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by Daiju Narita

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Keywords: Carbon capture and storage (CCS), climate change, energy, integrated assessment models, dynamic optimization

JEL classification: Q32, Q43, Q54

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Simulation with the DICE Model

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August 2008

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Abstract

This study attempts a numerical simulation of potential CCS (carbon dioxide capture and storage) use by using a modified version of the DICE (Dynamic Integrated model on Climate and Economy) model (Nordhaus, 1994; Nordhaus and Boyer, 2000). In DICE, CO_2 emissions are controlled to the extent in which a hypothetical optimal carbon tax justifies CO_2 reduction by firms: in our analysis, CCS is used when the optimal tax level is higher than the price of CCS. The analysis assesses the economic optimality of CCS use with a range of different assumptions. The simulation particularly focuses on the difference of results originating from two sets of general assumptions on climate change modeling, reflecting the current debate on the economics of climate change (see for example, Heal, 2008): (1) Parameterization of the standard DICE; (2) Alternative assumptions whose hints are drawn from Stern (2007). In the standard DICE cases, the model calculation shows that at the price level of \$25/tCO_2 (\$92/tC), CCS is introduced around in the middle of the twenty-first century. With the alternative assumptions (e.g., near-zero discount rate), CCS begins to be utilized massively earlier in the century. The two sets of results lead to contrasting policy implications on the future CCS use; this is particularly problematic in the CCS context since its benefits are not always clear-cut (e.g., limitedness of secondary benefits besides CO_2 reduction, uncertainties about the validity of technology itself). Settlement of the current intellectual debate on the economics of climate change would greatly benefit the debate on the role of CCS as well.

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Introduction

With a growing recognition that climate change is a real policy issue involving significant control of greenhouse gas emissions, many policymakers are beginning to consider stringent policies to reduce greenhouse gases which lead to emission levels less than a half of the current ones by the mid-century.[1] Meanwhile, the experience of the Kyoto Protocol system in recent years suggests that a number of countries face political, if not technical or physical, challenges in reducing even minor amounts of greenhouse gas emissions – a notable example is the United States, which even failed to ratify the Protocol. As a response to this dilemma of perceived needs for strong long-term emission control and actual difficulties to reduce emissions, many climate change experts are beginning to pay attention to carbon dioxide capture and storage[2] (CCS), an emerging technology for carbon dioxide (CO_2) emissions reduction. CCS is a set of techniques of separating and capturing CO_2 from emission sources, transporting it to storage sites, and storing it in secure locations semi-permanently in order to reduce atmospheric CO_2 emissions (for a technical review of CCS, see IPCC, 2005). CCS is not yet fully developed to accommodate widespread use in various types of location, but there already exist several commercial-scale projects across the world. Although CCS generally provides little auxiliary benefit besides CO_2 reduction (except for enhanced oil recovery, which provides additional oil production), the concept is relatively straightforward from

[1] Such proposals have been issued by the European Commission (50% reduction of greenhouse gases from the 1990 levels by 2050), the British government (60% reduction of CO_2 emissions from the current level by 2050), and the State of California (80% reduction of greenhouse gases from the 1990 levels by 2050), to name a few.

[2] Carbon dioxide capture and storage is also called *carbon capture and storage*, or *carbon capture and sequestration* (the abbreviation is the same: CCS).

the technological standpoint, given the wealth of fossil fuel extraction or mining technologies already accumulated. Another strength of CCS is the fact that its reducing potential is expected to be very large; for example, the IPCC has estimated that CCS could sequester at least 2,000 gigaton (Gt) of CO_2, the amount comparable with the total global CO_2 emissions for several decades at the current annual level of emissions (IPCC, 2005). In accordance with the growing recognition of CCS in the policy circles, a number of influential academic studies have been issued over the last several years with regard to the potential role of CCS in future climate policy (Pacala and Socolow, 2004; Lackner and Sachs, 2005; IPCC, 2005; Stern, 2007; MIT, 2007). All these studies argue that CCS is an important, in some circumstances indispensable, mitigation option which deserves a serious look, although there is some variance in opinions about the possible scale and timing of CCS's introduction.

Another development in recent climate change debates is the publication of the Stern Review (2007), which catalyzed an extensive debate on the economics of climate change. A number of fundamental conceptual issues on this matter are raised by various prominent economists in response to the Review (a detailed review of the debate is given by Heal, 2008). A fact that was clarified over the debate is that long-term cost-benefit estimates of climate change and policy (whose examples include Cline, 1992, Nordhaus, 1994, and Stern's own analysis) can produce very different results even if their general methodology (intertemporal cost-benefit analysis) is the same. A well-cited example is the difference in optimal climate policy calculated by Nordhaus's and Stern's simulation models: the former predicts that gradual tightening of carbon emissions is the best policy, while the latter calls for much stronger actions immediately. Such significant differences in the estimates in fact could arise from relatively small changes in assumptions, such as the choice of pure time preference.

The critical scrutiny about the fundamentals of the economics of climate change in the post-Stern debate is in a striking contrast with the concurrent discussions about the potential role of CCS in carbon management, whose participants assume some urgent needs of deep CO_2 reduction more or less *a priori*. This study attempts to bridge the gap between the two sets of scholarship in examining the question of optimality regarding CCS use, namely, when and how much CCS should be used. In the analysis, we use the 2007 version of DICE (Dynamic Integrated model of Climate and the Economy), which is one of the most widely used optimization models in the field and whose parameterization is well scrutinized by various preceding studies. We simulate the future use of CCS with alternative assumptions (such as those following Stern's reasoning) as well as Nordhaus's original assumptions. The main claim of this paper will be that this CCS's optimality question is not clear-cut as it is inseparable from the fundamental conceptual questions on the economics of climate change, whose consensus is yet to be made.

To be sure, there are a number of precedent works that simulated potential application of CCS (in addition to the above-listed works: Keller et al., 2003; Ha-Duong and Keith, 2003; Riahi et al., 2004; Smekens and van der Zwaan, 2006; Gerlagh and van der Zwaan, 2006; van der Zwaan and Smekens, 2007). However, with the exception of Keller et al.

and Stern, all the works adopt some arbitrary emission targets or scenarios and thus cannot be directly contrasted with the insights of the current conceptual debate on the economics of climate change. For example, Ha-Duong and Keith (2003) and Gerlagh and van der Zwaan (2006) discuss the optimality of potential CCS use by using a discounted utility framework, but they assume some arbitrary stabilization targets of greenhouse gas concentrations in their modeling. Also, Riahi et al. (2004), Smekens and van der Zwaan (2006), and van der Zwaan and Smekens (2007) do not examine the optimality of CCS use but instead take scenario approaches conducting simulation with some given scenarios of future energy use and policy targets. Meanwhile, one should be reminded that Stern's review naturally does not investigate the counterarguments to his approach appeared after the release of the report, and also that CCS is only one item of the wide range of issues discussed in the Review, and consequently its analysis on this subject is limited.

The approach of our following analysis is similar to the one by Keller et al. (2003), who discussed the impacts of CCS in carbon management by using the RICE model, the sister model of the DICE. However, there are a few important differences between the two. First, as a reflection of growing scholarship on climate change over the last several years, the model assumptions Keller et al. adopt seem too optimistic even relative to Nordhaus's own parameterization for the latest DICE. In the results by Keller et al., CCS only comes into play after 2100, which is seriously off the range of opinions in the current discussions of CCS's application (the current version of DICE indeed produces less optimistic results, as we will see). In fact, their study wisely does not explore the CCS's timing question deeply and instead limit their discussion to conceptual matters (effects of leakage and technological change on the model results). This in turn means that their results give little insight about current policy debates on CCS in the context of application within the next several decades. Second, Keller et al. simply adopt Nordhaus's original assumptions of general modeling and make no comparison with other sets of assumptions. As discussed earlier, Nordhaus's view does not necessarily fall onto the middle of the current variety of opinions, and alternative assumptions can lead to very different conclusions. Third, a number of other works came out since the release of their paper, a newer study of optimization analysis can make comparisons of results by different works with adequate sensitivity analysis.

Method

We use the 2007 version of the DICE model to simulate future potential use patterns of CCS and their economic and climatic impacts. The programming code is open to the public on Professor Nordhaus's website (http://nordhaus.econ.yale.edu/) and written in GAMS (General Algebraic Modeling System). The detailed description of the DICE model is given by Nordhaus (1994) and Nordhaus and Boyer (2000). We incorporate additional variables into this model and modify some functions.

Here we summarize the major features of the DICE model. The DICE is essentially a Ramsey model, which maximizes the sum of discounted utility over time with climatic feedback. In the model, the externality of climate change is internalized by an optimal carbon tax equivalent with the social shadow price of carbon dioxide (corresponding to its negative environmental effects). The effect of tax is translated into the control rate of carbon, representing the proportion of CO_2 emissions to deal with the tax burden. Meanwhile, uncontrolled emissions of CO_2 are a declining function of gross output as an effect of energy-efficient technological change (the effect of "decarbonization").

The industrial carbon dioxide emission[3] $E(t)$ is thus a function of gross output and the decarbonization parameter and is expressed as follows:

$$E(t) = (1 - \mu(t))\sigma(t)Y(t)$$

where $\mu(t)$ is the control rate, $\sigma(t)$ the industrial CO_2 emissions to output ratio, $Y(t)$ the output gross of climate damage and abatement costs.

The damage of climate change is formulated as the fractional loss of gross output due to global average temperature increase. In assessing the magnitude of damages, the DICE considers the following seven potential causes of economic damage from climate change: agriculture, sea-level rise, effects on other market sectors, health, non-market amenity

[3] Another source of carbon dioxide emissions is forests (e.g., deforestation). In the DICE, emissions from forests are determined exogenously.

impacts, human settlements and ecosystems, and catastrophes. The damage function $D(t)$ is a parameter linking the gross output $Y(t)$ and the net output (climate change damage subtracted) $Q(t)$, represented in the following relationship:

$$Q(t) = \frac{1}{1 + D(t)} \cdot (1 - AC(t)) \cdot Y(t)$$

where $AC(t)$ is the abatement cost.

The abatement cost of carbon emissions in the model is calculated according to the following function:

$$AC(t) = b_1(t)\mu(t)^{b_2} Y(t)$$

where $Y(t)$ is the gross output, μ is the control rate, and b_1 and b_2 are coefficients.[4] The control rate is the fractional reduction of CO_2 emissions relative to uncontrolled emissions (the hypothetical rate of emissions without the carbon tax). Note that the coefficient b_1 equals the cost of backstop as a ratio to the gross output (i.e., if one pays b_1 $Y(t)$ for backstop, one can reduce CO_2 emissions to zero). The model assumes that the

[4] The abatement cost comes from the direct short-term welfare loss incurred by the introduction of the carbon tax. In other words, the cost represents the direct impact of tax on production exclusive of all the long-term environmental impacts (akin to deadweight loss), although in optimal carbon control, the net welfare impact of carbon tax is always positive (note that if one focuses on the net effects, there is no such thing as "mitigation costs" in optimal carbon dioxide reduction since mitigation is by definition carried out to increase social welfare). It should be noted that this cost does not directly represent deployment costs of energy-saving technologies but rather means the net loss welfare due to decrease in energy use and consequently production.

coefficient b_1 slowly declines over time (in 2005, the backstop cost is set as \$1,170/tC). The economy eventually ceases its use of fossil fuel by exhausting it (set as 6,000 GtC in total) and shifting its economy to the one based on the backstop technology.

In the current debate of the economics of climate change, one of the most debated issues is the choice of the pure time preference, a human preference parameter which represents how much the future is important for us in comparison to the present (in other words, the degree of impatience or myopia). DICE is criticized for its high pure time preference, especially relative to Stern's, which is set as near zero (0.1% per year) on the normative ground. In fact, in earlier versions of the DICE, the time preference was set as 3% at the initial year, and then the rate declines by 0.257% per year. The major justification for the level of the initial time preference (3% per year) was consistency with statistical evidence of market interest rates.[5] Partly responding to the recent criticism, the 2007 version of the DICE lowered the time preference to 1.5% per year (while setting the elasticity of marginal utility as 2) [6]. Still, some conceptual difference remains clearly between DICE's approach and the normative zero discount rate.[7] As we discuss later, as alternative runs, we modulate the time preference parameter.

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[5] At equilibrium in a competitive economy, the interest rate meets the following condition, $r = \rho + \eta g$, where r is the interest rate, ρ is the time preference, η is the elasticity of marginal utility, and g is the consumption growth rate. If ρ is 3% and η is 1, r = 6% and g = 3%, which roughly match actual statistics, satisfy the condition. It should be noted, however, that there is criticism about the validity of this way of argument. See Heal (2008).

[6] Coupled with the debate on pure time preference, there is also some discussion about appropriate levels of the elasticity of the marginal utility. For discussion, see Dasgupta (2007).

[7] By following the classification by Arrow et al. (1996), they are taking fundamentally different approaches to assess the pure time preference: Stern is taking the prescriptive approach, while Nordhaus is taking the descriptive approach.

We modify the model to incorporate CCS simply by adding terms representing reduced emissions by CCS and additional costs from running CCS processes. Now, the modified industrial carbon dioxide emissions ($E(t)$) correspond to the ones which would be produced without CCS ($E_{NOCCS}(t)$) minus the ones reduced by CCS ($E_{CCS}(t)$).

$$E(t) = E_{NOCCS}(t) - E_{CCS}(t) = (1 - \mu(t))\sigma(t)Y(t) - E_{CCS}(t)$$

Meanwhile, the operation of CCS incurs some cost and reduces the net output.

$$Q(t) = \frac{1}{1 + D(t)} \cdot (1 - ACP(t)) \cdot Y(t) - p_{CCS}(t)E_{CCS}$$

where $p_{CCS}(t)$ is the unit cost of CCS operation.

Note that in this formulation, the operation of CCS is considered to generate pure costs for the economy (assuming profits of CCS, such as oil production from enhanced oil recovery, are negligible).

The time horizon of simulation is the years 2005 to 2585, and the time step is 10 years. In this study, however, computational outputs beyond 2105 will not be shown because the accuracy of numbers is expected to be low.[8]

[8] For example, Nordhaus and Boyer note that agreement of outputs from the DICE models with those from the RICE model, the other version of their climate-economy integrated assessment models, is not well after the first 150 years of model runs.

Description of Cases

We simulate the optimal use of CCS with DICE. In parallel with cases with the parameterization of the standard DICE, we also consider cases with alternative assumptions of climate change modeling, such as those with a low discount rate (Stern's assumption) and higher climate change damage. For each group, we calculate several sub-cases with additional assumptions specific to CCS. Below are detailed descriptions of cases.

1. Simulations with DICE's standard formulations on climate change modeling

Case 1-a. Base run

In this analysis, we carry out several runs in terms of optimal use patterns of CCS. The base run of the model corresponds to the optimal economic path with the most efficient carbon tax levels (carbon control rate) in presence of CCS.

For calculation of this case, we simply adopt the figures that Nordhaus used for parameterization except those relevant to CCS. Parameters regarding CCS are set as follows: The marginal cost of CCS use is set as \$25/tCO_2 (\$92/tC), a number within the range of estimates by IPCC and others and a common number used by other CCS simulation studies. For simplicity, we assume that this marginal cost neither increases nor decreases over time due to technological change or temporal relocation of operation to less accessible CCS storage sites – the effects on which there is no robust quantitative estimate at the moment. Meanwhile, in the model, carbon dioxide is permanently stored and there is no leakage from reservoirs. Another assumption is that CCS can remove all the industrial CO_2 emissions. It should be noted that this looks a somewhat cavalier assumption if one considers applications of CCS in the short run: currently, CCS is thought to be applied only to coal or gas power generation and irrelevant to other forms of fuel use such as transportation. However, it would be fair to assume that this sector specificity of CCS will be relaxed over a few decades because of multiple reasons, such as the use of hydrogen as a secondary energy carrier or development and penetration of plug-in electric vehicles. These assumptions on CCS are set unchanged throughout all the following runs unless indicated otherwise. Finally, as an assumption specific to Case 1-a, there is no constraint in resource size of CCS, while fossil fuel, which is always used when CCS is used, does have a resource size limit of 6,000 GtC as in the original DICE model.

Case 1-b. Optimal use with a total capacity constraint on CCS

Note that the no-resource-limit of CCS assumption is in fact a very strong assumption – this means that a backstop technology for carbon emissions is usable just at the price of $25 per ton CO_2. As for the second run of the model (Case 1-b), we introduce a total resource constraint in the use of CCS. The limit is set as 600 GtC, roughly corresponding to a representative number of total global potential for CCS that the IPCC 2005 Report presented, 2,000 $GtCO_2$ (545 GtC).[9]

Case 1-c. Optimal use – high CCS unit cost

A conservative number for the price of CCS operation, \$40/tCO_2 (\$147/tC), is used. The other parameters are the same as in Case 1-b.

Case 1-d. Gradual introduction of CCS

The DICE being an optimization model does not include detailed formulations of the energy sector, and thus its original model does not calculate small-scale introduction of CCS, which many economic studies on CCS focus their analysis on. However, a minor, parsimonious modification could make the DICE capable to simulate gradual CCS deployment and thus comparable to other studies' arguments discussed above. In the modified case, CCS is only applied to new (fossil-fuel-burning) facilities (in other words, retrofitting is assumed to be too expensive to be put in practice[10]), and the facilities are assumed to have a 40-year lifetime. CCS may be operated in newly built facilities

[9] This figure is based on inference by the authors of report from the existing body of literature. It should be noted that assessment data of CCS's capacity are still very sparse, especially for the developing regions.

[10] Alternatively, it is possible to assign a specific operational CCS cost for retrofitting plants (say, \$50 per tCO_2). With this alternative assumption, the use of CCS is more pronounced (especially in later periods) relative to the results shown in Figure 8.

accommodating increases of energy demand or in replaced old plants just having terminated their 40-year life. Limitation in the size of introduction results in gradual penetration of CCS (approximately +2GtC per decade).

2. Alternative assumptions on the economics of climate change

Case 2-a. Optimal use – Stern's near-zero discount case

Stern (2007) argued that only zero time preference is justifiable from the ethical standpoint and sets the time preference as 0.001 (0.1%) per year in his estimates,[11] which is distinctively different from the formulation of the DICE (the 2007 version sets the pure time preference as 1.5% per year). In this run, we use the discount rate of 0.1% per year by following Stern's formulation.[12] The unit cost of CCS is again $25 per ton CO_2, and CCS opportunities have a total limit of 600GtC.

[11] The actual time preference Stern used is a little higher than zero as it accounts for the hazard rate of disappearance of humans as species – if all of us disappeared, we would not need to consider consequences of the periods beyond.

[12] To be consistent with Stern's discussion, in this run, the elasticity of marginal utility is set as 1, as opposed to 2 used in the other cases, although this parameter choice by Stern is debated (see for example, Dasgupta, 2007).

Case 2-b. Stern's near-zero discount with high CCS cost

This is a low-time-discount run with a higher unit operational cost of CCS at $40/t$CO_2$. All the other assumptions are the same as in Case 2-a.

Case 2-c. Gradual introduction of CCS with Stern's near-zero discount rate

In this case, we consider possible gradual implementation of CCS with a low discount rate by taking the same approach to Case 1-d's. All the other assumptions are the same as in Case 2-a.

Case 2-d. Optimal case – climate damage tripled

DICE's estimation of median climate change damages are not necessarily set low in comparison to those of most other integrated assessment models, although it might be neglecting some socially contingent damages (reviewed in Chapter 6.3., Stern, 2007). Nonetheless, Stern (2008) implies that the DICE might be still significantly underestimating the damages purely because of its deterministic modeling scheme.[13] He

[13] His argument is based on the reasoning that climate change damage is approximated in a power function of temperature (in the form of AT^{γ} where T is the temperature, γ is the exponent representing the economy's vulnerability to temperature change, and A is a fixed coefficient). He argues that both the temperature (T) and the exponent of the power function (γ) have uncertainties, and that the damage estimated from expected values of these parameters is significantly less than the real expected value (mathematically, $E[T]^{E[\gamma]} < E[T^{\gamma}]$), as the worst cases (high T and high γ), however low in likelihood, exhibit extremely large damages and thus are influential on the expected value in driving the value up. In the standard formulation of Stern's

comments that "replacing all random variables in the PAGE [an integrated assessment model that he is using] model by their modes brings down the central case of damages from BAU [business as usual] from 10-11% to 3-4%" (Stern, 2008, p50). The deterministic DICE and findings of stochastic modeling are not directly linkable, and modeling with uncertainties in the climate change context involves some conceptual issues whose consensus has yet to be made (see Heal, 2008). Given these caveats, though, it gives at least a fair reason to conduct a sensitivity run with higher damage.[14] With this logic, in this case, we triple the DICE's climate damage parameter.

Case 2-e. Emission limit case

This case is not strictly to calculate optimal scenarios since it uses an arbitrary target, but is a reference run to be compared with the results of existing studies. In this case, the global carbon dioxide emissions (including those from forests) are controlled at 7 GtC per year, the same in spirit as Pacala and Socolow's (2004) influential proposal. They discussed possibility of CCS's immediate introduction from their base year, the year 2004. They argue that the use of CCS should start at the present (the year 2004) and gradually increase by 2054. They considered "stabilization wedges," each of which represents a triangle whose vertical span is zero at the year 2004 and linearly increased to 1GtC at

PAGE model, the exponent is defined by a triangular probability distribution, with minimum of 1, a mode of 1.3, and a maximum of 3 (Stern, 2007, p660). Meanwhile, DICE's damage function takes a quadratic form (γ=2 plus a linear term).

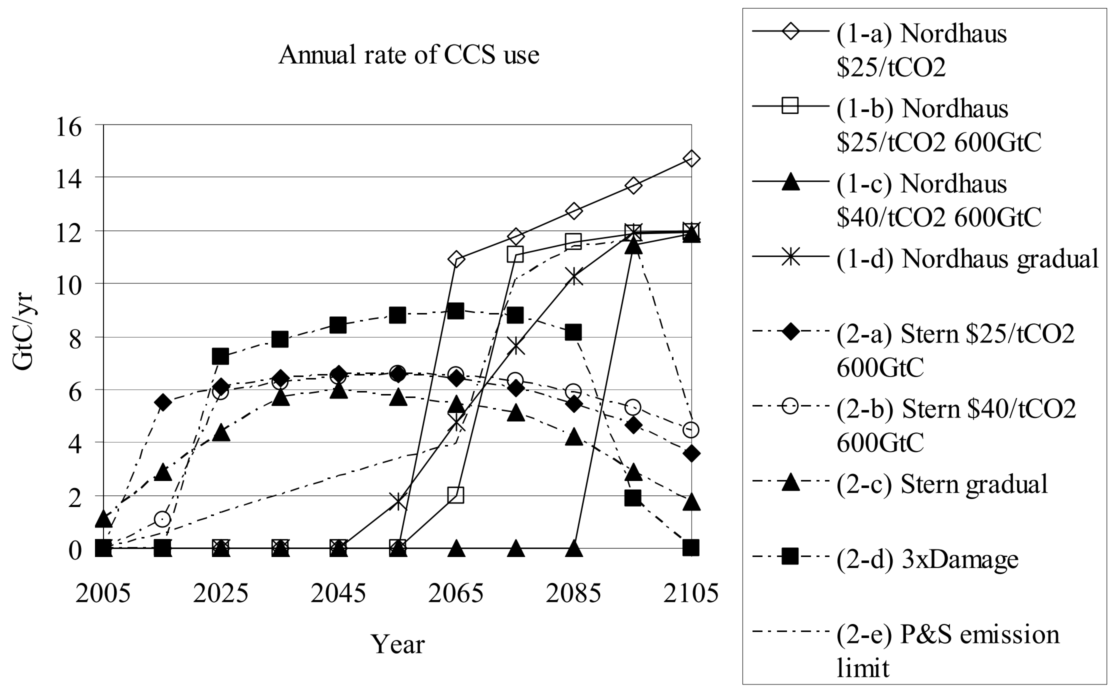
[14] In fact, there is also another factor that could aggravate estimates of climate damage: the economic damage from the loss of environmental stocks, which is not explicitly assessed in the standard DICE. See Sterner and Persson (2008).

2054. They estimated that CCS could make up one to a few of these triangles; in other words, CCS is operated by 1 to a few GtC annually at the year 2054, and used by around 25 to 75 GtC in total by that year. Case 2-e is to show how this proposal could be interpreted in the framework of DICE.

Results and Discussion

The trends of annual rate of CCS use for all cases are shown in Figure 1. In the base run (Case 1-a), CCS starts at 2065 and sequesters most of the industrial carbon dioxide emissions after that year (Figure 1 and Figure 2-a). At 2065, 0.6% of output (world GDP) is spent for implementation of CCS. This abrupt shift around a particular year is a consequence of model assumptions and persistent in most model runs. In calculation, the unit cost of CCS is set as independent of the amount used. Thus, when the carbon tax is higher than the price, CCS is extensively used and in fact makes CO_2 emissions zero. In contrast, CCS use is zero in the opposite case. Abrupt introduction of CCS is observed also in the preceding optimization studies, especially Keller et al. (2003) and Ha-Duong and Keith (2003), although their results show slightly smoother paths since they incorporate scale effects of CCS costs which make the costs comparatively high at the beginning and therefore slow the speed of penetration.

Figure 1. Annual rate of CCS use (all cases)



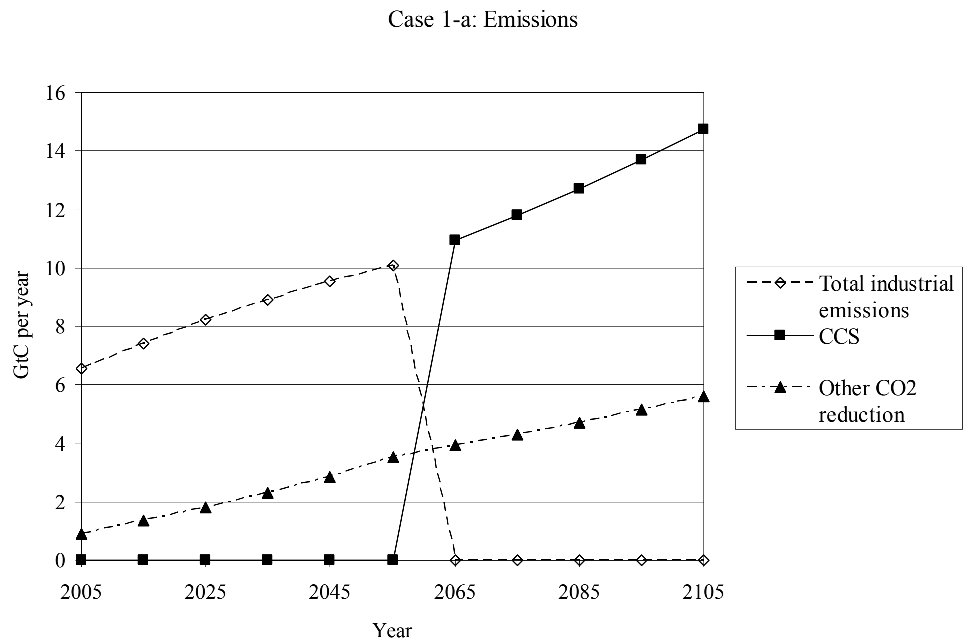
As shown in Figure 2(ii), the year 2065 in Case 1-a corresponds to the time when the optimal carbon tax reaches the level of the CCS unit cost. After 2065, carbon tax is fixed at the level of CCS unit cost (\$25 tCO_2 or \$92 tC) since CCS as the backstop remove all the CO_2 forever at that price level.

In Case 1-a, massive use of CCS after 2065 limits carbon dioxide concentrations below 450ppm at 2105, while concentrations has a peak of 514 ppm at 2065 and then experience a decline due to the equilibrium of partial pressure with the ocean (Figure 2(iii)).[15] Consequently, by the end of the century, temperature change (relative to 1900) is controlled around 2°C – this conversely means that climate could be controlled below 2°C or the 550ppm level if CCS can be unlimitedly implemented at this price. Meanwhile, the use of fossil fuel (equivalent with the sum of carbon emissions and CCS use) is clearly larger in the presence of CCS, and the carbon control (carbon emissions reduction in response to tax) is also less in that case.

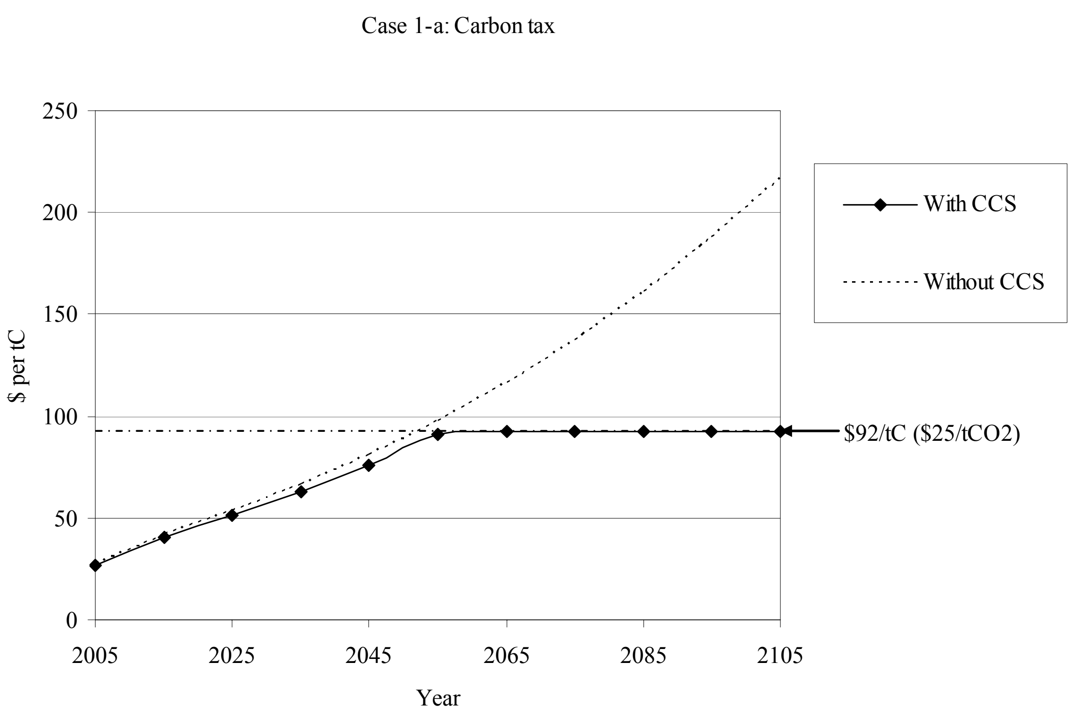
[15] One caveat about this result is that the stabilization of CO_2 concentrations at around 450ppm is achieved due to a steady decline of concentrations after 2075, a result of a significant CO_2 uptake by the ocean. It is important to note that the DICE model, whose primary focus is to simulate economic behavior, is fairly lean in terms of modeling the atmospheric-oceanic circulation of masses (in DICE, the climate system is reduced to a three-box model, consisting of the atmosphere, the upper ocean and the lower ocean).

Figure 2. Outputs for Case 1-a (standard DICE – no CCS capacity limit)

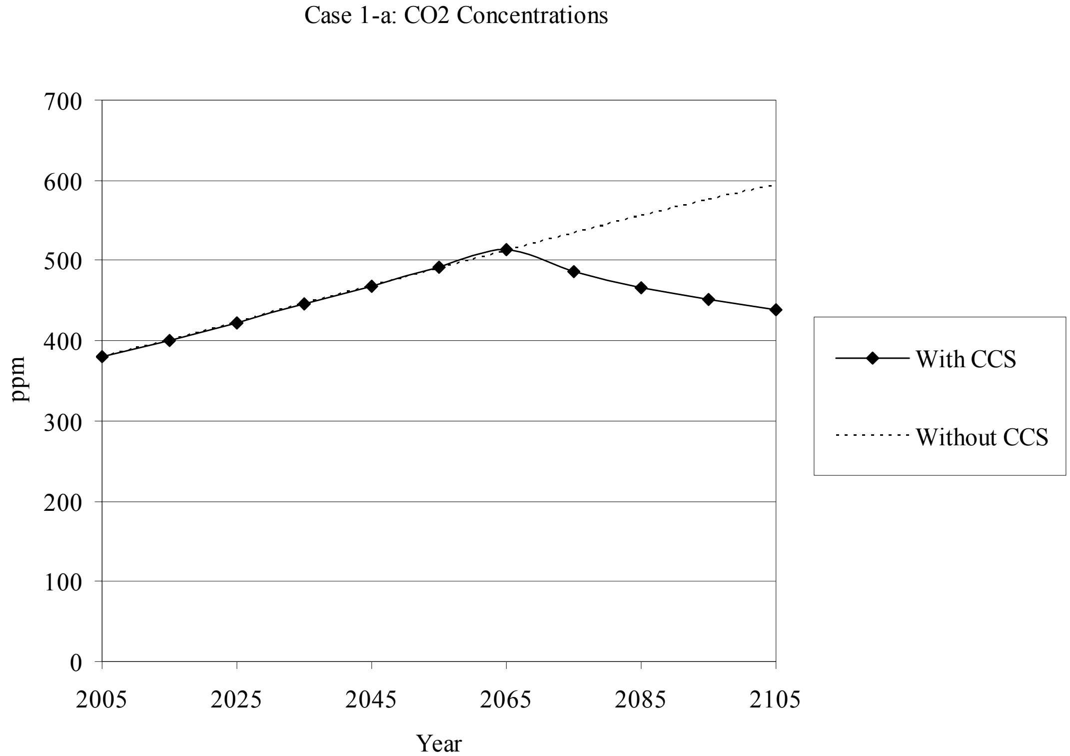
(i) Trends of industrial CO_2 emissions and CCS use



(ii) Trend of carbon tax



(iii) Trend of CO_2 concentrations



Major features of Case 1-a are unchanged in Case 1-b, except that the trend of carbon tax is considerably different after the introduction of CCS (it keeps rising, see Figure 3) and consequently carbon abatement (CO_2 reduction effort other than CCS) plays a much important role in the overall climate mitigation (Figure 4). The difference between the unit operational cost and the actual price of CCS corresponds to the shadow price of CCS: if CCS opportunities are limited relative to the total resource size of fossil fuel, the use of CCS is conceptually identical with the extraction of a non-renewable resource and thus should involve a shadow price (Narita, 2008). Indeed, in this case, the difference between carbon tax (the price of mitigation) and the unit cost of CCS is significant ($21 per tC) even at the beginning of CCS use at 2065 (Figure 3).

The result of Case 1-c (higher CCS unit cost) has similar features as that of Case 1-b except that CCS starts at 2095 in this case (Figure 1). The difference of unit cost only results in the delay of introduction. In fact, the trend of carbon tax for the two cases is at similar levels throughout the period (Figure 3).

Figure 3. Trends of carbon tax (selected cases)

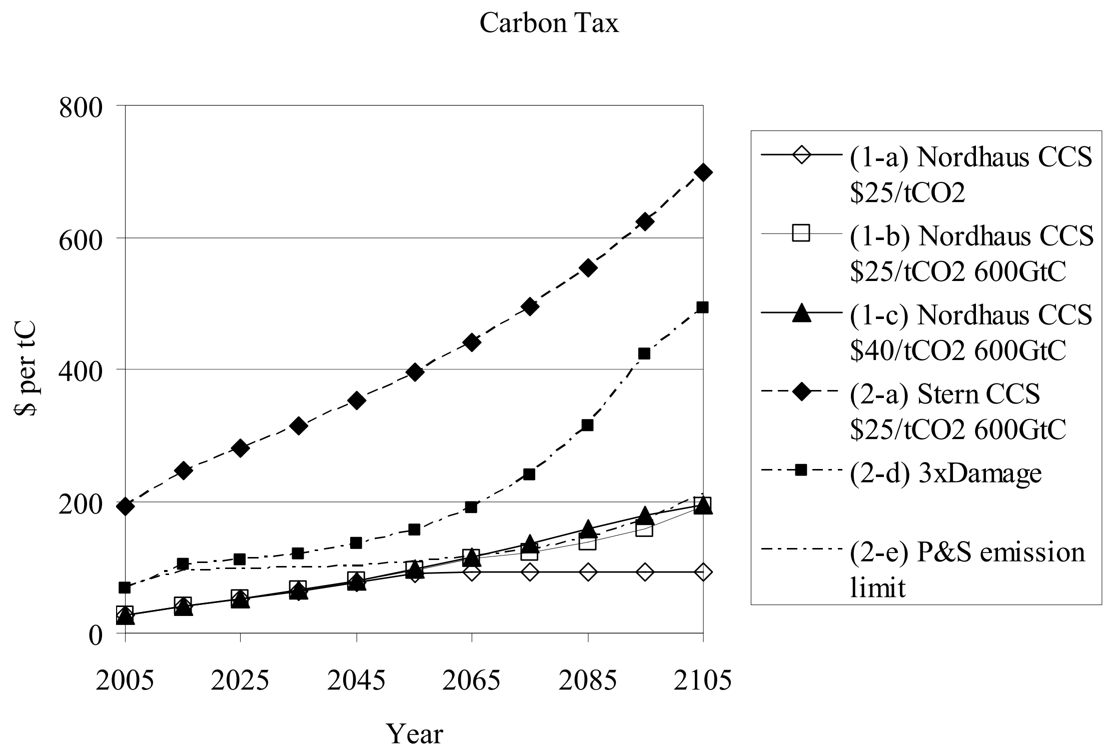
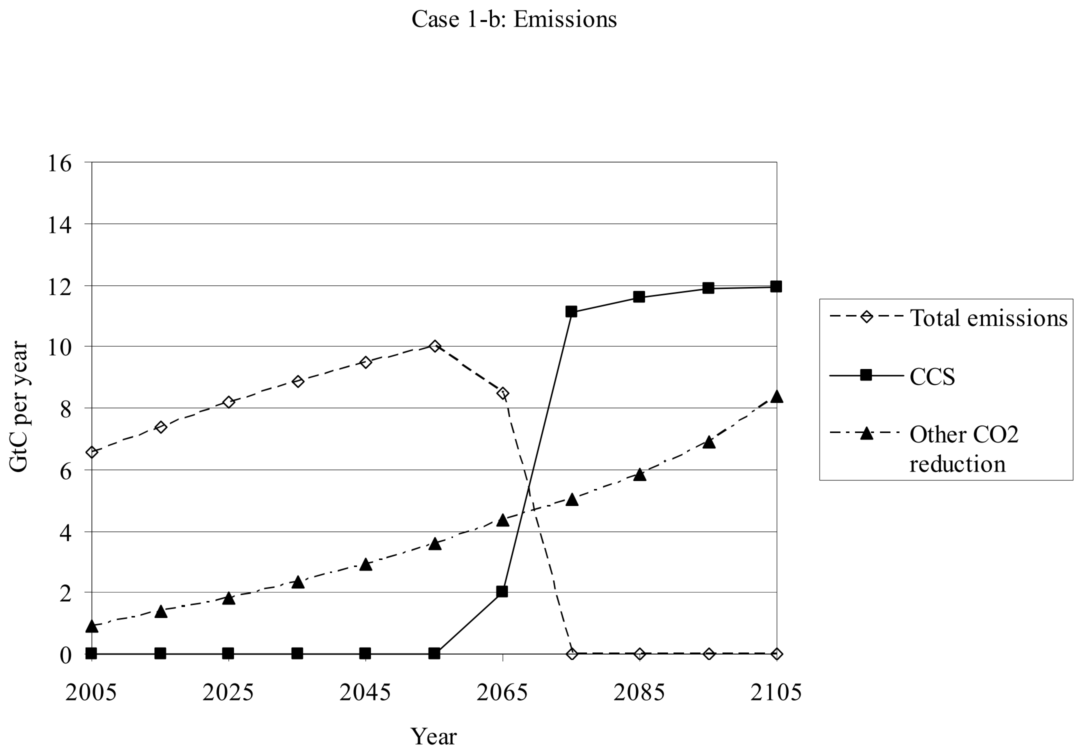


Figure 4. Trends of industrial CO_2 emissions and CCS use for Case 1-b (600GtC CCS capacity limit)



Remarkably different from the first group of cases is the case of low discount rate (Case 2-a). In this case, CCS is favorable right after 2015 (Figure 1 and Figure 5). This result comes from the high carbon tax level (Figure 3). In fact, the carbon tax level is so high with the low discount rate that CCS begins to be used early even with a higher unit cost of operation (Case 2-b). Comparatively high levels of tax with low discount rates would not be unique to this model run, as Stern (2007, p322) mentions that his model analysis computed the optimal carbon tax level of $85/t$CO_2$ ($312/tC) at the beginning of the twenty-first century. Tax levels become high at low discount rates because future damages of climate have more significance for the present decision making in such a case. The low discount rate is, however, not the only factor leading to a high tax and allowing early use of CCS. As seen in Case 2-d (climate damage tripled), more significant climate change damage also elevates the carbon tax level. Consequently, Case 2-d also shows early implementation of CCS (see Figure 1).[16]

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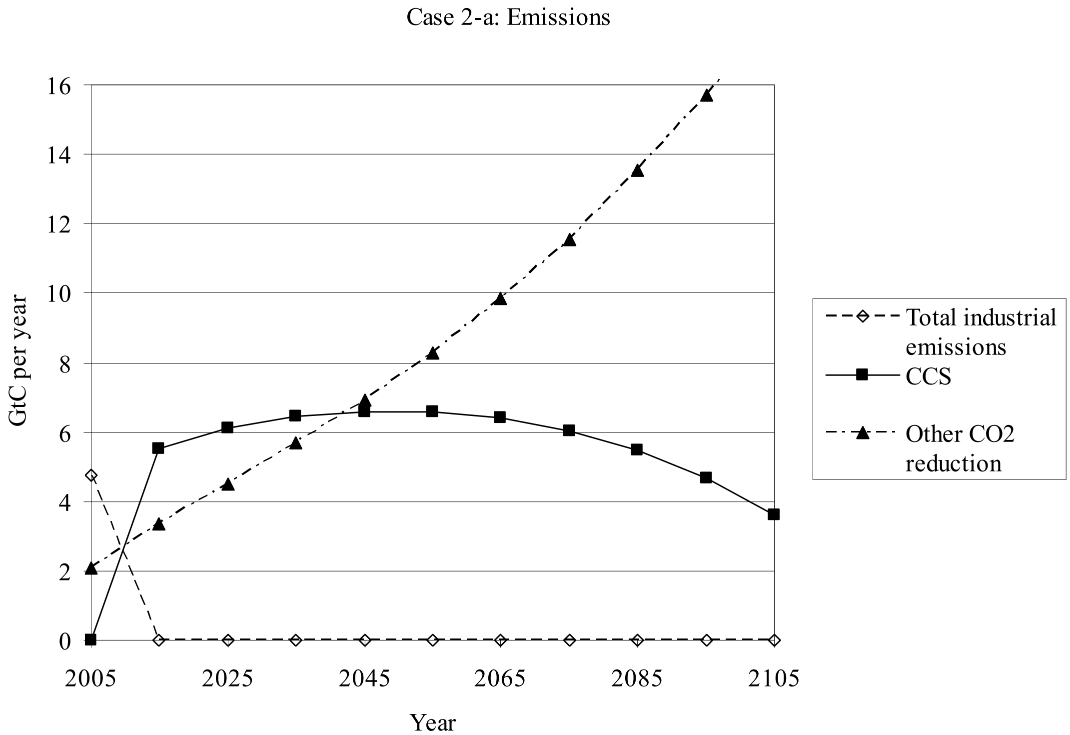
[16] In Case 2-d, the trend of CCS use shows a sharp drop in level near the period of depletion (Figure 1). This feature is persistent in all the cases except the Case 2-a (Stern's near-zero discount rate) run, though for the other cases, the drop takes place after 2105, being excluded from the graphs. This pattern is different from the one that standard Hotelling models exhibit, that is, a gradual decline of resource use over time. The direct cause of the sharp drop in Case 2-d and others is a slower rise of carbon tax (around 1% per year) than the rate of time preference (1.5% per year), which makes CCS use in earlier periods comparatively attractive – in fact, this is the reason why Case 2-a, whose time preference is near zero, shows a much more gradual pattern of decline. In this model, there are two determinants of the carbon tax schedule, which are independent of the level of pure time preference: the first is the marginal (negative) welfare of carbon dioxide emissions (MWE), and the second is the marginal welfare of investment (MWI: in other words, the marginal welfare of money). The optimal carbon tax (τ: equal to the environment shadow price of carbon, ESP) is proportional to the former and inversely proportional to the latter, as expressed below:

$$\tau = ESP = -\frac{MWE}{MWI}$$

(The absolute value of) MWE decreases over time because the aggregate marginal impact of carbon emissions on climate change is high in early periods because CO_2 stays as stock in the atmosphere, while the marginal welfare of investment (aggregate marginal return to investment) decreases over time as capital accumulates. In the model's parameterization, the latter factor is more prominent, and that is why the optimal carbon tax increases over time. Meanwhile, in this CCS use, an important cause of gradual decline in resource use in standard Hotelling models, an increase in the marginal utility due to a decrease in

Figure 5. Trends of industrial CO_2 emissions and CCS use for Case 4 (Stern zero discount)



resource use, plays a minor role since climate damage (less than a few percent of GDP) and the cost of CCS (less than 1% of GDP) are small relative to the output thus do not alter the utility level very much.

It should be noted that in all the above three alternative cases, we are placing a conservative constraint that the CCS potential is finite (at 600 GtC). In other words, CCS is not a backstop which could be utilized forever at some finite unit cost. The results suggest that we should employ CCS significantly from early in this century despite its possible limitation in ultimate capacity. At the same time, a large reduction of CO_2 is expected also as a direct effect of high carbon tax – in other words, the presence of CCS is translated into deeper reduction of CO_2 rather than decreasing CO_2 reduction by other means (Figure 5).

The result of Case 2-e is consistent with the trend that Pacala and Socolow (2004) presented in the sense that a gradual scaling-up of CCS use is projected (Figure 1). However, the DICE result also predicts that real significance of CCS comes after 2050 rather than before 2050 even in this case. In the model output, the bulge of CCS use in the latter half of the century reflects the fact that it is optimal to reduce CO_2 to zero even without the 7GtC cap in the period of bulge.

In general, the results of the group 1 of cases and those of the group 2 show strikingly different patterns. The results with the standard DICE assumptions show that CCS's role becomes significant in the second half of the century, while CCS can be used massively in the first half of the century if one adopts the alternative assumptions on climate change modeling (i.e., the zero discount rate, higher-than-expected climate damage, and the capping on emissions).

In comparison to other existing estimates, the first group of results (with the original Nordhaus assumptions) show conservative patterns of CCS's deployment, whereas the second group of results correspond to generally more ambitious scenarios than those of most preceding works.

IPCC (2005, p.356) modeled potential CCS deployment by utilizing its standardized "scenario families" (A1, A2, B1, B2), sets of plausible cases where people take various specific socio-economic or technological choices. Among a number of IPCC's model estimates, the DICE results with the original assumptions are most similar to the 450ppm stabilization case of "A1B" scenario (a scenario in which the economy experiences high growth rates[17] and resource use and the progress of energy technology is "balanced"), in which the accumulated amount of sequestered CO_2 from 2000 to 2100 sums up to 2,614 $GtCO_2$ (713 GtC). In other words, DICE's standard run with CCS (with the original Nordhaus assumptions) corresponds to the world with a rapid economic growth and a stringent emission control. The major difference between the DICE and the A1B is the timing of CCS introduction. In the A1B case, unlike the DICE results, CCS begins in the early twenty-first century and its use gradually increases.[18]

Another major work dealt with potential usage patterns of CCS is the recent MIT report (2007) on the future of coal. Its approach is to calculate optimal outlays of power

[17] In A1 scenarios, the gross world product at 2100 is set as $550 trillion (1990 currency scale) as a result of approximately 3% annual growth.

[18] This contrast would be a reflection of IPCC estimates essentially being projections of the current statistics. This approach is better able to capture detailed structure of energy markets (in this case, opportunities of CCS being cheaper than the average) into analysis, while it does not deal with the question of optimality.

generation with and without CCS under exogenous carbon tax constraints.[19] It estimated possible temporal patterns of CCS use (on the global scale) in two cases, the "high CO_2 price case" where the carbon tax of \$25/tCO_2 is introduced in 2015 and then the tax gradually increases by 4% per year, and the "low CO_2 price case" where the carbon tax of \$7/tCO_2 is introduced in 2010 and then the tax gradually increases by 5% per year. The report shows that in the high CO_2 price case, CCS comes into play in 2025, then by 2050 CCS-equipped coal combustion accounts for 60% of the total coal energy, while in the low CO_2 price case, CCS plays a marginal role until 2050 (constituting only 4% of coal energy at 2050). The DICE results for standard cases (with the original Nordhaus assumptions) are in agreement with the low CO_2 price case both in the temporal profile of carbon tax and in little importance of CCS until 2050.

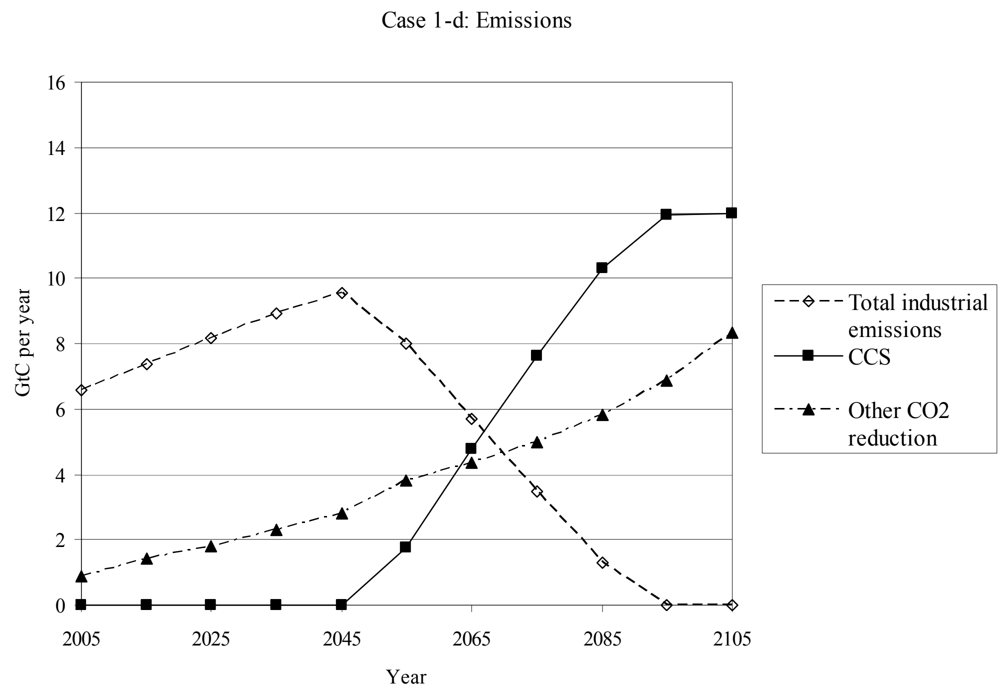
Apart from Pacala and Socolow, Lackner and Sachs (2005) also discussed potential implementation of CCS before the middle of the century. They assumed all fossil-fuel-fired plants are equipped with CCS and estimated 17GtCO_2 (4.6 GtC) will be reduced by CCS at 2050 with the cost of \$16 to \$49 per ton (of avoided CO_2). The scenarios considered by IEA(2006) would be also in this category; most of its scenarios expect CCS accounts for around 20% of emission reductions (around 7 GtCO_2) in 2050. These pre-2050 studies could be compared with the gradual introduction cases (Figure 6), where the abrupt pattern of initial implementation is circumvented. Between the two cases shown in Figure 6, the more similar to the pre-2050 studies (Pacala and Socolow, Lackner and Sachs, IEA) is Case 1-d (Figure 6(i)), where approximately 2GtC of CO_2 is

[19] A similar approach was taken by McFarland et al. (2004) (a precedent study by the MIT coal-research group).

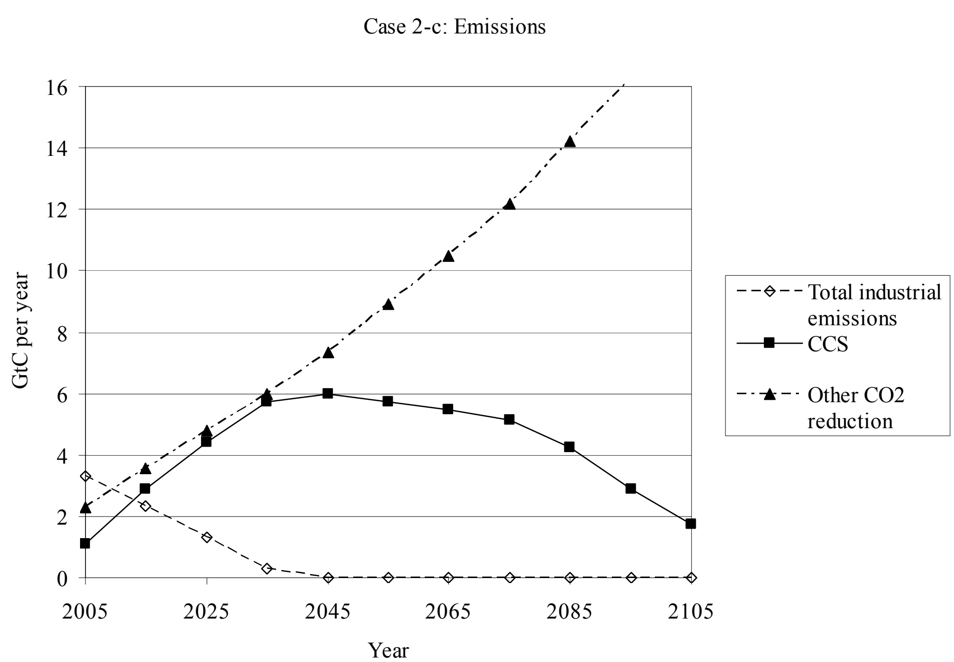
reduced through CCS in 2055 relative to the total 6GtC of CO_2 reduction in that year. The pattern of emission trend in this case, slowly rising till the mid-century and then declining to a very low level, also resembles that of some of the stabilization scenarios discussed in IPCC's Fourth Assessment Report (IPCC, 2007). In the Stern's zero-discount case (Case 2-c), the use of CCS is even greater partly because significant reduction of total carbon emissions in the first half of this century is justified under these cases. Note that all those cases are assuming a 600GtC limit of CCS total capacity. With the Stern's near-zero discount, the significant use of CCS to achieve a zero-carbon economy in a few decades may be justified even if CCS resource is significantly less than the total fossil fuel resource.

Figure 6. Trends of industrial CO_2 emissions and CCS use in the case of gradual implementation ((i): Standard DICE world (Case 1-d); (ii) Stern discount (Case 2-c)).

(i)



(ii)



Conclusion

This study performed a simulation of potential CCS use by using a modified version of DICE. The analysis assessed the economic optimality of CCS use with a range of alternative assumptions. A particular focus for the analysis was the difference of results originating from two sets of general assumptions on climate change modeling: (1) Parameterization of the standard DICE; (2) Alternative assumptions whose hints are drawn from Stern's (2007). In the results, the cases with the former set of assumptions generally exhibited a late implementation of CCS after the middle of the century. By contrast, the results in the latter group of cases showed early implementation, in fact, immediate introduction in the majority of runs.

The two sets of results would give contrasting ramifications for policy making. The general pattern of results with the standard DICE assumptions, namely, the introduction of CCS after the mid-century, would have two major implications. First, because large-scale implementation of CCS would not be cost-effective until the middle of the century, CCS will remain to be a niche technology of which only cheapest opportunities (e.g., enhanced oil recovery producing substantial extra oil as byproduct) could be exploited within the next several decades. A relatively long lead time to large-scale deployment means that an advantage of CCS as being relatively in an advanced stage of demonstration does not have significance relative to other more unproven, revolutionary energy solutions possessing their own strengths (such as large-scale installation of solar power generation), and it might be wise not to prioritize CCS to others in terms of allocation of research efforts.[20] In fact, this view paradoxically supports unfavorable views on CCS held by some environmental groups, questioning CCS's high costs as well as its relative attractiveness over other energy technologies.[21] Second, the CCS's large migration potential that we keep intact in the first half of the century leaves us opportunities to use it in a massive scale afterwards. In fact, the simulation result of the base case shows that thanks to extensive use of CCS in the second half of the century, atmospheric CO_2 concentrations are controlled below 450ppm at the end of the century, a benchmark level which rather falls on the conservative end in the current policy discussion of climate change. In a sense, CCS would allow us some indulgence for the next several decades.

On the other hand, the alternative cases (in the spirit of Stern's) present very different pictures about the role of CCS in the future carbon management as compared to the former. First, large-scale deployment of CCS is an immediate issue, corroborating the view by most advocates. The fact that CCS's total potential might have a limitation does not lead to its late implementation. Also, in the model results, an extensive reduction of fossil fuel use accompanies the use of CCS, in other words, the major effect of CCS use is deeper cuts of CO_2 emissions rather than the sustainment of the level of fossil fuel use – a consequence of generally high carbon tax levels in the model's world. All of these would support a strong policy for CCS's wide implementation. While the model does not

[20] One argument against research investment in CCS is that CCS does not involve network externality and is not likely to be diffused easily. See Barrett (2006).

[21] One of such groups being skeptical of CCS is Greenpeace. For its stance on the issue, see its recent report published on May 2008 (downloadable at http://www.greenpeace.org/usa/press-center/reports4/false-hope-why-carbon-capture).

take into account possible extra costs for initial installation due to shortage of infrastructure or expertise, it could still make a case for removing non-economic institutional barriers regarding CCS (e.g., lack of appropriate legal framework) expeditiously for smooth penetration of technology. It would be worthwhile to note that the model results of this category generally exhibited even more intensive use of CCS than that currently discussed by most advocates.[22]

Nonetheless, the most important conclusion of this model analysis would be that the question of the optimal use of CCS is inseparable from the current intellectual debate on the economics of climate change, and the settlement of the debate would strongly benefit us to have a firm view about how to position CCS in our portfolio of climate change mitigation. In the CCS context, insights of optimization economic analysis would be particularly useful since the technology's benefit is not necessarily always obvious because of its limitedness of secondary benefits as well as uncertainties about the validity of technology itself, such as permanence of CO_2 storage.

[22] This suggests that opportunities of CCS themselves should be expanded: it would justify maximal use of CCS to decarbonize a broad range of sectors, through, for example, the use of hydrogen (produced in new-type coal plants) as an energy carrier, as opposed to apply CCS only to the power sector, which most analysts are currently assuming.

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