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Asymmetric and nonlinear pass-through of energy prices to CO_2 emission allowance prices

Shawkat Hammoudeh[#] *Amine Lahiani*[*] *Duc Khuong Nguyen*[†] *Ricardo M. Sousa*[$]

Abstract

We use the recently developed nonlinear autoregressive distributed lags (NARDL) model to examine the pass-through of changes in crude oil prices, natural gas prices, coal prices and electricity prices to the CO2 emission allowance prices. This approach allows one to simultaneously test the short- and long-run nonlinearities through the positive and negative partial sum decompositions of the predetermined explanatory variables. It also offers the possibility to quantify the respective responses of the CO2 emission prices to positive and negative shocks to the prices of their determinants from the asymmetric dynamic multipliers. We find that: (i) the crude oil prices have a long-run negative and asymmetric effect on the CO2 allowance prices; (ii) the falls in the coal prices have a stronger impact on the carbon prices in the short-run than the increases; (iii) the natural gas prices and electricity prices have a symmetric effect on the carbon prices, but this effect is negative for the former and positive for the latter. Policy implications are provided.

JEL classification: Q47.
Keywords: CO2 allowance price, energy prices, NARDL model, asymmetric pass-through.

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1. Introduction

The atmospheric carbon dioxide (CO_2) is the largest component of the greenhouse gases which cause global warming. About 72% of the greenhouse gases emitted is completely CO_2, and thus the CO_2 emissions are the major cause of global warming. CO_2 is considered harmful to human health and has profound deleterious effects on the environment as a whole.

Governments have come together to restrict human production of the greenhouse gases, mainly the carbon dioxide (CO_2). International organizations have also recognized the dangers on climate change associated with the CO_2 emissions. About 75% of this contaminant gas's emissions come from the use of fossil fuels including coal, natural gas and oil and may remain in the atmosphere for 80 to 200 years.

In this context, governments and financial markets have placed in the market a price on the CO_2 emissions to reduce the amount of pollution. This market-based approach is employed to control the carbon pollution by providing economic incentives for achieving reductions in those emissions. In most of the cases, governments set a limit on the amount of pollutants that can be emitted. This 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 the greenhouse gases, the largest trading program for the permits is the European Union Emission Trading Scheme (EU-ETS).

The on-going developments in the markets for the CO_2 emission allowances have far-reaching implications for environmental policy, financial institutions and industries in a variety of sectors. In this article, we investigate how fluctuations in energy prices are passed on to the carbon emission allowance prices, viewing it from the United States’ perspective, over both the short- and long-run, by using the newly developed nonlinear autoregressive distributed lags (NARDL) model.

This approach is a significant improvement over the typical univariate and multivariate linear econometric models prevailing in the carbon economics literature. In contrast to the traditional (linear) error-correction model, this modeling approach is a two-regime dynamic error-correction representation which allows for asymmetric responses of the CO_2 allowance prices to negative and positive changes in energy prices. It is particularly advantageous in that reliable long-run inferences can be achieved by bounds tests regardless of the integration order of the variables in the system (Shin et al., 2014). This approach also takes into account non-linearities due to the presence of new regulations such as governments mandating that a sizeable part of power generation be fuelled by clean alternative sources of energy such as solar and wind. It is also better suited to deal with the impact of major discoveries in the primary energy sources such as shale gas that led to reshuffles in energy prices, substitution among primary fuels and caused some coal-fired power plants to close. Changes in the National Allocation Plans (NAP) in the form of revisions or cuts of national emission caps have also consequences that may be sudden price jumps, spikes or phases of extreme volatility in the allowance prices. Furthermore, the CO_2 allowance prices can be relatively high during periods of strong economic expansion or when new low-carbon technologies are slow in entering the market. On the other hand, during times of economic slumps and low prices of clean fuels, the carbon allowance prices can be low. These major changes may lead to asymmetry and structural changes in the relationships between energy prices and pollution emissions.

The consideration of nonlinearity and asymmetry in the price interactions is also of great importance because of the complexity of the economic system that governs the data-generating process in the energy and carbon emission markets. Indeed, factors such as episodes of financial turbulence, sudden policy shifts, extreme events, geopolitical tensions, financial markets sophistication, and regulation multiplicity may induce regime-switching behavior, asymmetric responses to news and leverage effects. Consequently, the price of carbon emissions is likely to be nonlinearly related with energy prices.

Our research is closely linked to the strand of the literature on the determinants of the CO_2 emission allowance markets, in particular the study by Kim and Koo (2010). Using the linear ARDL model of Pesaran and Shin (1999) and Pesaran et al. (2001), Kim and Koo (2010) find that the price of coal is the main driver of the carbon allowances trading in the United States over the long-run. In the short-run, their results indicate that changes in the prices of crude oil, coal and natural gas significantly affect the trading of carbon allowances. In contrast to Kim and Koo (2010), we use the nonlinear ARDL model and also include, in addition to the prices of coal, crude oil and natural gas, the price of electricity which is generated by a mix of fuels and can cause major energy substitution in response to regulatory policy changes. We also attempt to quantify the asymmetric pass-through of energy prices (negative versus positive changes) to the carbon allowance prices.

Relying on monthly data for the period 2006-2011 where the end period is dictated by the availability of the coal price series, we find evidence that the crude oil prices have a long-run asymmetric effect on the carbon prices. This effect is negative and consistent with the fall in oil demand over time, which makes the build-up of carbon inventory less warranted. In the case of the coal prices, we also uncover a negative and asymmetric relationship of these prices with the carbon prices in the short-run, but the linkage is stronger when the coal prices fall which leads to more pollution.

As for natural gas and electricity, our findings do not reveal the presence of asymmetry in the relationship between the prices of each of those energy sources and the CO_2 allowance prices. However, although changes in the electricity price have a negative effect on the carbon prices over the short-run, they have a positive impact on the carbon prices, reflecting the presence of strong regulations, the lack of energy substitution and the inelastic demand in the electricity sector.

The rest of the article is organized as follows. Section 2 reviews the related literature. Section 3 introduces the empirical framework and describes the data. Section 4 reports the obtained results. Section 5 concludes the article.

2. Brief review of the literature

The literature on the dynamics of CO_2 allowance prices and volatility has grown rapidly over the last decade, following the concerns over the harmful effects of greenhouse gases and climate change. It particularly deals with price drivers, price volatility structure and price discovery in the spot and futures markets for the carbon emission allowances. Previous works have been mainly challenged by the existence of different price regimes when analysing the European Union (EU) emission allowances market and the potential of nonlinear dynamics of the CO_2 prices which are caused by frequent market imperfections, regulatory policy changes, heterogeneous investors and episodes of financial market instability.

The linear and nonlinear dynamic behavior of the CO_2 allowance prices has been analyzed by Daskalakis et al. (2005), Paolella and Taschini (2008), Seifert et al. (2008) and Chevallier (2010a), among others. These studies generally find evidence of jumps and regime-dependent volatility structure as well as evidence of spot-futures price relationships that facilitate the price discovery.[1] For instance, Daskalakis et al. (2005) examine the spot and futures prices obtained from the European Energy Exchange (EEX) in Germany and show that the spot prices of the CO_2 emission allowances exhibit a random walk volatility behavior which can be captured by a jump-diffusion model. Those authors also find that market participants adopt standard no-arbitrage pricing. Paolella and Taschini (2008) use a GARCH approach to examine the distribution and predictability of the prices of the SO_2 and CO_2 emission allowances in accordance with the U.S. Clean Air Act Amendment and the EU Emission Trading Scheme, respectively. They show that a parametric GARCH with a generalized asymmetric *t*-distribution works well for modeling the CO_2 allowance prices. Seifert et al. (2008) adopt a tractable stochastic equilibrium model to analyze the CO_2 spot price dynamics in the EU ETS market. They argue that the CO_2 prices do not follow any seasonal patterns and the CO_2 price process exhibits a time- and price-dependent volatility structure. Benz and Trück (2009) investigate the evolution of the EU allowances spot prices and show that the CO_2 price returns exhibit nonlinear dynamics which can be reproduced by Markov-switching models. The study by Chevalier (2010a) emphasizes that the CO_2 futures prices are relevant for the price discovery in the spot emission allowance market.

There is another strand of literature that focuses on the price drivers of the CO_2 emission allowance markets. Hintermann (2010) investigates the UE allow-

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[1] Taking a different perspective, Chevalier (2010b) models the risk premia in the CO2 allowance spot and futures prices under the EU ETS and finds evidence of positive time-varying risk premia, which are strictly higher for the post-2012 contracts than for the Phase II contracts.

ance price drivers around the price crash of April 2006 and highlights the role of fuel prices, summer temperature, and precipitation in governing the post-crash CO_2 allowance prices. Kim and Koo (2010) examine the potential factors affecting the U.S. carbon allowance market and show that the price of coal is the main driver of the carbon allowance prices over the long-run. Moreover, changes in the prices of crude oil, coal and natural gas significantly affect the trading of carbon allowances over the short-run. Wang et al. (2013) use an input–output structural decomposition to analyze the driving forces behind the CO_2 emissions in Beijing over the period 1997-2010. Their findings indicate that the CO_2 emission growth there is mainly driven by the production structure change and the population growth. However, this growth is partly offset by the CO_2 emission intensity reduction and the decline in per capita final demand volume during the study period.

Other studies have considered the linkages between the spot and futures carbon allowances markets, as well as the possible predictability involving these two markets. For example, Uhrig-Homburg and Wagner (2006) conduct an empirical examination of the relationship between the spot and futures prices in the EU ETS markets and find that the futures contracts lead the price discovery process of CO_2 emission allowances. Uhrig-Homburg and Wagner (2009) examine the joint dynamics of the EU spot and futures allowance prices during Phase I and find a long-run relationship between the observed futures prices and the theoretical futures prices which are obtained from a cost-of-carry model. This evidence is however not consistent with the finding of Milunovich and Joyeux (2010) who reject the existence of a long-run relationship between the EU allowance spot and futures prices. In a more recent study, Arouri et al. (2012) employ a Vector Auto-Regression (VAR) model and a Switching Transition Regression-Exponential

GARCH model to capture the asymmetry and nonlinearity effects in both the return and the volatility of the spot and futures prices of the EU emission allowances during Phase II. The authors find that the spot and futures returns of carbon prices are linked in an asymmetric and nonlinear fashion.

In an earlier study, Milunovich and Joyeux (2007) address the issues of market efficiency and price discovery in the EU allowance markets by applying Granger causality and linear cointegration tests. Their findings show that the spot and future allowance prices efficiently share information and jointly contribute to price discovery in view of the bilateral information transmission. While there is a long-run relationship between the futures and spot prices, the spot prices have no significant forecasting power for the futures prices. Rittler (2012) provides empirical evidence that corroborates the works of Milunovich and Joyeux (2010) and Chevalier (2010a) when daily data are used, but contrasts with them when intraday data are used. In a related study, Daskalakis et al. (2009) use technical analysis rules and naïve forecasts to examine the efficiency of the EU emission allowance market during Phase I. They show that the behavior of the three predominant EU allowance exchanges under the EU ETS (European Climate Exchange, Nord Pool and Powernext) is not consistent with the weak-form market efficiency. This inefficient behavior is explained by the immaturity of the EU ETS, as well as by the restrictions imposed on the banking and short-selling of the emission allowances.

Our study extends the previous works by examining the nonlinear and asymmetric pass-through of energy prices to the prices of CO_2 emission allowances from the U.S. perspective. The empirical analysis allows for capturing the asymmetric response of the carbon allowance prices to each of the energy prices over both the short- and long-run. We are also able to show the nonlinear adjustment of carbon and energy prices from their initial equilibrium to their new steady state. With the implementation of the Acid Rain Program of the U.S. Environmental Protection Agency (EPA) in the United States, the majority of the existing works has focused on the price behavior of the SO_2 tradable emission allowances to the detriment of the research on the CO2 allowance prices (Ellerman and Montero, 1998; Schennach, 2000; Böhringer and Lange, 2005; Schleich et al., 2006). This study will help to pick up some of what the literature has dropped.

3. Econometric methodology

3.1. The NARDL model

The recent Nonlinear Auto-Regressive Distributed Lag model (NARDL) proposed by Shin et al (2014) is used to examine the strength of the pass-through of coal prices, crude oil prices, electricity prices and natural gas prices into the CO_2 emission allowance prices over both the short- and long-run. This methodology presents important advantages over the existing modelling techniques (such as the Error Correction Model (ECM), the threshold ECM, the Markov-switching ECM and the Smooth Transition ECM) in modeling jointly the cointegration dynamics and asymmetries. Besides its estimation simplicity, the NARDL model provides greater flexibility in relaxing the assumptions that the time-series should be integrated of the same order, contrary to the ECM which is binding in this sense. It also allows one to accurately distinguish between the absence of cointegration, linear cointegration and nonlinear cointegration (Katrakilidis and Trachanas, 2012) and performs better in testing for cointegration in small samples (Romilly et al., 2001).

It is now commonly accepted that the short-run deviations of first-order integrated variables from their common long-run equilibrium can be reproduced by the linear ECM developed by Granger (1981), Engle and Granger (1987) and Johansen (1988). The linear ECM takes the following form:

$$\Delta CO2_t = \mu + \rho_{CO2} CO2_{t-1} + \rho_x Y_{t-1} + \sum_{i=1}^{p-1} \alpha_i \Delta CO2_{t-i} + \sum_{i=0}^{q-1} \beta_i \Delta Y_{t-1} + \varepsilon_t \tag{1}$$

where $CO2_t$ refers to the CO$_2$ emission allowance prices in logarithm and Y_t represents one of the energy prices in logarithm (i.e. coal prices, crude oil prices, electricity prices and natural gas prices) that we consider. The symbol Δ denotes first-differences. The model in Eq. (1) allows for investigating the short- and long-run links between the variables when these relationships are linear and symmetric. However, the model will be misspecified when they are nonlinear and/or asymmetric.

In this context, Granger and Yoon (2002) introduce the concept of hidden cointegration, which is detected if two time-series are not cointegrated in the conventional sense, but their positive and negative sums are cointegrated with each other. The NARDL model of Shin et al. (2014) allows one to jointly examine the short- and long-run response of the CO$_2$ emissions prices to each of the prices of coal, crude oil, electricity and natural gas and detects hidden cointegration. This methodology employs the decomposition of the exogenous variable Y into its positive and negative partial sums, i.e., Y_t^+ and Y_t^-, of increases and decreases such as

$$Y_t^+ = \sum_{j=1}^{t} \Delta Y_j^+ = \sum_{j=1}^{t} \max\left(\Delta Y_j, 0\right) \text{ and } Y_t^- = \sum_{j=1}^{t} \Delta Y_j^- = \sum_{j=1}^{t} \min\left(\Delta Y_j, 0\right) \tag{2}$$

Accounting for the short- and long-run asymmetries in the linear ECM model as presented in Eq. (1), Shin et al. (2014) extend this model to the general NARDL model which is expressed as follows:

$$\Delta CO2_t = \mu + \rho\, CO2_{t-1} + \theta^{+} Y_{t-1}^{+} + \theta^{-} Y_{t-1}^{-} + \sum_{i=1}^{p-1} \alpha_i \Delta CO2_{t-i} + \sum_{i=0}^{q-1} \left(\omega_i^{+} \Delta Y_{t-i}^{+} + \omega_i^{-} \Delta Y_{t-i}^{-} \right) + \varepsilon_t \qquad (3)$$

The superscripts (+) and (–) in Eq. (3) stand for the positive and negative partial sums decomposition as defined above. The symbols *p* and *q* denote the respective lag orders for the dependent variable and the exogenous variable in the distributed lag part, respectively. In particular, the long-run symmetry can be tested by using a Wald test of the null hypothesis that $\theta^{+} = \theta^{-}$ in Eq. (3). We can then compute the positive and negative long-run coefficients as follows: $L_{Y^{+}} = -\theta^{+}/\rho_{CO2}$ and $L_{Y^{-}} = -\theta^{-}/\rho_{CO2}$. The short-run adjustments to the positive and negative shocks affecting the prices of coal, crude oil, electricity and natural gas are captured by the parameters ω_i^{+} and ω_i^{-}, respectively. The short-run symmetry can equally be tested by using a standard Wald test of the null hypothesis that $\omega_i^{+} = \omega_i^{-}$ for all $i = 0, \ldots, q-1$.

Eq. (3) is reduced to the traditional (linear) ECM if both null hypotheses of short-run and long-run symmetry cannot be rejected. The non-rejection of either the long-run symmetry or the short-run symmetry will yield the cointegrating NARDL model with short-run asymmetry (Eq. (4)) and with long-run asymmetry (Eq. (5)), respectively:

$$\Delta CO2_t = \mu + \rho_{CO2} CO2_{t-1} + \rho_Y Y_{t-1} + \sum_{i=1}^{p-1} \alpha_i \Delta CO2_{t-i} + \sum_{i=0}^{q-1} \left(\omega_i^{+} \Delta Y_{t-i}^{+} + \omega_i^{-} \Delta Y_{t-i}^{-} \right) + \varepsilon_t \qquad (4)$$

$$\Delta CO2_t = \mu + \rho_{CO2} CO2_{t-1} + \rho_Y^{+} Y_{t-1}^{+} + \rho_Y^{-} Y_{t-1}^{-} + \sum_{i=1}^{p-1} \alpha_i \Delta CO2_{t-i} + \sum_{i=0}^{q-1} \omega_i \Delta Y_{t-i} + \varepsilon_t \qquad (5)$$

When asymmetry is detected in the NARDL model (either in the short-run or in the long-run or in both), the asymmetric responses to positive and negative one-unit shocks (i.e., increases or decreases) in the energy prices are respectively captured by the positive and negative dynamic multipliers associated with unit changes in Y^{+} and Y^{-} as follows:

$$m_h^{+} = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial Y_t^{+}} \text{ and } m_h^{-} = \sum_{j=0}^{h} \frac{\partial CO2_{t+j}}{\partial Y_t^{-}} \text{ with } h = 0,1,2,\ldots \qquad (6)$$

when $h \to \infty$, $m_h^{+} \to L_{Y^+}$, and $m_h^{-} \to L_{Y^-}$, where L_{Y^+} and L_{Y^-} are the positive and the negative asymmetric long-run coefficients, respectively. Based on the estimated multipliers, we can observe the nonlinear dynamic adjustments of the two variables (CO_2 emission allowance prices and either one of the prices of coal, crude oil, electricity and natural gas) from their initial equilibrium to their new steady state over time, following a shock affecting the cointegrating system.

Overall, the NARDL model accounts for the short-run dynamics through the distributed lag part and the long-run dynamics via a single common cointegrating vector. Both parts are allowed to be asymmetric. Further, the NARDL model allows for combinations of I(1) and I(0) variables by making use of a bounds testing procedure for the presence of the equilibrium vector. This means that we are not constrained by the normal requirement of cointegrating models that all variables must be I(1).

4. Data and empirical results

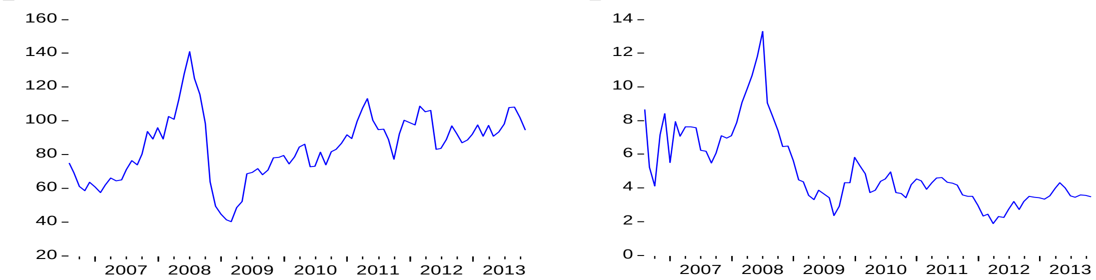
4.1 Data

We examine the asymmetric pass-through of the four energy prices to the CO2 allowance prices from the U.S. perspective. Our data include daily time-series of the prices of the CO_2 emission allowances, coal, crude oil, electricity and natural gas. The data are sourced from Datastream and cover the period from July 17, 2006 to November 19, 2013. The length of this sample period is dictated by the availability of the coal price series. Thus, this sample enables to investigate the price interactions between the prices of energy and the price of the CO_2 emission allowances under changing market conditions. Accordingly, we are able to compare our results with those of several previous studies.

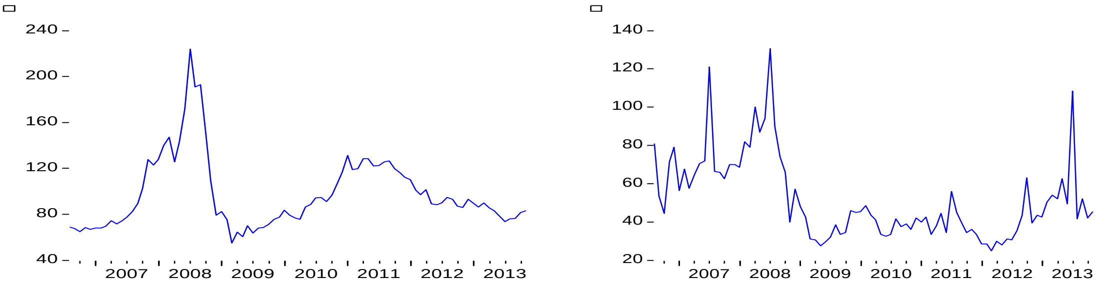
The CO_2 emission allowance price corresponds to the spot price of the European Union CO2 emission allowances (EEXEUAS) accessed from the European Energy Exchange (EEX). These prices which are expressed in euros are converted into US dollars by using the WM/Reuters closing spot rates of the U.S. dollar to euro exchange rate. The crude oil price is the spot price of the benchmark West Texas Intermediate and is expressed in U.S. dollars per barrel (CRUDOIL). The natural gas price corresponds to the Henry Hub natural gas spot price which is also expressed in U.S. dollars per million British thermal units (NATGHEN). The coal price is the Coal Intercontinental Exchange API2 cost, insurance and freight Amsterdam, Rotterdam and Antwerp NR coal price and is expressed in U.S. dollars per metric ton (LMCYSPT). The electricity price corresponds to the South Path 15 Firm Peak electricity price which is expressed in U.S. dollars per megawatt hour (WSSPDPF).

Figure 1 displays the time-variation of the energy and carbon prices. This figure shows that the energy prices behave in a similar way over the study period, with price peaks occurring in the middle of 2008 which preceded the onset of the global financial crisis. While the prices of crude oil and coal have started to recover from their lowest levels since mid-2009, the price of electricity had remained low until mid-2013. As to the natural gas price, it fluctuated around its lowest level recorded at the end of August 2009. The dynamics of the carbon emission allowance price follow the different subperiods of the European Union Emission Trading Scheme (EU ETS) which started in 2005 in order to help the EU meet its targets under the Kyoto Protocol, i.e., 8% reduction in greenhouse gas emissions from the 1990 levels.

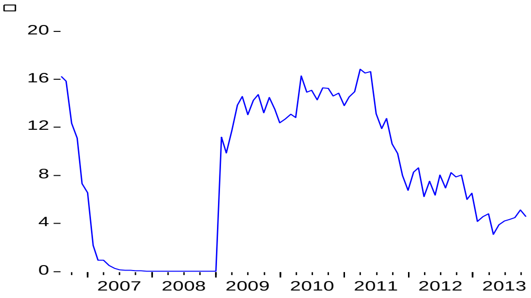
Figure 1. Dynamics of energy and carbon allowance prices, 2006-2013.



Crude oil Natural Gas



Coal Electricity



CO2

In Phase I from January 2005 to December 2007, the EU ETS included about 12,000 installations, which represent close to 40% of the EU CO2 emissions. These installations covered energy activities (combustion installations, coke ovens and mineral oil refineries), mineral industry (cement clinker, ceramic bricks and glass), production and processing of ferrous metals, and pulp, paper and board activities. In 2007, the carbon prices dropped to close to zero because the aggregate emissions were far below the number of allowances issued, thus, weakening the incentive to reduce emissions. The fall in prices was caused by an excessive number of

EU allowances issued due to lobbying by firms and the consequent reduction in carbon emissions that took place in 2005-2006.

Phase II, which ranges from January 2008 to December 2012, expanded the scope of the EU ETS as a result of three non-EU members (Iceland, Liechtenstein and Norway) joining it. Moreover, the "Linking Directive" introduced the Clean Development Mechanism (CDM) which produces Certified Emission Reductions (CERs), each of each representing the successful emissions reduction equivalent to one tonne of CO_2 equivalent. Similarly, the Directive introduced the Joint Implementation (JI) projects which produce Emission Reduction Units (ERUs), each representing the successful emissions reduction equivalent to one tonne of CO_2 equivalent. Despite the importance of the inclusion of aviation emissions, the adverse reaction of the airline industry and countries like China, India, Russia and the U.S. led the EU to go ahead with its own scheme while including an exemption clause for countries with "equivalent measures".

During Phase II, the CO_2 emission allowances were reduced by 3% and at least 80 million tons of "carbon offsets" were bought. On April 27, 2012, the EU Emissions Trading System single registry was fully activated, including the migration of over 30,000 EU ETS accounts. In the first half of 2009, the carbon price fell to €13/tCO2 due to the recession, the downward revision in expectations about future fossil fuel prices and the disappointing outcome of the Copenhagen climate summit. Too low incentives for firms to reduce emissions and over-supply of permits continued to negatively impact prices. Thus, in June 2012, the EU allowances for delivery in December 2012 traded at €6.76, a 61 percent year-on-year decline.

Finally, in Phase III which dates January 2013 to December 2020, additional constraints were included on the use of the offsets, limiting the banking of allowances between Phases II and III. It consists in a move from allowances to auctioning and the implementation of an overall cap where allowances can be allocated to EU members.

Table 1 reports the descriptive statistics and statistical properties of the energy and carbon allowance prices under consideration. It can be seen that the prices of crude oil, coal and electricity exhibit the highest variability over the period, as indicated by their respective standard deviations, while those of the natural gas prices and the carbon allowances are the least volatile. All the series display excess kurtosis and are positively skewed, with the exception of the carbon price which is negatively skewed. The Jarque-Bera test for normality shows that all the series depart from the normal distributions, except the crude oil price.

Table 1. Stochastic properties of energy and carbon allowance prices at monthly frequency.

	Crude Oil	Natural Gas	Coal	Electricity	CO$_2$
Mean	84.728	5.042	97.642	51.812	7.826
Maximum	141.060	13.280	224.000	130.500	16.830
Minimum	40.070	1.880	54.900	25.000	0.020
Std. dev.	19.428	2.260	31.349	21.644	5.865
Skewness	0.004	1.299	1.557	1.385	-0.058
Kurtosis	3.120	4.543	5.942	4.893	1.534
JB	0.060	33.469^{++}	67.307^{++}	41.290^{++}	7.933^{+}
PP	-2.569^{b}	-3.006^{a}	-2.357^{b}	$-4.532^{a,\,++}$	-1.644^{c}
ZA	-4.545	-4.865	-3.357	-5.251^{+}	-4.301

Notes: JB denotes the empirical statistics of the Jarque-Bera test for normality. PP is the Phillips–Perron unit root test. ZA is the empirical statistic of the Zivot and Andrews (1992) unit root test which is robust to structural breaks. $^{+}$, and $^{++}$ indicate rejection of the null hypotheses of normality and unit root at the 5%, and 1% levels, respectively. (a) stands for models with trend & intercept, (b) for models with intercept, and (c) for models without trend nor intercept.

We also perform the Phillips–Perron unit root test (PP) and the Zivot and Andrews (1992) unit root test (ZA) which takes a potential structural break into account. The obtained results indicate that all the price series are I(1) at the 5% level, except the electricity price which is stationary in levels. As noted earlier, this evidence does not generate statistical biases when the NARDL is used.

4.2 Specification testing

Our empirical analysis involves the selection of the best fitting NARDL specifications. To do so, we estimate the symmetric and asymmetric pass-through of energy prices to CO2 prices using Eqs. (1) and (3), and perform the Wald test for detecting the short- and long-run symmetry.[2] Table 2 reports the results of the Wald test.

Table 2. Results of the short- and long-run symmetry tests.

	Long-run W_{LR}	Short-run W_{SR}	Conclusion
WTI - CO_2	38.300^{++} [0.000]	3.127 [0.081]	NARDL with LR asymmetry
Natural gas - CO_2	0.557 [0.458]	1.752 [0.190]	Symmetric ARDL
Coal - CO_2	0.185 [0.669]	20.750^{++} [0.000]	NARDL with SR asymmetry
Electricity - CO_2	0.302 [0.584]	0.761 [0.386]	Symmetric ARDL

Notes: The estimation is based on Eqs. (1) and (3). The table reports the results of the short- and long-run symmetry tests for pairs of the CO_2 price and one energy price. W_{SR} denotes the Wald test for short-run symmetry, which tests the null hypothesis that $\omega_i^+ = \omega_i^-$ in Eq. (3). W_{LR} corresponds to the Wald test for long-run symmetry, which tests the null hypothesis that $\theta^+ = \theta^-$ in Eq. (3). The associated p-values are in brackets. $^+$ and $^{++}$ indicate rejection of the null hypotheses of short- and long-run symmetry at the 5% and 1% levels, respectively.

As to the pair of the Crude oil–CO_2 prices, we can see that the null hypothesis of long-run symmetry is clearly rejected at the 1% level, while the null of short-run symmetry is only rejected at the 10% level. Crude oil is not used in electricity generation but is used heavily in transportation, which makes it different from the other primary fuels. Declines in oil prices during recessions limit the reduction in oil consumption because the income effect dominates the substitution effect which is small because of the high inelasticity of demand for oil. This in turn restricts the decline in the carbon allowance prices. On the other hand, increases in oil prices during booms coupled with more elastic demand would have stronger impacts on

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[2] The optimal number of lags for the two models in Eqs. (1) and (3) is selected on the basis of the SIC information criterion.

the carbon prices. Methodologically, the finding for this pair suggests that an NARDL allowing for long-run asymmetry is best-suited for reproducing the dynamic interactions between the crude oil and carbon emission prices. This conclusion is also supported by the commonly-used information criteria (AIC and BIC).

In the case of the coal–CO_2 pair, the tests only reject the short-run symmetry, highlighting the suitability of using the NARDL in the presence of short-run asymmetry and long-run symmetry. This result is interesting as the “fuel of choice” is being affected by natural gas and renewables over time and its demand share a downward trend with the carbon prices over time.

For the two remaining pairs (natural gas–CO_2 and electricity gas–CO_2), a standard symmetric ARDL is selected as both the short- and long-run symmetry hypotheses cannot be rejected at conventional significance levels. Natural gas is considered cheap and is getting more abundant, while electricity is regulated and relies on fuel substitution. These characteristics seem to produce symmetry as the prices of these energy sources and carbon prices share a common path.

Overall, our findings show that the pass-through mechanisms are not alike across the pairs of the energy and carbon prices we consider, and that imposing the linear symmetric pass-through models to characterise their relationship leads to misspecification in two out of four cases. When reviewing the existing empirical literature on price asymmetries in commodities from 38 studies in terms of econometric models, type of asymmetries and empirical findings, Frey and Manera (2007) find that half of the past studies report evidence of asymmetry, five of them document symmetry and the remaining studies report mixed results. More specifically, the authors highlight that price asymmetries are typically found in energy markets (such as oil and petroleum products) and reflect either a monopolistic behaviour (Brown and Yucel, 2000) or market shocks, i.e. events or rumours that significantly change the actual or expected supply or demand (General Accounting Office, 2003). These sources of energy asymmetry seem to lead to asymmetry with the carbon prices in certain cases.

4.3 Pass-through of energy prices to CO_2 emissions prices

Table 3 provides a summary of the estimation results of the best-fitting NARDL specifications for the four pairs of the energy and carbon allowance prices. We find evidence of significant short-run and long-run dynamics for all four models. The Breusch-Godfrey Lagrange Multiplier test for serial correlation and the ARCH test for conditional heteroscedasticity, applied to the estimated residuals, indicate that our models are correctly specified for all pairs, except for the crude oil–CO_2 where residuals exhibit significant autocorrelation at the 5% level.

The results for the crude oil-CO_2 pair show that there is evidence of long-run asymmetric effects of the crude oil prices on the carbon emission prices. The asymmetric long-run coefficients (L_{wti^+} and L_{wti^-}) are negative and statistically significant at the 1% level, suggesting that oil price increases and decreases reduce the price of carbon allowances in the long-run. This is in line with the observation of a somewhat downward trend in the carbon allowance prices over the period under study as a consequence of the decline in the oil and energy demand, which reduces the need for carbon inventory build-ups. Similarly, it is close in spirit with the work of Balabanoff (1993), who shows that although the symmetry tests are never rejected when it comes to the total cumulative effect of crude oil prices on retail prices, the persistence of crude price variations is notably asymmetric. Our findings are also in accordance with Hammoudeh et al. (2013) who use a VECM model and uncover a negative relationship between the price of crude oil and the price of CO_2 allowance emissions over the long-run.

As to the natural gas-CO_2 pair, the symmetric ARDL is the best-suited model to identify the pass-through effects of natural gas prices to carbon prices. The long-run coefficient (L_{NatGas}) specifying the equilibrium relationship between the natural gas and carbon allowance prices is also negative and significant at the 1% level. This evidence is consistent with the negative effect of natural gas prices on the carbon emission prices over the long-run. More specifically, an increase in the price of natural gas lowers its consumption and, thus, reduces the price of the CO_2 emission allowance. The same result is found in the short-run.

The NARDL with short-run asymmetry is selected for the coal-CO_2 pair. We find evidence of a negative and marginal impact (significant at the 10% level) of coal prices on the carbon allowance prices. The coal prices also impact asymmetrically the carbon prices in the short-run ($\Delta Coal_t^+$ versus $\Delta Coal_t^-$), particularly for the lags from 1 to 4. However, the effects are much more pronounced when the coal price falls. Kim and Koo (2010) also find evidence of a negative long-run equilibrium between the coal and CO_2 allowance prices in the United States. Moreover, short-term changes in the price of coal significantly affect the trading of carbon allowances. However, the empirical framework used by the authors is not able to detect the asymmetric (negative versus positive) short-term effects of the coal prices on the CO_2 allowance prices.

Table 3. Pass-through of energy prices to carbon emission prices.

Crude oil – CO$_2$		Natural gas – CO$_2$		Coal – CO$_2$		Electricity – CO$_2$	
NARDL with LR asymmetry		Symmetric ARDL		NARDL with SR asymmetry		Symmetric ARDL	
$CO2_{t-1}$	-0.234** (0.050)	$CO2_{t-1}$	-0.135** (0.048)	$CO2_{t-1}$	0.112* (0.048)	$CO2_{t-1}$	-0.216** (0.062)
wti^{+}_{t-1}	-1.665** (0.427)	$NatGas_{t-1}$	-0.740* (0.295)	$Coal_{t-1}$	0.673* (0.270)	$Elect_{t-1}$	-1.519** (0.465)
wti^{-}_{t-1}	-2.294** (0.515)	$\Delta CO2_{t-1}$	0.027 (0.107)	$\Delta CO2_{t-1}$	-0.568** (0.121)	$\Delta CO2_{t-1}$	0.026 (0.111)
$\Delta CO2_{t-1}$	-0.093 (0.106)	$\Delta NatGas_{t}$	-0.909^{v} (0.480)	$\Delta CO2_{t-2}$	-0.212^{v} (0.123)	$\Delta Elect_{t}$	-0.863* (0.386)
$\Delta CO2_{t-2}$	-0.093 (0.106)	$\Delta NatGas_{t-1}$	-0.162 (0.467)	$\Delta CO2_{t-3}$	-0.088 (0.099)	$\Delta Elect_{t-1}$	0.699 (0.493)
$\Delta CO2_{t-3}$	-0.013 (0.107)	Constant	-0.371* (0.175)	$\Delta CO2_{t-4}$	-0.295** (0.099)	$\Delta Elect_{t-2}$	1.016* (0.483)
$\Delta CO2_{t-4}$	0.032 (0.104)			$\Delta CO2_{t-5}$	-0.337** (0.101)	$\Delta Elect_{t-3}$	-0.059 (0.471)
$\Delta CO2_{t-5}$	0.004 (0.107)			$\Delta Coal^{+}_{t}$	0.737 (1.363)	$\Delta Elect_{t-4}$	0.011 (0.420)
Δwti_{t}	-0.707 (0.848)			$\Delta Coal^{-}_{t}$	0.977 (1.255)	Constant	-0.644** (0.219)
Δwti_{t-1}	1.280 (0.927)			$\Delta Coal^{+}_{t-1}$	-2.147 (1.391)		
Constant	-0.815** (0.222)			$\Delta Coal^{-}_{t-1}$	3.344** (1.187)		
				$\Delta Coal^{+}_{t-2}$	1.054 (1.338)		
				$\Delta Coal^{-}_{t-2}$	-4.720** (1.262)		
				$\Delta Coal^{+}_{t-3}$	1.343 (1.366)		
				$\Delta Coal^{-}_{t-3}$	-6.978** (1.359)		
				$\Delta Coal^{+}_{t-4}$	2.937* (1.278)		
				$\Delta Coal^{-}_{t-4}$	-9.163** (1.646)		
				Constant	-1.073** (0.242)		
$L_{wti^{+}}$	-7.108**	L_{NatGas}	-5.466***	L_{Coal}	-6.016^{v}	L_{Elect}	-7.042**
$L_{wti^{-}}$	-9.794**						
AIC	178.3603	AIC	191.6395	AIC	130.9125	AIC	182.9826
SIC	204.8342	SIC	206.3656	SIC	174.2334	SIC	204.7521
B-G (12)	2.514^{+}	B-G (12)	0.356	B-G (12)	1.001	B-G (12)	0.445
ARCH	5.575	ARCH	1.991	ARCH	2.930	ARCH	2.448

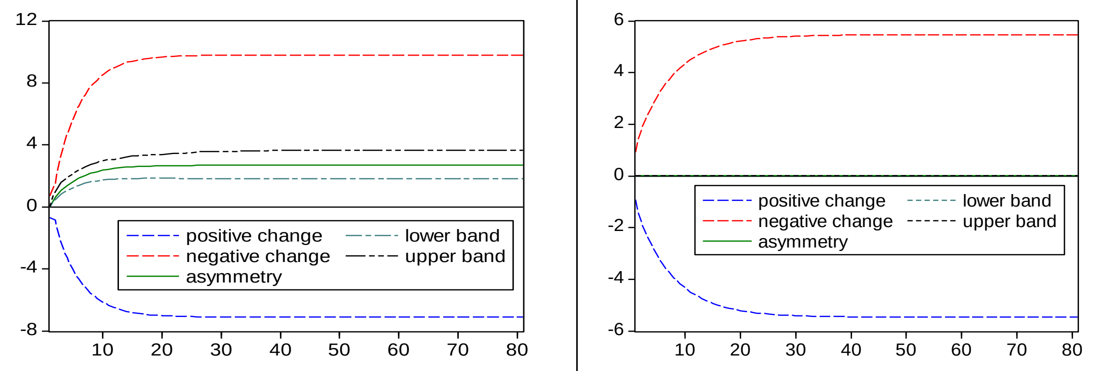
Notes: The table reports the estimation results of the best-suited NARDL specifications for pairs of energy and carbon emission prices. $L_Y = -\rho_Y/\rho_{CO2}$ indicates the long-run effect of a specific energy price (Y) on CO$_2$ prices. $L_{Y^+} = -\theta^+/\rho_{CO2}$ and $L_{Y^-} = -\theta^-/\rho_{CO2}$ are the asymmetric long-run coefficients. Standard deviations are in parenthesis. B-G (12), and ARCH(12) refer to the empirical statistics of the Breusch-Godfrey LM test for serial correlation, and the Engle (1982) test for conditional heteroscedasticity, both applied to residuals with 12 lags. * and ** denote significance at the 5% and 1% levels, respectively. ^{v} indicates significance at the 10% level. $^+$ indicates rejection of the null hypotheses of autocorrelation and no remaining ARCH effects at the 5% level.

Similar to the case of the natural gas-carbon prices pair, the symmetric ARDL model is also selected for reproducing the interactions between the electricity and carbon prices. The evidence suggests that increases in the price of electricity reduce the carbon prices in the long-run, as the estimated coefficient (L_{Elect}) is negative and significant at the 1% level. There is also some empirical support to the idea that carbon prices increase following a rise in the electricity price in the short-run. This positive, short-run relationship between the electricity prices and the carbon prices reflects the strong regulations on electricity prices and the inelastic demand for electricity (Green, 1999; Ciarreta and Espinosa, 2012), which makes the degree of substitution between electricity and other sources of energy to be low in the short-run.

4.4 Asymmetric adjustment paths

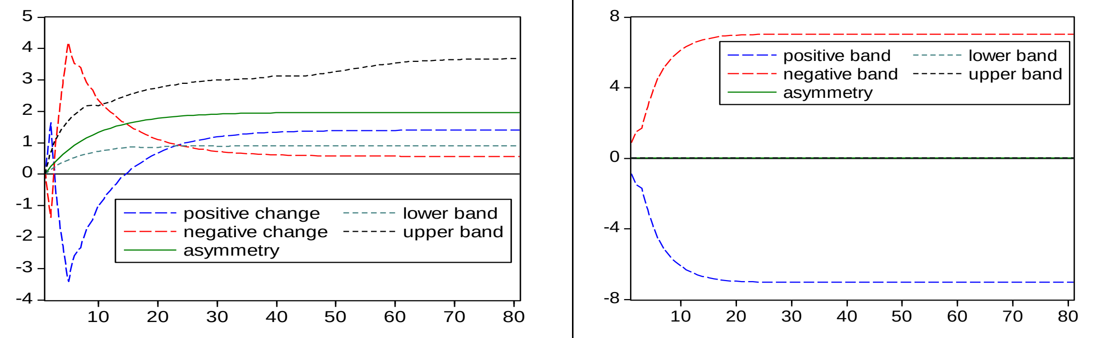
We now turn to the dynamic multipliers showing the patterns of dynamic asymmetric adjustments of the carbon allowance price from its initial equilibrium to the new steady state in the long-run, following a unit shock (negative or positive) affecting a specific energy price. The predicted dynamic multipliers for the nonlinear adjustment of the CO_2 prices to the shock in the price of crude oil, coal, natural gas and electricity are displayed in Figure 2. These multipliers are estimated based on the four best-fitting NARDL specifications that we report in Table 3. The positive (blue dotted line) and negative (red dotted line) change curves show the asymmetric adjustment to positive and negative shocks at a given forecast horizon, respectively. The asymmetry curve (green line), which is the linear combination of the dynamic multipliers associated with positive and negative shocks, is plotted together with its lower and upper bands at the 95% confidence interval.

Figure 2. Cumulative asymmetric adjustments of CO$_2$ prices to energy prices.



Crude oil – CO$_2$ (NARDL with LR asymmetry)

Natural gas - CO$_2$ (Symmetric ARDL)



Coal - CO$_2$ (NARDL with SR asymmetry)

Electricity - CO$_2$ (Symmetric ARDL)

The computed dynamic multipliers confirm the existence of three different pass-through mechanisms from energy prices to carbon allowance prices. First, the adjustment dynamics is linear for the cases of the natural gas–CO$_2$ price pair and the electricity–CO$_2$ price pair. It is also very similar in terms of adjustment patterns and magnitude. We can also see that that the CO$_2$ price adjustments are relatively quick and strong over the first 20 months after the occurrence of the shock; then, they stabilize until the end of the forecast period.

Second, the dynamic multiplier computed from the best-suited model for the crude oil-CO$_2$ price pair provides evidence of a strong nonlinear adjustment of the carbon allowance price to changes in the price of crude oil. However, this asymmetric crude oil pass-through is the strongest among the various energy price transmission effects and is dominated by the effects of negative oil price changes and. It takes about 18 months to converge to the long-run multipliers.

Third, as to the coal-CO_2 price pair, the adjustment pattern is relatively more complex, albeit asymmetric and dominated by the effect of negative changes in the price of coal. Indeed, while the cumulative price responses are positive and significant, the impact of the positive changes in the price of coal causes a positive reaction of the carbon price up to 2 months after the shock strikes. This reaction is then followed by a negative response between months 3 and 12 after the shock, and finally by a positive reaction from the 13th month onwards. The inversed pattern is observed for the impact of the negative changes in the price of coal. The new equilibrium state is reached about 33 months since the occurrence of coal price shock.

4.5 Robustness check

To examine the robustness of our previous results, we also estimate the symmetric and asymmetric NARDL models for our four pairs of energy and carbon allowance prices by using price data at the daily frequency.

Table 4 reports the results of the Wald test on the short- and long-run symmetry for the best-suited model of each pair. Moreover, Table 5 presents the estimated results of the corresponding best-suited NARDL models. The results of the Breusch-Godfrey LM and Engle (1982) tests indicate that all the models using daily data are correctly specified as there is no evidence of serial correlation and remaining ARCH effects. These results generally highlight the robustness of the monthly estimates.

Table 4. Results of the short- and long-run symmetry tests (daily data).

	Long-run W_{LR}	Short-run W_{SR}	Conclusion
Crude oil - CO_2	5.013^{+} [0.025]	0.266 [0.606]	NARDL with LR asymmetry
Natural gas - CO_2	0.575 [0.449]	0.038 [0.846]	Symmetric ARDL
Coal - CO_2	3.447 [0.064]	0.109 [0.742]	Symmetric ARDL
Electricity - CO_2	0.024 [0.876]	0.182 [0.670]	Symmetric ARDL

Notes: The estimation is based on Eqs. (1) and (3). This table reports the results of the short- and long-run symmetry tests for the pairs of the CO_2 price and one energy price. W_{SR} denotes the Wald test for short-run symmetry, which tests the null hypothesis that $\omega_i^+ = \omega_i^-$ in Eq. (3). W_{LR} corresponds to the Wald test for the long-run symmetry, which tests the null hypothesis that $\theta^+ = \theta^-$in Eq. (3). The associated p-values are given in brackets. $^{+}$ and $^{++}$ indicate the rejection of the null hypotheses of short- and long-run symmetry at the 5% and 1% levels, respectively.

Table 5. Pass-through of energy prices to carbon emission prices (daily data).

Crude oil - CO_2		Natural gas - CO_2		Coal - CO_2		Electricity - CO_2	
NARDL with LR asymmetry		Symmetric ARDL		NARDL with SR asymmetry		Symmetric ARDL	
$CO2_{t-1}$	-0.004** (0.001)	$CO2_{t-1}$	-0.004* (0.002)	$CO2_{t-1}$	-0.003** (0.001)	$CO2_{t-1}$	-0.005* (0.002)
wti_{t-1}^{+}	-0.0011* (0.0005)	$NatGas_{t-1}$	-0.008 (0.005)	$Coal_{t-1}$	-0.0001 (0.0003)	$Elect_{t-1}$	-0.0014* (0.006)
wti_{t-1}^{-}	-0.0012** (0.0005)	$\Delta CO2_{t-1}$	-0.002 (0.023)	$\Delta CO2_{t-1}$	-0.002 (0.023)	$\Delta CO2_{t-1}$	-0.0017 (0.023)
$\Delta CO2_{t-1}$	-0.001 (0.023)	$\Delta CO2_{t-2}$	-0.045^{v} (0.023)	$\Delta CO2_{t-2}$	-0.044^{v} (0.023)	$\Delta CO2_{t-2}$	-0.045^{v} (0.023)
$\Delta CO2_{t-2}$	-0.048* (0.0.23)	$\Delta CO2_{t-3}$	0.014 (0.023)	$\Delta CO2_{t-3}$	0.013 (0.023)	$\Delta CO2_{t-3}$	0.013 (0.023)
$\Delta CO2_{t-3}$	0.010 (0.0.23)	$\Delta CO2_{t-4}$	0.045^{v} (0.023)	$\Delta CO2_{t-4}$	0.045^{v} (0.023)	$\Delta CO2_{t-4}$	0.045^{v} (0.023)
$\Delta CO2_{t-4}$	0.044^{v} (0.023)	$\Delta NatGas_t$	-0.020^{v} (0.044)	$\Delta Coal_t$	0.004 (0.004)	$\Delta Elect_t$	-0.001 (0.001)
$\Delta CO2_{t-5}$	-0.004 (0.023)	$\Delta NatGas_{t-1}$	-0.009 (0.044)	$\Delta Coal_{t-1}$	-0.001 (0.004)	$\Delta Elect_{t-1}$	0.001 (0.001)
Δwti_t	0.018** (0.004)	$\Delta NatGas_{t-2}$	-0.049* (0.044)	Constant	0.019 (0.018)	Constant	-0.007 (0.016)
Δwti_{t-1}	-0.004 (0.005)	Constant	-0.002 (0.017)				
Constant	-0.002 (0.018)						
$L_{wti^{+}}$	-0.247*	L_{NatGas}	-1.873^{v}	L_{Coal}	-0.056	L_{Elect}	-0.258
$L_{wti^{-}}$	-0.260*						
AIC	1612.880	AIC	1628.814	AIC	1633.023	AIC	1627.763
SIC	1673.925	SIC	1684.315	SIC	1682.974	SIC	1677.614
B-G(12)	0.977	B-G(12)	1.918	B-G(12)	1.033	B-G(12)	1.019
ARCH	9.127	ARCH	8.574	ARCH	11.578	ARCH	7.963

Notes: This table reports the detailed estimation results of the best-suited NARDL specifications for pairs of energy and carbon emission prices. $L_Y = -\rho_Y/\rho_{CO2}$ indicates the long-run effect of a specific energy price (Y) on CO_2 prices. $L_{Y^+} = -\theta^+/\rho_{CO2}$ and $L_{Y^-} = -\theta^-/\rho_{CO2}$ are the asymmetric long-run coefficients. Standard deviations are in parenthesis. B-G (12), and ARCH(12) refer to the empirical statistics of the Breusch-Godfrey LM test for serial correlation, and the Engle (1982) test for conditional heteroscedasticity, both applied to the residuals with 12 lags. * and ** denote significance at the 5%, and 1% levels respectively. ^{v} indicates significance at the 10% level. $^{+}$ indicates the rejection of the null hypotheses of autocorrelation and no remaining ARCH effects at the 5% level.

Globally, the results for daily data are similar to those presented in Tables 2 and 3. Two notable differences can be observed. First, the pair of the coal and carbon prices is now best described by a symmetric ARDL instead of the NARDL with short-run asymmetry for the monthly data. As a result, three out of the four models are linear when the daily data are used. Second, the price interactions are much less intensive and significant than those we observe for the monthly data. These results are not surprising given that the impacts of energy prices on carbon allowance prices are generally not immediate. The reason is that industries and corporations take time to adjust their production levels in response to changes in energy prices, as well as their CO_2 emission quotas. Thus, the models estimated with the monthly data are more relevant for both investment and policy purposes in the carbon emission markets.

5. Conclusion

The market dynamics of the CO_2 emission allowance prices have important environmental policy implications, but have also gained a renewed relevance for the financial sector in recent years. In this article, we assess the relationship between the carbon prices and four energy prices in the U.S. through the lenses of a nonlinear autoregressive distributed lags (NARDL) model. By doing so, we are able to capture the asymmetric responses of the CO_2 allowance prices to negative and positive changes in the energy prices and both over the short- and the long-run.

Using monthly data for the period 2006-2011, we find that the crude oil prices have long-run asymmetric effects on the carbon emission prices. This impact is negative in line with the trend decline in the oil and energy demand in the United States, which makes the carbon inventory build-ups less stringent.

As for the natural gas prices, the empirical evidence suggests that although an increase in the prices lowers both the consumption of natural gas in the short-run and in the long-run (thereby, leading to a fall in the prices of the CO_2 allowance emissions), this effect is rather consistent with a symmetric pass-through.

Regarding the responses of the carbon prices to the coal prices, we uncover a negative, asymmetric and significant relationship in the short-run, but the effects of changes in the coal prices are much more pronounced in the case of a fall than when the prices go up.

Finally, in the case of the electricity-carbon prices pair, our model corroborates the existence of a symmetric link, which is positive in the short-run. This emphasizes the lack of substitution between electricity and other sources of energy over such time window, as a result of strong regulations and inelastic demand in the electricity sector.

From a policy perspective, our findings highlight that energy price volatility has a significant impact on the CO_2 allowance prices. This effect takes place not only in the short-run, but also over the long-run. Moreover, it is typically asymmetric in the case of the crude oil and coal prices. This is naturally important, as carbon price volatility might, in turn, be an impediment to R&D investment in clean energy technologies and renewable energy sources.

Thus, policy measures aimed at reducing the volatility of CO_2 allowance emission prices and, thus, dampening the effects of changes in energy prices can prove fruitful along these lines. For instance, by imposing limits on firms' banking emissions allowances during periods when the allowance price is low, and borrowing allowances when the price is high, the costs of carbon emissions can be reduced in a substantial manner. Similarly, safety valves, where the government steps in to supply additional allowances to the market if the allowance price hits a ceiling or trigger level can help stabilize the price of carbon emissions. Additionally, price collars which restrain price swings by creating a price floor or a price ceiling and operate by providing additional allowances at a predetermined price can mitigate the negative carbon price volatility. Therefore, it provides a boost to the investment in renewable energies.

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