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Crucial relationship among energy
commodity prices

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CRUCIAL RELATIONSHIP AMONG ENERGY COMMODITY PRICES

CRISTINA BENCIVENGA AND GIULIA SARGENTI*

ABSTRACT. This study investigates the short and long run relationship between crude oil, natural gas and electricity prices in US and in European commodity markets. The relationship between energy commodities may have several implications for the pricing of derivative products and for risk management purposes. Using daily price data over the period 2001-2009 we perform a correlation analysis to study the short run relationship, while the long run relationship is analyzed using a cointegration framework. The results show an erratic relationship in the short run while in the long run an equilibrium may be identified having different features for the European and the US markets.

1. INTRODUCTION

During the last 10 years the energy sector has been widely modified by a slow deregulating process. Energy commodities in this context started to play a strategic role in the global economy.

One main aim of deregulation is to allow markets to respond to supply and demand conditions causing more competitive markets environments. This has been particularly true in the electricity and natural gas markets (Park et al. 2006, 2008) where prices are going to be determined by market participants more than by regulators.

A more competitive market for electricity implies that spot market prices may promptly respond to price changes in input fuel source markets. So oil and gas prices should end up being interrelated with electricity prices.

In a static framework economic theory suggests a relationship should exist between input and output prices (increasing the marginal cost of the inputs leads to an increase in the product price in a static supply and demand model. See Mjelde and Bessler, 2009).

A dynamic context and a more complex network including numerous locations and various inputs for power generation require a more accurate analysis of the possible relationship existing among the various energy commodities.

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The short run dynamics of the relationship between these commodities are crucial for the definition of risk measurement and management tools especially for the pricing of derivatives contracts, i.e., spread options. One of the most useful and important structure in the world of energy is represented by the spread¹. The joint behavior of commodity prices as well as gas, oil and electricity, is crucial for a proper valuation of spread contracts. This requires a real understanding of the nature of volatility and correlation in energy markets.

Economic theory suggests the existence of a relationship between natural gas and oil prices being competitive substitutes and complements in the electricity generation and in the industrial production. Historically a simple rule of thumb to relate natural gas prices to crude oil prices was used according to which a deterministic function was able to relate gas prices to oil prices². The deregulation caused gas prices to move in some more independent way and the recent oil price dynamic not exclusively linked to the supply and demand conditions, may cause this relationship to fail. At certain extents, oil prices may be expected to remain the main drivers of energy price dynamics through inter-fuel competition and price indexation clauses in some long-term gas contracts. At present, many exchanges and over the counter (OTC) markets offer a wide variety of energy derivatives issued on a large set of energy products providing economic benefits, such as a more efficient offsetting exposure among hedgers or transfer risk.

The aim of this work is to analyze the relationship existing between the main energy commodity prices in Europe and in the United States. Gas and electricity markets, unlike the oil market, are regional markets and the prices of these commodities heavily depend on the location where they are produced, shipped and distributed. An analysis of the relationship between energy prices has therefore to be developed on a regional basis. Given the various time horizons of hedging and investment strategies we investigate the relationship between gas, oil and electricity on a short term and long term basis. The short run relationship is analyzed studying the correlation among the various series. A long run relationship is analyzed using the cointegration approach in order to measure the common stochastic trends between the three commodities. A possible integration of these energy markets is also examined using an Error Correction Model (ECM) framework.

Using daily price data over the period 2001-2009 for natural gas at the National Balancing Point (NBP) UK and at the Henry Hub (HH), the Brent ICE and the West Texas Intermediate (WTI) for crude oil and European Energy Exchange (EEX) and Pennsylvania, New Jersey, Maryland Interconnection (PJM) for electricity, we examine the dynamics of the energy prices in the European and US markets. We try to measure

¹The intracommodity spread and the intercommodity spreads are by far the most important class of commodity derivatives. For an extensive description of energy spread options see Eydeland, 2003.

²See Geman, 2005.

a possible relationship between them to adequately set up risk management strategies. The analysis of the two markets is performed over the period 2001-2009 in order to get rid of possible influence of transition dynamics. For the European market we tried to choose as a starting date a period where market data could be considered reliable given the liquidity of the exchanges and, for the case of gas prices, taking into account the introduction of the link between the UK and European market which occurred in 1998 with the introduction of the Interconnector UK NBP. For the US market the choice of the data set refers mainly to the electricity market where we chose the PJM being the largest competitive wholesale electricity market.

The paper is organized as follows. Section 2 provides an overview of the relevant literature on this topic. Section 3 describes the data set and provides some standard statistics of energy commodity prices. In Section 4 the short run relationship is examined. Section 5 presents the empirical results for the long run relationship and Section 6 draws some conclusions.

2. RELEVANT LITERATURE

The relationship between natural gas and crude oil has been largely investigated, using different set of historical data and different methodologies. Over the period 1996-2003 evidences of a long run equilibrium among UK gas prices and Brent oil prices have been found (Panagiotidis and Rutledge, 2006). The existence of a cointegration relationship prior to the inauguration of the Interconnector (1998) indicates that despite the highly liberalized nature of UK gas market, gas prices and oil prices are moving together in the long-run. Bachmeier and Griffin (2006) using an ECM framework evaluate the degree of market integration among crude oil, coal, and natural gas market. A longer time period, 1989-2005, is used in Villar and Joutz (2006) to capture a cointegration relationship between oil and natural gas prices despite periods where they may have appeared to decouple. A cointegration relationship between WTI crude oil and HH natural gas has been measured in Brown and Yücel (2007) and Hartley, et al. (2008). Brown and Yücel (2007) find that short run deviations from the estimated long run relationship could be explained by influence of weather, seasonality, natural gas storage, and production in the Gulf of Mexico. Hartley, et al. (2008) find that seasonal fluctuations and other factors such as weather shocks and changes in storage have significant influence on the short run dynamic adjustment of prices.

Analysis of the relationship between electricity and fossil fuel prices can only be performed at regional level and on limited dataset given the nature of the market and the recent introduction of spot electricity markets. Serletis and Herbert (1999) use North America natural gas, fuel oil and power prices from 1996 to 1997 to find that the HH, Transco Zone 6 natural gas prices and the fuel oil price are cointegrated, whereas power

prices series appear to be stationary. In Gjolberg (2001) the existence of a medium and long term correlation between electricity and fuel oil in Europe is analyzed. Natural gas, crude oil and electricity prices result to be cointegrated and a leading role of crude oil is also identified in Ashe et al. (2006) during an interim period 1995-1998, after deregulation of the UK gas market (1995) and the opening up of the Interconnector. More recently (Mjelde and Bessler, 2009) for the US market, using a multivariate time series framework, interrelationships among electricity (peak, off-peak) prices from two diverse markets, PJM and Mid-Columbia (Mid-C), and four major fuel sources, natural gas, crude oil, coal, and uranium have been examined in the period 2001-2008. They find that the eight price series are cointegrated but they do not find $n - 1$ cointegrating vectors in order to detect one single source of randomness (one common trend) but find that fuel source prices move electricity prices. A slightly different approach has been used using US annual data for the period 1960-2007 (Mohammadi, 2009). The paper examines long-run and short-run dynamics between electricity prices and three fossil fuel prices (coal, natural gas and crude oil), finding that fuel prices do not affect electricity prices significantly. Significant long-run relationships are found only between electricity and coal prices.

At the best of our knowledge the level of integration between gas, oil and electricity market in Europe and in US and an understanding of possible different dynamics occurring in these markets has not been investigated. The purpose of this study is mainly to perform an analysis of the level of integration for the US and the European energy markets in order to capture possible different long run or short run dynamics caused by a different level of deregulation existing on each market. The existence of a cointegration relationship provides arbitraging opportunities among the various commodities, which is crucial for pricing of derivatives involving couple of commodities as well as spread options.

3. THE DATASET

The US and European daily prices for natural gas, crude oil and electricity are used. We refer to the period October 2001-March 2009 for both markets.

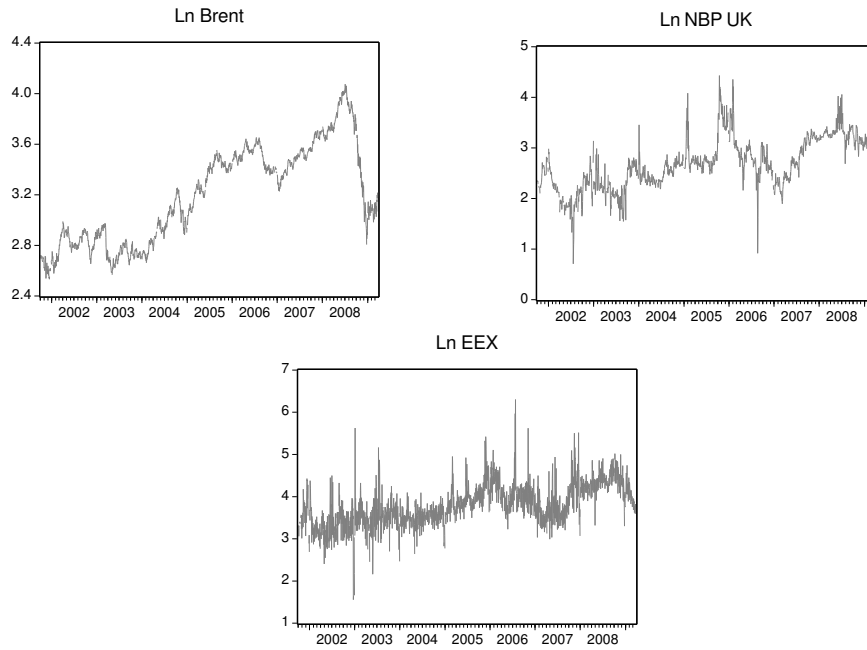


FIGURE 1. Crude oil, natural gas and electricity EU logged prices 2001-2009 (in €/MWh).

The European dataset includes daily price for ICE Brent crude oil³, natural gas at the NBP UK⁴, and EEX electricity⁵. The dynamics of the energy logged prices⁶ are represented in Fig. 1.

³Brent blend is the reference crude oil for the North Sea and is one of the three major benchmarks in the international oil market (Geman, 2005).

⁴The NBP is the most liquid gas trading point in Europe. The NBP price is the reference for many forward transactions and for the International Petroleum Exchange (IPE) Future contracts (Geman, 2005).

⁵EEX is one of the leading energy exchange in central Europe (Geman, 2005).

⁶Oil prices are expressed in US\$/barrel per day (bd), gas in UK p/therm and electricity prices in €/Megawatt hour (MWh). We choose to convert all prices in €/MWh using the conversion factors for energy content provided by the Energy Information Administration (EIA).

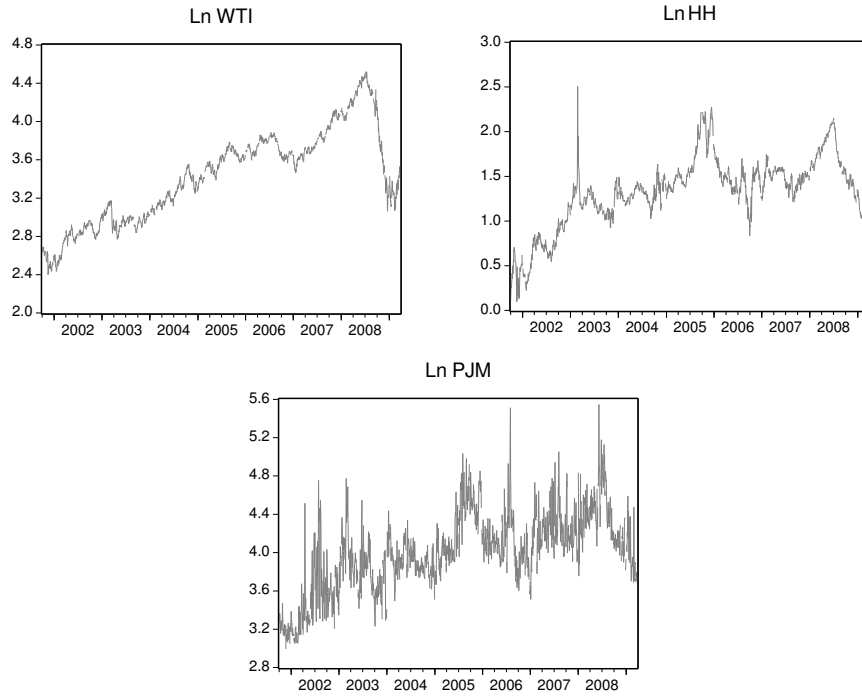


FIGURE 2. Oil, natural gas and electricity logged US prices (in \$/MWh).

The US dataset comprises daily prices for natural gas at the HH⁷, WTI for crude oil⁸ and PJM electricity⁹. The dynamic of natural gas, crude oil and electricity logged prices¹⁰ is presented in Fig. 2.

We first pay explicit attention to whether or not the variables are stationary, i.e. any price measured over time is not tied to its historical mean. We test the order of integration of a time series using the Augmented Dickey-Fuller (ADF) type regression:

⁷HH is the pricing point for natural gas futures contracts traded on NYMEX. Spot and future prices set at HH are generally seen to be the primary price set for the North America natural gas markets (Geman, 2005).

⁸WTI is a type of crude oil used as a benchmark in crude oil pricing and the underlying commodity of NYMEX's oil future contracts (Geman, 2005).

⁹PJM is currently the world's largest competitive wholesale electricity market which covers the eastern interconnection in the US (Geman, 2005).

¹⁰Oil prices are expressed in US\$/bd, gas in US\$/MBtu and electricity prices in \$/MWh. We choose to convert all prices in \$/MWh.

TABLE 1. Unit root test results for the logged EU price series.

| Series | t_γ | τ_0 | τ_1 | τ_d | Decision |
|--------|------------|-------------|--------------|------------|----------|
| Brent | 0.36 (1) | -1.56 (1) | -1.46 (1) | -48.4 (0) | I(1) |
| NBP | -0.54 (6) | -3.44** (6) | -5.82** (2) | -22.7 (5) | I(1) |
| EEX | -0.19 (14) | -3.40* (15) | -4.75** (15) | -20.4 (13) | I(1) |

TABLE 2. Unit root test results for the logged US price series.

| Series | t_γ | τ_0 | τ_1 | τ_d | Decision |
|--------|------------|-------------|-------------|-----------|----------|
| WTI | 0.57 (1) | -1.64 (1) | -1.48 (1) | -46.7 (0) | I(1) |
| HH | -0.46 (2) | -3.02* (2) | -2.71 (2) | -37.7 (1) | I(1) |
| PJM | -0.28 (6) | -4.45** (6) | -5.76** (6) | -26.5 (5) | I(1) |

$$(3.1) \quad \Delta y_t = \alpha_0 + \alpha_1 t + \gamma y_{t-1} + \sum_{j=1}^k \beta_j \Delta y_{t-j} + \epsilon_t$$

where $\Delta y_t = y_t - y_{t-1}$ and the lag length, k , is automatic determined based on Schwarz information criterion (SIC). The results of the unit root test for the various time series are reported in Table 1 and in Table 2¹¹.

We run the test using Eq. (3.1), we also run the test assuming a constant and exogenous variables included. The reported t-statistics are t_γ , τ_0 and τ_1 , respectively. τ_d is the t-statistic for the ADF tests in first-differenced data. The key value is represented by the coefficient γ ¹² and its statistical significance, denoted by t_γ . For all the tested variables the t-value for γ , t_γ , exceeds the critical values, so the series are non stationary. We also reject the hypothesis when we run the test for the first-differences, hence we conclude that both the European and the US variables are first-difference stationary, i.e., they are $I(1)$.

¹¹The 5% significance levels are -1.94 for ADF without exogenous variables, -2.86 for ADF with a constant, and -3.41 for ADF with a constant and trend. (*) denotes acceptance of the null at the 1%, (**) denotes rejection of the null at the conventional statistical level. The SIC-based optimum lag lengths are in parentheses. All the series are in logs.

¹²The level of γ is not relevant for the purpose of our analysis. For reasons of space it has not been reported on Table 1 and 2.

4. THE SHORT RUN RELATIONSHIP

Electricity and fuel prices are expected not to be independent of each other, basically we expect similar economic forces to influence each market with a different strength. This means that the different energy commodity prices should be tied together showing some clear steady relationship both in the short and in the long run.

Alexander (1999) presents the applications of correlation analysis to the crude oil and natural gas markets. Correlation measures co-movements of prices or returns and can be considered a short-term measure. It is essentially a static measure and it cannot reveal any dynamic causal relationship. Even when energy markets are sufficiently liquid to admit correlation hedging, these correlations may be too unstable to be effective for hedging. In addition estimated correlations can be significantly biased or “nonsense” if the underlying variables are polynomials of time or when the two variables are non stationary (Yule, 1926). Given the non stationarity of the underlying processes and the seasonality occurring in gas and electricity prices, the correlation coefficient shows some time changing structure. Volatilities of commodity prices are time dependent, therefore time dependencies of covariance and of the unconditional correlation follows. This means that we can only attempt to catch seasonal changes in correlations, a finer time resolution will be dominated by noise.

The existing relationship between each couple of commodity prices is first performed estimating the rolling correlation over a pre-specified interval¹³. Rolling correlation over $\tau_j = 100$ days¹⁴ is estimated to measure the short term relationships according to:

$$(4.1) \quad \rho_s[x, y] = \frac{\frac{1}{\tau_j - 1} \sum_{i=s}^{s+\tau_j} (x_i - \hat{x})(y_i - \hat{y})}{\hat{\sigma}_x \hat{\sigma}_y}, \quad s = 1, \dots, T - \tau_j,$$

where the entire period 2001-2009 is made by T observations, $\hat{\sigma}_x$ and $\hat{\sigma}_y$ are the standard deviation of x and y , respectively, estimated on the corresponding time window.

The unconditional correlation coefficients¹⁵, ρ_T ($T = 1897$), together with the main statistical features of the rolling correlations between the European energy price series, ρ_s , are reported in Table 3.

It is interesting to notice that the rolling correlations between gas and oil show some counterintuitive behavior. The swinging behavior may be partly explained by the non

¹³Eydeland suggests to choose a time window large enough to capture meaningful dynamics between the two series and at the same time, given the limited number of observations, small enough to provide unbiased estimations.

¹⁴This window period seems to be the most adequate for over time series according to Eydeland (2003). We also perform the analysis with smaller and larger windows ($\tau_j = 60, 90, 100, 150$ days). $\tau_j = 100$ seems to be capturing the yearly effect.

¹⁵The unconditional correlation for the entire period is given by $\rho_T = \frac{cov(x, y)}{\hat{\sigma}_x \hat{\sigma}_y}$.

TABLE 3. Unconditional correlation and statistical features of the rolling correlations between EU log prices.

| Matrices | ρ_T | $E(\rho_s)$ | $\sigma(\rho_s)$ | Max(ρ_s) | Min(ρ_s) |
|-----------|----------|-------------|------------------|-----------------|-----------------|
| Brent/NBP | 0.677 | -0.127 | 0.359 | 0.126 | -0.382 |
| NBP/EEX | 0.622 | 0.603 | 0.102 | 0.676 | 0.531 |
| Brent/EEX | 0.613 | -0.022 | 0.462 | 0.304 | -0.349 |

TABLE 4. Unconditional correlation and statistical features of the rolling correlations between US log prices.

| Matrices | ρ_T | $E(\rho_s)$ | $\sigma(\rho_s)$ | Max(ρ_s) | Min(ρ_s) |
|----------|----------|-------------|------------------|-----------------|-----------------|
| WTI/HH | 0.800 | 0.396 | 0.215 | 0.549 | 0.244 |
| HH/PJM | 0.813 | 0.638 | 0.247 | 0.813 | 0.463 |
| WTI/PJM | 0.749 | 0.276 | 0.293 | 0.484 | 0.069 |

stationarity of oil and gas prices, however ρ_s varies between a minimum -0.382 and a maximum 0.126 showing an average rolling correlation equal to -0.127 against an overall correlation equal to 0.677 . The overall correlation coefficient witness an expected positive correlation among the two commodities, while the rolling correlation shows a low negative correlation which may be partly explained by the occurrence of seasonality in the gas prices and partly by the fact that oil prices were experiencing long increasing trends which were not followed by similar gas price changes. Similar dynamics is found for the electricity/oil relationship with an overall correlation $\rho_T = 0.613$ and a rolling correlation varying between -0.349 and 0.304 . The relationship between gas and electricity prices shows a less puzzling behavior given a total correlation equal to 0.622 and a rolling correlation varying between 0.531 and 0.676 . The relationship between oil and the other two commodities may be affected mainly by the seasonality component present in the gas and electricity prices and not in the oil prices.

Correlation analysis, also for US market, shows time dependence, however in this case the rolling correlation analysis is able to catch some important co-movements between energy commodity prices. The results for the unconditional correlation ρ_T (T=1856) and the main statistical features of the rolling correlations ρ_s between the US energy price series are reported in Table 4.

Unlike the European market the overall correlation and the rolling correlation analysis for the US market provide more coherent results. A positive overall correlation coefficient for each couple of relationship is supported by an average rolling correlation coefficient

of the same sign among the various markets. The unconditional correlation coefficient between gas and oil for the entire dataset is particularly high. This is in line with common expectations since in this country the energy market deregulation has led to a real competition.

5. THE LONG RUN RELATIONSHIP

The analysis performed using the simple correlation analysis represents the first step to capture relationships between the main energy commodities. However, the obtained results highlight how this instruments is not able to capture a meaningful relationship. Following Eydeland's suggestion in order to be able to adequately describe the nature of the relationship a certain model has to be assumed, we use a cointegration framework in order to investigate a possible existing integration of these markets and a long run relationship.

Cointegration means that one or more linear combinations of two or more variables are stationary, even though individually they are not. From an economic point of view, cointegration implies that variables can drift apart in the short run, but they will show a long run equilibrium to which the system converges over time. In other words the series are drifting together at roughly the same rate, they have the same long wave or common (stochastic) trend (or shared trends). The existence of a long run equilibrium relationship in a financial context implies no arbitrage opportunity between these markets as well as no leading market in the price discovery process. This is a key feature for risk management purposes.

We estimate a possible cointegration relationship among the energy commodity prices using two broad approaches. A first approach based on VAR (Johansen, 1988, 1994; Stock and Watson, 1988) aimed to find all possible cointegrating relationships existing among n series in order to be able to identify some shared trends. In particular if $n - 1$ cointegrating vectors may be identified a unique common trend may be detected.

The second approach (Engle and Granger, 1987) is based on assessing whether single equation estimates of the equilibrium errors are stationary and testing the cointegration among two variables in order to understand the relationship between each pair of commodities.

The number of cointegrating vectors is tested estimating a vector error correction model (VECM) based on the so-called reduced rank regression method (Johansen, 1995). We assume that the n -vector of non-stationary $I(1)$ variables Y_t follows a vector autoregressive (VAR) process of order p ,

$$(5.1) \quad Y_t = A_1 Y_{t-1} + A_2 Y_{t-2} + \dots + A_p Y_{t-p} + \epsilon_t$$

TABLE 5. Cointegration rank test for the EU log prices.

| Nr. of coint. vec. | Eigenvalue | λ_{trace} | $\lambda_{\text{trace}}^{0.05}$ | λ_{max} | $\lambda_{\text{max}}^{0.05}$ |
|--------------------|------------|--------------------------|---------------------------------|------------------------|-------------------------------|
| $r = 0$ | 0.044 | 116.6 | 29.79 | 86.92 | 21.13 |
| $r \leq 1$ | 0.014 | 29.74 | 15.49 | 27.03 | 14.26 |
| $r \leq 2$ | 0.001 | 2.708 | 3.841 | 2.708 | 3.841 |

TABLE 6. Cointegration rank test for the US log prices.

| Nr. of coint. vec. | Eigenvalue | λ_{trace} | $\lambda_{\text{trace}}^{0.05}$ | λ_{max} | $\lambda_{\text{max}}^{0.05}$ |
|--------------------|------------|--------------------------|---------------------------------|------------------------|-------------------------------|
| $r = 0$ | 0.063 | 139.0 | 29.79 | 120.6 | 21.13 |
| $r \leq 1$ | 0.008 | 18.45 | 15.49 | 15.45 | 14.26 |
| $r \leq 2$ | 0.001 | 2.995 | 3.841 | 2.995 | 3.841 |

with ϵ_t as the corresponding n -dimensional white noise, and $n \times n$ A_i , $i = 1, \dots, p$, matrices of coefficients¹⁶. Eq. (5.1) is equivalently written in a VECM framework,

$$(5.2) \quad \Delta Y_t = D_1 \Delta Y_{t-1} + D_2 \Delta Y_{t-2} + \dots + D_p \Delta Y_{t-p+1} + D Y_{t-1} + \epsilon_t$$

where $D_i = -(A_{i+1} + \dots + A_p)$, $i = 1, 2, \dots, p-1$ and $D = (A_1 + \dots + A_p - I_n)$. The Granger's representation theorem (Engle and Granger, 1987) asserts that if D has reduced rank $r \in (0, n)$, then $n \times r$ matrices Γ and B exist, each with rank r , such that $D = -\Gamma B'$ and $B' Y_t$ is $I(0)$. r is the number of cointegrating relations and the coefficients of the cointegrating vectors are reported in the columns of B .

The cointegration results for the European and the US log prices are shown in Table 5 and Table 6, respectively.

A rejection of the null 'no cointegrated' relationship and 'r at most 1' in favor of 'r at most 2' at the 5% significance level is provided. This provides evidence of the existence of two cointegrating relationships among the three commodity price series in both markets. In a VECM framework, the presence of $r = n - 1 = 2$ cointegrating vectors allows to estimate $n - r = 1$ common trend (Stock and Watson, 1988). The common trend may be interpreted as a unique source of randomness which affects the dynamics of the commodity prices. The most natural assumption is to identify as main source of randomness the oil price¹⁷. Oil price volatility has been largely investigated and little understood, it is not always explained by the supply and demand dynamics but requires

¹⁶In the following, for the VAR(p) model we exclude the presence of exogenous variables.

¹⁷This may be surprising given that in Europe there are also large countries as France and UK where oil does not represent the main source of energy in power generation.

other factors, i.e., i) the "reflexive" tendency for the supply of oil to fall as the price rises reversing the normal shape of the supply curve, ii) the increase of the demand for speculation that tends to reinforce market trends; only to cite some of them¹⁸.

To better analyze the dynamics of the various markets we use the Engle-Granger two-step methodology. The first step requires to estimate the parameters of the cointegrating vector (the stationary linear combination of the two series), in the second step the estimated parameters are used in the Error Correction form. Given two price series $y_{1,t}$ and $y_{2,t}$, both $I(1)$, the "cointegration regression"

$$(5.3) \quad y_{1,t} = \alpha + \beta y_{2,t} + z_t$$

is estimated to fit the long run or equilibrium relationship. The coefficients β in Eq. (5.3), which represent the factors of proportionality for the common trend, are estimated by ordinary least squares (OLS), getting the linear combination with the smallest variance. OLS estimates provide consistent coefficients of long run model but standard errors are unreliable. The OLS residuals z_t from regression (5.3) are estimates of the equilibrium errors. The results may be very sensitive to the choice of the "dependent" variable in the regression analysis. We test each couple of the time series twice in order to use as "dependent" variable both of the series and verify the stationarity of z_t in both cases. The results for the European market are reported in Table 7 and those for the US market are reported in Table 8¹⁹. In step 2, the OLS residuals are tested for stationarity using the ADF test²⁰ with critical values compared with MacKinnon tables (MacKinnon, 1991).

The null hypothesis of no cointegration is rejected at the 1% in all cases²¹. This confirms the existence of a long run equilibrium between the energy commodity prices.

¹⁸In 2008 there has been a bubble superimposed on an upward trend in oil prices, a trend that has strong foundations in reality. Without a recession demand would grow faster than the supply of available reserves and this would persist even if speculation and commodity index buying were eliminated.

¹⁹ t_β are the t-statistics for the coefficients β in Eq. (5.3). The last column reports the p-values for the unit root tests on the regression residuals.

²⁰Engle and Granger (1987) had proposed a set of seven different test statistics for testing the stationarity of two variables. By comparing the performance between these tests, Engle and Granger indicated as the recommended approach the ADF test. The critical values, however, could not be read on the DF tables but specific critical values needed to be identified (Davidson and MacKinnon, 1993; Engle and Granger, 1987; Engle and Yoo, 1987; Philips and Ouliaris, 1990) given that the Dickey-Fuller tables were inadequate.

²¹The null hypothesis of no cointegration is rejected at the 7% and at the 6% significance level for the regression Brent vs EEX with a constant and a constant plus a linear trend as exogenous variable, respectively.

TABLE 7. Engle and Granger cointegration test for the EU log prices.

| Dep. variable | Indep. variable | β | t_β | P-value |
|---------------|-----------------|---------|-----------|---------|
| Brent | EEX | 0.476 | 33.77 | 0.00 |
| EEX | Brent | 0.788 | | 0.00 |
| Brent | NBP | 0.517 | 40.07 | 0.00 |
| NBP | Brent | 0.886 | | 0.00 |
| NBP | EEX | 0.633 | 34.61 | 0.00 |
| EEX | NBP | 0.611 | | 0.00 |

TABLE 8. Engle and Granger cointegration test for the US log prices.

| Dep. variable | Indep. variable | β | t_β | P-value |
|---------------|-----------------|---------|-----------|---------|
| WTI | PJM | 0.885 | 48.79 | 0.00 |
| PJM | WTI | 0.635 | | 0.00 |
| WTI | HH | 0.975 | 57.48 | 0.00 |
| HH | WTI | 0.657 | | 0.00 |
| HH | PJM | 0.788 | 60.25 | 0.00 |
| PJM | HH | 0.839 | | 0.00 |

According to the Granger representation theorem, if two series cointegrate the short-run dynamics can be described by the ECM which is commonly used to investigate the degree of integration among different markets. As suggested by Bachmeier and Griffin (2006) the basic ECM, focusing on the pairwise series analysis, has the merit to be more transparent and elegant than its generalization, VECM. The underlying intuition of this basic model is that if two markets are integrated, prices tend to be affected by common factors, therefore price changes in one market tend to be linked with price changes in the second market. The ECM framework allows to statistically measure the degree of market integration using this representation:

$$(5.4) \quad \Delta y_{1,t} = \phi \Delta y_{2,t} + \theta (y_{1,t-1} - \alpha - \beta y_{2,t-1}) + \epsilon_t$$

where $(y_{1,t-1} - \alpha - \beta y_{2,t-1})$ represents the error correction term z_{t-1} of Eq. (5.3), ϕ measures the contemporaneous price response, θ represents the speed of the adjustment towards the long term cointegrating relationship, and ϵ_t are i.i.d. $\sim N(0, \Sigma)$.

TABLE 9. ECM parameters for the EU log prices.

| Dep. variable | Indep. variable | ϕ | t_ϕ | P-value | θ | t_θ | P-value |
|---------------|-----------------|--------|----------|---------|----------|------------|---------|
| Δ NBP | Δ Brent | -0.020 | -0.175 | 0.860 | -0.053 | -7.224 | 0.000 |
| Δ EEX | Δ Brent | -0.291 | -0.954 | 0.339 | -0.425 | -22.70 | 0.000 |
| Δ EEX | Δ NBP | 0.094 | 1.558 | 0.119 | -0.437 | -23.19 | 0.000 |

TABLE 10. ECM parameters with lags for the EU log prices.

| Dep. variable | Indep. variable | ϕ | t_ϕ | P-value | θ | t_θ | P-value |
|---------------|---------------------|--------|----------|---------|----------|------------|---------|
| Δ NBP | Δ Brent (-7) | -0.223 | -1.944 | 0.051 | -0.053 | -7.258 | 0.000 |
| Δ EEX | Δ Brent (-1) | 0.752 | 2.455 | 0.014 | 0.422 | 22.50 | 0.000 |
| Δ EEX | Δ NBP (-2) | -0.260 | -4.318 | 0.000 | -0.443 | -23.54 | 0.000 |

This model highlights that the deviations from the long run cointegrating relationship are corrected gradually through a series of partial short run adjustments. In the long run equilibrium the error correction term, z_{t-1} will be equal to zero. Different values of z_{t-1} are caused by deviation from the long run equilibrium and some forces are going to bring the two variables back in equilibrium. These forces are measured by θ which represents the speed of adjustment towards the equilibrium. The parameter ϕ approximates the correlation coefficient between first differences in prices ($\Delta y_{1,t}$ and $\Delta y_{2,t}$). ϕ will be close to 1 when the two commodities are in the same market. Therefore, a higher value of ϕ is a sign of a stronger integration of the market.

To test for a possible market integration among primary energy data in Europe we perform the ECM between each couple of variables. Estimation of equation (5.4) with no lags is reported in Table 9. For each couple of series the coefficient ϕ does not result statistically significant. We may expect some delay in the adjustment process for the European market where deregulation is not uniformly reached among the various countries.

We then estimate the ECM introducing some lags to the independent variable. The results for market integration among the energy commodities are reported in Table 10, lags are shown in parenthesis near the independent variables.

In the case of gas and oil, Eq. (5.4) with 7 day lags provides a significative coefficient $\phi = -0.223$ and $\theta = -0.053$. θ measures the speed of adjustment toward the long run equilibrium which appears to be negative but very small in absolute value showing a very

TABLE 11. ECM parameters for the US log prices.

| Dep. variable | Indep. variable | ϕ | t_ϕ | P-value | θ | t_θ | P-value |
|---------------|-----------------|--------|----------|---------|----------|------------|---------|
| Δ HH | Δ WTI | 0.224 | 5.243 | 0.000 | -0.023 | -4.852 | 0.000 |
| Δ PJM | Δ WTI | 0.251 | 1.984 | 0.047 | -0.158 | -12.58 | 0.000 |
| Δ PJM | Δ HH | 0.711 | 10.88 | 0.000 | -0.194 | -14.15 | 0.000 |

slow pace. The value of ϕ can be interpreted as a measure of the short run relationship between the two commodity prices. In this case it shows a negative correlation which is performed with 7 days of delay between the two prices. In the case of electricity and oil the equation is estimated with 1 day lag, the coefficient $\phi = 0.752$ shows that the oil price affects the electricity behavior with a lag of one day. For electricity and gas the coefficient ϕ is significative considering the independent variable with a two days lag, also in this case, the short run adjustment in price occurs with the delay of two days. In general we find a variable level of integration among the various energy markets in Europe. This could be explained by the still ongoing process of deregulation for the gas and the electricity market which makes markets not highly integrated.

Different results are found for the US markets. The estimation of the ECM representation is reported in Table 11.

For the US markets, where deregulation has been taking place over the last 20 years, no lags need to be introduced and the coefficients ϕ and θ result statistically significative in all cases and a short run relationship is found ($\phi_{HH,WTI} = 0.224$; $\phi_{PJM,WTI} = 0.251$; $\phi_{PJM,HH} = 0.711$), witnessing a higher level of integration among the various markets. The long run relationship is also confirmed by values of θ all statistically significative, showing that these markets are all integrated.

6. CONCLUSION

This paper analyzes the European and US daily price data for natural gas, crude oil and electricity in order to understand the nature of the existing relationship among these commodities. Price volatility is strongly time dependent and the covariance and the unconditional correlation are time dependent as well. Using a rolling correlation approach we study the short run relationship between these commodities, finding no conclusive results and confirming the need to assume some time varying model to capture a correct dynamic.

The long run relationship is investigated using a cointegrating approach. Using the Johansen method two cointegrating relationships are found, implying one common trend among the three commodity price series. The common trend may be interpreted as one

source of randomness affecting the dynamics of the two other commodities within each market. The oil price may be considered the source of randomness which represents the main driver of the electricity and gas markets.

To further analyze the possible cointegration relationships among each pair of commodities we adopt the Engle-Granger approach. This witnesses a long run equilibrium between electricity and oil prices as well as between electricity and gas prices or gas and oil prices both for the European and the American dataset.

The degree of integration among these markets is testing using the ECM framework. We find that, despite the efforts of the European Commission the integration of energy markets in Europe is lower than in the US, particularly if we consider gas and oil markets. The ECM framework shows a higher level of integration between the energy commodities for the US market confirming that deregulation of electricity and gas market has reached a more advanced level respect to the European market.

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