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by Daiju Narita

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Keywords: Carbon dioxide capture and storage (CCS), climate change, energy, dynamic optimization

JEL classification: Q3, Q4, Q54

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Abstract

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Introduction

CCS (carbon dioxide capture and storage¹) is an item that has increased its recognition over the past several years in the multi-faceted debates on climate change. This emergence is to a large extent a reflection of the policy environment, facing conflicting needs for stringent long-term control of carbon dioxide (CO₂) emissions and for devising politically feasible policy paths given the current economy's reliance on fossil fuel. CCS is a set of techniques for separating and capturing CO₂ from emission sources (e.g., coal power plants), transporting and storing it in secure locations (e.g., underground saline aquifers, which are not usable for drinking water or irrigation) semi-permanently in order to reduce atmospheric CO₂ emissions (for a technical review of CCS, see IPCC, 2005). Although CCS is still in a development stage with only a handful of active demonstration projects across the world, the concept is technically straightforward given the wealth of fossil fuel extraction or mining technologies already accumulated, and its potential is thought to be extremely large – according to IPCC (2005), CCS could sequester at least 2,000 gigatons (Gt) of CO₂,² the amount comparable with the total global CO₂ emissions for several decades at the current annual level of emissions.

In parallel with the growing recognition of CCS in the policy field, some seminal academic studies have been issued over the last several years in terms of the potential role of CCS in future climate policy ([16], [12], [8], [23], [14]). While they devote a substantial amount of their discussion to possible near-future application of CCS in limited circumstances (e.g., coal

¹ Carbon dioxide capture and storage is also called *carbon capture and storage*, or *carbon capture and sequestration* (the abbreviation is the same: CCS).

² It should be noted that this is a number obtained by expert elicitation (i.e., the best guess by scientists). Estimates of CCS's ultimate potential are still very limited (especially for the developing regions), and the IPCC does not claim that the above number is definite. See [8] for the methodology of estimation and the exact meaning of this number which it claims.

power generation), they all foresee immense long-term implications for CCS: in other words, CCS is not assumed to be a niche technology that could be deployed only in a small scale, but a major component of future carbon reduction portfolio that could be utilized extensively, possibly to the extent of several gigatons annually worldwide.³

With this potential significance of CCS, however, it is also likely that CCS is not going to become a technology which could supersede all the other CO₂ mitigation options, as the technology provides little secondary benefits besides CO₂ reduction in most forms of potential application. In addition, some skeptics question the viability of this entire approach by pointing out a variety of possible weaknesses, ranging from high costs⁴ to environmental risks. In this sense, CCS is not a method which will automatically solve the dilemma with regard to carbon dioxide emissions and climate change. In other words, the importance of CCS can be only judged in a relative way, in presence of a range of other mitigation options and carbon policy schemes.

This paper is to give a perspective for future cost-benefit discussions on CCS, an issue which inherently needs fine comparisons with other options for effective policy making as suggested above. The central idea in the subsequent discussion is that CCS opportunities can be treated as a non-renewable resource and should involve a scarcity rent, and therefore that cost-benefit considerations about CCS in the carbon management portfolio should be made by taking account of the real price of CCS, inclusive of the shadow price. It might sound peculiar to talk

³ In fact, CCS's application could be potentially extended to the entire fossil fuel sectors by making use of additional technologies such as coal liquification or direct CO₂ collection from the air. For discussion, see [12].

⁴ CCS could in fact dramatically increase the cost of power generation. The IPCC [8] 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%) and also some CO₂ is emitted during the process of CCS itself (i.e., how much CO₂ is *captured* and how much CO₂ is *avoided* are different questions). It should be noted, however, that the cost of CCS should be matched with the social cost of CO₂ emissions, not the cost of power generation.

about the scarcity of CCS opportunities, as CCS is estimated to have a gigantic potential. However, one should be also reminded that CCS is expected to be used in a gigantic scale. Moreover, CCS's total capacity is probably significantly smaller than the resource size of fossil fuel, with which CCS would be used: the IPCC's figure mentioned above, 2,000 GtCO₂ (545 Gt of carbon (GtC)), is about one tenth of the estimated total resource size of fossil fuel (5,000-6,000 GtC: see for example [19]).

To address the above aspect, the paper examines the economic optimality of CCS use with a simple resource-economic analytical model. While there has already been a fairly ample accumulation of economic studies on CCS, the economic optimality of CCS has not been clearly discussed in the debate, as CCS has been considered only as an item to fill the accounting gap between future projections of carbon emissions and some stabilization target. Meanwhile, intertemporal characteristics of cost determinants have been investigated for the case of *forest* carbon sequestration (e.g., [1], [17], [22], [15], [21]). For example, Sohngen and Mendelsohn [21] 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, all of these works do not analyze in depth the shadow values associated to forest carbon sequestration due to the fact that the effect of forest carbon sequestration is impermanent. To the author's knowledge, this study is the first analysis which explicitly considered the scarcity rent of CCS or of carbon sequestration in general.

The Basic Model

Here, we describe a simple resource-economic model about CCS⁵ and energy use. The scope of the model is to find an optimal path of CCS use in presence of the necessity of carbon dioxide control and alternative technology to reduce emissions. The key idea behind the model is to treat CCS as a non-renewable resource with a limited capacity (i.e., once CCS geological reservoirs are filled up with CO₂, one cannot sequester CO₂ with those reservoirs anymore).

The model uses the approach of dynamic optimization, which is a well-established method for resource-economic modeling.⁶ In the model, the single-sector economy gains welfare from 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 ones⁷: since today's CCS use indirectly affects CCS's unit operational cost in the future (since 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 rate of use and price.

In the model, the 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

⁵ It should be noted that "CCS" referred here signifies a set of processes involving underground CO₂ storage (which already has some commercial-scale demonstrations), and that it excludes theoretically more abundant yet less proven options such as mineral carbonization. In the framework of this model, these alternative CCS methods (which are likely to be more expensive than the underground injection approach) could be interpreted as elements among the "alternative" mitigation portfolio (which eventually work as a backstop).

⁶ For general discussions of this approach in the resource-economic context, see [3].

⁷ 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.

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 are two ways to reduce CO₂ emissions: CCS and the use of alternative energy.
- (ii) CCS opportunities are limited (carbon storage capacity is a scarce resource).
- (iii) The marginal cost of CCS use is constant.
- (iv) Emissions without CCS are allowed up to a certain cumulative target.

In the model, two methods can be used to reduce CO₂ emissions: CCS and the bundle of alternative energies which has an aggregate cost function with the standard convex shape (the assumption (i)). Meanwhile, there is limitation in the total amount of CCS use, thus optimization must take account of this scarcity (the assumption (ii)). The third condition (iii) is to say the practice of CCS is uniform in all cases and can be conducted at the same marginal cost (later, we discuss an alternative case relaxing this assumption). The fourth assumption (iv) comes from the idea that CO₂ concentrations should be stabilized below a certain level, assuming that modest CO₂ increases below the target do not cause significant welfare impact (damage). This is in accordance with some of the actual policy targets such as EU's long-term climate target to keep the increase of global average temperature below 2 °C. This accumulative emission target could be incorporated by treating it as another “non-renewable resource”: we could define some total emission target R^{T0} , which is a cumulative limit of carbon emission under which some emission f^t is allowed per unit of time. Later, we consider a more general case where uncontrolled emissions incur disutility through climate change.

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

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

subject to

$$\begin{aligned} \frac{dZ}{dt} (\equiv \dot{Z}) &= -x \quad (Z = Z^0 - \int_0^t x ds) \\ \frac{dR^T}{dt} (\equiv \dot{R}^T) &= -f^T \quad (R^T = R^{T0} - \int_0^t f^T ds) \\ x + f^T &= f \\ \text{and } x, f^T, a &\geq 0 \end{aligned}$$

where,

- f : Rate of fossil energy use/ carbon emissions
- x : Rate of CCS use ($0 \leq x$)
- Z : Capacity remaining in CO₂ reservoirs
- Z^0 : Total size of CO₂ reservoirs (>0)
- f^T : Rate of uncontrolled emissions ($0 \leq f^T$)
- R^T : Allowable emissions left
- R^{T0} : Cumulative emission target (upper constraint for R^T i.e., $R^{T0} > R^T$)
- a : Rate of alternative energy use ($0 \leq a$)⁸
- δ : Discount rate (>0)
- t : Time

The following are the definitions of functions. 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 $W'' < 0$)

⁸ Alternatively, 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 ($C^a(a)$).

$C^f(f)$: Cost of fossil fuel
 *We assume a constant marginal cost, thus $C^f(f)=c_f*f$ ($c_f>0$)

$C^x(x)$: Cost of CCS operation
 *We assume a constant marginal cost, thus $C^x(x)=c_x*x$ ($c_x>0$)

$C^a(a)$: Cost of alternative energy
 ($C^{a'}>0$, $C^{a''}>0$, 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)).

The maximization problem could be solved with the following Hamiltonian with constraints.

$$H = [W(f + a) - c_f f - c_x x - C^a(a)] - x p^x - f^T p^{fT}$$

subject to $x + f^T = f$, $x, f^T \geq 0$,⁹ $R^0 > Z$, and $R^{T0} > R^T$.

where p^x and p^{fT} are the shadow prices of CCS use and allowable (uncontrolled) emissions, respectively.

By replacing f with $x+f^T$, the Lagrangian for the above problem is expressed as follows:

$$L = [W(x + f^T + a) - c_f(x + f^T) - c_x x - C^a(a)] - x p^x - f^T p^{fT} + \lambda_1 x + \lambda_2 f^T$$

where λ_1 and λ_2 are Lagrangian multipliers.

⁹ As explained in the text, a could be exploited at infinitesimal cost in the vicinity of 0 and therefore always satisfies $a \geq 0$ in this model setting. Also, $f \geq 0$ if $x, f^T \geq 0$.

The following is the necessary conditions for solutions with regard to the Lagrangian multipliers:

$$\lambda_1 \geq 0, x \geq 0, \lambda_1 x = 0 \quad (1)$$

$$\lambda_2 \geq 0, f^T \geq 0, \lambda_2 f^T = 0 \quad (2)$$

$$\frac{\partial L}{\partial x} = W'(x + f^T + a) - c_f - c_x - p^x + \lambda_1 = 0 \quad (3)$$

$$\frac{\partial L}{\partial f^T} = W'(x + f^T + a) - c_f - p^{f^T} + \lambda_2 = 0 \quad (4)$$

The following four cases are possible for solutions.

Case A ($\lambda_1 = 0$ and $\lambda_2 > 0$): All emissions are controlled with CCS

In this case, $f=x$ and $f^T=0$, and from (3),

$$W'(f + a) = c_f + c_x + p^x \quad (5)$$

Also, the following two conditions are obtained from the Hamiltonian.

$$\begin{aligned} \frac{\partial H}{\partial a} &= W'(f + a) - C^{a'}(a) = 0 \\ \leftrightarrow W'(f + a) &= C^{a'}(a) \end{aligned} \quad (6)$$

$$\begin{aligned} -\frac{\partial H}{\partial Z} &= 0 = -\dot{p}^x + \delta p^x \\ \leftrightarrow p^x &= p^x(0)e^{\delta t} \end{aligned} \quad (7)$$

where $p^x(0)$ is the shadow price at $t=0$.¹⁰

¹⁰ The transversality condition $\lim_{t \rightarrow \infty} e^{-\delta t} \cdot p^x(0)e^{\delta t} \cdot Z = 0$ is satisfied for all $p^x(0)$ because $Z \rightarrow 0$ as $t \rightarrow \infty$.

The interpretations of these conditions are as follows. First, the condition (7) represents the standard Hotelling-type¹¹ equation for the shadow price of CCS use (p^x). The shadow price increases at the rate of discount rate (δ).

The condition (5) 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 the shadow price. The right-hand side of the condition deals with the total costs of fossil fuel use and CCS as a package.

The condition (6) 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 (5) as well.

Case B ($\lambda_1 > 0$ and $\lambda_2 = 0$): All emissions are uncontrolled

In this case, $x=0$ and $f^f=f$, and from (4),

$$W'(f + a) = c_f + p^{ff} \quad (8)$$

The condition (6) also holds in this case.

$$W'(f + a) = C^a(a) \quad (6)$$

In addition, the Hamiltonian gives the following condition.

¹¹ See [6].

$$\begin{aligned}
-\frac{\partial H}{\partial R^T} &= -\dot{p}^{fT} + \delta p^{fT} \\
\leftrightarrow p^{fT} &= p^{fT}(0)e^{\delta t}
\end{aligned} \tag{9}$$

where $p^{fT}(0)$ is the shadow price at $t=0$.

The meaning of those conditions is similar to that of the conditions in Case A. The condition (9) represents the shadow price of uncontrolled CO₂ emissions (p^{fT}) with geometric growth. This price corresponds to the optimal carbon tax if emissions are produced by multiple agents. The condition (8) implies 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 the shadow price of uncontrolled emissions. The right-hand side of the condition deals with the total costs of fossil fuel use without emissions control.

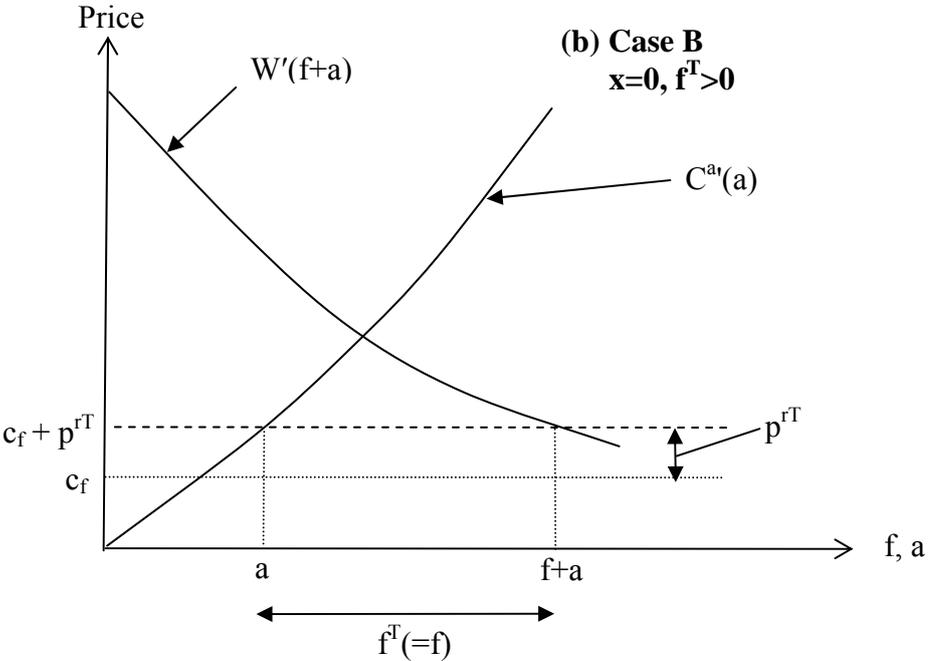
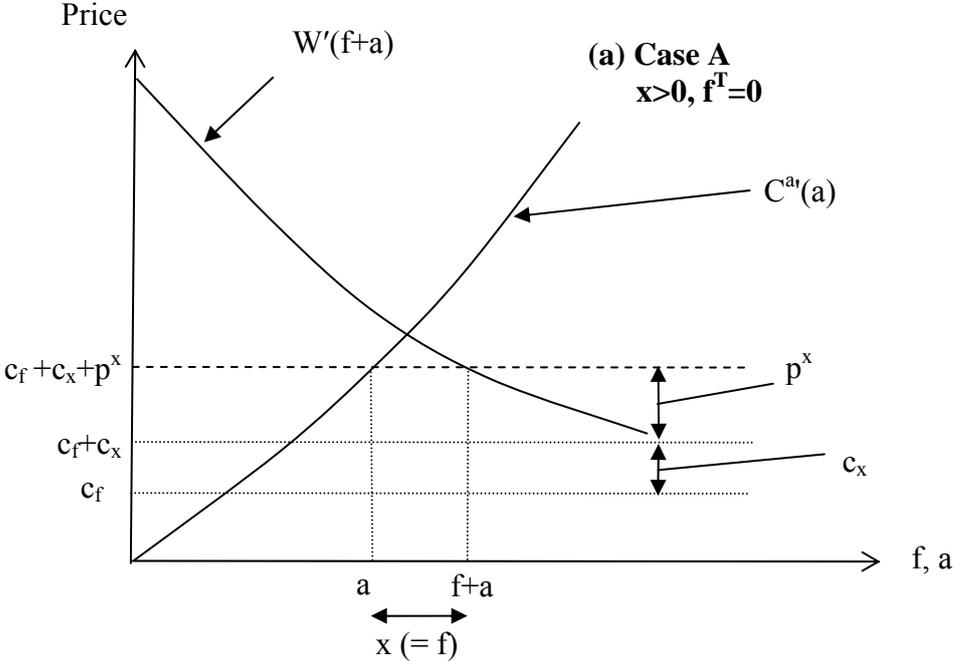
Figure 1 (a) and (b) show the relationships between marginal benefit or costs and shadow prices ((a) Case A with CCS; (b) Case B with uncontrolled emissions). The basic intuition is that effective marginal costs and benefits should be at the same level for energy use, alternative energy costs, and CCS costs or effective costs of uncontrolled CO₂ emissions. In Figure 1(a), 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 ($c_f+c_x+p^x$) are equal in order to satisfy the first-order conditions (5) and (6). 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: the use of fuel, f , is equal to x .

The diagram shows that the total effective price of fossil fuel with CCS ($c_f+c_x+p^x$) should be located within a band whose upper bound is the price level at which fossil fuel is totally

replaced by alternative energy and whose lower bound corresponds to the level of the price of fossil fuel itself (c_f). 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.

The patterns for Case B (with uncontrolled emissions: Figure 1(b)) are almost symmetrical with those for Case A (with CCS), except that the marginal cost of CCS operation (c_x) is absent in this case. Similar to the case of Figure 1(a), the shadow price of uncontrolled emissions reduces the use of fossil fuel while uncontrolled emissions are still comparatively attractive than the case where fossil fuel is totally replaced by alternative energy.

Figure 1. Schematic diagrams about relationships between fuel use, CCS use, uncontrolled emissions, and the use of alternative energy ((a) CCS is used; (b) emissions are uncontrolled)



Case C ($\lambda_1 = \lambda_2 = 0$): Part of emissions is controlled with CCS, and the rest is uncontrolled

If $\lambda_1 = \lambda_2 = 0$, all the conditions (5)-(9) hold, and this represents the case where both CCS and uncontrolled emissions take place. However, this state is unstable since the two shadow prices (p^x and p^{fT}) cannot grow exponentially by sustaining the constant difference by c_x .

Case D ($\lambda_1 > 0$ and $\lambda_2 > 0$): Emissions (and CCS) are zero

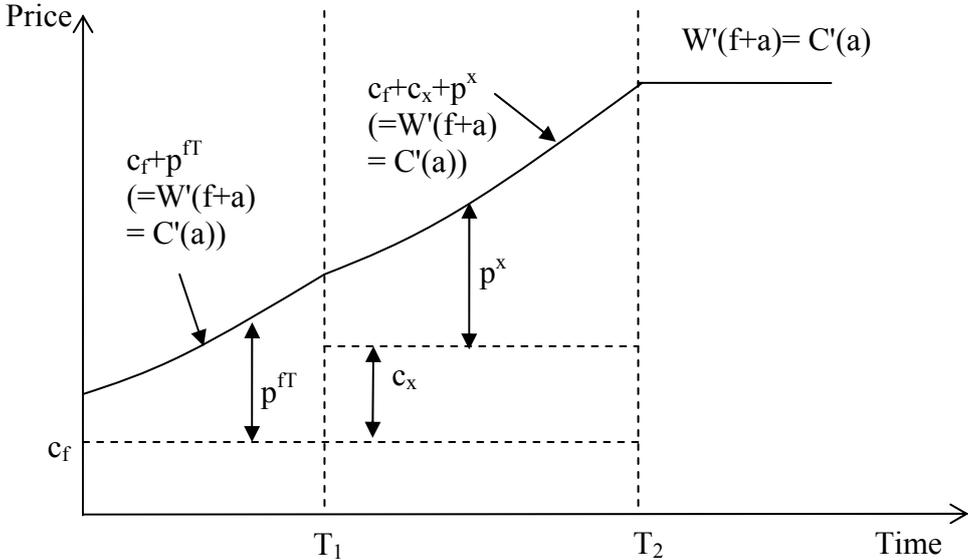
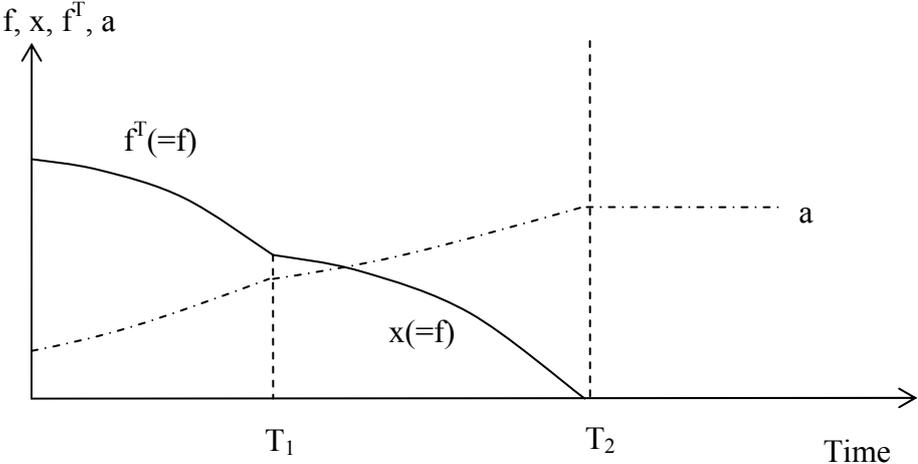
In this case, $f=x=f^T=0$, and only the condition (6) holds:

$$W'(f + a) = C^{a'}(a) \quad (6)$$

This is the case in which fossil fuel use is totally replaced by alternative energy.

The discussion of Case C implies that due to the inherently higher cost of CCS relative to uncontrolled emissions, CO₂ are first emitted without control up to the cumulative target before CCS kicks in. After CCS is introduced, its real price (inclusive of the shadow price) rises over time, and eventually the CCS resource is depleted. Finally, the alternative energy takes all the energy supply. In other words, the system experiences the following transition: Case B → Case A → Case D. Figure 2 shows the dynamics of the system. The times T₁ and T₂ correspond to the points at which the switch between the types of energy use (uncontrolled emissions → CCS → full renewable) takes place.

Figure 2. Schematic diagrams of the trend of f , x , f^{Γ} , a , and their prices



Discussion: More reflections on the shadow price of CCS

In the above basic 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 real 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.¹²

A question that might arise is whether the shadow price of CCS could have actual meaning in real-world policy making. The first key point regarding this question is how contingent the presence of shadow price is on the assumption of climate change policy in the model, which is represented with an accumulative emission target. A more general model would require a function of climate change damage proportional to accumulative CO₂ emissions, and optimality of CCS use would be assessed in comparison to the importance of climate change damage. In fact, it is easy to show that a minor modification to the basic model could incorporate the damage function, and that CCS's shadow price still appears in the modified model. The loss of welfare due to climate change (function of climate change damage) could be indexed with the accumulative use of fossil fuel (or accumulative emissions), in other

¹² Interestingly, this conclusion of decreasing CCS use over time is in contrast to Pacala and Socolow's "wedges" proposal, in which they presupposed that CO₂ reduction is scaled up over time [16]. The two analyses (the current model and Pacala and Socolow's study) are based on very different assumptions from different viewpoints, but the contrast 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).

words, the damage function could be defined as $D(R^{T0}-R^T)$ ($D' > 0$ as the function of R^T : note R^T is to *decrease* over time). The modified form of Hamiltonian is expressed as:

$$H = [W(f + a) - D(R^{T0} - R^T) - c_f f - c_x x - C^a(a)] - xp^x - f^T p^{f^T}$$

(subject to the same constraints as in the basic case: $x + f^T = f$ and $x, f^T \geq 0$)

The shape of solution depends on the shape of $D(R^{T0}-R^T)$, and a simple pattern could not be shown analytically. Still, it is straightforward to show that CCS's shadow price exists. In the context of shadow price discussion, what is new with this modification is that depending on the functional form of D , there could be a case where x and f^T are both non-zero at the same time (i.e., when Case C sets in). If this is the case, the condition (9) is replaced with the solution of the following equation:

$$-\frac{\partial H}{\partial R^T} = -D'(R^{T0} - R^T) = -\dot{p}^{f^T} + \delta p^{f^T}$$

The alternative set of conditions however does not change the model features in terms of the presence of CCS's shadow price, as long as there is a finite R^{T0} that it is reasonable for any climate policy to observe (in other words, $D(R^{T0}) = +\infty$ with a finite R^{T0}).

The question concerning the actual implications of CCS's shadow price could be further viewed from two angles: the possibility of CCS's shadow price being superseded by other factors (e.g., geopolitics), and the possibility of CCS's shadow price being perfectly woven in business decisions and carrying no bearing on policy making. For the former point, CCS storage reservoirs are likely to be geographically evenly distributed across the world, according to estimation by the IPCC and others. Presence of many potential reservoirs in the

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 less prone to be subjected to OPEC-like price manipulation than oil. Also, historical patterns of CO₂ emissions suggest that the “demand” for carbon emissions might be steadier than that of most commodities. In this sense, although there is a chance that an increasing number of inexpensive reservoirs are going to be discovered in the future, it is possible to at least expect that CCS is less likely to face severe price volatility such as oil’s, which can eclipse the effect of scarcity rent.

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

Another consideration in discussing the shadow price of CCS is the cost structure of CCS operation. The marginal cost of CCS operation may not be constant, and the price path may not take the standard Hotelling pattern. Even though the cost structure could be different,

however, a shadow price should still exist as we will see in the following example. One possible case of alternative cost structure is that the marginal cost of CCS use rises according to the accumulated amount of use since less expensive reservoirs would be exploited first. The operating costs of CCS may depend on reservoir types of CO₂ storage (e.g., the depth of the reservoir, the distance between the site and industrial centers), but in principle the costs should be independent of the rate of CCS use itself if the market can adjust its scale of CCS operation swiftly.

While the shift of operation from cheaper to more expensive reservoirs could raise the marginal cost of CCS operation over time, there are also some potential mechanisms that could facilitate an initial decrease of the resource cost, such as efforts of resource exploration and technological change ([18], [20], [4]; a review on this matter is given by [11]).¹³ Technological change is a straightforward reason for a non-monotonic resource cost (i.e., a resource cost that decreases initially and then increases) ([4]): with lack of experience, resource extraction requires extra costs at the beginning.

The temporal profile of CCS's cost can be 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 the narrow sense of advancement of engineering techniques, but also development of institutions (regulatory systems, business structure, etc.), or change in public perception (understanding and acceptance of risks, etc.).

¹³ There are also a number of empirical studies which investigated the trends of resource rents for various commodities. For example, Berck and Roberts [2] estimated that resource rents of major mineral resources would be unlikely to increase in the near future, a conclusion against Slade's [20] prediction of future resource price increases.

With these additional assumptions, an alternative cost function of CCS operation can be expressed as $c(Z)x$, with the rate of CCS use x and the accumulated amount of CCS Z as in the basic model. In the long run, the marginal cost $c(Z)$ should rise with a larger Z because of the shift in exploited reservoir types. Meanwhile, until CCS becomes a well-received technology for the economy, $c(Z)$ could fall as Z increases. These features can be expressed by assuming 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 (as in the standard case), and the other, $c^2(Z)$, corresponds to the additional costs in early implementation due to immaturity of technology.

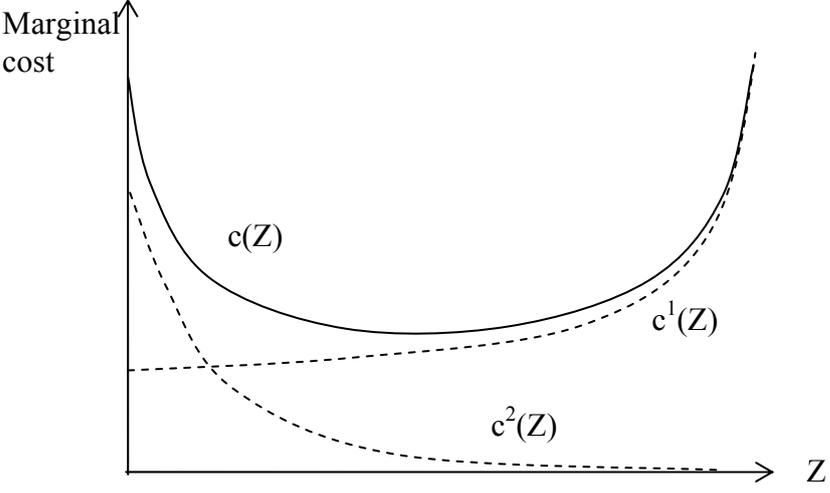
$$c(Z) = c^1(Z) + c^2(Z)$$

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

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

In this formulation, $c(Z)$ is the sum of $c^1(Z)$ and $c^2(Z)$, and as Figure 3 shows, the profile of $c(Z)$ may exhibit a U-shaped curve.

Figure 3. Schematic diagram about alternative formulation of the CCS marginal cost ($c(Z)$)



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

Meanwhile, the cost of alternative energy could also decline over time due to technological improvement in response to a growing scale of installation.¹⁴ Indeed, in reality, many energy technologies have experienced a price decline in parallel with cumulative electricity production.¹⁵ In the presence of technologically-driven cost reduction of alternative energy, some contrast could arise between CCS and alternative energy with regard to long-term cost trends: the cost of CCS rises with exploitation in the long run, while that of alternative energy decreases by the learning-by-doing effect (which is an externality) as the technique is widely adopted.¹⁶

For this case, the Hamiltonian for the maximization problem is rewritten as follows:

$$H = [W(f + a) - c_f f - c(Z)x - C^a(a, G)] - xp^x - f^T p^{fT} + ap^a$$

subject to $x + f^T = f$ and $x, f^T \geq 0$

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^a is the shadow price associated with G .¹⁷

Similar to the case of the basic model, the following conditions for solutions are obtained

when CCS is used:

¹⁴ See [9] and [10] for review of general issues existing in the relationship between technological change and environmental policy.

¹⁵ See for example, *Experience Curves for Energy Technology Policy*, IEA, 2000, p21.

¹⁶ 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, [5].

¹⁷ The sign of the shadow price is reversed from that of p^x and p^{fT} just to imply that G increases with accumulative use of a as opposed to the case of Z or R^T . However there is no fundamental conceptual difference between p^a and the other two shadow prices.

$$W'(f + a) = c_f + c(Z) + p^x \quad (10)$$

$$W'(f + a) = C_a^a(a, G) - p^a \quad (11)$$

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

*See Appendix for derivation

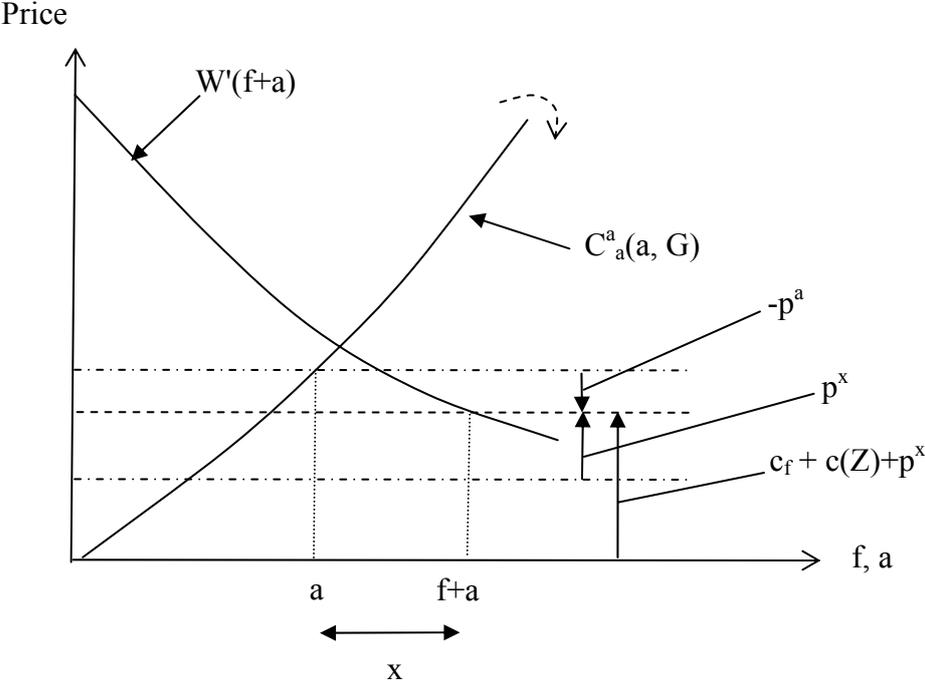
$$p^a = -e^{\delta t} \int_t^{\infty} C_G^a(a, G) e^{-\delta s} ds \quad (13)$$

*Derivation similar to (12)

Figures 4 and 5 show the relationships and dynamics of fuel use, CCS and alternative energy use. With a U-shaped marginal cost of CCS, the trend of CCS use may take a hump-back shape as in Figure 5. Other basic features are unchanged as compared to Figures 1 and 2, except that in the current case, alternative energy is more favored due to the negative shadow price.

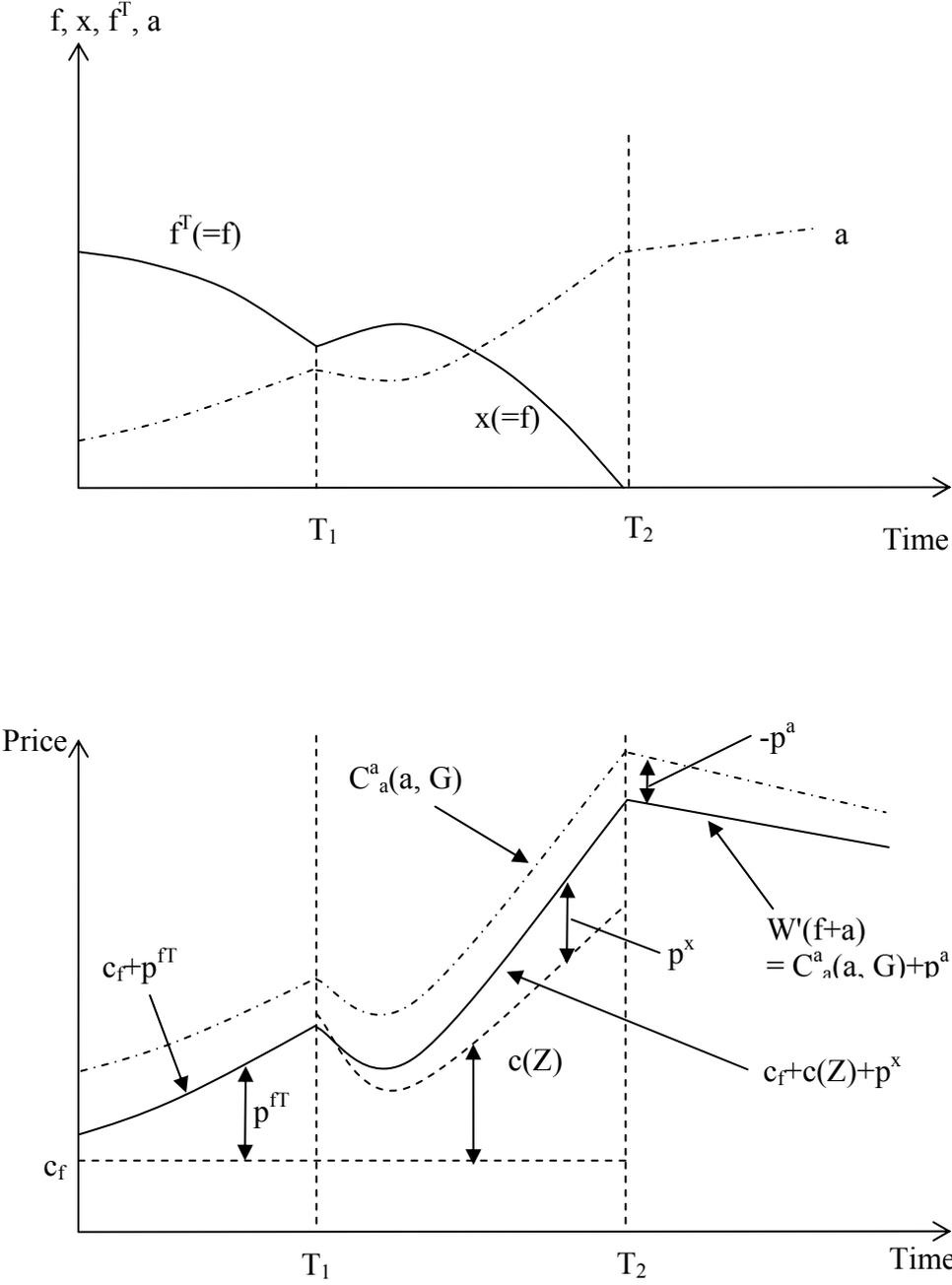
In fact, one could notice that the sign of shadow price is opposite for CCS (in the long run) and for alternative energy as $c(Z) \geq 0$ and $C_G^a \leq 0$. As seen in Figure 5, in the optimal case, the shadow price for alternative energy drives its use higher, while that for CCS use is a decreasing factor of the use in the long run. 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.

Figure 4. Schematic diagrams about relationships between fuel use, CCS use, and the use of alternative energy (with alternative cost functions for CCS and alternative energy).



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

Figure 5. Schematic diagrams of the trend of f , x , f^T , a , and their prices (with alternative cost functions for CCS and alternative energy).



Endogeneity of the shadow prices for CCS and alternative energy could complicate the value assessment of both options, and it is possible 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 $p^a + p^x$ in order to obtain the optimal outcome.

In sum, the model favors a somewhat conservative policy with regard to CCS use, i.e., to limit its use relative to others, while it certainly shows one 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 ([23] 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.¹⁸ 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.

The above argument in fact would require careful examination 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 interventionist economic model of high-performance East Asian economies (e.g., [24]). In

¹⁸ One of the promising proposals of such alternative CCS approaches is the one with the injection of CO₂ under deep-sea sediments below 3,000m. Though this approach has not been verified yet in actual demonstration, it has a couple of potential 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 [7].

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 the long run. In fact, this shadow price differential could partly explain the uneasiness about CCS (relative to other alternative energies) that some critics express:¹⁹ the differentiated incentive between CCS and alternative energy would clarify and ease the current skepticism about CCS.

¹⁹ 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.

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Appendix. Derivation of Equation (12)

The Hamiltonian has the following first-order condition:

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

The above condition is identical with:

$$p^z = p^z(0)e^{\delta t} - e^{\delta t} \int_0^t c'(Z)x e^{-\delta s} ds \quad (14)$$

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 (14) into the above:

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

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

$$\rightarrow p^z = e^{\delta t} \int_t^{\infty} c'(Z)x e^{-\delta s} ds \quad (12)$$