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Cutting Costs of Catching Carbon
Intertemporal effects under imperfect climate policy

Abstract:
We use a two-period model to investigate intertemporal effects of cost reductions in climate change mitigation technologies for the power sector. With imperfect climate policies, cost reductions related to carbon capture and storage (CCS) may be more desirable than comparable cost reductions related to renewable energy. The finding rests on the incentives fossil resource owners face. With regulations of emissions only in the future, cheaper renewables speed up extraction (the `green paradox'), whereas CCS cost reductions make fossil resources more attractive for future use and lead to postponement of extraction.

Keywords: climate change, exhaustible resources, carbon capture and storage, renewable energy, green paradox

JEL classification: Q30, Q42, Q54

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1 Introduction

Are some 'climate friendly' technologies preferable to others? Should policy makers discriminate between supporting renewable energy sources such as wind or solar power and carbon capture and storage (CCS)? Adding to the many conceivable arguments for and against differentiation, we suggest one more: in a world with imperfect climate policies, developing these technologies alters the incentives fossil fuel owners face differently. While cheaper renewables cause extraction to speed up, lower costs of CCS may delay extraction.

Climate change is to be expected as a result of human activity. On aggregate, it will almost certainly affect the human condition adversely. Carbon dioxide emissions from producing power are the single largest contribution to this process. In order to stabilize greenhouse gas (GHG) concentrations in the atmosphere at a level likely to avoid the most harmful damages, emissions need to be reduced and eventually to stop. A concentration of 450 parts per million carbon dioxide-equivalent for example is estimated to give a 50 per cent chance of limiting the rise in global average temperature to 2 degrees Celsius (Solomon et al., 2007). This target temperature would leave about half a trillion tonnes of carbon to be burned (Allen et al., 2009).[1]

Quitting emitting GHGs and at the same time securing sufficient energy supplies requires the development and deployment of new, climate friendly technologies. Two promising options are electricity generation from renewable sources such as wind and solar, and carbon capture and storage (CCS). Wind and solar energy are in principle physically available at a sufficient scale to replace fossil fuel power generation (MacKay, 2008). They are however at present not fully competitive,[2] and various technological challenges

[1] See also Meinshausen et al. (2009). For an accessible introduction to climate science, see Socolow and Lam (2007).

[2] Barrett (2009) reports that the best locations are at present competitive if a ton of carbon dioxide is priced at about 35 US Dollars (2006 value).

remain.[3] CCS is a technology under development meant to abate carbon dioxide emissions from large point sources by capturing them and storing them underground.[4]

As using those technologies is more expensive than fossil fuel energy, climate policies are necessary to encourage their deployment. But a comprehensive international agreement to limit GHG concentrations does not exist today.[5] The best one therefore can expect is a future commitment to limit climate change. This lack of strong climate policy today gives owners of fossil fuels a possibility to sell their exhaustible resources prior to climate policies being implemented and climate friendly technologies being competitive. Such intertemporal reallocation undermines policy objectives as more carbon dioxide is emitted in early periods, and potentially total emissions remain unchanged. This supply side effect has become known as the 'green paradox' (Sinn, 2008).

The present paper contributes to the literature on fossil fuel supply under imperfect climate policies by focusing on differences in prospective climate friendly technologies. In particular, we ask how reductions in the costs of the abatement technology CCS affect the market outcome. We contrast this with improvements in renewable energy technology (reproducing results from Hoel, 2008). To that end, we build an analytical model with two linked markets, one for fossil fuels and one for power. We look at two periods. In period one, emission free technologies play no role, only conventional energy is available. However, actors know about the arrival of alternatives in the second period. By that time, three types of energy technology are available: conventional fossil energy, fossil energy with CCS technology and renewable energy.

[3]Examples are the lack of adequate power storage possibilities, buffering varying wind speeds and sun hours, or the need for distributed transmission networks (Heal, 2009).

[4]So far, no full scale test plants are operating. Golombek et al. (2009) review several studies and find that the most promising types of CCS plants could be competitive at about 30 USD (2007 value) per ton carbon dioxide.

[5]Barrett (2005) has a game theoretical treatment of international climate agreements, while Røgeberg et al. (2010) offer more of a political economy approach.

Fossil fuel suppliers optimize dynamically and sell fossils to conventional and (in period two) CCS power generators. Those sell power competitively in the same market as renewable energy suppliers to energy end users, who are indifferent with regards to the source of their energy. Climate policy is enacted either in both periods (as a first best benchmark) or in the second period only.

We find that with imperfect climate policies, cost reductions related to CCS may be more desirable than comparable cost reductions related to renewable energy. The finding rests on the incentives fossil resource owners face. With regulations of emissions only in the future, cheaper renewables speed up extraction, whereas CCS cost reductions potentially make fossil resources more attractive for future use and lead to postponed extraction.

1.1 Literature

The early literature on the interaction of fossil resource extraction and climate change focuses on optimal policies.[6] The contributors investigate how varying assumptions on accumulation of pollutants in the atmosphere, damage functions, backstop technologies, extraction costs, etc. impact the optimal tax on emissions. Both rising and falling tax paths are possible, mirroring the net present value of future damages by emissions today. Also the transition to backstop technologies can take different shapes, dependent on cost functions and pollution accumulation.

In a more recent work on optimal policy, Ayong Le Kama et al. (2009) determine cost conditions under which it is optimal to use CCS as an abatement technology and describe the optimal path of usage. In their model, the sequestration rate should decrease over time. Other later contributions relax the assumption of perfect policy and add new trade-offs: With a cap on pollution, renewable and fossil energy may be produced simultaneously,

[6] Sinclair (1994); Ulph and Ulph (1994); Withagen (1994); Hoel and Kverndokk (1996); Tahvonen (1997).

while (constant unit cost) abatement is never used before the cap is reached, or at the same time as renewable energy is produced (Chakravorty et al., 2006). A constant cap on emissions may lead to substitution away from a relatively clean to a dirty fossil fuel in early periods if these are imperfect substitutes (Smulders and van der Werf, 2008). Food prices may be influenced by the scarcity of fossil fuels and the strictness of a pollution limit when land is scarce and used for both food and biofuel production (Chakravorty et al., 2008). And with a fixed carbon tax, the presence of learning by doing in renewable energy technologies may speed up the extraction of fossil fuels (Chakravorty et al., 2010).

The assumption of comprehensive climate policy implemented today and globally is hard to defend as descriptive. When climate policy is implemented in the future only, present emissions remain unpriced.[7] Long and Sinn (1985) investigate reactions of fossil fuel owners to surprise changes in current and expected future prices. Sinn (2008) points explicitly at role of the supply side in climate policy. He shows that fossil fuel owners respond to taxation by re-allocating extraction over time: If high future taxes are expected, extraction takes place earlier, and, under extreme assumptions, the total amount extracted remains unaltered (the green paradox).

Di Maria et al. (2008) model multiple fossil resources differing in their carbon content, finding that policy announcements may lead to more extraction of the relatively dirty resource earlier. Strand (2007) focuses on climate friendly technologies. He demonstrates that if a technology policy today leads to fossil fuel becoming superfluous in the future and other policies are absent, present carbon dioxide emissions will increase. Hoel (2008) shows that such an effect will also be observed if an incomplete climate policy is in place, even if alternative energy technologies become only marginally cheaper. He illustrates that it is possible for such a technological improvement to lower

[7] Another imperfection arises when not all judicial entities participate in a climate agreement (carbon leakage), see Eichner and Pethig (2009); van der Werf (2009).

social welfare.

Several authors have examined conditions under which the green paradox arises. Gerlagh (2010) differentiates between a 'weak' (an increase in current emissions) and a 'strong' (higher cumulative damages) green paradox. Increasing extraction costs counteract the strong version, while imperfect substitutes counteract both. Independently, Grafton et al. (2010) define a weak green paradox in the same way, while they call a rise in total atmospheric carbon dioxide a 'strict' green paradox. They look into effects of biofuel subsidies under both linear and nonlinear demand schedules, and with constant and rising extraction costs. They find numerically that the weak green paradox may arise for a wide range of specifications. Also Hoel (2010) looks at extraction costs. In addition he investigates carbon tax expectations when policy makers cannot commit to future tax paths. Van der Ploeg and Withagen (2010) show that expensive but not cheap backstops cause the green paradox to occur.

Finally, a line of research analyzes various aspects of the CCS technology without taking the dynamics of the supply side into account, establishing cost estimates and the optimal use of the technology in numerical models.[8]

2 The model

Consider owners of some fossil resource that plan for two periods of time. The interest rate is r. There is a given total stock of the resource (F), all of which can be extracted at constant marginal costs, for simplicity set to zero. In the first period, they can sell their fossil fuel to power generators that have a conventional technology turning it into power. Again we disregard costs. The competitive price for fossil resources in period one is p_1. We define that one unit of fossils results in one unit of conventional energy and one unit of

[8] See Al-Juaied and Whitmore (2009); Golombek et al. (2009); Islegen and Reichelstein (2009); Lohwasser and Madlener (2009).

GHG emissions (table 1). There is no natural absorption of GHGs.[9] In the

Table 1: *Conversion between energy, fossil fuel and emissions*

technology	*energy*	*fossil fuel*	*emissions*
conventional ($t = 1/2$)	x_1/x	x_1/x	x_1/x
CCS	x^{CCS}	$x^{CCS}(1+\gamma)$	0[a]
renewable	x^{RE}	0	0

[a] In section 6 we will consider residual emissions from CCS and replace 0 with δx^{CCS}.

second period, the fossil fuel owners again sell to conventional power generators, and in addition also to power generators using CCS technology (call the competitive second period fossil resource price p). CCS requires $1 + \gamma$ units of fossils to generate one unit of energy and causes no emissions. In addition, each unit of energy generated has a non-energy cost of c. Finally, the conventional power generators (potentially) pay a carbon tax for emissions, τ_1 in period one and τ in period two. The taxes are set by a regulator who wishes to limit the GHG emissions from the sector to an exogenously determined cap G for period two. Note that for the cap to be meaningful, we must require $G < F$.[10]

The power producers convert fossils to energy and supply it to the energy market. It follows from above that they do so at constant marginal costs: $p_1+\tau_1$ for conventional in period one, $p+\tau$ for conventional in period two and $p(1 + \gamma) + c$ for CCS. The latter two need to be equal for conventional and CCS producers to produce at the same time. Call the competitive energy prices (to consumers) P_1 and P for periods one and two. In addition to conventional and CCS energy, also renewable energy is supplied competitively

[9] Thus we focus on the share of GHGs that can be regarded as remaining in the atmosphere indefinitely, see Socolow and Lam (2007).

[10] The inequality $G < F$ implies that if CCS was not available in period 2, the resource would not be scarce. In this case the resource rent would be zero in both periods, and consumer prices would be equal to carbon taxes.

in the second period. We assume that the costs of renewables are location dependent, leading to increasing marginal costs. We get a standard supply function $\tilde{S}(P, b)$. Here b is a shift parameter, and to simplify we assume $\tilde{S}(P, b) = S(P - b)$. Demand for energy by end users in period one and two is denoted $\tilde{D}_1(P_1)$ and $D(P)$ respectively, and these have standard properties.

We assume that functional forms, parameters and the constraints G and F have properties that imply an interior solution, so all types of energy are supplied in the second period. The model can then be solved as follows. In the energy market, price in each period is equal to the marginal costs for all energy producers. They make zero profits and are hence indifferent to how much to produce. The energy market equilibrium conditions are

$$x_1 = \tilde{D}_1(P_1) \tag{1}$$

$$x + x^{CCS} + x^{RE} = D(P) \tag{2}$$

where x_1 is conventional energy in period one and x, x^{CCS} and x^{RE} are the quantities of conventional, CCS and renewable energy in period two. For a given market price, the supply function for renewables determines x^{RE}

$$x^{RE} = S(P - b) \tag{3}$$

We can then write $x + x^{CCS} = D(P) - S(P - b)$. For energy prices we have

$$P_1 = p_1 + \tau_1 \tag{4}$$

$$P = p + \tau \tag{5}$$

$$P = p(1 + \gamma) + c \tag{6}$$

This describes the energy market. Turning to to the market for fossil fuels, we use the conversion factors (table 1). Fossil fuel owners anticipate the energy market behavior, thus facing a derived demand for fossils in each period. Their dynamic optimization leads to the Hotelling rule

$$p = p_1(1 + r) \tag{7}$$

As they have no costs of extraction, it is also straightforward to conclude that they want to extract all of F, implying that

$$x_1 + x + x^{CCS}(1 + \gamma) = F \tag{8}$$

Only conventional power causes emissions, which are limited to G, so

$$x_1 + x = G \tag{9}$$

Note that the quantity of CCS fossil fuel use is determined by the exogenous assumptions in the model: CCS use is the only way to avoid exceeding G, so $x^{CCS}(1 + \gamma) = F - G$.[11]

To have an identified system of equations, we need an additional assumption on the carbon taxes τ_1 and τ. We explore two different scenarios. First, we assume that taxation is socially cost efficient. As only GHGs in the atmosphere in period two are of concern and they accumulate linearly, optimal taxation requires $\tau = \tau_1(1 + r)$. Second, climate policy being in place in period two only translates into setting $\tau_1 = 0$. Either assumption allows

[11]This is unnecesarily rigid. In section 6 we will however show that the effect we are interested in does not rest on this simplification.

solving the system, which after some simplifications reduces to

$$F + \gamma G = (1+\gamma)\left[\tilde{D}_1\left(\frac{p}{1+r} + \tau_1\right) + D(P) - S(P-b)\right] \tag{10}$$

$$P = p + \tau \tag{11}$$

$$P = p(1+\gamma) + c \tag{12}$$

$$\tau_1 = 0 \tag{13}$$

$$\tau = \tau_1(1+r) \tag{14}$$

We have two sets of four equations in four unknowns (P, p, τ_1, τ).

3 A perfect world – taxation in both periods

Assume the GHG constraint is implemented by a intertemporally cost efficient taxation scheme, i.e. $\tau = \tau_1(1+r)$. So τ represents carbon taxes in both periods. Demand in period one can then be written as $\tilde{D}_1\left([p+\tau](1+r)^{-1}\right) = D_1(p+\tau) = D_1(P)$. End users face the same energy price in net present value terms in both periods. The model from section 2 can be reduced to

$$F + \gamma G = (1+\gamma)\left[D_1(P) + D(P) - S(P-b)\right] \tag{15}$$

$$p = \frac{P-c}{1+\gamma} \tag{16}$$

$$\tau = \frac{\gamma P + c}{1+\gamma} \tag{17}$$

What happens to prices and the emission profile if one of the technology/cost parameters c, b or γ is reduced (and this is correctly anticipated)? First note that (15) implies that lower non-energy CCS costs c have no effect on the energy price P, even though it is now cheaper to abate. Looking at p and τ ('breaking up' P) helps with the intuition. Knowing that $\frac{dP}{dc} = 0$, one sees from (16) and (17) that

$$\frac{dp}{dc} = -\frac{1}{1+\gamma} \tag{18}$$

$$\frac{d\tau}{dc} = \frac{1}{1+\gamma} \tag{19}$$

The reason is that even though CCS energy is now cheaper, the amount optimally used is unaffected: it is given by the limit on GHGs, the available resource and the technology. But if the amount of CCS energy produced remains unchanged, no adjustments in allocation are desirable and the energy price is the same as before. What happens though is that limiting GHGs gets cheaper and fossil fuel resources become more valuable. Taxes go down and fossil fuel prices increase by the same amount. Some of the economic surplus shifts from the regulator to the fossil fuel owners.[12]

Turning next to the energy cost of CCS γ, the effect on P is obtained from (15). The reactions by p and τ are then retrieved from (16) and (17). Recall that $G = x_1 + x$, $D_1 = x_1$ and $D - S = x + x^{CCS}$. We get

$$\frac{dP}{d\gamma} = \frac{G + S - D_1 - D}{(1+\gamma)[D_1' + D' - S']} = \frac{-x^{CCS}}{(1+\gamma)[D_1' + D' - S']} > 0 \tag{20}$$

$$\frac{dp}{d\gamma} = \frac{1}{1+\gamma}\frac{dP}{d\gamma} - \frac{P-c}{(1+\gamma)^2} \tag{21}$$

$$\frac{d\tau}{d\gamma} = \frac{\gamma}{1+\gamma}\frac{dP}{d\gamma} + \frac{P-c}{(1+\gamma)^2} > 0 \tag{22}$$

A decrease in the extra energy required for CCS lowers energy prices, has an ambiguous impact on fossil fuel prices and decreases the carbon tax.

The price of energy for both periods (P) has to go down. Less energy is

[12] Intuitively: Cheaper CCS at a given P *ceteris paribus* makes CCS energy producers want to supply infinitely much. They demand more fossils and p must go up until they are indifferent again. At the new p and the given τ, conventional producers would not produce in period two. The GHG constraint would be underutilized. The change in τ exactly offsets the rise in p.

needed for CCS to reduce GHGs, so more is available to end users. Extraction is in response shifted forward in time. The tax has to be lowered too. Preventing GHG emission has become cheaper, so a lesser opportunity cost is needed. The effect on fuel price is indeterminate. More CCS energy is supplied from the same amount of fossil fuels, lowering demand for fossils. But the fall in energy price means less renewable energy is supplied, increasing demand. After some manipulations of (21) one gets the following condition (recall that $F - G = x^{CCS}(1+\gamma)$)

$$\frac{dp}{d\gamma} > 0 \quad \Leftrightarrow \quad F - G > (1+\gamma)(P-c)[S' - D_1' - D'] \tag{23}$$

Large carbon reserves in the ground (F) work in favor of a dropping fuel price, and so does a strict limit on carbon emissions (G). On the contrary, high CCS energy costs, a high equilibrium fossil fuel price (recall that $P - c = (1+\gamma)p$), steep demand curves and a steep supply curve for renewables pull in the direction of a rising fuel price as the energy cost (γ) declines.

What are the distributional consequences? Consumer surplus increases, the regulator's revenues decrease while the effect on the Hotelling rent is ambiguous. Owners of renewable power production lose some Ricardian rent.

Finally, for a shift in the cost curve of renewables we get

$$\frac{dP}{db} = -\frac{S'}{D_1' + D' - S'} \qquad \in (0,1) \tag{24}$$

$$\frac{dp}{db} = \frac{1}{1+\gamma}\frac{dP}{db} \qquad \in \left(0, \frac{1}{1+\gamma}\right) \tag{25}$$

$$\frac{d\tau}{db} = \frac{\gamma}{1+\gamma}\frac{dP}{db} \qquad \in \left(0, \frac{\gamma}{1+\gamma}\right) \tag{26}$$

P is again reduced, and also p and τ go down. A source of energy becoming cheaper leads to a falling energy price. As it is a substitute for fossil energy, the derived value of the fossil resource is decreased. And the tax is reduced to make sure that the resulting fall in opportunity costs is reflected. Some of the fossil fuel is re-allocated to the first period ($D_1'(P) < 0$). Hotelling rent and regulator revenues are decreased, while consumer surplus and the Ricardian rent for owners of renewable power go up.

Summing up, all adjustments in response to technological changes in the current section are socially cost efficient. Taxation in both periods allows policy makers to price emissions correctly. Table 2 summarizes the results.

Table 2: *Impacts of changes in cost parameters on prices, taxes and emissions in period one under taxation in both periods*

	lower c (CCS non-energy)	lower γ (CCS energy)	lower b (renewable)
P (energy)	0	$-$	$-$
p (resource)	$+$	?	$-$
τ (tax)	$-$	$-$	$-$
x_1 (early emissions)	0	$+$	$+$

All improvements lower the carbon tax path: it becomes cheaper for society to 'solve' the climate problem. For renewables and CCS energy costs, the consumers benefit from lower energy prices in both periods. One major difference is how the fossil fuel price is affected by changes in non-energy costs of CCS and more efficient renewables: the former makes a complement to fossil resources in energy production cheaper, the latter a substitute. Total emissions are given exogenously by G. But emissions are accelerated by a lower γ or b and left unchanged by a reduction in c. Some economic rent is shifted from the government (the taxation revenue falls) to resource owners (the Hotelling rent rises) when c is reduced. A lower γ increases consumer surplus, decreases tax revenues and has no conclusive effect on fossil fuel owners. Renewable energy producers lose some Ricardian rent due to the lower energy price. A cut in costs of renewables finally benefits the owners of renewables and the consumers while it reduces the Hotelling rent and the regulator revenues.

4 Plan B – fixing it tomorrow

Now suppose a carbon tax is imposed only in the second period, i.e. $\tau_1 = 0$. This represents a scenario where in the medium term the major emitting countries agree upon a target level for GHG concentrations. Demand in period one can be written as $\tilde{D_1}(p(1+r)^{-1}) = D_1(p)$. Note that p is now both: the resource price (for both periods due to the Hotelling rule) and the energy price in period one.[13] P is the energy price for period two only.

By using $D_1(p)$ in (10) and replacing p (from 12), the equilibrium conditions can now be reduced to

$$F + \gamma G = (1+\gamma)\left[D_1\left(\frac{P-c}{1+\gamma}\right) + D(P) - S(P-b)\right] \tag{27}$$

$$p = \frac{P-c}{1+\gamma} \tag{28}$$

$$\tau = \frac{\gamma P + c}{1+\gamma} \tag{29}$$

What do market and policy reactions to technological changes look like

[13] More precisely, the energy price in the first period is $p(1+r)^{-1}$.

now? Implicit derivation of (27) and using (28) and (29) yields

$$\frac{dP}{dc} = \frac{D_1'}{D_1' + (1+\gamma)[D' - S']} \qquad \in (0,1) \tag{30}$$

$$\frac{dp}{dc} = \frac{1}{1+\gamma}\left(\frac{dP}{dc} - 1\right) \qquad \in \left(\frac{-1}{1+\gamma}, 0\right) \tag{31}$$

$$\frac{d\tau}{dc} = \frac{1}{1+\gamma}\left(\gamma\frac{dP}{dc} + 1\right) \qquad \in \left(\frac{1}{1+\gamma}, 1\right) \tag{32}$$

First, a lower c now decreases second period energy price P. Given standard supply and demand function properties the fraction is positive. Intuitively: the amount of CCS used remains the same.[14] To keep conventional energy competitive in period two, the regulator must lower the tax. This makes fossil fuel sales in period two more attractive, fuel prices (and hence energy prices in period one) rise and extraction is postponed.[15]

Secondly, changes in the energy requirement of CCS plants (γ) lead to

$$\frac{dP}{d\gamma} = \frac{G + S - D_1 - D + D_1' \cdot \frac{(P-c)}{1+\gamma}}{D_1' + (1+\gamma)[D' - S']} = \frac{-x^{CCS} + D_1' \cdot \frac{(P-c)}{1+\gamma}}{D_1' + (1+\gamma)[D' - S']} \qquad > 0 \tag{33}$$

$$\frac{dp}{d\gamma} = \frac{1}{1+\gamma}\frac{dP}{d\gamma} - \frac{P-c}{(1+\gamma)^2} \tag{34}$$

$$\frac{d\tau}{d\gamma} = \frac{\gamma}{1+\gamma}\frac{dP}{d\gamma} + \frac{P-c}{(1+\gamma)^2} \qquad > 0 \tag{35}$$

The cost drop for CCS energy requires that the regulator adjusts the tax downward. The energy price in period two must thus fall, and renewable supplies decrease. Both effects make fossil fuel sales in period two more attractive. But as more energy is derived from the constant amount of fossil fuel used for CCS energy, residual demand drops. Thus the final effect on fossil fuel prices is indeterminate. Manipulating (34) yields a condition for

[14] The GHG cap G, the resource stock F and the conversion factor γ are unchanged.

[15] Also, more fossil energy supply in period two decreases P and lowers supplies of renewables.

lower energy costs of CCS leading to a drop in fossil fuel price, which is very similar to the one derived in section 3

$$\frac{dp}{d\gamma} > 0 \quad \Leftrightarrow \quad F - G > (1+\gamma)(P-c)(S'-D') \tag{36}$$

Finally, a change in the cost of renewable energy b gives the following changes

$$\frac{dP}{db} = -\frac{(1+\gamma)S'}{D_1' + (1+\gamma)[D' - S']} \qquad \in (0,1) \tag{37}$$

$$\frac{dp}{db} = \frac{1}{1+\gamma}\frac{dP}{db} \qquad \in \left(0, \frac{1}{1+\gamma}\right) \tag{38}$$

$$\frac{d\tau}{db} = \frac{\gamma}{1+\gamma}\frac{dP}{db} \qquad \in \left(0, \frac{\gamma}{1+\gamma}\right) \tag{39}$$

The expressions are formally almost identical to those in section 3,[16] but mind the difference in interpretation. A cut in b increases supply of renewable energy. P drops. For fossil based energy to be sold in period two, p must go down. The reduction is worth γ more to CCS than to conventional power producers, so τ must be reduced too. As p is also the energy price in period one, more fossils are allocated to the first period.

In summary, the policy instrument in this scenario is incomplete: Conventional power producers in period one pay a zero carbon tax. Hence from the outset more of the fossil resource than socially optimal is extracted in the first period. Table 3 summarizes the results. All improvements again lower the tax and the second period energy price as it becomes cheaper to solve the climate problem. Of most interest is the difference in cost cuts in non-energy costs of CCS c and renewables b on the extraction profile: a smaller c shifts extraction to the second period, while lower b does the opposite.

[16] The denominator is by $\gamma D_1'$ smaller.

Table 3: *Impacts of changes in cost parameters on prices, tax and emissions in period one under taxation in period two only*

	lower c (CCS non-energy)	lower γ (CCS energy)	lower b (renewable)
P (price $t = 2$)	$-$	$-$	$-$
p (price $t = 1$)	$+$	?	$-$
τ (tax)	$-$	$-$	$-$
x_1 (emissions $t = 1$)	$-$	?	$+$

5 Welfare effects of technological changes

In our model, earlier extraction is not worse *per se*.[17] Is it still possible (and likely) that a reduction in c is preferable to a reduction in b due to the intertemporal inefficiency? Yes, provided that the comparison is between parameter changes that give the same total cost reductions. To see this, consider first the welfare effects of an incremental change Δc in the cost of CCS. The total effect on social welfare W (discounted to period 1) is[18]

$$\Delta W = -\left(1+r\right)^{-1} x^{CCS} \Delta c + P_1 \Delta x_1 + \left(1+r\right)^{-1} P \Delta x \tag{40}$$

[17]Hoel (2008) shows that in such a case a lower b may lower welfare.

[18]$W = \int_0^{x_1} P_1(y)dy + (1+r)^{-1} \left(\int_0^{x+x^{CCS}+x^{RE}} P(y)dy - cx^{CCS} - K(x^{RE}) \right)$, where $K(x^{RE}) = bx^{RE} + g(x^{RE})$ are the costs of renewable energy, and $P(y)$, $P_1(y)$ are the inverse demand functions. Taking the differential and noting that $P = K'$ yields the following results.

The first term is the direct cost effect. Initial social CCS costs are cx^{CCS}. The second and third term give the welfare effects of changes in conventional fuel use in period one and two. The changes in these quantities are multiplied by the consumer prices, i.e. the marginal utilities. Changes in the two other energy sources in period two are not included. For renewable energy, consumer price minus marginal costs is equal to zero. CCS energy use does not change with changes in c ($\Delta x^{CCS} = 0$).

Since $\Delta x = -\Delta x_1$ (from $x_1 + x = G$), we may rewrite this expression as

$$\Delta W = -\left(1+r\right)^{-1} x^{CCS} \Delta c + \left[P_1 - \left(1+r\right)^{-1} P\right] \Delta x_1 \tag{41}$$

In the social optimum (section 3) the term in square brackets is zero, so the total welfare effect consists only of the direct effect $-(1+r)^{-1} x^{CCS} \Delta c$. However, when there is no carbon tax in the first period, the model in section 2 implies[19] that the term in square brackets equals $\left(1+r\right)^{-1}\left(-\tau\right)$, giving

$$\Delta W = -\left(1+r\right)^{-1} x^{CCS} \Delta c - \left(1+r\right)^{-1} \tau \Delta x_1 \tag{42}$$

or

$$\Delta W = \left(-\Delta c\right)\left(1+r\right)^{-1} \left[x^{CCS} + \tau \frac{\Delta x_1}{\Delta c}\right] \tag{43}$$

We know that a reduction in c decreases extraction in period 1, i.e. $\frac{\Delta x_1}{\Delta c} > 0$. The second term in square brackets thus adds to the direct positive effect on welfare of reduced costs.

Proceeding in exactly the same way with a change in b, we find

$$\Delta W = \left(-\Delta b\right)\left(1+r\right)^{-1} \left[x^{RE} + \tau \frac{\Delta x_1}{\Delta b}\right] \tag{44}$$

We know that a reduction in b increases extraction in period one, i.e. $\frac{\Delta x_1}{\Delta b} < 0$.

[19] Recall that $P_1 = p_1$, $p = p_1(1+r)$ and $P = p + \tau$.

The second term in square brackets thus reduces the direct positive effect on welfare of reduced costs. For decreases in c and b that give the same total cost reductions, i.e. $\Delta c x^{CCS} = \Delta b x^{RE}$, it follows that reduced costs of CCS increase welfare more than reduced costs of renewables.

Notice also that the term $\left[x^{RE} + \tau \frac{\Delta x_1}{\Delta b}\right]$, and thus ΔW, can be negative if x^{RE} is sufficiently small and $S'(C'(x^{RE}) - b) \geq \bar{s} > 0$ for all $x^{RE} \geq 0$ (where $C' - b$ is the marginal cost of renewables). To see this, rewrite $\frac{\Delta x_1}{\Delta b}$

$$\frac{\Delta x_1}{\Delta b} = \frac{1}{\Delta b}\frac{1}{D_1'}\Delta p = \frac{1}{\Delta b}\frac{1}{D_1'}\frac{dp}{db}\Delta b$$

which after inserting from (38) gives

$$\frac{\Delta x_1}{\Delta b} = \frac{1}{-D_1'}\frac{S'}{D_1' + (1+\gamma)[D' - S']}$$

The term $\frac{\Delta x_1}{\Delta b}$ will have an upward bound that is below zero provided that $S'(C'(x^{RE}) - b) \geq \bar{s} > 0$ for all $x^{RE} \geq 0$. For sufficiently small values of x^{RE} the term $\left[x^{RE} + \tau \frac{\Delta x_1}{\Delta b}\right]$ must therefore be negative (for $\tau > 0$), implying that social welfare declines as a response to reduced costs of renewable energy. The intuition is that for a sufficiently low initial value of renewable energy, the direct effect of the reduced cost is so small that it is dominated by the indirect negative welfare effect of reallocating extraction from the future to the present.

6 Extensions

The model used so far is quite rigid. It has been assumed that: (1) There are no residual emissions from CCS power stations. (2) There is a fixed amount of fossil fuel resources available, all of which can be extracted at the same constant unit cost (set to zero). (3) The level of GHG concentration is exogenous and the timing of emissions is irrelevant. We now relax all of these assumptions for the case of taxation in period two only. We show that the difference between improvements in renewables and CCS persists.

6.1 Residual emissions from CCS

At present, CCS is expected to remove 90 per cent of carbon dioxide emissions. About ten per cent would still reach the atmosphere (IPCC, 2005). In the model, let producing one unit of CCS energy cause δ units of emissions ($\delta \in (0,1)$).[20] Two changes occur. CCS energy producers now pay $\tau\delta$ in carbon tax per unit of energy, and the GHG cap changes to

$$x_1 + x + \delta x^{CCS} = G \tag{49}$$

The amount of CCS used is now

$$x^{CCS} = \frac{F - G}{1 + \gamma - \delta} \tag{50}$$

As emissions from CCS decrease, the total amount of CCS energy does too while the amount of avoided emissions from CCS is constant by assumption.

6.2 Extraction costs

Assume that the extraction costs are independent of the extraction rate, but increase with accumulated extraction. The original model in section 2 treated the limiting case, where we assumed constant (zero) unit cost of extraction combined with an absolute upper limit on accumulated extraction. Total extraction F becomes endogenous.[21]

Formally, we let each unit of the resource be indexed by a continuous variable z, and let $a(z)$ be the cost of extracting unit z, with $a' \geq 0$. In the

[20] Per unit of fossil fuel burned $\hat{\delta}$ emissions are caused, so that $\delta = \hat{\delta}(1+\gamma)$.

[21] This is a specification frequently used in the resource literature, see e.g. Heal (1976) and Hanson (1980).

two-period model x_1 is extraction in period one and $x + x^{CCS}(1+\gamma) = F - x_1$ is extraction in period two. The cost of extracting x_1 is thus given by $A(x_1) = \int_0^{x_1} a(z)dz$, and cost of extracting $F - x_1$ is $\int_{x_1}^{F} a(z)dz = \int_0^F a(z)dz - \int_0^{x_1} a(z)dz = A(F) - A(x_1)$. Notice that these relationships imply that $A'(x_1) = a(x_1)$ and $A'(F) = a(F)$. The limiting case of a constant unit cost a of extraction up to an exogenous limit $\bar{F}$ would imply that $A(x_1) = ax_1$ and $A(F) - a(x_1) = a \cdot (F - x_1)$ (up to $\bar{F}$).

We now simplify and assume that extraction costs are zero for all extraction up to a level f which is larger than the equilibrium extraction in period one, so that $A(x_1) = 0$ for all relevant values of x_1 in period one. Moreover, let extraction costs $a(F)$ be positive and rising for extraction levels above f, so that costs in period two are $A(F)$ which is rising for $F > f$ and strictly convex.

With these assumptions the simple Hotelling rule remains valid, so that the resource price in period one is $(1 + r)^{-1}p$, as before. In the second period, the amount extracted will be determined by $A'(F) = p$, giving F as an increasing function of p: $F = F(p)$ with $F' > 0$. The case treated previously was the limiting case of $F' = 0$.

6.3 Climate costs

Instead of the limit on GHGs G being exogenous, we now let it be determined endogenously. Clearly, total emissions G are important for the climate costs. According to Allen et al. (2009), the peak temperature increase is approximately insensitive to the timing of emissions. However, we would expect this peak temperature increase to occur earlier the more of the emissions occur at an early stage. It also seems reasonable to expect climate costs to be higher the more rapidly the temperature increases, for a given peak temperature increase. Within our model, it thus seems reasonable to assume that climate costs are increasing in the two variables (G, x_1). To make our derivations slightly simpler without changing anything of substance, we assume that the function the climate cost function is given by $E(G + \sigma x_1)$, where E' and σ are positive.

The optimal (Pigovian) carbon tax in period two is

$$\tau = E'(G + \sigma x_1) \tag{51}$$

giving G as

$$G = E'^{(-1)}(\tau) - \sigma x_1 = \Lambda(\tau) - \sigma x_1 \tag{52}$$

If there is no carbon tax in period one, we simply have $x_1 = D_1(p)$.[22]

6.4 The extended model

With residual emissions, extraction- and climate costs, the model now is described by

$$\begin{aligned}
&[1-\delta]F\left(\frac{(1-\delta)P - c}{1+\gamma-\delta}\right) + \gamma\Lambda\left(\frac{\gamma P + c}{1+\gamma-\delta}\right)\\
&= (1+\gamma(1+\sigma)-\delta)D_1\left(\frac{(1-\delta)P - c}{1+\gamma-\delta}\right) + (1+\gamma-\delta)\left[D(P) - S(P-b)\right]
\end{aligned} \tag{53}$$

$$p = \frac{(1-\delta)P - c}{1+\gamma-\delta} \tag{54}$$

$$\tau = \frac{\gamma P + c}{1+\gamma-\delta} \tag{55}$$

In the appendix we show that the main results obtained from the original, simplified model are robust to the extensions discussed here. The qualitative effects of changes in b on prices and carbon tax remain the same (see table 4). An important addition is that the reduced resource price leads to less

[22] If taxes are set optimally also in period one, x_1 will depend on this tax. If $\sigma = 0$ as before $\tau_1 = (1+r)^{-1}\tau$. However, if $\sigma > 0$, the optimal tax in period one will be higher.

cumulative extraction (F goes down). Total emissions and climate damage also decrease (G and E down). The effects of a decline in c on second period energy price P are indeterminate in the extended model. The first period energy price p however rises. This means that the shift in extraction towards the second period still takes place: less is extracted in period one. In addition, more is extracted in total. As the carbon tax also goes down, the climate damage decreases (while total emissions are indeterminate).

Table 4: *Impacts of changes in cost parameters on prices (p, P), tax (τ), early emissions (x_1), fossil fuel extraction (F), total emissions (G) and climate damage (E) in the extended model under taxation in period two only*

	lower c (CCS non-energy)	lower b (renewable)
P (price $t = 2$)	?	$-$
p (price $t = 1$)	$+$	$-$
τ (tax)	$-$	$-$
x_1 (emissions $t = 1$)	$-$	$+$
F (extraction)	$+$	$-$
G (total emissions)	?	$-$
E (climate damage)	$-$	$-$

7 Concluding remarks

We set out to analyze how an improvement in CCS technology influences energy and fossil fuel prices and the timing of GHG emissions, and how it compares to a downwards shift in renewable energy costs. We used a simple two period model that links a market for some stylized fossil fuel to a market for energy. One robust result is that all types of technological improvement give a lower optimal carbon tax in period two. Other effects of technological improvements depend both on the type of technological improvement and on whether climate policy is optimally designed in both periods or only in period two. Key results are summarized in tables 2 to 4. One important conclusion is that if there is no carbon tax in period one, lower non-energy costs for CCS have the opposite effect on period one emissions of lower costs of renewable energy. This is an important difference, as emissions are too high in period one when there is no carbon tax in this period. We showed that the increase in period one emissions resulting from reduced costs of renewable energy might even lead to lower social welfare. A lower non-energy cost of CCS will decrease period one emissions, and therefore always increase social welfare.

As for policy implications, under specific circumstances supporting the development of CCS is preferable from supporting renewables. What are these circumstances? One has to believe that a future climate policy will come into being. Second, fossil fuel producers' ability to reallocate production needs to be large enough for the effect to matter. Also, both technologies are assumed to be available on sufficient scale at the same time. If renewables are ready earlier (or later), the picture changes. And if one believes that climate policy will not even be implemented in the future, supporting renewables may be preferable for another reason: they at least potentially can compete with conventional energy, while CCS will always impose an additional cost.

References

Al-Juaied, M. and A. Whitmore (2009). Realistic Costs of Carbon Capture. Discussion Paper 2009-08, Energy Technology Innovation Research Group, Belfer Center for Science and International Affairs, Harvard Kennedy School.

Allen, M. R., D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen, and N. Meinshausen (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature 458*(7242), 1163–1166.

Ayong Le Kama, A., M. Fodha, and G. Lafforgue (2009). Optimal carbon capture and storage policies. TSE Working Papers 09-095, Toulouse School of Economics (TSE).

Barrett, S. (2005). The theory of international environmental agreements. In K.-G. Mäler and J. R. Vincent (Eds.), *Economywide and International Environmental Issues*, Volume 3 of *Handbook of Environmental Economics*, pp. 1457–1516. Elsevier.

Barrett, S. (2009). The Coming Global Climate-Technology Revolution. *Journal of Economic Perspectives 23*(2), 53–75.

Chakravorty, U., A. Leach, and M. Moreaux (2010). Would Hotelling Kill the Electric Car? TSE Working Papers 09-149, Toulouse School of Economics (TSE).

Chakravorty, U., B. Magne, and M. Moreaux (2006). A Hotelling model with a ceiling on the stock of pollution. *Journal of Economic Dynamics & Control 30*(12), 2875–2904.

Chakravorty, U., B. Magne, and M. Moreaux (2008). A dynamic model of food and clean energy. *Journal of Economic Dynamics & Control 32*(4), 1181–1203.

Di Maria, C., S. Smulders, and E. van der Werf (2008). Absolute Abundance and Relative Scarcity: Announced Policy, Resource Extraction, and Carbon Emissions. Working Papers 2008.92, Fondazione Eni Enrico Mattei.

Eichner, T. and R. Pethig (2009). Carbon Leakage, the Green Paradox and Perfect Future Markets. CESifo Working Paper Series 2542, CESifo GmbH.

Gerlagh, R. (2010). Too Much Oil. Working Papers 2010.14, Fondazione Eni Enrico Mattei.

Golombek, R., M. Greaker, S. Kittelsen, O. Røgeberg, and F. R. Aune (2009). Carbon capture and storage technologies in the European power market. Discussion paper 603, Statistics Norway, Research Department.

Grafton, R. Q., T. Kompas, and N. V. Long (2010). Biofuels subsidies and the green paradox. CESifo Working Paper Series CESifo Working Paper No. 2960, CESifo Group Munich.

Hanson, D. A. (1980). Increasing Extraction Costs and Resource Prices: Some Further Results. *The Bell Journal of Economics 11*(1), 335–342.

Heal, G. (1976). The Relationship between Price and Extraction Cost for a Resource with a Backstop Technology. *The Bell Journal of Economics 7*(2), 371–378.

Heal, G. (2009). The Economics of Renewable Energy. NBER Working Papers 15081, National Bureau of Economic Research.

Hoel, M. (2008). Bush Meets Hotelling: Effects of Improved Renewable Energy Technology on Greenhouse Gas Emissions. CESifo Working Paper Series 2492, CESifo GmbH.

Hoel, M. (2010). Is There a Green Paradox? CESifo Working Paper Series 3168, CESifo.

Hoel, M. and S. Kverndokk (1996). Depletion of fossil fuels and the impacts of global warming. *Resource and Energy Economics 18*(2), 115–136.

IPCC (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Technical report, Intergovernmental Panel on Climate Change.

Islegen, O. and S. Reichelstein (2009). Carbon capture by fossil fuel power plants: An economic analysis. Research papers, Stanford University, Graduate School of Business.

Lohwasser, R. and R. Madlener (2009). Impact of ccs on the economics of coal-fired power plants: Why investment costs do and efficiency doesn't matter. FCN Working Papers 7/2009, E.ON Energy Research Center, Future Energy Consumer Needs and Behavior (FCN).

Long, N. and H.-W. Sinn (1985). Surprise Price Shifts, Tax Changes and the Supply Behavior of Resource Extracting Firms. *Australian Economic Papers 24*(45), 278–289.

MacKay, D. J. (2008). *Sustainable Energy – without the hot air.* UIT Cambridge.

Meinshausen, M., N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen (2009). Greenhouse-gas emission targets for limiting global warming to 2C. *Nature 458*(7242), 1158–1162.

Røgeberg, O., B. Holtsmark, and S. Andresen (2010). International climate treaties – the case for pessimism. *Climate Law 1*(1), 177–197.

Sinclair, P. J. N. (1994). On the optimum trend of fossil fuel taxation. *Oxford Economic Papers 46*(0), 869–77.

Sinn, H.-W. (2008). Public Policies against global warming: a supply side approach. *International Tax and Public Finance 15*, 360–394.

Smulders, S. and E. van der Werf (2008). Climate policy and the optimal extraction of high- and low-carbon fossil fuels. *Canadian Journal of Economics 41*(4), 1421–1444.

Socolow, R. and S. Lam (2007). Good enough tools for global warming policy making. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365*(1853), 897–934.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, T. M., and H. Miller (2007). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC*. Cambridge University Press.

Strand, J. (2007). Technology treaties and fossil-fuels extraction. *The Energy Journal 28*(4), 129–142.

Tahvonen, O. (1997). Fossil fuels, stock externalities, and backstop technology. *Canadian Journal of Economics 30*(4), 855–74.

Ulph, A. and D. Ulph (1994). The optimal time path of a carbon tax. *Oxford Economic Papers 46*, 857–68.

Van der Ploeg, F. and C. A. Withagen (2010). Is there really a green paradox? CESifo Working Paper Series CESifo Working Paper No., CESifo Group Munich.

van der Werf, E. (2009). International carbon leakage with a non-renewable resource. Conference proceedings, EAERE Conference 2009 Amsterdam.

Withagen, C. (1994). Pollution and exhaustibility of fossil fuels. *Resource and Energy Economics 16*(3), 235–242.

A Appendix: solving the extended model

We focus on the effects of reducing the CCS non-energy costs c and the costs of renewables b. Again, with the changes from section (6) the model is

$$
\begin{aligned}
&[1-\delta]F\left(\frac{(1-\delta)P-c}{1+\gamma-\delta}\right)+\gamma\Lambda\left(\frac{\gamma P+c}{1+\gamma-\delta}\right) \\
&=(1+\gamma(1+\sigma)-\delta)D_1\left(\frac{(1-\delta)P-c}{1+\gamma-\delta}\right)+(1+\gamma-\delta)\left[D(P)-S(P-b)\right]
\end{aligned}
\tag{A.1}
$$

$$
p=\frac{(1-\delta)P-c}{1+\gamma-\delta} \tag{A.2}
$$

$$
\tau=\frac{\gamma P+c}{1+\gamma-\delta} \tag{A.3}
$$

Implicit differentiation of (A.1) with respect to b gives

$$
\frac{dP}{db}=\frac{-(1+\gamma-\delta)^2 S'}{[1+\gamma(1+\sigma)-\delta](1-\delta)D_1'+(1+\gamma-\delta)^2\left[D'-S'\right]-(1-\delta)^2F'-\gamma^2\Lambda'} \tag{A.4}
$$

The expression is positive (note that $\Lambda' > 0$ and $F' > 0$) and bounded above by one. This mirrors the results in the original model. Likewise do the effects on p and τ which can be obtained by inserting (A.1) in differentials of equations (A.2) and (A.3) respectively. Again the first period energy (and resource) price p goes down in response to a reduction of the costs of renewables, and so does the tax τ. Differentiating with respect to c we get

$$
\frac{dP}{dc}=\frac{[1+\gamma(1+\sigma)-\delta]D_1'-(1-\delta)F'+\gamma\Lambda'}{[1+\gamma(1+\sigma)-\delta](1-\delta)D_1'+(1+\gamma-\delta)^2\left[D'-S'\right]-(1-\delta)^2F'-\gamma^2\Lambda'} \tag{A.5}
$$

The effect on the second period price is ambiguous as the numerator contains negative as well as positive terms. It is positive if

$$(1-\delta)F' - [1+\gamma(1+\sigma)-\delta]D_1' > \gamma\Lambda' \tag{A.6}$$

In comparison, in the original model the effect was always positive. We observe that the ambiguity stems from the endogenization of the GHG cap G (in the original model we had $\Lambda' = 0$). Introducing extraction costs of the form $A(F)$ in period two does not change the qualitative results from the original model. The change in p can again be calculated from (A.2)

$$\frac{dp}{dc} = \frac{1}{1+\gamma-\delta}\left[(1-\delta)\frac{dP}{dc} - 1\right] \tag{A.7}$$

The effect is negative: If (A.5) is negative, it follows immediately. If (A.5) is positive, it needs to be true that $(1-\delta)\frac{dP}{dc} < 1$ for the effect to still be negative, so we require that

$$\begin{aligned}&[1+\gamma(1+\sigma)-\delta](1-\delta)D_1' - (1-\delta)^2F' + (1-\delta)\gamma\Lambda' \\ &> [1+\gamma(1+\sigma)-\delta](1-\delta)D_1' + (1+\gamma-\delta)^2\,[D'-S'] - (1-\delta)^2F' - \gamma^2\Lambda'\end{aligned} \tag{A.8}$$

Simplifying

$$[(1-\delta)\gamma + \gamma^2]\Lambda' > (1+\gamma-\delta)^2\,[D'-S'] \tag{A.9}$$

The last equation is always true. So the first period energy price rises in response to a fall in non-energy costs of CCS. Thus the main finding of the original model is robust towards the discussed generalizations.

In addition, it follows from $F'(p) > 0$ that the total amount of fossil resources extracted falls with lower costs of renewables and rises in response to cheaper CCS.

The effect on the carbon tax τ is (from A.3)

$$\frac{d\tau}{dc} = \frac{1}{1+\gamma-\delta}\left(\gamma\frac{dP}{dc}+1\right) \tag{A.10}$$

We see that if $\gamma\frac{dP}{dc} > -1$, then like in the original model the tax decreases in response to lower non-energy costs of CCS. Inserting and rearranging

$$\begin{aligned}&\gamma(1+\gamma(1+\sigma)-\delta)D_1' - \gamma(1-\delta)F' \\ &< -[1+\gamma(1+\sigma)-\delta](1-\delta)D_1' - (1+\gamma-\delta)^2\left[D'-S'\right] + (1-\delta)^2F'\end{aligned} \tag{A.11}$$

(A.11) shows that the inequality always holds. The LHS contains only negative terms, the RHS only positive ones. In line with the original model, the tax decreases in response to lower non-energy costs of CCS.

We can now also ask how the GHG stock in the atmosphere the climate costs are affected. The model produces reasonable effects: (52) states

$$G = \Lambda(\tau) - \sigma D_1(p)$$

We assume $\sigma > 0$. A reduction in b hence decreases G (both p and τ fall), while a reduction in c has an ambigious effect (due to p rising). Less early emissions decrease the additional harm they cause (as expressed by $\sigma > 0$), hence opening up for increased total emissions. The effect on climate costs can be read out of its definition (equation 51)

$$\tau = E'(G + \sigma x_1)$$

As τ falls in response to a lower b or c, so must E'. Since E is increasing and strictly convex, a lower derivative indicates lower total climate costs.