Impact of a Safety Valve in an Emission Trading System: A Real Options Approach

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

For more than 20 years, cap-and-trade system has served as an efficient market-based mechanism to reduce emission of air pollutants such as sulfur dioxide and greenhouse gas. In this system, a limited amount of emission allowances are traded between affected firms with no price restriction. A potential problem arises when market demand of the allowances significantly surpasses market supply: allowance prices could boom to unexpected high level that jeopardizes the overall economy. Safety valve, an innovative mechanism, sets an upper limit of the allowance price and eliminates the risk of allowance price spike. Yet individual firms would bear less incentive to undertake substantial investment in costly emission reduction equipment. This paper analyzes how firms would change their investment strategy when we add a safety valve to a cap-and trade system.

Since the allowance price evolution process is time dependent and does not follow the standard Geometric Brownian Motion, there is no analytical solution to this problem, hence we base our analysis on numerical analysis. Using a lattice model, we conclude that a safety valve would undoubtedly delay firms' actual investment in emission reduction equipment. We also conduct sensitivity tests to analyze how would a firm's investment strategy respond to change in some model parameters.

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Chapter 1. Introduction

As growing attention has been focused on solving the global environment problems, an increasing number of policies has been carried out to reduce greenhouse gas emissions. Recent decades have witnessed the widespread use of the cap-and-trade system due to its flexibility and low cost of reaching the environmental goal of emission reduction. (Insley, 2003) Under the cap-and-trade mechanism, the total number of emission allowances is determined to meet the overall pollution reduction goal, and government allocates a certain number of allowances to each targeted firm. The affected firms should emit pollution within the allocated allowances or purchase the allowances if pollution exceeds the allocated amount of allowance. The emission allowance (as a unit of ton) serves as a type of currency, and firms can trade the allowances with each other. This mechanism has been testified to be successful in reducing pollution emission at a lower cost (Pizer, 2002).

Regardless of the satisfying emission reduction result of the cap-and-trade system, one problem emerged to cause abating firms' concern. With the pre-determined "cap" serving as an upper limit of allowance quantity, a temporary spike in the demand for emission allowances, or speculation activities, could drive the allowance price so high that it would harm the affected firms and hinder the economy as a whole.

A potential solution to this problem is to add a safety valve to the traditional cap-and-trade mechanism. The central idea of safety valve is that emission allowance prices are forced to stay below a certain level. Under this new mechanism, allowances are traded as in a traditional cap-and-trade system until the allowance price reaches a considerably high level, at which the regulatory authority intervenes the market by selling whatever quantity is demanded at the pre-determined price. (Jacoby and Ellerman, 2004) With this setup, if allowance prices soar to a level that would even surpass the marginal benefit brought by emission reduction, extra allowances would be sold out at the safety valve price, ensuring the smooth economic activities of affected firms.

To satisfy the environmental regulations, firms are faced with the choice of whether to invest the emission reduction equipment or to purchase emission allowances. The decision depends on the price of emission allowance, investment cost and operation cost of the equipment, and emission reduction performance. Much research work has been carried out to study the trigger price – the threshold allowance price that prompts an affected unit to execute the capital investment, and real option theory has been widely used in this literature. (Herbelot, 1992; Insley, 2003; Laurikka, 2005) With a safety valve introduced to the system and lower expected price, firms would have less incentive to make the capital investment in emission reduction. Hence we would expect more greenhouse gas emission at the early stage of the emission trading program, due to the lowered abatement cost.

The major purpose of this thesis is to analyze how the trigger price would be affected by this safety valve. If the trigger price has been lifted up by a considerable level, firms would delay their capital investment in the emission reduction equipment. Through the study of the trigger price, we hope to find out the abatement strategy of individual firms and hence the overall effects of this safety valve mechanism on the environment. It is important to discover how individual firms' investment strategy would change due to the safety valve mechanism, we can estimate the overall environmental impact given what strategy firms adopt to abate to environmental legislation.

We discover that trigger prices under a safety valve mechanism have been greatly increased, hence firms would likely defer their investment in emission reduction equipment under our base case scenario. Changing basic parameters would not cause a great difference to this result. However, a symmetric safety valve that sets both a higher limit and a lower limit on allowance price would likely contain both economic stability and environmental integrity.

Chapter 2. Development of Emission Trading System

2.1. Brief Introduction of Emission Trading System

Emission trading, or cap-and-trade, is a market-based approach used to control pollution by providing economic incentives for achieving reductions in the emissions of pollutants. (Stavins, 2001) Under such arrangements, affected firms must have a corresponding amount of emission allowances to legally cover the emissions of pollutants. The regulating institutions set an upper limit of the total emission amount, and distribute allowances to affected units for free or through auction. The affected units are allowed to trade the allowances on a secondary market, where allowance prices will be determined by market demand and supply. Under such a mechanism, those who emit more must purchase allowances from those who emit less, so the “dirtier” organizations will be punished and the “cleaner” organizations will be rewarded. This cap-and-trade system makes the polluting plants pay their due social cost while assuring the overall emission reduction goal is reached.

The Coase theorem argues that without transaction costs, people will bargain until the resource is efficiently distributed regardless of the initial allocation (Coase, 1960). The theorem laid the ground for the “cap-and-trade” mechanism which carries a relatively low transaction cost. Substantial amount of subsequent studies have been done to extend the idea of cap-and-trade system (Montgomery, 1972; Roberts and Spence, 1976; Pizer, 2002). Montgomery(1972) provided solid theoretical support to the idea of emission licenses which are freely transferable.

There has been a long debate on the relative merits of price versus quantity instruments to achieve emission reductions. A traditional instrument such as an emission tax, is a price instrument which sets the abatement cost (i.e. price) of emitting and allows the emission amount to vary according to the unit's production activity. In contrast, a cap and trade system is a quantity instrument because it limits the overall emission amount (i.e. quantity) and allows the price to vary (Weitzman, 1974). Weitzman showed that price instruments work better when the marginal benefit curve is relatively flat, and vice versa for quantity instruments.

Roberts and Spence (1976) later showed that a hybrid of price and quantity instrument such as tradable emission permits mechanism with price ceiling and price floor, would be socially superior by minimizing the overall social abatement cost. They proposed a cap-and-trade system with a safety valve by setting a maximum permit price. Emitters have the choice of either obtaining permits from the market or purchasing them from the authority at the specified price. The rationale behind this idea is to maintain a balance within emission and abatement cost uncertainty. Pizer (2002) further developed this idea into the design of climate policy and showed that the hybrid policy is more attractive than a pure price or quantity instrument using a simulation. The U.S. experience on emission trading market of national SOx and regional NOx pollution control has provided empirical proof for the success of market-based quantity controls (Pizer, 2002). Nevertheless, Pizer (2002) indicates that a price-based mechanism would generate more social welfare, although quantity mechanism is more favored due to its political appeal. He suggests that a hybrid mechanism, cap-and-trade scheme with a safety valve, would prompt a significant and feasible policy improvement

The idea of adding a safety valve to a traditional cap-and-trade program emerged out of discussions in the United States regarding to their emission reduction policies. Jacoby and Ellerman (2004) pointed out that a safety valve would help control the volatility of allowance price given the overly stringent emissions target. They also discussed in detail how this hybrid system could serve domestic and international emission trading scheme.

Another hybrid price-and-quantity instrument, “allowance reserve”, was also proposed with a slight change on cap-and-trade with a safety valve (Murray et al., 2009). While the safety valve ensures an unlimited number of emission allowances available at a ceiling price, the allowance reserve sets a maximum number of allowances to be issued in exercising the cost relief. Compared to the safety valve mechanism, an allowance reserve ensures the environmental integrity of the emission trading because the total emission amount is limited at a pre-determined level. Nevertheless if the allowance reserve is exhausted, the huge abatement cost will seriously jeopardize the overall economy. Murray indicates that the reserve-based mechanism would be a welfare-enhancing policy considering the economic and environmental effect trade-off. This allowance reserve scheme was adopted by the California Air Resource Board in its emission reduction policy design, and the California greenhouse reduction program with an allowance reserve started in 2012.

2.2. U.S. Acid Rain Program

The cap-and-trade scheme was first introduced in Title IV of the 1990 Clean Air Act Amendment (the U.S. Acid Rain Program), under which electric power companies must legalize their emission of sulfur dioxide (SO_2) by holding according amount of emission allowances (Insley, 2003). Affected units are allocated with free allowances at the initial stage, and the amount of initial allocation is proportional to the unit's historical emission volume. Companies can trade the emission allowances at a considerably low transaction cost. Although unused allowances could be banked for future use, no allowance from prospective years could be borrowed to cover the current year's emission. The total reduction goal of the Acid Rain program is to reduce annual SO_2 emissions by 10 million tons below 1980 levels. (Environmental Protection Agency, EPA, July 2000)

The execution of Title IV of the US 1990 Clean Air Act turned out to be successful as the Acid Rain Program units have reduced annual SO2 emissions by 67 percent compared with 1980 levels, and the total amount of emission reduction has outperformed the original reduction goal (Environmental Protection Agency, 2009). In order to comply with the legislation, electricity-generating units reduced their emission either by installing scrubbers or switching to low-sulfur coal (Insley, 2003).

After about 20 years of the first implementation of the national SO2 allowance-trading program, it remains widely regarded as a milestone step in the worldwide history of environmental regulation (Chan et al. 2012). Carlson et al. (2000) employed econometric estimation to conclude that allowance trading in the Acid Rain Program, in the long run, may achieve cost savings of $700-800 million per year, compared to a traditional command-and-control program.

Before the Acid Rain Program was launched, projections about future allowance price were made available to buyers and sellers, and the projected allowance price range was $250-$350 for Phase I and $500-$700 for Phase II. (Joskow et al., 1998). However, the actual allowance price turned out to be much lower than projected level, ranging within 60-200, due to an unanticipated decline of sulfur dioxide emission. (Ellerman et. al, 1998)

2.3. The Kyoto Protocol and Emission Trading System

After the success of the first large scale trial of cap-and-trade scheme in the United States, policy makers tried to apply this mechanism to reduce greenhouse gases, mainly carbon dioxide. In 1997, most industrialized nations signed and ratified the Kyoto Protocol, which sets internationally binding emission reduction targets (United Nations Framework Convention on Climate Change, UNFCCC, 2013). Most member countries of the Kyoto Protocol agreed to the legally binding reductions of their greenhouse gas emission during the two commitment periods, the first between 2008-2012 and the second between 2013-2020 (UNFCCC, 2013). The United States signed but did not ratify the agreement. Canada signed but withdrew from the Kyoto Protocol in 2012. The Protocol allows for three flexible mechanisms to meet their emission reduction commitments: international emission trading (IET), clean development mechanism (CDM), and joint implementation (JI).

The regulation of greenhouse gas emission activity relies on the emission allowance, in which one emission allowance, or permit, is equivalent to one metric ton of carbon dioxide (CO_2) emissions. The international emission trading mechanism allows ratified countries that have extra emission allowances to sell their unused capacity to countries that emitted more than the limited target (Kyoto Protocol, Article 17). The clean development mechanism (CDM) allows countries with commitment to reduce or limit emission (“Annex I parties”) to implement an emission-reduction project in developing countries (“non-Annex I parties”). Such projects will generate certified emission reduction (CERs) credits, each equivalent to one tonne of CO2 emission and tradable in emission trading schemes. (Kyoto Protocol, Article 12) The joint implementation allows Annex I countries to earn Emission Reduction Units (ERUs) from investing in an emission-reduction project in another Annex I country. ERUs are tradable and can be applied to meet emission reduction objectives defined by Kyoto Protocol. (Kyoto Protocol, Article 6). Both CDM and JI mechanisms are project-based mechanisms that provide extra sources of emission allowances.

2.3.1. European Union Emissions Trading System

To comply with the emission reduction objective determined by the Kyoto Protocol, a number of emission trading schemes have been implemented, among which the most influential one being the European Union Emissions Trading System (EU ETS). In 2005, European Commission launched the EU ETS to regulate greenhouse gas emission in its member countries and it became the world’s largest implementation of the emission trading program to date (Ellerman, 2007). The EU ETS covers about 45% greenhouse gas emissions in EU from more than 11,000 power stations and manufacturing plants in the 27 EU member states as well as Croatia, Iceland, Liechtenstein and Norway. (European Union, 2013) The overall objective is to reduce emission by 20% till year 2020 and by 80-95% till year 2050, compared to 1990 levels. Similar to the 1990 US Acid Rain Program, the EU ETS operates under the “cap-and-trade” principal, with an gradually tightening annual cap. In early years of implementation (2005-2012), allowances are given away for free in the first stage. Since 2013, auctioning becomes the main method of allocating allowances, and EU legislation will completely cease free allocation by year 2027.

The European Climate Exchange (ECX) provides an official platform for allowance trading among covered units. Allowances traded in the EU ETS are named EU emission allowances (EUA). During 2005 to 2006, EUA price crawled stably to its peak at 30 euros/ton, but after that peak, the price dived to as low as 0.10 euro/ton in September 2007. The reason for the price drop is that some countries planned to give their industries such generous emission caps that there was no need for them to reduce emissions. Owing to the surplus of allowances, the first phase of the scheme did not obtain an ideal mitigation amount. Realizing the cap was too generous to the local entities, the EU proposed to reduce the tradable emission allowances from 2080 million tons in 2007 to 1974 million tons in 2012, followed by 1720 million tons by 2020.

Following the rapid development of spot and futures trading on the exchanges, more sophisticated carbon products have been gradually introduced. Options, for example, came to be traded on European Climate Exchange (ECX) on October 13, 2006. Chevallier et al. (2011) suggested that the introduction of the option market decreased the level of volatility in the EU ETS while impacting its dynamics.

Ample research has been done to demonstrate that this EU ETS scheme has indeed motivated affected firms to reduce greenhouse gas emission. Delarue et al. (2007) argued that in the trial period (2005-2007) of the EU ETS, the mitigation objective could only be achieved by firms' switching from coal-fired power generation to gas-fired power generation. They find out the historic EUA prices in 2005 could have motivated power plants to switch their power generation technique, through a simulation work. Denny and O'Malley (2009) pointed out that this cap-and-trade mechanism brought to cost internalization within power generating industry, because heavy polluters will burden more emission cost while light polluters will be rewarded for their environmental efficiency. Their study explained how the EU ETS scheme led to emission reduction while effectively controlling the social cost.

Although EU ETS and the earlier US Acid Rain program (ARP) were both established under the cap-and-trade principle, differences exist between these two programs. Firstly, the EU ETS has a much larger scale in emission regulating compared to the US ARP, in the aspects of regulated emission volume, covered emitting sources, geographical area, etc. (Ellerman et al., 2007) Secondly, since the EU ETS is a multi-national program, it is managed in a highly decentralized fashion, while the US ARP focuses on US entities and is regulated by one sovereign jurisdiction (Kruger et al., 2007).

2.3.2. Clean Development Mechanism

The objective of the Clean Development Mechanism is to help developing countries achieve sustainable development. It makes economic sense to include developing countries in the global efforts to reduce emissions, since emission mitigation is thought to be less expensive in developing countries. (Goldemberg et al., 1996) Because environmental regulation in developing countries is not as strict as it is in developed countries, there exists more potential for developing countries to cut back its emissions. Hence from the viewpoint of global reduction in GHG emissions, focusing on developing countries is certainly advantageous.

Carbon Emission Reduction (CER), the carbon credit generated in CDM, became listed on the EU ETS in March 2008. By February 2013, 6558 projects had been registered by the CDM Executive Board as CDM projects, which are expected to result in potential supply of 4.3 billion CERs by end of year 2015. By February 2013, the CDM

Board had issued 1.2 billion CERS, about 64.7% of which are generated from projects in China. India, the Republic of Korea, and Brazil were issued with 16.4% of the total CERS. (UNFCCC official website). The CER price fluctuated between 15 and 25 euros per ton initially and dropped since August 2008. By September 2012, prices for CERs had collapsed to below 5 euro, which was partly due to the Eurozone debt crisis, which has reduced industrial activity and the over-allocation of emission allowances. In December 2012, CER prices reached another record low of 31 cents. Although both EUA and CER can be used for compliance with the EU ETS, and both of them allow for the emission of one tonne of carbon dioxide into the atmosphere, CER price consistently lies below EUA price. (Nazifi, 2013) Since affected units are allowed only to use CERs to cover a certain proportion of GHG emission, this constraint becomes the major driver of the price spread between EUA and CER.

2.4. US Regional Greenhouse Gas Initiative

In pace with other developed countries, the United States has also launched greenhouse gas (GHG) reduction plans in year 2005 up to 2020. The Regional Greenhouse Gas Initiative (RGGI) is the nation’s first mandatory, market-based program to reduce carbon dioxide emissions. The nine states participating in RGGI (including Connecticut, Delaware, Marine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont), have established a regional cap on CO2 emissions from the power sector and are requiring power plants to possess a tradable CO2 allowance for each ton of CO2 they emit.

Unlike the earlier cap-and-trade programs, this initiative allocates a large part of the initial allowance to auctions, and the auction revenue is then re-invested in the clean energy economy. Auctioning CO2 allowances ensures that all parties have access to CO2 allowances under uniform terms, and the auction realizes the value of CO2 allowances for reinvestment in eco-friendly programs. A well-designed allowance auction can help maximize the benefits of the RGGI program. (Holt, 2007) This program started in 2009 and the emission reduction scheme is planned to last till 2018, with three years as a compliance period. The main structure of RGGI has influenced the development of other cap-and-trade programs such as the Western Climate Initiative (WCI) and the European Union Emissions Trading Scheme for CO2 (EU-ETS) which adopted auction as the major method of initial allocation.

Since this RGGI program is fairly new, there exists limited literature discussing its implementation strategy, outcome, and influences. Several scholars have discussed it from an angle of environmental policy design. Bird et al. (2008) summarizes key issues for renewable energy markets that are emerging with carbon regulation, such as the implications for emissions benefit claims and voluntary market demand and the use of renewable energy certificates (RECs) in multiple markets. They also discovered policy options under consideration for designing carbon policies to enable carbon markets and renewable energy markets to cooperate. Jeev et al. (2010) point out that the emission market under RGGI will have a major impact on the developing deregulated wholesale electricity markets. They model and study the interaction of these two markets and estimate the influence of the emissions market on wholesale electricity prices. Ruth et al. (2010) conducted an empirical research in order to find out optimized strategies for carbon dioxide emissions reductions in Maryland. Yet little research has been done analyzing the evolution process of allowance price.

2.5. California Global Warming Solutions Act

California, the second largest [1]emitter of greenhouse gas in the U.S., has passed the Global Warming Solutions Act of 2006 and initiates the program on January 1, 2012. This law mandates that California's emissions of GHGs be reduced to 1990 levels by year 2020, an approximate 30% reduction from those expected otherwise. (Abadie, 2011) This short duration (i.e., from year 2012 to 2020) of CA AB32 is understandable because at the current stage, it is hard to forecast: i) future emission volume, ii) future emission reduction technology development, iii) performance of allowance reserve as a newly introduced cost containment mechanism. Furthermore, Jacoby and Ellerman (2004) also pointed out that despite its merits, safety valve is unlikely to serve as a long-term feature of a cap-and-trade system, because it will hamper the system of international emission trading. The program is designed to achieve 273 MtCO2e of cumulative emission reductions in the 2012-20 period and will cover more than 80% of the CA economy, including 350 businesses and 600 facilities. Similar to the Clean Development Mechanism, offsets may be used by affected units to gain extra allowances. The offset protocols apply to projects located in the United States, and eventually may apply to projects located all of North America. This program introduces a cost-containment measure called "strategic reserve". Approximately 4% of the total allowances are set aside in a strategic reserve, which can only be purchased by covered firms at fixed prices that increase over time.

Opposition to the adoption of a GHG reduction policy has always been geared toward concerns about abatement cost. Since any regulatory policy to limit emissions will

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[1] Texas ranks no.1 among all the states of the U.S. in GHG emission amount. (EPA, 2010)

result in higher costs for activities that emit carbon dioxide and other GHGs, emission reduction can lead to a heavy financial burden on the US economy (Tatsutani and Pizer, 2008). The allowance price containment reserve was established to provide a safety valve, helping to keep allowance price within a pre-determined reasonable range. (Bailey et al., 2012) Once the safety-valve price is touched, the system behaves like a tax, fixing the cost of emission while leaving the emission amount to be determined by the affected utilities. (Murray, 2009) Unlike an explicit price ceiling, the amount of allowances that could be purchased at the reserve price is limited under the setup of California AB 32. Once the reserve is exhausted, i.e., all reserved allowances have been sold out at the reserve price, the allowance price will be again determined by the market conditions and can certainly rise above the reserve price. Hence this design of allowance reserve maintains the environmental integrity of the program while also eliminating the possibility of economy downturn caused by unexpected high allowance price.

A heated discussion has been raised about the price containment mechanism. Jacoby et al. (2004) indicates that the usefulness of the safety valve depends on the conditions under which it might be introduced, and that this mechanism is unlikely to serve as a long-term feature of a cap-and-trade system. It’s complicated to coordinate price and quantity instruments, and this mechanism will interfere with the development of systems of international emissions trade. Bailey et al. (2012) point out that this mechanism improves the integrity of the market for several reasons. First, short-run disruption to the market due to unexpected reasons such as severe drought or long-lasting power plant outages, would lead to sharp increase in permit prices and negatively impact the California economy without the reserve. Second, without the “ceiling” of allowance prices, speculative trading could manipulate the allowance market and harm the market. While this reserve would set up a clear and transparent ceiling and allow covered firms to purchase allowances at the ceiling price only under certain conditions, attempts to manipulate the allowance market are not worth trying at the first stage. Murray (2009) addresses some other benefits of the allowance reserve. Since the reserve price is determined before the launch of the program, the authority can send signals concerning its current expectations about the long-term cap and expected price. With guidance of the price signal, the market will probably adjust allowance price to its real value more efficiently.

Consideration should be given to the price level at which the reserve is activated. On the one hand, if the reserve price is too low, the limited amount of reserved allowance could be exhausted easily, hence casting doubts on the program's environmental integrity. On the other hand, if the reserve price is set too high, the reserve may not successfully accomplish its function of cost containment. The California electricity crisis demonstrated that a price-cap that is easily circumvented is both ineffective and ultimately counter-productive. (Bailey et al., 2012) Even some minor adjustments of allowance price can greatly impact the outcome in environment and economy. An ideal reserve price, which is an indicator of marginal abatement cost, should stay in line with the marginal benefit of emission reduction.(Murray, 2009) However, the marginal benefits of GHG reduction is not well defined and sometimes out of the policy makers' control.

Some empirical analysis about this California's AB 32 program has been conducted. Anders et al. (2009) present a summary of possible local efforts to reach the overall goal of GHG reduction. With historical emission data and reasonable prediction about future emission, the paper demonstrates that the region could achieve the AB 32 target. Although state measures are the most important drivers for about 50% of the GHG emissions reductions in the transportation and electricity categories, actions to reduce emissions at all levels – state, regional, and local – will be required to achieve the AB 32 target and to place within reach California’s Executive Order target.

Chapter 3. Economic Model of the Emission Trading System

3.1. Real Option Approach and Firm's Investment Strategy

One of the main approaches to evaluate an investment decision, the Net Present Value approach, tends to underestimate the opportunity cost of making a capital investment (Myers 1977). When future cash flows of an investment are uncertain and the investment is irreversible, firms will benefit from waiting the investment in order to observe the cash flow pattern for a longer period to gather more information. The fundamental idea of the real option analysis is to include the value of waiting when making a capital investment decision.

Real option approach employs financial option valuation techniques to the capital budgeting decisions (Campbell, 2002). A real option is the right, not the obligation, to undertake certain business activities, such as delaying, abandoning, upgrading, initializing a capital investment project. Real options distinguish from conventional financial options in that the underlying assets traded do not involve a financial security. Several studies show that the real option approach works well to evaluate corporate investment opportunities and various operational flexibilities (Myers, 1977; Mason and Merton, 1985).

In the context of the emission trading, individual firms face uncertain future abatement costs and irreversible investment for the emission reduction equipment. These features make the emission trading problem an ideal application of the real option theory. Similar to the optimal investment rule by McDonald and Siegel (1986), Majd and Pindyck (1987) derived the steady state solution to the emission allowance price by assuming a log-normal process of the allowance price and an infinite horizon of the investment project. Insley (2003) later analyzed similar problem by assuming a finite project life and lengthy investment period.

To implement the real option approach, the binomial lattice method is commonly used in the numerical analysis. Herbelot (1992) used the binomial lattice method to analyze the investment decision of a power plant to address the sulfur dioxide emission regulation. The plant could either install a scrubber or switch to low-sulfur coal, and he showed that the investment decision can be critically affected by the value of flexibility to decide when and how to meet the emission reduction requirement. His binomial model incorporates two underlying stochastic variables and could be numerically applied easily.. Abadie et al. (2011) studied the abandonment decision of a coal-fired power plant using a three-dimensional binomial lattice model and reached a conclusion for the abandonment criteria given different scenarios. Given the lack of empirical data on the recently implemented California Global Warming Solution Act and its specific feature of the allowance price evolution process, this thesis adopts the lattice method to analyse a firm's investment problem.

We consider an environment in which a firm, say a fossil fuel power plant, faces an investment decision to reduce the carbon emission. The firm's planning horizon is assumed to be finite, because existing environmental policies are designed to be effective through a limited time period. The firm has to decide whether to adopt the Carbon Capture and Storage (CCS) process to cut down the carbon emission. The CCS is a process which separates CO_2 from industrial and energy-related sources and transports CO_2 to a storage location, thus isolating CO_2 from the atmosphere in the long term (IPCC report, 2011). Odenberger and Johnsson (2010) argue that under the stringent greenhouse gas (GHG) reduction policy in most countries, the CCS process is highly likely to be adopted because it can capture more than 90% of the GHG emission. Other GHG reduction measures include using solar, wind, or biomass energy and building advanced nuclear power plant to generate electricity (Rausch et al., 2010). If the firm adopts the CCS process by incurring investment costs, it can reduce its CO_2 emission and sell the emission allowances in the emission trading market. If not, the firm will continue to emit CO_2 by purchasing the emission allowances in the trading market.

The objective of a firm is to minimize the overall abatement costs for emission reduction given the uncertain fluctuation of the emission allowance price. The firms' decision largely depends on the investment cost of the CCS process and the expected price of the emission allowances. Price of the emission allowances is believed to increase in the long term due to the growing demand for electricity, but fluctuates with uncertainty in the short term (Insley, 2003). This thesis focuses on the cap-and-trade system with a safety valve, in which there exists an upper limit on the allowance price. Higher allowance price increases firms' potential abatement costs and encourages firms to adopt the CCS process. The threshold allowance price that prompts firms to adopt the CCS process is defined as the "trigger price." Dixit and Pindyck (1994) derived an analytical solution for the trigger price when the price follows a Geometric Brownian model (GBM) process and the investment has an infinite life. However, the model considered in this thesis does not follow the typical GBM process due to the safety valve.

3.2. Formulation of the Lattice Model

3.2.1. Evolution Process of Allowance Price

If the emission allowance price follows the Geometric Brownian Motion (GBM) process, the continuous stochastic process of the allowance price X_t is described as following:

$$\frac{dX_t}{X_t} = \mu dt + \sigma dW_t \tag{3.1}$$

where dW_t is the increment of a Wiener process, dt is a very short time period, μ is the constant drift rate, and σ is the constant volatility rate. μ is the expected growth rate of the price and σ is the variance of the price. If let X denote the current price of an asset following GBM, and X^* denote for the asset price after time period Δt. According to the GBM assumptions, the following two conditions regarding expectation and variance of the change rate of X must hold:

$$\mathrm{E}\left[\log\left(\frac{X^*}{X}\right)\right] = \mu\Delta t \tag{3.2}$$

$$\mathrm{Var}\left[\log\left(\frac{X^*}{X}\right)\right] = \sigma^2\Delta t \tag{3.3}$$

Cox and Ross (1979) demonstrated that a discrete-time binomial model, or lattice model, can simulate the process of GBM. Their approach can easily be extended to the problem of non-GBM process, and this thesis adopts their approach to derive numerical solutions for non-GBM process of the allowance price.

The fundamental assumptions of a discrete-time binomial lattice model include (i)price evolves through many discrete periods, (ii)at each period, the price could move either up or down by a certain size, and (iii) the probability of upward or downward movement is constant across periods. The size of the upward or downward movement and their probability is assumed as below, following Cox and Ross (1979).

$$u = \mathrm{e}^{\sqrt{\sigma^2 dt}} \tag{3.4}$$

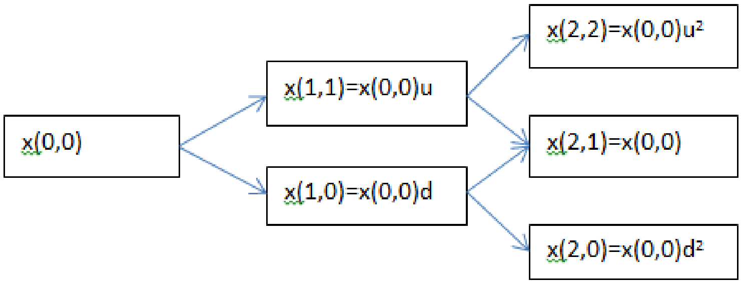
$$d = \mathrm{e}^{-\sqrt{\sigma^2 dt}} \tag{3.5}$$

$$q = \frac{1}{2} + \frac{\mu}{2\sigma}\sqrt{dt} \tag{3.6}$$

where *u* is the size of the upward movement, *d* is the size of the downward movement, and *q* is the probability of an upward movement. Note that *u* and *d* is reciprocal to each other.

We first discuss a traditional GBM process without a safety valve. Let *x(i,j)* denote the allowance price at time *i* (*i* = 0, 1,…, N) with status *j* (*j* = 0, 1,…,*i*). *N* is the number of total time period. At any time *i*, there are (*i* + 1) possible levels of the allowance prices. Ranking the (*i* + 1) prices from high to low, we identify the status by *j*, with a greater *j* meaning a higher allowance price. *x*(0, 0) stands for the initial allowance price. At a node *x(i ,j)*, it could move to *x(i +1, j + 1) = x(i, j)u* with probability *q* and *x(i +1, j) = x(i, j)d* with probability (1 – *q*) in the next period. Figure 3.1 illustrates an example of the price movement for the first three time period of the lattice nodes.

Figure 3.1. Example of the price movement in the lattice model



Using the above relation of the price movement, we can easily show the following equations:

$$x(i,j) = x(0,0) \times u^{j} \times d^{i-j} \tag{3.7}$$

$$\text{Prob}\big(x(i) = x(i,j)\big) = \binom{i-1}{j-1} q^{(j-1)}(1-q)^{(i-j)} \tag{3.8}$$

Equation (3.7) illustrates the method to calculate the allowance price for a given time and status, and equation (3.8) shows the probability that the allowance price equals to a specific value at a certain time *i*. Cox and Ross (1979) proved that given the parameters of *u*, *d*, and *q* defined by (3.4) – (3.6), the binomial model simulates the general GBM process described in (3.1) and ensures that the expected drift rate and volatility rate converge to the real parameters setting and satisfy requirements (3.2) and (3.3).

If there exists a safety valve in the GBM process, the form of the allowance price is different from equation (3.7). With a safety valve, the allowance price, $\bar{x}$ (i,j), would be bounded above at *s(i)*, the safety valve price at time *i*. The safety valve price is assumed to change over time, in order to accommodate the change in the expected emission amount. The allowance price with a safety value $\bar{x}$ (i, j) is described as follows:

$$\begin{cases} \bar{x}(0,0) = x(0,0) \\ \bar{x}(i,j) = min\big(x(i-1,j) \times d, s(i)\big) \quad \text{for } j = 0,1,\dots,i-1 \\ \bar{x}(i,j) = min(x(i-1,j-1) \times u, s(i)) \qquad \text{for } j = i \end{cases} \tag{3.9}$$

Equations (3.9) mean that at each node, allowance price takes either an up-jump or a down-jump. For the up-jump, allowance price cannot surpass the upper limit set by the safety valve, that is to say, allowance price $\bar{x}$ (i, j) would be the minimum value between allowance price under a system without safety valve, $x(i,j)$, and the safety valve price, *s(i)*.

3.2.2. Firm's Investment Strategy

With the binomial lattice model carrying information about the allowance price and probability at each node, we can calculate the expected abatement cost under different investment decisions of the CCS process. Given the fixed lump-sum construction cost of the CCS process F and the discounted future operation and maintenance costs at time *i*, the total cost of adopting the CCS process at time *i* is $C(i) = F + c(i)$. The value of allowances avoided/created by adopting the CCS process at time *i* with status *j* is defined as the product of the amount of emission reduction from adopting the CCS process at each time l and the emission allowance price: $a(i,j) = l \times \bar{x}(i,j)$. The expected sum of the discounted future values of *a(i,j)* is

$$A(i,j) = [qA(i+1,j+1) + (1-q)A(i+1,j)]e^{-rdt} + a(i,j) \tag{3.10}$$

where r is the discount rate. The firm's payoff of investing the CCS process right now is *A(i ,j) - C(i)*.

Under the traditional Net Present Value (NPV) approach, the firm invests now if the expected NPV is positive, i.e., $A($i, j$)$ - $C($i$)$ > 0. On the other hand, when the future benefit from the investment of the CCS process is uncertain, the real option approach compares firm's immediate payoff with its next year expected payoff discounted at the risk-free rate. The size of the option value at time N is simply V(N,j)=max(A(N,j)-C(N),0), which equals the nonnegative part of firm's payoff if investing in CCS at time period N. To derive the option value at any time, we introduce two equations.

$$V(i,j,1)= \frac{qV(i+1,j+1)+(1-q)V(i+1,j)}{exp(rdt)} \tag{3.11}$$

$$V(i,j,0) = A(i,j) - C(i) \tag{3.12}$$

V(i, j, 1) in equation (3.11) is the discounted expected payoff of the next period, and V(i, j, 0) in equation (3.12) is the payoff of an immediate investment. If V(i, j, 1) > V(i, j, 0), the firm would choose not to invest the CCS process immediately and wait till the next period for more information. The difference in values between V(i, j, 1) and V(i, j, 0) is defined as the option value of waiting, or the opportunity cost of an immediate investment. We denote $W(i, j) = V(i, j, 1) - V(i, j, 0)$, when $V(i, j, 1) > V(i, j, 2) > 0$. If $V(i, j, 1) < V(i, j, 0)$, the firm's optimal strategy is to adopt the CCS process immediately. The option value $V(i, j)$ is the maximum of the payoff between the immediate investment and delayed investment.

$$V(i,j) = \max(V(i,j,1), V(i,j,0)) \tag{3.13}$$

At each time i, there is one threshold allowance price, or trigger price, above which the firm decides to make an immediate investment on the CCS project. Yet it's not practical for firms to observe allowance price at each time period and make timely decisions. Therefore we assume the firm makes annual decision regarding this investment and only concern about the trigger prices at the beginning of each year.

3.3. Calibration of the Model

The parameters of the allowance price evolution process are mainly drawn from the U.S. Environmental Protection Agency (EPA, 2009). The scenarios for CO_2 emission allowances discussed by EPA the starting price in 2012 within the range from \$12 to \$23, with an annual increase of 5%. This thesis assumes the base case with a starting allowance price of \$15/ton CO_2 emission and a drift rate (μ) of 5%. For the volatility rate (σ), Insley (2003) argues that the market volatility for the U.S. Acid Rain Program is believed to be about 30%. Paolella and Taschini (2007) estimated the cap-and-trade markets' price volatility for EU ETS is around 21%, and Maniloff and Murray (2011) use 15% for the EU ETS. This thesis uses the base case volatility rate of 20% and conducts the sensitivity analysis for different values of σ. The time interval i is assumed to be one week. The annual discount rate is assumed to be 3% based on the interest rate of a US 20-year treasury bond (Herbelot, 1992).

For the safety valve, we follow the allowance reserve mechanism by California Global Warming Solutions Act Assembly Bill 32 (CAAB32). Although the safety valve mechanism has been proposed by many studies (Jacoby and Ellerman, 2004; Burtraw et al., 2009), no emission trading program has actually implemented it until the CAAB32. Maniloff and Murray (2011) demonstrated through Monte Carlo simulation that the allowance reserve of CAAB32 is unlikely to go exhausted; that is, there is high probability that the allowance reserve under the CAAB32 will serve as a safety valve. This thesis uses the design of the CAAB32 to set up our safety valve in the base case.

Electric Power Research Institute (EPRI, 2011) proposed the CAAB32's reserve price to be at around \$40 - \$50 in 2012, increasing 5% annually. Jacoby and Ellerman (2004) addressed that the safety valve price should be designed to increase annually because this corresponds to the market expectation of allowance price evolution and sends an early price signals to affected firms, enabling firms to make more informative decisions. We set our base case safety valve price to start at \$40 in 2012, increasing by 5% per year. CAAB32 takes effect only during 2012 to 2020, although U.S. has the emission reduction plan until year 2050. This thesis assumes the safety valve mechanism will last from 2012 to 2020, and the allowance price after 2020 will remain at end of 2020 level.

Data on the cost and emission reduction performance of the CCS process are taken from Intergovernmental Panel on Climate Change (IPCC, 2005) and Bert Merz et al. (2005). For the base case, we consider a 400mW power plant with a service life of 30 years. The construction cost of the CCS process is \$846/kW, and the operation and management (O&M) cost is \$3.36/kW/week. By installing the CCS process, the power plant could reduce its carbon emission by 0.1281t/kW/week. The summary of the parameter values are listed in table (3.1).

Table 3.1 Parameter Assumptions

Notation	Description	Value	Source
x(0,0)	Starting allowance price	\$15	EPA(2009)
μ	Allowance price drift rate	0.05	EPA(2009)
σ	Allowance price volatility rate	0.2	Paolella(2007)
u	Price up-jump size	1.0281	Author's calculation
d	Price down-jump size	0.9726	Author's calculation
q	Probability of an up-jump	0.5173	Author's calculation
r	Discount rate	3%	Herbelot(1992)
$s(0)$[2]	Starting safety valve price	\$40	EPRI(2011)
F	Fixed cost of CCS construction	846\$/kW	IPCC(2005)
c(i)	Sum of future O&M cost	$\frac{0.75(1-e^{-\frac{r(1457-i)}{52}})}{1-e^{-r/52}}$\$/kW	IPCC(2005); Author's calculation
L	Periodical emission reduction volume	0.1281t/kW/week	IPCC(2005)

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[2] Safety valve price increases by 5% annually during 2012-2013. S(0) represents for the safety valve price at year 2012.

Chapter 4. Results and Analysis

4.1. Base Case Results

Table 4.1 Base case trigger price

Cases		Trigger price in different years						
		2013	2014	2015	2016	2017	2018	2019
1	Base case	-	-	-	-	-	49.65	29.94
2	No safety valve	16.76	16.76	17.72	17.72	18.73	18.73	18.73

Under the base case scenario of table (3.1), the firm would not invest in the CCS process until 2017 for any price with a safety valve. It may invest in year 2018 and 2019 if the allowance price reaches the trigger price level in table (4.1). As a comparison, table (4.1) also shows the trigger prices when the cap-and-trade program without a safety valve (case 2), in which the trigger price will be within the range between \$16.76 and \$18.73. A lower trigger price induces an earlier investment in the CCS process, because the probability of reaching the trigger price will be larger. This implies that a safety valve mechanism in the emission trading system would significantly delay the investment of costly emission reduction equipment. Note that in neither case would the firm invest in CCS at the beginning of 2012, which is also the starting time of the emission trading system defined in this model, because at the starting point, allowance price is too low to justify such a costly investment.

When a firm makes a significant investment decision in emission reduction equipment, it would protect itself from the risk of high abatement cost (or high emission allowance price). With a safety valve, the fluctuation of the allowance price will be limited within a certain range, and the risk of unexpectedly high allowance price will be reduced. Therefore, the safety valve mechanism would increase the trigger price of investment and lower the probability that firm undertakes the immediate investment in emission reduction.

From the policy perspective, the best emission trading mechanism is to balance between the economic development and environmental integrity. A safety valve helps firms maintain stable financial costs and protects them from risk of unexpected financial burden, hence promoting smooth operation of individual firms and benefiting the overall economy. On the other hand, it weakens firms' incentive to reduce GHG emission by active investment and leaves environment in danger.

4.2. Sensitivity Analysis

4.2.1. Effects of the Safety Valve Price

We now conduct some sensitivity analysis to examine how changes in some parameter values from the base case will affect firm's investment decision.

Table 4.2 Trigger price VS safety valve price

Cases		Trigger price in different years						
		2013	2014	2015	2016	2017	2018	2019
1	s(0)=20	-	-	-	-	-	-	-
2	s(0)=30	-	-	-	-	-	-	29.63
3	s(0)=40	-	-	-	-	-	49.65	29.94
4	s(0)=50	-	-	-	-	-	51.12	30.82
5	s(0)=60	-	-	-	-	-	50.52	31.35
6	No safety valve	16.76	16.76	17.72	17.72	18.73	18.73	18.73

Table (4.2) presents the results from different values of the safety valve price[3].

In case 1 where the safety valve price is set at $20, the firm will never invest in the CCS process, because the safety valve has limited the allowance price in a considerably low range that the significant capital investment would never be justified. The firm would rather purchase the emission allowances in the market. As the safety valve price increases, the firm is more likely to invest in the CCS process in earlier years, though the difference in trigger prices is not large (case 2 – 5).

In base case assumption, safety valve price increases 5% per year. If we change this increase rate to 2%, 10%, and 20%, we could discover that higher increase rate in safety valve leads to lower trigger prices and hence earlier investment in CCS. With

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[3] The change in safety valve price would not affect the other functioning parameters such as drift rate μ, or volatility rate σ. Nevertheless, in reality we might expect some correlation between these parameters.

greater safety valve increase rate, expected allowance prices in the future will be higher, generating more benefits if investing in CCS. This effect is similar to increasing the starting safety valve price, *s*(0), so is the result in trigger prices.

4.2.2. Effects of the Initial Allowance Price

Instead of the initial allowance price of $15 in 2012, we can consider different initial prices from $10 to $30 (EPA 2009). The results for the triggering price is exactly the same as the base case. In the lattice model algorithm, the trigger price is calculated backwards. Unless the price evolution parameter values are changed, the initial allowance price distribution will soon converge to the base case.

4.2.3. Effects of the Volatility Rate

Table 4.3 Trigger prices VS volatility rate

	case	Sigma	Trigger prices in different years						
			2013	2014	2015	2016	2017	2018	2019
With safety valve	1	0.1	-	-	-	39.75	33.44	26.97	20.44
	2	0.2	-	-	-	-	-	49.65	29.94
	3	0.3	-	-	-	-	-	-	43.54
No safety valve	4	0.1	13.42	13.8	14.19	14.59	15	15.42	16.30
	5	0.2	16.76	16.76	17.72	17.72	18.73	18.73	18.73
	6	0.3	20.92	20.92	20.92	20.92	22.74	22.74	22.74

Table (4.3) considers different volatility rate (0.1 – 0.3). Regardless of the existence of the safety valve, higher volatility rate would lead to higher trigger price, delaying the investment of the CCS process. This result is consistent with the existing conclusion in which greater uncertainty increases the option value to invest and tends to delay the actual investment time (Margaret, 2003). With a higher σ, future allowance price will have greater fluctuation, and the firm will be able to make more informative decision by observing the price evolution process for a longer time, hence delaying the investment. This regular pattern is not changed by adding a safety valve mechanism to a cap-and-trade system. Comparing the case with and without a safety valve, we discover that changing volatility rate causes a greater difference in trigger prices when there exists a safety valve. This is due to the fact that given these parameter settings, trigger prices when safety valve exists are much higher than in the opposite case.

4.2.4. Effects of Other Parameters

We conducted more sensitivity tests to detect how trigger prices would respond to the change of some other parameters, such as drift rate μ, investment cost F, and risk free interest rate, r. Except for F , the effects of changing the other parameter values are very weak. If initial investment cost F is set at a lower level, the trigger prices would decrease and investment would occur earlier. This would likely be the case when technology improvement occurs and lowers the investment cost.

Changes in drift rate μ has little effect on trigger prices. In traditional GBM process, a higher μ raises the expectation of future allowance prices, hence raising the potential benefit of undertaking the investment. Under this situation firms would have higher incentive to exercise the option and adopt the investment. However in the case with a safety valve, the upper limit of allowance price eliminates the potential for the allowance price to increase beyond the safety valve price. Therefore the increase in μ would not lead to lower trigger prices.

The change in risk free interest rate, *r*, does not lead to significant difference in the trigger prices. The present value of future benefits increases with a lower interest rate, resulting in lower trigger prices and earlier investment (Conrad and Kotani, 2005). This conclusion remains the same whether there exists a safety valve. Here due to the similar reason explained in the former paragraph, if firms adopt the investment, their expected future benefits generated from allowances are limited to a great extent. Although change in discount rate r would still cause differences in present worth of future benefits, this difference would be hard to observe if future benefits are not large enough.

4.2.5. Bounded Safety Valve

By setting the upper limits of the allowance price with a safety valve, the investment in the CCS process will be delayed at least for several years, no matter how the parameter values are changed within a reasonable range. This means that simply adopting this safety valve mechanism might cause hazard to the environment as firms would emit more GHG to the atmosphere during the early years of the emission trading program. Burtraw et al. (2010) proposed that a symmetric safety valve, which sets both a price ceiling and a price floor, could provide environmental and welfare improvements compared to the conventional one-sided approach. We consider the effects of the symmetric safety valve on the trigger prices.

Given the floor prices, $\underline{s}$(i), the allowance price is set as equation (4.1).

$$\bar{\bar{x}}(i,j) = \max(\bar{x}(i,j), \underline{s}(i)) \tag{4.1}$$

We set the price floor value increases by 5% per year and examine how changes in $\underline{s}(0)$, the starting floor price in 2012, would affect the trigger prices. In the base case scenario, the initial allowance price in 2012 is \$15, and thus $\underline{s}(0)$ should range from 0\$ to 15\$. The effects of the price floors are reported in table (4.4).

Table 4.4 Trigger price VS Floor price

Cases	Starting floor price $\underline{s}(0)$	Trigger prices in different years						
		2013	2014	2015	2016	2017	2018	2019
1	0	-	-	-	-	-	49.65	29.94
2	8	-	-	-	-	-	49.65	29.94
3	9	-	-	44.1	45.04	47.29	45.69	29.94
4	10	22.12	23.46	24.63	26.59	29.51	32.76	29.12
5	11	11	11.55	12.13	12.73	13.37	14.04	14.74
6	12	12	12.6	13.23	13.89	14.59	15.32	16.08

Case 1 of $\underline{s}(0) = 0$ represents the base case of a traditional one-sided safety valve. When $\underline{s}(0)$ ranges within \$0 to \$8, the results of trigger prices are exactly the same as case 1. This implies that when the floor price is considerably low, the price floor would not provide incentive for firms to adopt investment earlier, and the symmetric safety valve is equivalent to a one-sided safety valve. In case 3 and 4 where $\underline{s}(0)$ is set at \$9 and \$10, the trigger prices change significantly and are very sensitive to the floor prices $\underline{s}(i)$. The firm expedite the investment of the CCS process in these cases. In case 5 and 6, the resulting trigger prices are always binding with the floor prices, which implies that the floor prices are set too high and firms would not have the flexibility to alter their investment strategies.

The discussion in this section manifests that a symmetric safety valve which combines price floor together with price ceiling provides more incentive for firms to undertake the capital investment at an earlier time, on condition that the floor price is carefully determined.

Chapter 5. Conclusion

We employed numerical analyses to discover how an added safety valve would affect an emission trading system. With base case assumptions, the allowance price that will trigger firms' investment activity increased significantly. This suggests that: i) Investments are less likely to occur; ii) With prerequisite that investments do occur, they will likely be delayed to later periods.

We conducted sensitivity tests to discover how changes in parameter assumptions will affect trigger prices. Safety valve prices are the key to the mechanism design. Safety valve prices that are set too low could stop firms from investing completely. The higher the safety valve price is, the more likely investment will take place. Greater volatility in allowance price evolution process would delay the investment, as is the case without a safety valve. Different from the case without safety valve, starting allowance price and drift rate would not cause a difference in the result of trigger price. Initial investment cost and risk-free interest rate only indicate minor impacts on the trigger prices. These facts are mainly because that a safety valve significantly decrease expected future allowance prices, weakening the impacts of related parameters.

In addition, we tested the effect of adopting a symmetric safety valve mechanism that sets both upper and lower limits to allowance prices. Our conclusion is that the symmetric safety valve mechanism works better in maintaining the environmental integrity of the emission trading system. The floor price even when slightly different, is very important because trigger prices would incur significant changes.

This thesis provides an explicit numerical method to forecast an individual firm's strategy to invest in emission reduction equipment, in an emission trading scheme that has a safety valve mechanism. However, estimation errors may be generated from biased parameter assumptions and ignored correlation between parameters.

Future research work could extend this thesis from the following approaches: First, with more emission-trading data from the California GHG reduction program, we could find out the correlation between different model parameters and improve our model to include the correlation effects. Second, it would benefit the policy designers if social welfare could be calculated for the case with and without a safety valve. To achieve this objective, we need to analyze the economic benefit of maintaining allowance price stability and the social cost of greenhouse gas emission. Third, with data about trading price and volume, we could estimate the effect of an allowance reserve, which sets a limited amount of allowances available to be purchased at a predetermined price. This mechanism is an upgraded version of a safety valve and would undoubtedly be worthy of analysis.

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Appendix MATLAB Code

```
%%%%%%%%% base case scenario %%%%%%%%%
% all parameter assumption and description are in table 3.1
clc;
clear;
sigma=0.2;
r=0.03;
x0=15; % starting allowance price
y0=40; % starting safety valve price
inv=846;
omc=0.75; %operation and management cost
mu=0.05;
yr1=1456; %parameter for operating yea
yr2=89.8652; %parameter for operating year
sg=1.05; % safety valve price growth rate

vol=sigma^2; % volitility rate
u=exp(sqrt(vol/52)); % size of an up jump
d=1/u; % size of a down jump

q=0.5+mu*sqrt(1/52)/(2*sigma); % probability of an upward jump
x(1,1)=x0; % initial allowance price

for i=2:417
    y(i)=y0*sg^(fix((i-2)/52)); % safety valve price
end
for i=2:417
       % with a greater j, the allowance price will be higher
       if y0>0
           for j=1:i-1
               x(i,j)=min(x(i-1,j)*d,y(i));
               x(i,i)=min(x(i-1,i-1)*u,y(i));
           end
       else
           for j=1:i
           x(i,j)=x(1,1)*(u^(j-1))*(d^(i-j));
           end
           % for the case where there is no safety valve, we set y0=0
       end
       for j=1:i
       a(i,j)=0.1281*x(i,j); % periodical allowance revenue at node
(i,j)
       end
end
for i=1:417
    k(i)=inv+omc*(1-exp(-0.04*(yr1-i)/52))/(1-exp(-0.04/52));
    % amount of capital investment at time i
end
for j=1:417
    A(417,j)=yr2*x(417,j);
    % discounted future revenue from allowance at end of year 2013
    V(417,j)=max(A(417,j)-k(417),0);
    % if V>0, capital investment will be beneficiary
```

```
end
for i=416:-1:1
    for j=1:i
        A(i,j)=(q*A(i+1,j+1)+(1-q)*A(i+1,j))/exp(0.04/52)+a(i,j);
        V1(i,j)=(q*V(i+1,j+1)+(1-q)*V(i+1,j))/exp(0.04/52);
        % V1 is expected payoff of waiting, always nonnegative
        V2(i,j)=A(i,j)-k(i);
        % V2 is payoff of immediate investment, could be negative
        V(i,j)=max(V1(i,j),V2(i,j));
        if V1(i,j)<V2(i,j)
            pointer(i,j)=1;
            % pointer=1 means the capital investment should be made at
node (i,j)
        else pointer(i,j)=0;
        end
    end

end
for i=2:417
    j=1;
    maxx(i)=max(pointer(i,:).*x(i,:));
    while j<=i&&pointer(i,j)==0
        j=j+1;
    end
    if j==i+1
        minx(i)=0;
    else
    minx(i)=x(i,j);
    end
end
for i=1:8
    disp(['trigger price of year ',num2str(2011+i),' =
',num2str(minx(52*(i-1)+1))]);
end
```