An Investment Decision under the Clean Development Mechanism: A Real Options Approach

by

Hisatoshi Kurehira

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Applied Science

in

Management Sciences

Waterloo, Ontario, Canada, 2009

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.

I understand that my thesis may be made electronically available to the public.

Abstract

One of the main challenges that investors in the Clean Development Mechanism (CDM) project face is the management of the volatility of the price of Certified Emission Reduction (CERs). Large scale CDM projects require a long-term investment with significant amount of costs, and this type of investment is often irreversible. Project investors should quantitatively assess the CER trigger price that justifies the initiation of a CDM investment. The traditional discounted cash flow valuation is unable to capture the option value associated with uncertain investment, and thus it tends to underestimate the trigger price which initiates the investment.

Real options theory explicitly considers the option value of delayed investment and can provide a better measurement of the trigger price. This paper presents a theoretical model of the CDM investment project and derives the CER trigger prices that guide investment decisions by using historical market data. It develops a stochastic dynamic programming model for both the geometric Brownian motion process and the mean-reverting process. An analytical solution for the trigger price is derived for the former process, and the trigger price is numerically estimated for the latter. By considering various parameter values, it analyzes the effects of different market environments on the trigger price.

Acknowledgements

I heartily appreciate my supervisor, Dr Bon Koo, for devoting time and directing me through this thesis. I would like to extend my gratitude to two other readers. I especially thank my parents for their support in my education.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1 Research Outline

Over the past decade, emissions trading of greenhouse gases has moved from academia to the frontline of business. Market mechanisms are believed to be a better way of achieving an abatement target than governmental regulations because of cost efficiency. Two principal market mechanisms, Clean Development Mechanism (CDM) and Emission Trading, were adopted by the Kyoto Protocol, which was ratified by most industrialized states.

The CDM allows governments or private firms to accumulate Certified Emission Reductions (CERs) from project activities in developing countries. The Emissions Trading, most notably the European Emissions Trading Scheme (EU ETS), allows trade of surplus emission allocations among the participants.

This radically new carbon market has brought business opportunities – and managerial judgments at the same time – to a wide range of firms that are now under the regulations of the Kyoto Protocol. Such a firm needs to either invest in a CDM project and obtain CERs or purchase CERs from a carbon market.

The purpose of this thesis is to study the valuation of CDM projects with the underlying price of CERs traded on the EU ETS. While much work has been done on policy analysis and instrumental comparison with regards to the CDM scheme, less work has been done on empirical evaluation of the outcomes of the market mechanism. With real options theory, this research quantitatively examines the implications of the CDM scheme on investors' decision process.

This thesis evaluates CER trigger prices for an ongoing CDM projects that justifies the investment, using the historical market history of the European Climate Exchange. It examines numerical results and performs sensitivity analysis with various parameter values. Understanding this type of valuation is of particular importance for both policy makers and corporate managerial decision-makers who need to make challenging investment decisions in the era of global warming.

1.2 Motivation of Research

During the past few decades, the issues of greenhouse gases and global warming have attracted lots of attention and several alternative approaches have been proposed to reduce the emission of greenhouse gases. Market-based mechanisms such as tradable permits are considered an efficient way to achieve the abatement targets. The Kyoto Protocol proposed three such flexible mechanisms: emissions trading, Joint Implementation (JI) and Clean Development Mechanism (CDM).

The cap-and-trade programs, or emission trading, have become one of the main policy instruments among the ratified countries. JI is a project-based market mechanism that allows two ratified countries to obtain credits from a joint emissions abatement project. Likewise, CDM is also a project-based market mechanism that transfers emission credits from a project in a non ratified country to a ratified country.

Under the CDM, firms can accumulate emission credits, namely Certified Emission Reductions (CERs), from their abatement projects in developing countries, and firms can achieve the same amount of emission reductions with a lower cost. Thus, firms are faced with the decision of whether to invest CDM projects in developing countries or instead to purchase CERs in permit markets.

The objective of this thesis is to analyze the firm's decision making process in the context of the CDM projects. With uncertain evolution of the price of CERs, firms compare the profit under the CDM projects with the profit from the direct purchase of emission permits. Historical trend on the European Climate Exchange shows that CER prices fluctuated substantially from 9 euros to 30 euros over the past few years. Based on the various parameters from empirical data, this thesis derives the trigger price that induces firms to invest in the CDM projects. This type of study will be important for both firms which have to make informed investment decisions under volatile price changes and policymakers who have to make accurate valuations of CDM projects to achieve the emission target efficiently.

1.3 Outline of the Paper

Chapter 2 introduces the tradable permits in the context of environmental economics. It is followed by the institutional aspects of market mechanisms, such as the EU ETS and the CDM, which are institutionalized under the Kyoto Protocol

Chapter 3 reviews the literature on emission trading and real options approach. A particular focus is on real options applications in environmental economics.

Chapter 4 constructs two dynamic programming models - geometric Brownian motion process and mean-reverting process. Mathematical expressions for the trigger price in both models are derived.

Chapter 5 investigates the trigger prices for a plausible CDM project by using CER historical prices. I will further perform a sensitivity analysis on models parameters.

Chapter 6 summarizes the numerical results as well as possible future improvements.

The Matlab code that was used to implement the two models is included in the Appendix.

Chapter 2. Institutional Aspects of Emission Permits

Pollution is a typical example of market failures in which the private cost of pollution abatement is different from the social cost, and it is often recommended that government intervention is necessary. Several policy instruments are proposed to regulate pollution, including traditional command-and-control regulations, industry voluntary agreements, market-based instruments, and informational devices (Sarkis and Tamarkin, 2005). Command-and-control requires the government to set a cap on each firm and to penalize the firms that exceed its cap. An industry voluntary agreement is achieved by imposing and complying with a voluntary target set by the industry. An example of informational devices is a public campaign for hybrid cars.

The most discussed market-based instrument is the cap-and-trade program, which is the basis for both the U.S. sulfur trading program and the Kyoto Protocol. There have been debates over the past few decades that whether market-based mechanism is superior to command-and-control approach in reducing pollutions, and the consensus is shifted toward the market-based mechanism (Schmalensee et al., 1998). Among the various types of market-based instruments, this thesis focuses on the tradable permits, in which the government allocates an initial quota of pollution permit to polluters and allows them to trade surplus permits among polluters. By reducing pollution by various abatement efforts, polluters with surplus permits can increase the revenue through the trade of extra allowances.

The U.S. sulfur dioxide trading program proved that the tradable permit approach is superior to command-and-control regulation. The advantage of the tradable permits approach is the economic efficiency; it achieves a target level at the lowest level by allowing firms the flexibility of minimizing the abatement costs (Joskow et al., 1998). Several conditions are required to ensure a successful tradable permits program.

First, the pollution source must be non-isolated with global effects. Otherwise, the pollution permits will not be tradable across regions. Second, there should be a large number of participants in order to ensure a price discovery function which matches the seller and the buyer in a market. An emission market with too few participants may lack the liquidity of permits and limit its functionality. Third, the tradable scheme rests on accurate emissions monitoring and strict enforcement of the property rights of permits. Finally, an initial allocation of quota should be fairly implemented.

2.1 U.S. Sulfur dioxide trading program

The sulfur dioxide cap-and-trade program implemented under the 1990 U.S. Clean Air Act is the first large-scale, long-term tradable permits scheme to cut sulfur dioxide and nitrogen dioxide. This program aimed to cut sulfur dioxide emission from power plants to half of their 1980 level by 2005.

The commitment period was divided into two phases: Phase I was from 1995 through 1999 and Phase II from 2000 through 2005. In Phase I, annual emissions from the 263 most polluting coal-fired power plants must go below a cap. During Phase II, almost all existing fossil-fired power units were capped under the annual emission limits.

Under this cap-and-trade program, the government issues a total amout of tradable permits, or allowances, which give firms the right to emit pollution up to permitted allowances of SO_2 in a given year. If a firm wants to go beyond its allowance, it has to purchase additional allowances from other sources in the permit market. On the other hand, firms with extra allowances can sell them or carry over for future use.

In both phases, newly established power units must buy allowances from existing plants. The initial allowance quotas are determined by historic emissions and are freely traded anywhere in the United States.

Since the government issues fewer amount of allowances than needed, allowances are valuable and traded with a positive price. Thus, polluting firms are faced with two choices; either they purchase extra amount of permits from the market or they invest in abatement technologies to reduce the emission. If the investment in abatement technologies is cheaper than purchasing allowances, firms have an incentive to reduce their emission through investment.

Many firms aggressively switched to low-sulfur coal and installed scrubbers, and as a result the aggregate amount of sulfur dioxide emission dropped to a 33% below the target level in 1996 (Schmalensee et al., 1998). According to the US Environmental Protection Agency (EPA), SO2 emissions went down from an annualized amount of 9.7 million tons in 1980 to 4.7 million tons in 1998 (US EPA 1999). The average cost of emission reduction was $187/ton, which is at the low end of the estimated range, and the typical allowance price was between $100/ton - $150/ton during 1995 to1996. The relatively low allowance prices were due to the large initial investments in scrubbers. A large volume of allowance transactions ensured the allowance market work properly. The program helped reduce the pollution target level at a much lower cost than projected, and several studies show successful achievements of the program (Schmalensee et al., 1998).

During Phase II, total affected sulfur dioxide emissions dropped to 11.2 million tons in 2000: almost 40% below 1980 levels. In 2003, total emissions fluctuated up to 10.6 million tons due to low utilization of nuclear plants and high natural gas prices. Overall, during Phase II, annual emissions exceeded the caps by 1 to 1.5 million tons every year (Burtraw et al., 2005). However, these excesses were met by banked allowances during Phase I.

2.2 The Kyoto Protocol

With the success of the U.S. sulfur dioxide trading program, the tradable permits scheme has been adopted to deal with the global greenhouse gas problems. The Kyoto Protocol was signed in 1997 by most industrialized nations, which came into force on February 16, 2005.[1]

The protocol requires the ratified parties to reduce green house gases by an individual quota during its first commitment period from 2008 to 2012, using the 1990 base level. In order to prompt abatement efforts, the protocol has adopted three market mechanisms: Emission Trading, Clean Development Mechanism and Joint Implementation.

The first mechanism, emissions trading, according to Article 17 of the Kyoto Protocol, allows countries which would not otherwise meet their targets to purchase credits from other nations. It includes: Certified emission reductions from projects under the Clean Development Mechanism, Emission reduction units from projects under Joint Implementation. The largest implementation of emissions trading to date is the EU Emission Trading Scheme (EU ETS) (Hepburn 2007).

[1] It has been ratified by most major developed countries except the United States.

The European Emissions Trading Scheme (EU ETS), allocates carbon dioxide caps to major energy-intensive industries in the EU region and allows the trade of surplus emission allocations among the participants. This radically new carbon market has brought cost-saving opportunities to a wide range of firms that have advanced low-carbon technology.

The Joint Implementation (JI) is a market-based instrument that enables a state with binding targets to obtain credit from projects undertaken in another ratified country. Projects under the JI yield Emission reduction units (ERUs), which is equivalent of one ton carbon dioxide emission. Produced ERUs must be approved by relevant parties. Major JI host countries include Russia and Eastern European states because they experienced an economic downturn after 1990, and they enjoyed more relaxed targets compared to the other participating nations. With regards to major obstacles of implementing JI, Rose et al. (1999) argue that extraction-biased technological change and cumulative abatement effects increase future abatement costs of hosting countries.

The Clean Development Mechanism (CDM) allows the government or private firms in a ratified state to accumulate Certified Emission Reductions (CERs) from project activities in developing countries so as to meet its commitment. Firms can invest in a CDM project in a developing country and gain CERs, resulting in a lower cost than investments in abatement at home or purchasing CERs from other parties.

2.3 The European Emission Trading Schemes (EU ETS)

The EU Emission Trading Scheme (EU ETS) was launched by 25 EU countries on January 2005, to achieve the target of an 8% reduction under the Kyoto Protocol. The initial phase of the EU ETS which ends on December 2007 was designed to familiarize EU firms with carbon trading. The second phase which runs through January 2008 to December 2012 exactly coincides with the commitment period of the Kyoto Protocol. This scheme is considered the largest tradable carbon dioxide permits scheme to date Ellerman et al. (2007).

The scheme is targeted on over 11,000 emissions sites, including power plants, oil refineries, coke ovens, steel plants, cement factories. They are collectively responsible for some 45% of carbon dioxide emissions. EU firms now are governed by carbon constrains in form of legally emission targets. Each installation is allocated with free carbon permits, EU Allowances (EUAs), for free based on the past emissions. Alternatively, member states can auction up to 10% of their EUAs. The scheme covers almost half of the total EU carbon dioxide emissions (Convery and Redmond, 2007).

EUAs are actively and freely traded on the European Climate Exchange (ECX). Firms are to purchase EUAs to cover excessive emissions. More importantly, the EU ETS is driving much of the activity in the CDM. The EU ETS has become the hub of the global carbon trading due to the implementation of the Linking Directive on November 2004.

EUA was listed on the ECX on April 2005, and the EUA price had been fluctuating between 15 and 30 euro. But, it has been in a downward shift, within a range of 10 to 15 euro, since 2008 summer primary because of the world financial crisis.

2.4 The Clean Development Mechanism (CDM)

The Clean Development Mechanism (CDM) under the Kyoto Protocol allows the government or private firms of a ratified state to accumulate Certified Emission Reductions (CERs) from project activities in a non ratified country. CERs are created if all parties give their voluntary approval and if the emissions reductions are real, measurable, and additional. The process of investing a project under the CDM requires the project investor to satisfy a number of procedural stages.

Projects are first proposed in a formal Project Design Document, which contains detailed information. It includes a study of what would have been without the project, the baseline, and the monitoring and verification plan to determine the quantity of emissions abatement that is indeed additional to the status quo. It also presents an estimate of expected emissions reduced. Projects are assessed by the CDM Executive Board (CDM EB) against approved methodologies for determining monitoring process and the baseline (Hepburn, 2007).

The Project Design Document has to be validated by a Designated Operational Entity which evaluates whether the project meets the relevant criteria, most crucially the additionality criteria that show project outputs are indeed additional emission reductions. After the validation process, the CDM project is registered by the CDM EB and becomes a formal project. Thereafter, the project's monitored emissions reduced are periodically verified and certified by a Designated Operational Entity. Based on a certification report, the CDM EB issues CERs and forwards them into the registry accounts of project participants (Hepburn, 2007).

Typical CDM projects to date have included renewable energy projects (wind, smaller-scale hydro, renewable biomass) and the capture of damaging greenhouse gases such as methane, nitrous oxide, and hydrofluorocarbons.

CERs yielded from a CDM project can be traded over-the-counter or on a market, most notably the EU ETS. CER was listed on the EU ETS on March 2008. The CER price had initially been volatile between 15 and 25 euro. However, likewise the EUA price, it has seen a downward trend since 2008 summer.

2.4.1 Relation between CDM and EU ETS

The Linking Directive is an implementation of the EU ETS which allows the use of CERs credits from CDM projects as the EUAs in the EU ETS, and they are commonly counted by one carbon dioxide equivalent ton. Therefore, EUAs and CERs have been inter-exchangeable in the form of swaps. Trading through the major subsidiary scheme of the Kyoto Protocol, the EU Emission Trading Scheme (EU ETS), has large transactions. Carbon trading on the EU ETS in 2006 comprised 67% of the global carbon markets by volume, and 81% by value (Hepburn, 2007).

In the following models, I assume that CDM projects can be evaluated by using the price of CERs traded on the ECX. The basic assumption is that carbon markets are efficient in that all participants are equally informed and there is no insider dealing. The monetary value of a CDM project equals the cash flows yielded by its underlying asset, CERs. In addition, CERs are highly liquid so that they are traded in carbon markets like any other commodities. CER units have the same price in carbon markets regardless of where it was produced.

2.4.2 A Clean Development Mechanism Project Case

N2O Emission Reduction in Brazil

The Project Design approved by the CDM Executive Board gives a brief project outline as the following.

Adipic acid is a white crystalline solid used primarily as the main input of nylon, representing about half of the nylon molecule. It is also used in low-temperature synthetic lubricants, coatings, plastics, polyurethane resins, as well as for tangy flavor of imitation food products. It is manufactured in a two-stage process: first the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture and then the oxidization of cyclohexanol or cyclohexanone with nitric acid. N2O is generated as a by-product of the second stage and vented to the atmosphere as waste gas.

The host of the project is Rhodia Energy Brazil. Rhodia has a plant at Paulinia in the state of Sao Paulo, Brazil, and it manufactures adipic acid with both stages of production. The CDM project consists of the installation of a dedicated facility to convert the nitrous oxide into nitrogen, using the process of thermal decomposition, and to reduce N2O emission. The investors of this project include Rhodia Energy Brazil (Brazil), Rhodia Energy SAS (France) and Rhodia Energy GHG SAS (France). The annual emission reductions are estimated to be 5,961,165 tones of CO2 equivalent. The yielding started in 2007 and will end in 2013.

Chapter 3. Literature Review

3.1 Emission Trading

The idea of tradable permits dates back to Coase in 1960 who showed that allocating permits and allowing permit holders to trade can be an efficient method. Emission trading rests on the Coasian solution to the tragedy of the commons—privatize the commons and trade the resulting property rights. With regards to environmental assets, under some relatively straightforward conditions, economic theory implies that an emission trading framework will deliver emission reductions at the lowest cost to society.

There is evidence to support this assertion from experience in the 1990 U.S. Sulfur dioxide emissions trading program. Several studies show that the U.S. sulfur dioxide trading program was successful in that it achieves the emission target levels at a much lower cost than projected (Burtraw et al., 2005; Schmalensee et al., 1998).

However, some people view market trading in environmental assets as ethically dubious. Lohmann (2006) is critical of carbon trading in that it reduces the political space available for education, movement building and planning around the needed fair transition away from fossil fuels.

Apart from ethical disagreements, orthodox economists argue that an efficient outcome, where it is not able to make someone better off without making someone else worse off, may not necessarily be desirable or equitable. In emission markets, equity primarily depends on the initial allocation of the permits.

Some studies point out that the implementation of the EU-ETS was not fair in that the initial allocation of permits were not equitably distributed. Lohmann (2006) argues that the permits were disproportionally acquired by those who have the most power to appropriate them and the most financial interests. Pearce (2002) also argues that efficiency does not necessarily lead to equitable results.

The tradable permits mechanism, represented by the EU-ETS, is designed to enable emissions abatement to occur in the least costly locations. By economic theory, with some conditions, the EU-ETS will deliver carbon abatement at the lowest cost (textbook). Evidence exists to support this claim from the U.S. sulfur dioxide trading program.

3.2 Clean Development Mechanism (CDM)

While the framework of EU-ETS is to achieve carbon reduction at the least cost within the EU region, linked with the Kyoto Protocol scheme later, the Clean Development Mechanism started as an equivalent of the EU-ETS in the Kyoto Protocol ratified countries, including the EU. Likewise EU firms which are regulated by the EU-ETS, now need to secure permits, which are CERs (Certified Emission Reductions) if they believe it is cheaper than purchasing CERs (Brechet and Lussis, 2006). However, several issues are involved.

Firstly, as a result of short-term efficient outcome, CDM projects are unevenly distributed in a few countries according to a CDM Executive Board statistics; particularly China, India, and Brazil. The reason why the abatement projects are concentrated leads to the second issue.

Since those countries have become power-houses of manufacturing in the past decade, a large number of greenhouse gases intensive factories, such as refrigerator plants which emit HFC-23, are located at home. Reducing one ton of HFC-23 emissions has the same impact as reducing 11,700 tons of carbon dioxide emissions (Hepburn, 2007). As such, it is easy to generate large amounts of CERs from HFC-23 capture. In short, the CDM has directed private-sector efforts to the short-term efficient outcome.

Thirdly, the consequence of capturing economically efficient greenhouse gases emissions by firms of industrialized nations is criticized by some people as the "low-hanging fruit" problem. Narain and Veld (2007) argue that if developing countries allow their cheap abatement sources to be used now, they may find themselves worse off in future when they take on emissions reduction commitments of their own as only costly abatement options will remain.

Fourth, the CDM can be viewed as a subsidy rather than a market-based mechanism because the Protocol participating countries transfer funds to less industrialized nations (Wara, 2007). It is pointed out that, although the CDM seeks out the cheapest projects, it is not cost-effective because the investors pay a substantially higher price than a marginal abatement cost in developing countries.

The CDM has become evident that its design has several issues in efficiency and equity. A received criticism is high transaction costs due to complicated certification processes and lengthy waiting times, which in turn require the project will reduce emissions beyond and above the baseline scenario.

As Hepburn (2007) points out, it does little to prevent the energy sector from locking in high-carbon capital assets. For example, fuel-hungry emerging economies keep adding low cost but inefficient coal-fired plants in order to meet energy demands. Moreover, because of the imbalance between the demand and the supply of CDM projects, recipients in developed countries have to pay substantially more than marginal abatement costs.

Therefore, this mismatch results in the CDM being a subsidy to developing countries rather than a market mechanism.

The tradable permits scheme that requires internal organizational decision making is the interest of this paper. A variety of decision tools are needed for firms to respond to the policy instrument. Simply put, a firm has to decide whether to reduce emissions by itself or to purchase permits.

3.3 Real Options Approach

According to Laurikka and Koljonen (2006), in a given period, emissions trading alters cash flows by four factors: operating cost, value of allocated permits, output price, and additional revenue from permits surplus. Corporate decision-makers have a need for selection methodologies that allow them to choose the most profitable scenario. Some of the issues may be well dealt with standard cost/benefit analysis. However, in the case of coping with significantly irreversible investments, the outcomes are highly uncertain. Therefore real options analysis can better serve the purpose with the flexibility to defer the investment.

One of the earliest applications of monetary valuation theory in environmental economics is the work of Brennan and Schwartz (1985). Self-financing portfolio approach, in which a portfolio's cash flows replicate the value of the asset of interest, is introduced to develop a model valuing the cash flows from a natural resource investment. Thereafter the model is applied to a numerical example so as to consider the optimal timing of natural resource investment including the possibilities of operating, closing, and reopening a project.

However, it is Dixit and Pindick (1994) on which the first systematic foundation of options theory in resources/environmental economics was built. An analogy from financial theory is drawn to present real options theory as a powerful tool in dealing with irreversible investments, often seen in environmental economics, with uncertainty.

Indeed, theoretically, the option value that has arisen in environmental economics is no different from the option value concept in financial theory. In the environmental option approach, a value of information, whether or not to invest in the second period with no new forthcoming information, appears as a separate component. By contrast, such a value is implicitly embedded in the financial option value. Fisher (1999) sheds a light on this saddle difference by theoretically comparing the two concepts.

In the context of applying real options theory into tradable emissions permit, pollutants always have a great interest on the option to build and the options to stop construction and/or operations at a series of discrete times, since it is a costly and irreversible investment.

The option value of an abatement investment as well the critical prices of emissions allowance have been explored in the literature.

Insley (2003) uses a numerical finite difference approach to demonstrate a problem of sulfur emissions abatement investment under the 1990 U.S. Clean Air Act. In particular, regulated polluters have the option either to cut off sulfur dioxide emissions or to install scrubbers. There is no need to purchase permits if the option to install scrubbers is exercised. It is clear that the projected benefit of installing scrubbers depends on how the polluter expects the permit price to evolve. Insley studies the impact of uncertainty in the permit price on the polluter's decision to install scrubbers.

Firms must consider the monetary value of the installation option and the optimal exercise time. This takes the form of a trigger permit price above which the firm needs to install scrubbers immediately. Otherwise, the firm is better off to wait and hold the option until the permit price reaches a trigger level. The paper further examines whether or not firm investment decision under the Clean Air Act has been consistent with optimal decision that is predicted, based on the asset valuation model. This follow-up study reveals both the validity and the limitation of options theory in environmental economics.

Since the Clean Development Mechanism (CDM) has been in practice only since 2005, few studies of economic evaluation have been done in this emerging area. It is clear from Insley (2003) and others that inducing high permit prices is a necessary condition for a cap and trade program to be effective and successful. This quality is empirically confirmed again in the CDM.

Sarkis and Tamarkin (2005) evaluate the application of options theory for corporate abatement investments under the CDM regime with an actual case study. In particular, they consider a project of carbon re-injection. The abatement project involves re-injection and long-term underground storage of carbon dioxide in the reservoir from which natural gas was extracted. Likewise the Insley case, the firm has the option to postpone installation of the re-injection unit until a future date. This option to defer comes with a cost: it has to purchase permits while it extracts natural gas. As such, the firm has to decide the optimal time to install the re-injection unit.

They use the internal trading experience of British Petroleum for projected carbon price in the future and how the price evolves. Furthermore, the analysis study concludes that the optimal managerial decision on CO2 emission reduction is purchasing credits rather than initiating abatement investments given relative low credit prices in the past.

Abadie and Chamorro (2008) consider a power firm located in the EU which operates a coal-fired plant. Electricity Generation on a sustained basis now requires either to install a carbon capture and storage or to purchase EU Allowances (EUAs) from the EU-ETS. If the firm initially has EUAs, it makes economic sense to install the carbon capture and storage so as to sell EUAs to at a high price. The power company has to evaluate the EUAs with the cost of the carbon capture and storage. As is the case with Insley and Sarkis & Tamarkin, the installation cost, the carbon capture and storage in this case, is well known, however the EUA price is uncertain.

Though, the carbon capture and storage unit also consume the plant's electricity output, which stochastically evolves. What differs from the previous two papers is that both the output, electricity, price and the permit, EUA, price are uncertain. Therefore, valuation of the carbon capture and storage unit must take uncertainty on the revenue side and the cost side in to consideration. The power firm looks ahead while trying to exploit any further information about the future EUA prices. The EU-ETS plays a crucial role in this regard as well as electricity markets.

They employ a two-dimensional binomial lattice to derive the optimal exercise price because two stochastic prices are involved. In particular, they study the trigger EUA prices above which the option to install the carbon capture and storage is optimal. The conclusion is that at EUA prices in 2007 immediate installation of the carbon capture and storage cannot be justified from a economic point of view. However, the EU-ETS trend changes dramatically or carbon capture technology undergoes significant improvements this will not be the case.

In order to determine trigger prices for an abatement investment being initiated the focus of interest is how the underlying asset price, the credit price for the instance of the CDM, evolves over the time. Two stochastic processes; geometric Brownian motion and mean-reverting, are commonly adopted for predicting it. It is interest to see whether the two processes will result in different trigger prices. Conrad and Kotani (2005) examine both the two processes on an irreversible oil drilling problem and ask what the trigger price for crude oil is in order to justify the investment and the loss of a wildness amenity dividend. The model is applicable to a wide range of economic valuation of investments with uncertainty.

Since my research question is to identify trigger emission credit prices for abatement investments, I will discuss this model in details and suggest potential improvements.
Little empirical study on valuation of CDM projects has been done to date. This paper will contribute to the existing literature by enriching empirical studies on the valuation of CDM projects based on CERs traded on emerging carbon markets. It will also certainly benefit policy makers in further improving the market mechanisms in practice and CDM project owners/investors in making investment decisions and managing price volatility associated with their projects.

Chapter 4. Models

4.1 Model with geometric Brownian motion

4.1.1 Present Value of CDM Project

Consider a firm in a developed country which uses a polluting input in its production process. To simplify the discussion, we consider a single input-single output framework. The firm has to purchase emission allowances (CERs) by the amount of A to produce output Q: i.e., $Q = f(A)$. The firm has two options of acquiring emission allowances; either it purchases CERs in the emission trading market or it invests in a CDM project in a developing country. By investing I in a CDM project, it acquires a credit of A for emission allowance.

If the firm purchases CERs with a price of P in the emission trading market, its profit function becomes $\pi_0 = R(A) - PA$, where $R(A)$ is the revenue from the sale of output. On the other hand, if the firm invests I in a CDM project, its profit (excluding the investment cost) is simply $\pi_1 = R(A)$. Thus, the value of the investment for CDM is the difference in profits:

$$v(P) = PA.$$

We now assume that the price of CERs follows a geometric Brownian motion:

$$dP = \mu P dt + \sigma P dz$$

where μ is the drift parameter, $\sigma > 0$ is the variance parameter and dz is the increment of a Wiener Process with $dz = \varepsilon_t \sqrt{dt}$. The expected price of CERs grows at a constant rate μ, with variance increasing over time.

If the construction period lasts for T years and the project life lasts for additional L years, the present discount value of the CDM investment over L years is

$$V(P) = \int_{T}^{T+L} [Pe^{\mu(t-T)} A] e^{-r(t-T)} dt = \frac{\left(1 - e^{-(r-\mu)L}\right) PA}{r - \mu} \tag{4.1.1}$$

where r is the discount rate. For this problem to make sense, we assume that $r > \mu$.

4.1.2 Derivation of the trigger CER price

If we denote the option value of the investment as a function of the CER price $F(P)$, the Bellman equation becomes

$$rF(P)dt = E[dF(P)].$$

Over a time interval dt, the total expected return on the investment opportunity, $rFdt$, should equal to its expected rate of capital appreciation (Dixit and Pindyck, 1994, p.140). By expanding $dF(P)$ using Ito's Lemma, we get

$$\frac{1}{2}\sigma^2 P^2 F''(P) + \alpha P F'(P) - rF(P) = 0. \tag{4.1.2}$$

where $F'(P) = dF/dP$ and $F''(P) = d^2F/dP^2$. The value function $F(P)$ should satisfy the above differential equation and the following three boundary conditions.

$$F(0) = 0. \tag{4.1.3}$$

$$F(P^*) = V(P^*) - I. \tag{4.1.4}$$

$$F'(P^*) = V'(P^*). \tag{4.1.5}$$

Condition (3) implies that the option value of investment is zero when the CER price is zero. Condition (4) is the value-matching condition which says that the option value of investment equals its net value of investment at the trigger price P^*. Condition (5) is the smooth-pasting condition which says that the change in the option value should equal the change in the expected present value of the investment at the trigger price.

To satisfy the boundary condition (3), the solution must take the form

$$F(P) = aP^{\beta} \tag{4.1.6}$$

Where a is a constant to be determined and $\beta > 1$ is a constant which depends on the parameters of the differential equation (2). By substituting equation (6) into equations (4) and (5), we get

$$a\left(P^*\right)^{\beta} = \frac{\left(1-e^{-(r-\mu)L}\right)P^*A}{r-\mu} - I$$

and

$$a\beta\left(P^*\right)^{\beta-1} = \frac{\left(1-e^{-(r-\mu)L}\right)A}{r-\mu}$$

Rearranging these two equations gives the trigger price P^*.

$$P^* = \left(\frac{\beta}{\beta-1}\right)\frac{(r-\mu)I}{\left(1-e^{-(r-\mu)L}\right)A} \tag{4.1.7}$$

The value β can be derived from the positive root of the quadratic equation (2)

$$\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{\mu}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}\,.$$

4.2 Model with Mean-Reverting

4.2.1 Present Value of CDM Project

As shown in Figure 5.1.2, the trend of CERs may follow a mean reverting process rather than geometric Brownian motion. We now assume that the price of CER follows a mean-reverting process, and derive the trigger price. We consider a commonly used mean-reverting process, called an Ornstein-Uhlenbeck process. The CER price evolves according to

$$dP = \eta(\overline{P} - P)dt + \sigma dz$$

where η is the speed of reversion to the long-run equilibrium price $\overline{P}$, σ is the variance parameter and dz is the increment of a Wiener process. If the price of CERs follows the mean-reverting process and the current price is P, the expected price at future date t is

$$E[P_t] = \overline{P} + (P - \overline{P})e^{-\eta t}$$

We constructed two value functions for the previous geometric Brownian motion, and likewise we do the same for mean-reverting. The option value to develop a CDM project will be denoted by $F(P)$, and the present value when the development is initiated, which will be denoted by $V(P)$. Recall that there is a construction phase of T years before the project starts yielding CERs and the production is expected to last L years, with an average output of A CER units per year.

The present value of the CDM project when construction is initiated is:

$$V(P) = A\int_T^{T+L}[\overline{P} + (P-\overline{P})e^{-\eta(t-T)}]e^{-r(t-T)}dt$$
$$= \frac{(1-e^{-rL})\overline{P}A}{r} + \frac{(1-e^{-(r+\eta)L})(P-\overline{P})A}{r+\eta}$$

(4.2.1)

4.2.2 Derivation of the CER trigger price

The option value while waiting to develop the project $F(P)$ must satisfy the Hamilton-Jacobi-Bellman equation:

$$rF(P) = F'(t) + \eta(\overline{P} - P)PF'(P) + (\frac{\sigma^2 P^2}{2})F''(P)$$

(4.2.2)

Since there is no analytic solution for $F(P)$, we have to solve it numerically.

Because there is no analytic solution, the value-matching and smooth-pasting condition cannot be applied.

Instead, this problem may be formulated as a linear complementarity problem. Define PV such that:

$$PV \equiv rF(P) - [F'(t) + \eta(\overline{P} - P)PF'(P) + (\frac{\sigma^2 P^2}{2})F''(P)]$$

The three boundary conditions for the linear complementarity problem require:

$$PV \geq 0$$

(4.2.3)

$$F(P) - \{V(P) - I\} \geq 0 \tag{4.2.4}$$

$$PV[F(P) - \{V(P) - I\}] = 0 \tag{4.2.5}$$

where I is the fixed construction cost.

Condition (4.2.3) states that $rF(P)$ must be greater than or equal to the expected capital gain of the value function while waiting to develop. Otherwise, it does not make economic sense for investors to develop the CDM project.

Condition (4.2.4) says that the option value while waiting should be larger than or equal to the expected net revenue from exercising the option now. Again, otherwise, the option to develop should be postponed.

Condition (4.2.5) implies that either (4.2.3) or (4.2.4) must hold as an equality. In other words, if $PV = 0$, then $F(P) - \{V(P) - I\} > 0$, and it is optimal to hold the option. If $PV > 0$, then $F(P) - \{V(P) - I\} = 0$, and it is optimal to exercise the option.

Chapter 5. Models Implementations and Results

5.1 European Climate Exchange Market History

The EU Allowances (EUAs) and the Certified Emission Reductions (CERs) are traded on

different carbon markets and over-the-counter markets as well. Because of its volume of trade and liquidity, the European Climate Exchange (ECX) is the largest carbon market up to date. EUA and CER prices data from the ECX are used in this paper. Contract unit is 1000 ton of carbon dioxide equivalent. Prices are quoted in euros/tone. As usual in future markets, all open contracts are marked-to-market daily and trading takes place continuously (Abadie & Chamorro, 2008).

December 2009 and December 2012 contracts are drawn on the following figures, where the December 2012 has the longest maturity as the first commitment period of the Kyoto Protocol expires on the end of 2012. Since daily prices seemed too volatile, I took weekly averages of them in order to make price trends clear. I performed the same for the volumes. As easily expected, for both the CER and the EUA the December 2012 contract is always quoted slightly higher that the December 2009 contract because the former has a longer maturity.

It is not obvious to tell if the EUA price and the volume are significantly correlated. While the volume has continued to climbing, the price rises as frequent as it drops. With regard to the CER, as the volume has become steady and abundant after the first four months the price took a downturn.

The two prices made a steep decline alike on September 2008 and onward. It is reasonable to conclude that the world financial crisis has caused massive defunds from the carbon market.

Figure 5.1.3 indicates that the CER price and the EUA price share almost an identical trend. The reason is that they are a physically identical asset, one ton of carbon dioxide equivalent, and they are often practically swapped on the ECX.

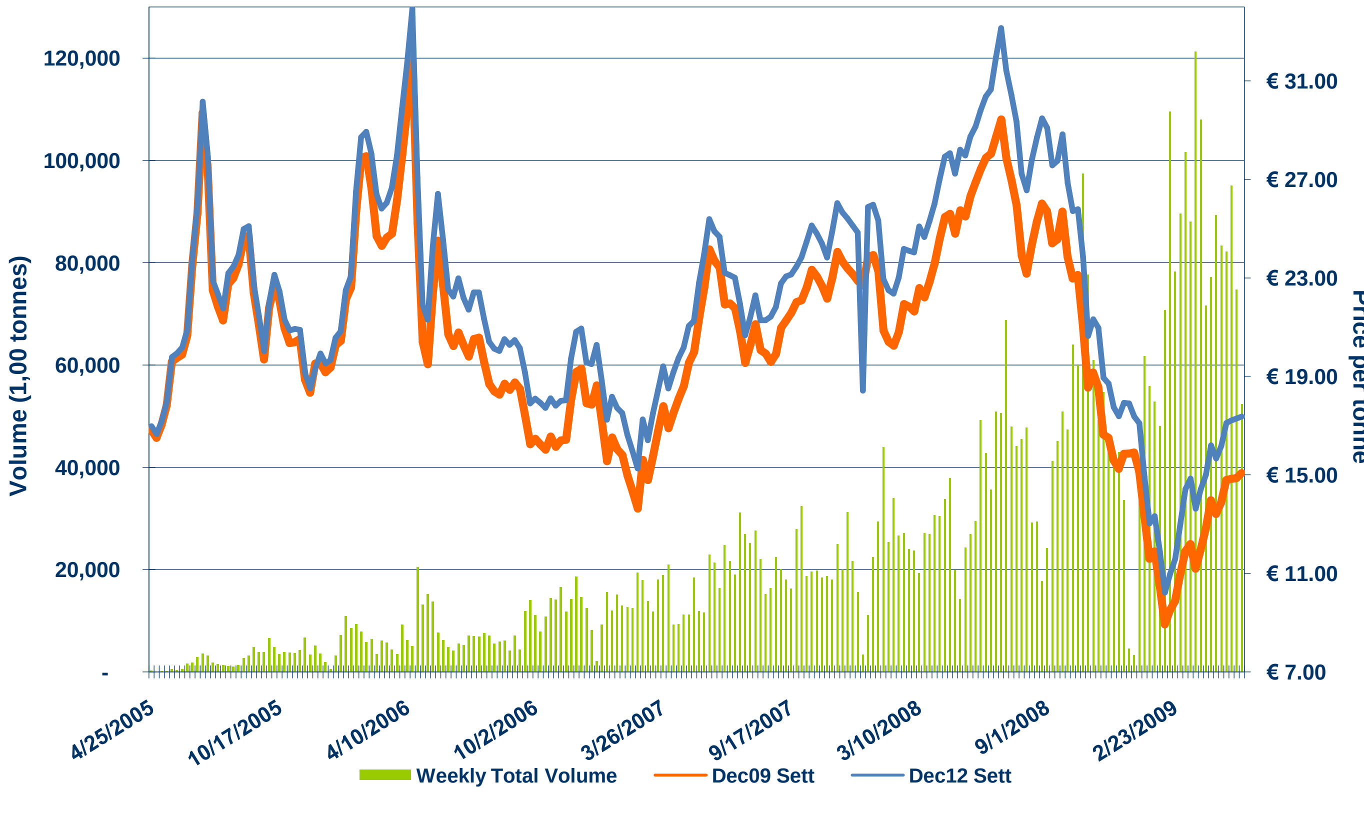

Figure 5.1.1 EUA: price and volume

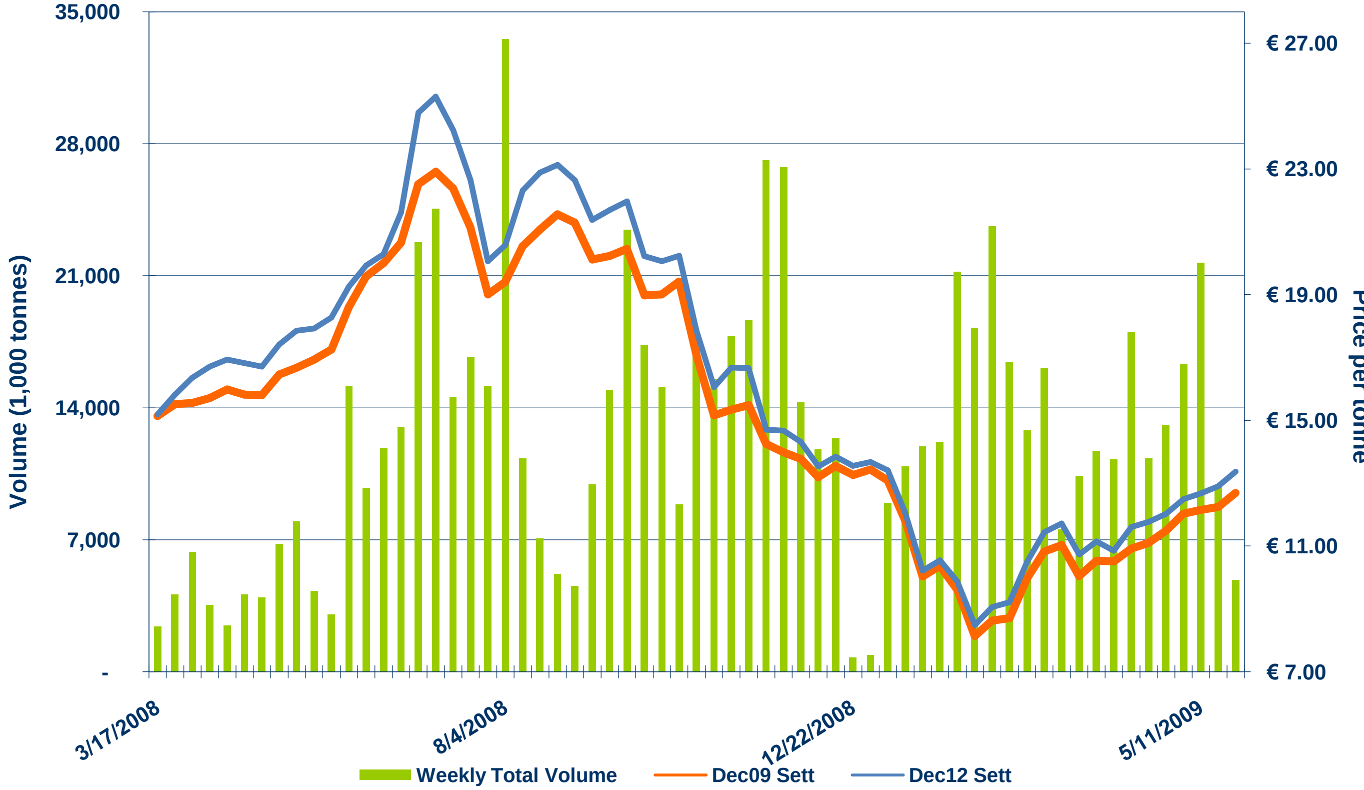

Figure 5.1.2 CER: price and volume

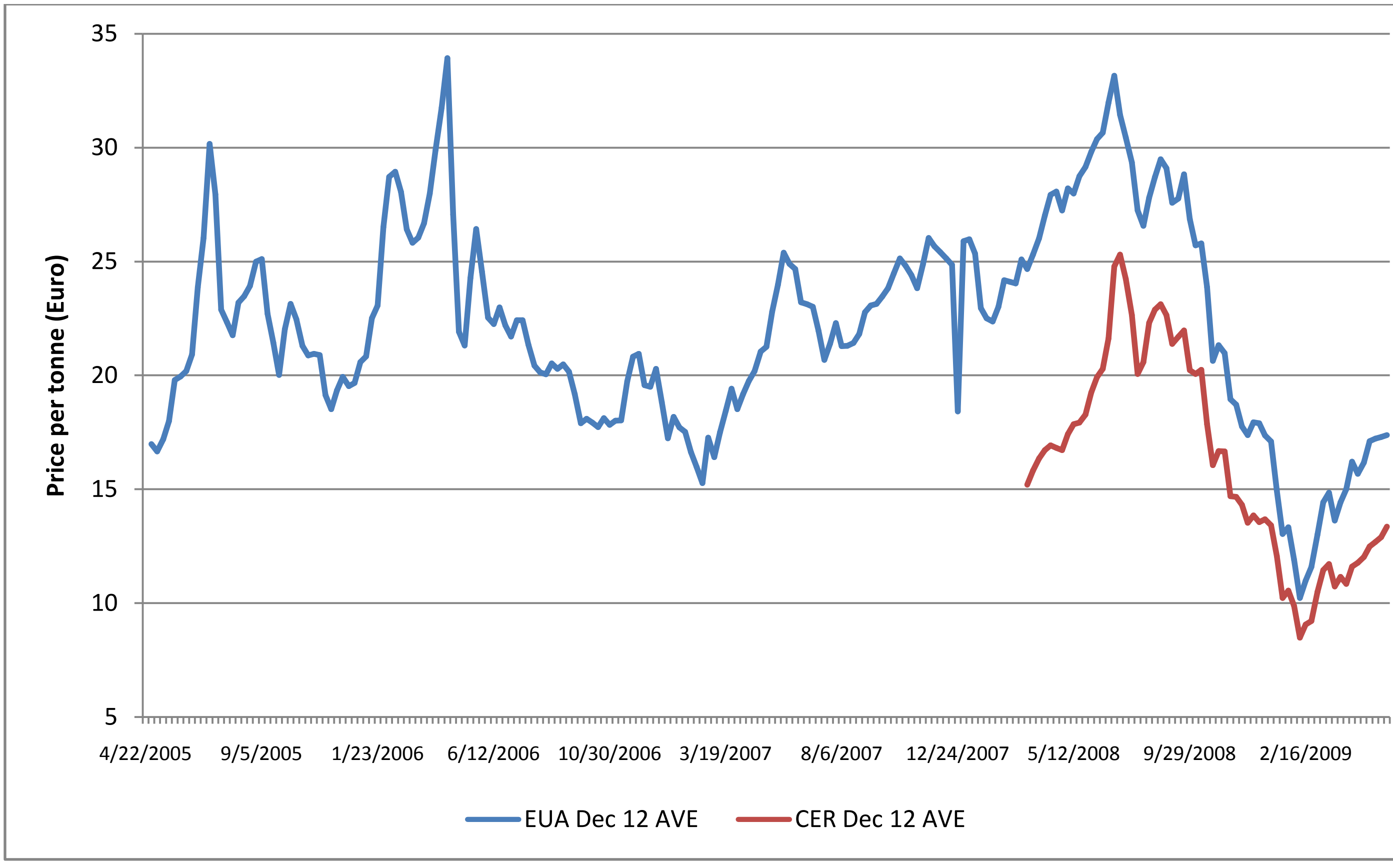

Figure 5.1.3 EUA and CER: price

5.2 Model Implementation with Geometric Brownian Motion

5.2.1 Parameters Estimation

The Matlab code can be found in Appendix A.1.

In order to estimate drift rate μ and the volatility rate σ for the geometric Brownian motion, I used daily CER prices up to the end of May 2009 publicized from the European Climate Exchange. By Dixit and Pindyck (1994), the Maximum Likelihood Estimates can obtain the mean, m, and the standard deviation, s of the series $\ln(P_{t+1}) - \ln(P_t)$. Then

$$\mu = m + \frac{s^2}{2}$$

$$\sigma = s$$

The drift rate μ turned out to be negative, and I believe this is predominantly due to a strong downward trend after the world financial crisis occurred in September 2008. Thus, I decided to use only the daily prices up to September 14, 2008.

Since the selection of the discount rate depends on an investor's risk sensitivity, its value is crucial in real options valuing, ultimately, making investment decisions. I varied it from 2% to 8%. The lower limit was set to 2% in reference to 10-year U.S. Treasury Yield rates in 2008.

5.2.2 Model Implementation

The Matlab code can be found in Appendix A.2.

As I discussed in 4.1 Model with geometric Brownian motion, there is an analytical expression for the trigger price P^*. I simply implemented the equations on Matlab.

5.3 Model Implementation with Mean-Reverting

5.3.1 Parameters Estimation

The Matlab code can be found in Appendix B.1.

Same as the geometric Brownian motion model I used daily CER prices up to the end of May 2009 so as to estimate the mean price $\overline{P}$, the reverting speed η, and the volatility rate σ. By Dixit and Pindyck (1994), I ran the regression

$$P_{t+1} - P_t = a + bP_t + \varepsilon_t$$

which yields two constants a and b. Then,

$$\overline{P} = -\frac{a}{b}$$

$$\eta = -\log(1+b)$$

$$\sigma = \sigma_{\varepsilon}\sqrt{\frac{2\log(1+b)}{(1+b)^2 - 1}}$$

where σ_{ε} is the standard error of the regression.

Again, I varied the discount rate from 2% to 8% for the same reason as the geometric Brownian motion model.

5.3.2 Model Implementation

The Matlab code can be found in Appendix B.2.

I use the finite difference method described in Pelet (2003) to solve (4.2.2) of the mean-reverting model.

$$rF(P) = [F'(t) + \eta(\overline{P} - P)PF'(P) + (\frac{\sigma^2 P^2}{2})F''(P)] \tag{4.2.2}$$

The partial derivatives can be approximated by the differences:

$$F'(t) \approx \frac{F_{i,j} - F_{i,j-1}}{\Delta t}$$

$$F'(P) \approx \frac{F_{i+1,j} - F_{i-1,j}}{2\Delta P}$$

$$F''(P) \approx \frac{F_{i+1,j} - 2F_{i,j} + F_{i-1,j}}{(\Delta P)^2}$$

The central difference approximation is used for the variable P and the backward difference approximation for the variable t. Substituting these approximation terms in (4.2.2):

$$F_{i,j-1} = p^+ F_{i+1,j} + p^0 F_{i,j} + p^- F_{i-1,j}$$

where

$$p^+ = \frac{\Delta t}{r\Delta t + 1}\left(\frac{i^2\sigma^2}{2} + \frac{i\eta\overline{P}}{2} - \frac{i^2\eta\Delta P}{2}\right)$$

$$p^0 = \frac{\Delta t}{r\Delta t + 1}\left(\frac{1}{\Delta t} - i^2\sigma^2\right)$$

$$p^- = \frac{\Delta t}{r\Delta t + 1}\left(\frac{i^2\sigma^2}{2} - \frac{i\eta\overline{P}}{2} + \frac{i^2\eta\Delta P}{2}\right)$$

Then, the boundary conditions (4.2.3) – (4.2.5) can be expressed by:

$$F_{0,j} = 0$$

$$F_{i,n} = \max[Ai\Delta P - I, 0]$$

$$F_{i^*,j} = Ai^*\Delta P - I$$

where the trigger price is $i^*\Delta P$.

5.4 Numerical Results for Trigger Prices

5.4.1 Trigger Prices with respect to the Discount Rate

The parameters are shown in Table 5.4.1.

	P^{-} (€)	η	μ	σ	r (%)	I (€)	A (CER unit)	L (year)
GBM	n.a.	n.a.	0.0029	0.0205	4.68	7800000	41728155	7
M-R	15.65	0.295	n.a.	0.32	4.68	7800000	41728155	7

Table 5.4.1 Baseline Prameters

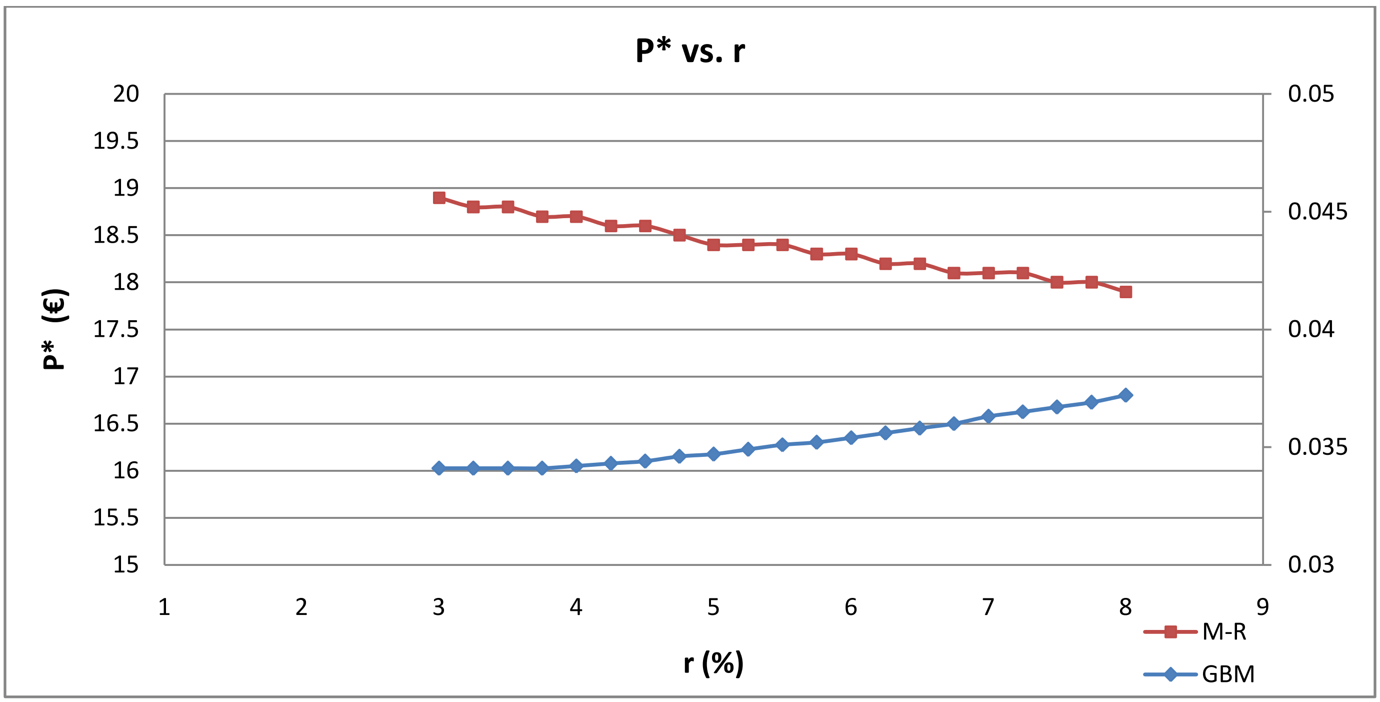

Figure 5.4.1 Trigger prices with respect to the discount rate

It is shown in Figure 5.4.1 that under the geometric Brownian motion model the discount rate increases the trigger price. Intuitively speaking, suppose that I have the money to pay off an investment option in the bank. If the interest rate goes up, I have less incentive to buy the option. Using the analytical expression for the trigger price (4.1.7), this characteristic can be confirmed with some algebraic manipulation.

Recall that:

$$P^* = \left(\frac{\beta}{\beta - 1}\right)\frac{(r-\mu)I}{\left(1 - e^{-(r-\mu)L}\right)A}$$

(4.1.7)

Now let us consider the constant terms in the equation as one constant C.

$$P^* = C\frac{(r-\mu)}{1 - e^{-(r-\mu)L}}$$

where $$C = \frac{\beta I}{(\beta - 1)A}$$

Let $r-\mu$ be x. Then $x > 0$, since $r - \mu > 0$.

$$P^* = C\frac{x}{1 - e^{-xL}}$$

(5.4.1)

As $x > 0$, $1 > e^{-xL} > 0$, and thus $1 > 1 - e^{-xL} > 0$.

Therefore, the discount rate r, or x increases as the trigger price does. A change in x is extremely small, in a scale of one hundredths, compared to L. We can see the denominator $1 - e^{-xL}$ as a part of the constant C'. Thus:

$$P^* = C'x$$

The numerical results indeed represents an approximately linear growth.

Paddock, Siegel and Smith (1988) present that with a geometric Brownian motion model the trigger price for an oil field development option, an analogy to my case, increases the discount rate, where petroleum production is the underlying asset of the development option. A sensitivity analysis done by Conrad and Kotani (2005) also confirms that the trigger price for an oil development project and the discount rate are positively correlated.

As it is seen from Figure 5.4.1, the discount rate decreases the trigger price under the mean-reverting model. Since there is no analytical expression for the trigger price in the mean-reverting process, I argue the reasoning with parameters analysis.

A convenience yield which exists in the geometric Brownian motion model is not a input parameter for the mean-reverting model. However, it is well known that a convenience yield equivalent δ can be expressed by:

$$\delta = r - \eta(\bar{P} - P)$$

Regardless of the price level, an increase in the discount rate r leads to a larger convenience yield. A convenience yield can be seen as the flow of benefits associated with the underlying asset. As Dixit and Pindyck (1994) point out, the higher the convenience yield, the lower the option value while waiting, and thus so is the trigger price.

Pelet (2003) and Fackler (2007) support that the discount rate reduces the trigger price for an oil field development option under the mean-reverting model.

5.4.2 Trigger Prices with respect to the Investment Cost

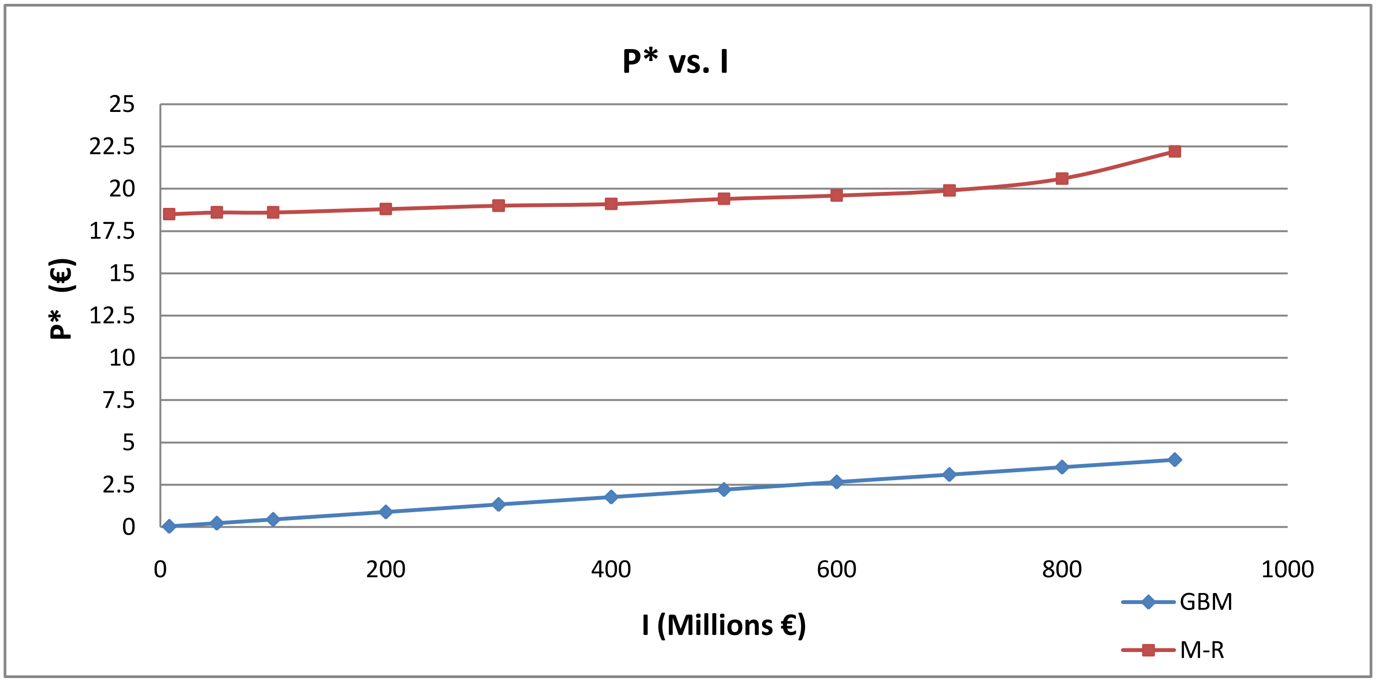

Figure 5.4.2 Trigger prices with respect to investment cost

It is shown in Figure 5.4.2 that the trigger price under the geometric Brownian motion increases as the investment cost grows. Intuitively, a higher investment cost requires a larger present value of the project to pay off, and in turn leads to a higher trigger price. The analytical expression for the trigger price is consistent with this tendency.

Again recall that:

$$P^* = \left(\frac{\beta}{\beta-1}\right)\frac{(r-\mu)I}{\left(1-e^{-(r-\mu)L}\right)A}$$

(4.1.7)

We can think of all variables but I as one constant term C. Then:

$$P^* = CI$$

where $$C=\left(\frac{\beta}{\beta-1}\right)\frac{(r-\mu)}{\left(1-e^{-(r-\mu)L}\right)A}$$

Figure 5.4.2 presents that the trigger price is a linear function of the investment cost.

A sensitivity analysis of Conrad and Kotani (2005) shows that the trigger price under the geometric Brownian motion has a positive correlation with the investment cost.

The investment cost increases the trigger price under the mean-reverting model in Figure 5.4.2. Since there is no analytical expression for the mean-reverting, I can use only a general expression for the reasoning. At the trigger price it can be seen at large:

$$V(P)=AP^{*}-I$$

Then, $$P^{*}=\frac{V(P)+I}{A}$$

We know $V(P)$ from (4.2.1):

$$V(P)=\frac{(1-e^{-rL})\overline{P}A}{r}+\frac{(1-e^{-(r+\eta)L})(P-\overline{P})A}{r+\eta}$$

Thus, $$P^{*}=\frac{(1-e^{-rL})\overline{P}}{r}+\frac{(1-e^{-(r+\eta)L})(P-\overline{P})}{r+\eta}+\frac{I}{A}$$

(5.4.2)

Therefore it has been shown that the trigger price grows as the investment cost increases.

A sensitivity analysis performed by Conrad and Kotani (2005) also confirms that the trigger prices under the mean-reverting process and the investment cost are positively correlated.

5.4.3 Trigger Prices with respect to Project Period

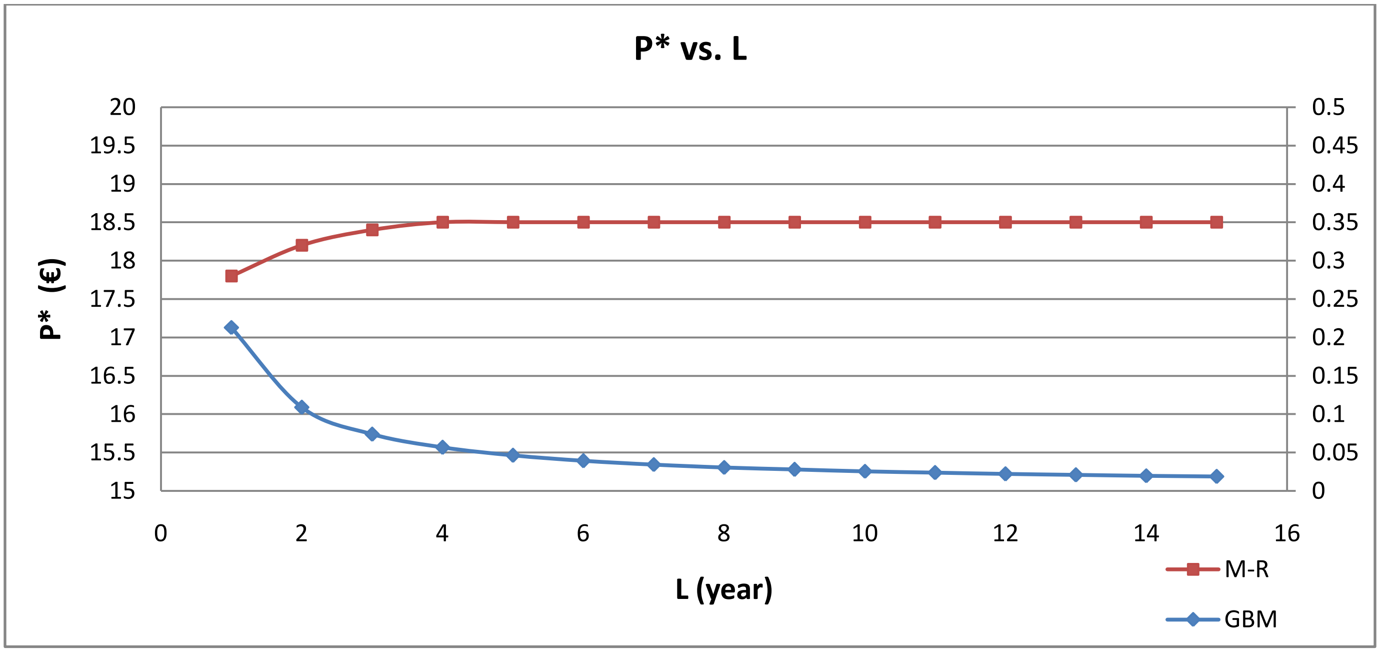

Figure 5.4.3 Trigger prices with respect to project period

It is seen from Figure 5.4.3 that the project period reduces the trigger price under the geometric Brownian motion model. Intuition tells us that a longer project period has more time for recovering the investment cost, and thus it allows lower trigger prices. Using a more rigorous derivation, recall from (5.4.1):

$$P^* = C\frac{x}{1-e^{-xL}}$$

where

$$C = \frac{\beta I}{(\beta - 1)A}$$

$$x > 0$$

As $x > 0$, $1 > e^{-xL} > 0$, and thus $1 > 1 - e^{-xL} > 0$.

Therefore, the trigger price drops as the project period L increases. The trigger price approaches to the lower bound Cx as the denominator goes to 1.

Pelet (2003) supports that a project period reduces the trigger price for an oil development option under the geometric Brownian motion process.

The trigger price under the mean-reverting process in Figure 5.4.3 indicates a growth as the project period increases. I explain this relation in a general term because there is no analytical expression for the trigger price in the case of the mean-reverting. From (5.4.2) we know in general at the trigger price:

$$P^* = \frac{(1-e^{-rL})\overline{P}}{r} + \frac{(1-e^{-(r+\eta)L})(P-\overline{P})}{r+\eta} + \frac{I}{A}$$

Let us group the constant terms as:

$$P^* = C_1(1-e^{-rL}) + C_2(1-e^{-(r+\eta)L}) + C_3$$

where $C_1 = \frac{\overline{P}}{r}$, $C_2 = \frac{(P-\overline{P})}{r+\eta}$, $C_3 = \frac{I}{A}$.

As L grows the terms $1-e^{-rL}$ and $1-e^{-(r+\eta)L}$ increase, and in turn so does the trigger price. The trigger price approaches an upper bound $C_1 + C_2 + C_3$ as the project period L goes to an infinitely large number.

Pelet (2003) shows that the trigger price for an oil development option under the mean-reverting model approaches an upper bound as the project period increases.

Chapter 6. Conclusion

The benefit of the mean-reverting model lies in describing a stochastic variable which reverts to a mean in the long run. Many commodities such as crude oil are regarded to follow the mean-reverting process. However, it comes at a cost in real options theory. The fact that it has no analytical solution makes the calculation complicated, and thus it is less pursued by the researcher and the practitioner alike.

With no doubt the market history fits the mean-reverting model better than the geometric Brownian motion model. The reason is two-folded. First, the geometric Brownian motion does not seem to be a valid assumption for the historical data. The data does not have an upward drift. Second, the trigger prices for the geometric Brownian motion turn out to be extremely off of historical CER prices, while those for the mean-reverting are in a reasonable range.

One can observe large differences between the trigger prices yielded by the geometric Brownian motion model and the mean-reverting model. The trigger prices under the geometric Brownian motion process are far below the mean-reverting level because the market history lacks an upward drift, while the geometric Brownian motion assumes it as a fundamental condition. Therefore, the calculation ends up underestimating the present value of the CDM project, yielding unjustifiable low trigger prices.

Finally, comparisons with analytical analysis are consistent with the empirical results and thus confirming the validity of both the models. It is interesting to notice that the discount rate increases trigger prices with the geometric Brownian motion process, as intuitionally expected, but reduce those with the mean-reverting model. Unlike the geometric Brownian motion process the inexplicit convenience yield of the mean-reverting grows as the discount rate increases.

I would like to mention a few potential extensions to this paper. First, the mean-reverting process with jumps may better serve the cases where abnormal price shocks are frequently observed. This approach takes the possible arrival of abnormal information into consideration by adding a binomial variable following a probability density function, which is either zero or a jump size.

Second, as an alternate to the CER price one can use the EUA price in order to calculate parameters. The EUA price has more than four years of market history and thus is likely to yield more realistic parameters compared to the CER price. Indeed, the CER and the EUA are virtually pegged on the European Climate Exchange in a way that they are inter-exchangeable. However, it involves an issue of choosing a fixed change rate between the two stochastically evolving variables.

Nevertheless, it is arguable that none of the two models is a valid framework for CER prices. As Fackler (2007) points out, it one factor is often the time inadequate in modeling the dynamic behavior of stochastic prices and that at least two or three factor models are needed to capture the term structure implied by those prices. Meanwhile, I believe that real options theory will have a variety of applications in the evaluation of emerging irreversible CDM projects.

Appendix MATLAB Code

A.1 Geometric Brownian Motion Parameters

```
price;
x=log(price);
for i=1:length(price)-1
    delta_x(i)=x(i+1)-x(i);
end
m = mean(delta_x);
s = std(delta_x);

mu = m+(s^2/2)
sigma = s
```

A.2 Geometric Brownian Motion

```
mu = 0.0029;
sigma=0.0205;
I=7800000;
A=41728155;
L = 7;
R = 0.0468

alpha=(1/2)-(mu/sigma^2);
beta=alpha+sqrt(alpha^2+(2*r/sigma^2));
c = 1-exp(-(r-mu)*L);

P_star=(beta/(beta-1))*((r-mu)*I/(c*A))
```

B.1 Mean-Reverting Parameters

```
price; % price history
x=log(price);
for i=1:length(price)-1
    delta_x(i)=x(i+1)-x(i);
    x_short(i)=x(i);
end

p = polyfit(x_short, delta_x, 1);%
pop = polyval(p, x_short);%
res = delta_x - pop;%
a = p(2);
b = p(1);
disp('mean of residual, should be zero =');%
disp(mean(res));
sigma_eps = var(res);%
eta_star = -log(1+b);%
x_bar = -a/b;%
sigma_star = sigma_eps*sqrt(2*log(1+b)/((1+b)^2-1));
%%%%%%%
eta = 365*eta_star * log(mean(price))/mean(price)%
sigma = 365*sigma_star%
P_bar = mean(price)*x_bar/log(mean(price)) + sigma^2/(2*eta)
```

B.2 Mean-Reverting

```
function out=MR(rho,D,T)
% Real Options, Mean-Reversion
% Solution of the Finite Difference Problem
format compact
filename = input('Enter test number: ', 's');

%%%%%%%%%%%%
% Real Option Parameters :
%rho=0.0468; % Exogeneous discount rate
sigma = 0.32; % Volatility
eta = 0.295; % Reversion speed
Pbar = 15.65; % Average CER price (euro)

%D = 0.187; % Investment cost (CER/euro)
%T = 7; % production period (Expiry) (in years)
q = 1; %1 CER unit = 1 CO2 ton
```

```
% Finite Difference Grid :
Pm = 45; % Truncation of the space grid
dP = 0.1; % Space Grid interval
dt = 1e-4; % Time Grid interval

% Jump characteristics
% Reference to function pdf_phi

% Grid Parameters :
m = Pm/dP; % Number of space steps, better be an integer
n = T/dt; % Number of time steps, better be an integer

%%%%%%%%%%%%
% Initialisation
t_stor=100;
A = dt/(rho*dt+1);

for i = 0:m
    P(i+1) = dP*i; % Prices scale
    payoff(i+1)= max(q*P(i+1) - D , 0); % Payoff boundry condition
    pplus(i+1) = A*1/2*(sigma^2*i^2+i*eta*Pbar-i^2*eta*dP);
    pzero(i+1) = A*(1/dt-sigma^2*i^2);
    pminus(i+1)= A*1/2*(sigma^2*i^2-i*eta*Pbar+i^2*eta*dP);
 if pplus(i+1)<0
    disp('pplus is negative at i=')
    disp(i)
 end
 if pzero(i+1)<0
    disp('pzero is negative at i=')
    disp(i)
 end
 if pminus(i+1)<0
    disp('pminus is negative at i=')
    disp(i)
 end
end
pause
vold = payoff;

%%%%%%%%%%%%
% Time loop
h = waitbar(0,'Please wait...');
time(n+1)=n*dt;
Stor(n/t_stor+1,:) = vold;
thres(n+1)=D/q;

for t = n-1:-1:0
```

```
    time(t+1)=t*dt;
    F(1)=0;

 % Space loop
 for i = 1:m

  % Expectation term

  % Calculation of the Option value at time t
  vold(m+2)=max(q*(m+1)*dP - D, 0);
  F(i+1) = pplus(i+1)*vold(i+2) + pzero(i+1)*vold(i+1) +
pminus(i+1)*vold(i);
  if F(i+1)<payoff(i+1)
     F(i+1)=payoff(i+1); % Boundary condition
  end

%%%%%%%%%%
  % Threshold
  if (F(i+1)==payoff(i+1)) && (F(i)~=payoff(i))
      thres(t+1)=i*dP;
  end
 end

 vold = F; % New initial guess
 % Reduction of vectors sizes
 if t/t_stor==floor(t/t_stor)
 tt=t/t_stor;
 Stor(tt+1,:) = vold; % Storage
 end

 waitbar((n+1-t)/(n+1),h)
end

close(h)
F_init=F; % Initial value of the option
save(filename)
```

Bibliography

Abadie, L. M., & Chamorro, J. M. (2008). European CO2 prices and carbon capture investments. *Energy Economics, 30*(6), 2992-3015.

Brechet, T., & Lussis, B. (2006). The contribution of the clean development mechanism to national climate policies. *Journal of Policy Modeling*, *28*(9), 981-994.

Burtraw, D., Evans, D. A., Krupnick, A., Palmer, K., & Toth, R. (2005). Economics of pollution trading for SO2 and NOx. *Annual Review of Environment and Resources, 30*, 253-289.

CDM Executive Board. (October 12, 2005). *N2O Emission Reduction in Paulinia, SP, Brazil Project Design Document*. Retrieved February 5, 2009, from http://cdm.unfccc.int/Projects/DB/DNV-CUK1130160031.78/view

Conrad, J. M., & Kotani, K. (2005). When to drill ? trigger prices for the arctic national wildlife refuge. *Resource and Energy Economics, 27*(), 273.

Convery, F. J., & Redmond, L. (2007). Market and price developments in the european union emissions trading scheme. *Review of Environmental Economics and Policy, 1*(1), 88-111.

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty*. New Jersey: Princeton Press.

Ellerman, A. D., & Buchner, B. K. (2007). The european union emissions trading scheme: Origins, allocation, and early results. *Review of Environmental Economics and Policy, 1*(1), 66-87.

European Climate Exchange. (2009, May). *Prices and Volume: ECX EUA Futures Contract*. Retrieved June 1, 2009, from http://www.ecx.eu/EUA-Futures

European Climate Exchange. (2009, May). *Prices and Volume: ECX CER Futures Contract*. Retrieved June 1, 2009, from http://www.ecx.eu/CER-Futures

Fisher, A. C. (2000). Investment under uncertainty and option value in environmental economics.

Hepburn, C. (2007). Carbon trading: A review of the Kyoto mechanisms. *Annual Review of Environment and Resources, 32*, 375-393.

Insley, M. C. (2003). On the option to invest in pollution control under a regime of tradable emissions allowances. *Canadian Journal of Economics, 36*(4), 860-883.

Israel, D. (2007). Environmental participation in the U.S. sulfur allowance auctions. *Environmental and Resource Economics, 38*(3), 373-390.

Laurikka, H. & Koljonen, T. (2006). Emissions trading and investment decisions in the power sector-a case study in finland. *Energy Policy, 34*(9), 1063-1074.

Lohmann, L. (2006). Carbon trading: A critical conversation on climate change, privatisation and power. *Development Dialogue, 1*(48), 1-359.

Narain, U., & van't Veld, K. (2008). The clean development mechanism's low-hanging fruit problem: When might it arise, and how might it be solved? *Environmental and Resource Economics, 40*(3), 445-465.

Paddock, J. L., Siegel, D. R., & Smith, J. L. (1988). Option Valuation of Claims on Real Assets: the Case of Offshore Petroleum Leases. *The Quarterly Journal of Economics, 103*(3), 479-508.

Pelete, M. (2003). Real Options in Petroleum: Geometric Brownian Motion and Mean-Reversion with Jumps. Oxford University.

Pearce, D. (2002). An intellectual history of environmental economics. *Annual Review of Energy and the Environment, 27*, 57-81.

Rose, A., Bulte, E., & Folmer, H. (1999). Long-run implications for developing countries of joint implementation of greenhouse gas mitigation. *Environmental and Resource Economics, 14*(1), 19-31.

Sarkis, J. & Tamarkin, M. (2005). Real options analysis for "green trading": The case of greenhouse gases. *Engineering Economist, 50*(3), 273-294.

Schmalansee, R., Joskow, P. L., Ellerman, A. D., Montero, J. P., & Bailey, E. M. (1998). An interim evaluation of sulfur dioxide emissions trading. *The Journal of Economic Perspectives, 12*(3), 53-68.

United States Environmental Protection Agency (1999), *Progress Report on the EPA Acid Rain Program*. EPA430-R-99-011, Environmental Protection Agency, Washington, D.C.

Wara, M. (2007). Is the global carbon market working? *Nature, 445*(7128), 595-596.