Emissions Abatement in a Production Economy: Cost-Minimization versus Investment-Consumption Optimization

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Abstract

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This article proposes a baseline-and-credit emission abatement system in the CIR production economy settings by Cox, Ingersoll, and Ross (1985a, 1985b). Under the CIR production economy, individuals can invest directly or indirectly in a set of abatement technologies through firms. In this production economy, the investments pay physical dividends in the form of a capital-consumption good, that is, greenhouse gas (GHG) reduction credits, that can be used to reinvest in the abatement technologies or consumed to offset actual GHG emissions. The mechanism improves the cap-and-trade system in three respects: (1) Instead of free-of-charge emission allowances, carbon credits are produced via physical reductions; therefore, the over-supply of emission allowances in a cap-and-trade system can be avoided. Moreover, the amount of emission reductions is proportional to the GHG emission baseline. (2) By featuring growth of the investments in abatement technologies, the mechanism provides an incentive for further investments in abatement technologies. (3) The risk of changing demands in baseline GHG emissions is hedged via a zero-coupon bond, which provides an ideal fixed-interest-debt financing instrument so that individuals can borrow and lend capitals at a risk-free interest rate r.

By adjusting the risk-free interest rate *r*, in equilibrium, all the resources and wealth within the economy are invested in the abatement technologies. Compared to the emission-reduction-cost minimizing cap-and-trade system, the proposed mechanism maximizes the total benefits in different aspects and provides an alternative mechanism for fighting global warming.

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A climate policy to reduce CO_2 emissions includes benefits such as improving the unemployment rate and prior tax distortions and recycling revenue, as well as bringing about the secondary benefits of reducing greenhouse gas (GHG) emissions (Ekins 1995). For example, the benefits of the green tax policy are examined in the double dividend hypothesis, either in its weak form, in which revenues from green tax can be used to cut distorting taxes, or in its strong form, in which green tax improves both the environment and non-environmental welfare (Schob 2003). Bustamante et al. (2009) show that if a tax were imposed on CO_2 emissions and the resulting revenues were used to cut labor taxes, then employment would rise by 0.5 per cent by 2014. The aggregate net benefits of climate policies also include the even larger gains due to technological changes, for example, the adoption of more efficient environmental technologies, the growth of energy-saving technology innovations, and production expansions (Jackson 1995; Buchner and Carraro 2006; Aldy, Barrett, and Stavins 2003).

Considered the largest international instrument with wide support, the Kyoto Protocol, aimed at stabilizing and reducing GHG emissions. It was adopted on 11 December 1997 in Kyoto, Japan, and the commitments it set up became enforceable on 16 February 2005. As of September 2011, 191 states have signed and ratified the protocol. On Dec. 12, 2011, the United Nations climate summit in Durban had extended the current Kyoto Protocol—originally set to expire at the end of 2012—to 2017.

Under the Kyoto treaty, the Annex 1 countries must meet their greenhouse gas (GHG) emission targets of an average 5.2% reduction of their 1990 level in the period 2008–2012. Nevertheless, the failure to secure agreements from countries such as the United States, thus far, has made progress toward the emission reduction commitments insignificant (Buchner and Carraro 2006). In the Annex I non-Economies-in-Transition (non-EIT) Parties, emissions in 2005 were 5% higher than 1990 levels (World Bank 2008), while their Kyoto target for 2008–2012 is for a 6% reduction in emissions. For Annex I non–Kyoto Protocol Parties, including Turkey and the United States, emissions were 18% above their 1990 levels in 2005. According to the International Energy Agency (IEA), energy-related GHG emissions reached 30.6 giga metric tons in 2010, which is five percent higher than the 2008 level and is the highest level ever since, making it "extremely challenging" to prevent global temperatures from rising to dangerous levels (*World Energy Outlook* 2011).

In summary, the success of the Kyoto Protocol as a climate change policy for solving the climate problem is inconclusive (Prins and Rayner 2007; Gupta et al. 2007). A major criticism is centered on the Kyoto Protocol's International Emissions Trading (IET) mechanism that allows Annex I countries to trade their assigned units (AAUs or emission allowances) to achieve their countries' GHG emission reduction targets over the 2008–2012 commitment period, and in which one unit of AAU corresponds to the right to emit one ton of GHG into the atmosphere. The economic basis for International Emissions Trading (IET) is that the marginal emission abatement cost differs among countries, and trade allows emissions to be abated first in countries where the marginal costs of abatement are lowest. With a trading system, it is expected that the Annex I countries can meet their emission reduction commitments at a reduced cost.

As the negotiations leading up to the Kyoto Protocol had focused only on cost-effectiveness, they failed to account for the aggregate net benefits that can be achieved compared to other global climate policies, for example, a Research and Development Protocol (Barrett 2001; Buchner and Carraro, 2006) or a Hybrid of International Trading Program (Aldy et al. 2003). Early literature (Woerdman 2000) expected that through the other two mechanisms of the Kyoto Protocol, the Clean Development Mechanism (CDM) and Joint Implementation (JI), investors could increase their value via the export potential of advanced emission abatement technologies. In a survey of nine respondents composed of executives linked to the environment (with three of them from banks, five from consulting companies, and one belonging to a NGO), the hypothesis that companies developing CDM projects can generate higher profit margins was not rejected (Kerr et al. 2009). In a comprehensive analysis of technology transfer in the CDM to-date, covering 3,296 registered and proposed projects (Seres 2009), it is claimed that roughly 36% of the projects accounting for 59% of the annual emission reductions claim to involve technology transfer. In this respect, emission abatement projects in CDM or JI yield not only emission savings but also potentially generated revenues that can be used to pay back the investments of the projects.

Under the Kyoto Protocol's IET, emissions trading schemes may also be established as climate policy instruments at the regional or domestic level. Under such schemes, governments set emissions obligations to be reached by the participating entities. In Europe, the European Union's Emissions Trading Scheme (EU ETS) is the world's largest regional emission trading system and is a cornerstone of the EU's efforts to meet its obligation under the Kyoto Protocol. Under the EU ETS, a cap-and-trade system is adopted in which an allowable overall cap of GHG emissions is established and allocated among installations in the form of permits or allowances (with one EU allowance unit of one metric ton of CO_2 or EUA, which is equivalent to the AAU of CO_2 defined under the Kyoto Protocol). With a cap-and-trade system, yearly EUAs can be freely allocated on the basis of the National Allocation Plan (NAPs) made for the trading period by responsible governments to mandatory participating installations, such as businesses or entities with operations that are responsible for significant GHG emissions, or through sale via auction by the government. Installations with surplus EUAs are allowed to sell to the market, although they are not obliged to do so. Those with surplus EUAs may also choose to abate emissions in order to have even more EUAs to sell. On the other hand, when the volume of emissions exceeds installations' allocated EUAs, they will either abate some of their emissions or buy the EUAs from the market. If the participating installations fail to comply, penalties will be imposed on them.

The challenge in a cap-and-trade system is to determine the appropriate level of the cap, which should be stringent enough to induce the desired level of reduction, and the subsequent allocation of the EUAs. On this ground, EU ETS also allows for a certain number of offsets to come from emissions reductions that are generated by projects from baseline and-credit systems, for example, credits from CDM and JI can be used interchangeably with EUAs. Although allowing credits from CDM and JI will increase the number of compliance units, it makes achieving reductions potentially more cost effective.

Nevertheless, a cap-and-trade system still suffers the critique that it provides insufficient incentives for investment in technology development because it does not address two interacting market failures, namely, the negative externality by GHG emissions and the positive externality by new technology (Jaffe, Newell, and Stavins 2005). Given that the development of environmentally beneficial technology is subject to two interacting market failures, it is unlikely that environmental policy alone creates sufficient incentives (Jaffe, Newell, and Stavins 2005). To the contrary, both theory and empirical evidence suggest that the rate and direction of technological advance can be cost-effectively harnessed through the use of economic-incentive based policy (Jaffe, Newell, and Stavins 2005).

Additional policies may be necessary to increase government funding or incentives for private funding of the investments in emission abatement technologies. The optimal public policies portfolio should also include instruments designed explicitly to foster environmentally beneficial technologies. Because of this, a baseline-and-credit system based on a CIR production economy setting (Cox, Ingersoll, and Ross 1985a; 1985b), aimed directly at the stimulation of environmentally beneficial technological changes in an investment-consumption prospect, is proposed. In a baseline-and-credit system, each firm has an emission baseline, which is derived by multiplying a measure of a firm's scale, for example, energy input or product output, by a performance standard specifying a required ratio of emissions to input or output (Fischer 2001, 2003). Firms create reduction credits by emitting fewer than their baseline emissions, which can be sold to firms who exceed their baselines. The variable emission baseline introduces a critical difference between a baseline-and-credit system and a cap-and-trade system. In addition, in a baseline-and-credit system, credits can only be traded before they are certified and registered. Usually, credits cannot be registered until the emission reductions have actually occurred (Buckley 2005).

The outline of the paper is as follows: The next section introduces the two emission reduction mechanisms: the cap-and-trade mechanism versus the baseline-and-credit mechanism in the CIR production economy settings by Cox, Ingersoll, and Ross (1985a, 1985b). The section following that gives a simulation study that compares the two mechanisms, and the final section is devoted to concluding remarks.

Mechanism of GHG Emission Abatement Based on a Cap-and-Trade System

Cap-and-trade systems have been used in the United States for regulations such as the reduction in the use of CFCs and halons to comply with the Montreal Protocol, an international agreement aimed at slowing the rate of stratospheric ozone depletion. They have also been used to reduce the emission of SO_2 and NO_X, the primary precursors of acid rain, to comply with the U.S. Clean Air Act Amendments of 1990. Under a cap-and-trade system, SO_2 emissions from the electric power sector decreased from 15.7 million tons in 1990 to 10.2 million tons in 2005, and a robust market in SO_2 allowances emerged, resulting in cost savings on the order of $1 billion annually compared with some command-and-control alternatives (Carlson et al. 2000). Nevertheless, cap-and-trade systems have a very limited history as a method of reducing CO_2 emissions.

Two of the main objectives of a cap-and-trade system are to fulfill environmental targets and, on the other hand, to achieve these targets at the lowest costs for the regulated installations by the regulatory authority. The two objectives can be attained by making use of differentiated marginal abatement costs among different regions as well as different sectors. Countries or installations with higher marginal abatement costs can upload their obligation for emission reduction commitment by purchasing emission allowances from parties with lower marginal abatement costs. By making optimal use of these marginal abatement cost differences, it is hoped that the overall abatement costs can be greatly reduced (Richels et al. 1996; Seifert 2009). Rubin (1996) shows that in a cap-and-trade system, joint cost is minimized when each firm individually minimizes its abatement costs

and emission allowances' purchased expenses. In Fehr and Hinz (2006), it was shown that an optimal reduction policy that minimizes the global abatement and penalty costs exists and, if that policy is followed, the equilibrium allowance's price equals to the penalty per ton of emission times the probability that the actual emissions exceeding the targets. Overall, a well-designed cap-and-trade system thus minimizes the costs of achieving any given emissions target and provides certainty regarding emissions from the regulated installations as a group, because aggregate emissions from all regulated installations cannot exceed the emission cap.

General Critique of a Cap-and-Trade System

The difficulty in setting the emission cap due to uncertainty in the baseline CO_2 emission demand year by year has become the major source of risks in a cap-and-trade system. In addition to the difficulty of setting an appropriate cap level, two other issues—the subsequent allocations of AAUs to various installations (Burtraw, Palmer, and Kahn 2005; Fowlie 2009) and the efforts in administering and ensuring compliance with the system—show the difficulty of implementing an effective cap-and-trade program while avoiding the so called “carbon bubble” (Daskalakis and Markellos 2008).

If free-of-charge AAUs are oversupplied, no efforts on the emission abatements will be made. Russia, for example, had a tremendous surplus in its free-of-charge AAUs because the targets under the Kyoto Protocol were based on 1990’s emission levels, but emissions in Russia dropped dramatically as a result of its economic declines after the 1990s. In this case, instead of making any abatement efforts, Russia was able to sell the surplus AAUs or “hot air” with no actual emission reductions (Victor et al. 1998; Woerdman 2005). The oversupply of AAUs also occurred within the Regional Greenhouse Gas Initiative (RGGI) program designed to cap the CO_2 emissions from 250 power plants in ten Northeastern and Mid-Atlantic states in the United States for the years 2009 through 2014. In 2009, because the projected goal was 188 million tons but the actual emissions from the power plants were only 124 million tons, less than one third of the allowances offered were bid on and sold. This results in a huge oversupply of allowances.

In Seifert, Uhrig-Homburg, and Wagner (2008) and Fehr and Hinz (2006), it was shown that under conditions in which allowances are not bankable (see EU ETS phase 1) and there is no minimum auction reserve price, and provided that a sufficient number of the allowances are auctioned, if the baseline GHG emission is below the emission target, then the allowance’s price will drop to zero. The price collapse of the EUAs in EU ETS in 2006 (it was halved by May 2, 2006), was a manifestation of the excess allocation of emission permits (Paolella et al. 2006). In light of the ongoing eurozone sovereign debt woes and the fears of a second, deeper, recession, the price expectations for EUAs continue to be in flux and dependent on uncertain policies. The recent situation has also created a surplus of EUAs: Their price has fallen by 40% since June of 2011 and is expected to fall to €3 in 2012–2013. The collapse of the EUA price due to the financial crisis in Europe is expected to take until 2025 to disappear, which can dramatically weaken the efficiency of a cap-and-trade system as an economic-incentive-based environmental policy.

Nevertheless, to create incentives for firms to invest in the development and deployment of low- or non-emitting technologies, a cap-and-trade system must provide commitments to meeting long-run emission targets. A lack of commitments makes the payoff from investments in the new technologies highly uncertain and the investments in those emission abatement technologies will lag (Montgomery and Smith 2007). On the other hand, policymakers also need to maintain flexibility to adjust long-term emission targets as new information is obtained regarding the economic environment as well as the costs of mitigating GHG emissions. Managing the trade-off between the commitments and the flexibility of long-run targets has made the success of a cap-and-trade system more difficult (Stavins 2007). In the following section, a baseline-and-credit system in the CIR production economy settings is developed.

Emission Reduction via Benefits Maximization: CIR Production Economy

The continuous-time optimal consumption and portfolio choice problem was first formulated by Merton (1969, 1971, 1972). Later, Cox, Ingersoll, and Ross (1985a, 1985b) proposed a production economy in which a single capital-consumption good, which can be either consumed or transformed to capital to invest, in perfectly elastic supply is produced by *n* different technologies available in the system. The framework is characterized by the growth of the *n* technologies in a changing investment environment. Individuals within the economy can either consume the outputs or invest the *n* technologies with their wealth and part of the produced outputs so that their consumption utilities are maximized. That is, the output of the *n* technologies, the single capital-consumption good, is both the input and output of the production process. In Prieto (2010), the relationship between innovation and risky investments in research and development (R&D), productivity growth, consumption, and asset price in equilibrium is analyzed based on the CIR production economy.

In this study, the capital-consumption good specifically refers to the carbon credits that are produced by the *n* abatement technologies via physical emission abatement, which can be consumed to offset GHG emissions with one unit of reduction credit equivalent to one ton of GHG emissions. Or, by selling the reduction credits to firms who exceed their baselines, the produced outputs can be transformed into capital to re-invest in the *n* abatement technologies.

Under the CIR production economy, there are a fixed number of individuals, identical in their initial endowment and preferences for the consumption of the capital-consumption good. Each individual seeks to maximize his or her lifetime expected utility of consumption in the form

$$E_t\left[\int_t^T U(C_s, t)ds\right] \tag{1}$$

where C_s is the consumption rate at time *s*, *U* is the twice-differentiable utility function that is increasing and strictly concave. This study specifically considers logarithmic utility function

$$U(C, t) = e^{-\rho t} \, ln(C_t) \tag{2}$$

To describe the growth of the *n* technologies, let S_i represents amounts of the capital-consumption good invested in the *i*th abatement technology. The instantaneous return rate of the *i*th technology is

$$dS_i(t)/S_i(t) = \mu_i x(t)dt + \sigma_i \sqrt{x(t)}\, dZ_i(t), \qquad i=1,..., n \tag{3}$$

where $\mu_1,\ldots, \mu_n$ are the mean return rate coefficients, and $Z_1(t),\ldots, Z_n(t)$ are Brownian motions representing *n* sources of risks associated with the production processes. Define the variance-covariance matrix $\Omega=[\sigma_{ij}]$, where $\sigma_{ij}dt=\sigma_i\sigma_j dZ_i(t)dZ_j(t)$.

In Equation 3, the growth of the investments in the *n* abatement technologies depends on the state variable $x(t)$ that describes the changing production opportunities of the economy over time. In the case of GHG emission abatement technologies, the apparent key state variable is the baseline GHG emission rate. In Equation 3, it is assumed that the mean return rate increases as the baseline GHG emission rate $x(t)$ increases. This is due to the fact that as more GHG is emitted, the more GHG emission reductions are in demand and the more emission reductions are produced.

In general, the baseline GHG emission depends on the weather and fuel prices, as well as economic growth (Benz and Truck 2009). All these factors show mean reversion behaviors in that high (low) factor levels induce supply and demand adjustments that gradually pull down (raise up) the factor levels to their long-run means. Therefore it is assumed here that the aggregate baseline GHG emission rate $x(t)$ follows a nonnegative stochastic mean-reversion process in the form

$$dx(t) = \{a_0 - a_1 x(t)\} dt + b\sqrt{x(t)}\, dY(t) \tag{4}$$

where $a_0>0$, $a_1>0$, and $b>0$, $Y(t)$ is a Brownian motion representing uncertainty (risks) associated with the emission rate (Wachter 2002).

In Equations 3 and 4, there are total $(n+1)$ sources of uncertainties (risks) in the system. Under such uncertainties, an investment basis of $(n+1)$ opportunities is required (Cox, Ingersoll, and Ross, 1985a). In Cox et al. (1985a), the $(n+1)$ opportunities consist of the *n* abatement technologies and a contingent claim, that is, a zero-coupon bond that guarantees payoffs on a specific date in the future. In the CIR production economy, it is assumed that a market exists for the zero-coupon bond, which is in zero-net-supply, that is, the number of long and short positions held by the individuals in the economy are the same. With this assumption, in equilibrium, all the resources or wealth within the system are allocated among the technologies. With the zero-coupon bond, individuals can borrow or lend capitals at a risk-free interest rate *r*. To complete the description of the CIR production economy, it is also assumed that physical investment and trading in securities, either the stocks of the firms for the *n* abatement technologies or the zero-coupon bond, take place continuously with no adjustment or transaction costs.

The existence of the zero-coupon bond guarantees that the risk associated with the changing baseline GHG emission can be hedged since the equilibrium price of the zero-coupon bond is negatively associated with the baseline GHG emission. According to Cox, Ingersoll, and Ross (1985a,b), the equilibrium price of the zero-coupon bond, or the equilibrium risk-free interest rate *r*, will depend on the individuals' preferences for the consumption of the capital-consumption good. This determines individuals' decisions about how much of their wealth is to be consumed versus invested in the *n* abatement technologies so as to maximize their expected lifetime utility of consumptions in (1) subject to the budget constrain

$$dW_t=W_t\left(\sum_{i=1}^{n} w_i\mu_i x(t)\right)dt-C_t dt+W_t\left(\sum_{i=1}^{n} w_i\sigma_i\sqrt{x(t)}\right)' d\boldsymbol{Z} \tag{5}$$

where W_t is the time-*t* aggregate wealth, C_t is the time-*t* consumption rate, the vector of Brownian motions $d\boldsymbol{Z}=(Z_1(t),\ldots, Z_n(t))$, $w_1,\ldots, w_n$ are proportions of aggregate wealth W invested in the *n* technologies, respectively.

As shown by Cox et al. (1985b), subject to the market equilibrium constraint, the optimal consumption rate C^* and proportions $\boldsymbol{w}^* = \left(w_1^*,\ldots, w_n^*\right)'$ of aggregate wealth W invested in the *n* technologies, subject to $\sum_{i=1}^{n} w_i^* = 1$, are

$$\boldsymbol{w}^*=\Omega^{-1}\left(\mu-\alpha\mathbf{1}\right) \tag{6}$$

$$C_t^* = \frac{\rho}{1-(1-\rho)e^{-\rho(T-t)}}W_t \tag{7}$$

where $\mathbf{1}$ is a $n\times 1$ vector with all elements ones. The vector $\boldsymbol{\mu}=(\mu_1, \ldots, \mu_n)'$ and the covariance coefficient matrix $\Omega=[\sigma_{ij}]_{1\le i,j\le n}$ with $(\sigma_i\sqrt{x}\, dZ_i)(\sigma_j\sqrt{x}\, dZ_j)=\sigma_{ij}x dt$, where $\mu_1, \ldots, \mu_n$ and $\sigma_1,\ldots, \sigma_n$ are constants given in (3). The coefficient

$$\alpha=\left(\frac{1'\Omega^{-1}\mu-1}{1'\Omega^{-1}1}\right) \tag{8}$$

Given the optimal consumption rate C^* and portfolio weights $\boldsymbol{w}^*$, the market's risk-free interest rate $r(t)$ can be derived as the constant α multiplying the aggregate baseline GHG emission rate $x(t)$, that is,

$$r(t)=\alpha x(t)$$

Plugging in the stochastic mean-reversion process of $x(t)$ in (1), the risk-free interest rate r is

$$dr=a_1(p-r)dt+\nu\sqrt{r}\,dY \tag{9}$$

where $\nu=b\sqrt{\alpha}$, $p=\alpha a_0/a_1$. The price of the bond that matures at time $T>t$ follows as

$$P(t, Y)=\exp\{A(t, T)-B(t, T)r(t)\} \tag{10}$$

where

$$A(t, T)=\frac{2a_1\pi}{\nu^2}log\left(\frac{2\gamma e^{(\gamma+a_1)(T-t)/2}}{(\gamma+a_1)\left(e^{\gamma(T-t)}-1\right)+2\gamma}\right)$$

$$\gamma=\sqrt{a_1^2+2\nu^2}$$

$$B(t, T)=\frac{2e^{\gamma(T-t)}-2}{(\gamma+a_1)\left(e^{\gamma(T-t)}-1\right)+2\gamma}$$

Simulation Study

In this Section, a simulation study is given to compare the proposed baseline-and-credit system in a CIR production economy framework with a cap-and-trade system. The parameters have been chosen to reflect some stylized facts in the EU ETS for the three-year period between 2005 and 2007. The amount of capital-consumption goods are measured in units of carbon credits, with one unit of carbon credit corresponding to one metric ton of CO_2 emission reduction. The annual fossil fuel CO_2 emission data of Germany from 1960 to 2006 is used for calibration of the mean-reversion process of the "baseline" GHG emission rate $x(t)$ in Equation 4. The annual CO_2 emission data are from the Carbon Dioxide Information Analysis Center (CDIAC). Given the annual CO_2 emissions $x(1), \ldots, x(T)$, T=47, from 1960 to 2006, the log-likelihood of $x(1), \ldots, x(T)$ is

$$\frac{T}{2}\log\left(\frac{b^2}{2a_1}\right)-\frac{T}{2}\log\left(1-e^{-2a_1}\right)-\frac{b^2}{a_1}\sum_{t=1}^{T}\frac{\left[\left(x(t)-\frac{a_0}{a_1}\right)-e^{-a_1}\left(x(t-1)-\frac{a_0}{a_1}\right)\right]^2}{1-e^{-2a_1}} \quad (11)$$

Maximum likelihood estimates of the parameters a_0, a_1, and b of the mean-reversion process in Equation 4 are a_0=1.1625×10^5, a_1= 0.4536, and b=174.381, respectively. The estimated total GHG emission for the period between 2005 and 2007 is therefore 7.7125×10^5 thousand metric tons.

In a cap-and-trade system, if assuming an emission reduction target of 5% during the period between 2005 and 2007, then 3.856×10^4 thousand metric tons of CO_2 emission needs to be reduced, and 7.327×10^5 thousand metric tons of CO_2 emission allowances will be allocated into the system at the beginning of the 2005–2007 period. Simulations of 10^4 sample paths of the cumulated CO_2 emission from 2005 to 2007 show that the proportion of over-supply of the emission allowances is 16.43%. In such cases, no incentives are provided for the investments of abatement technologies. Even if the emission allowances are under-supply, a cap-and-trade system tends to provide a transference of wealth from firms with high abatement costs to those with low abatement costs. Without considering the growth of the investments in the abatement technologies and the corresponding benefits other than emission abatement, the incentives for the investments are still insufficient.

Instead, consider a baseline-and-credit system based on the CIR production economy settings, in which carbon reduction credits are considered as capital-consumption goods that can be either consumed or reinvested in abatement technologies. Suppose there are five different abatement technologies (n=5), each of which can produce the capital-consumption goods in terms of carbon credits that can be consumed or used to re-invest in the n=5 abatement technologies.

To describe the growth of the n=5 abatement technologies in Equation (3), consider four scenarios with different return rates and risks associated with the 5th abatement technology. In the first scenario, low mean return coefficient μ_5, and low risk (variance) σ_{55} but high covariance coefficients $\sigma_{5j}, j\neq5$, i.e., variance-covariance matrix Ω_1, are adopted. In the second scenario, high mean return coefficient μ_5 and variance-covariance coefficient matrix Ω_1 are adopted. In the third scenario, high mean return coefficient μ_5, and high risk (variance) σ_{55} and high covariance coefficients $\sigma_{5j}, j\neq5$, i.e., covariance coefficient matrix Ω_2, are adopted. In the fourth scenario, a high mean return coefficient μ_5 and covariance coefficient matrix Ω_3 with high risk (variance) σ_{55} but zero covariance coefficients $\sigma_{5j}, j\neq5$, are adopted. The mean return rate coefficients and variance-covariance coefficient matrix of the four different scenarios are exhibited in Figure 1.

Figure 1: Coefficients of Return Rates in Equation (3) of Five Abatement Technologies

Coefficients of Mean Return Rates $\mu_1, \ldots, \mu_5$					
	μ_1	μ_2	μ_3	μ_4	μ_5
Low	0.521×10^{-7}	0.781×10^{-7}	1.042×10^{-7}	1.302×10^{-7}	1.563×10^{-7}
High	0.521×10^{-7}	0.781×10^{-7}	1.042×10^{-7}	1.302×10^{-7}	3.125×10^{-7}

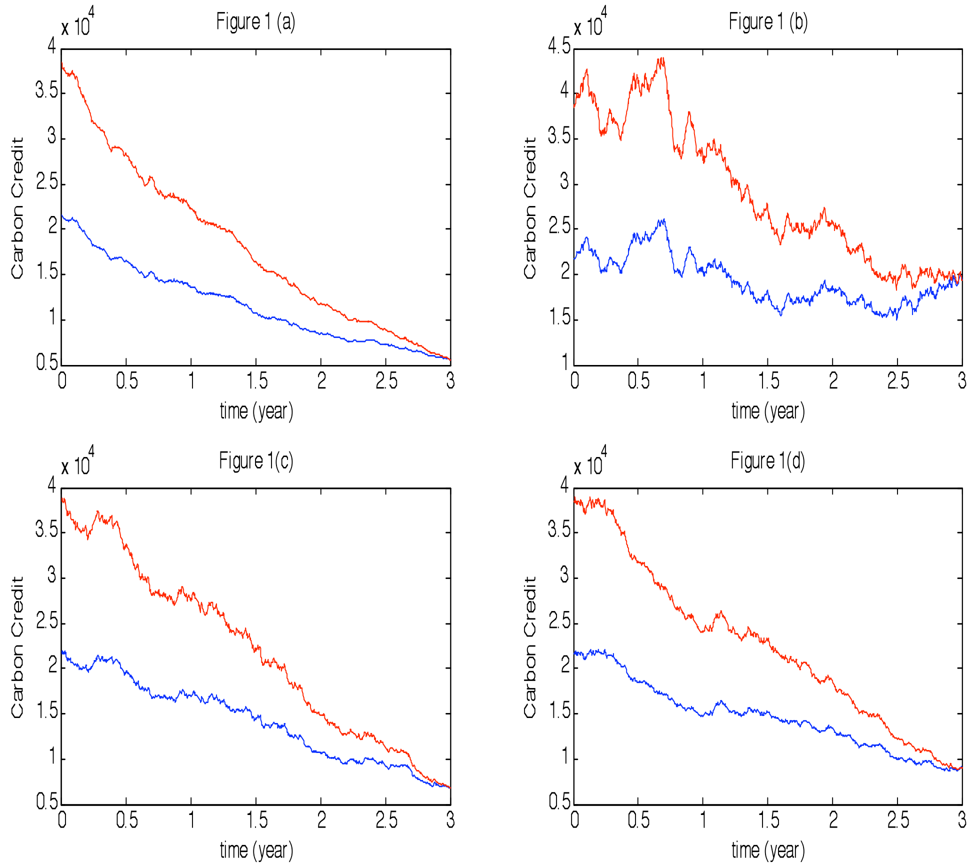
Coefficients of Variance-covariance Matrix Ω	
Ω_1	$10^{-7}\times\begin{pmatrix} 0.3960 & 0.1727 & 0.2087 & 0.1790 & 0.1540 \\ 0.1727 & 0.4153 & 0.1957 & 0.1737 & 0.1367 \\ 0.2087 & 0.1957 & 0.4513 & 0.2453 & 0.1927 \\ 0.1790 & 0.1737 & 0.2453 & 0.4753 & 0.1777 \\ 0.1540 & 0.1367 & 0.1927 & 0.1777 & 0.5507 \end{pmatrix}$
Ω_2	$10^{-7}\times\begin{pmatrix} 0.3960 & 0.1727 & 0.2087 & 0.1790 & 0.1540 \\ 0.1727 & 0.4153 & 0.1957 & 0.1737 & 0.1367 \\ 0.2087 & 0.1957 & 0.4513 & 0.2453 & 0.1927 \\ 0.1790 & 0.1737 & 0.2453 & 0.4753 & 0.1777 \\ 0.1540 & 0.1367 & 0.1927 & 0.1777 & 1.2845 \end{pmatrix}$
Ω_3	$10^{-7}\times\begin{pmatrix} 0.3960 & 0.1727 & 0.2087 & 0.1790 & 0. \\ 0.1727 & 0.4153 & 0.1957 & 0.1737 & 0. \\ 0.2087 & 0.1957 & 0.4513 & 0.2453 & 0. \\ 0.1790 & 0.1737 & 0.2453 & 0.4753 & 0. \\ 0. & 0. & 0. & 0. & 1.2845 \end{pmatrix}$

Figure 2: Summary of Simulated Emission, Emission Reduction, and Final Wealth in Four Scenarios of Baseline-and-Credit System in CIR Production Economy Settings

Scenario	Mean	Covar-iance	Initial Wealth	Emission	Emission Reduction	Final wealth
1	Low	Ω_1	3.856×10^4	7.688×10^5	3.496×10^4	5.570×10^3
2	High	Ω_1	3.856×10^4	7.613×10^5	5.806×10^4	1.930×10^4
3	High	Ω_2	3.856×10^4	7.660×10^5	4.250×10^4	6.776×10^3
4	High	Ω_3	3.856×10^4	7.691×10^5	4.398×10^4	9.017×10^3
Note: All values are in units of carbon credit.						

For each scenario, 10^4 simulation runs with initial wealth $W_0=3.856\times10^4$ thousand metric tons of carbon credits are implemented. The averages of the 10^4 simulation runs are given (Figure 2). Also exhibited is the annual emission consumption rate C_t of Equation 7, or the annual emission reduction rate, versus the evolution of the total wealth in the system (Figure 3). As can be seen, the annual emission reduction rate exhibits the same pattern as the total wealth in the system (Figure 3). The second scenario, with higher mean return rate and low risk technology, generates not only the highest total emission reduction of 5.806×10^4 units of reduction credits, but also the highest final wealth of 1.930×10^4 units of reduction credits (Figure 2). Not only that, but as can be seen, the second scenario generates the highest annual emission reduction rate during the period 2005–2007 (Figure3(b)). On the other hand, the first scenario, with low mean return rate and low risk, generates the lowest

Figures 3a–d: Realization of the Averages of 10^4 Simulation Runs



Note: Figures 3(a)- (d) illustrate the time paths of emission reduction rate (in blue) versus total wealth (in red) for scenarios one through four, respectively.

emission reduction and final wealth of 3.496×10^4 and 5.570×10^3 units of reduction credits, respectively. For the third and fourth scenarios, with higher mean return rate but higher risk technology, the final wealth and total emission reduction are all lower than those of the second scenario. However, compared to the third scenario with highly positively correlated technologies, the fourth scenario generates higher final wealth as well as higher total emission reduction. The simulation result exemplifies the advantage of investment in a diversified portfolio of technologies.

In either scenario, as credits can be registered only until the emission reductions have actually occurred, the over-supply of the emission allowances can be avoided. In addition, as the growth of the investments in the abatement technologies are taken into consideration, the emission reduction together with final wealth exceed the initial wealth $W_0=3.856\times10^4$ in all scenarios. The simulation result highlights the largest difference between a cap-and-trade and a baseline-and-credit system.

Concluding Remarks

To avoid global warming, simultaneous and rapid industry growth across all mitigation opportunities is required (Mackenzie and Ascui 2009). On this ground, this study provides a different mechanism for emission reduction, namely, in the context of a CIR production economy, instituting a baseline-and-credit system instead of a cap-and-trade system. The rationale behind the mechanism is that investments in emission abatement technologies should be considered as "carbon assets," rather than "liabilities." In addition, the growth of these investments is taken into consideration. Emission reduction credits are produced via physical emission abatement by the technologies instead of via free-of-charges assigned emission allowances under a fixed cap in a cap-and-trade system, in which the largest risk is the changing "baseline" GHG emission.

The advantages of the proposed mechanism are threefold. First, as the credits can only be registered and traded until physical reductions have actually occurred, the over-supply of free-of-charges emission allowances in a cap-and-trade system can be avoided. In addition, by assuming that the productivities of the abatement technologies increase as the "baseline" GHG emission increases, it can be expected that the more GHG is emitted, the more emission reductions are produced. Second, the growth of the investments in abatement technologies is taken into consideration, which provides an incentive for further investments in abatement technologies. Third, a zero-coupon bond that pays its principle plus interests with a risk-free rate r at the maturity date can hedge the risk associated with the fluctuated "baseline" GHG emission. In the case of climate change mitigation, zero-coupon bonds provide an ideal fixed-interest-debt financing instrument since investments typically involve long payback periods and large capital costs but relatively secure operating margins. Not only that, but by adjusting the price of the zero-coupon bond and the risk-free interest rate r, the market equilibrium can be achieved—an equilibrium in which all the resources or wealth within the economy are invested in the n abatement technologies, that is, investment opportunities other than the n abatement technologies have zero net supply.

By aiming directly at the stimulation of environmentally beneficial technological changes in an investment-consumption prospect, it is possible that the proposed baseline-and-credit system can provide a better mechanism to resolve the global warming issue rapidly.

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