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Modeling and forecasting the volatility of carbon dioxide emission allowance prices: A review and comparison of modern volatility models☆

Mawuli Segnon[a], Thomas Lux[b,c,*], Rangan Gupta[d]

[a] Center of Quantitative Economics, University of Münster, Germany
[b] Department of Economics, University of Kiel, Kiel, Germany
[c] Bank of Spain Chair of Computational Economics, Department of Economics, University Jaume I, Castellón, Spain
[d] Department of Economics, University of Pretoria, South Africa

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ABSTRACT

The launch of the markets for carbon dioxide emission allowances was guided by the aim to use the supposedly efficient price formation mechanism of an organized exchange to optimally allocate a certain quantity of emissions among potential polluters. While this introduction of a centralized trading arrangement should have helped to achieve required emission reductions with a minimum of economic losses, from the viewpoint of market participants it has raised concerns about appropriate risk management provisions to cope with the fluctuations of time-varying allowance prices. The present review provides an overview over state-of-the-art models for price volatility expanding the scope from relatively simple GARCH-type models to models with long-term dependence and regime switches including the relatively recent class of so-called multifractal models. We provide a comparative application of these models to carbon dioxide emission allowance prices from the European Union Emission Trading Scheme and evaluate their performance with up-to-date model comparison tests based on out-of-sample forecasts of future volatility and value-at-risk.

1. Introduction

The introduction of regulated emission markets in many industrialized countries has constituted a change in paradigm in environmental economics and policy away from the Pigouvian taxation of external effects to a market-based allocation scheme that was designed to impose certain emission limits with a minimum of economic costs. An important role in this trend to market-based allocation has been played by the prevailing optimism on the allocative efficiency of financial markets, and carbon emission allowances are just one important example in the general trend towards financialisation of commodity markets that could be observed over the last decades. The establishment of official exchanges and standardized products has indeed led to price formation in such markets that in its statistical properties closely resembles traditional financial products such as shares, bonds or foreign exchange. For instance, commodity returns seem to share the properties of fat tails (high frequency of relatively large returns) and volatility clustering (high fluctuations of market prices appear to be autocorrelated) that have been universally observed as salient characteristics of traditional asset classes. However, despite these similarities, commodities differ in their behavior in that their level of fluctuations of prices are even much higher than what is traditionally recorded for traditional assets (cf. [66]). Indeed, many commodities have experienced extreme price changes and carbon dioxide allowances are no exception. An extreme case in question is the drop of the carbon price to €0.01/tCO_2 on March 11, 2008.

From the viewpoint of financial economics, availability of price records from various emission allowance exchanges opens the possibility of learning about the price formation process, the influence of various fundamental factors on allowance prices, the relationship to other markets (such as for electricity) and the study of market inefficiencies and possible bubbles and bursts. It also provides the necessary input for the study of dynamic properties of the time variation of the second moment of returns. The later is very well-developed field of study in financial economics with a vast literature on models and applications to all standard asset classes. While modeling of volatility is of crucial importance in risk management of market participants in the presence of the large observed fluctuations of carbon allowance prices (and, indeed, most active market participants have been investing into the built-up of quantitative analysis groups within

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* Corresponding author at: Department of Economics, University of Kiel, Olshausenstrasse 40, 24118 Kiel, Germany.
E-mail addresses: segnon@uni-muenster.de (M. Segnon), thomas.lux@bwl.uni-kiel.de (T. Lux), rangan.gupta@up.ac.za (R. Gupta).

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their companies), the academic literature on this subject is somewhat sparse and, in particular, has not reached out to the most up-to-date developments available in volatility modeling and comparative assessment of such models. Against this background, the present paper provides a review and comparative illustrative application of current volatility models to European Union Allowance spot prices. While most available contributions in the literature use simple GARCH-type models for carbon price volatility, we also include more advanced models incorporating the important characteristics of long-term dependence in volatility and possible regime shifts.

To this end, we also consider a new class of volatility models that has been introduced only relatively recently based on multifractal processes. Such processes have first been developed in the theory of turbulent flows (e.g. [60]) and have been adapted to model financial volatility by Calvet and Fisher [16,17]. The robustness and the capacity of this family of models to dominate GARCH-type models in terms of forecasting volatility of various financial time series has been demonstrated in Calvet and Fisher [17], Lux [54], Lux and Morales-Arias [56], Lux et al. [57], and Lux et al. [59]. The attractiveness of the multifractal model stems from the fact that it provides a simple uniform framework for both long-term persistence in the volatility process and structural breaks through regime switching. These built-in properties motivate the choice of the multifractal model as a competitor against a range of GARCH-type models. The relevance of long-term dependence and regime shifts is supported by recent findings by Gil-Alana et al. [39] on the persistence properties of fluctuations of CO_2 allowance prices and the presence of structural breaks.

We also illustrate the performance of the various models using a broader range of current tools for model comparison than available in extant literature. Previous studies of carbon dioxide emission allowances have mostly concentrated on the comparison of one-day ahead forecasting performance of volatility models with constant and conditional variances. However, volatility forecasts for longer horizons are vital inputs for option pricing and risk management decisions. We, therefore, compare the forecasting ability of the new Markov-switching multifractal (MSM) models with those of the standard generalized autoregressive conditional heteroscedasticity (GARCH), fractionally integrated GARCH (FIGARCH) and the two-state Markov-switching GARCH (MS-GARCH) at short and long horizons, thereby filling these gaps in the existing literature. We also go beyond comparison of pairs of models and apply so-called tests for superior predictive ability that allow for a simultaneous comparison of any single model to all its competitors. We find that forecasts based on the multifractal models cannot be outperformed by other models under the majority of forecast criteria and forecasting horizons. While this applies to both volatility forecasts and value-at-risk comparisons, so-called backtesting procedures do not detect significant differences in value-at-risk diagnostics between the different models.

The rest of the paper is organized as follows. Section 2 briefly reviews the literature on CO_2 emissions. Section 3 presents the CO_2 prices and their descriptive statistics. The volatility models are described in Section 4. In Section 5 we provide the results of the empirical application and finally, Section 6 concludes.

2. Literature review on price formation and volatility dynamics in the market for carbon emission allowances

Since the market for European Union Allowances (EUAs) had been launched on January 1, 2005, it has become by far the largest market for CO_2 emissions worldwide. Empirical studies of price formation in the carbon market are almost exclusively based on data collected for EUAs. A large number of studies have investigated factors that may affect the carbon price in the European Union Emissions Trading Scheme (EU ETS). Christiansen et al. [27] find that policy and regulatory issues, market fundamentals such as the emissions-to-cap ratio, the role of fuel-switching, weather and production levels are important price determinants in the EU ETS. Chevalier [19] identifies several macroeconomic drivers of EUA prices. Other studies have focused on the role of energy prices (oil, gas, coal and electricity prices), and weather (temperatures and extreme weather events) in the determination of carbon prices. Examples include Christiansen et al. [27], Mansanet-Bataller et al. [62], Alberola et al. [4], Bunn and Fezzi [15], Kim and Koo [51], Hintermann [49], Keppler and Mansanet-Bataller [50], Bredin and Muckley [12], Mansanet-Bataller et al. [61], Creti et al. [33], Aatola et al. [1], and Hammoudeh et al. [44,45]. In all these papers the authors find a strong relationship between energy prices and the price of EUA (cf. [15,50,61], among others) and between weather and the price of EUA (cf. [62,61,49], among others). In other papers economic activity and financial market shocks have been revealed to be among the fundamental drivers of CO_2 prices (cf. [5,64,19,35,22,61,43,12], among others). For example, Bredin and Muckley [12] report a significant correlation between carbon prices and stock prices and an index of industrial production. It appears from these and related studies that the influence of compliance and the large list of potential fundamentals makes the carbon market more complex than other commodity markets and explains the significant attention that is paid to this market (cf. [37,32,31,80,25], for a detailed literature review on the carbon price development in the EU ETS and its operating mechanism and economic effect).

Alberola et al. [4], Chevalier [19], Alberola and Chevallier [3] have analyzed in detail the effects of institutional decisions (the emissions shortfall factor and banking restrictions) on the price path of carbon. Chevalier [23] provides a theoretical literature review on how banking instruments can be used to manage the stock of allowances in a flexible inter-temporal way in the context of the European Union Emissions Trading Scheme (EU ETS). Papers by Uhrig-Homburg and Wagner [74], Chevalier [20,21], Chevalier [24], Arouri et al. [6], Gorenflo [41], Trück et al. [73], among others, have investigated the relationship between carbon emission spot and futures prices. For example, Arouri et al. [6] employ vector autoregressive (VAR) models and switching transition regression exponential GARCH (STR-EGARCH) models to investigate the dynamic relationships between the EU Emission Allowances (EUA) spot and futures prices during Phase II and find that carbon spot and futures returns are asymmetrically and non-linearly linked.

However, less attention has been paid to modeling and forecasting EUA spot price volatility, which with the development of derivative markets appears to be of particular importance for investors and energy companies. Most of the extant studies on modeling and forecasting EUA spot price volatility focus on relatively time-honored GARCH-type processes (cf. [65,10,9,70]) that, in fact, may not offer enough flexibility to properly model the dynamic properties of CO_2 price volatility. Seifert et al. [69] develop a stochastic equilibrium model to analyze CO_2 spot price dynamics. They find that CO_2 prices are not characterized by seasonal patterns and that an appropriate CO_2 price process should exhibit a time- and price-dependent volatility. Daskalakis et al. [34] adopt a geometric Brownian motion with an additional jump component to describe the random behavior of the carbon dioxide (CO_2) emission spot price. They find that the jump-diffusion model properly reproduces the non-stationarity and abrupt discontinuous shifts observed in CO_2 price levels. Benz and Trück [10] use a Markov-switching model, and a standard GARCH(1,1) model to analyze the heteroscedastic behavior of carbon dioxide emission allowance return series, while Paolella and Taschini [65] employ an AR(1)-GARCH(1,1) model with different innovations (Student's-t, symmetric and asymmetric stable, and the generalized asymmetric t-distributions). Different GARCH models with conditional means following AR, ARMA and ARIMA processes are compared by Spiesova [70].

Benz and Trück [10] evaluate and compare the one-day ahead forecasting performance of their models via the mean squared error (MSE), the mean absolute error (MAE) and the Kolmogorov-Smirnov