

Daiju Narita (Nov. 12, 2007)

**Carbon Dioxide Capture and Storage (CCS) and Climate Change Mitigation:
A Resource-Economic Perspective**

by

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Abstract

As scientific evidence of climate change has been getting solid, many are beginning to see a dilemma in designing medium- to long-term policy on carbon dioxide (CO₂) reduction: while climate science suggests that substantial CO₂ reduction (i.e., more than half the current human emissions) might be necessary worldwide in the long term, many national governments are currently facing gridlock in meeting even the very modest emission targets of the Kyoto Protocol. As a prospective solution for this conundrum, many climate change experts are beginning to pay attention to carbon dioxide capture and storage (CCS). CCS is a technology which separates carbon dioxide from emission sources (e.g., power plants) and stores it permanently in geological reservoirs. Its long-term effectiveness is as yet unproven, but scientists reckon that CCS could sequester at least 2,000 gigaton CO₂, a number comparable with the accumulated amount of the total human carbon dioxide emissions for several decades at the current level. There exist several studies that have estimated the potential role of CCS in a future carbon management policy (e.g., Pacala and Socolow, 2004). However, in those studies, CCS is merely treated as an item to fill the accounting gap between the ideal level of CO₂ reduction and the business-as-usual emission projection without CCS. This study is an attempt to provide an economic analysis of CCS *itself*. From the resource-economic point of view, CCS reservoirs are a non-renewable resource with a limited capacity: once CCS geological reservoirs are filled up with CO₂, we cannot sequester CO₂ with those reservoirs anymore. By using a simple analytical dynamic optimization model, we will examine the optimal paths of CCS use, CCS's social costs, and their difference from the operational costs. A particular implication of the model is that all else equal, the social costs of CCS should be higher than those of renewable energy due to CCS's reliance on scarce reservoirs. This serves as a justification for giving differentiated incentives to different CO₂ reduction options: more precisely, more encouragement should be given to renewable energy in comparison to CCS. On the other hand, it is clear that in the resource economic sense, appropriate use of CCS could increase social welfare as well. Hence, the model result presents a reconciling view for the proponents of CCS who stresses CCS's merit in climate change mitigation (the fossil fuel industry, some governments and others) and the opponents who are concerned with CCS's potentially negative impact on development of renewable energy (some environmental groups such as Greenpeace): CCS is better to be used, but its level of use should be commensurate with its higher social costs vis-à-vis those of other renewable energy technologies.

Introduction

Dilemma of Climate Change Policy: Limited Success of the Kyoto System and the Perceived Need for Stringent Control of Carbon Emissions

Over the last decade, evidence of human-induced climate change has become almost unquestionable. The Intergovernmental Panel on Climate Change (IPCC) estimates that the global mean surface temperature has risen by about 0.7 °C during the twentieth century and that this increase of temperature is attributable to human emissions of greenhouse gases, especially of carbon dioxide (IPCC, 2007). The most conspicuous data provoking the urgency of the problem are atmospheric concentrations of carbon dioxide, which have jumped from about 280 ppm in the pre-industrial time to around 380 ppm at present, and this trend is in accordance with massive use of fossil fuel by humans. Assuming the economy follows the business-as-usual track, significant changes are likely to appear in temperature and precipitation patterns at various places on earth, and, consequently, on human activities and ecosystems.

A notable character of the climate change problem is its long time frame; since the effects of carbon dioxide (CO₂) emissions are cumulative in the atmosphere, long-term planning is needed to control atmospheric levels of the gas and prevent deleterious consequences of the problem. On the other hand, many scientists and policy-makers are beginning to believe that long-term policy targets for emissions might have to be very stringent as they start paying careful attention to the current trends of carbon emissions and atmospheric CO₂.

Some national and transnational bodies have already begun considering substantial long-run CO₂ reduction for their policy goals. The leader in this debate is Europe. The European Commission has set a benchmark that “by 2050 global emissions must be reduced by up to 50% compared to 1990, implying reductions in developed countries of 60-80% by 2050.”¹ In order to achieve this goal, the EU will seek at least a 20% reduction of greenhouse gases emissions by 2020 until a comprehensive international agreement is obtained. Also, independently from the consensus of the EU, the British government has declared that the country will reduce CO₂ emissions to 60% of current levels by about 2050.

The need for stringent, long-term control of greenhouse gases emissions is gradually being perceived outside Europe as well. For instance, the State of California has already stated that it will aim at a reduction of greenhouse gases emissions to 80% below 1990 levels by 2050.² Also, more recently, the Japanese government announced a plan calling

¹ European Commission, *Communication from the commission to the council, the European parliament, the European economic and social committee and the committee of the regions: limiting global climate change to 2 degrees Celsius: the way ahead for 2020 and beyond*, January 10, 2007.

² At the federal level, US’s posture on climate change is still tenuous. However, its policy is gradually being aligned with the calls for climate change mitigation as evidenced by the government’s plan trying to reduce domestic gasoline consumption by 20% by 2017 (President George W. Bush, State of the Union speech, January 23, 2007).

for 50% reduction of global greenhouse gases emissions from 1990 levels by 2050, in concert with German and British initiatives.^{3 4}

These ambitious targets are, however, in stark contrast to the current impasse of the Kyoto Protocol framework, the acting international system to deal with climate change. The Kyoto Protocol is an international treaty adopted in December 1997 at Kyoto, Japan, which entered into force in February 2005. It is an accord based on the United Nations Framework Convention on Climate Change (UNFCCC), the umbrella international treaty on climate change which was adopted in 1992. To realize the broad objective of climate change control, as laid out by the UNFCCC, the Protocol sets quantitative targets on greenhouse gases emissions (including those of carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) for participating countries. One of the Protocol's distinctive features is that only a limited number of countries have obligations to reduce greenhouse gases; high-income economies and eastern European countries (the Annex I parties) are required to reduce greenhouse gases emissions by a certain percentage relative to 1990 levels (for example, 8% for most western European countries, 7% for the US, and 6% for Japan and Canada) during the commitment period of 2008-2012, and no emission goals are defined for other developing countries.⁵ Another important characteristic of the Protocol is the concept of carbon sinks; countries can offset part of their emissions by enhancing carbon dioxide absorption through certain types of land use, land-use change and forestry.

The Kyoto Protocol also adopted an innovative scheme, the so-called Kyoto mechanisms, to reduce costs of implementation and facilitate its compliance. These mechanisms include the Joint Implementation (JI), the Clean Development Mechanism (CDM), and emissions trading. JI is a system which allows Annex I parties to operate projects in the territory of other Annex I entities so as to claim the resulting greenhouse gases reduction. Meanwhile, the Annex I countries could obtain credits by reducing emissions of *non-Annex I* parties (i.e., developing countries with no specific reduction targets) as well through CDM projects. In addition, the Protocol legalizes exchange of credits among parties through the form of emissions trading.

To date, the most important application of the Kyoto mechanisms is the EU emission trading scheme (ETS). The ETS was launched by the European Union in January 2005 in order to meet the Kyoto targets efficiently. Its implementation is proceeding in two

³ See for example, *Financial Times* (2007) ("Abe's post-Kyoto plan eyes 50% cut in global emissions," in USA 1st Edition, May 25, 2007).

⁴ The EU, Japan, and Canada jointly presented the proposal of halving emissions by 2050 at the 2007 G8 Summit at Heiligendamm, Germany, and the Summit Statement (June 7, 2007) declared the member states "consider seriously" this long-term target.

⁵ It is worth noting that some developing nations have set up voluntary domestic targets for carbon emissions reduction independent of Kyoto requirements. For example, in the Eleventh Five Year Plan (for the years 2006-2010), the Chinese government declared that China will reduce energy intensity (the amount of energy use per unit of GDP) by 20% during the period for the Plan.

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phases, the first period (2005-2007) and the second period (2008-2012; corresponding to the actual Kyoto commitment period). The scheme is essentially a cap-and-trade system, in which member states distribute a certain number of emission permits to business entities of polluting industries, and the companies can sell excess allowances if they emit less than the amount prescribed by their granted credits. While ETS's primary focus is emissions trading among European companies, participants can seek JI and CDM projects as well to satisfy their requirements. So far, the target of the scheme is large emitters of greenhouse gases (e.g., power and heat generation, oil refineries, coke ovens, iron and steel plants and factories producing cement, glass, ceramics, and paper).

Despite such novel carbon-reduction approaches and relatively insubstantial target-setting, the Kyoto system faces a serious challenge in terms of its effectiveness. Many nations are unwilling or unable to achieve Kyoto's goals. The United States, the largest carbon dioxide emitter in the world, failed to ratify the Protocol, although a limited number of states (e.g., California and northeastern states) are taking more progressive stances on climate change.⁶ Australia, another major industrial nation, has not ratified the treaty either. Even among countries ratifying the Protocol, the stakes seem too high; Canada has already announced that its government has in effect given up meeting the Kyoto targets,⁷ not to mention that it is still quite uncertain that other parties such as Europe and Japan will in fact fulfill their commitments by 2012.

The case of the Kyoto Protocol illustrates that considerable difficulties exist in formulating and implementing long-term climate policy after Kyoto, which many governments now anticipate to be very comprehensive. Such difficulties would be partly a matter of political processes; climate change can be solved only through global collective efforts, but history shows that international cooperation is not easy because of different domestic interests across countries and lack of a supranational body sanctioning rule-breaching. At the same time, the enormity of the climate change problem and its control is also up to a portfolio of solutions, especially technological ones. The political landscape may be altered by discoveries of novel solutions that are technologically simple, inexpensive, and large in size.

Role of CCS in Climate Change Policy: Major Arguments

As a solution to the conundrum of long-term climate change mitigation described above, many climate change experts are beginning to pay attention to carbon dioxide capture and

⁶ Such US state-level initiatives include a regional cap-and-trade system to be started from 2009 by northeastern and some mid-Atlantic states (the "Regional Greenhouse Gas Initiative").

⁷ See for example, *The Economist* (2007) ("The Americas: Greener; Canada" *The Economist*. London: May 5, 2007. Vol. 383, Iss. 8527).

storage (CCS),⁸ an emerging technology for carbon dioxide emissions reduction. CCS is a set of techniques of separating and capturing CO₂ from emission sources, transporting it to storage sites, and storing it in secure locations semi-permanently in order to reduce atmospheric CO₂ emissions. Appendix A-1 presents a technical summary of CCS. CCS is not yet fully developed to accommodate widespread use in various types of location, but there already do exist a few commercial-scale operations.⁹ Although CCS generally provides little auxiliary benefit besides CO₂ reduction, the concept is relatively straightforward from the technological standpoint, and its potential for reduction is expected to be large (the IPCC has estimated that CCS could sequester at least 2,000 GtCO₂ of carbon dioxide – see Appendix A-1).

To be sure, however, there are still diverging views about how the climate change problem should be handled in the first place, and as a result, not all the serious observers of the climate change issue have yet agreed on indispensability of CCS in future carbon control.

Today, almost all major opinions on climate change policy do more or less seriously take account of economic viewpoints in justifying their stances. Economic studies on climate change were pioneered by Cline (1992), who sought solutions for the global climate change as a problem of public good provision and analyzed the problem through a lens of rigorous cost-benefit estimation. Since Cline, knowledge in this field has expanded on a few important fronts. The first major development is the evaluation of climate change impact by using real socio-economic data: an example of this is Ricardian studies on potential agricultural impacts of climate change (e.g., Mendelsohn et al., 1994; Schlenker et al., 2005). The second advancement is the development of integrated assessment models (IAMs) (e.g., Nordhaus, 1994; Nordhaus and Boyer, 2000; Mendelsohn et al., 2000; Tol, 2002). The IAMs are computer models which include both physical and economic parameters to simulate climate change impacts, and they are a useful tool for discussing the optimal economic policy to control climate change. Third, extensive debates have been conducted about economically-reasonable policy designs for carbon dioxide reduction (reviewed by Aldy et al., 2003 and Barrett, 2005).¹⁰

In spite of such development in scholarship, a consensus on approaches to the climate change problem is far from being reached even in the academic domain. At present, major general climate policy strategies proposed by economists could be classified into two broad categories, the *stabilization* approach (e.g., Stern, 2007; IPCC Assessment Reports) and the *climate policy ramp* approach (e.g., Nordhaus, 1994; Nordhaus and

⁸ Carbon dioxide capture and storage is also called *carbon capture and storage*, or *carbon capture and sequestration* (the abbreviation is the same: CCS). However, here I use the term *carbon dioxide capture and storage* since it is the name the International Panel on Climate Change (IPCC) is currently adopting.

⁹ Recently, the Conference of Parties of the UNFCCC debated on whether it would certify three proposals involving CCS as CDM operation under the Kyoto Protocol. These proposals were eventually rejected at its 2006 meeting at Nairobi due to opposition from a number of developing countries.

¹⁰ Kolstad and Toman (2001) review theoretical basics of climate policy from the economic perspective.

Boyer, 2000; Kelly and Kolstad, 1999),¹¹ with some degree of overlap between the two. The former emphasizes precautionary actions to avoid future unknown catastrophe, whereas the latter focuses on cost effectiveness of carbon control mainly concentrating on well-identified effects of climate change in the future.¹² The “stabilization” proponents argue that carbon emissions must be reduced not to surpass a certain threshold (e.g., atmospheric CO₂ concentrations of 550ppm) beyond which serious (perhaps catastrophic) consequences are likely. Their recommendations tend to be immediate and stringent actions for carbon dioxide emissions reduction, often necessitating innovative (in other words, unproven) technological means including CCS. Meanwhile, the “climate policy ramp” advocates claim that the optimal climate policy deduced from rigorous cost-benefit calculations is rather a gradual tightening of emissions, not a radical cut of fuel use. Consequently, critics in this group tend not to stress unconventional technological solutions. To date, almost all the exponents of CCS are the ones implicitly or explicitly adopting the stabilization view.

Among experts who regard CCS as the key to carbon control, a major source of diversity in opinion is the *timing* of CCS’s introduction and the way of *combination* with other mitigation options. Such differences are, however, based on a great deal of common understanding about the nature of the carbon problem we face today. A clear portrayal of such fundamentals of the problem is laid out by Lackner and Sachs (2005), whose background understanding is largely shared with authors of other studies on the climate policy and CCS as well. In essence, Lackner and Sachs’s argument is that CCS is an important CO₂ management alternative because of the following three characteristics of the current carbon problem: strong dependence on fossil fuels as primary energy, relatively ample reserves of those fuels, and paucity of good alternatives for reducing CO₂ emissions.

Lackner and Sachs begin their discussion by indicating the heavy reliance of the current world economy on fossil fuels. At present, fossil energy (oil, coal, and natural gas) provides about 85 % of the world total primary energy consumption. The patterns of consumption are also characterized by striking disparities in use across countries. The fossil fuel consumption of the OECD countries is about 8 times as high as that of the non-OECD countries on a per capita basis. This feature has two implications: the current fast economic growth in some developing countries (notably China and India) may result in further huge increase in fossil fuel consumption and CO₂ emissions in the future; on the other hand, developed countries should be responsible for a great deal of CO₂ reduction from the viewpoint of fairness.

¹¹ Another popular argument on this issue is that climate change *is not happening at all* (hence we do not need any action to prevent it). But this is becoming a very minority view among serious analysts lately as scientific evidence of climate change is getting ample.

¹² The divide between two groups of approaches partly comes from their different interpretations on desirable public choice. A striking difference exists in the way how they discount future: the future is just as much as important as the present (conducive to relatively strong climate policy), or some myopia on the future should be taken into account, as actual individuals are often subjected to (conducive to relatively weak climate policy). Arrow et al. (1996) named the former the prescriptive approach (focusing on how the world ought to be) and the latter the descriptive approach (focusing on how the world is going to be).

While massive amounts of fossil fuels have been extracted and consumed up to the present, the size of remaining resources is still over 5,000 gigaton carbon (GtC), a sizable quantity even in comparison to the current world consumption level of around 7 GtC/year. This large size of resource is mainly a result of copious reserves of coal. While oil might be in fact quite a limited resource, coal can be readily converted into liquefied fuel with currently available technology (the Fischer-Tropsch process).¹³ In short, the limitation in availability of fossil fuels is unlikely to stop the world's considerable fossil energy consumption and reduce atmospheric CO₂ in the near future.

On the other hand, our current portfolio of technological solutions for climate change mitigation is quite limited. None of the available technologies can reduce CO₂ emissions on its own to the level where significant climate change is no longer likely. Wind power and some forms of biomass energy are already available in many countries at affordable prices, but there are physical limits in resource size due to limitations in the total wind power on earth and the low energy efficiency of photosynthesis. Solar energy is in theory sufficient to provide all the potential future energy demand on the global basis, but the costs of energy conversion are still too high. Even nuclear fission, a CO₂-free energy source currently used in many countries, cannot be an ultimate solution of CO₂ reduction due to a limited size of uranium resource¹⁴ along with the security concern of uncontrolled nuclear proliferation. The potential of biological CO₂ sequestration is also not enough to totally nullify the effects of anthropogenic carbon emissions,¹⁵ even ignoring the impermanent nature of such sequestration.

Given the above circumstances of the energy problem and the serious need for carbon emissions reduction to mitigate climate change, they argue, CCS must play a significant role in the policy balancing energy demand and climate control. The question then is one of a quantitative assessment of potential CCS deployment. To this end, Pacala and Socolow (2004) have made an influential proposal.¹⁶ They discussed carbon dioxide control policy over the next 50 years (2004-2054). The starting point of their estimate is

¹³ To be sure, coal liquefaction is not controversy-free even apart from the concern of extra carbon dioxide emissions from enhanced coal use. One of the criticisms about this solution is that the Fischer-Tropsch (FT) process requires a sizable amount of water and potentially puts stress on water availability around the sites of operation. Indeed, DOE/NETL (2006) shows that depending on techniques and the type of coal, the FT process needs 1 to more than 7 gallons of water per 1 gallon of product. This could be a barrier for FT operations in dry coal-producing regions such as the western United States (Wyoming and Montana for example), where distribution of water rights is a contested social and political issue.

¹⁴ Fuel efficiency of nuclear fission may be dramatically increased by using breeding reactors. Commercialization of these techniques is, however, not likely to happen in the near future. Meanwhile, nuclear fusion is a different strand of nuclear technology which does not rely on uranium at all (it uses hydrogen isotopes as fuel). However, its research and development is still in a nascent stage.

¹⁵ According to the estimate of IPCC's Third Assessment Report (2001), the terrestrial ecosystems' climate change mitigation potential is in the order of 100GtC by 2050 (cumulative).

¹⁶ One piece of evidence showing the paper's influence is that this proposal was a base material of Al Gore's well-received movie and book, *An Inconvenient Truth*.

the view that the world needs to stabilize carbon dioxide concentrations at 500ppm to avoid dangerous effects of climate change while carbon emissions would double by the mid-century under the business-as-usual scenario. This assumption is paraphrased as the necessity of keeping carbon emissions at around 7 GtC/yr (the current level) until 2054 against the business-as-usual trend of steady increase to 14 GtC/yr of that year. This means that in total $7 \times 50/2 = 175$ GtC of carbon dioxide must be reduced between 2004 and 2054. Pacala and Socolow split this hypothetical chunk of carbon dioxide into 7 wedges, each representing a triangle starting at zero today and increase linearly to 1 GtC/yr 50 years later (totaling up to 25 GtC). They then discuss options to populate those wedges.

Pacala and Socolow's main claim is that there already exist alternatives which could fill those triangles. They list 15 candidate methods for those wedges, including efficient vehicles, efficient buildings, nuclear and wind power, energy conservation, forest carbon sequestration (reforestation, afforestation, and reduced deforestation).¹⁷ Among them, three involve CCS (capture CO₂ at baseload power plant, capture CO₂ at hydrogen plant, and capture CO₂ at coal-to-synfuels plant). As for CCS, they are assuming the technology is immediately deployable; they refer to the Sleipner project, a successful commercial operation of carbon storage in Norway (see Appendix A-1), and argue that the only thing we need is just to scale up that practice by building 3,500 similar sites across the world.

Pacala and Socolow's paper was originally conceived as a counterargument to the precedent article by Hoffert et al. (2002), who claimed that currently available technology is not sufficient for solving climate change and called for an increase of concerted research efforts to develop new technologies. By contrast, Pacala and Socolow's standpoint is that although there is no single technological solution to totally offset the carbon emissions, some combination of currently available means is indeed able to solve the problem. Comparison of Hoffert et al.'s paper and Pacala and Socolow's discussion reveal three particular features of the latter's argument. First, Pacala and Socolow's discussion is exclusively concentrated on the first half of the twenty-first century, and they implicitly assume that some revolutionary solution could eliminate the climate change problem permanently after the second half of the century. Second, in light of CCS, they make a relatively strong assumption that the technology has already passed the experimental stage and is ready to be widely implemented without fundamental technological or institutional hindrance. Third, they do not consider economic rationale to defend their proposal at least explicitly.

Another group of discussions dealing with CCS's implementation is IPCC's assessments, namely, the Third Assessment Report in 2001 and its Special Report on CCS released in 2005. In the 2001 Report, the IPCC recognized the potential role of CCS in climate

¹⁷ More precisely, these methods are: 1. Efficient vehicles; 2. Reduced use of vehicles; 3. Efficient buildings; 4. Efficient baseload coal plants; 5. Gas baseload power for coal baseload power; 6-8 CCS (see text for detail); 9. Nuclear power (for coal power); 10. Wind power (for coal power); 11. Photovoltaic power (for coal power); 12. Wind hydrogen in fuel-cell car for gasoline in hybrid car; 13. Biomass fuel for fossil fuel; 14. Reduced deforestation, plus reforestation, afforestation, and new plantations; 15. Conservation tillage.

change policy by introducing the technology with several pages of review. Its assessment on the future status of CCS was, however, rather ambiguous; it only discussed CCS as one of the elements of emission reduction technology for fossil fuel combustion and did not specifically address costs or mitigation potential of CCS, though many engineers now point out that CCS's potential is dominant relative to other emission reduction techniques in the fossil fuel sector. As for the timing of introduction, the 2001 report noted that “[p]ilot CO₂ capture and storage facilities are expected to be operational by 2010, and may be capable of making major contributions to mitigation by 2020.”¹⁸

IPCC's assessment of CCS is more detailed in the 2005 Special Report that exclusively targeted CCS. This Special Report is a thorough review of CCS techniques including some cost estimates. In the Report, the Panel formally acknowledged that CCS could be a viable option for climate change mitigation if several remaining issues (e.g., long-term security and liabilities in storage) are properly addressed. The assessment also includes an in-depth discussion of possible future scenarios of CCS deployment. In the scenario analysis, most results indicate that while substantial penetration of CCS might occur in the first half of the twenty-first century, the majority of deployment will take place in the second half of the century. Also, data suggest that CCS would be utilized to the extent of 220-2,200 GtCO₂ (60-600GtC) cumulatively, corresponding to 15-55% of the cumulative mitigation effort worldwide until 2100.¹⁹ The estimates also show that the utilization of CCS could reduce the costs of mitigation by 30% or more as compared to without.²⁰

In both reports (2001, 2005), the IPCC is distinctively embracing the stabilization view mentioned earlier, resonating with the objective of the UN Framework Convention on Climate Change to “prevent dangerous anthropogenic interference with the climate system,”²¹ which is also the basis of IPCC's stance. While IPCC's reports discuss various possibilities of stabilization, it is to some degree partial to the 550ppm stabilization benchmark (most cases considered in the reports deal with the 550ppm goal), with a disclaimer that the emphasis on 550ppm stabilization scenarios “is based on the fact that the majority of studies in the literature analyze this level, and does not imply any endorsement of this level as a target for climate change mitigation policies.”²² Quite remarkably, the 2001 assessment presents an optimistic prospect to meet reasonable stabilization goals by pointing out that “most model results indicate that known technological options could achieve a broad range of atmospheric CO₂ stabilization levels, such as 550ppmv, 450ppmv or, below over the next 100 years or more.”²³ It should be noted that this view is in contrast with Hoffert et al.'s, which made a contrary argument

¹⁸ IPCC (2001), Working Group III (WGIII), Technical Summary (TS) 3.3.5.

¹⁹ IPCC (2005), Summary for Policymakers (SPM) 19.

²⁰ Ibid. SPM 20.

²¹ UN Framework Convention on Climate Change, Article 2.

²² IPCC (2001), WGIII, TS, footnote 4.

²³ Ibid. WGIII, SPM 9.

that current options are not enough. Also, the IPCC in effect made a stronger assertion than Pacala and Socolow's, which set aside the question of post-2050.

The 2005 IPCC report on CCS did not overturn the assertion by the 2001 report but rather clarified the Panel's standpoint further. The key assumption for IPCC's optimistic assessment is seen in the scenario discussion of the 2005 report. In its estimates, the most case similar to Pacala and Socolow's is the one in which the use of fossil fuel is most intensive (the "A1FI" scenario). In most other scenarios, business-as-usual emissions are significantly lower than that of Pacala and Socolow and the majority of other authors discussing this topic. Particularly distinctive in the IPCC's scenario discussion is relative emphasis on a set of scenarios called "B families," whose assumption is that people choose to live in "environment-emphasized worlds": in these cases, carbon dioxide emissions are naturally reduced without explicit policy because of strong awareness of environmental protection. In sum, while IPCC's analyses are in fact comprehensive, one should be aware that its worldview is not necessarily identical with the view held by many mainstream macroeconomic analyses, which exclude possibilities of communitarian behavior.

Apart from Pacala and Socolow and the IPCC, CCS is an important element of Stern's (2007) assessment as well. His overall argument on climate change policy is also strongly based on the stabilization view: he suggests that the stabilization goal for the world is 550 ppm CO₂e (CO₂ equivalent: 550 ppm CO₂e corresponds to 440-500 ppm CO₂ only) as the upper bound (the lower bound is 450 ppm CO₂e, but with this target, challenges of carbon reduction are naturally more difficult). He claims that the 550 ppm CO₂e greenhouse gases concentrations level lies in the range where cost and benefit are roughly balanced with some degree of latitude, to account for some leeway for the factors such as risk aversion and unknown non-market impacts (Chapter 13). In order to achieve this stabilization target, he calculates that global emissions should peak in 10 to 20 years from now and then fall at a rate of at least 1-3 % per year. By 2050, this decline leads to world emissions around 25% below the current levels (18 GtCO₂e/year as opposed to 24 GtCO₂e/year in 2002), whose reduction cost approximately corresponds to 1% of the global GDP annually. He argues that the average cost of carbon reduction will be \$22/tCO₂ at 2050, and that the total carbon reduction amounts to 43 GtCO₂ (p261). In his estimate, CCS, whose storage amounts to approximately 1GtCO₂ at 2025 and 6 GtCO₂ at 2050, is an important element of carbon dioxide reduction along with energy efficiency improvements, nuclear power, biofuels, dCHP (i.e., decentralized power generation: micro-generation, combined heat and power, etc.), and solar-, wind- and hydropower.

Another major work dealing with potential usage patterns of CCS is the recent MIT report (2007) on the future of coal. Its approach is to calculate optimal configurations of power generation with and without CCS under exogenous carbon tax constraints.²⁴ It estimated possible temporal patterns of CCS use (on the global scale) in two cases, the "high CO₂ price case" where the carbon tax of \$25/tCO₂ is introduced in 2015 and then the tax gradually increases by 4% per year, and the "low CO₂ price case" where the

²⁴ A similar approach was taken by McFarland et al. (2004) (a precedent study by the MIT team).

carbon tax of \$7/tCO₂ is introduced in 2010 and then the tax gradually increases by 5% per year. The report shows that in the high CO₂ 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 CO₂ price case, CCS plays a marginal role until 2050 (constituting only 4% of coal energy at 2050). A similar type of calculation was conducted by Lackner and Sachs (2005), who assumed all fossil-fuel-fired plants are equipped with CCS and estimated that 17GtCO₂ (4.6 GtC) will be reduced by CCS at 2050 with the cost of \$16 to \$49 per ton (of avoided CO₂).

It should be noted that appreciation of CCS as a serious option for climate change mitigation is not yet unanimous even among mainstream commentators of the issue. An example of mainstream thinkers being relatively skeptical about CCS is Barrett (2005). In his book, he presents a negative view about CCS by listing its risks including slow long-term leakage (undermining efficacy of CCS) or sudden release (suffocating local organisms including humans) of CO₂ from underground storage reservoirs. Mirrored by this description, CCS does not explicitly appear in his policy recommendation for climate change. In assessing CCS, he concludes that “[i]n reducing one risk – the risk of climate change – we create others” (Barrett, 2005, p. 392).

Focal Points of the Current CCS Controversy

The ultimate goal of this essay is to contribute to the ongoing debate about the role of CCS in climate control policy. As previously discussed, the need of substantial carbon dioxide reduction is beginning to be perceived in the climate change policy context. Accordingly, many people in the policy circles are starting to pay attention to CCS as a serious alternative for climate change mitigation. At present, even some large environmental NGOs such as Friends of the Earth and WWF cautiously admit that CCS could be a viable option.²⁵ At the same time, it is getting clear that many observers have some reservations about this technology. Criticisms about CCS could be largely classified into the following four categories:

(i) High costs

Many critics note that CCS could dramatically increase the cost of power generation. In fact, the IPCC (2005) estimated that usage CCS would lead to increase in power generation costs by 40-85% (2-3 cents per kWh) for conventional coal (pulverized coal) power plants and by 20-55% (1-2 cents per kWh) for new-type IGCC plants. Also, the real cost of carbon reduction through CCS would be even higher than these numbers as the efficiency of CO₂ capture for those plants is not 100% (about 80-90%).

²⁵ Meanwhile, among the largest environmental NGOs, a group basically opposing CCS is Greenpeace. Also, there are some smaller environmental groups that are explicitly doubtful of CCS. For example, Friends of the Mountains, a coalition of environmental groups in the Appalachian region of the United States, has expressed a concern about CCS that they have "reservations about a technology that sweeps CO₂ under the rug for our descendants to deal with," as quoted by *The Economist* ("Endangered species: The environmental movement," *The Economist*, Feb 18, 2006)

(ii) Risk and uncertainty

Risk and uncertainty are another concern about CCS. Risks of underground CO₂ storage are not very well identified, and possible risk factors include sudden gas release to the surface (causing suffocation of plants and animals) and contamination of ground drinking water sources. Probably more important than risk is uncertainty of storage, in other words, permanence of gas containment. The attractiveness of CCS in carbon management would be much reduced if substantial leakage of gas was unavoidable. Theoretical analysis and empirical results of monitoring suggest that carbon dioxide could be contained in reservoirs fairly securely for a long period of time, but clearly, security of storage over thousands of years cannot be proved by experiment.

(iii) CCS enhances dependency on fossil fuel

This is a straightforward argument. In case that we somehow cap the total carbon emissions to the atmosphere, fossil fuel consumption would be higher under presence of CCS than without it. It leads to faster exploitation of fossil fuel, which is a scarce resource.

(iv) CCS discourages energy efficiency improvement and renewable energy use

Some environmentalists argue that use of CCS results in continuous heavy investment in fossil fuel sectors and diverts resources from investments in renewable energies and energy efficiency improvement. The idea behind this argument is that renewable energies and energy efficiency improvement are fundamentally more desirable than operation of CCS, and thus it is better to spend money on non-fossil-fuel investment if we face trade-offs of financial resource allocation between CCS and other energy technologies. Seemingly, their belief of inherent undesirability of fossil fuel use (and CCS) chiefly comes from the 'dirty' image of fossil fuel combustion (e.g., coal-burning plants with smoking stacks are an emblem of the air pollution problem).²⁶

Of those four arguments, some appear reasonable, while others are rather based on flawed reasoning. First, costs are certainly a very important aspect in discussion of CCS application. But the question to be asked is, *relative to what*. CCS almost necessarily increases energy costs (except for some special cases of enhanced oil recovery), and thus its deployment should be coupled with some public mechanism to correct market failure associated with carbon emissions. Accordingly, costs of CCS should be compared with *true* social costs of carbon dioxide emissions and the costs of other abatement options, *not with the current price of coal power generation*. Estimates of the social cost of carbon

²⁶ A similar logic ('fossil fuel use is wrong even if it is offset by sequestration') is observed in other claims pronounced by environmentalists. For example, Greenpeace (2006) criticized Kyoto Protocol's inclusion of biological carbon sequestration in the following way: "Its [Kyoto Protocol's] greatest weakness is the mixing of fossil carbon emissions and organic carbon stocks, so called 'carbon sinks', which result in more fossil carbon being introduced into the biosphere in the name of emissions reductions" ("Greenpeace Briefing: A guide to the climate negotiations in Nairobi, Nov 6-17, 2006")

vary in level,²⁷ but Stern (2007, p.322) suggests that a standard number based on literature survey is around \$30 tCO₂, a figure within the range of existing CCS cost estimates. Meanwhile, it is certainly true that there are a number of methods of CO₂ reduction that are less expensive than CCS, but many authors suggest that those inexpensive alternatives (e.g., wind power) cannot meet all the potential need of carbon reduction to avoid serious consequences of climate change (e.g., Pacala and Socolow, 2004; Lackner and Sachs, 2005).

The second criticism (risk and uncertainty) is important. In fact, we do not have conclusive information about risk and uncertainty of CCS yet, and extensive additional research would be needed both on safety and security of existing carbon storage methods and on development of more stable ways of storage (e.g., mineral carbonization). Unproven risk and uncertainty can in fact be a strong reason against *immediate* implementation of CCS in a large scale. However, if one discuss carbon management policy in the medium- to long-term, it may not be wise to completely reject CCS as an option for climate change mitigation for the following two reasons. First, current observational data and theoretical analysis (however limited) are basically corroborative for long-term safety and security of CCS practices. Second, none of alternative energy technologies, not to mention nuclear power, are totally risk-free (e.g., extensive deployment of wind power generation could kill a large number of birds).

The third argument (fossil fuel dependency) could be valid only if fossil fuel scarcity is serious. However, as Lackner and Sachs (2005) clearly described, fossil fuel as a whole is not running out (although oil could be). In this sense, at first approximation, the problems of climate change and fossil fuel exhaustion are separable.

The fourth claim (impacts on development of other technologies) deserves to be scrutinized. In fact, historical evidence of energy technology shows that cost reduction occurs in parallel with increase in installation and learning through operation (See for example, Stern, p.254). Given that CCS has a physical limit in potential due to a finite total storage capacity and fossil fuel scarcity, excessive reliance on CCS may not be favorable as it could inhibit improvement of alternative technologies which would bring about infinite flow of carbon-free energy or carbon dioxide reduction.

Objective of This Study

The landscape of the CCS controversy illustrates that one element missing in the current debate is the consideration of social optimality with CCS use – potential future consequences of CCS use and social costs incurred by them. To address this aspect, this study aims to examine the economic optimality of CCS use. While there has already been a fairly ample accumulation of economic studies on climate change as mentioned above,

²⁷ It should be noted that the social cost of carbon emissions also depend on how much CO₂ will be sequestered through CCS in the future. In this sense, we should not put too much credence on existing numbers of social costs for the purpose of our discussion.

economic optimality has not necessarily been clearly discussed in the debate on CCS, as CCS has been considered only as an item to fill the accounting gap between future projections of carbon emissions and some stabilization target. In this study, we will discuss a simple resource economic analytical model. The main claim of this essay will be that potential future consequences of CCS use and social costs incurred by them could be an important factor in designing the best policy of CCS use (even with deterministic assumptions of the model). To show this, we will use a dynamic optimization model that explains the best use of CCS and highlights key determinants of optimal patterns of use. Then, we extend the discussion to examine one of the above arguments of the CCS controversy, that is, CCS's indirect impacts on development of other energy technologies.

While the scope of this study is to conceptually present alternative viewpoints in the current CCS debate by using an analytical resource economic model, it is clear that an economic analysis of CCS should come with some numerical examination as well. Such numerical aspect of analysis is addressed in a separate work (Narita, 2007), where numerical simulation of potential CCS use is attempted by using a modified version of the DICE (Dynamic Integrated model on Climate and Economy) (Nordhaus, 1994; Nordhaus and Boyer, 2000), one of the most widely-used integrated assessment models on climate change.

An advantage of the DICE model is that it is used in various contexts of climate change studies and thus the parameters used by the model are relatively well tested. This serves as strength for the model in assessing the optimal timing of introduction of CCS, whose estimation involves a long time horizon. The basic feature of the DICE model is to calculate the optimal trends of future carbon dioxide emissions and economic variables. The model incorporates a climate damage function and considers a hypothetical carbon tax that is equal to the shadow price of carbon emissions, the present value of the total (intertemporal) marginal damage of carbon emissions. In the model, CO₂ emissions are controlled to the extent which the carbon tax justifies CO₂ reduction by firms.

In the world of the DICE model, the introduction of CCS takes place in a particular fashion with a few distinct characteristics. First, CCS begins to be used when its price becomes equal to the level of the ever-increasing carbon tax trend (a robust feature of the DICE model). Second, if CCS's price is invariable (i.e., independent of the amount used), the introduction of CCS means that firms obtain incentive to use CCS to totally cancel off their emissions, in other words, once the carbon tax exceeds the price of CCS, firms prefer performing CCS to paying carbon tax. Third, CCS has an effect of decreasing the shadow price of carbon emissions as it reduces future climate change mitigation costs.

Preliminary calculation of the modified DICE²⁸ shows that at the price level of \$25/tCO₂ (\$92/tC), CCS is introduced around in the middle of the twenty-first century and used by approximately 4,000 GtCO₂ by the end of the century.

²⁸ Based on a version of the DICE (the version of DICE-99 whose parameters are set identical to the one used by the Nordhaus group to conduct simulation for the Stern Review) with incorporation of some parameters regarding CCS.

The Resource Economic Model

Scope of the Model

In this section, we describe basic features of the dynamic optimization model about CCS and energy use. The scope of model is to find an optimal path of CCS use in presence of necessity of carbon dioxide control and alternative technology to reduce emissions. Intertemporal optimization is a well-established method of resource economic modeling.²⁹ Essentially, this method is to find solutions to maximize a weighted temporal sum of the aggregate welfare for an economy. Such utilitarian assumptions (i.e., to focus on aggregate welfare) by no means have a priori philosophical basis: for example, the ‘optimal’ results would not be the same as the utilitarian solutions if the society chooses to adopt Rawls’s criterion, which exclusively cares for the welfare of the least well-off (Solow, 1974; Heal, 1998). However, because those alternatives have as many technical or conceptual problems as the utilitarian framework does,³⁰ intertemporal optimization largely remain to operative with utilitarian formulations, which are operatively more straightforward than most alternatives. The discussion below will also follow conventions of the standard discounted utilitarian type of optimization.

Dynamic optimization studies on climate change often model the whole body of complex climate-economy interactions: since climate is not priced in the market, costs of climate change are calculated from step-by-step simulation of causal links from carbon emissions to climatic responses to economic impacts. While this approach has an advantage in modeling non-linearity of climate-economy interactions, such formulations would incorporate excessive complexity and obscurity for the purpose of this study, i.e., assessment of relative impacts of CCS vis-à-vis the total set of climate change control measures. From this standpoint, in the following model, climatic factors are represented by an exogenous policy system to control carbon emissions. As for the control scheme, we consider a simple system of a Kyoto-style emission limit: the level of carbon dioxide emissions is kept under a certain emission target not to cause any significant damages due to climate change.

To be sure, scientifically speaking, the effect of carbon dioxide emissions is basically *accumulative*: the level of climate change is primarily determined by the stock of carbon dioxide in the atmosphere rather than by its flow. With this fact, justification for adopting a flow emission target in the model would be either of the following: (i) With emissions kept below the target, the climate is controlled within a certain range that does not bring about any significant climatic impacts (say, 2°C change from the pre-industrial age) in the long run, or (ii) the emission limit is set in such a way that emissions are paced at the same rate as removal of carbon dioxide from the atmosphere (through uptake by the ocean or mineralization to carbonate rock), or (iii) the focus of the model is the medium term in which more thorough reduction is anticipated in later periods. Implicitly, the

²⁹ For example, see Dasgupta and Heal (1979).

³⁰ For complete examination of this point, see Heal (1998).

author adheres to the view (i) in the following discussion, but the model structure does not change for any cases.

In the model, the single-sector economy gains welfare out of fossil fuel consumption. With this setting, the decision-maker faces a choice: whether to limit fuel use, or to use CCS, or to go for alternative energy. He or she makes decisions based on the costs of each option. It should be noted that these costs are the total social costs, not pure operational ones:³¹ since today's CCS use indirectly affects CCS's unit operational cost in the future (cheaper reservoirs are exploited first), CCS use entails shadow prices, which could push up the social costs. This factor could substantially influence dynamic characters of CCS's amount of use and price.

Assumptions of the Model

We use the optimal control technique to simulate intertemporal patterns of optimal use of carbon capture and storage (CCS). In the model, the single-sector economy uses fossil fuel to increase its welfare while keeping carbon dioxide emissions in control with CCS to avoid economic effects of climate change. In this world, CCS does not cause any environmental harm, and its permanence of storage is certified. The following is major assumptions of the model:

- (i) There exists a fixed CO₂ emission target.
- (ii) There are two ways to reduce CO₂ emissions: CCS and the use of alternative energy.
- (iii) Fossil fuel resource is limited (resource scarcity).
- (iv) Cost function of CCS is dependent on both the rate of use and the accumulated amount of use, but the *marginal* cost of CCS is independent from the rate of use.

The first assumption (i) comes from the idea that carbon dioxide emissions may have to be below a certain level in order to have stable climate. This is based on an observation that many political bodies (both national governments and international entities) are in fact seeking the approach of stabilization, i.e., to control emissions under the level which could avoid any strong effects of climate change. In the model, we could use two methods to reduce fossil fuel use within the emission limit, CCS and the use of alternative energy whose aggregate cost function has the standard convex shape (the assumption (ii)). Meanwhile, there is limitation in the total amount of CCS use as well as that of fossil fuel, thus optimization must take account of two distinct types of scarcity (iii). Finally, we assume that while the CCS cost function is dependent on the rate of use and the accumulated amount of use, the marginal cost of CCS is independent from the rate of use. This constant marginal cost assumption is based on the nature of CCS

³¹ As we will see, depending on economic structure, the social costs of CCS could be equal to the private costs. However, the social costs are at least different from the operational costs of CCS.

technology – carbon dioxide is stored in large reservoirs, and we can increase the rate of storage simply by scaling up the amount of injection (thus a large increase of the marginal cost is unlikely). On the other hand, the cost is dependent on the *accumulated* amount of use because less expensive reservoirs are exploited first.

Mathematically, the intertemporal optimization of CCS use with the above assumptions is expressed as the following welfare maximization problem:

$$\max \int_0^{\infty} [W(f+a) - C^f(f) - C^x(x, Z) - C^a(a)] e^{-\delta t} dt$$

subject to

$$\frac{dR}{dt} (\equiv \dot{R}) = -f \quad (R = R^0 - \int_0^t f ds)$$

$$\frac{dZ}{dt} (\equiv \dot{Z}) = x \quad (Z = \int_0^t x ds)^{32}$$

$f - x \leq f^T$ (The emission target condition)
and $f, x, a \geq 0$

where,

- f : Fossil energy use/ carbon emissions
- f^T : Emission target (>0 , constant)
- R : Fossil fuel stock
- R^0 : Total resource size of fossil fuel (>0)
- x : Use of CCS ($0 \leq x$)
- Z : Stock of carbon dioxide in reservoirs
- a : Rate of alternative energy use ($0 \leq a$)³³
- δ : Time preference or discount rate (>0)
- t : Time

Also, the following is the definitions of functions. Hereinafter, a prime (') represents (total) derivative, a subscript, the partial derivative unless otherwise noted, e.g., $d[a(b)]/db \equiv a'$ and $\partial[c(d, e)]/\partial c \equiv c_d$.

- $W(f+a)$: Welfare from energy use ($W(0) > 0$, $W' > 0$ and $W'' < 0$)
- $C^f(f)$: Cost of fossil fuel
*In this model, we assume a constant marginal cost, thus $C^f(f) = c_f * f$
- $C^x(x, Z)$: Cost of CCS

³² When Z has an absolute capacity upper limit, Z^0 , Z satisfies the following inequality: $Z = \int_0^{\infty} x ds \leq Z^0$

³³ It is also possible to define this variable as the effect of energy efficiency improvement. In such a case, the *effective* amount of energy use becomes $f+a$ (due to efficiency improvement, welfare from energy use is $W(f+a)$, instead of $W(f)$), while the effort of improvement entails costs ($C^a(a)$).

*We assume the following conditions for $C^x(x, Z)$:

$$C^x_x = C^x_x(Z) > 0 \text{ (only the function of } Z)$$

$$C^x_{xx} = 0$$

$$C^x_Z = 0 \text{ at } x=0 \text{ and } C^x_Z > 0 \text{ otherwise}$$

$$C^x_{xZ} > 0 \text{ (and constant for any } x)$$

With them, $C^x(x, Z)$ is rewritten as $c(Z)x$ where $c'(Z) > 0$ for $Z > 0$ (henceforth we use the latter formulation).

The assumptions for the CCS cost function require some explanation. We assume that the marginal cost of CCS (C^x_x or $c(Z)$) only depends on the accumulated amount of carbon storage (i.e., the cost is a linear function of (the rate of) CCS use). The logic behind this assumption is that costs of CCS would depend on reservoir types (e.g., geological features) rather than the rate of use, and that reservoirs would become filled up from the cheaper ones first. This means that the second derivative of the cost function with regard to x is zero (C^x_{xx} or $\partial c(Z)/\partial x = 0$). The marginal cost becomes larger as the accumulated amount of storage increases (i.e., C^x_{xZ} or $c'(Z) > 0$).

$C^a(a)$: Cost of alternative energy
 $(C^{a'} > 0, C^{a''} > 0, \text{ and } C^a(0) = \lim_{a \rightarrow 0} C^{a'}(a) = 0)$

The cost function of alternative energy use has a convex shape. We assume $\lim_{a \rightarrow 0} C^{a'}(a) = 0$ since some forms of alternative energy could be introduced virtually at no marginal cost in a small scale (e.g., riding a bicycle instead of a car (use of physical energy in place of fossil energy)).

Conditions for the Model Solutions

To derive solutions of the model, it is useful to consider two cases separately: when CCS is used, and when CCS is not used (see Appendix A-2 for a formal discussion on case classification). Intuitively, it is clear that when CCS is used, the amount of use (x) always equal $f - f^T$: On the one hand, the emission target condition says that the use of CCS should be equal to or more than the difference of the fossil fuel use and the emission target ($x \geq f - f^T$). On the other hand, since emissions below the target (f^T) do not involve costs while CCS does, it is not optimal to use CCS to more than compensate the difference of the fossil fuel use and the emission target (an x that satisfies $x > f - f^T$ is not an optimal solution), thus $x = f - f^T$. Also, when CCS is used, the use of fuel (f) is clearly above the emission limit (i.e., $f > f^T$).

Hence, we have the following cases in which CCS is used and not used:

<Case A>

Fossil fuel use is above the emission limit and CCS is used to keep total emissions at f^T ($f > f^T$ and $x = f - f^T > 0$).

<Case B>

Fossil fuel use is within the emission limit and CCS is not used at all ($f \leq f^T$ and $x = 0$).

Note that $a > 0$ for both of the two cases because by assumption, alternative energy could be used at zero marginal cost if its amount is miniscule ($\lim_{a \rightarrow 0} C^{a'}(a) = 0$).

We will examine the conditions for solutions in each of the two cases.

I. Case A: CCS is used

As $x = f - f^T$, the current-value Hamiltonian for Case A is expressed as follows:

$$H = [W(f + a) - c_f e - c(Z) \cdot (f - f^T) - C^a(a)] - fp^r + (f - f^T)p^z$$

where p^r and p^z are the shadow price of fossil fuel and CCS use, respectively.

First-order necessary conditions are:

$$\begin{aligned} \frac{\partial H}{\partial f} &= [W'(f + a) - c_f - c(Z)] - p^r + p^z = 0 \\ \leftrightarrow W'(f + a) &= c_f + c(Z) + p^r - p^z \end{aligned} \quad (1)$$

$$\begin{aligned} \frac{\partial H}{\partial a} &= W'(f + a) - C^{a'}(a) = 0 \\ \leftrightarrow W'(f + a) &= C^{a'}(a) \end{aligned} \quad (2)$$

$$\begin{aligned} -\frac{\partial H}{\partial R} &= 0 = \dot{p}^r - \delta p^r \\ \leftrightarrow p^r &= p^r(0)e^{\delta t} \end{aligned} \quad (3)$$

where $p^r(0)$ is the shadow price at $t=0$.³⁴

³⁴ The transversality condition $\lim_{t \rightarrow \infty} e^{-\delta t} \cdot p^r(0)e^{\delta t} \cdot R = 0$ is satisfied for all $p^r(0)$ because $R \rightarrow 0$ as $t \rightarrow \infty$.

$$-\frac{\partial H}{\partial Z} = c'(Z)x = \dot{p}^z - \delta p^z$$

$$\leftrightarrow p^z = -e^{\delta t} \int_t^{\infty} c'(Z)x e^{-\delta s} ds \quad (4)$$

(See Appendix A-3 for the derivation of the equation (4))

The interpretations of these conditions are as follows. First, the third condition (3) represents the standard Hotelling-type equation of the shadow price of fossil fuel³⁵ (p^r). The shadow price increases at the rate of discount rate (δ).

Second, the fourth condition (4) says that both the discount rate and CCS's cost responsiveness of CCS to the accumulation of carbon dioxide stock ($c'(Z)$) affect the shadow price of CCS. Since $c'(Z)$ is non-negative by assumption, p^z is non-positive. p^z could be either increasing or decreasing over time as \dot{p}^z can be both positive and negative, as the condition is re-expressed below:

$$\dot{p}^z = c'(Z)x + \delta p^z$$

The intuition behind the fact that CCS's cost responsiveness to the accumulation of carbon dioxide stock affects the shadow price is the following; CCS use at present has indirect welfare effects for the future because it pushes up future cost levels of CCS by increasing carbon dioxide stock (or depleting carbon dioxide reservoirs).³⁶

Note that the fourth condition takes a special form (the Hotelling rent) if CCS costs are constrained by an absolute limit of reservoir capacity, Z^0 . Specifically, if:

$$c(Z) = \begin{cases} c^0 & (\text{if } Z < Z^0, c^0 \text{ is a positive constant}) \\ \infty & (\text{if } Z \geq Z^0) \end{cases}$$

$-p^z$ is the ordinary Hotelling rent ($-p^z = \hat{p}_0^z e^{\delta t}$) until Z becomes Z^0 (since $c'(Z)=0$, if $Z < Z^0$, $\dot{p}^z - \delta p^z = 0$). In other words, the shadow price ($-p^z$) increases at the same rate as the discount rate – *this is additional to the operational cost of CCS*.

³⁵ See Hotelling (1931).

³⁶ Note that this is different from the *direct* effect of CCS use at present on future use: CCS use at present takes some opportunities of CCS use in future because it *directly* reduces resource availability.

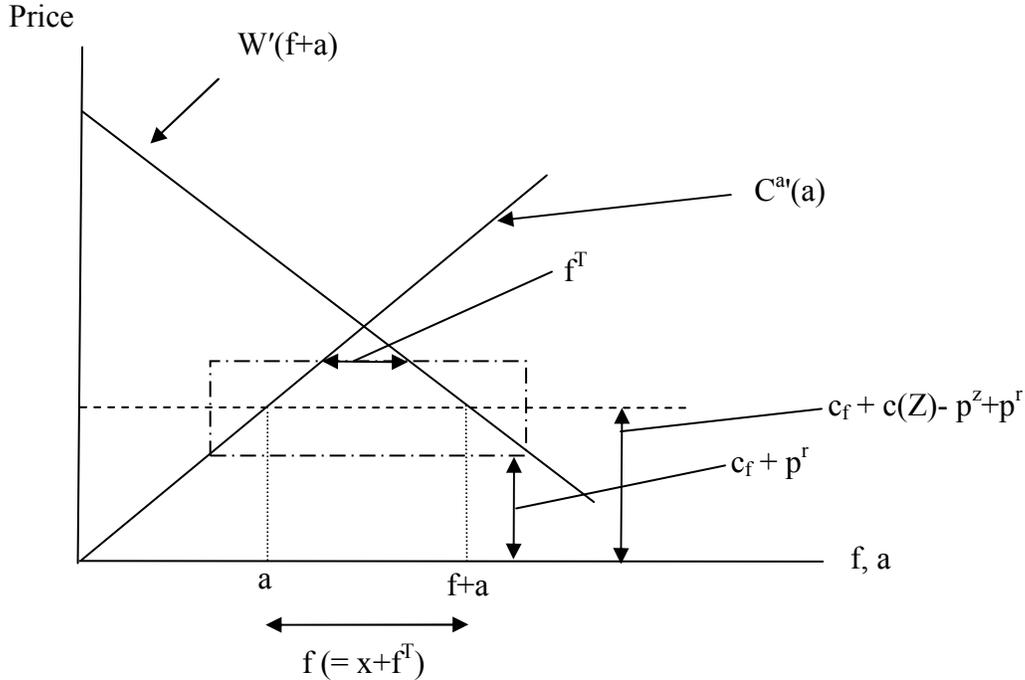
The condition (1) says that the marginal welfare of energy use (i.e., the total use of both fossil fuel and alternative energy) equals the marginal costs of fossil fuel and CCS plus their shadow prices. The right-hand side of the condition deals with the total costs of fossil fuel use and CCS as a package.

The condition (2) means that the marginal welfare of energy use equals the marginal cost of alternative energy use, which should be equal to the right-hand side in the condition (1) as well.

Figure 1 shows the relationships between marginal benefit or costs and shadow prices. The basic intuition for the graph's patterns is that effective marginal costs and benefits should be at the same level for energy use, alternative energy costs, and CCS costs. In the Figure, the marginal benefit of energy use ($W'(f+a)$), the marginal cost of alternative energy ($C^a(a)$), and the marginal costs and shadow prices associated with CCS ($c_f+c(Z)-p^z+p'$) are equal in order to satisfy the first-order conditions (1) and (2). As the graph suggests, the amounts of alternative energy use (a) and fuel use (f) are uniquely determined in this case (corresponding to the unique intersections of the horizontal dash line and $C^a(a)$ or $W'(f+a)$ in the graph). Consequently, the amount of CCS (x) is also uniquely determined: use of fuel, f , is equal to the sum of x and the emission target (f^T).

The diagram shows that the total effective price of fossil fuel with CCS ($c_f+c(Z)-p^z+p'$) is located within the window (circled by dash-dotted lines in the graph) whose upper bound is the price level at which fossil fuel is used just as much as the emission target (f^T) and whose lower bound corresponds to the level of the effective price of fossil fuel itself (c_f+p'). This implies that CCS lowers the effective costs of energy and enhances welfare relative to the case in which emissions are reduced only by use of alternative energy. Meanwhile, extra costs incurred by CCS on fossil fuel use have augmenting effects on alternative energy use and diminishing effects on fossil fuel use, relative to the business-as-usual case of fossil fuel use.

Figure 1. Relationships between fuel use, CCS use, and use of alternative energy (when $x > 0$). ∞



The first-order conditions say that the marginal benefit of energy use ($W'(f+a)$), the marginal cost of alternative energy ($C^a(a)$), and the marginal costs and shadow prices associated with CCS ($c_f + c(Z) - p^z + p^r$) should be equal. The amounts of alternative energy use (a) and fuel use (f) are uniquely determined in this case (corresponding to the unique intersections of the horizontal dash line and $C^a(a)$ or $W'(f+a)$ in the graph). The total effective price of fossil fuel with CCS ($c_f + c(Z) - p^z + p^r$) is located within the window (circled by dash-dotted lines in the graph) whose upper bound is the price level at which fossil fuel is used just as much as the emission target (f^T) and whose lower bound corresponds to the level of the effective price of fossil fuel itself ($c_f + p^r$). This implies that CCS lowers the effective costs of energy and enhances welfare relative to the case in which emissions are reduced only by use of alternative energy.

II. Case B: CCS is not used

Case B includes circumstances in which CCS is *not* used ($x = 0$). In this case, the current-value Hamiltonian is expressed as follows:

$$H = [W(f + a) - c_f f - C^a(a)] - fp^r$$

where p^r is the shadow price of fossil fuel.

As for first-order necessary conditions, the equations (2) and (3) shown above hold in this case as well from $\frac{\partial H}{\partial a} = 0$ and $-\frac{\partial H}{\partial R} = \dot{p}^r - \delta p^r$.³⁷

Meanwhile, for $\frac{\partial H}{\partial f} = [W'(f + a) - c_f] - p^r$, $\frac{\partial H}{\partial f} < 0$ and $\frac{\partial H}{\partial f} > 0$ are possible as well as $\frac{\partial H}{\partial f} = 0$. This leads to the following three possibilities of fuel use patterns, referred to as Phase Ba-Bc below (see Appendix A-2 for a more formal discussion).

$$\text{If } \frac{\partial H}{\partial f} > 0 \quad f = f^T \quad (\text{Phase Ba})$$

$$\text{If } \frac{\partial H}{\partial f} = 0 \quad W'(f + a) = c_f + p^r \quad (0 \leq f \leq f^T) \quad (\text{Phase Bb})$$

$$\text{If } \frac{\partial H}{\partial f} < 0 \quad f = 0 \quad (\text{Phase Bc})$$

All the above three sub-cases occur only if the cost of CCS is too high in comparison with those of other admissible choices, that is, use of alternative energy and fuel use under the emission target. Relative expensiveness of CCS is partly determined by given levels of parameters, and partly by temporal trends of shadow prices.

Phase Ba corresponds to the situation in which the economy chooses to keep the fuel use at the emission target level rather than use CCS. When fossil fuel is too expensive to be equipped with CCS but still inexpensive relative to full replacement by alternative energy, the amount of fuel use (f) is exactly as much as the emission limit (f^T), with the remaining energy need supplied by alternative energy. Figure 2(a) shows the relationships between the variables and functions in this phase. The total marginal cost of CCS (the marginal of costs of CCS and fossil fuel use plus shadow prices associated with them) is higher than the cost of alternative energy in case which CCS is not used at all. Because of this, CCS

³⁷ There exists a positive a that satisfies (2) in any cases as $\lim_{a \rightarrow 0} [W(f + a) - C^a(a)] > 0$ and

$W(f + a) - C^a(a)$ is a decreasing function of a .

is not operated in this phase, and the total use of energy is simply equal to f^r+a , the sum of the emission target and the alternative energy use.

Fuel use f can take some value between 0 and f^r when the condition for Phase Bb holds. As shown in Figure 2(b), in this phase, the marginal benefit of energy use ($W'(f+a)$) and the marginal cost of alternative energy ($C^{a'}(a)$) is equal to c_f+p^r , the effective marginal cost of fossil fuel use (not dependent on the level of f).

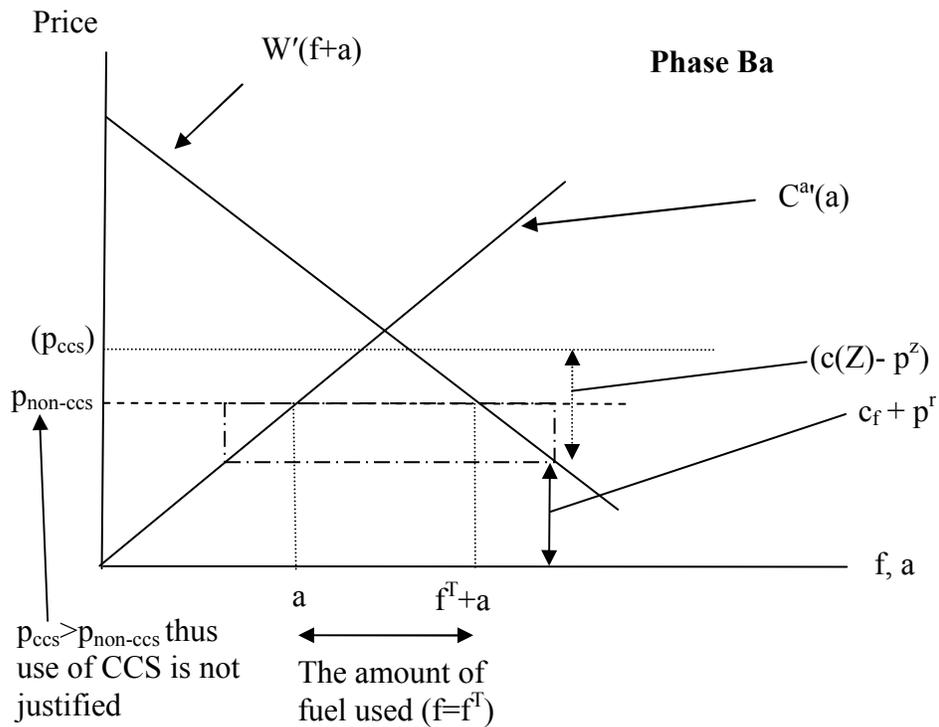
If the marginal cost of fuel plus the shadow price is higher than the marginal cost of alternative energy, alternative energy becomes the only source of energy (Phase Bc). The level of a is fixed at the intersection of $W'(f+a)$ and $C^{a'}(a)$ in Figure 2(c). Note that to reach this phase, fossil fuel resource should be depleted (i.e., $R=0$) or the price of fuel (c_f) should be higher than the equilibrium $C^{a'}(a)$.

Since p^r is increasing, phases make transition from Ba to Bb to Bc, not the other way round. The three graphs show the relationships between the marginal welfare and costs and the shadow price.

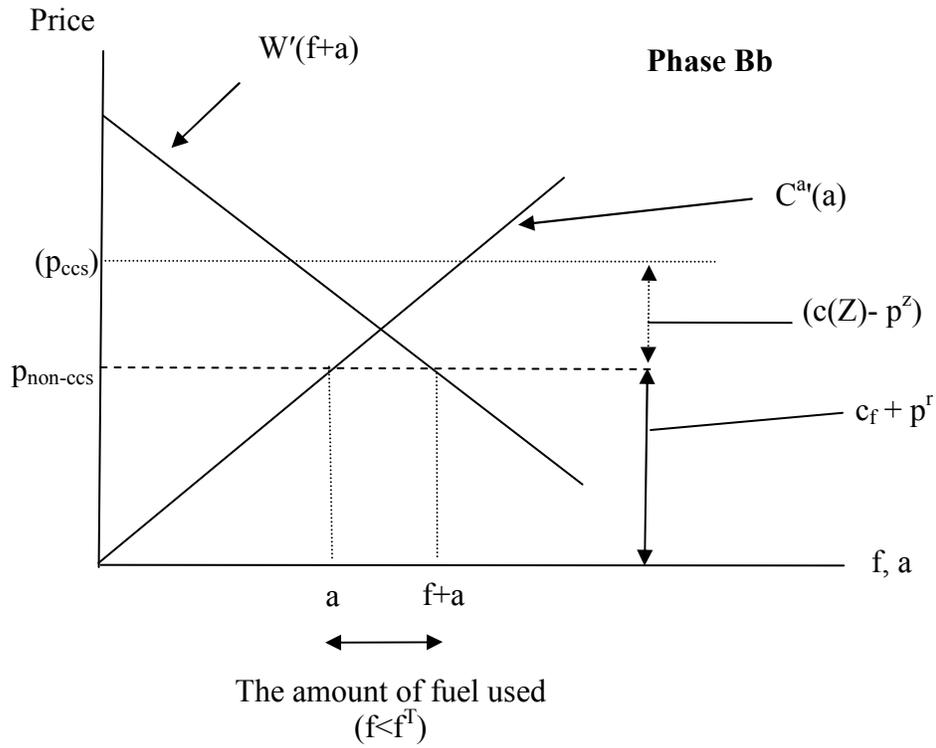
Figure 2. Relationships between fuel use and use of alternative energy (when $x=0$).

* The following phases all correspond to cases where fuel use (f) is less than the emission target (f^T) and CCS is not used at all ($x=0$). There are three possibilities in such cases: fuel use is f^T (Phase Ba); fuel use is between f^T and zero (Phase Bb); fuel use is zero (Phase Bc).

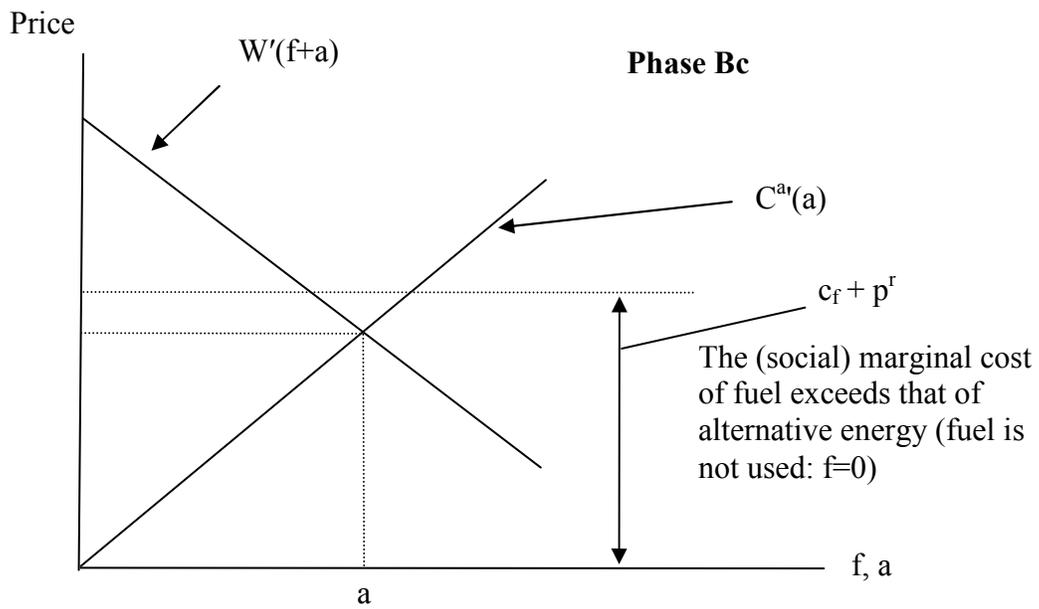
(a)



(b)



(c)



Dynamics

In discussing the dynamics of the model, the first point to be noted is that CCS is *never* used if the initial marginal cost of CCS is above a certain level. Mathematically, the condition is expressed as follows: CCS is never used if there is $a_1 (>0)$ which satisfies $W'(f^T+a_1)=C^{a'}(a_1)$ and $C^{a'}(a_1)\leq c_f+c(Z=0)+p^r(0)$ (note that $c_f+c(Z=0)+p^r(0)$ is equal to $c_f+c(Z=0)-p^z+p^r(0)$ since $p^z=0$ when x remains zero forever). Under this condition, either of the above Phase Ba-Bc starts from the beginning.

Otherwise, CCS is used from the beginning until $c_f+c(Z)-p^z+p^r$ equals $C^{a'}(a_1)$, in other words, the sum of marginal costs and shadow prices associated with fuel use and CCS becomes the same as the marginal cost of alternative energy. Note that $c_f+c(Z)-p^z+p^r$ is an increasing function in time because c_f is constant, p^r is an increasing function and $c(Z)-p^z$ is also an increasing function as shown below.

$$\begin{aligned} & \frac{d}{dt} [c(Z) - p^z] \\ &= \frac{d}{dt} c(Z(t)) - \dot{p}^z \\ &= c'(Z(t)) \frac{dZ}{dt} - \delta p^z - c'(Z)x \quad (* \text{ Using the condition (4)}) \\ &= c'(Z(t))x - \delta p^z - c'(Z)x \\ &= c'(Z)x - \delta p^z - c'(Z)x = -\delta p^z > 0 \end{aligned}$$

When CCS is used ($x>0$), the dynamics of x and f follows the function shown below.

$$\dot{f} = \dot{x} = \frac{C^{a'''} - W''}{C^{a''} W''} \delta (W' - c_f - c(Z))$$

(See Appendix A-4 for derivation)

Because $C^{a'''} - W'' > 0$, $C^{a''} W'' < 0$, and $W' - c_f - c(Z) (= -p^z + p^r) > 0$, f and x monotonically decline over time. Meanwhile, the dynamic of a is determined by the following equation, implying that a monotonically increases over time.

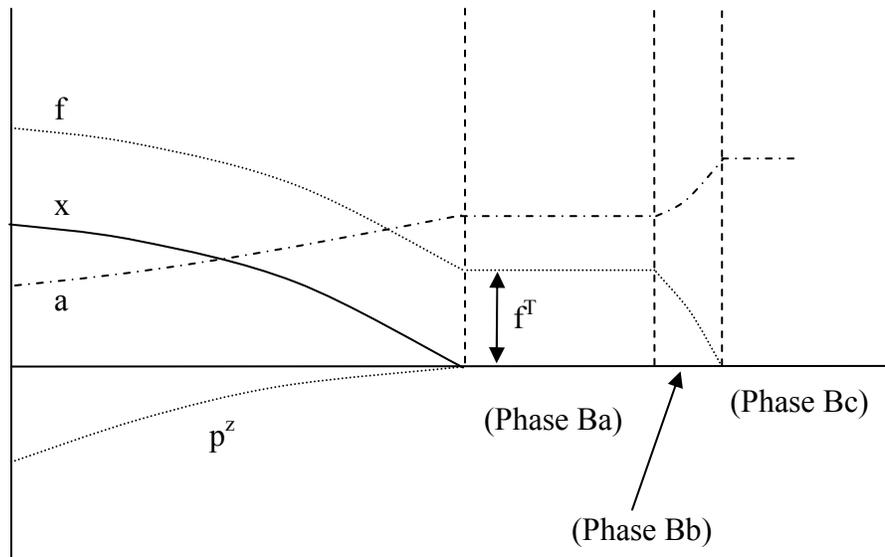
$$\dot{a} = \frac{\delta}{C^{a''}} (W' - c_f - c(Z))$$

(See Appendix A-4 for derivation)

When x becomes zero, $p^z = -e^{\delta t} \int_t^{\infty} c'(Z) x e^{-\delta s} ds$ also becomes zero.

Figure 3 shows a schematic diagram of the trends of f , x , a , and p^z .

Figure 3. Schematic diagram of the trends of f , x , a , and p^z



When CCS is used, the fossil fuel use (f) and the CCS use (x) decline over time whereas the alternative energy use (a) increases. The shadow price p^z is negative and gradually reaches zero. Phases Ba-Bc correspond to the periods in which CCS is not used.

After the use of CCS ceases, the patterns of fossil fuel use and alternative energy use shift from Phase Ba \rightarrow Phase Bb \rightarrow Phase Bc. The interpretation of this transition is straightforward. First, the cost of alternative energy becomes lower than the costs resulted from CCS use ($c_f+c(Z)-p^z+p^f$) but is nonetheless higher than those associated with simple fuel use (c_f+p^f), and the level of a is primarily controlled by the emission constraint (Phase Ba). Then, fuel use between f^* and 0 becomes feasible (Phase Bb). In this phase, the costs of alternative energy and fuel are balanced. Finally, the sum of the marginal cost of fuel and the resource shadow price exceeds the marginal cost of alternative energy, and alternative energy completely takes over the use of fossil fuel (Phase Bc). The stationary solution is $f=x=0$ and $a=a_2 (>0)$ which satisfies $W'(a_2)=C^{a_1}(a_2)$.

The results of the model thus far indicated that when CCS is used, the rate of CCS use monotonically declines. At the beginning of CCS use, x (the rate of use) has a sudden increase (jump) from zero to some finite amount. A possible counterargument to the result is that in practice, it is unlikely that gigaton-scale deployment of CCS instantaneously takes place.

While we do not know practically where is the cutoff between “unlikely” levels and feasible levels of initial deployment of CCS, the theory of resource economics could in fact provide some explanations for potential pathways that the rate of CCS use sees some gradual initial increase rather than the first jump and subsequent monotonic decrease. The heart of these theoretical arguments is to discuss potential mechanisms that facilitate an initial *decrease* of the resource cost, either because of resource exploration, technological change, or both (Pindyck, 1978; Slade, 1982; Farzin, 1992; a review on this matter is given by Krautkraemer, 1998).³⁸

Technological change is a straightforward reason for a non-monotonic resource cost (i.e., a resource cost that decreases initially and then increases) (Farzin, 1992). With lack of experience, resource extraction requires extra costs at the beginning: the temporal profile of cost is thus an outcome of competition between the learning-by-doing effect (which decreases costs over time) and the Hotelling effect or the effect of shifts to more expensive resource deposits (which increases costs over time); and a non-monotonic cost trend could appear if these effects are balanced in some manner. In the case of CCS, technological change could mean not only a narrow sense of advancement of engineering techniques, but also development of institutions (regulatory systems, business structure, etc.), or change in public perception (concerns on safety, etc.).

For the case of the present model, a simple way to incorporate the initial technological hindrance is to adopt an alternative formulation of $c(Z)$. Until CCS becomes a well-received technology for the economy, $c(Z)$ could fall, not rise, as Z increases. For example, we could consider that $c(Z)$ consists of the following two components: one of them, $c^1(Z)$, represents cost differentials across reservoirs and the total capacity constraint

³⁸ There are also a number of empirical studies which investigated the trends of resource rents for various commodities. For example, Berck and Roberts (1996) estimated that resource rents of major mineral resources would be unlikely to increase in the near future, a conclusion in contrast to Slade's (1982) prediction of future resource price increases.

(as in the standard case), and the other, $c^2(Z)$, corresponds to the additional costs in early implementation due to immaturity of technology.

$$c(Z) = c^1(Z) + c^2(Z)$$

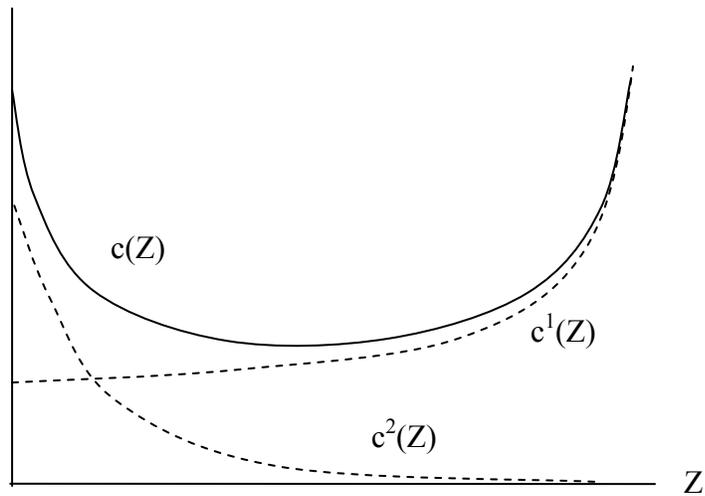
$$c^{1'}(Z) > 0, c^{1''}(Z) > 0, c^1(Z) > 0, \lim_{Z \rightarrow \infty} c^1(Z) = \infty$$

$$c^{2'}(Z) < 0, c^{2''}(Z) > 0, c^2(Z) > 0, \lim_{Z \rightarrow \infty} c^2(Z) = \lim_{Z \rightarrow \infty} c^{2'}(Z) = 0$$

In this formulation, $c(Z)$ is the sum of $c^1(Z)$ and $c^2(Z)$, and as Figure 4 shows, the profile of $c(Z)$ exhibits a U-shaped curve.

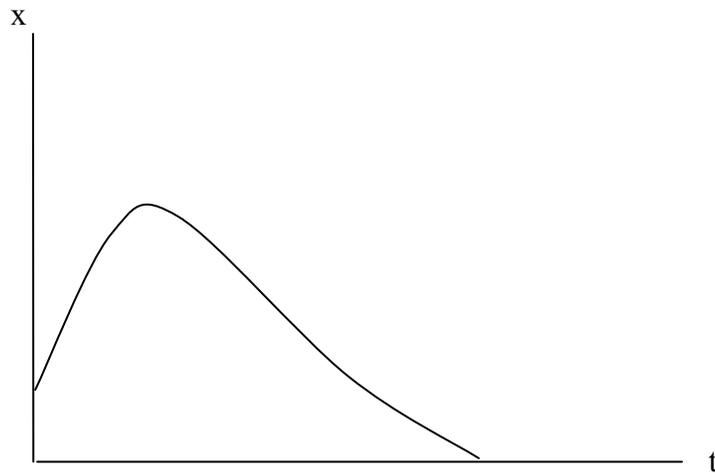
The dynamics of CCS use changes from the standard case. Under the standard case, p^z was always non-positive when CCS is used: the right-hand side of the equation (4) is non-positive if $c'(Z) > 0$. Accordingly, $W'(f+a) \geq c_f + c(Z)$, and x monotonically declines as implied by the equation (1). With the modified formulation, the system may show a different picture. With $c'(Z) < 0$ at early periods, p^z may be positive if t is small. Consequently, with $W'(f+a) < c_f + c(Z)$, \dot{x} may be positive in early periods, in other words, x may increase rather than decrease until the effect of $c^1(Z)$ dominates the other. Thus, with a choice of parameters, the trend of x could show a one-peaked shape as in Figure 5. In other words, a large-scale, sudden introduction of CCS could be suppressed because the operators or the society in general are yet to be fully accustomed or adjusted to extensive use of CCS. It should be noted, however, that the hump-shaped path is only one of the possibilities even with the modified formulation of $c(Z)$.

Figure 4. Formulation of the CCS marginal cost ($c(Z)$) with an assumption of high introductory costs ($c^1(Z)$: the factor with the standard assumptions; $c^2(Z)$: the factor of extra costs at early stages of implementation)



$c(Z)$ takes a U-shaped shape since extra costs are involved in early stages of implementation because of relative lack of knowledge (represented by $c^2(Z)$).

Figure 5. One-peaked trend of x with high initial CCS marginal costs



With certain choices of parameters, x will take a hump-shaped path rather than a monotonic trend.

Discussion: Differentiated Incentives for Various Mitigation Options

The resource economic model illustrated basic features of intertemporally optimal use of CCS. CCS and alternative energy are consumed in such a way that marginal benefits and costs are equalized, and the “costs” referred to here are *social* costs, rather than operational costs. The social costs of CCS depend not only on present patterns of use, but also on those in the future. The intertemporal characters of cost determinants have been investigated for the case of forest carbon sequestration (e.g., Alig et al., 1997; Platinga et al., 1999; Stavins, 1999; Newell and Stavins, 2000; Sohngen and Mendelsohn, 2003). For example, Sohngen and Mendelsohn (2003) discussed a simple analytical optimal control model similar to this model. They considered intertemporal cost minimization of climate damage and mitigation. They showed that the marginal costs of tree planting, lengthening of rotations, and forest management improvement should be equal to the marginal cost of other forms of climate change mitigation. However, they did not analyze in depth the shadow values associated to forest carbon sequestration on the ground that the effect of forest carbon sequestration is impermanent.

In the simplest case of the model in which the marginal cost of CCS is constant until reaching an absolute limit of storage capacity, the use of CCS involves a Hotelling-type increasing shadow price due to scarcity of storage reservoirs. The true price of CCS is higher than the marginal cost of CCS operation, and this discrepancy widens over time. Accordingly, the optimal level of CCS use decreases over time. Interestingly, this conclusion of decreasing CCS use over time is in contrast to Pacala and Socolow’s “wedges” mentioned earlier (a proposal of increasing use of CO₂ reduction options to fill the gap between the increasing CO₂ trend of the business-as-usual scenario and the stabilizing trend of the climatically desirable scenario), in the sense that they suggest that larger effort of CO₂ reduction is needed as time progresses (Pacala and Socolow, 2004).

The two analyses (the current model and Pacala and Socolow’s study) are based on very different assumptions from different viewpoints, but the contrasts in the results is noteworthy. One important reason for the difference between the two sets of results is that the present model captures the effect that mitigation effort drives up the effective price of energy and thus suppresses energy consumption, while this factor is ignored in the wedges argument; Pacala and Socolow conservatively estimated that carbon reduction exclusively comes from choices of technologies, not from the fact that an energy cost increase by mitigation would reduce energy use. Meanwhile, another factor for the discrepancy between the two analyses is the assumptions about energy use trends: while fossil energy use follows a decreasing trend (the optimal pattern) in the present model, carbon emissions (essentially the same as fossil energy demand) increases over time due to pressure of economic growth in Pacala and Socolow’s assumption. This increasing energy demand is in essence a result of income effects, which the current model does not account for: as the world population grows richer, people want more energy (and importantly, in Pacala and Socolow’s assumption, income effects outweigh substitution effects: with higher income, they do not switch consumption from fossil energy to other goods significantly). In the framework of the current model, this effect means that the

slope of the welfare function would become steeper over time because higher income would allow them to get more welfare from unit consumption of fossil energy.

In considering the actual importance of the above effects, the level of CCS's shadow price has a critical meaning. Now the question is, does the shadow price really matter in the real world? This question could be viewed from two angles: whether the shadow price could be eclipsed by other price determinants such as geopolitics and subsequent resource discovery as in the case of petroleum, and whether private companies could internalize the shadow price into their economic decision-making.

For the former point, it should be noted that CCS storage reservoirs are expected to be geographically evenly distributed across the globe. Figures 6(a) and (b) show the world distribution of potential CCS reservoirs and oil reserves. The maps indicate that potential carbon storage sites are distributed in all the continents (except Antarctica, which is excluded from the map), whereas oil reserves are concentrated in the Arabian Peninsula and Russia, which have been politically unstable at least up to the present. This evenness of geographical distribution is favorable for CCS even apart from purely the factor of political stability. Existence of many reservoirs in areas with high fossil fuel consumption such as North America, Europe, and East and South Asia means that much of CCS can be carried out domestically within the regions. In other words, CCS is unlikely to be subjected to OPEC-like price manipulation.

Also, "demand" for carbon emissions may be very steady as compared to that of most commodities. Indeed, as shown in Figure 7, the level of carbon dioxide emissions are almost unaffected by highly volatile petroleum price trends against the intuition that these two values have some correlation with each other.³⁹ This smooth increasing pattern of emissions is not likely to experience abrupt change in the future, either, if carbon control policy is predictable and well-defined. In this sense, although there is a chance that an increasing number of inexpensive reservoirs are going to be discovered in the future, we could at least expect that CCS may not face severe price volatility.

Meanwhile, the possibility that companies could internalize CCS's shadow price is more ambiguous. On the one hand, the social costs of CCS could perfectly be woven into the market mechanism (or more precisely, into a quasi-market mechanism with some public incentives for carbon dioxide reduction) if property rights are appropriately assigned. For example, if the shadow price takes the form of a Hotelling rent, standard theory tells us that competitive companies could internalize it in their pricing as they rationally estimate current and future values of their resource. However, in practice, the shadow price could be taken as an externality as well since the capacity of carbon sequestration is after all an 'artificial' resource i.e., it is valuable as long as there exist policy incentives for carbon dioxide reduction, and companies may not expect permanency of CCS's resource values in presence of unpredictability on policy or development of alternative technologies. If it

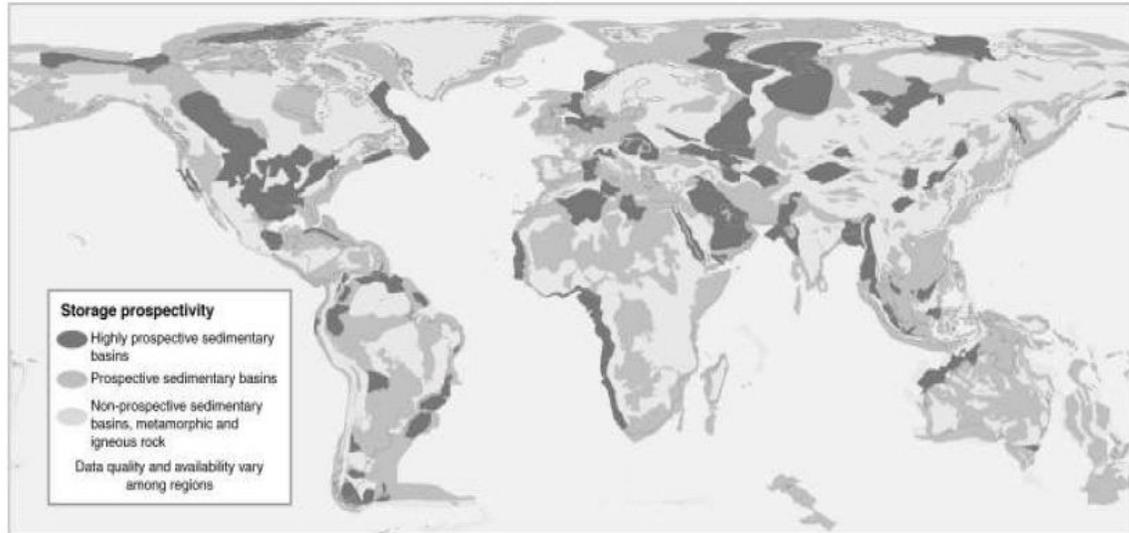
³⁹ This tendency (independence of carbon emissions levels from oil price trends) is consistent with more formal studies of energy statistics: many authors note that the price elasticity of energy demand is very low, at least in the short run (estimates largely fall in the range of -0.1 to -0.3). See for example Krichene (2002).

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were the case, the competitive outcome would not be the optimal pattern of use, and some corrective policy for CCS pricing would be favorable.

Figure 6. Worldwide distributions of potential CCS reservoirs (a) and oil resource (b)

(a) Prospective areas in sedimentary basins where suitable saline formations, oil or gas fields, or coal beds may be found (taken from IPCC, 2005)



(b) World distribution of oil resource (taken from *World Conventional Crude Oil and Natural Gas: Identified Reserves, Undiscovered Resources and Futures*, US Geological Survey Open-File Report 98-468)

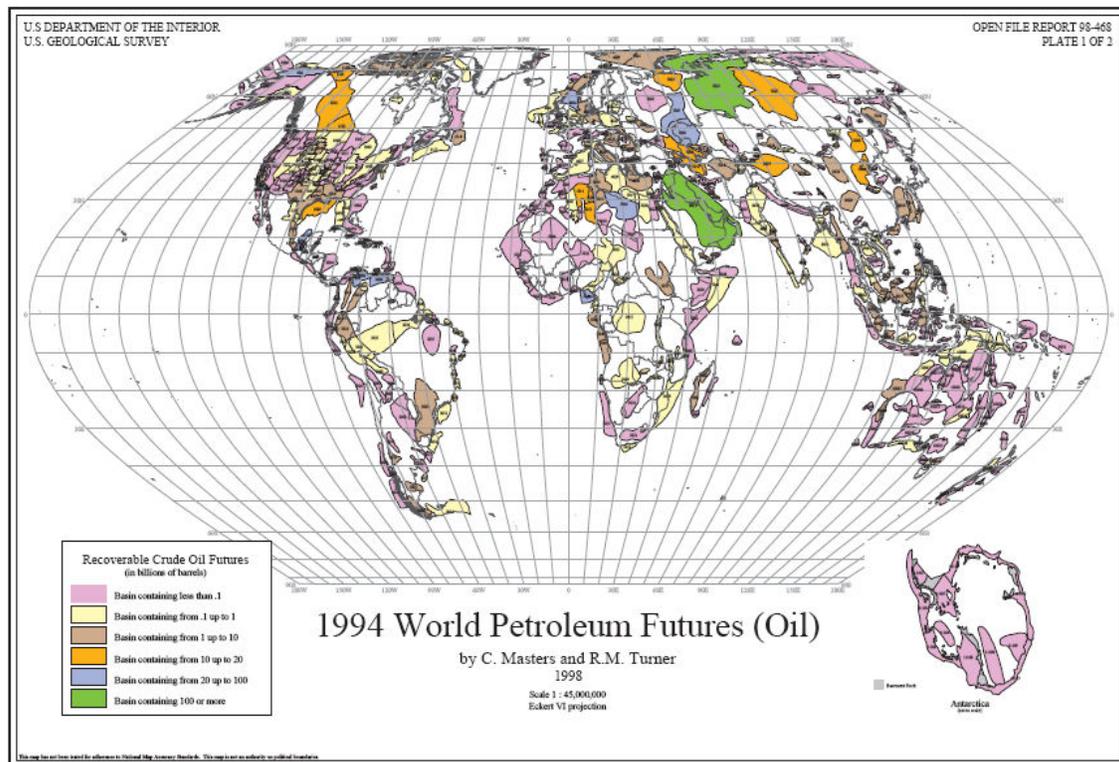
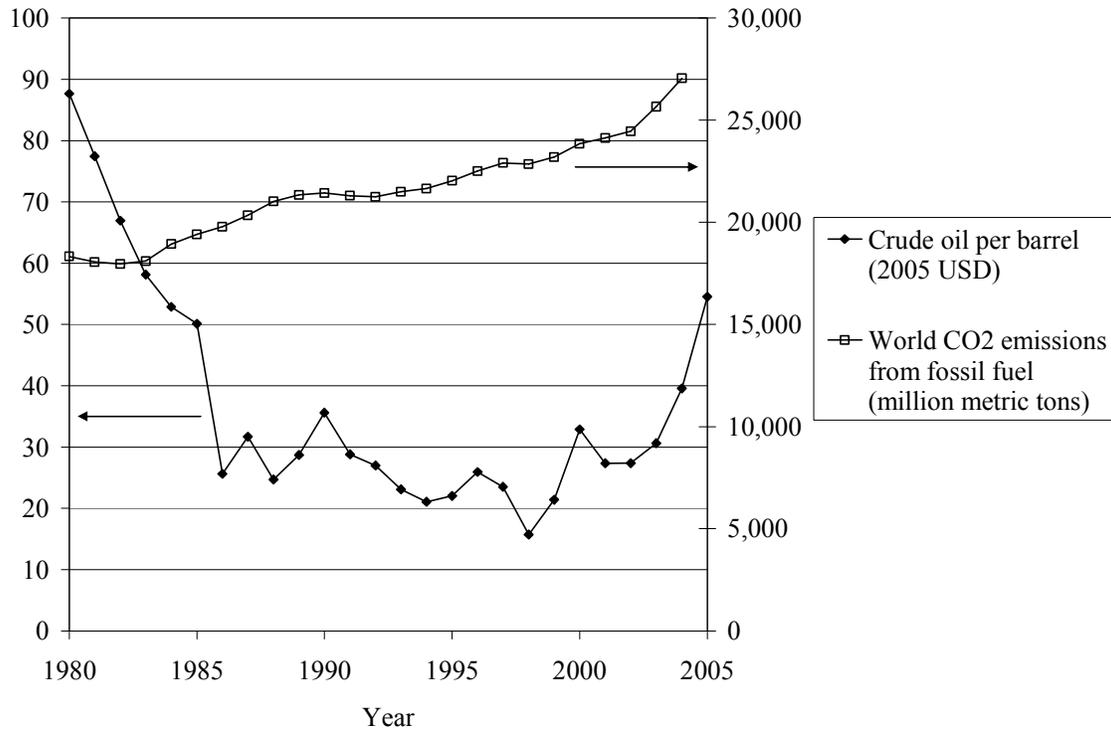


Figure 7. Trends of oil prices and global carbon dioxide emissions



Source: BP statistics (oil price) and DOE Energy Information Administration (CO₂ emissions)

The implication of CCS's shadow price becomes clearer if we introduce an additional assumption to the model: the cost of alternative energy declines over time due to technological improvement in response to a growing scale of installation.⁴⁰ As shown in Figure 8, many technologies indeed experience price decline in parallel with cumulative electricity production.⁴¹ In the presence of technologically-driven cost reduction of alternative energy, there is a clear contrast between CCS and alternative energy in terms of cost trends: the cost of CCS rises with exploitation, while that of alternative energy decreases by the learning-by-doing effect (which is an externality) as the technique is widely adopted.⁴²

For this case, the Hamiltonian (corresponding to Case A) is rewritten as follows⁴³ (here we consider the original formulation of $c(Z)$, without extra costs for CCS in the introductory phase):

$$H = [W(f + a) - c_f f - c(Z) \cdot (f - f^T) - C^a(a, G)] - fp^r + (f - f^T)p^z + ap^g$$

where G is the accumulated amount of use in a (i.e., $\dot{G} = a$). As G is increased, the cost level of alternative energy declines ($C^a_G < 0$ and $\lim_{G \rightarrow \infty} C^a_G = 0$ for any $a > 0$). p^g is the shadow price associated with G .

As for the first-order necessary conditions derived from this Hamiltonian, the conditions (1), (3), (4) in the standard case (Case A) also hold in this case.

$$W'(f + a) = c_f + c(Z) + p^r - p^z \quad (1)$$

$$p^r = p^r(0)e^{\delta t} \quad (3)$$

$$p^z = -e^{\delta t} \int_t^{\infty} c'(Z)xe^{-\delta s} ds \quad (4)$$

Also, the following is the conditions original to this case.

⁴⁰ See Jaffe et al. (2002, 2005) for a review of general issues existing in the relationship between technological change and environmental policy.

⁴¹ A caution about this graph is that the data are not controlled with regard to the *rate* of electricity production. While the graph does indicate possibilities of technologically-induced price reduction, some of the price decline might have originated from the scaling-up of operation, not from technological change. Still, there is ample anecdotal evidence suggesting that significant improvement of energy technologies and resultant cost decline have in fact been under way.

⁴² In terms of advancement of environmental technologies, some stress the role of *induced technological change* in addition to the learning-by-doing effect. Induced technological change comes from innovations as a result of research investment that is conducted in response to environmental regulation. See for example, Goulder and Mathai (1999).

⁴³ Inclusion of the learning-by-doing effect is an established technique of economic modeling that was first proposed by Arrow (1962). For reference, see Barro and Sala-i-Martin (2003).

$$\begin{aligned} \frac{\partial H}{\partial a} &= w'(f+a) - C_a^a(a, G) + p^g = 0 \\ \leftrightarrow W'(f+a) &= C_a^a(a, G) - p^g \end{aligned} \quad (5)$$

$$\begin{aligned} -\frac{\partial H}{\partial G} &= C_G^a(a, G) = \dot{p}^g - \delta p^g \\ \leftrightarrow p^g &= -e^{\delta t} \int_t^{\infty} C_G^a(a, G) e^{-\delta s} ds \end{aligned} \quad (6)$$

Note that the sign of shadow price is opposite for CCS and for alternative energy as $c(Z) \geq 0$ and $C_G^a \leq 0$. As seen in Figure 9, in the optimal case, the shadow price for alternative energy drives its use higher, while that for CCS use is a decreasing factor of the use. It should be noted that the increase of alternative energy use due to its shadow price has an indirect effect on the shadow price level *for CCS* as well since the enhancement of alternative energy use decreases CCS use. In particular, if the CCS resource has a constant marginal cost until an absolute resource limit (a Hotelling-type case), rapid and significant cost reduction of alternative energy could totally offset CCS's shadow price.

Endogeneity of the shadow prices for CCS and alternative energy complicates value assessment of both options, and it is likely that CCS's shadow value becomes an externality due to inadequate property rights assignment. If the shadow prices for both CCS and alternative energy are in fact externalities, the social planner should introduce an incentive differential between CCS and alternative energy corresponding to the price difference by $p^g + p^z$ in order to obtain the optimal outcome.

Figure 8. Costs of electric technology in EU, 1980-1995 (taken from *Experience Curves for Energy Technology Policy*, IEA, 2000, p21)

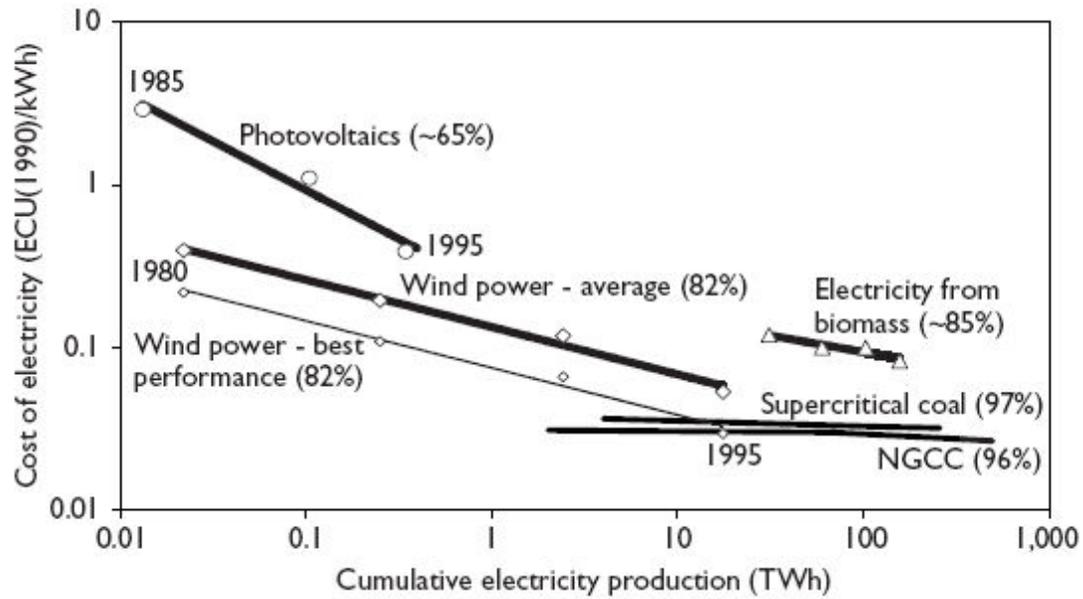
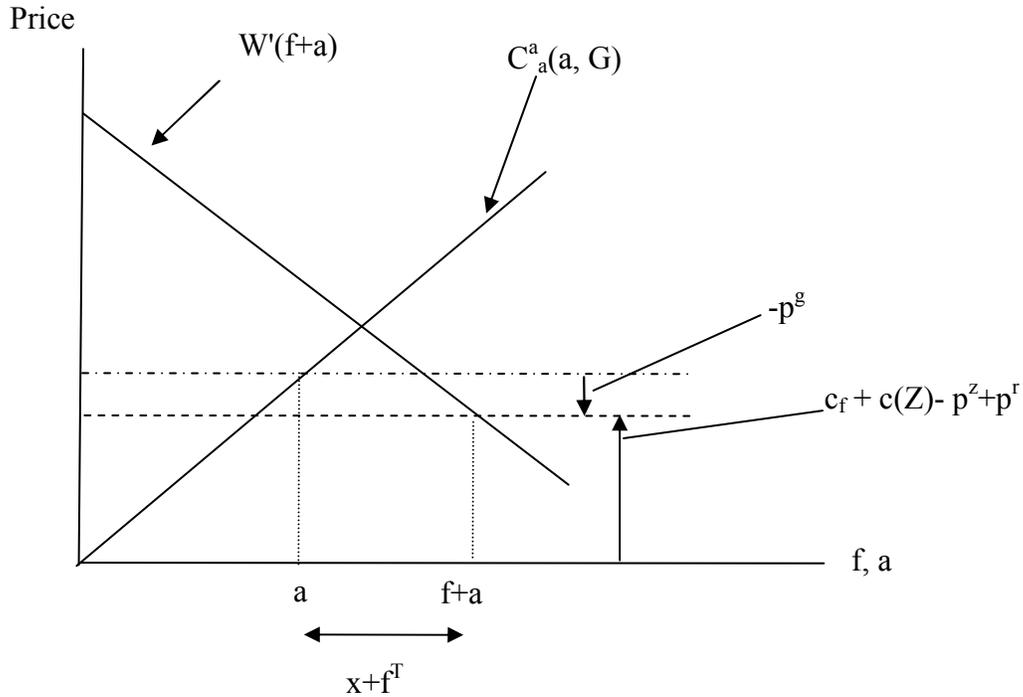


Figure 9. Relationships between fuel use, CCS use, and use of alternative energy (with technological change in alternative energy technology).



With future technological change, alternative energy involves a negative shadow price ($p^g < 0$). This is a reducing factor for the amount of CCS use (x) relative to the case without technological change of alternative energy.

In sum, the model results favor a somewhat conservative policy with regard to CCS use, i.e., to limit its use relative to others, while it certainly shows we should use some CCS even in presence of fossil fuel scarcity and improving alternative technologies (on the condition that it is safe and secure). Those results in fact support one of Stern's arguments on climate change policy that it would be effective for governments to use differentiated incentives for technology deployment according to nature (potential) of various mitigation technologies (Stern, 2007, p. 418). Also, as a corollary to this argument, more incentive could be given to more plentiful options (in terms of capacity) *among* different methods of CCS. While the formulation of this model is very simple (only accounting for learning-by-doing as the cause of technological improvement), a further implication of the model is that such differentiated incentives could be a form of different tax levels based on technology types.

Stern's argument is in fact controversial since governments tend to make serious mistakes in "picking the winners" i.e., to find out and nurture most successful technologies for the future. Indeed, industrial policy only made partial success at best even in the most interventionist economic model of high-performance East Asian economies (e.g., World Bank, 1993). In the context of the current model, however, the contrast of CCS and alternative energy is rather clear-cut as these differ in the sign of shadow price trends. In fact, this shadow price differential could partly explain uneasiness about CCS (relative to other alternative energies) that some critics have: the differentiated incentive between CCS and alternative energy would clarify and ease the current skepticism about CCS.

This study leaves some issues to be addressed in later work. They include the use of alternative assumptions in modeling (e.g., general equilibrium settings) and the investigation of potentially effective institutions to realize optimal outcomes (or lack thereof). Most importantly, this study on CCS leaves the half part of a full economic study: numerical examination. As noted earlier, such numerical aspect of the analysis is addressed in a separate work, where numerical simulation of potential CCS use is attempted by using a modified version of the DICE model, which has been widely used in climate change studies and thus accumulated ample information for comparative analysis.

Appendices

Appendix A-1. Overview of CCS Technology⁴⁴

CCS is a fairly broad concept that includes many different methods of carbon dioxide capture and storage. These methods differ in stage of development, potential capacity, and inherent risk. In this sense, it is crucial to grasp the whole landscape of technology for discussing CCS. Here we briefly overview major features of the CCS technology.

The basic concept of CCS is to capture CO₂ being released from emission sources and store it securely in locations isolated from the atmospheric system. If the gas is insulated from the atmosphere, CO₂ does not affect climate through its heat-trapping function. The challenges for this technology are thus efficient capture and transport of CO₂ from emission sources, and stable semi-permanent storage of large amount CO₂.

CCS is a set of component technologies for CO₂ capture, transport and storage (See Figures 10 and 11). While some of them are already well-established, many are still under research.

A variety of methods are possible for CO₂ capture. Most engineering studies on capture have been carried out on separation of CO₂ from the flue gas of power plants, which are a large point source of CO₂. Those capturing techniques, however, can be applicable to CO₂ extraction from other types of plants such as those for natural gas purification. Retrofitting gas separation facilities onto conventional power plants (such as pulverized coal or natural gas combined cycle plants) is a way of incorporating CO₂ capture function in the electricity generation process. On the other hand, some new types of power plants allow efficient separation of CO₂ from the exhaust.

Retrofitting can be performed with various existing methods of gas separation, including absorption (chemical or physical), adsorption (chemical or physical), membrane separation, and cryogenics. In a retrofitted plant, CO₂ is produced from the standard combustion process and captured in some of the gas separation techniques. Many of those separation methods are commercially available for gas extraction in other industrial processes. In fact, some techniques, such as amine chemical absorption, are already used even for isolation of CO₂ gas.

A number of new plant designs for efficient capture, such as oxy-fuel combustion or the integrated gasification combined cycle (IGCC), are also studied. Oxy-fuel combustion is a type of process in which fuel is combusted in pure oxygen or a mixture of oxygen, water, and carbon dioxide. For the CO₂ capture perspective, this technique can improve the efficiency of the capture process because flue gas from an oxy-fuel plant contains little amount of nitrogen compounds (which originates from nitrogen gas existing in the air). The integrated gasification combined cycle (IGCC) is a method of power generation in which fuel (hydrocarbons or coal) is gasified, and the gas is used as a medium to drive

⁴⁴ A more detailed technical review of CCS is given by IPCC (2005).

gas and steam turbines. With IGCC, it is possible to separate CO₂ from other gas species during the gasification process. Although those innovative types of plant are not yet cost-effective, these new technologies have benefits not only for CO₂ capture but also for elimination of other air pollutants such as nitrogen oxides.

Transport of CO₂ from emission sources to storage sites is not technically challenging.⁴⁵ Either pipelines or ships could be used depending on distances between CO₂ sources and storage locations. Both are well-established technologies for transport of various substances such as liquefied petroleum gas (LPG), whose physical and chemical properties are similar to liquid CO₂.

The major challenge for large-scale implementation of CCS lies in storage techniques. Human emissions of CO₂ are too large to be fully recycled for industrial purposes or contained in tanks or other man-made structures, so current techniques rely on the natural environment for storage sites. This implies that storage must satisfy rigorous requirements of environmental safety and long-term security or effectiveness.

There are three major alternatives in CO₂ storage: geological storage, ocean storage, and mineral carbonate storage. Among these, geological storage has been most studied so far. A number of techniques for geological CO₂ storage have been proposed or researched, including storage in depleted or half-depleted oil and gas fields, storage in deep saline aquifers, and storage in unminable coal seams.⁴⁶ All these methods involve injection of CO₂ into underground reservoirs and long-term containment of the gas in those sites.

One of the methods of geological CO₂ storage is storage in depleted or half-depleted oil and gas fields. An advantage of this approach is relative wealth of existing knowledge. Geological and physical properties of oil and gas fields are extensively studied both theoretically and through actual field practices. In addition, existence of oil or gas fields is already a natural proof of some geological stability since they must have kept liquid or gas securely over a long period of time. Another plus of oil or gas fields as CCS storage reservoirs is that in the case of half-depleted oil fields, additional oil production might be expected by injecting CO₂ into the fields (enhanced oil recovery, EOR).

On the other hand, the merit of deep saline aquifer storage is relative abundance of reservoirs to other types (see Table 1). Deep saline aquifers are expected to exist

⁴⁵ Large transport facilities may not be needed if CO₂ is collected directly from the ambient air, rather than from point sources of emissions. Feasibility of this 'air capture' technique has not been proven yet, but there is an ongoing research project in Arizona seeking this approach. See Lackner (2003) and Wall Street Journal ("Climate Control: As Planet Heats Up, Scientists Plot Innovative Fixes; Appetite for Oil, Coal Drives Search for 'Painless Cure' To Global-Warming Ills; Storing Carbon Inside a Rock," Eastern edition, Oct 22, 2004).

⁴⁶ A latest proposal of geological storage is on injecting CO₂ under deep-sea sediments below 3,000m. Though this approach has not been verified yet empirically, it has a couple of definitive advantages: due to high pressures and low temperatures in deep sea, injected CO₂ is liquefied and gravitationally stable, and the storage capacity is virtually limitless. See House et al. (2006).

widespread around the world. Because of salinity of water, those aquifers are unsuitable for drinking water supply or irrigation, and thus this type of storage can be implemented without compromising underground water resource. In some geophysical structures, aquifer CO₂ storage could be very stable because of multiple trapping mechanisms (Figure 11): the cap rock of the formation physically contains CO₂ into the reservoir (structural trapping); once CO₂ is dissolved into brine, it loses buoyancy that drives itself upward (solubility trapping); after a long period of time, dissolved CO₂ can form stable carbonate by reacting with surrounding rocks (mineral trapping).

CO₂ can also be injected into some coal seams. Many of CO₂ molecules can be tightly attached to the surface of numerous pores of solid coal. In this process, methane may be displaced from the pores, which can then be used as fuel.

Ocean storage is a technique that uses the ocean's absorptive capacity of CO₂. The ocean is a natural sink of CO₂. The purpose of ocean storage technology is to introduce CO₂ into the ocean by engineering means and enhance the rate of absorption by the ocean. Proposed techniques include diluted dispersal of CO₂ by moving ship and formation of dense "CO₂ lakes"⁴⁷ in the deep ocean. These techniques, however, involve direct release of CO₂ into the ocean and may cause unknown ecological effects through acidification of sea water.

Mineral storage is a technique which fixes CO₂ as carbonate minerals. Calcium or magnesium silicate, which is abundant in earth's crust, is used as reactants with CO₂. This is theoretically the most secure method of storage since carbonate rocks are chemically and physically very stable as storage media. The practicality of this approach, though, has not yet been proven.

Table 1 shows storage capacity estimates for various reservoir types according to the IPCC (2005). Despite uncertainties and data insufficiency, the estimates show that each reservoir type has a sizable storage capacity, comparing with the current global anthropogenic CO₂ emissions of around 25 GtCO₂ (~ 7 GtC) per year. Underground aquifers may have a much larger storage capacity than oil or gas fields and coal seams do. Ocean storage, although speculative, could also hold a large amount of CO₂. The Table also shows the estimated range of costs for each method based on the review by the IPCC. These numbers are again subject to large uncertainties, but they present some indications about possible roles of CCS in actual carbon management (for example, one can read that the estimated costs of CCS are still much higher than the current carbon trading price in Europe around US\$20/tCO₂).

Research and development (R&D) on CCS has been under way for nearly three decades. Concerted efforts on large-scale R&D, however, only started fairly recently. The concept of CCS from the environmental perspective dates back to the late 1970s. Marchetti (1977) made the first proposal about avoiding CO₂ emissions by physical capture of the gas from fossil fuel power plants. However, some techniques for CCS existed before

⁴⁷ In the ocean deeper than 3,000m, CO₂ (liquid) is denser than sea water. Because of this property, CO₂ in the deep ocean is likely to collect on the sea floor and form a lake-like structure.

Marchetti's proposal. A number of technology components of CCS or their analogues, such as enhanced oil recovery (EOR), a technique that has been commonly used in North American oil fields, existed prior to the late 1970s. Nonetheless, the original purpose of those technology components was not mitigation of climate change but utilization for other functions such as efficient oil production or gas purification.

It was in the 1990s that various international R&D programs on CCS began, including the establishment of the IEA Greenhouse Gas R&D Programme (IEA GHG), a leading research consortium on CCS, by the International Energy Agency (IEA) in 1991. Governments of some industrialized countries have also engaged in R&D on CCS fairly extensively since the 1990s. The most notable is Norway. This country hosted the first commercial-scale project on geological CO₂ storage for the purpose of CO₂ emission reduction. The storage project was started in 1996 at Sleipner, a gas field in the North Sea about 250km off the coast of Norway. Statoil, a natural resource company primarily owned by the Norwegian government, runs this project. The company is storing CO₂ from its natural gas production process. In the operation, about 3,000t/day of CO₂ is injected into a saline aquifer (unusable as a drinking water source) 800m below the ocean floor, which is sealed by stable cap rock. An objective of this project is to examine the long-term effects of underground CO₂ storage. In fact, Statoil, along with the IEA GHG, is conducting several different monitoring and research activities around the Sleipner field. This project has a clear commercial purpose as well; by carrying out the storage project, Statoil has significantly eased its carbon tax burden (approximately \$50 per ton at the beginning of the operation) by its CCS practice. The amount of CO₂ processed by this operation (about 1Mt CO₂ annually) is remarkable even for the whole country of Norway; it is equivalent to about 3% of Norway's total annual CO₂ emissions (Herzog, 2001). Up to the present, no leakage of gas or other adverse effects on the environment have been identified with regard to the Sleipner operation. Encouraged by the solid track record of the Sleipner project, several other commercial-scale projects of underground carbon dioxide storage similar to Sleipner are currently proposed or conducted across the world.

Table 1. Estimated storage capacity for various reservoir types according to IPCC (2005)

Reservoir type	Estimated storage capacity (GtCO ₂) ^a	Estimated cost range (US\$/tCO ₂)
Underground geological		17 – 91 ^c
Oil and gas fields	675 - 900	-
Deep saline aquifers	10 ³ - possibly 10 ⁴	-
Unminable coal seams	3 – 200	-
Ocean	Theoretically around 6,000 at 550ppm level ^b	20 – 105 ^d
Mineral	Unknown (Potentially very large)	66 – 183 ^c

a. As a reference, the current direct human emissions of CO₂ (i.e., emissions excluding indirect components such as deforestation) are around 30 GtCO₂. If one simply projects this figure to be the constant emission level in the future, the storage potential of oil and gas fields corresponds to CO₂ emissions over 22-30 years, whereas that of saline aquifers is commensurate with the emissions over 33-333 years.

b. The theoretical maximum capacity depends on atmospheric CO₂ concentrations.

c. Sum of capture (capture from conventional coal or gas plants), transport and storage costs.

d. Sum of capture (capture from conventional coal or gas plants) and storage costs.

Figure 10. System components of CCS

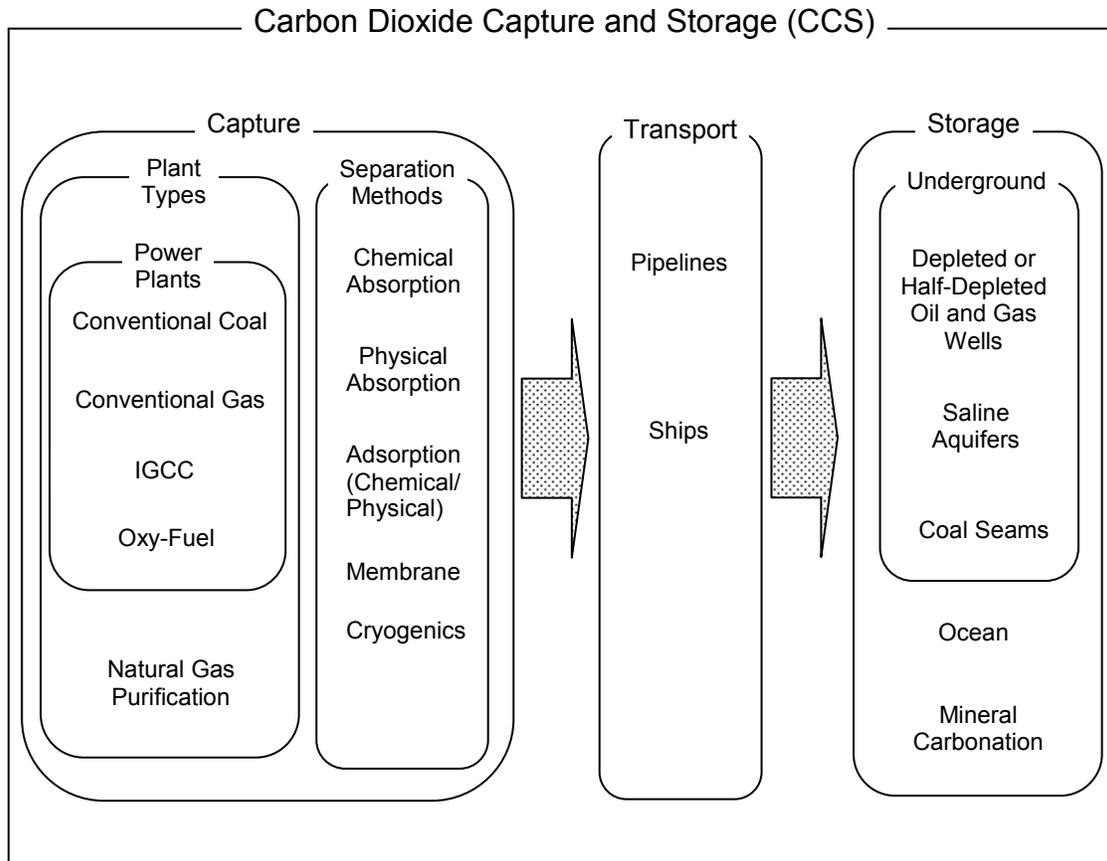
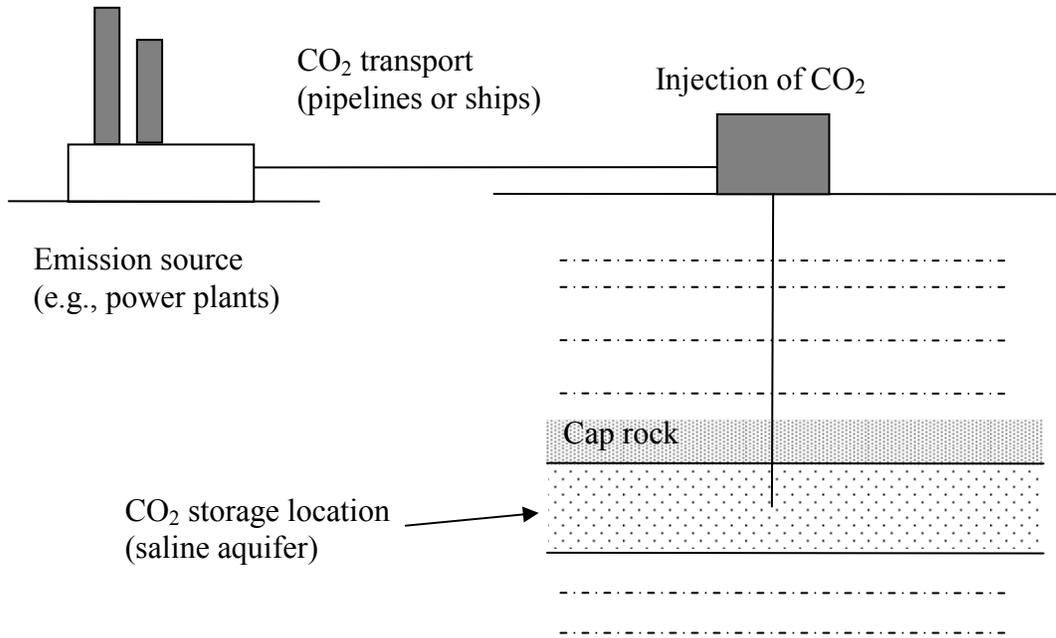


Figure 11. Schematic diagram of a CCS system (example of underground aquifer storage)



Appendix A-2. Formal Discussion of Case Classification

The maximization problem for CCS use is a bounded control problem that could be solved by using the following Hamiltonian:

$$H = [W(f + a) - c_f f - c(Z)x - C^a(a)] - fp^r + xp^z$$

subject to $f - x \leq f^T$ (The emission limit condition)
and $f, x \geq 0$ ⁴⁸

where p^r and p^z are the shadow price of fossil fuel and CCS use, respectively.

The Lagrangian for the above problem is:

$$L = [W(f + a) - c_f f - c(Z)x - C^a(a)] - fp^r + xp^z + \lambda_1(x - f + f^T) + \lambda_2 x + \lambda_3 f$$

where λ_1 , λ_2 , and λ_3 are Lagrangian multipliers.

The following is the necessary conditions for solutions:

$$\lambda_1 \geq 0, \lambda_1(x - f + f^T) = 0 \quad (7)$$

$$\lambda_2 \geq 0, \lambda_2 x = 0 \quad (8)$$

$$\lambda_3 \geq 0, \lambda_3 f = 0 \quad (9)$$

$$\frac{\partial L}{\partial f} = W'(f + a) - c_f - p^r - \lambda_1 + \lambda_3 = 0 \quad (10)$$

$$\frac{\partial L}{\partial x} = -c'(Z) + p^z + \lambda_1 + \lambda_2 = 0 \quad (11)$$

$$\begin{aligned} -\frac{\partial H}{\partial R} &= 0 = \dot{p}^r - \delta p^r \\ \leftrightarrow p^r &= p^r(0)e^{\delta t} \end{aligned} \quad (3)$$

where $p^r(0)$ is the shadow price at $t=0$.

$$\begin{aligned} -\frac{\partial H}{\partial Z} &= c'(Z)x = \dot{p}^z - \delta p^z \\ \leftrightarrow p^z &= -e^{\delta t} \int_t^{\infty} c'(Z)x e^{-\delta s} ds \end{aligned} \quad (4)$$

(See Appendix A-3 for derivation)

⁴⁸ As explained in the text, a always satisfies $a \geq 0$ in this model setting.

The cases and phases shown in the text correspond to the contingencies of the above conditions.

Case A $\leftrightarrow x > 0$

If $x > 0$, from the condition (8), $\lambda_2 = 0$.

Then, the equation (11) is rewritten as $\lambda_1 = c(Z) - p^z$

From the assumption of $c(Z)$ and (4), $c(Z) > 0$ and $-p^z > 0$ (as at least $x > 0$ at present), thus $\lambda_1 = c(Z) - p^z > 0$.

This means that from the condition (7), $x - f + f^T = 0$ or $x = f - f^T$ (this also means $f > 0$).

Case B $\leftrightarrow x = 0$

(Phase Ba $\leftrightarrow \lambda_1 > 0$)

If $\lambda_1 > 0$, the condition (7) implies $f = f^T$.

As $f = f^T > 0$, from the condition (9), $\lambda_3 = 0$.

With $\lambda_1 > 0$ and $\lambda_3 = 0$, the condition (10) becomes:

$$W'(f + a) - c_f - p^r > 0$$

(Also, as $\lambda_2 \geq 0$, the condition (11) identical with $c(Z) - p^z > 0$)

(Phase Bb $\leftrightarrow \lambda_1 = 0$ and $\lambda_3 = 0$)

If $\lambda_3 = 0$, the condition (9) implies $f \geq 0$. Also, with $x = \lambda_1 = 0$, the condition (7) says $f \leq f^T$.

With $\lambda_1 = \lambda_3 = 0$, the condition (10) is rewritten as:

$$W'(f + a) = c_f + p^r$$

(Also, as $\lambda_1 = 0$ and $\lambda_2 \geq 0$, the condition (11) is identical with $c(Z) - p^z \geq 0$)

(Phase Bc $\leftrightarrow \lambda_1 = 0$ and $\lambda_3 > 0$)

If $\lambda_3 > 0$, the condition (9) implies $f = 0$.

With $\lambda_1 = 0$ and $\lambda_3 \geq 0$, the condition (10) is rewritten as:

$$W'(f + a) - c_f - p^r < 0$$

(Also, as $\lambda_1 = 0$ and $\lambda_2 \geq 0$, the condition (11) is identical with $c(Z) - p^z \geq 0$)

Appendix A-3. Derivation of Equation 4

The condition $c'(Z)x = \dot{p}^z - \delta p^z$ is identical with:

$$p^z = p^z(0)e^{\delta t} + e^{\delta t} \int_0^t c'(Z)x e^{-\delta s} ds \quad (12)$$

Meanwhile, the transversality condition for Z:

$$\lim_{t \rightarrow \infty} (e^{-\delta t} p^z Z) = 0$$

Since Z is non-negative as $t \rightarrow \infty$ in this case, this condition is identical with

$$\lim_{t \rightarrow \infty} (e^{-\delta t} p^z) = 0$$

Plug (12) into the above:

$$p^z(0) + \int_0^{\infty} c'(Z)x e^{-\delta s} ds = 0$$

$$\leftrightarrow p^z(0) = - \int_0^{\infty} c'(Z)x e^{-\delta s} ds$$

$$\rightarrow p^z = -e^{\delta t} \int_t^{\infty} c'(Z)x e^{-\delta s} ds \quad (4)$$

Appendix A-4. Derivation of \dot{f} , \dot{x} and \dot{a}

$$\text{From (1): } p^r - p^z = W'(f+a) - c_f - c(Z) \quad (13)$$

$$\text{From (2): } W'(f+a) = C^{a'}(a)$$

$$\text{From (3): } \dot{p}^r = \delta p^r \quad (14)$$

$$\text{From (4): } \dot{p}^z = \delta p^z + c'(Z) \cdot [f - f^T] \quad (15)$$

The equation (2):

$$W'(f+a) = C^{a'}(a)$$

Time derivative

$$[\dot{f} + \dot{a}] \cdot W''(f+a) = \dot{a} C^{a''}(a)$$

$$\leftrightarrow \dot{a} = \frac{W''}{C^{a''} - W''} \dot{f}$$

(14) and (15)

$$\dot{p}^r - \dot{p}^z = \delta[p^r - p^z] - c'(Z) \cdot [f - f^T] \quad (16)$$

For the equation (16):

$$\begin{aligned} LHS &= \dot{p}^r - \dot{p}^z \\ &= [\dot{f} + \dot{a}]W''(f+a) - \dot{Z}c'(Z) \quad (* \text{ Using the time derivative of (13)}) \\ &= [\dot{f} + \dot{a}]W''(f+a) - [f - f^T]c'(Z) \\ &= \frac{C^{a''}W''}{C^{a''}-W''}\dot{f} - c'(Z) \cdot [f - f^T] \end{aligned}$$

$$\begin{aligned} RHS &= \delta[p^r - p^z] - c'(Z) \cdot [f - f^T] \\ &= \delta\{W'(f+a) - c_f - c(Z)\} - c'(Z) \cdot [f - f^T] \quad (* \text{ Using (13)}) \end{aligned}$$

These result in:

$$\begin{aligned} \frac{C^{a''}W''}{C^{a''}-W''}\dot{f} - c'(Z) \cdot [f - f^T] &= \delta\{W'(f+a) - c_f - c(Z)\} - c'(Z) \cdot [f - f^T] \\ \frac{C^{a''}W''}{C^{a''}-W''}\dot{f} &= \delta(W' - c_f - c(Z)) \end{aligned}$$

Therefore,

$$\dot{f} = \frac{C^{a''}-W''}{C^{a''}W''}\delta(W' - c_f - c(Z))$$

Since $f=f^T$, this equals \dot{x} .

Also,

$$\dot{a} = \frac{\delta}{C^{a''}}(W' - c_f - c(Z))$$

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References

Aldy, J.E., S. Barrett, and R.N. Stavins, "Thirteen Plus One: A Comparison of Global Climate Policy Architectures," *Climate Policy*, 3, 373-397 (2003).

Alig, R., D. Adams, B. McCarl, J.M. Callaway, and S. Winnet, "Assessing Effects of Mitigation Strategies for Global Climate Change with and Intertemporal Model of the U.S. Forest and Agriculture Sectors," *Environmental and Resource Economics*, 9, 259-274 (1997).

Arrow, K.J., "The Economic Implications of Learning by Doing," *Review of Economic Studies*, 29(3), 155-173 (1962).

Arrow, K.J., Cline, W.R., Mäler, K.-G., Munasinghe, M. and Stiglitz, J.E., "Intertemporal Equity, Discounting, and Economic Efficiency," in Bruce, J.P. Lee, H. and Haites, E.F. (eds.) *Climate Change 1995: Economic and Social Dimensions—Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge (1996).

Barrett, S., *Environment and Statecraft: The Strategy of Environmental Treaty-Making*, Oxford; New York: Oxford University Press (paperback edition, 2005)

Barrett, S., "Kyoto and Beyond: Alternative Approaches to Global Warming, Climate Treaties and 'Breakthrough' Technologies," *American Economic Review (Papers and Proceedings)*, 96 (2), 22-25 (2006).

Barro, R.J. and X. Sala-i-Martin, *Economic Growth (2nd Edition)*, Cambridge, MA: MIT Press (2003).

Berck, P., and M. Roberts, "Natural Resource Prices: Will They Ever Turn Up," *Journal of Environmental Economics and Management*, 31, 65-78 (1996).

Cline, W., *The Economics of Global Warming*, Washington DC: Institute of International Economics (1992).

Dasgupta, P., and G. Heal, *Economic Theory and Exhaustible Resources*, Cambridge: Cambridge University Press (1979).

DOE/NETL, *Energy Issues for Fossil Energy and Water: Investigation of Water Issues Related to Coal Mining, Coal to Liquids, Oil Shale, and Carbon Capture and Sequestration*, DOE/NETL-2006/1233, June 2006 (2006).

Farzin, Y.H., "The Time Path of Scarcity Rent in the Theory of Exhaustive Resources," *Economic Journal*, 102(413), 813-830 (1992).

Daiju Narita (Nov. 12, 2007)

Goulder, L.H., and K. Mathai, "Optimal CO₂ Abatement in the Presence of Induced Technological Change," *Journal of Environmental Economics and Management*, 39, 1-38 (2000).

Heal, G.M., *Valuing the Future: Economic Theory and Sustainability*, New York: Columbia University Press (1998).

Herzog, H., "What Future for Carbon Capture and Sequestration?" *Environmental Science and Technology*, 35:7, pp 148A–153A, April 1 (2001).

Hoffert, M.I. et al., "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet," *Science* 298, 981-987 (2002).

Hotelling, H., "The Economics of Exhaustive Resources," *Journal of Political Economy*, 39, 137-75 (1931).

House, K.Z., D.P. Schrag, C.F. Harvey, and K.S. Lackner, "Permanent Carbon Dioxide Storage in Deep-Sea Sediments," *PNAS*, 103(33), 12291-12295 (2006).

IPCC, *IPCC Third Assessment Report: Climate Change 2001* (2001).

IPCC, *IPCC Special Report on Carbon Dioxide Capture and Storage* (2005).

IPCC, *IPCC Fourth Assessment Report* (2007).

Jaffe, A.B., R.G. Newell, and R.N. Stavins, "Environmental Policy and Technological Change," *Environmental and Resource Economics*, 22, 41-69 (2002).

Jaffe, A.B., R.G. Newell, and R.N. Stavins, "A Tale of Two Market Failures: Technology and Environmental Policy," *Ecological Economics*, 54, 164-174 (2005).

Kelly, D.L. and C.D. Kolstad, "Integrated Assessment Models for Climate Change Control," H. Folmer and T. Tietenberg (eds.) *International Yearbook of Environmental and Resource Economics 1999/2000: A Survey of Current Issues*, Cheltenham, UK: Edward Elgar (1999).

Kolstad, C.D., and M. Toman, "The Economics of Climate Policy," Resource of the Future Discussion Paper 00-40REV, June 2001 (2001).

Krautkraemer, J.A., "Nonrenewable Resource Scarcity," *Journal of Economic Literature*, 36(4), 2065-2107 (1998).

Krichene, N., "World Crude Oil and Natural Gas: A Demand and Supply Model," *Energy Economics*, 24, 557-576 (2002).

Lackner, K.S., "A Guide to CO₂ Sequestration," *Science* 300, 1677-1678 (2003).

Daiju Narita (Nov. 12, 2007)

Lackner, K.S. and J.D. Sachs, "A Robust Strategy for Sustainable Energy Use," *Brookings Papers on Economic Activity* 2, 215-284 (2005).

MacFarland, J.R., J.M. Reilly, and H.J. Herzog. "Representing Energy Technologies in Top-Down Economic Models Using Bottom-Up Information," *Energy Economics*, 26, 685-707 (2004).

Marchetti, C., "On Geoengineering and the CO₂ Problem," *Climatic Change* 1(1), 59-68 (1977).

Massachusetts Institute of Technology (MIT), *The Future of Coal: Options for A Carbon-Constrained World* (2007).

Mendelsohn, R., W.D. Nordhaus, and D. Shaw, "The Impact of Global Warming on Agriculture: A Ricardian Analysis," *American Economic Review*, 84(4), 753-771 (1994).

Mendelsohn, R., W. Morrison, M.E. Schlesinger, and N.G. Andronova, "Country-Specific Market Impacts of Climate Change," *Climatic Change*, 45, 553-569 (2000).

Narita, D., "The Use of CCS in Global Carbon Management: Simulation with the DICE Model," in progress (2007).

Newell, R.G., and R.N. Stavins, "Climate Change and Forest Sinks: Factors Affecting the Costs of Carbon Sequestration," *Journal of Environmental Economics and Management* 40, 211-235 (2000).

Nordhaus, W.D., *Managing the Global Commons: the Economics of Climate Change*, Cambridge, MA; London, England: MIT Press (1994).

Nordhaus, W.D., and J. Boyer, *Warming the World: Economic Models of Global Warming*, Cambridge, MA; London, England: MIT Press (2000).

Pacala, S., and R. Socolow, "Stabilization Wedges: Solving the Climate problem for the Next 50 Years with Current Technologies," *Science* 305, 968-972 (2004).

Plantinga, A.J., T. Maulding, and D.J. Miller, "An Econometric Analysis of the Costs of Sequestering Carbon in Forests," *American Journal of Agricultural Economics* 81(4), 812-824 (1999).

Pindyck, R.S., "The Optimal Exploration and Production of Nonrenewable Resources," *Journal of Political Economy*, 86(5), 841-861 (1978).

Schlenker, W., A.C. Fisher and W.M. Hanemann, "Will U.S. Agriculture Really Benefit From Global Warming? Accounting for Irrigation in the Hedonic Approach," *American Economic Review*, 95(1), 395-406 (2005).

Daiju Narita (Nov. 12, 2007)

Slade, M., "Trends in Natural Resource Commodities Prices: An Analysis of the Time Domain," *Journal of Environmental Economics and Management*, 9, 122-137 (1982).

Sohngen, B., and R. Mendelsohn, "An Optimal Control Model of Forest Carbon Sequestration," *American Journal of Agricultural Economics*, 85(2), 448-457 (2003)

Solow, R.M., "Intergenerational Equity and Exhaustible Resources," *Review of Economic Studies*, 71, Symposium on the Economics of Exhaustible Resources, 29-45 (1974).

Stavins, R.N., "The Costs of Carbon Sequestration: A Revealed-Preference Approach," *American Economic Review* 89(4), 994-1009 (1999).

Stern, N., *The Economics of Climate Change: the Stern Review*, Cambridge, UK: Cambridge University Press (2007).

Tol, R.S.J., "Estimates of the Damage Costs of Climate Change, Part II. Dynamic Estimates," *Environmental and Resource Economics*, 21, 135-160, (2002).

World Bank, *The East Asian Miracle: Economic Growth and Public Policy*. World Bank Policy Research Report, Washington D.C.: World Bank (1993).