or hidden and benefits are concentrated and explicit. By contrast, the benefits of carbon pricing are far more spread out (in fact, across the globe and into the future) and can involve costs that are concentrated on a few sectors and companies that are well-organized.

[2] We use the term second-best as follows: An optimal second-best policy is a policy that maximizes social welfare given that the policy space is constrained.

capture and sequestration (CCS) as well as portfolios of technology policies.

The underlying supply-side argument providing the basis for our analysis of CCS policies was made by Sinn (2008): Policies reducing the demand for fossil resources can – if ill-designed – accelerate resource extraction and, thus, emissions. This issue has been discussed for suboptimal carbon taxes as well as suboptimal renewable energy subsidies (Sinn, 2008; Grafton et al., 2010; Hoel, 2010; Edenhofer and Kalkuhl, 2011; Gerlagh, 2011). In addition to intertemporal re-allocation of carbon extraction, unilateral carbon pricing policies can induce supply-side leakage via reduced (global) fossil resource prices (Eichner and Pethig, 2009). CCS differs from other mitigation options (here: energy efficiency increases, renewable energy use) as it allows using fossil resources with low atmospheric emissions. Hence, promoting CCS could increase fossil resource demand and simultaneously reduce carbon emissions. Therefore, we concentrate on the role of CCS policies and their difference to renewable energy policies in particular regarding the supply-side dynamics of fossil resources.

So far, there has been only little research that focuses on the second-best aspect of CCS policies. A number of theoretical papers address the efficient use of CCS under several geological and economic conditions (Amigues et al., 2010; Coulomb and Henriet, 2010; Le Kama et al., 2011). Several numerical models have estimated the role of CCS for reducing mitigation costs (e.g. Edenhofer et al., 2005; van der Zwaan and Gerlagh, 2009; Edenhofer et al., 2010). However, only few papers provide an explicit analysis of policy instruments. Fischer and Salant (2010) find within a Hotelling model framework that mal-adjusted carbon taxes, renewable energy subsidies or energy efficiency improvements can be ineffective or even accelerate extraction and emissions. An obligatory mandate to capture and sequester a certain share of emissions, however, does always reduce emissions and is, thus, the most robust policy. Hoel and Jensen (2010) show in a two-period Hotelling model that reducing the long-term costs for renewable energy can lead to higher emissions while reducing the long-term costs for CCS always reduces emissions.

We start our analysis with a reduced formal analytical model to elaborate the basic dynamic of CCS policies for reducing carbon emissions (Sec. 2). We then extend the intertemporal general equilibrium model PRIDE (Kalkuhl et al., 2012) by a CCS technology to study the performance of CCS policies in a second-best setting where carbon prices are restricted. To integrate the supply-side dynamics of fossil resource extraction, a general equilibrium model on a global scale is necessary. Although there is no real-world government at a global scale that could implement carbon pricing or technology policies, our model results give an important (least-cost) estimation about the performance of several policies instruments. The model presented in Sec. 3 takes a similar approach as the DEMETER model (Gerlagh et al., 2004; Gerlagh and van der Zwaan, 2004) or the top-down energy-economic model developed by Grimaud et al. (2011). As DEMETER does not contain an intertemporal fossil resource sector, it cannot capture the supply-side dynamics of fossil fuels. Within a second-best policy analysis in DEMETER, Gerlagh and van der Zwaan (2006) explore the role of renewable energy subsidies and a portfolio standard for CCS for climate change mitigation when innovation spillovers exist. In contrast to DEMETER, the model of Grimaud et al. (2011) contains an intertemporally optimizing fossil resource sector. While Grimaud et al. (2011) focus on carbon pricing and R&D subsidies, no policy analysis is conducted with respect to explicit technology deployment policies under carbon-pricing constraints.

In our general equilibrium model, we consider several second-best settings with respect to the carbon price (Section 4). In Section 4.1, the implemented carbon price is lower than the carbon price necessary to achieve a certain mitigation target and governments can use low-carbon technology policies to reduce emissions further. This corresponds to a world where governments want to reduce emissions but are reluctant to introduce the efficient carbon prices. Instead, they aim to reduce emissions by promoting low-carbon technologies in form of renewable energy or CCS. Section 4.2 assumes that the international community is not able to establish a global carbon price very soon. Instead, governments and firms expect that a carbon price will eventually be introduced in the future and use technology policies for bridging the gap.

We then perform a sensitivity analysis with respect to crucial parameters (Section 5.1) and deviations from optimal second-best policies (Section 5.2). The latter suggests how sensitively carbon emissions respond to suboptimally chosen policies. Finally, we sum up our main findings and conclude with some further considerations on the design of technology policies for mitigation (Section 6).

Our main findings are as follows: In our analytical model, we identify conditions when a pure CCS policy can be an *efficient* policy if carbon prices are missing or too low. The basic intuition behind this finding is that CCS subsidies increase the demand for fossil resources which in turn leads to higher resource prices (scarcity rent markup). If fossil resources are relatively scarce, this scarcity rent markup can be increased to the same level as the carbon price – an efficient outcome is then achieved. This result, however, depends on the restrictive assumptions that leakage is zero, all emissions can be captured and fossil resources are scarce relative to underground storage.

In the numerical model, we consider more realistic geological assumptions about CCS. We find that CCS policies can achieve a mitigation target in many cases at lower costs than renewable energy policies, in particular, when fossil resources are scarce. By increasing the fossil resource prices, renewable energy deployment is also accelerated. However, CCS policies are only feasible under favorable geological conditions, while renewable energy subsidies are always capable to achieve the mitigation target but costs may be large. When reducing the time span during which carbon prices are missing, CCS policies become more likely to be a feasible second-best policy and costs decrease further. Hence, CCS policies can be an attractive short-term option to buy time until optimal carbon prices have been established. As the delay of carbon pricing stretches out, renewable energy subsidies become more and more important as long-term second-best policy. A smart combination of CCS and renewable energy policies can therefore simultaneously reduce mitigation costs and the risk of exceeding the mitigation target.

2 Analytical model: The fundamental dynamics of CCS policies

This part of the paper focuses on a partial equilibrium model that highlights the fundamental dynamics of CCS policies within a cost-effectiveness analysis. The model extends a standard Hotelling (1931) model by a constraint on cumulative fossil resource extraction to represent government policy, and by an option to capture emissions and store them underground. This basic model provides some important insights for our subsequent analysis within a numerical general equilibrium model.

2.1 The social planner economy

In the social planner economy, fossil resources R are used to generate output $f(R)$.[3] The fossil resources can be used in conventional plants to generate energy but also emissions which are released into the atmosphere. We denote these resources as R_N. Alternatively, fossil resources R_C can be converted to energy in CCS plants, whereby a share $\theta \leq 1$ of carbon is captured and only the corresponding share $1-\theta$ is released into the atmosphere.[4] As capturing requires additional energy, we introduce an energy penalty parameter $\tilde{\alpha} \leq 1$. This parameter indicates how much additional fossil resources is used to generate the same amount of energy as with the conventional technology, i.e. $R_N = R_C/(1+\tilde{\alpha})$. Since the evolving temperature increase can be approximated by the amount of cumulative emissions (Meinshausen et al., 2009), we simply consider the mitigation target as cumulative constraint on emissions. We also denote this constraint B_0 the carbon budget.

The initial fossil resource stock S_0 under ground limits cumulative total extraction by $\int_0^\infty R\ dt \leq S_0$. Storage capacity X for captured carbon is assumed to be finite and decreases with the captured carbon. However, stored carbon may also leak out of the storage into the atmosphere at the rate $\delta_X \geq 0$. The remaining carbon budget B decreases by non-captured resources R_N and $(1-\theta)R_C$ as well as leaked carbon $\delta_X(X_0 - X)$. Unit extraction costs $g(S)$ depend on the remaining stock size S, and capture and storage costs $h(X)$ depend on the remaining storage capacity X. Hence, we define the social planner's problem of finding a cost-effective extraction and capture path as:

$$\max_{R_N,R_C} \int_0^\infty \left[f(R_N + \alpha R_C) - g(S)R - \theta h(X)R_C\right] e^{-rt}\ dt$$

[3] To improve the readibility of this article, we will usually omit the time indicies for most variables.

[4] The capture rate depends on the chosen capture method (post-combustion, pre-combustion, oxy-fuel combustion) and separation technology (i.e. physical or chemical solvents) (IPCC, 2005, Ch. 3).

subject to:

$$\dot{S} = -R = -(R_C + R_N) \tag{1}$$

$$\dot{B} = -(R_N + (1-\theta)R_C + \delta_X(X_0 - X)) \tag{2}$$

$$\dot{X} = -\theta R_C + \delta_X(X_0 - X) \tag{3}$$

where $R_C, R_N, B, S, X \geq 0$, $\alpha := 1/(1+\tilde{\alpha})$ and r is the discount rate. The corresponding Hamiltonian is $H = f(R_N + \alpha R_C) - g(S)R - \theta h(X)R_C - \lambda R - \mu(R_N + (1-\theta)R_C + \delta_X(X_0 - X)) - \psi(\theta R_C - \delta_X(X_0 - X))$ where λ, μ and ψ are the shadow variables associated with the fossil resource base S, the atmospheric carbon budget B and the underground storage for carbon dioxide X, respectively. With $f'(\cdot)$ denoting the first derivative (i.e. $f'(R) := \partial f(R)/\partial R$), the first-order conditions including the equations of motion and terminal conditions are:

$$\alpha f'(R_N + \alpha R_C) - g(S) - \theta h(X) - \lambda - (1-\theta)\mu - \theta\psi \leq 0 \qquad (= 0 \text{ if } R_C > 0) \tag{4}$$

$$f'(R) - g(S) - \lambda - \mu \leq 0 \qquad (= 0 \text{ if } R_N > 0) \tag{5}$$

$$\dot{\lambda} = r\lambda + g'(S)R \tag{6}$$

$$\dot{\mu} = r\mu \tag{7}$$

$$\dot{\psi} = r\psi + \theta h'(X)R_C - \delta_X(\mu - \psi) \tag{8}$$

$$0 = \lim_{t\to\infty} S(t)\lambda(t)e^{-rt} \tag{9}$$

$$0 = \lim_{t\to\infty} B(t)\mu(t)e^{-rt} \tag{10}$$

$$0 = \lim_{t\to\infty} X(t)\psi(t)e^{-rt} \tag{11}$$

The system of (differential) equations (4–11) implicitly describes the optimal solution in the social planner economy. This solution serves as benchmark for the decentralized market equilibrium that is discussed subsequently.

2.2 The decentralized economy

The resource sector maximizes discounted profit for given resource prices p and increasing extraction and capturing costs similar to the social planner above. Additionally, the resource sector has to consider an emission tax τ on non-captured and leaked carbon as well as a subsidy σ for captured carbon. As the atmospheric carbon deposit is an open-access resource, the resource sector does not take the carbon budget B into account. The optimization problem reads:

$$\max_{R_N, R_C} \int_0^{\infty} [p(R_N + \alpha R_C) - g(S)R - \theta h(X)R_C - \tau(R_N + (1-\theta)R_C + \delta_X(X_0 - X)) + \sigma R_C]e^{-rt}\, dt$$

subject to:

$$\dot{S} = -R = -(R_C + R_N) \tag{12}$$

$$\dot{X} = -\theta R_C + \delta_X (X_0 - X) \tag{13}$$

where $R_C, R_N, S, X \geq 0$. Eqs. (12–13) are the same as in the social planner problem (1–3), except for the missing equation for the carbon budget. The corresponding Hamiltonian is $H = p(R_N + \alpha R_C) - g(S)R - \theta h(X)R_C - \lambda R - \tau(R_N + (1-\theta)R_C + \delta_X(X_0 - X)) + \sigma R_C - \psi(\theta R_C - \delta_X(X_0 - X))$ The first-order conditions describing the market equilibrium are:

$$\alpha p - g(S) - \theta h(X) - \lambda - (1-\theta)\tau + \sigma - \psi \leq 0 \qquad (= 0 \text{ if } R_C > 0) \tag{14}$$

$$p - g(S) - \lambda - \tau \leq 0 \qquad (= 0 \text{ if } R_N > 0) \tag{15}$$

$$\dot{\lambda} = r\lambda + g'(S)R \tag{16}$$

$$\dot{\psi} = r\psi + \theta h'(X)R_C - \delta_X(\tau - \psi) \tag{17}$$

$$0 = \lim_{t\to\infty} S(t)\lambda(t)e^{-rt} \tag{18}$$

$$0 = \lim_{t\to\infty} X(t)\psi(t)e^{-rt} \tag{19}$$

2.3 Efficient policies

By comparing the first-order conditions of the social planner problem and the decentralized economy, we can identify cost-efficient policies. As intuition suggests, a carbon tax τ on emissions which equals the shadow price of the carbon budget μ in the social planner economy will reduce emissions at lowest costs and reproduce the socially optimal outcome:

Proposition 1. *Let $\mu^*(t) = \mu_0^* e^{rt}$ denote the shadow price of the carbon budget from the optimal social planner solution given by (4–11). If the regulator implements carbon tax τ with $\tau(t) = \mu^*(t)$, an optimal allocation is achieved.*

Proof. Simply set $\tau = \mu^*$ in Eqs. (14–17). The first-order and terminal conditions in the market model (for $\sigma = 0$) equal the corresponding conditions in the social planner model. □

As argued in the Introduction, carbon prices are difficult to implement in reality. Under specific conditions, however, it is possible to achieve efficient carbon reduction without any carbon pricing by merely subsidizing CCS:

Proposition 2. *Assume that the following conditions hold: (i) In the social planner model, the optimal solution yields $\lim_{t\to\infty} S(t) = 0$, i.e. all fossil resources are used under the carbon budget, (ii) the carbon budget is a binding constraint (i.e. $\mu_0^* > 0$), (iii) leakage is zero ($\delta_x = 0$) and (iv) the capture rate is 100 percent ($\theta = 1$). Then, a* *combined tax-subsidy policy with $\tau = \beta\mu^*$ and $\sigma = (1-\beta)\mu^*$ for any $\beta \in \mathbb{R}$ reproduces the (optimal) social planner outcome (with $\mu^* = \mu_0^* e^{rt}$ equal to Proposition 1 the shadow price of the carbon budget from the social planner model).*

Proof. See Appendix A. □

Proposition 2 says that if fossil resources are scarce under a carbon budget, if there is no leakage and if there is perfect capture, a carbon price instrument – which reflects the scarcity of the atmospheric budget – can be replaced by CCS subsidies (set $\beta = 0$) or any combination of carbon taxes and CCS subsidies without sacrificing efficiency. As the subsidies on CCS increase the demand for fossil resources, they increase the associated scarcity rent λ. With an appropriate choice of the subsidy the resulting scarcity rent $\tilde{\lambda}$ can be equalised with the sum of the socially optimal shadow price for resources, λ^*, and the carbon price μ^* (see the proof in Appendix A for details). In other words, the CCS subsidies create an implicit carbon price through the scarcity price of fossil resources which reduces resource demand to the socially optimal level.

In case of leakage or an imperfect capture rate the subsidy policy cannot be efficient as an additional carbon tax (for the emitted carbon) would be necessary. When the fossil resource base is so large that it is not exhausted in infinite time, the shadow price λ cannot be increased sufficiently to achieve an optimal extraction and capture path. In particular, for an undersized underground storage,[5] cumulative extraction has also to be lowered and $\lim_{t\to\infty} S(t) > 0$. In that case, CCS subsidies cannot replace a carbon tax.

Proposition 2 shows that infinitely many efficient tax-subsidy combinations are possible. Note that the CCS subsidy σ always increases exponentially in time at the discount rate r. Although these policies do not affect extraction and prices, it is easy to see that they influence discounted profits in the resource sector:

Corollary 1. *Under the assumptions of Proposition 2, the net present value of the resource rent is:*

$$\Pi = \int_0^\infty \Psi e^{-rt}\, dt + \mu_0^*(S_0 - B_0) - \beta\mu_0^* S_0 \tag{20}$$

with $\Psi := p(R_N + \alpha R_C) - g(S)R - \theta h(X)R_C$ and μ_0^* the initial shadow price of the carbon budget from the social planner model.

Proof. Setting $\theta = 1$ and $\delta_X = 0$ and substituting $\tau = \beta\mu_0^* e^{rt}$ and $\sigma = (1-\beta)\mu_0^* e^{rt}$ into the discounted profit (objective) function, we obtain $\int_0^\infty [\Psi e^{-rt} - \beta\mu_0^* R_N + (1-\beta)\mu_0^* R_C]\, dt$. Using $\lim_{t\to\infty} S(t) = 0$ together with (1–2), we obtain $\int_0^\infty R_C\, dt = S_0 - \int_0^\infty R_N\, dt = S_0 - (B_0 - \lim_{t\to\infty} B(t))$. As the carbon budget is binding and $\mu_0^* > 0$, it follows from (10) that $\lim_{t\to\infty} B(t) = 0$ which leads to (20). □

[5] This is the case if $X_0 < S_0 - B_0$ which follows directly from (1–3) if $\theta = 1$ and $\delta_X = 0$.

Therefore, without influencing efficiency, the rent of resource owners is affected by the policy choice β, i.e. to what extend carbon taxes and CCS subsidies are used. The lower β, the higher are the profits in the resource and sequestration sectors. In particular, a pure carbon tax policy ($\beta = 1$) gives lower discounted profits than a pure CCS subsidy policy ($\beta = 0$). Resource owners can thus receive an arbitrarily high non-distortionary lump-sum transfer.

The analysis above indicates that CCS subsidies can – under restrictive assumptions – be a first-best alternative to carbon pricing. However, such a CCS policy does only work if there is no leakage and storage capacities are high relative to the fossil resource base. Leakage or scarce storage capacities inhibit the existence of an efficient CCS policy. In order to study the performance of CCS subsidies for less restrictive conditions, we use in the following a numerical general equilibrium model. We focus on the question whether well-designed CCS subsidies can reduce emissions at low efficiency costs if carbon taxes are not available or imperfect.

3 Numerical model: Analysis in PRIDE

The model PRIDE (Policy and Regulatory Instruments in a Decentralized Economy) is an intertemporal general equilibrium model with a generic top-down representation of different energy technologies. Its formulation as non-linear program and its implementation in GAMS (General Algebra Modeling System, Brooke et al., 2005) allows calculating welfare maximizing policies subject to environmental constraints (i.e. a mitigation target) or political constraints (i.e. restriction on carbon prices).

For the following numerical analysis we extend the PRIDE model described in Kalkuhl et al. (2012) by an additional fossil energy sector that sequesters emissions from fossil fuel combustion, and a storage sector that transports and stores carbon underground. In contrast to the analytical model of the previous section, PRIDE allows to consider general equilibrium effects on the energy market and imperfect substitutability between different energy technologies. We model the government as Stackelberg leader that anticipates the reaction of the market economy on its policies. With this top-level optimization of the government, the welfare-maximizing potential of a variety of policy instruments ranging from carbon taxes to subsidies for renewable energy and CCS are studied. In particular, we will focus on cases where the conditions of Proposition 2 are violated due to leakage, imperfect carbon capture, imperfect substitutability between energy technologies, or due to an abundance of fossil resources.

3.1 The technological structure of PRIDE

The basic model equations are presented in Kalkuhl et al. (2012); here, we restrict the explanation to a general description of the economic sectors and focus in more detail on the sectors affected by CCS. If not stated otherwise, the first-order conditions can be found in Kalkuhl et al. (2012).

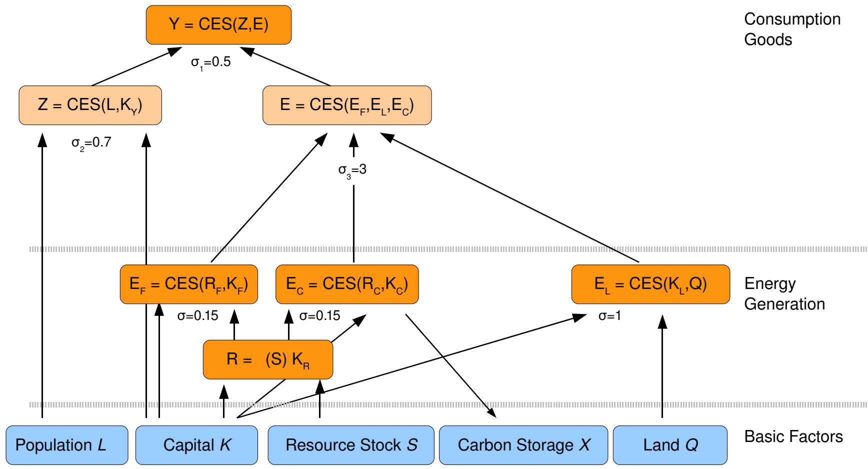

Figure 1: Production technology.

Final output sector

Fig. 1 gives an overview of the technological structure of the economy. Economic output Y is generated by energy E and a composite Z of capital K_Y and labor L. Energy is composed of conventional fossil energy E_F causing carbon emissions, carbon-neutral renewable energy E_L, which exhibits learning-by-doing effects, and a CCS fossil energy technology E_C which sequesters carbon emissions. The constant-elasticity-to-scale (CES) production technology is described by:

$$Y(Z,E) = \left(a_1 Z^{\frac{\sigma_1-1}{\sigma_1}} + (1-a_1)E^{\frac{\sigma_1-1}{\sigma_1}}\right)^{\frac{\sigma_1}{\sigma_1-1}} \quad (21)$$

$$Z(K_Y,L) = \left(a_2 K_Y^{\frac{\sigma_2-1}{\sigma_2}} + (1-a_2)(A_Y L)^{\frac{\sigma_2-1}{\sigma_2}}\right)^{\frac{\sigma_2}{\sigma_2-1}} \quad (22)$$

$$E(E_F,E_L,E_C) = \left(a_3 E_F^{\frac{\sigma_3-1}{\sigma_3}} + b_3 E_L^{\frac{\sigma_3-1}{\sigma_3}} + c_3 E_C^{\frac{\sigma_3-1}{\sigma_3}}\right)^{\frac{\sigma_3}{\sigma_3-1}} \quad (23)$$

where σ are the respective elasticities of substitution, a_1,a_2,a_3,b_3,c_3 are share parameters and A_Y is an exogenously growing labor productivity factor. Population L grows exogenously. Due to the high aggregation level, we do not distinguish between different technologies within one of the three generic energy types. We also abstract from different uses of energy ranging from electricity generation, transportation, heating/cooling or industry processes. However, integrating the different energy technologies within one CES nest allows to study a wide range of substitution possibilities that captures to some extend the different properties in energy generation and usage (see Kalkuhl et al. (2012) for a discussion on substitutability between energy technologies).

Firms in the production sector sell output, pay wages w for labor input, interest rates r for capital input and energy prices p_F, p_C, p_L for conventional fossil, CCS fossil and renewable energy, respectively. Additionally, subsidies for renewable energy τ_L and CCS fossil τ_C energy can be imposed by the government. By deriving the profit function $\pi_Y = Y(K_Y, L, E_F, E_L, E_C) - rK_Y - p_F E_F - (p_L - \tau_L)E_L - (p_C - \tau_C)E_C$ with respect to the inputs, we obtain the usual first-order conditions.

Conventional fossil energy sector

The conventional fossil energy sector uses capital K_F and fossil resources R_F for energy generation according to:

$$E_F(K_F, R_F) = \left(a_F K_F^{\frac{\sigma-1}{\sigma}} + (1-a_F) R_F^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{24}$$

Firms sell energy at the price p_F, rent capital at the interest rate r and purchase fossil resources at the price p_R. Additionally, the government may levy a carbon tax τ_R for fossil resources R_F that directly translate into carbon emissions. The profit function reads $\pi_F = p_F E_F(K_F, R) - rK_F - (p_R + \tau_R)R_F$.

CCS fossil energy sector

The basic fossil energy production technology (24) remains unchanged when capturing of carbon emissions for sequestration is added. However, due to the energy panelty and the need to install additional equipment (capital costs), productivity $A_C \leq 1$ is lowered and the relative factor inputs may change due to a_C:

$$E_C(K_C, R_C) = A_C \left(a_C K_C^{\frac{\sigma-1}{\sigma}} + (1-a_C) R_C^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{25}$$

In contrast to the conventional fossil energy sector, the CCS energy sector has to pay the transportation and storage price p_X per unit of captured carbon R_X. We assume that a fixed share $\theta \leq 1$ of carbon emissions is captured, i.e. $R_X = \theta R_C$. Thus, a carbon tax on non-captured emissions $(1-\theta)R_C$ applies. With the corresponding profit function $\pi_C = p_C E_C(K_C, R_C) - rK_C - p_R R_C - p_X \theta R_C - \tau_{R,t}(1-\theta)R_C$ the usual static first-order conditions result.

Fossil resource sector

Fossil resources $R = R_F + R_C$ that are used in both fossil energy sectors are extracted from a finite resource stock S with capital input K_R according to $R(S, K_R) = \kappa(S)K_R$. With ongoing depletion of S, more capital is needed to extract one unit of resources. We use a typical extraction cost curve (Rogner, 1997; Nordhaus and Boyer, 2000; Edenhofer et al., 2005) to describe the decrease of capital productivity $\kappa(S)$, implying increasing extraction costs $\kappa(S) = \chi_1 / \left(\chi_1 + \chi_2 \left(\frac{S_0 - S}{S_0}\right)^{\chi_3}\right)$. The profit function in the extraction sector reads $\pi_R = p_R R(S, K_R) - rK_R$ where additionally the depletion dynamics $S_{t+1} = S_t - R_t$ have to be considered.

Sequestration sector

The sequestration sector transports captured carbon R_X from the plant and stores it underground in storage X. As storage is limited, storage becomes essentially an exhaustible resource. Leakage R_L at the rate $\delta_X \geq 0$, however, increases the storage capacity and is taxed with the carbon price τ_R.[6] Similar to the fossil resource sector, storage costs $h(X)$ depend on the size of the remaining storage and decrease in X: Usually easily accessible storage sites are used first while sites with difficult access and monitoring or a long-distant location from the plant are used later. With the instantaneous profit function $\pi_X = (p_X - h(X))R_X - \tau_R R_L$, the intertemporal optimization problem reads:

$$\max_{R_{X,t}} \sum_{t=0}^{T} \pi_{X,t} \Pi_{s=0}^{t} \left[1 + (r_s - \delta)\right]^{-1}$$

subject to:

$$X_{t+1} = X_t - (R_{X,t} - R_{L,t}), \qquad X_t \geq 0, \qquad X_0 \text{ given} \tag{26}$$

$$R_{L,t} = \delta_X (X_0 - X_t) \tag{27}$$

$$h(X_t) = c_1 + c_2 \left(\frac{X_0 - X_t}{X_0} \right)^{c_3} \tag{28}$$

where X_0 is the (initial) size of the storage and δ denotes the capital depreciation rate which is subtracted from the marginal rate of capital productivity r to obtain the net discount rate. The first-order conditions are stated in Appendix B.

Renewable energy sector

Renewable energy is generated from capital K_L and land Q; its generation costs decrease in cumulative output H. This learning-by-doing effect is modeled as a productivity increase $A_L(H)$, which is perfectly anticipated by the market economy (e.g. as if innovation spillovers were already internalized through a technology policy). In Kalkuhl et al. (2012), we analyze how spillovers or risk-premiums can lead to costly lock-ins into intertemporally inefficient low-carbon technologies. In order to concentrate on the efficiency cost of second-best policies for imperfect carbon pricing, we abstract from these additional market failures in the renewable energy sector.

By selling renewable energy at price p_L and renting capital at the interest rate r, the instantaneous profit function reads $\pi_L = p_L E_L(A_L(H), K_L, Q) - rK_L$. The production technology is Cobb-Douglas $E_L(A_L, K_L, Q) = A_L K_L^{\nu} Q^{\nu-1}$ with $A_L = \frac{A_{L,max}}{1+\left(\frac{\Omega}{H}\right)^{\gamma}}$ and $H_{t+1} = H_t + (E_{L,t} - E_{L,t-1})$. $A_{L,max}$ and Ω are scaling factors, γ is the learning exponent.

[6] We consider the simplifying case of exponential leakage. A possible alternative is found in van der Zwaan and Gerlagh (2009), who develop a two-layer leakage model where leakage rates are non-constant.

Household sector

The representative household maximizes intertemporal utilitarian social welfare $\sum_{t=0}^{T}(1+\rho)^{-t}L_t U(C_t/L_t)$ with the discount rate ρ and the CES-utility function in per-capita consumption $U(C/L) = (C/L)^{1-\eta}/(1-\eta)$. The household receives wages, capital income, the firms' profits $\pi = \sum_j \pi_j$ and (positive or negative) lump-sum government transfers Γ. It invests I in the aggregate capital stock $K = \sum K_j$. Thus, consumption is $C = wL + rK + \pi + \Gamma - I$ and the capital stock evolves at $K_{t+1} = (1-\delta)K_t + I_t$ with δ the depreciation rate. The government balances tax incomes and subsidy expenditures with the household's lump-sum tax according to $\Gamma = \tau_R(R_F + (1-\theta)R_C + R_L) - \tau_L E_L - \tau_C E_C$.

3.2 Atmospheric carbon emissions and the carbon budget

Emissions occur at several points in the economy: Conventional fossil energy firms emit R_F; in the CCS fossil energy sector, the non-captured share of fossil resources $(1-\theta)R_C$ is released into the atmosphere; and finally, carbon R_L leaks from the CCS storage. Total emissions amount to $Em = R_F + (1-\theta)R_C + R_L$. The government's mitigation target is formulated as cumulative constraint on emissions with $B_{t+1} = B_t - Em_t$ where $B_t \geq 0$ and $B(0) = B_0$ is the size of the carbon budget.

3.3 Implementation and policy assessment

We consider three types of equilibria: (i) the *social planner optimum* is obtained by maximizing the households utility subject to the technological constraints; (ii) the *laissez-faire market equilibrium* is defined as the solution of the system of equations describing technology, profits, budgets and the first-order conditions where all policies are set to zero (i.e. $\tau_R = \tau_L = \tau_C = 0$); (iii) the *optimal policy market equilibrium* is calculated from (ii) by additionally maximizing the household's utility over the policy variables (τ_R, τ_L, τ_C).[7]

Without a mitigation target (i.e. if $B_0 \geq S_0$) the laissez-faire economy equals the social optimum because there are no further market failures in the economy. Since no emissions are reduced, we also denote this case as the *business-as-usual* (BAU) scenario. When the mitigation target is considered and the government has all policy instruments available, the optimal policy market equilibrium equals the social optimum.[8]

We will focus on optimal second-best policies for fossil-CCS and renewable energy when the carbon tax variable τ_R is constrained. τ_L and τ_C are calculated to achieve the carbon budget at least costs. We evaluate the policies with respect to the laissez-faire (BAU) economy (without mitigation) and the social planner optimum under a

[7] This is done in GAMS (Brooke et al., 2005) as a non-linear program (NLP) using the CONOPT solver with the intertemporal first-order conditions as additional constraints.

[8] In this paper, there are no additional market failures beyond the mitigation target. Therefore, it is in line with Proposition 1 sufficient for the government to appropriately choose τ_R. No additional technology policies are needed.

mitigation target. Policies are evaluated according to their welfare change measured in balanced-growth equivalences (BGE) (Mirrlees and Stern, 1972).

3.4 Calibration of the model

The parameters for the economy without CCS equal those in Kalkuhl et al. (2012). We employ a moderate mitigation target by limiting cumulative emissions to 450 GtC. This corresponds roughly to a 50% probability of achieving the two-degree target. For the CCS technology added in this study, we reproduce typical estimations of costs and factor inputs available for CCS.

IPCC (2005, Tab. TS.3) estimates 11–40% more energy use to generate electricity under the CCS technology. If we set the share and productivity parameter to $a_C = 0.95$ and $A_C = 0.65$, we obtain a 20% higher fossil resource input for one unit of energy than for non-captured fossil energy ("energy penalty") and costs for fossil energy with carbon capture increase by roughly 2 ct/kWh. This lies in the range of the IPCC (2005, Tab. TS.3) estimation of 1.2–3.4 ct/kWh cost increase. We set $\theta = 0.9$ in our basic parameterization in line with the current ability of technologies to capture 85–95% of the emissions (IEA, 2010, Tab. 10.2).

There is high uncertainty regarding the costs of carbon storage and transportation. In IPCC (2005, p. 260), costs for storage in depleted oil and gas fields as well as in saline formations range between 1 and 111 \$/tC. IEA (2010, p. 184) estimates transportation costs of 7–22 \$/tC per 100 km pipeline, IPCC (2005, p. 42) only 1–12 \$/tC per 100 km pipeline or shipping. We parameterize the CCS cost curve (Eq. 28) such that initial transportation and storage costs are 50 \$/tC; they increase to 65 \$/tC in 2100 when 710 GtC are stored in the social planner optimum. IPCC (2005, p. 197) estimates the size of geological storage in oil and gas fields between 184 GtC and 245 GtC, in unminable coal seems between 1 and 55 GtC, and in deep saline formations between 273 and 2,730 GtC.[9] In our basic parameterization, we chose a very large storage capacity of 3,500 GtC in order to avoid a hard constraint for CCS. Costs increase sharply if X approaches zero and in most of our model runs stored carbon does not exceed 1,500 GtC in 2100. Within geological formations IPCC (2005) finds it very likely that $\geq 99\%$ of stored carbon remains underground within 100 years (i.e. $\delta_X \leq 10^{-4}$) and likely that $\geq 99\%$ remains underground within 1,000 years (i.e. $\delta_X \leq 10^{-5}$). We assume a leakage rate of 0.01%. In the sensitivity analysis we vary this value as well as the storage capacity and the capture rate.

[9] Besides geological storage, there is also the possibility to store carbon in the oceans or in solid carbonates after accelerated mineral carbonation. The storage capacity of the oceans is practically unlimited. However, there are high uncertainties about the impacts for marine ecosystems and the permanency of storage. Mineral carbonation offers also a practically infinity large sink. However, both costs and land consumption from mining and disposal are high (IPCC, 2005, Ch. 6–7).

4 CCS policies if carbon pricing is imperfect

In the following we analyze the performance of second-best technology policies for CCS and renewable energy if carbon prices are imperfect. The basic idea of using second-best technology policies is to increase the relative price of emission-intensive technologies compared to low-carbon technologies. While carbon pricing provides a direct measure for this objective, subsidizing low-carbon technologies has an indirect effect on the relative price between low-carbon and carbon-intensive technologies: if energy from low-carbon technology becomes sufficiently cheap through subsidies, energy consumers will switch to the latter and, hence, cause less emissions.

In the first subsection, we consider the case when carbon prices are too low to achieve the mitigation target. This is motivated by the observation that international or domestic compensation for the distributional effects of high carbon taxes is difficult to implement. The international community therefore may only agree on suboptimally low harmonized carbon taxes and a financing mechanism for additional technology policies. In the second subsection, we assume that the introduction of carbon prices is delayed substantially because no agreement can be achieved in the near future. Once scientific knowledge or social perception about climate damages may change, first impacts of global warming become visible or global coordination between nation states has been improved, the optimal tax can be implemented in the future. We therefore analyze how far technology policies can substitute temporarily missing carbon prices. Although our main focus lies on CCS subsidies, we will also discuss their performance relative to renewable energy subsidies being a popular second-best policy option (Kalkuhl et al., 2011).

4.1 Second-best policies for suboptimally low carbon prices

In our first analysis, we calculate optimal second-best policies if carbon taxes τ_R are set to a fixed fraction $0 \leq \vartheta < 1$ of the socially optimal carbon tax τ_R^*. This tax is obtained from the shadow price of the social planner optimum or directly from the optimal policy market equilibrium when τ_R is unconstrained. The optimal carbon tax τ_R^* limits cumulative emissions efficiently to the carbon budget constraint. Subsidies on CCS or renewable energy are not needed in this case. However, if a suboptimal tax $\tau_R = \vartheta\tau_R^*$ is implemented, the carbon budget is violated – unless further instruments are used to reduce emissions. For this case, we consider three second-best policies:

`CCS` a pure CCS technology policy τ_C that limits emissions by subsidizing CCS; renewable energy subsidies τ_L are set to zero. Thus, the policy space is constrained to $\{\tau_R = \vartheta\tau_R^*, \tau_L = 0, \tau_C \in \mathbb{R}\}$

`REN` a pure renewable energy policy that limits emissions by subsidizing renewable energy; CCS subsidies are zero and the policy space is $\{\tau_R = \vartheta\tau_R^*, \tau_L \in \mathbb{R}, \tau_C = 0\}$

`CCS+REN` a hybrid CCS and renewable energy policy that limits emissions by subsidizing CCS and renewable energy, i.e. $\{\tau_R = \vartheta\tau_R^*, \tau_L \in \mathbb{R}, \tau_C \in \mathbb{R}\}$

The optimal time paths of the policies are calculated for several values of ϑ and evaluated with respect to their welfare losses compared to the optimal carbon pricing policy ($\vartheta = 1$) and the business-as-usual (no mitigation) case.

The effect of technology policies on welfare and emissions Fig. 2a shows the performance of the second best policies compared to the optimal carbon pricing policy. Where data points are missing, no feasible solution was found.[10] The lower ϑ, the higher are the welfare losses of the technology policies because it becomes more and more difficult to reduce emissions at low carbon prices. In particular, for $\vartheta < 0.5$ costs become substantial. If the carbon price is lower than 20% of the optimal carbon price, the pure CCS policy is even infeasible, due to the imperfect capture rate $\theta = 0.9$. While the 'pure' policies begin to become prohibitively expensive or infeasible for carbon prices below 20% of the optimal level, a hybrid technology policy achieves the mitigation target at an additional welfare costs of only 3% even if carbon prices are missing.

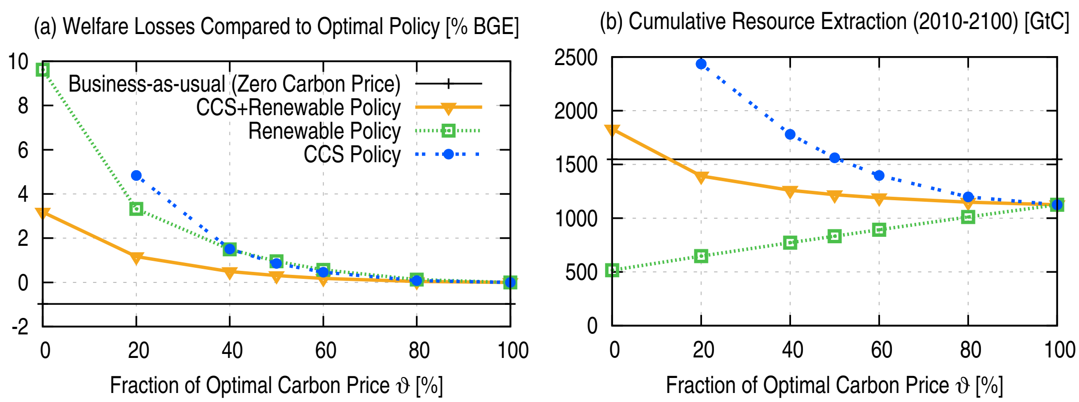

Figure 2: (a) Welfare losses (in balanced-growth equivalents) of optimal second-best policies compared to the social optimum ($\vartheta = 100\%$) under a carbon budget. The negative welfare losses of the laissez-faire (business-as-usual) economy indicate the mitigation costs due to the carbon budget constraint. (b) Impact on cumulative fossil resource extraction within the time span 2010–2100.

Although a pure CCS policy and a pure renewable energy policy provoke similar welfare losses for $\vartheta \geq 0.4$, they lead to completely different fossil resource extraction (Fig. 2b): The renewable energy policy increases the relative price of all fossil-resource based technologies compared to the price of renewable energy technologies and therefore

[10] In principle, this may just be a failure of the numerical solver and a solution (although difficult to find) may exist nevertheless. Due to our stepwise reduction of ϑ in 0.01 intervalls and the use of successful solutions as starting point for the next calculation, we judge it very unlikely that a feasible solution, particularly one that is similar to the last successful solution, exists.

reduces fossil resource demand. In contrast, the pure CCS policy induces a relative price advantage for CCS energy compared to conventional fossil and renewable energy. Consequently, CCS is scaled up enormously and fossil resource extraction increases with lower ϑ. If carbon prices fall below 50% of the optimal carbon price, fossil resource extraction exceeds the business-as-usual scenario extraction.

The supply-side dynamics of technology policies Proposition 2 relied on the fact that subsidies on CCS can increase the demand for fossil resources, which produces a scarcity rent and thereby creates an implicit carbon price that reduces emissions. This policy was even an efficient first-best policy under restrictive conditions. By displaying the components of the resource price, Fig. 3a confirms that CCS subsidies have a similar effect in a second-best setting: At the optimal carbon tax ($\vartheta = 1$), the tax dominates the net resource price. As the tax is reduced, CCS subsidies cause more extraction. Extraction costs and scarcity rents increase and almost compensate the decreasing carbon tax. Hence, increasing scarcity rents and extraction costs constitute an implicit carbon price for conventional fossil energy firms. Contrary, a pure renewable energy subsidy decreases the scarcity component of the resource price (Fig. 3b). As cheap renewable energy forces the fossil resource price to decrease, increasingly high subsidies are needed to maintain a large price differential between conventional fossil and renewable energy (see Kalkuhl et al. (2011) for a detailed discussion on this aspect of renewable energy subsidies).

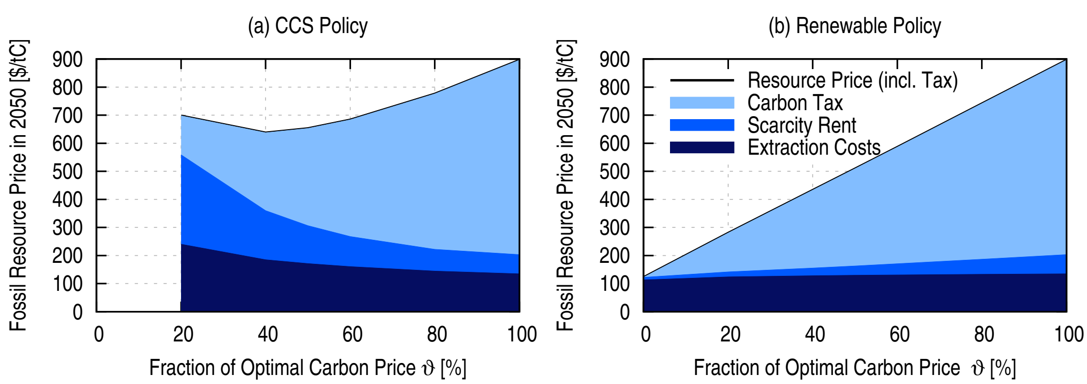

Figure 3: Snapshot of fossil resource prices and their components in 2050 for imperfect carbon prices under (a) a pure CCS policy and (b) a pure renewable energy policy.

The different supply-side dynamics translate directly to the level of the fossil resource rent: As CCS policies increase fossil resource demand, fossil resource rents increase drastically for lower ϑ (Fig. 4a). The introduction of the optimal carbon price reduces fossil resource rents by roughly one third compared to the business-as-usual economy. This impact on the fossil resource rent may constitute one important obstacle for implementing a globally harmonized carbon price. However, if carbon taxes are reduced sufficiently and complemented by CCS subsidies, fossil resource rents can even be higher than in the business-as-usual economy. While this also applies for the hybrid CCS and renewable energy policy with zero carbon prices, a pure renewable energy subsidy policy decreases fossil rents even further. The reason is that renewable energy subsidies do not only decrease conventional fossil energy deployment but also fossil energy with CCS, implying less fossil resource extraction as in the social optimum (see also Fig. 2b). This contrasts our previous findings in a model without CCS technology, where a pure renewable energy policy hardly affected fossil resource rents as cumulative extraction is of the same magnitude as under the optimal carbon pricing policy (Kalkuhl et al., 2011).

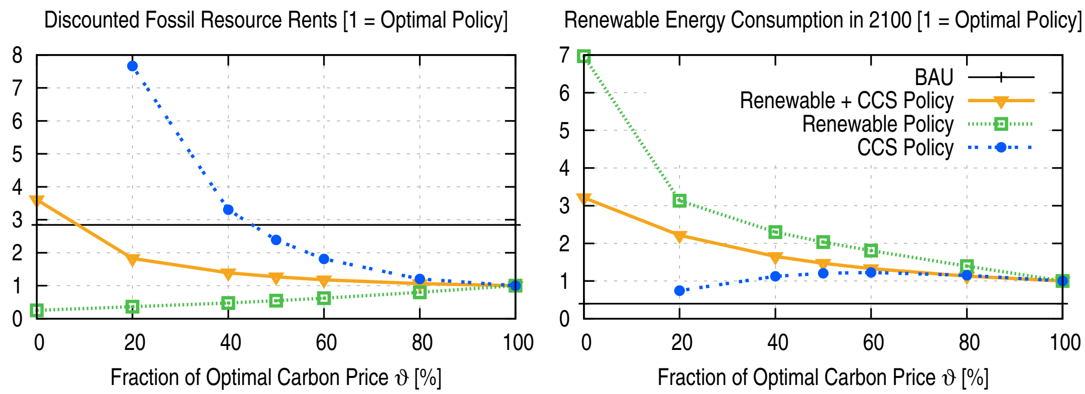

Figure 4: Impact of technology policies on (a) discounted fossil resource rents and (b) renewable energy production in 2100. For the optimal carbon pricing policy, discounted fossil resource rents amount to 0.34% of GDP.

With respect to renewable energy generation, Fig. 4b indicates that all policies lead to higher renewable energy deployment than in the BAU economy. Except for the pure CCS policy under low carbon prices ($\vartheta < 0.4$), pure CCS policies lead to even higher renewable energy deployment than under an optimal carbon price. The reason is once more the supply-side dynamics: As CCS subsidies increase fossil resource prices they also decrease the relative price of renewable energy compared to fossil energy.

The time-path of technology policies How do second-best technology policies evolve over time? Fig. 5 shows the trajectory of optimal CCS and renewable energy policies for $\vartheta \in \{0, 0.2, 0.4\}$. While the efficient CCS subsidy in Proposition 2 in the analytical model increases exponentially, the second-best CCS subsidies are inverted U-shaped: After an initial increase for several decades, subsidies decline and even turn into taxes in the long run to prevent high leakage. Although CCS is taxed in the long-run, extraction costs and fossil resource prices have become so high due to the early extraction boom that conventional fossil energy generation remains sufficiently low. The taxes on CCS provide now an additional price advantage for renewable energy deployment.

In contrast to the CCS subsidies, renewable energy subsidies remain on a more or less stable level after an initially high support phase to exploit the learning-by-doing

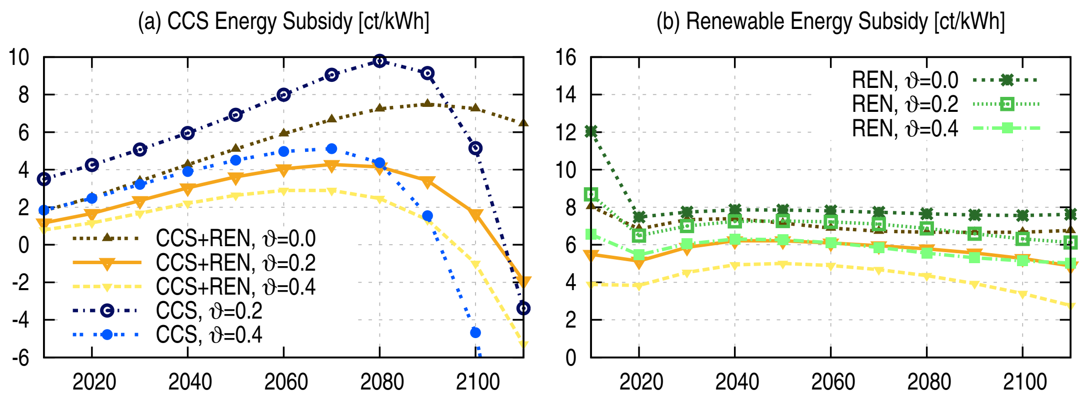

Figure 5: (a) Optimal CCS subsidy and (b) optimal renewable energy subsidy for selected policy scenarios.

effect. Both figures show that in the hybrid policy case, the subsidy level for each technology is lower than under a pure CCS or renewable energy policy.

Impact on energy prices Besides reducing fossil resource rents, carbon taxes also increase energy prices and thereby induce further pressure of voters and energy-intensive industries on regulators. Fig. 6 shows how different policies change the energy price relative to the business-as-usual economy. Energy from different technologies are good but imperfect substitutes; we calculate an average energy price by: $\tilde{p}_E = (p_F E_F + (p_L - \tau_L)E_L + (p_C - \tau_C)E_C)/E$. As all second-best policies subsidize energy, they lead to substantially lower energy prices by 2050. Although initially lower, the pure CCS policy leads to higher energy prices in the very long run because fossil resources become more expensive due to their early exploitation.

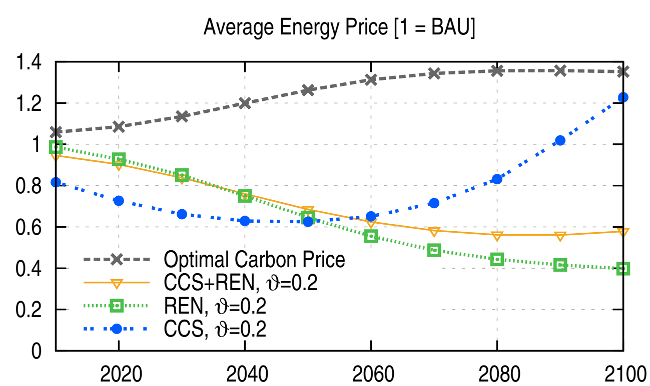

Figure 6: Impact of the optimal carbon prices and second-best policies with 20% of the optimal carbon price on energy prices.

4.2 Second-best policies for delayed carbon pricing

So far we analyzed the capability of technology policies to reduce emissions if carbon prices are permanently low or missing. In this section, we relax this permanence condition and focus on a delayed-carbon pricing scenario.

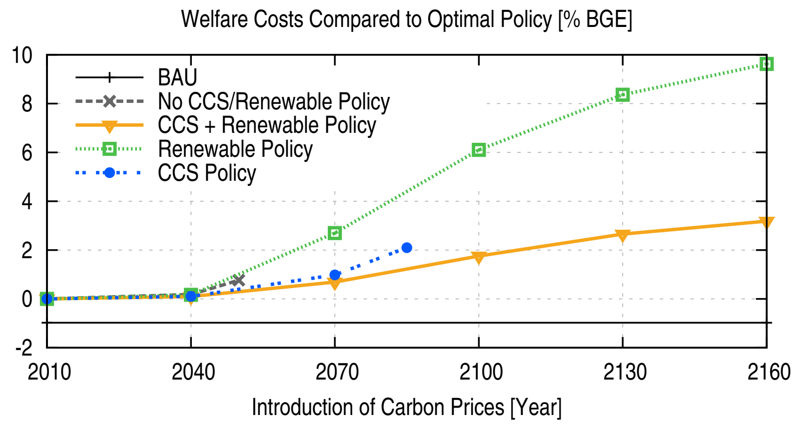

Figure 7: Welfare losses of delayed carbon pricing policies. The right-sided end of trajectories corresponds to the feasibility frontier with respect to delaying carbon pricing. Note that the x-axis denotes the year when a carbon price is introduced.

For the policy analysis, we set carbon taxes τ_R to zero for $t < T^*$. For $t > T^*$, the government sets an optimal carbon tax. Fig. 7 shows the welfare costs of delaying the introduction of carbon pricing to the year $T^* \in [2010, 2160]$ for several policy scenarios. First, a no CCS/renewable energy policy scenario is considered that is only feasible up to a delay until 2050. Without the use of further instruments, delaying the introduction of carbon prices beyond 2050 leads to a violation of the carbon budget. Second, if CCS subsidies are available before the introduction of carbon prices, the critical value of T^* can be postponed until 2085. In this case, additional welfare costs due to the delayed carbon price increase up to 2%. Third, if renewable energy subsidies are available, the carbon pricing can be delayed arbitrarily. The pure renewable energy subsidy causes approximately twice the welfare losses of the CCS policy. If carbon prices are introduced before 2070, adding renewable energy subsidies to the pure CCS policy brings only marginal welfare gains. If carbon pricing is introduced far later than 2070, a combination of CCS and renewable energy subsidies is clearly the cheapest second-best policy.

5 Sensitivity analysis

5.1 Sensitivity of key parameters

Many uncertainties exist with respect to our chosen parameterization: CCS is still a relatively new technology with little experience, and capture rates θ, leakage rates δ_X

and underground storage capacity X_0 are uncertain. The substitutability σ_3 between the three generic energy technologies is also difficult to measure directly and might change with further innovations and the invention of new technologies. Further, the stringency of the mitigation target B_0 is difficult to predict because there are scientific uncertainties regarding the climate system and the magnitude of climate damages as well as political uncertainties regarding the international negotiations for a harmonized mitigation policy. Finally, the size of exploitable fossil resources S_0 in the ground is speculative: BGR (2010) quantifies the size of proven oil, gas and coal reserves with 856 GtC (both, conventional and unconventional). There are further 2,064 GtC oil and gas and 12,417 GtC coal resources estimated where technical feasibility, extraction costs and the magnitude of extractable carbon is speculative.[11]

We vary the parameters θ, δ_X, X_0, σ_3, B_0 and S_0 and calculate the mitigation costs (welfare losses of the optimal carbon pricing policy) as well as the pure and combined CCS and renewable energy policies. As the pure CCS policy is already infeasible in our standard parameter setting, we also consider a delayed carbon pricing policy with $T^* = 2070$. Hence, we compare the CCS policy (CCS_60) with the renewable energy policy (REN_60) if carbon pricing is delayed by six decades. We summarize the main insights of the parameter sensitivity analysis and focus in more detail on the size of fossil resources in the ground (Tab. 1). The results for the other parameter variations are listed in Tab. 3 in Appendix D.

Before discussing the relative performance of instruments, we examine the mere feasibility of CCS policies for achieving the mitigation target. The sensitivity analysis indicates that pure long-term CCS policies are feasible if the capture rate θ is sufficiently high, the carbon budget B_0 not too ambitious or fossil resources sufficiently scarce (Tab. 1 and Tab. 3). The temporary CCS policy is always feasible except for the case of high leakage rates. In contrast to CCS policies, renewable energy policies are always feasible.

Regarding the costs of second-best policies, we find that CCS policies – where feasible – are in most cases cheaper than renewable energy policies. An exception is when the storage capacity is low, or when fossil resources are abundant and renewable energy generation costs is low. Complementing the pure renewable energy subsidy by a CCS policy leads to substantial welfare gains. Only when leakage is very high, an additional CCS policy hardly improves the renewable energy policy. Finally, while the pure renewable energy policy is fairly insensitive to the capture rate and the underground storage capacity, CCS policies perform best for high capture rates, low leakage rates and high storage capacity. A higher resource base and a more ambitious carbon budget increase the second-best costs of both CCS and renewable energy policies remarkably.

With respect to the resource base S_0 (Tab. 1), our calculations suggest a somewhat paradoxical conclusion: When (cheap) fossil resources are scarce, subsidizing CCS is,

[11]The uncertainties about CCS storage costs and fossil resource extraction costs are already reflected in the parameter variations of X_0 and S_0, respectively. Due to the functional form of (28) and the extraction cost curve, reductions of X_0 and S_0 imply stronger costs increases if X and S decrease.

Resource Base S_0 [GtC]	2,000	3,000	4,000*	6,000	10,000	15,000
Normal renewable energy costs (9 ct/kWh after learning; $A_{L,max} = 0.60$*)*						
Mitigation costs [%]	0.48	0.77	0.97	1.21	1.44	1.56
2nd-best costs (CCS+REN) [%]	0.40	1.25	3.18	4.77	6.56	7.37
2nd-best costs (CCS_60) [%]	0.34	0.69	0.98	1.42	1.91	2.16
2nd-best costs (REN_60) [%]	1.07	2.12	2.69	3.20	3.51	3.61
2nd-best costs (CCS) [%]	0.40	1.26				
2nd-best costs (REN) [%]	6.03	8.47	9.62	10.57	11.11	11.29
Low renewable energy costs (6 ct/kWh after learning; $A_{L,max} = 0.85$*)*						
Mitigation costs [%]	0.26	0.47	0.61	0.80	0.98	1.07
2nd-best costs (CCS+REN) [%]	0.36	1.10	2.07	3.01	3.90	4.24
2nd-best costs (CCS_60) [%]	0.21	0.52	0.80	1.20	1.63	1.86
2nd-best costs (REN_60) [%]	0.35	0.85	1.15	1.43	1.59	1.65
2nd-best costs (CCS) [%]	0.36	1.10				
2nd-best costs (REN) [%]	2.83	4.20	4.86	5.42	5.74	5.84

Table 1: Mitigation costs (welfare losses of the optimal carbon pricing policy relative to the BAU scenario) and additional second best costs (welfare losses relative to the optimal carbon pricing policy) for different fossil resource bases in balanced-growth equivalents. The asterisk is assigned to the value used for the standard parameterization. Blank entries denote infeasibilities, i.e. the policy instrument cannot achieve the mitigation target. CCS_60 denotes the CCS policy if carbon pricing is delayed by 60 years; REN_60 the corresponding renewable energy policy, if carbon pricing is introduced in 2070.

assuming normal renewable energy costs, a far cheaper second-best policy than subsidizing renewable energy. Although the economy's fossil resource use peaks within the 21st century in the laissez-faire (BAU) economy and renewable energy dominates in the 22nd century, subsidizing renewable energy instead of CCS causes substantial welfare losses. The explanation for this outcome is again rooted in the supply-side dynamics: A pure renewable energy subsidy has to be very high to reduce fossil resource extraction. In contrast, a moderate CCS subsidy does not only encourage capturing of carbon emissions, it also encourages fossil resource exploitation. This accelerated depletion increases extraction costs and scarcity rents, making renewable energy attractive without renewable energy subsidies. Hence, a CCS policy can be a cheaper way to accelerate the energy transition to renewable energy.

For our standard parameterization of renewable energy costs, the CCS_60 policy outperforms the REN_60 policy even if the resource base is very large. In this case, the CCS policy cannot provoke a substantial increase in fossil resource prices through a stimulated demand. Whether the CCS or renewable energy policy is cheaper, depends then on the technological costs of energy generation: If future costs of renewable energy generation are low, they can replace temporary missing carbon prices at lower costs (Tab. 1).

Fig. 8a addresses the fossil resource rents as an indicator for political feasibility. As suggested by Corollary 1, it shows that temporary CCS policies can diminish rent losses without increasing total mitigation costs substantially. However, a pure CCS policy – if feasible – overcompensates fossil resource owners by increasing rents by a multitude (data points beyond the range of Fig. 8a). In contrast, most renewable energy policies

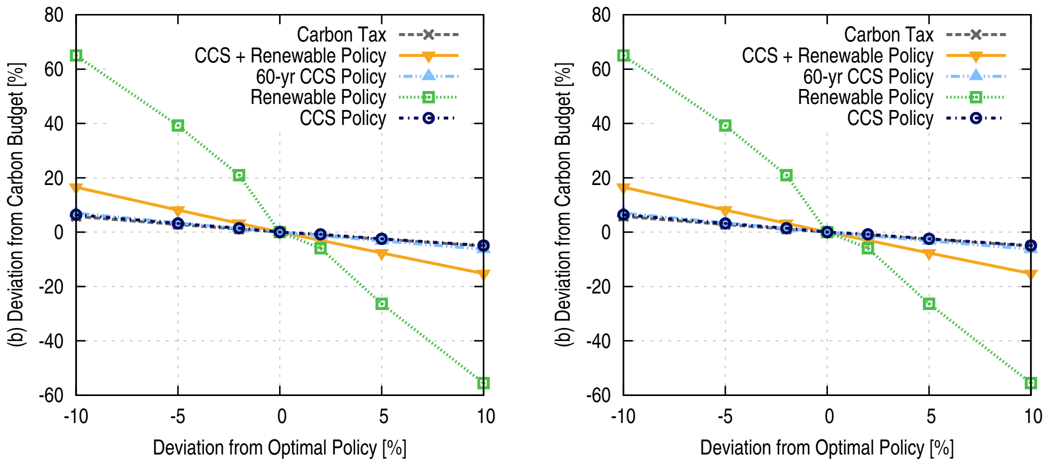

Figure 8: (a) Correlation between resource rent change and mitigation costs under all parameter variations shown in Tab. 1 and Tab. 3. The data points for the pure CCS subsidy policy are excluded as they lie far outside the other data points. (b) Change in emissions if the policy instrument is changed around its optimal value. As the pure CCS subsidy is not feasible under the standard parameterization, we set the resource base at $S_0 = 3000$ for the CCS subsidy analysis.

decrease fossil resource rents below the optimal carbon pricing policy at high welfare losses.

5.2 Sensitivity of policies

So far, we studied how different parameter changes influence the performance of policies. In the following, we focus on the sensitivity of policy instruments with respect to emission reductions and welfare. Policy-makers do not have perfect information about all economic parameters and technologies and the political implementation process is an outcome of a complex interplay of interests. Thus, taxes or subsidies will likely deviate from the optimal value.

For Fig. 8b, we first changed each of the labeled policy instrument by 2, 5 and 10 percent (in each time step) compared to the respective optimal value. We then implemented these policies in the laissez-faire economy and displayed the change in cumulative emissions. As intuition suggests, lower carbon taxes and lower subsidies for low-carbon technologies lead to higher emissions. However, in line with our findings in Kalkuhl et al. (2011), cumulative emissions react highly sensitive to a pure renewable energy policy: If subsidies are only 2 percent lower than their optimal value, carbon emissions increase by 18 percent. In contrast to renewable energy policies, the sensitivity of carbon pricing and CCS policies is very low and hardly distinguishable. The high sensitivity for renewable energy subsidies is due to the learning-by-doing dynamics: if subsidies are too low, learning-by-doing is slowed down, which leads to additionally cost increases for renewable energy (and *vice versa* if subsidies are too high). Hence, the impact on the energy mix is amplified in both directions.

6 Conclusions

It is questionable whether the world's governments will agree on a substantial global price on carbon in the next decades. As a response to this global policy failure, second-best technology policies for reducing carbon emissions become an important alternative. Our model analysis suggests that short-term policies promoting carbon capture and storage could play a key role for transforming the energy system. Due to the supply-side dynamics of fossil resource extraction, subsidies for CCS can accelerate the transformation to a carbon-free economy at lower cost than renewable energy policies – assuming favorable geological and technical conditions. As CCS subsidies increase the demand for fossil resources they lead to higher fossil resource prices. Thus, an implicit price on carbon is created that co-benefits renewable energy deployment. As a result, renewable energy deployment can be even higher than under an (efficient) first-best carbon pricing policy. In contrast, a pure renewable energy policy decreases fossil resource prices by reducing the demand. Consequently, they act as an implicit small subsidy on carbon, making high renewable energy subsidies necessary to crowd out fossil energy.

An at first glance paradoxical conclusion is that the comparative cost advantage of CCS policies over renewable energy policies is greater the scarcer fossil resources are. Although the future belongs to the 'renewables' and renewable energy might be a cheaper *technology* than CCS, a temporary CCS subsidy could be the cheaper *policy* to transform the energy sector when carbon prices are missing. In particular, if fossil resources are sufficiently scarce and leakage is low, a permanent CCS policy can achieve the mitigation target without any additional carbon price or renewable energy subsidy. Furthermore, second-best costs of CCS policies are lower (i) the better carbon can be captured in power plants, (ii) the lower carbon leakage is, and (iii) the higher the underground storage capacity is. For the limiting case of zero leakage and 100% carbon capture of carbon emitting sources, a permanent CCS policy can even be as efficient as a carbon pricing policy (Proposition 2). If, in contrast, fossil resources are abundant and renewable energy costs low or carbon taxes are permanently on suboptimally low levels (rather than delayed), renewable energy subsidies can outperform CCS subsidies.

While renewable energy policies are always a feasible (but often more expensive) second-best policy in case of missing carbon prices, CCS policies cannot always guarantee to achieve ambitious mitigation targets: underground storage capacity, capture rates and the politically targeted carbon budget have to be sufficiently high and carbon leakage sufficiently low. If the introduction of carbon is delayed, CCS subsidies can replace carbon pricing for a certain time span, but become more difficult and even infeasible for very long time horizons. CCS policies are therefore an attractive short-term option to buy time until the international community agreed on a carbon price. Due to the feasibility constraints, a long-term CCS policy, however, may also be a risky policy.

CCS and renewable energy subsidies differ in their impact on fossil resource rents: As CCS policies increase fossil resource extraction and, thus, fossil resource prices, they lead to higher energy prices in the long run. In contrast, renewable energy subsidies decrease energy prices substantially below the business-as-usual price. This benefits energy-intensive industries and possibly also low-income-households which could increase the political support for this policy. With respect to fossil resource rents, CCS policies mitigate the rent losses associated with climate policy and can even overcompensate fossil resource owners at moderate additional costs.

Although there is no global government to implement these policies, international negotiations about emission reductions could use these insights when focusing on technology protocols and technology financing mechanisms. The cost mark-ups for CCS in developing countries could be paid by OECD countries. This establishes a no-regret option for developing countries, allowing them to extend their energy system in an almost business-as-usual way without substantial additional costs. If a critical mass of countries adopts CCS policies, the increasing fossil resource prices could also lead to lower emissions in countries not participating.

There are, of course, several limitations of our model that raise further important questions. First, we do not explicitly differentiate between coal, gas and oil, the latter being practically not suitable for CCS. The imperfect substitutability between conventional fossil energy and CCS fossil energy as well as the imperfect carbon capture rate consider this to a certain extent. Nevertheless, there might be additional second-best policies required for the transportation sector if carbon pricing is not implemented. Secondly, increasing fossil resource prices due to CCS policies could increase exploration activities leading *ceteris paribus* to lower scarcity rent increases. This effect could be integrated in a modified formulation of the extraction cost curve (by including exploration costs) and the initial resource base (by including estimations about fossil resources). We paid tribute to this consideration partly in our sensitivity analysis with respect to the resource base. Fossil resource price increases might also have adverse effects on deforestation and food prices due to the expansion of energy crop cultivation. Thirdly, (temporary) CCS policies conserve or even strengthen the existing fossil-fuel based industrial metabolism. While this eases political implementation in the short-term, it could impede the delayed transformation to renewable energy. In particular, if fossil resources turn out not to be scarce (and the implicit carbon tax effect of CCS subsidies is low), there is low economic pressure to invest into renewable energy. As underground carbon storage fills up and fossil resource prices are continuously low, additional political measures are necessary to decarbonize the energy system. However, when large investments into fossil capital have been already undertaken, introducing carbon prices or renewable energy subsidies might become even more difficult. Finally, there has to be a proper management of CCS storage sites, including an effective monitoring system which detects leakage as well as an appropriate design regarding the long-term liability for leakage and the sharing of environmental risks between firms and the public (Held and Edenhofer, 2009; IPCC, 2005). Underground storage is a further scarce exhaustible resource requiring well-defined and secure property rights for an efficient intertemporal allocation. This could, in particular, become crucial if scarce storage has to be used for capturing emissions from combustion of biomass. As this technology can create negative net emissions, the remaining storage capacity might become highly valuable in the future. Our model calculations suggest that CCS policies could increase the scarcity rent associated with limited storage capacity up to 0.5% of the total GDP. If there are no auctions or fees for use concessions of underground storage, this scarcity rent is transferred implicitly to CCS operators.

Beside these limitations, our findings suggest an important conclusion: Pure CCS as well as pure renewable energy policies aiming to replace a permanently missing carbon price are not a pragmatic policy approach. Both, CCS and renewable energy policies carry specific risks of failure: CCS policies rely on favorable physical and technological conditions; pure renewable energy policies are costly and lead to a highly sensitive outcome in emissions that undermines environmental effectiveness. A smart combination of both policies, however, might be a robust second-best strategy. Such a hybrid policy would initially push CCS to increase fossil resource prices in a sustained way. With ongoing depletion, extraction costs and scarcity rents increase. This makes lower CCS subsidies necessary and even turns the optimal CCS subsidy into a tax in the long run. As fossil resource prices continue to increase, renewable energy – permanently backed by moderate subsidies – becomes more and more the dominant low-carbon technology. The second best-costs of this hybrid policy approach and its risks decrease further in case carbon pricing can be introduced eventually in the future.

A Proof of Proposition 2

With the policy $\tau = \beta\mu^*$ and $\sigma = (1-\beta)\mu^*$, the first-order conditions (14–15) read:

$$\alpha p - g(S) - \theta h(X) - \lambda - (1-\theta)\beta\mu^* + (1-\beta)\mu^* - \theta\psi \leq 0 \qquad (= 0 \text{ if } R_C > 0)$$
$$p - g(S) - \lambda - \beta\mu^* \leq 0 \qquad (= 0 \text{ if } R_N > 0)$$

Using the transformation $\tilde{\lambda} := \lambda - (1-\beta)\mu^*$ we can rewrite the first-order conditions to:

$$\alpha p - g(S) - \theta h(X) - \tilde{\lambda} - (1-\theta)\beta\mu^* - \theta\psi \leq 0 \quad (= 0 \text{ if } R_C > 0) \tag{29}$$
$$p - g(S) - \tilde{\lambda} - \mu^* \leq 0 \quad (= 0 \text{ if } R_N > 0) \tag{30}$$

Furthermore, substiting the transformation for $\tilde{\lambda}$ and $\dot{\lambda} = \dot{\tilde{\lambda}} + (1-\beta)\dot{\mu}^*$ into (16) and using the fact that $\dot{\mu}^* = r\mu^*$ from (7), we obtain:

$$\dot{\tilde{\lambda}} = r\tilde{\lambda} + g'(S)R \tag{31}$$

Finally, the transversality condition for λ reads:

$$0 = \lim_{t\to\infty} S(t)\lambda(t)e^{-rt} = \lim_{t\to\infty} S(t)(\tilde{\lambda}(t) + (1-\beta)\mu^*(t))e^{-rt} \tag{32}$$

$$= \lim_{t\to\infty} S(t)\tilde{\lambda}(t)e^{-rt} + \lim_{t\to\infty}(1-\beta)\mu_0^* S(t) \tag{33}$$

The first order conditions (30) and (31) now equal those of the social planner system (5–6). The equation of motion for ψ (17) is only equal to the corresponding social-planner condition (8) if $\delta_X = 0$. It becomes apparent that the first-order condition (29) of the decentralized economy equals that of the social planner system (5) if $(1-\theta)\beta = (1-\theta)$. The latter condition implies that either $\theta = 1$ (and $\beta \in \mathbb{R}$) or that $\beta = 1$ if $\theta \neq 1$. Finally, the transversality condition (33) equals the social planner condition (9) if $\lim_{t\to\infty} S(t) = 0$. If $\lim_{t\to\infty} S(t) > 0$, the transversality condition of the decentralized resource sector and the social planner differ and the policy cannot achieve the social optimum (as $\mu_0^* > 0$). □

B First-order conditions of the CCS sector

Maximizing the associated Lagrangian with λ_X as co-state variable for X, we obtain as dynamic first-order conditions:

$$\lambda_{X,t} = p_{X,t} - h(X_t) \tag{34}$$

$$\lambda_{X,t-1}(1 + (r_t - \delta)) - \lambda_{X,t} = -\left(\frac{\partial h(X_t)}{\partial X_t} R_{X,t} + \delta_X \tau_R\right) \tag{35}$$

$$\lambda_{X,t} X_{t+1} = 0 \tag{36}$$

C Parameters

Symbol	Parameter	Value
ρ	pure time preference rate of household	0.03
η	elasticity of intertemporal substitution	1
δ	capital depreciation rate	0.03
L_{max}	population maximum (bill. people)	9.5
f	population growth parameter	0.04
a_1	share parameter in final good production	0.95
σ_1	elasticity of substitution energy–intermediate	0.5
b_2	share parameter in intermediate production	0.7
σ_2	elasticity of substitution labor–capital	0.7
a_3, b_3, c_3	share parameter (energy usage)	1
σ_3	elasticity of substitution energy types	3
a_F	share parameter in fossil energy generation	0.8
σ	elasticity of substitution fuel–capital	0.15
a_C	share parameter in fossil energy generation	0.95
A_C	productivity factor	0.65
θ	capture rate	0.9
χ_1	scaling parameter	20
χ_2	scaling parameter	700
χ_3	slope of extraction curve	2
c_1	scaling parameter (10^4\$/tC)	0.05

c_2	scaling parameter (10^4\$/tC)	0.45
c_3	slope of storage and transportation cost curve	2
δ_X	leakage rate	10^{-4}
ν	share parameter learning carbon-free energy generation	0.95
$A_{L,max}$	maximum productivity learning carbon-free energy	0.6
Ω	scaling parameter	200
γ	learning exponent	0.27
Q	land	1
K_0	Initial total capital stock (trill. US\$)	165
S_0	Initial stock of fossil resources (GtC)	4000
S_0	Underground carbon storage capacity (GtC)	3500
B_0	Carbon budget (GtC)	450
H_0	Initial experience stock renewable energy	0.2
L_0	Initial population (bill. people)	6.5
$A_{Y,0}$	Initial productivity level	6
T	time horizon (in years)	150

Table 2: Parameters used for the numerical model.

Population L grows exogenously from L_0 to L_{max} according to $L_t = L_0(1-q_t)+q_t L^{max}$ with $q_t = 1-\exp(-ft)$. Labor productivity A_Y grows exogenously at the variable rate $[1-g_0\exp(-\zeta t)]^{-1}-1$ implying for $g_0 = 0.026$ and $\zeta = 0.006$ an initial growth rate of 2.7% which decreases to 1.5% in 2100.

D Sensitivity analysis

Capture rate θ	0.8	0.85	0.9*	0.95	1
Mitigation costs [%]	1.24	1.11	0.97	0.81	0.64
2nd-best costs (CCS+REN) [%]	5.73	4.49	3.18	1.99	1.03
2nd-best costs (CCS_60) [%]	2.42	1.48	0.98	0.65	0.36
2nd-best costs (REN_60) [%]	2.77	2.75	2.69	2.50	1.64
2nd-best costs (CCS) [%]					2.18
2nd-best costs (REN) [%]	9.72	9.66	9.62	9.75	9.58
Leakage rate δ_X	0	0.01*	0.1	1	2
Mitigation costs [%]	0.94	0.97	1.16	2.11	2.34
2nd-best costs (CCS+REN) [%]	2.97	3.18	5.28	10.54	10.87
2nd-best costs (CCS_60) [%]	0.91	0.98	2.04		
2nd-best costs (REN_60) [%]	2.60	2.69	3.13	3.65	3.65
2nd-best costs (CCS) [%]					
2nd-best costs (REN) [%]	9.60	9.62	9.76	10.73	11.20
Elasticity of Substitution σ_3	2	3*	4	5	6
Mitigation costs [%]	0.56	0.97	1.17	1.30	1.40
2nd-best costs (CCS+REN) [%]	3.89	3.18	2.54	2.14	1.87
2nd-best costs (CCS_60) [%]	0.53	0.98	0.94	0.87	0.82
2nd-best costs (REN_60) [%]	0.78	2.69	3.73	4.25	4.51
2nd-best costs (CCS) [%]					
2nd-best costs (REN) [%]	10.62	9.62	8.75	7.83	7.82
Storage Capacity X_0 [GtC]	200	500	1000	1500	3500*
Mitigation costs [%]	1.43	1.12	1.01	0.99	0.97
2nd-best costs (CCS+REN) [%]	7.34	5.39	3.85	3.40	3.18
2nd-best costs (CCS_60) [%]		10.11	1.17	1.06	0.98
2nd-best costs (REN_60) [%]	2.46	2.60	2.66	2.68	2.69
2nd-best costs (CCS) [%]					
2nd-best costs (REN) [%]	9.37	9.51	9.58	9.60	9.62

Carbon Budget B_0 [GtC]	250	350	450*	550	650
Mitigation costs [%]	2.00	1.36	0.97	0.70	0.51
2nd-best costs (CCS+REN) [%]	8.77	5.10	3.18	1.65	1.01
2nd-best costs (CCS_60) [%]	5.96	2.09	0.98	0.49	0.25
2nd-best costs (REN_60) [%]	8.02	4.76	2.69	1.40	0.64
2nd-best costs (CCS) [%]				1.65	1.01
2nd-best costs (REN) [%]	17.62	12.96	9.62	7.15	5.30

Table 3: Mitigation costs (welfare losses of the optimal carbon pricing policy relative to the BAU scenario) and additional second best costs (welfare losses relative to the optimal carbon pricing policy) for several parameter variations in balanced-growth equivalents. The asterisk is assigned to the value used for the standard parametrization. Blank entries denote infeasibilities, i.e. the policy instrument cannot achieve the mitigation target. CCS_60 denotes the CCS policy if carbon pricing is delayed by 60 years; REN_60 the correxponeding renewable energy policy, if carbon pricing is introduced in 2070.

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