Theory and empirical research on carbon price dynamics

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Abstract

This paper provides an overview of theoretical and empirical studies on emission permit price dynamics. Equilibrium models have been proposed in literature with the aim of describing the evolution of the price of emission permits. At the same time, the permit price behaviour (characterised by high volatility, jumps, convergence to zero during the first phase) of the largest emissions trading scheme (EU ETS) has been investigated with the help of standard statistical methods. Recently, so-called reduced-form equilibrium models have been used to link the empirical and theoretical approach.

Key words: CO_2 emission allowances, Equilibrium model, Model calibration.

JEL Classifications: C02, C61, C63, C65, G13.

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Acknowledgements: We would like to thank Rüdiger Kiesel, Marc Chesney, and Max Fehr for their valuable comments and discussions. Taschini gratefully acknowledges financial support from LSE. The usual disclaimers apply.

Preprint submitted to ISI 2011 *15 April 2011*

1 Introduction

In the past, environmental laws and regulations were dominated by command-and-control approaches, typically under the form of technology or emission standards. Starting from the mid 70', environmental policy makers increasingly explored market-based policy instruments, and, in particular, transferable emission permits. In principle, market-based instruments provide economic incentives for firms and individuals to carry out cost-effective pollution control. In particular, the rationale behind transferable permits is that participants trade permits thereby minimizing the cost of pollution control to society. The source of these cost savings is the capacity of this instrument to take advantage of the large differentials abatement costs across different regulated agents.[1] Transferable permits are typically used in cap-and-trade programs. In a cap-and-trade system, an environmental regulator sets a target level for pollution emissions (i.e. the cap) and issues emission permits (also called allowances). Permits are allocated to regulated entities (industries, firms, etc.) according to different allocation criteria (auctioning, grandfathering, etc.). To enforce the cap, at the end of each compliance period a penalty is levied for each unit of pollutant that is emitted and not offset with an allowance. Regulated firms can meet compliance by abating emission, using allocated permits, trading allowances and any combination thereof. By exchanging permits, agents achieve compliance at minimum costs; firms that can cheaply reduce emissions will do so, while those that cannot purchase permits. In 2005 the European Union, in an effort to meet its target under the Kyoto Protocol, launched the so-called European Union Emission Trading Scheme (EU ETS) creating the largest existing market for emission permits. More recently, the use of market for permits have been at the center of several discussions in the U.S., Australia, Japan and, nowadays, China. Given the prevalence of cap-and-trade schemes in such discussions, the need for a more clear understanding of the functioning of these systems and of the permit price formation is natural. This paper addresses the second aspect and discusses the theoretical and empirical research on emission price dynamics.

2 Equilibrium price modeling

One of the first references to transferable permits for dealing with pollution problems can be found in the seminal works of Coase [8] and Dales [9]. Based on such an idea, Montgomery [17] provides a rigorous theoretical justification

[1] We refer to Baumol and Oates [2] for a complete discussion on market-based policy measures, and to Taschini [21] for an introductory review on fundamental concepts in environmental economics.

of how such a market-based approach leads to the efficient allocation of abatement costs across various pollution sources. The equilibrium allowance price is obtained by solving the firm's cost optimisation problem. This solution, quite remarkably, corresponds to the solution of the joint cost minimum. Few year later, Rubin (1996) extends the work of Tietenberg (1985) and Cronshaw and Kruse (1996) providing a more general treatment of a market for permits in continuous time by means of optimal-control theory. Similar to the previous cited studies, the equilibrium allowance price is obtained under certainty, i.e. relevant variables are deterministic.

Allowing for stochastic production costs, revenues from selling produced goods and emission quantities, Carmona et al. [4] showed in a general setting that the price of emission permits equals the discounted penalty multiplied by the probability of the event of shortage (i.e. the aggregated cumulative emissions exceed total number of permits). A similar result is obtained by Seifert et al. [20] and Chesney and Taschini [7]. [2]

In other words, at time t the futures price of emission permits can be represented as:

$$F(t,T) := P \cdot \mathbb{P}\left(q_{[0,T]} > N|\mathcal{F}_t\right), \tag{1}$$

where, after abatement reductions, $\mathbb{P}\left(q_{[0,T]} > N|\mathcal{F}_t\right)$ measures the probability of the final amount of emissions, net of abatements, exceeding the initial amount of permits. P denotes the penalty that has to be paid for each emission unit that is not covered by a permit at the compliance date T and N is the total amount of permits allocated by the policy regulator to relevant companies, i.e. the cap. The models of Chesney and Taschini [7] and Grüll and Kiesel [11] specify the process for the cumulative emissions in the framework of Carmona et al. [4] by assuming that the firms' emission rate follows a geometric Brownian motion. This means that the cumulative emissions are described by the integral over a geometric Brownian motion for which no closed-form density is available. The models of Chesney and Taschini [7] and Grüll and Kiesel [11] differ in the way the cumulative emissions are approximated.

All these papers propose different models to derive the theoretical properties of emission trading systems and, ultimately, derive policy implications. Carmona et al. [4] analyze the effect of windfall profits, Chesney and Taschini [7] investigate the effect of asymmetric information on the permit price and Grüll and Kiesel [11] provide a theoretical sound discussion about the

[2] Carmona et al. [4] obtain such a result in a discrete-time setting by showing the equivalence between the market equilibrium and the joint cost minimum problem. Chesney and Taschini [7] derive Equation (1) by arguing that the price of an allowance at the end of the regulated period equals the value of a digital option.

permit price slump in 2006 in the EU ETS. Grüll and Taschini [13] examine permit price properties of existing cap-and-trade systems and proposed hybrid schemes. This paper, in particular, investigates whether permit price bounds are enforced effectively in hybrid schemes without relaxing the original environmental targets. Further, Grüll and Taschini [13] extend the model of Carmona et al. [4] to a cap-and-trade system with banking and show that in such a cap-and-trade scheme the permit price is the sum of the compliance value (as in the scheme without banking) and the banking value. A similar result is obtained by Hitzemann and Uhrig-Homburg [15]. All these paper, however, do not assess the ability of the models to capture the stylised fact of real data.

3 Empirical studies

Recently, in an effort to bridge the gap between theory and observed market-price behavior, an increasing number of empirical studies have investigated the historical time series of the price of permits in the European market. The EU ETS, the world's largest emission trading system which covers approximately 50% of the CO_2 emissions in the European Union, consists of three different phases. Phase I lasted until the end of 2007. Phase II started in 2008 and ends in 2012. A third phase will start in 2013. Due to bankability restrictions between phase I and II, it is necessary to treat the existing price series of each phase separately - see Alberola and Chevallier [1]. In the first phase the price of permits is characterized by a significant volatility level. The prominent market correction between the end of April 2006 and the beginning of May 2006 (see Figure 1) occurred when the information about verified emissions for the first compliance year became public. The revelation of such information confirmed the suspects about an overall overestimation of total emissions. A long-lasting price decrease of the December 2007 futures contract to zero started in August 2006.

The study of the evolution of the permit price in the EU ETS has been the subject of several empirical papers. The following classes of processes have been applied to the permit price series: jump-diffusion models (Wagner [23], Daskalakis et al. [10]), GARCH-models (Benz and Trück [3] and Wagner [23]), regime-switching models (Wagner [23], Benz and Trück [3]), Mix-Normal GARCH-models (Paolella and Taschini [18]) and two-factor models (Cetin and Verschuere [6]). Other authors support the argument that the permit price responds to macroeconomic fundamentals and try to explain the price evolution of emission permits in terms of electricity, gas, oil and coal prices and weather effects (cf. Hintermann [14] and Mansanet-Bataller et al. [16]). The majority

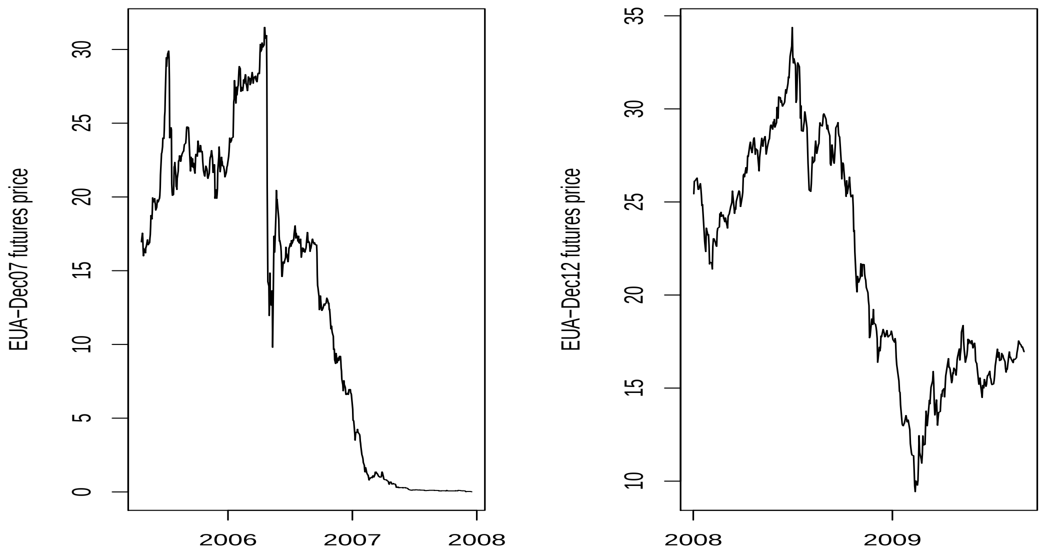

Fig. 1. Left: EUA-Dec07 futures price (22 April 2005 - 17 December 2007), right: EUA-Dec12 futures price (2 January 2008 - 31 August 2009)

of these empirical papers neglect, however, the relationship between statistical and equilibrium models: how are the properties of the permit dynamics reflected in the time series?

4 Empirical analysis of permit price models

With the objective to provide tractable pricing models for options on emission permits, Carmona and Hinz [5] were the first to address the complexity of the calibration of the equilibrium model of Carmona et al. [4]. The authors introduce a simple risk-neutral reduced-form model for the price of emission permits and calibrate it to historical options data. The reason for introducing a reduced-form model is that it is not possible to map a full equilibrium model to existing data. Grüll and Taschini [12] derive estimation methods for the calibration of reduced-form equilibrium models to permit price data. The authors compare the in-sample performances of the reduced-form models to standard continuous-time stochastic processes such as a geometric Brownian motion (GBM) and a Normal Inverse Gaussian process (NIG).

From a theoretical point of view, the observed price convergence to zero at the end of the first compliance period in the EU ETS does not come at a surprise (cf. Equation 1). This is a consequence of the fact that at compliance time the permit price can only take the values zero (overallocation) or the penalty fee (permit shortage). Reduced-form models have a similar behaviour. Therefore, when compared to GBM or NIG, reduced-form models have an advantage in capturing the observed price dynamics in phase I. Grüll and Taschini [12] test this hypothesis by splitting up the price series into two parts - the period of the crash in May 2006 is taken as a cutting point. As expected, the empirical analysis of Grüll and Taschini [12] shows that reduced-form models perform well at the end of the compliance period. When considering the post-crash price series, reduced-form models outperform both GBM and NIG. Yet, reduced-form models cannot fully capture the price dynamics in this particular period. A significant volatility level and low trading volumes can perhaps justify this result. At the beginning of each compliance period the NIG captures better the permit price dynamics, outperforming the reduced-form models. Compared to GBM, instead, the reduced-form models perform slightly worse at the beginning of the first phase and at par at the beginning of the second phase. Finally, the two competing reduced-form models of Grüll and Taschini [12] and Carmona and Hinz [5] have similar performances.

5 Conclusions

Transferable permits are considered as a cost-effective instruments and, therefore, nowadays they are a quite popular policy instrument. Relying on this instrument, policy makers set up permit schemes with the objective to cap pollution emissions. The European Union Emission Trading Scheme, by far the world's largest emissions trading scheme, is an example. In the recent past several papers investigated the theoretical properties of emission permits and, more recently, quite few papers explored the statistical properties of the permit price series. Only two papers, so far, attempted to bridge these two streams of research by proposing a reduced-form version of the equilibrium models and empirically testing these models. In this paper we briefly review this entire literature.

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