Carbon Emission Markets

Walid Mnif and Matt Davison

Abstract New regulatory frameworks designed to comply with the Kyoto protocol have been developed with the aim of decreasing global greenhouse gas emissions over both short and long time periods. Incentives must be established to encourage the transition to a clean energy economy. Emissions taxes represent a “price” incentive for this transition, but economists agree this approach is suboptimal. Instead, the “quantity” instrument provided by cap-and-trade markets are superior from an economic point of view. This chapter summarizes the current state of world cap-and-trade schemes as well as recent literature devoted to quantitative pricing and hedging tools for these markets.

Keywords Carbon · Emission · Markets

1 Introduction

In 1997, an international agreement known as the Kyoto Protocol was adopted by over 184 states with the aim of reducing global greenhouse gas emissions. Greenhouse gases (GHGs), as defined by the World Bank, are the gases released by human activity that are responsible for climate change and global warming. The six gases listed in the Kyoto Protocol are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). For each gas a Global Warning Potential (GWP) indicator is defined to measure the impact of a particular GHG on the additional heat/energy retained in the earth’s ecosystem through an addition of an unit of the gas given to the atmosphere. The unit of measure is ton of CO_2 equivalent (tCO_2e). Table 1 summarizes the (GWP) for each GHG.

W. Mnif and M. Davison
The University of Western Ontario, London, ON, Canada
e-mail: wmnif@uwo.ca; mdavison@uwo.ca

D.D. Wu (ed.), *Quantitative Financial Risk Management*, Computational Risk Management, 95
DOI 10.1007/978-3-642-19339-2_11,

Table 1 GWP for GHG
Source: World Bank, Sustainable Development Department

GHG	tCO_2e
Carbon Dioxide	1
Methane	21
Nitrous Oxide	310
Perflurocarbons	6,500
Hydroflurocarbons	11,700
Sulfur Fluoride	23,900

The Kyoto Protocol defines emission caps for industrialized and transition countries with the goal of decreasing GHG emissions by 5.2% relative to 1990 levels during the commitment period 2008–2012. The tools it provides for meeting this goal are the Clean Development Mechanism (CDM), Joint Implementation (JI) and International Emissions Trading (IET). The latter allows for Emission Allowances Trading (EAT) between governments. The CDM is a mechanism designed to assist developing countries in achieving sustainable development by permitting industrialized countries to finance projects for reducing greenhouse gas emission in developing countries and to receive credit for doing so. The JI is a mechanism whereby an industrialized nation as specified by Kyoto's Annex I[1] may acquire Emission Reduction Units (ERU) when it helps to finance projects that reduce net emissions in another industrialized country (including countries with economies in transition). For emission reductions resulting from JI projects, countries are granted Certified Emission Reductions (CERs). Both CER and JI projects have a number of conditions attached to them. Each project, together with the protocol used for measuring its emission reductions, must be approved by the executive board. Countries may use EATs, ERUs and CERs to comply with their emission caps.

The Kyoto commitment was introduced for the period 2008–2012. The role of the post 2012 portion is to stabilize atmospheric concentrations by 40–45% by 2050, compared to 1990 levels. As it takes time to achieve the target of the new regulations and to put incentives in place, companies must be confident that the system will endure in order to make decisions that require a long time line. To create this confidence, the World Bank is already buying credit for the post Kyoto commitment, while European policy makers are confident that 2012 will be followed by another compliance period.

We focus on allowances markets rather than project-based transactions and secondary Kyoto, which suffer from inefficiency and instable complex regulation. The effect of this inefficiency can be seen for the project-based transactions where the traded volume plummeted from 636 $MtCO_2e$ in 2007 to 283 $MtCO_2e$ in 2009. Little academic literature is available on this topic.

[1]Industrialized countries: Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom, United States of America.

The chapter is organized as follows. Section 2 summarizes the current state of world cap-and-trade schemes. The recent literature devoted to financial quantitative modeling for these markets is presented in Sect. 3. In a short final section, conclusions and future work are presented.

2 Carbon Markets

The new regulatory framework forces countries to transition into a clean energy economy. A policy instrument that could be used is a carbon emissions tax. Such a tax imposes a price that an emitter has to pay per unit of GHG emission. Companies will have to choose between paying the emission tax or reducing their pollution, encouraging emissions reductions if the marginal costs of abatement is less than the imposed tax. As consequence the optimal tax for each company must be equal to the marginal cost of abating. This marginal abatement cost varies across emitters and information about it is often unavailable to the regulator. As a result, the tax instrument is suboptimal. Furthermore it will be difficult to comply with the reduction commitment as the regulator does not directly control the emitted amount. Goers et al. (2010) provide more details about the inefficiency of emission taxes.

Inspired by the U.S. Acid Rain Program (1990) that was designed to control sulfur dioxide (SO_2) and nitrogen oxides (NO_x) from fossil fuel-burning power plants, some regulators decided to implement cap-and-trade mechanism as most cost-efficient instrument to comply with emission reduction target.

A cap-and-trade system is a market-based mechanism that uses market principles to achieve emissions reduction. The government running the cap-and-trade program sets an absolute limit, or cap, on the amount of GHG, and issues a limited number of tradable allowances which sum to the cap and represent the right to emit a specific amount. The market is aimed to provide price signals describing the true cost of the emission of a tonne of carbon. This is a crucial input for planning the transition to a clean energy economy, while protecting sensitive sectors from undue disruption and keeping local industry internationally competitive.

Higher emissions prices would induce companies with lower abatement costs to profit from the price difference by abating more CO_2 than they would need to comply with regulations, and then to sell the spare certificates for the higher certificate price. Each company faces a basic choice between buying or selling allowances, and reducing emissions through use of alternative technologies. Three general classes of techniques for the physical reduction of emissions are available. Firstly, emissions can be reduced by lowering the output scale. Secondly, the production process or the inputs used may be modified, for example fuels can be switched (Gas/Coal). Finally, tail end cleaning equipment can be installed to remove pollutants from effluent streams before they are released into the environment.

2.1 European Union Emissions Trading Scheme

The European Union Emissions Trading Scheme (EU ETS) market is a cap-and-trade system limited to European industrial installations. It is the largest carbon emission market in the world with 6.3 billion tCO_2e trading volume and US$118.5 billion exchanged value in 2009. It was established in 2005,[2] 3 years before the beginning of the first Kyoto commitment phase. It comprises combustion installations exceeding 20 MW, refineries and coke ovens as well as the metal, pulp and paper, glass, and ceramic industries. In total more than 12,000 installations among 30 countries (27 European Union States plus Iceland, Liechtenstein and Norway). Companies covered by the ETS subject receive at the end of every February a certain number of EU allowances (EUAs). The initial allocation assigned to each company depends on the National Allocation Plan.[3] Each allowance gives the right to emit one tCO_2 in the current calendar year. On April 30th of the following year, companies must submit EUAs to the national surveillance authorities. If companies do not provide EUAs that cover their total emission, they must pay a penalty[4] and deliver the missing EUAs in the following year. EUAs are initially allocated to the market participants for free with limited information during the first trading period.[5] Some companies have as consequence made gains described as windfall profits.

In addition to using carbon trading, only CDM were considered within the phase I (2005–2007). The JI was added during phase II (2008–2012). The contribution of CDM and JI are limited in order to ensure local emission reduction targets.

As the EU ETS market started in 2005, there are differences between the first trading period (2005–2007) and the first Kyoto commitment period (2008–2012). In fact, in most European countries, the EUAs issued in the first trading period were only valid during this trading period (although France and Poland allowed limited banking between 2007 and 2008). In France and Poland, companies could bank at most the difference between the initially allocated allowances and their accumulated emissions. Furthermore, companies can bank CERs from the first period, but we highlight the fact that the use of CERs is limited.

The EU ETS allows borrowing from a future year within the same trading period. As the compliance date is at the end of April, the company can use the received EUAs at the end of February to comply with the preceding year. The recent global economic crisis decreased the demand side of the market in 2009,

[2]The first trading started in 2004 in anticipation of the formal initiation of the scheme in January 2005. The traded volume was about 8.5 $MtCO_2$.

[3]An important component of each plan is a quantity set aside for new installations and new companies, known as the New Entrants' Reserve.

[4]Penalty is set at € 40 per metric ton of carbon equivalent above the cap in 2005–2007 period and € 100 for the phase 2008–2012.

[5]A very limited number of EUAs were auctioned during the first phase. Referring to Article 10 of the European Directives, auctioning will increase to 10% of total emissions in phase II (2008–2012).

with emissions falling by 11.2%. As a result some companies, such as steel and cement, raised cash by taking advantage of the overlap between the issuance of the 2009 allowances and the 2008 deadline for compliance. In fact they sold their 2008 EUAs and borrowed the 2009 allocations to comply with their 2008 emissions. The EUA prices dropped sharply from the € 31 reached in July 2008 to € 8 in February 2009. This is a strong illustration of the importance of banking and borrowing rules in driving spot prices and their volatilities.

Carbon futures markets seem to be more liquid than the corresponding spot markets. In fact, an EUA spot transaction is considered as a good so it is subjected to Value-Added Tax (VAT) while a futures and options contracts are VAT exempt because they are treated as financial transactions within the European Union. The largest and most liquid spot market for EUAs is the NYSE Euronext while the key futures market is the European Climate Exchange (ECX). Not only are companies regulated, but private or institutional investors are allowed to buy or sell allowances. The EU ETS allows non-emitting firms or individual investors to trade to increase liquidity and for speculation and diversification purposes. They need only establish an account in the emission registry of an European member state. U.S. funds are responsible for 10–15% of traded volume on ECX during the phase II.

Despite of the competition from NYSE Euronext, ECX does not have a spot market. They use the EUA Futures as underlying asset to write an option. For only the first period, futures with monthly expiries were traded in ECX. In 2008, quarterly futures contracts were introduced. These contracts are listed on an expiry cycle of: March, June, September and December contract months and they are listed up to June 2013. December annual contracts are also traded from December 2013 to December 2020. In October 2006, European style put and call options on EUA Futures started to be traded on ECX. In March 2009, ECX introduce EUA Daily Futures contracts which are exchange-traded cash contracts. Daily Futures Contracts will be physically delivered by the transfer of EUAs from the seller to the buyer.

Several empirical studies were done to understand the market behavior during the phase I. They show that the EU ETS is characterized by a very high historical volatility. Referring to Daskalakis et al. (2009), EUA spot prices in Powernext Carbon[6] and Nord Pool[7] moved closely with the average mean absolute difference being around 7 cents (fixed transaction costs are on the order of 3 cents per EUA). Moreover, the correlation coefficient of weekly spot returns between the Powernext and Nord Pool EUA markets is very strong, reaching almost 90%.

Daskalakis et al. (2009) found that there is no correlation between price returns for CO_2 and power. This result conforms to Sevendsen and Vesterdal (2003) who come to the conclusion that the largest CO_2 emitters do not have enough market share and thus all market participants are assumed to be pure price takers. At conventional significance levels, they also show that logarithmic spot process are non stationary. Since EUAs are considered to be commodities for consumption, this

[6]NYSE Euronext acquired Powernext Carbon in December 2007.

[7]Nord Pool was sold entirely to NASDAQ OMX to create the NASDAQ OMX Commodities.

result contradicts the common findings of mean reverting behavior observed in commodities and energy markets.

Daskalakis and Markellos (2008) examined the efficiency of EU ETS, concentrating on the weak-form of market efficiency according to which all the information contained in historical prices should be reflected in today's price. They conclude that the historical prices cannot be used to form superior forecasts or to accomplish trading profits above the level justified by the risk assumed.

Paolella and Taschini (2008) undertook an econometric analysis of emission allowance spot market returns and found that the unconditional tails can be well represented by a Pareto distribution while the conditional dynamics can be approximated by GARCH-type innovation structure.

Franke (2005) shows that if companies tacitly collude to manipulate the market, then CO_2 returns should have positive autocorrelations. A brief analysis of these autocorrelations in Seifert et al. (2008) reveals no strong empirical evidence in favor of this conjecture.

Ben and Trück (2009) analyze the behavior of CO_2 spot prices' log-returns over the period starting from January 3, 2005 until December 29, 2006. They compared results from a simple normal distribution, AR(1),[8] GARCH(1,1), and a Markov switching between two regimes (base regime and spike regime). They concluded that the GARCH(1,1) and Markov switching models outperform both the normal and AR(1) models, and are quite similar.

The European regulator set up the third compliance phase during 2013–2020. The emission target is to reach, in 2020, a level of 21% less than 2005. The detailed regulatory framework remains uncertain, but two major baselines consider carbon leakage and auctioning policy. "Carbon leakage" describes the transfer of a company to another country or state with less stringent constraints on carbon emissions in order to survive international competition. An auctioning policy will spur the carbon leakage as it will likely increase the production cost.[9] Economists agreed that auctioning will offset the downside effect of grandfathering and allow a more significant carbon price signal. Starting from 2013, the European regulator was engaged to set auctioning as an alternative for allowance allocation. To fight carbon leakage, company in a given sector need pay for only a fraction of their allowances with companies in sector deemed exceptionally (leaky) receiving allowances free. The assistance will decrease annually such that in 2027 full auctioning will be applied in all sectors.

Analysts believe that the EU ETS options market is mature enough to be comparable to other many options markets. Furthermore they expect the market to be short post 2012 which explains the active trading of the December 2013 EUA contracts.

---

[8]They studied the models AR(p), $p \geq 1$, and they found only AR(1) is significant.

[9]European policy makers are studying the possibility of imposing carbon taxes on goods imported from foreign countries which do not penalize emissions. Companies not exposed to foreign competition (e.g. in the electricity sector) will presumably pass the additional marginal cost to the final consumer.

2.2 Other Emissions Trading Markets

In 2009, New Zealand (NZ) opted for a carbon trading scheme to comply with its Kyoto protocol commitment. The scheme started in July 2010. It regulates stationary energy, industrial process and liquid fossil fuels for transport. It will progressively include some other sectors (i.e. synthetic gas and waste on January 2013) until fully implemented by 2015. 2010–2012 is the transition period in which one NZ allowance is used to surrender two tCO_2e. Within this period, the market is a combination between a cap-and-trade and a tax system, known as hybrid market. In fact initially the allowances are distributed for free with a possibility to purchase more from the regulator at a predefined price of NZ$25. In case of non-compliance, the company will have to cancel the allowances they failed to deliver with a penalty of NZ$30 per unit. Borrowing from post 2012 is prohibited while unlimited banking is permitted.

In the U.S., the American Clean Energy and Security Act of 2009, known as the Waxman-Markey Bill, was passed by the House of Representatives in June 2009. It consists of a cap-and-trade scheme to reduce emissions by 17% from 2005 levels by 2020. The Bill still need to be considered by the Senate, probably during the next legislative term. Despite the federal carbon regulation, the Regional Greenhouse Gas Initiative (RGGI) was set up in 2008 among the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont. It is a mandatory cap-and-trade market covering only the power sector. It aims to reduce 10% of its emission by 2018. In 2009, 805 $MtCO_2$ was traded for an equivalent value of US$ 2.2 billion.

Four western Canadian provinces (British Columbia, Manitoba, Ontario, Quebec) have developed the Western Climate Initiative (WCI) program together with seven U.S. states (Arizona, California, Montana, New Mexico, Oregon, Utah, Washington) to jointly implement a cap-and-trade scheme starting in January 2012. The initiative targets 15% emissions reduction below 2005 levels by 2020.

Some voluntary markets are implemented as domestic initiative to spur transition into clean energy (i.e. China, Japan). Brazil intends to establish a voluntary market-based instrument to reduce emissions up to 38.9% by 2020.

Several questions may arise: Is it possible to set up an international linkage between different emissions trading schemes? If yes, is it the most cost-effective method for abatement?

3 Modeling and Pricing in Emission Markets

Cap-and-trade is a policy instrument to combat the climate change impact. This mechanism allows to avoid climate risk at corporate level even though it adds some other operational risks (see Labatt and White 2007). As consequence companies need a financial modeling framework to price emission allowances and their derivatives for risk management purpose.

Several approaches to this problem were developed during the past decade. Existing work can (for the most part) be divided into those involving equilibrium models and those using quantitative finance style stochastic modeling. We review now this literature. We notice that some of the models that deal with allowances pricing under one compliance period are not flexible enough to take into consideration the impact of banking and borrowing possibilities under a multi-period trading scheme on allowance price dynamics. However they allow for good understanding of the market mechanism.

3.1 Equilibrium Models

Dales (1969) was the first economist to introduce market idea for trading the right to pollute. Three years later, Montgomery (1972) provided a theoretical foundation of a market in licenses and developed a decentralized system based for achieving environmental goals at a number of different locations. These two seminal papers are the origins of the development of the recent contributions.

Carmona et al. (2009) explore the relation between the price evolution of emission allowances and the way in which a multi-agent electricity producer decides when to switch from a hard coal power plant to a cleaner Combined Cycle Gas Turbine (CCGT). A one period discrete time mathematical model is developed to determine the optimal switching policy that minimizes the overall cost under zero net supply conditions. The resulting equilibrium carbon price is equal to the marginal price of an extra allowance to lower the expected penalty payment amount.

Seifert et al. (2008) assume that emission rate dynamics are given by a stochastic process, where the uncertainty is driven by a standard Brownian process. The existence of this term in the model is explained by a potential emission variation due to some external randomness (e.g. weather changes and economic growth). Under the assumption of risk-neutral market participants, the central planner choose an optimal abatement policy as function of time and total expected accumulated emissions over the entire compliance period. The latter variable is a controlled stochastic process with dynamics derived from the emission rate's stochastic differential equation with a drift controlled by the abatement policy undertaken. The marginal abatement costs is assumed to be linearly increasing with respect to the emissions abatement strategy. It is also defined as the spot price, and has a martingale property under the objective probability measure. Its motion is not correlated to the specification of the emission process rate. A logarithmic utility function was introduced to study the impact of risk aversion on allowances price.

Chesney and Taschini (2008) deal with pricing spot allowances price for one period market scheme and assume that the emitter release GHG exogenously and continuously under a geometric Brownian motion. A company may trade only at an initial time in order to minimize final costs comprising the sum of the initial trading cost[10] and the expected penalty payment applying to any future allowance shortages. The spot price obtained is equal to the discounted[11] penalty price times the probability weight of non-compliance scenarios. Chesney and Taschini (2008) extend the basic model to the case of an economy where two companies can trade at multiple discrete times. They suppose that the allowance price is equal to the penalty level at the compliance date when at least one company faces an allowance shortage. Also companies trade using only information about their own pollution and the accumulated emissions volume of their counterparty at the previous trading possibility. The equilibrium price process for each trading time is defined as function of the traded quantity. The latter is obtained by solving a system of two equations, incorporating the market clearing condition. Using the method of moments to approximate the sum of more than one geometric Brownian motion by another geometric Brownian motion, an extension of the model to a multi company framework is possible.

Carmona et al. (2010) propose a competitive equilibrium model under one compliance period. The output goods are assumed to be exogenous and inelastic. A producer in the economy has the choice between several technologies for each good characterized by different marginal cost production, emission factor and production capacity. The stochastic properties of the demand and costs are known for all firms from the beginning. The overall demand is considered to be satisfied and less than the total production capacity. To avoid paying penalties, the planner switches its production to a cleaner available technologies or has recourse to the ETS to buy allowances. The authors show the existence of market equilibrium such that the zero net supply condition is fulfilled, the demand is covered, and the strategies maximize the expected terminal wealth. To avoid issues with discounting, Carmona et al. (2010) work with forward prices applying at the compliance time T. The forward allowances prices in time T currency is a bounded martingale under the objective probability measure with value less than the penalty level. Also time T spot goods prices and optimal production strategy are merit-type equilibrium with defined adjusted costs. These properties are necessary conditions to the existence of the equilibrium. It is shown that the market equilibrium is equivalent to a representative agent problem where the emission is reduced at a cost-effective way. A generalized cap-and-trade scheme is introduced by including taxes and subsidies in the original formulated problem. Furthermore it allows the regulator to distribute allowances dynamically and linearly in the production quantity. By assigning adequate values to these variables, a comparative analysis is made between the standard cap-and-trade market (a), cap-and-trade market with auctioning of allowances (b), tax scheme (c), and a cap-and-trade scheme with relative allowance allocation (d) vis-à-vis emissions reduction, incentives to invest in a

[10]It can take positive values and be considered a gain when the company decides to sell allowances at the initial time, or negative and seen as a cost if allowances are purchased.

[11]The discount rate is the weighted average cost of capital.

Table 2 Comparison of schemes from Carmona et al. (2010)

	Reduction target	Incentives	Windfall	Social cost	Consumer cost
a	+	+	−	+	−
b	+	−	−	+	−
c	−	−	+	−	−
d	+	+	+	+	+

cleaner energy, windfall profits, social cost, and end-consumer cost. Table 2 reports the results.

Hinz and Novikov (2010) solve the central planner problem treated in Seifert et al. (2008), Carmona et al. (2009), and Carmona et al. (2010) by including additional assumptions in the equilibrium mathematical model. Under no-arbitrage condition, they assume the existence of an equivalent risk neutral probability Q such that the equilibrium price is a Q-martingale. Also the agent opts immediately to abate when allowance prices exceed its abatement cost. At the compliance date, the spot price is zero if the market is long and equals the penalty level otherwise. As consequence the spot price under Q will depends only on the cumulative abatement volume and the overall allowance shortage. The model is developed under a discrete time framework. As an illustrative example, they focus on the martingale case with independent increments for the cumulative emissions and deterministic abatement functions combined with the least-square Monte-Carlo method of Longstaff and Schwartz (2001). An algorithm is formulated to price allowances and European call written on the spot allowances price.

Borovkov et al. (2010) study the continuous time version of the solution obtained by Hinz and Novikov (2010). They show the existence of the allowance price when the conditional expectation of the total cumulative emissions is a Q-martingale diffusion process with a deterministic volatility. The allowance price is derived by solving a nonlinear partial differential equation (PDE), while a European call option is priced by solving a linear PDE. An extension to a jump diffusion setting is developed and the spot price is obtained by solving a partial integro-differential equation. Borovkov et al. (2010) prove uniqueness of the allowance price and use a numerical finite difference scheme to compute it.

Kijima et al. (2010) extend the work of Maeda (2004). They suppose the existence of a competitive market within a single-period economy, where the regulated emitters must comply with emission reduction target set up by the regulatory authority at the future time T. Two markets are available: the spot market, and the derivatives market written on the T allowances price and assumed to be complete. Financial traders are considered in the model and trade only in contingent claims market to hedge the risk in their exogenous income. The authors assume that each economic agent has a negative exponential utility with an appropriate risk-aversion coefficient. The key assumptions for their model to obtain closed-formulas are the following: they suppose the cost abatement function to be continuously differentiable, increasing and strictly convex with a derivative that starts at zero when there is no abatement, and goes to infinity asymptotically.

Infinite penalties are imposed, so that the emitter must abate emission or buy allowances at time T to comply with the regulatory emission target. The state price density is provided for each of the cases in which banking and borrowing are allowed or not, giving a pricing solution for any contingent claim. Moreover, the market clearing condition when banking and borrowing are forbidden must be satisfied, otherwise being replaced by the equality between the aggregate abatement target and the whole emission reduction over all the compliance period. Under a piecewise linear quadratic abatement cost function, price spikes may occur, more frequently in the forward than in the spot price (in contrast to intuition deriving from the usual Samuelson effect for commodities). The relationship between the spot and forward prices are analyzed. They show that when there are many financial traders the forward price is smaller than expected future spot price, known as normal backwardation.

3.2 Stochastic Modeling

We introduce the papers that use applied probability techniques in order to provide a pricing and hedging solution to the market participants. These approaches offer general flexible tools for pricing complex contingent claims.

Çetin and Verschuere (2009) present a probabilistic pricing and hedging framework. They assume that the market contains only two forward contracts P_t and S_t with subsequent maturities T_1 and T_2, $T_1 < T_2$, respectively. S_t dynamics are modeled by a Markov process with a drift expressed as an affine function of a càdlàg Markov chain taking values depending on the market position. Under the assumption of no banking, P_t is zero if the market is long; otherwise taking the value of the penalty level plus S_{T1}. If the market is short the investor must pay the penalty and deliver at later time T_2 the missing allowances. The model framework is incomplete because there are two sources of uncertainty in the stochastic differential equation for S_t, and one of them is not tradable. As a result, contingent claims have, in addition to the hedgeable risk, a relative intrinsic risk (Föllmer and Sondermann 1986) which cannot be covered. Çetin and Verschuere (2009) uses the Föllmer-Schweizer decomposition to price P_t as an expectation under an equivalent probability measure called the minimal martingale measure. The associated hedging strategy is a locally-risk minimizing strategy as defined by Föllmer and Schweizer (1991). A filtration projection technique is used to price the allowance and a digital option, which pays an unit amount of money if the market is short at time T_1, under incomplete information. The effect of intermediate announcements is also studied.

Carmona and Hinz (2009) assume the existence of an equivalent martingale measure Q such that the price process of a future contract A_t is a martingale. Within a single T compliance period model, A_T is equal to the penalty level π when the emitted quantity is greater than the number of allowances. Carmona and Hinz (2009) define N as a set of allowance shortage events. N is described as the set where some positive-valued random variable Γ is located above the boundary 1. The total normalized emission can be seen as a special choice. Carmona and Hinz (2009) identify a class of parameterized positive Q-martingales with values less than the penalty level. These Q-martingales satisfy the following condition: under the objective probability measure, the probability of the events such that the limit of A_t equals to π is the same as one minus the probability of the events such that the limit of A_t equals to 0. For ease of calibration to historical data, they provide a formulation of the likelihood density under the assumption that the market price of risk is constant over time. The model is extended to a two-period market model without borrowing, with unlimited banking and withdrawal. The prices of European call options written on futures contracts and maturing before the first compliance date are derived for both models.

Grüll and Kiesel (2009) assume that the emission rate follows a geometric Brownian motion, similar to the assumption of Chesney and Taschini (2008). They use the result of Carmona et al. (2010) and assume that the price of the futures contract maturing at the compliance date T may be computed from the penalty price times the probability of the set of events where the total cumulative emissions at time T exceeds the cap predetermined by the regulator. The spot price is approximated using three different approaches which depend on the approximation method used to compute the total cumulative emissions at time T. In the first, linear approach cumulative time T emissions are estimated using T times the emissions rate at time T. The second and third approaches are a bit more sophisticated, relying on moment matching techniques for the cumulative emissions estimate. They differ only because the second approach uses a log-normal distribution in the matching while the third uses a reciprocal gamma distribution.

Under a risk-neutral assumption, Huang (2010) models emission rate dynamics as a stochastic process. Instead of a geometric Brownian motion dynamics as in Chesney and Taschini (2008) and Grüll and Kiesel (2009), he assumes that the process can follow either an arithmetic Brownian motion or a mean reversion process. At the compliance date, the spot price is zero if the aggregate emissions exceed the allocated emissions limit and equals the penalty level otherwise. Formulas are provided for spot prices, European options prices (call and put) as well as their Greeks. Futures prices can be derived from the spot price when the convenience yield is neglected.

4 Conclusion

The regulatory framework related to carbon emissions market has not yet been solidified. For both political and economic reasons, a state of flux continues to exist in carbon market rules. As an example of rule changes rooted in economic theory, economists have recently reconsidered the conclusion that cap-and-trade markets are more efficient than carbon taxes. As an improvement over both tax and cap-and-trade regimes, economists have proposed a hybrid market which combines aspects of carbon taxes with features of cap-and-trade schemes. Much current research (Grüll and Taschini 2011; Mnif and Davison 2010) is concerned with presenting pricing and hedging frameworks for this new market design.

It is important that this uncertainty in market rules be resolved, since the result of this ambiguity is that companies do not yet have clear information signals for making clean energy investment decisions. Should they make these investments now, or wait for new regulations to be introduced? Quantitative finance techniques are ill suited to address such questions of regulatory risk.

References

Benz E, Trück S (2009) Modeling the price dynamics of CO_2 emission allowances. Energy Econ 31(1):4–15

Borovkov K, Decrouez G, Hinz J (2010) Jump-diffusion modeling in emission markets. Stoch Model 27:50–76

Carmona R, Hinz J (2009) Risk neutral modeling of emission allowance prices and option valuation. Princeton University, Technical Report

Carmona R, Fehr M, Hinz J (2009) Optimal stochastic control and carbon price formation. SIAM J Contr Optim 48(4):2168–2190

Carmona R, Fehr M, Hinz J, Porchet A (2010) Market design for emission trading schemes. SIAM Rev 52(3):403–452

Çetin U, Verschuere M (2009) Pricing and hedging in carbon emissions markets. Int J Theor Appl Finance 12(7):949–967

Chesney M, Taschini L (2008) The endogenous price dynamics of emission allowances: an application to CO_2 option pricing. Working paper.

Dales JH (1969) Pollution, property and prices: an essay in policy-making and economics. University of Toronto Press, Toronto

Daskalakis G, Markellos RN (2008) Are the European carbon markets efficient? Rev Fut Markets 17(2):103–128

Daskalakis G, Psychoyios D, Markellos RN (2009) Modeling CO_2 emission allowance prices and derivatives: evidence from the European trading scheme. J Bank Finance 33(7):1230–1241

Föllmer H, Schweizer M (1991) Hedging of contingent claims under incomplete information. In: Davis MHA, Elliott RJ (eds) Applied stochastic analysis, vol 5, Stochastics Monographs. Gordon and Breach, London/New York, pp 389–414

Föllmer H, Sondermann D (1986) Hedging of non-redundant contingent claims. In: Hildebrandt W, Mas-Colell A (eds) Contributions to mathematical economics. North Holland, Amsterdam, pp 205–223

Franke G (2005) What can we expect from the new trade of CO_2-allowances? Stiftung "Umwelt und Wohnen" Environment-Economy-Education 75–79.

Goers RS, Wagner AF, Wegmayr J (2010) New and old market-based instruments for climate change policy. Environ Econ Pol Stud 12:1–30

Grüll G, Kiesel R (2009) Pricing CO_2 permits using approximation approaches. Working Paper.

Grüll G, Taschini L (2011) Cap-and-trade properties under different hybrid scheme designs. J Environ Econ Manage 61:107–118

Hinz J, Novikov A (2010) On fair pricing of emission-related derivatives. Bernoulli 16 (4):1240–1261

Huang Y (2010) The price dynamics in the emissions market and the valuation of allowance derivatives. Working Paper.

Kijima M, Maeda A, Nishide K (2010) Equilibrium pricing of contingent claims in tradable permit markets. J Fut Markets 30(6):559–589

Labatt S, White RR (2007) Carbon finance: the financial implications of climate change. Wiley, New York

Longstaff FA, Schwartz ES (2001) Valuing American options by simulation: a simple least-squares approach. Rev Financ Stud 14(1):113–147

Maeda A (2004) Impact of banking and forward contracts on tradable permit markets. Environ Econ Pol Stud 6(2):81–102

Mnif W, Davison M (2010) Pricing and hedging strategies for contingent claims in an incomplete hybrid emissions market, 6th World Congress of the Bachelier Finance Society.

Montgomery DW (1972) Markets in licenses and efficient pollution control programs. J Econ Theory 5(3):395–418

Paolella MS, Taschini L (2008) An econometric analysis of emission allowance prices. J Bank Finance 32(10):2022–2032

Seifert J, Uhrig-Homburg M, Wagner MW (2008) Dynamic behavior of CO_2 spot prices. J Environ Econ Manage 56(2):180–194

Sevendsen GT, Vesterdal M (2003) How to design greenhouse gas trading in the EU? Energy Policy 31(14):1531–1539