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What explains the short-term dynamics of the prices of CO_2 emissions?

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Abstract

This paper analyzes the short-term dynamics of the prices of CO_2 emissions, using the vector auto-regression (VAR) and the vector error-correction Models (VECM). The data are monthly for the prices of oil, coal, natural gas, electricity and carbon emission allowances. The results show that: (i) a positive shock to the crude oil prices has a negative effect on the CO_2 prices; (ii) an unexpected increase in the natural gas prices raises the price of CO_2 emissions; (iii) a positive shock to the prices of the fuel of choice, coal, has virtually no significant impact on the CO_2 prices; (iv) there is a clear positive effect of the coal prices on the CO2 prices when the electricity prices are excluded from the VAR system; and (v) a positive shock to the electricity prices reduces the price of the CO_2 allowances. We also find that the energy price shocks have a persistent impact on the CO_2 prices, with the largest effect occurring 6 months after the shock. The effect is particularly strong in the case of the natural gas price shocks. Additionally, we estimate that it takes between 7.3 and 9.6 months to halve the gap between the actual and the equilibrium prices of the CO2 allowances, i.e., to erase any price over- or under-valuations after a shock strikes. Finally, the empirical findings suggest an important degree of substitution between the three primary sources of energy (i.e., crude oil, natural gas and coal), particularly, when electricity prices are excluded from the VAR system.

Keywords: CO2 emissions prices, crude oil, natural gas, coal, electricity.
JEL classification: Q47.

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1. Introduction

Carbon dioxide (CO_2) is the most important component of the greenhouse gases emitted by human activities. The 2007 report on climate change of the Intergovernmental Panel on Climate Change (IPCC) assesses that the CO_2 emissions account for 77% of all greenhouse gases at the global level. Furthermore, 75% of the CO_2 emissions come from the use of fossil fuels (coal, natural gas and oil) in energy production, transportation, industrial processes and land-use changes. The links between energy consumption and pollution emissions thus have important implications for economic growth, the environment and the quality of human life. Fast economic growth may produce carbon emissions that can lead to a degradation of the environment, which in turn affects human health and reduces the quality of life.

The United Nation Framework on Climate Change (UNFCC) was ratified by 37 industrialized countries on December 11, 1997 in Kyoto and came into force on February 16, 2005. This agreement is a major internationally coordinated policy action aimed to deal with global warming and the deterioration of environmental quality. Following the Kyoto Protocol, the right to emit a certain amount of CO_2 has become a trading commodity. Therefore, companies are forced to hold a certain amount of allowances in proportion to their carbon output. This implies that they can face a price risk based on fluctuations of the CO_2 allowance prices and a volume risk dependent on the fluctuations in energy demand.

These multinational policies suggest that the prices of the primary energy sources and emission allowances are major drivers which affect the relationships between energy consumption and carbon emissions. The substitutability between fossil fuels with different carbon intensities is also a fundamental driver of these relationships. The carbon allowances can also be considered a critical factor of production like labor, capital and fuel inputs because they affect companies' costs of production and profitability. In this scheme, examining the price relationships between the primary energy sources and carbon emissions is of paramount importance for making policy decisions and initiating the necessary adjustments related to fuel uses in production, stimulation of economic growth, and protection of the environment.

In contrast to the research on Sulfur dioxide (SO_2) emissions, the existing carbon literature has been relatively limited in dealing with the CO_2 emissions. The studies that are available deal particularly with the prices of emission allowances from the viewpoint of risk management. With advances in econometric techniques and greater flows of information and shocks among markets and economies, there is now a strong interest towards analyzing energy efficiencies, causality and substitutions among the different energy sources using multivariate techniques. Our study extends the related literature on carbon emissions by examining the transmission of shocks from the primary energy prices of crude oil, natural gas and coal as well as electricity to the price of CO_2 emission allowances. In other words, we assess the responses of the allowance prices to the shocks in their main determinants. Putting the United States in perspective, it will be interesting to determine which primary energy price is the main driver of the CO_2 prices. In this context, our research is thus in the same spirit of Alberola et al. (2008) who identify oil and gas as the main CO_2 price drivers. Along the same line, Oberndorfer (2009) identifies a positive relationship between the CO_2 prices and the stock returns in the electricity sector.

We accomplish our objective by employing a vector autoregressive (VAR) model and a vector error-correction model (VECM) to analyse the responses of the CO2 price emissions to the prices of different primary sources of energy. Unlike the previous literature that has typically relied on univariate models, these multivariate econometric models allow us to appropriately capture the potential endogenous relationships, the short-run dynamics and the long-run adjustments between the energy prices and the CO_2 emission allowance prices. They also help to investigate the magnitude and the persistence of the effects of the energy price innovations on the allowance prices. Finally, while the CO_2 emissions depend on a number of factors including policy and regulatory issues, weather conditions (e.g., temperature, rain fall, and wind speed) and industrial production, the changes in the energy prices are the underlying factors that affect the demand and supply sides of the CO_2 allowances, and the market prices of those allowances. For example, the cold weather conditions may increase energy consumption, which in turn increases the allowances prices. Similarly, the low wind speed can negatively affect the share of non-CO_2 power generating sources, thereby raising the prices of CO_2 emissions. Thus, the price of coal and the different prices for cleaner fossil fuels such as crude oil and natural gas provide a short-term signal for the investment needed in the CO_2 abatement projects. Therefore, assessing this source of price uncertainty is crucial for understanding the short-term dynamics of the price of the CO2 emission allowances.

Our main results show that the effects of changes in the energy prices on the CO_2 prices are not alike, underlying the differential impacts of those prices and the importance of the regulatory process. A positive shock to the crude oil and electricity prices, which lowers their consumption, should in turn reduce the prices of the CO_2 allowances. On the other hand, an unexpected rise in the prices of the cleaner natural gas drives up the prices of the CO_2 emissions. Besides, a positive shock to the price of coal, which is the fuel of choice, has virtually no significant impact on the CO_2 prices. The share of coal in power generation in the United States has dropped from more than 50 % in the last decades to 37% in 2012. Moreover, more coal-fueled power plants have closed down or are going into bankruptcy as the use of coal has become unprofitable due to the regulatory policy constraints on prices of electricity (Sweet, 2013).

As indicated, the negative effect of higher oil and electricity prices on the CO_2 prices can be explained by the decline in oil and energy demand, which reduces the need for carbon inventory build-ups. The insignificant impact of the price of coal may be due to country-specific natural resource reserves and environmental and electricity regulatory constraints which have sent some power plants in the United States to bankruptcy. We also find that the energy price shocks have a persistent impact on the CO_2 prices. The effect is particularly strong in the case of the shocks in the prices of the natural gas which is the switching fuel.

The remainder of this article is organized as follows. Section 2 reviews the related literature. Section 3 describes the empirical methods used to assess the short-term interactions between the fuel/energy prices and the CO2 emission prices, as well as the long-term adjustments towards the equilibrium. Section 4 presents the data and discusses the empirical findings. In Section 5, we conclude the article.

2. A Brief Review of the Literature

Carbon allowance trading has essentially been applied in the United States since 2003. Not surprisingly, the majority of the works in the field has focused on the price behavior of the SO_2 tradable emission allowances under the Acid Rain Program of the US Environmental Protection Agency (EPA). For instance, Rezek (1999) focuses on the importance of changes in technological parameters and Schennach (2000) assesses the impact of electricity demand on the SO_2 permits’ prices. Other authors investigate the role played by the changes in the market parameters (Burtraw et al., 2002; Böhringer and Lange, 2005; Kosobud et al., 2005; Schleich et al., 2006).

In what concerns the CO_2 emissions, the literature is very limited. The few exceptions include Daskalakis et al. (2005), Paolella and Taschini (2006), Uhrig-Homburg and Wagner (2006), and Seifert et al. (2008). For instance, Daskalakis et al. (2005) evaluate the prices and derivatives of the CO_2 allowances and find some evidence of no-arbitrage pricing behavior. Focusing on the returns of the CO_2 and SO_2 allowances, Paolella and Taschini (2006) uncover a GARCH-type structure and asymmetries in the carbon spot price dynamics. Uhrig-Homburg and Wagner (2006) analyze the optimal design of derivatives on the CO_2 emission allowances. Seifert et al. (2008) investigate the dynamics of the CO_2 spot prices and show that they should have a time- and price-dependent volatility structure. Relying on technical analysis, Daskalakis and Markellos (2008) examine the efficiency of the European markets for the CO2 emission allowances during Phase I. Benz and Strück (2009) concentrate on the out-of-sample forecasting performance of the forecasting models. Those authors propose the use of the Markov Switching and AR-GARCH models for stochastic modeling and explain such choice with the various phases of the price and the volatility of the CO2 returns, an aspect that can be seen as a substantial improvement in terms of price risk management.

As can be inferred from the discussion above, the above mentioned studies have typically looked at the CO2 allowance prices from the angle of risk management or focused on the stochastic properties of the spot and the future prices. In contrast, some authors have shifted the attention towards a more econometric perspective built on the Granger causality and linear cointegration tests. In this context, Milunovich and Joyeux (2007) focus on market efficiency and price discovery issues and show that spot and future prices jointly help uncovering equilibrium prices in the light of the bilateral information transmission. Milunovich and Joyeux (2010) reject the existence of a long-run relationship between the EUA spot and futures prices in Phase I, a result that is in contrast with the findings of Rittler (2012). Chevalier (2010) finds that the futures prices are relevant for the price discovery in the spot market. Arouri et al. (2012) use a VAR model and a Switching Transition Regression-Exponential GARCH model (STR-EGARCH) to capture asymmetry and nonlinearity effects in both return and volatility of the spot and futures prices of the EU Emission Allowances (EUA) during Phase II. They suggest that the spot and futures returns of carbon are linked in an asymmetric and nonlinear fashion. More recently, Atil et al. (2013) use a nonlinear autoregressive distributed lags (NARDL) model to examine the pass-through of crude oil prices into gasoline and natural gas prices. This approach allows the authors to simultaneously test the short- and long-run nonlinearities and to quantify the responses of gasoline and natural gas prices to positive and negative shocks in the prices of gasoline based on the asymmetric dynamic multipliers.

3. Empirical Methodology

3.1 The vector auto-regression (VAR) approach

When modeling the relationship between the prices of the CO_2 emission allowances and those of the primary energy sources, the single-equation approach is likely to fail to take into account the possible dependence between the time-series variables under analysis. Given the objective of our research, the multivariate framework is more convenient. Accordingly, we estimate the following structural VAR (SVAR)

$$\underbrace{\Gamma(\boldsymbol{L})}_{\boldsymbol{n}\times\boldsymbol{n}}\underbrace{\boldsymbol{X}_{\boldsymbol{t}}}_{\boldsymbol{n}\times 1} = \Gamma_0\boldsymbol{X}_{\boldsymbol{t}} + \Gamma_1\boldsymbol{X}_{\boldsymbol{t}-1} + ... = \boldsymbol{c} + \varepsilon_{\boldsymbol{t}} \tag{1}$$

$$v_t = \Gamma_0^{-1}\varepsilon_{\mathrm{t}} \ , \tag{2}$$

where $\varepsilon_t \mid X_s, s < t \sim \mathrm{N}(\underline{0}, \Lambda)$, *Γ(L)* is a matrix valued polynomial in positive powers of the lag operator *L*, *n* is the number of variables in the system, ε_t are the fundamental economic shocks that span the space of innovations to X_t, and v_t is the VAR innovation.

The price of the CO_2 emissions can be characterized as

$$CO2_t = f(\boldsymbol{\Omega}_t) + \boldsymbol{\varepsilon}_t^{CO_2} \tag{3}$$

where, $CO2_t$ is the price of the CO_2 emissions, *f* is a linear function, Ω_t is the information set, and $\boldsymbol{\varepsilon}_t^{CO_2}$ is the error term of the equation for the prices of CO2 emissions.

We consider a recursive identification scheme and assume that the price of the CO2 emissions can be explained by a set of variables, namely: (i) the price of crude oil; (ii) the price of natural gas; (iii) the price of coal; and (iv) the price of electricity.

The recursive assumptions can be summarized by

$$X_t = [CO2_t, Crude_t, NatGas_t, Coal_t, Electricity_t]'$$

and

$$\Gamma_0 = \begin{bmatrix} \underbrace{\gamma_{11}}_{1\times1} & \underbrace{0}_{1\times4} \\ \underbrace{\gamma_{21}}_{4\times1} & \underbrace{\gamma_{22}}_{4\times1} \end{bmatrix}. \tag{4}$$

The impulse-response function to a one standard-deviation shock under the normalization of $\Lambda = \boldsymbol{I}$ is given by:

$$\boldsymbol{B}(\boldsymbol{L})^{-1}\Gamma_0^{-1}, \tag{5}$$

where ***B(L)*** is a matrix valued polynomial in positive powers of the lag operator *L* associated with the regression coefficients. In accordance with the standard likelihood ratio tests, the selected optimal lag length is 1.

Finally, we use the generalized impulse-response functions proposed by Pesaran and Shin (1998), which are invariant to any re-ordering of the system variables. We also improve upon the work of Sims (1980) in that the impulse-response functions allow for a meaningful interpretation of the response of each variable to a particular structural shock.

3.2 The vector error-correction model (VECM)

The VAR framework has good properties when applied to covariance-stationary time series, but might encounter difficulties when applied to integrated processes. Furthermore, Engle and Granger (1987) raise the possibility that two or more integrated, non-stationary time series might be co-integrated, so that some linear combination of these series could be stationary even though each series is not. For instance, if two series are both integrated of order one, one could model their interrelationship by taking first differences and including the differences in a VAR. However, this approach might be suboptimal if the series are co-integrated, as in the VAR would only describe the short-run responses of the series to innovations in the different variables included in the system. Putting it differently, when the series are co-integrated, they move together in the long-run and, consequently, a VAR will not capture those long-run dynamics.

In our case, this is less of a problem, because we are interested in the short-term dynamics of the price of CO_2 emissions, and with a focus on fuel and energy prices. Moreover, over the long-run, other factors such as policy and regulatory issues, market fundamentals regarding the demand and the supply of the CO_2 allowances, and weather conditions (rain fall, temperature, and wind speed) may have an impact on the price of the CO_2 allowances, but we are not able to model them either because of the lack of the data or due to the absence of a good theoretical model. Similarly, to the extent that changes in some of these factors - namely, policy and regulations - are the outcome of long discussion processes, their effects can be to some extent anticipated and their impacts are largely transmitted to the CO_2 prices in the short-term. Finally, it is reasonable to assume that changes in these factors may have substantial consequences on the energy prices – via their effects on the actual demand and supply – and, thus, on the short-term price behavior of the emission allowances. Thus, a VAR framework would still be a good characterization of the CO_2 prices.

With these caveats in mind, we evaluate the dynamic relationship between the price of CO_2 allowances and the energy prices by means of a vector error-correction model (VECM), which takes the following form

$$\Delta \boldsymbol{X}_t = \mu + \rho ECT_{t-1} + \sum_{i=1}^{p-1} \Delta \boldsymbol{X}_{t-i} + \varepsilon_t \qquad (6)$$

where $\varepsilon_t \mid X_s, s < t \sim \mathrm{N}(\underline{0}, \Lambda)$, ECT_{t-1} is the lag of the error-correction term (i.e. the cointegrating vector among the variables in the system), Δ is the first-difference operator, and p is the number of lags included in the model. Therefore, the system in equation (6) allows us to identify the short-run deviations of the variables from their (long-run) equilibrium relationship.

4. Data and empirical results

4.1 Data

Our dataset consists of time-series of the prices of the CO_2 emissions, crude oil, natural gas, coal and electricity. The data are at monthly frequency and are sourced from Datastream. The study period runs from August 2006 to November 2013, which enables us to investigate the price interactions between energy and CO_2 emission allowances under market stress conditions. We are thus able to compare our results with those of several previous studies. In our study, the CO_2 emissions price corresponds to the spot price of the European Union CO_2 emission allowances (EEXEUAS) from the European Energy Exchange (EEX). The prices which are expressed in euros are converted into US dollars using the WM/Reuters closing spot rates of the US dollar to euro (USEURSP) exchange rate. The crude oil price corresponds to the spot price of the West Texas Intermediate crude oil benchmark. The oil price series is expressed in US dollars per barrel (CRUDOIL). The natural gas price corresponds to the Henry Hub natural gas spot price which is also expressed in US dollars per million British thermal units (NATGHEN). The coal price corresponds to the price of Coal Intercontinental Exchange (ICE) API2 cost, insurance and freight Amsterdam, Rotterdam and Antwerp NR in US dollars per metric tonne (LMCYSPT). Finally, the electricity price is the South

Path 15 Firm Peak electricity price which is also expressed in the US dollars per megawatt Hour (WSSPDPF).

4.2. Evidence from the VAR

We now focus on the investigation of the relationship between the price of CO_2 emissions and the prices of crude oil, natural gas, coal and electricity through the lenses of a five-variable VAR framework.

The estimation results are summarized in Table 1. The equation for the price of the CO_2 allowances demonstrates evidence of a significant and negative relation between the prices of crude oil and the price of CO_2 allowances. This shows that higher oil prices reduce oil consumption, consequently leading to a negative effect on the CO_2 prices. This result is not unexpected since rising oil prices tend to reduce economic growth (Hamilton, 1983, 2003; Lardic and Mignon, 2008; Kilian, 2008), which in turn diminish energy consumption and the need for carbon emission credits, leading to lower carbon emission prices. By contrast, the prices of the other types of energy do not significantly affect the price of CO_2 emissions allowances. It can also be seen that there is a substantial persistence in the price of the CO_2 emissions, as the coefficient associated with its own lag is significant and also large in magnitude. Overall, 91.6% of the variation in the price of the CO_2 emissions is explained by its own lag and the dynamics of the four energy prices. It is also worth mentioning that the equations for the prices of coal and electricity uncover a significant impact of the prices of crude oil, natural gas and coal, a feature that may reflect the fact that the generation of electricity is done by a mix of primary fuels which are substitutable.

Table 1. Estimation results of the five-variable VAR.

	EEXEUAS_USD	CRUDOIL	NATGHEN	LMCYSPT	WSSPDPF
EEXEUAS_USD(-1)	0.905***	0.044	-0.023	0.179	-0.668***
	(0.039)	(0.144)	(0.017)	(0.201)	(0.219)
CRUDOIL(-1)	-0.043**	0.920***	-0.003	0.270***	0.319***
	(0.022)	(0.081)	(0.009)	(0.113)	(0.123)
NATGHEN(-1)	-0.233	-0.591	0.870***	2.249**	6.851***
	(0.236)	(0.862)	(0.100)	(1.205)	(1.308)
LMCYSPT(-1)	0.024	-0.022	0.001	0.736***	-0.220***
	(0.015)	(0.056)	(0.007)	(0.078)	(0.085)
WSSPDPF(-1)	-0.010	0.082	-0.004	-0.039	0.014
	(0.023)	(0.083)	(0.010)	(0.116)	(0.126)

C	3.890*** (1.538)	7.400 (5.628)	1.149* (0.652)	-8.166 (7.870)	17.683 (8.543)
Adj. R-squared	0.916	0.808	0.804	0.855	0.637
Log likelihood	-194.126	-307.000	-119.538	-336.176	-343.309
AIC	4.601	7.195	2.886	7.866	8.030
BIC	4.771	7.365	3.0560	8.036	8.200

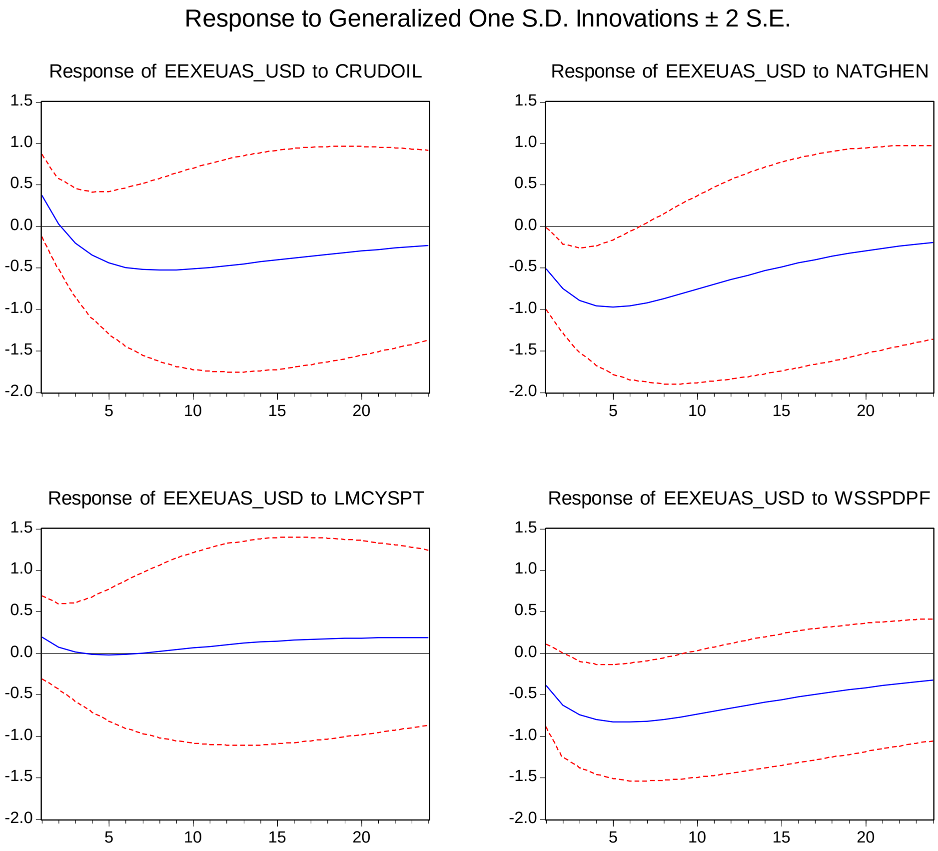
Notes: The standard errors are in parenthesis. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

In order to further investigate the effects on the price of the CO_2 allowances of the shocks to the various energy prices, we plot in Figure 1 the results of the generalized impulse-response function analysis for the CO_2 prices. More precisely, these results present the responses of the price of the CO_2 emissions to, respectively, a positive shock in a unit of standard deviation to the crude oil price, the natural gas price, the coal price, and the electricity price. The blue line denotes the mean response, while the red dashed lines correspond to the upper and lower bounds of the 95% confidence intervals. We can see that the price of the CO_2 emissions falls substantially in response to a shock affecting the prices of crude oil, natural gas and electricity. Again, this result shows that higher energy prices lead to a decrease in their consumption, thereby reducing the price of the CO_2 emissions. The effect on the price of CO_2 emissions is particularly large in the case of a shock to the price of natural gas. In all cases, the strongest impact is achieved around 6 months following the shock strike, but the effect is very persistent as the CO_2 prices are still below their original levels even 24 months after the shock occurred.

Our results also indicate no significant response of the price of the CO_2 allowances to a shock to the coal price. This lack of significance can be plausibly explained by the sharp difference in the coal's outlook across countries, which are largely determined by the coal price, and country-specific natural resource reserves and environmental regulatory constraints. In particular, the insignificant impact of coal price in the United States is due to cheap and abundant natural gas including largely shale gas. Since coal loses its competiveness to natural gas, power plants are moving away from this fuel. In 2012, the share of coal in power generation in the United States has been dropping from more than 50% in the last decades to 37% in 2012. As indicated earlier, some coal-fired power plants are closing or converting to natural gas-fueled plants as they become unprofitable.

Differently, the effect of the coal price on the CO_2 allowances price is expected to be greater in Europe and Asia. Indeed, the European legislations do not allow companies to produce shale gas, which implies that coal is more likely to be used to maintain power generation capacity given the relatively cheaper cost of this fuel despite its negative impacts on environmental quality. According to the June 2011 BP Statistical Review of World Energy, Asia is likely to continue building more new coal-fired power plants than any other region in the world, with a share of 67% of 2010 total world coal consumption.

Figure 1. Impulse-responses functions of CO_2 prices to shock within the five-variable VAR model.



In order to check the robustness of our previous results, we exclude the price of electricity from our VAR system as this energy source has a confusing impact on the effect of coal prices. This treatment is motivated by at least two reasons that motivate this treatment. First, the electricity markets worldwide are characterized by excessive market power concentration, inelastic demand and high prices which are particularly subject to government regulations in both the wholesale and retail sectors (e.g., Green, 1999; Wolfram, 1999; Ciarreta and Espinosa, 2012). The regulations aim at mitigating these problems and securing businesses from unexpected changes in the input and production costs. In most Western countries, these features suggest that firms in the electricity sectors are able to use their market power to set prices well above costs, and thereby maximizing their profits. All in all, strong regulations on electricity prices and demand inelasticity may cause the insensitivity of the CO_2 allowances price to changes in the price of electricity. Second, electricity is a sector that has undergone reforms started since the 1990s. While the power-generation technologies are relatively similar across countries, there are sharp differences in the endowment of fuel resources across countries. Indeed, some countries are more dependent on coal than others (e.g., China), and the same logic applies to other sources of primary energy.

Table 2 provides a summary of the estimation results of a four-variable VAR where we exclude the price of electricity from the rest of the system. We now see a clearer description of the main determinants of the price of the CO_2 allowances. Indeed, the equation for the CO_2 price shows that while an increase in the prices of crude oil and natural gas has a significant and negative effect on the price of CO_2 emissions, an increase in the price of coal raises significantly the CO_2 price. However, the impact of the coal price is only marginally significant at the 10% level. As before, the price of CO_2 allowances is particularly sensitive to the price of natural gas. In fact, the coefficient associated with this variable is almost seven times as large as the one associated with the price of crude oil and twelve times as large as the coefficient associated with the price of coal. Moreover, the price of CO_2 emissions reveals strong persistence as reflected by the statistical significance of the coefficient associated with the lagged CO_2 price. Overall, the adjusted-R^2 statistic of the equation for the price of CO_2 allowances is 91.7%.

Table 2. Estimation results of the four-variable VAR model (without electricity price).

	EEXEUAS_USD	CRUDOIL	NATGHEN	LMCYSPT
EEXEUAS_USD(-1)	0.911*** (0.037)	-0.004 (0.136)	-0.021 (0.016)	0.202 (0.189)
CRUDOIL(-1)	-0.046** (0.021)	0.948*** (0.076)	-0.004 (0.009)	0.257*** (0.105)
NATGHEN(-1)	-0.312** (0.158)	0.040 (0.582)	0.841*** (0.067)	1.948*** (0.810)
LMCYSPT(-1)	0.026* (0.015)	-0.039 (0.053)	0.002 (0.006)	0.744*** (0.074)
C	3.784*** (1.513)	8.247 (5.562)	1.110* (0.642)	-8.571 (7.737)
Adj. R-squared	0.917	0.808	0.806	0.856
Log likelihood	-194.237	-307.526	-119.622	-336.238
AIC	4.580	7.184	2.865	7.845
BIC	4.722	7.326	3.007	7.986

Notes: The standard errors are in parenthesis. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

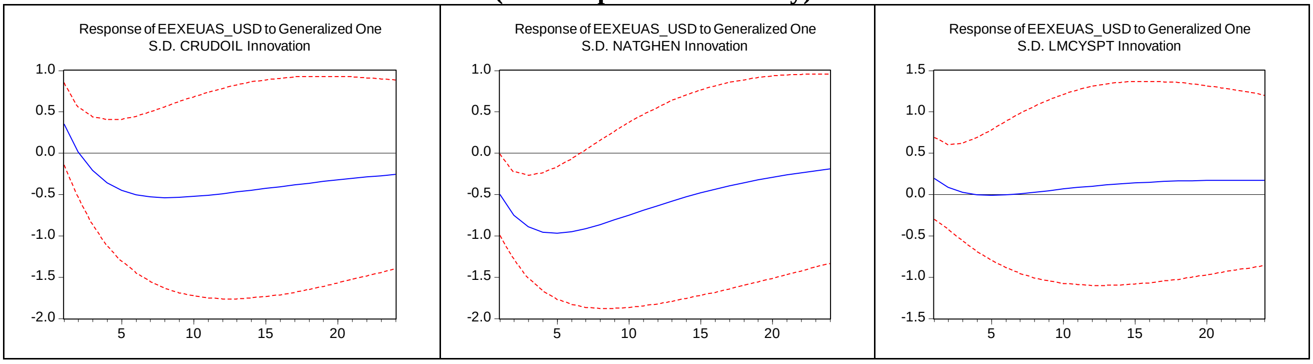
Interestingly, the equation of the price of coal shows that the prices of crude oil and natural gas enter significantly and have positive coefficients. This suggests an important degree of substitution between the three sources of energy, i.e., when the price of crude oil (or natural gas) increases, economic agents turn to cheaper sources of energy (such as coal), which, in turn, pushes their price upwards. As in the case of the CO_2 price, the price of coal appears to be highly responsive to variations in the price of natural gas.

Figure 2 provides an assessment of the responses of the CO_2 prices to the shocks to the prices of various sources of energy. Those responses are both qualitatively and quantitatively similar to the ones presented in Figure 1. As a result, the robustness of our results is confirmed in this case. In fact, we uncover a negative response of the price of the CO_2 allowances to a positive shock affecting the price of crude oil and the price of natural gas in particular. As in the case of the five-variable VAR model, the largest effect in this model takes place about 6 months after the shock strikes and in general the effects of the energy price shocks on the CO_2 prices are very persistent.

In the case of a shock to the price of coal, the empirical evidence suggests, once again, that the price of the CO_2 allowances does not significantly respond to this primary source of energy. Power plants are moving away from this fuel of choice to natural gas and renewables because the fuel is losing its competitiveness and of the drive towards clean energy. Thus, an increase in the price of this fuel should not affect the price of the carbon emission allowances. This result may also be explained by the nature of the regulatory environment which favors cleaner energy sources. More specifically, there are situations in which a certain percentage of power generation should come from high-cost renewables (e.g., in Germany). In such circumstances, it is likely that power plants try to offset the higher cost of using renewables by moving to the use of cheaper coal. This, in turn, can have an increase in the prices of both the coal and CO_2 emissions, as a result of more pollution emitted from using more coal than before the regulation. Putting these considerations together may explain the marginal significance of shocks in the price of coal.

Overall, excluding the electricity price from the VAR model, our empirical results support the idea that the price of crude oil and the price of natural gas in particular are the main drivers of the price of the CO_2 emissions.

Figure 2. Impulse-responses functions of CO_2 prices to shock within the four-variable VAR model (without price of electricity).



4.3 Evidence from the VECM

The previous section shows evidence of rich interactions between the price of the CO2 emissions and the prices of different energy sources. A natural question thus consists of asking whether there exists an equilibrium that tightens these prices together in the long-run. Since our cointegration tests in the top panel of Table 3 reveal two cointegration relationships between the price of carbon emissions and the prices of natural gas and electricity, a VECM can be straightforwardly implemented to simultaneously apprehend the short-run price interactions between those of the CO_2 emissions and different energy sources as well as their adjustments to a common equilibrium in the long-run.

The lower part of Table 3 reports the estimation results of the five-variable VECM model. In line with the evidence from the five-variable VAR, we find that the price of the natural gas enters significantly in the equation of the cointegrating vector. The large coefficient also corroborates the result that the price of this energy source plays a crucial role in the dynamics of the price of the CO_2 allowances.

Turning to the equation of the price of the CO_2 allowances, our results confirm that changes in the price of natural gas play a significant role in impacting the carbon emission prices. Similarly, changes in the price of electricity also help explain the short-term dynamics of the price of the CO_2 emissions. Interestingly, the coefficient associated with the residuals from the cointegrating vector is negative and significant (-0.069), which points to the existence of a cointegrating relationship between the variables in the system. Moreover, this shows that when the price of the CO_2 emissions is above its equilibrium level (i.e., when there is a price over-valuation), it is expected that the carbon price suffers a downward adjustment in the following months to return to its equilibrium established with the primary energy prices.

In the light of a coefficient of -0.069 associated with the error-correction term in the equation for the CO_2 emission prices, our VECM model suggests a half-life estimate of about 9.6 months, i.e., it takes 9.6 months to halve the gap between the actual and the equilibrium price of CO2 allowances.[2]

Table 3. Estimation results of the five-variable VECM model.

Cointegrating Eq:	CointEq1				
EEXEUAS_USD(-1)	1.000				
CRUDOIL(-1)	-0.158				
	(0.147)				
NATGHEN(-1)	-6.404***				
	(1.729)				
LMCYSPT(-1)	0.127				
	(0.101)				
WSSPDPF(-1)	1.050***				
	(0.162)				
C	-31.616				
Error Correction:	D(EEXEUAS_USD)	D(CRUDOIL)	D(NATGHEN)	D(LMCYSPT)	D(WSSPDPF)
CointEq1	-0.069**	-0.044	-0.003	-0.006	-0.765***
	(0.030)	(0.107)	(0.012)	(0.154)	(0.159)
D(EEXEUAS_USD(-1))	-0.062	-0.277	-0.005	-0.857	-0.179
	(0.113)	(0.398)	(0.046)	(0.573)	(0.595)
D(CRUDOIL(-1))	0.006	0.191	-0.002	0.426**	0.095
	(0.040)	(0.140)	(0.016)	(0.201)	(0.209)
D(NATGHEN(-1))	-0.594*	-0.340	-0.039	-0.090	0.707
	(0.348)	(1.230)	(0.141)	(1.769)	(1.835)
D(LMCYSPT(-1))	0.020	0.069	0.003	0.049	0.213
	(0.028)	(0.098)	(0.011)	(0.141)	(0.147)
D(WSSPDPF(-1))	0.043*	0.085	-0.003	-0.020	-0.180
	(0.023)	(0.082)	(0.009)	(0.117)	(0.123)
C	-0.195	0.198	-0.025	-0.112	-0.223
	(0.262)	(0.926)	(0.106)	(1.331)	(1.383)
Adj. R-squared	0.001	0.023	-0.067	0.045	0.415
Log likelihood	-194.042	-302.593	-116.057	-333.845	-337.031
AIC	4.6754	7.200	2.862	7.927	8.001
BIC	4.875	7.400	3.062	8.126	8.200

Notes: The standard errors are in parenthesis. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

Similarly, we also examine the robustness of the VECM results by considering a four-variable VECM which excludes the electricity price from the set of variables of the system as explained earlier. The results for this four-variable VECM are reported in Table 4. They clearly show that both the prices of crude oil and natural gas enter negatively and significantly in the cointegrating vector. Therefore, in the long-run, an increase in

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[2] The half-life estimate is computed as $\log(0.5)/\log(1-|\rho|)$ where ρ is the coefficient associated with the error-correction term in the equation for the changes in the price of the CO_2 emissions.

the prices of these sources of energy ends up leading to a fall in their consumption, which ultimately reduces the price of the CO_2 emissions. As for the price of coal, its coefficient in the cointegrating vector is positive, but insignificant. This evidence confirms again our results from the VAR analysis, owing to the fact that power plants move away from this fuel and only use it when other energy sources become more expensive.

It can also be seen that the coefficient associated with the error-correction term in the equation for the changes in the price of CO_2 emissions of this VECM is negative and significant (-0.090), giving some support to the existence of cointegration among the four variables of the system. In this case, the VECM model provides a half-time estimate of 7.3 months for the adjustment to the equilibrium.

Table 4. Estimation results of the four-variable VECM model (excluding the price of electricity).

Cointegrating Eq:	CointEq1			
EEXEUAS_USD(-1)	1.000			
CRUDOIL(-1)	0.767***			
	(0.155)			
NATGHEN(-1)	6.128***			
	(1.041)			
LMCYSPT(-1)	-0.488***			
	(0.111)			
C	-58.345			
Error Correction:	D(EEXEUAS_USD)	D(CRUDOIL)	D(NATGHEN)	D(LMCYSPT)
CointEq1	-0.090***	-0.161*	-0.006	0.230*
	(0.026)	(0.095)	(0.011)	(0.136)
D(EEXEUAS_USD(-1))	-0.112	-0.376	-0.008	-0.722
	(0.109)	(0.396)	(0.046)	(0.565)
D(CRUDOIL(-1))	0.046	0.270*	0.000	0.311
	(0.040)	(0.146)	(0.017)	(0.208)
D(NATGHEN(-1))	-0.042	0.529	-0.040	-0.557
	(0.281)	(1.019)	(0.118)	(1.455)
D(LMCYSPT(-1))	0.012	0.072	0.003	0.038
	(0.026)	(0.095)	(0.011)	(0.135)
C	-0.201	0.170	-0.025	-0.071
	(0.251)	(0.911)	(0.105)	(1.300)
Adj. R-squared	0.082	0.054	-0.056	0.089
Log likelihood	-190.922	-301.762	-116.124	-332.371
AIC	4.580	7.157	2.840	7.869
BIC	4.751	7.328	3.011	8.040

Notes: The standard errors are in parenthesis. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

5. Conclusion

Carbon dioxide (CO_2) is the largest component of the greenhouse gases, and international organizations have recognized the dangers that come from its emissions on climate change. About 75% of the CO_2 emissions come from the use of fossil fuels including coal, natural gas and oil. Governments and financial markets have placed in the market a price on its emissions to reduce the amount of pollution. This market-based approach is utilized to control carbon pollution by providing economic incentives for achieving reductions in the emissions. In the most cases, the governments set a limit on the amount of pollutants that can be emitted. The limit is allocated or sold to firms in the form of emission allowance permits which represent the right to emit a specific volume of the specified pollutants. For greenhouse gases, the largest trading program for the permits is the European Union Emission Trading Scheme.

In production of goods and service, the cost of emission allowances has been considered to be another factor of production that may affect firms' profitability. Thus, substitution between the primary energy sources is warranted based on their relationships with the allowance prices. Firms would reduce the usage of an energy source whose contribution to higher allowance prices outbids those of the other energy prices.

The existing literature has been relatively limited in dealing with the CO_2 emissions. Our study extends the related literature on carbon emissions by examining the transmission of shocks from the primary energy prices of crude oil, natural gas and coal as well as electricity to the price of CO_2 emission allowances in a multivariate setting. Our results mainly show that the effects of changes in the energy prices on the CO_2 prices are not alike. While a positive shock to the crude oil and electricity prices, which lowers their consumption, should in turn reduce the prices of the CO_2 allowances. On the other hand, an unexpected rise in the prices of the clean natural gas drives up the prices of the CO_2 emissions. Besides, a positive shock to the prices of coal, which is the fuel of choice, has virtually no significant impact on the CO_2 prices.

These findings are useful for a multiple of stakeholders. They should help organizations and businesses that track and manage their energy use and pollution emissions through environmental management programs. They can also be used in risk management in a similar way the relations between commodity prices are used to hedge against market risks, although the price behavior of emission allowances is different from those of commodities (Truck et al., 2012). The firm should know how to reduce the risk of facing substantial sanction payments or possible high prices for purchasing additional allowances (Bokenkamp et al., 2005). The results should also help in the environmental regulatory process that favors energy sources that lead to lower carbon emissions.

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