AN INVESTIGATION OF LONG RANGE RELIANCE ON SHALE OIL AND SHALE GAS PRODUCTION IN THE U.S. MARKET

Sakiru Adebola Solarin, Multimedia University, Malaysia

Luis A. Gil-Alana, University of Navarra, Pamplona, Spain and Universidad Francisco de Vitoria, Madrid, Spain

and

Carmen Lafuente, Universidad Francisco de Vitoria, Madrid, Spain

Abstract

Despite the rising profiles of both shale oil and shale gas plays in the U.S. and the importance of testing for their persistence, no study has examined the persistence of the availability of shale oil and shale gas plays in the country. This paper focuses on the analysis of shale oil and shale gas production using long range dependence techniques in the U.S. for the period, January 2000 to April, 2019. The empirical findings illustrate that the series examined are highly persistent, finding very little evidence of mean reverting patterns. Among the implications of the results, which are discussed in the paper, is that there is a hysteresis in shale oil and gas production in U.S., and therefore shocks resulting from new government policies relating to shale oil and gas in U.S. will have lasting impacts on their production. Besides, it will not be feasible to use forecasting as a basic instrument for unconventional energy sources as the previous values of shale oil and gas production cannot be utilised to accurately forecast their subsequent values.

Keywords: Shale oil; shale gas; long range dependence; persistence

JEL Classification: C22; Q42; N72

Corresponding author:
Luis A. Gil-Alana
University of Navarra
Faculty of Economics and ICS
31009 Pamplona
Spain

email: alana@unav.es

---

[*] Luis A. Gil-Alana gratefully acknowledges financial support from the Ministerio de Economía, Industria y Competitividad' (MINEIC), the Agencia Estatal de Investigación' (AEI), Spain and `Fondo Europeo de Desarrollo Regional' (FEDER). Comments from the Editor and four anonymous reviewers are gratefully acknowledged.

1. Introduction

Since the beginning of the 21st century, the importance of shale oil and shale gas have grown considerably, especially in the U.S. These two unconventional sources of energy offer countries such as the U.S. a vital chance to achieve more international competitiveness, expand their economies and generate jobs. (American Chemistry Council, 2013). The shale gas industry alone generated over 600,000 jobs in 2013 and the number is expected to exceed 1.6 million by 2035. (Le, 2018) Both shale gas and shale oil serve as possible additional energy sources with useful, abundant, and environment-friendly features. Their exploitation reduce the imbalance between energy demand and supply and therefore influence national energy policies (Hu et al., 2019). They have also led to affordable energy prices for industrial, commercial and residential consumers and have enhanced the possibility of meeting local energy demand. (Salisu and Adediran, 2018).

Partly due to the growing importance of shale oil and shale gas, several economic aspects of these unconventional sources of energy have been investigated, including their effects on global economic activities, price, exports of crude oil etc (Baffes et al., 2015; Kilian, 2016a,b). Other areas that have been investigated include the convergence of shale oil and shale gas (Hu et al., 2019), the relationship between the price of crude oil and the production of shale oil (Monge et al., 2017) and the effect of shale gas on the natural gas price-production relationship. (Feng et al., 2019).

However, the persistence of shale oil and shale gas has not been sufficiently investigated in the existing literature, which is important for several reasons. Persistence is a measure of the degree to which short term shocks in the present market situation generate permanent future changes. A shock is regarded as having a short term or temporary impact if, after a brief period, the variables returns back to its initial point (Barros et al., 2016).[1] First, the question of whether production of unconventional energy sources is persistent is important as this decides whether shocks have temporary or permanent impacts. If unconventional sources of energy are persistent, shocks to tight oil and gas will have a permanent impact.[2] The rationale is that if an unconventional source of energy contains a unit root, there will be a long-term deviation away from the long-run growth path of their production in the aftermath of a shock, thus conforming with hysteresis in unconventional energy production. If unconventional sources of energy and the national output are significantly connected (when there is a permanent shock), such a shock will spread to other industries and lead to persistence in several macroeconomic series (Lean and Smyth, 2013).

Second, the research into the stationarity of energy series is one of the initial steps required in the study of energy growth, which also regularly include cointegration and causality tests. The correct way to estimate the Granger causality between such variables is partly determined by the (non)existence of unit root(s) in the unconventional source of energy. (Cai and Menegaki, 2019). Third, the incidence of a unit root in the unconventional energy source has vital implications for projecting subsequent energy production. If production of either shale oil or shale gas production is stationary, it is feasible to project subsequent production figures, but if production of the unconventional energy has a unit root it is impossible to forecast (Lean and Smyth, 2013). Fourth, the extent of persistence in the unconventional energy production process is a vital concern both for economies that are net exporters as well as economies that are net importers. For energy-exporting countries, energy

---

[1] Hysteresis or path dependency is a term borrowed from the natural sciences and it implies that if the latter stages of a series are dependent on the earlier ones– including anything that can be interpreted as a long run outcome of the series. In other words, the series follows a non-ergodicity process. Therefore, decisions made in the present and the resulting actions and interactions must have an impact on what happens in the future and the decisions made in the future and the actions that result (Arestis and Sawyer, 2009).

[2] Shale oil (gas) and tight oil (gas) are the same and can be used interchangeably. In this study, we have used these terms interchangeably.

production serves as a mechanism for a revenue generating commodity for the countries. For instance, if energy production is persistent and consequently there is a decline in energy supply, energy exporting countries will experience a scenario whereby incomes from energy exports will not move back to their past mean/trend and that additional sources of income must be conceived in order to sustain income levels (Fallahi et al., 2016). Fifth, as energy production is related to several macroeconomic series, persistence in the production of unconventional energy is likely be transferred to other macroeconomic series. Therefore, a negative shock to energy production is likely to increase the rate of unemployment permanently and in a bid to drag back the rate of unemployment to its past trend, policy intervention is needed (Smyth, 2013).

The objective of this paper is therefore to examine the persistence of unconventional sources of energy in U.S. It adds to the extant literature by examining the degree of persistence in the output of the major shale oil and shale gas plays. The second contribution of this study is that it employs fractional integration techniques that permit us to examine the extent of persistence of the series in a more flexible way than the conventional approaches that are premised on integer degrees of differentiation.

The focus on the U.S. is due to several reasons. The U.S. has the largest economy in the world and the second largest energy consumer after China. The U.S. is among the very few countries to exploit and produce shale oil and shale gas commercially on a large scale. (Hu et al., 2019). Although the U.S. produces many different types and has many sources of energy, the drastic rise in energy production can be partly attributed to both shale oil and shale gas. Shale oil increased from 0.4 million barrels per day in January 2000 to 7.28 million barrels per day in December 2018 and further increased to 7.40 million barrels per day in April, 2019 (Energy Information Administration, 2019). Shale gas rose from 3.59 million barrels per day in January 2000 to 64.63 billion cubic feet (bcf) per day in December 2018 and further increased to 65.68 bcf per day in April, 2019 (Energy Information Administration, 2019).

Nearly all the major shale oil and shale gas plays in the U.S. have witnessed significant growth in their output. Texas's Eagle Ford produced a meagre 6 barrels per day shale oil in January 2000 but about 1.2 million barrels per day in April, 2019. Texas's Permain Spraberry produced just 78 thousand barrels per day shale oil in January 2000 but about 1.6 million barrels per day in April, 2019. (Energy Information Administration, 2019). The Marcellus shale, which stretches below the states of West Virginia, New York, Pennsylvania and Ohio recorded about 49 thousand cubic feet (tcf) per day output in January 2000 and this output rose to 21 bcf in both December 2018 and April 2019. Texas Permain produced 0.6 bcf of shale gas per day output in January 2000 but about 8.9 bcf shale gas per day output in April, 2019. (Energy Information Administration, 2019).

Shale oil accounted for 6.89% of the total crude oil production and 1.19% of the total primary energy production in January 2000. Shale oil accounted for 61.07% of the total crude oil production and 15.22% of the total primary energy production in December 2018. (Energy Information Administration, 2019). Shale gas accounted for 6.93% of the total dry natural gas production (or 6.10% of the total natural gas production) and 1.91% of the total primary energy production in January 2000. Shale gas accounted for 72.76% of the total dry natural gas production (or 61.70% of the total natural gas production) and 24.48% of the total primary energy production in December 2018. (Energy Information Administration, 2019).

The remainder of the paper is patterned as follows. Section 2 discusses the literature review. Section 3 presents the research methodology and in Section 4 data are described. Section 5 displays the empirical results; Section 6 includes some robustness checking while Section 7 discusses the results obtained. Section 8 contains the conclusion of the paper study and the related policy implications.

2. Literature review

In order to have a clear grasp of the research gap, which our current study intends to fill, the literature review has been divided into two sections. The first subsection involves the studies that have focussed on the underlying unit root properties of energy, while the second subsection encompasses the papers on economic aspects of unconventional sources of energy.

2.1 Studies on the stationarity of energy series

Beginning with Narayan and Smyth (2007), several studies have emerged that consider the energy consumption or production stationarity. While the majority of the papers in the literature have tested for stationarity of energy consumption, relatively few studies have examined stationarity of energy production. Papers on the persistence of energy consumption include, among others, Fallahi et al. (2016), that examined the persistence properties of energy consumption in 107 countries for the period, 1971–2011. Using a subsampling confidence interval method, their results show that highly oil dependent and developing countries have nonstationary energy consumption, while energy-rich and developed countries have stationary series.

Several components of energy consumption have also been examined in the literature. For instance, Shahbaz et al. (2014a) investigated the natural gas consumption stationarity in 48 countries over the 1971-2010 period. Using a nonlinear unit root test, there is evidence for stationarity of the series in most cases. Moreover, Shahbaz et al. (2014b) investigated the coal consumption per capita stationarity in 47 developing and developed economies for the time period, 1965–2010. The authors adopted a Lagrange Multiplier unit root test with breaks and their results show that coal consumption is stationary in almost all the analyzed countries. Solarin (2015) used a nonlinear test to examine the hydroelectricity consumption stationarity in 50 countries for the period, 1965-2012. The empirical findings show unit roots are present in the consumption series of 26 countries.

Solarin and Lean (2016) examined the total oil consumption stationarity in 57 countries from 1965 to 2012. Using a combination of nonlinear and linear stationarity methods, the results show evidence in favour of stationarity in 19 countries. Khraief et al. (2016) investigated the random walk hypothesis for electricity consumption in 17 sub-Saharan African countries for the 1971-2013 period. Using a panel unit root test with breaks, it is shown in the paper that stationarity holds in eleven countries. Cai and Menegaki (2019) utilised a quantile unit root test to examine the clean energy consumption stationarity in eight emerging countries for the period 1965-2016. Their results show that clean energy consumption is stationary in three countries, China, Pakistan and Thailand.

Studies focussing on the stationarity of energy production include Narayan et al. (2008) that used several univariate and panel unit root tests in the analysis of the production of crude oil stationarity for 18 OECD countries and 42 non-OECD countries from 1971 to 2003. They found evidence of stationarity in the series for crude oil production stationarity. Maslyuk and Smyth (2009) used a threshold autoregressive unit root test to examine crude oil production in 17 OPEC and non-OPEC countries from the period of January 1973 to December 2007. Their results illustrated that unit roots are present in two regimes in eleven countries, whilst a partial unit root was observed in the rest of the countries. Barros et al. (2011) focussed on the persistence of oil production in 13 members of OPEC for the period from January 1973 to October 2008. Using fractional integration techniques, the empirical findings suggest that there is mean reversion in most cases. Maslyuk and Dharmaratna (2013) examined the stationarity of black and brown coal production in the Australian economy. Using unit root tests that provide for one or two structural breaks, it is observed that there is mixed evidence for stationarity. Lean and Smyth (2013) examine the integration properties of biomass and biofuels production as well as the production of US total renewable energy. Using Lagrange Multiplier univariate unit root tests with breaks, their results support the existence of unit roots.

2.2 Economic dimensions of shale oil and shale gas

There are several investigations that examine the impact of the increase in shale oil and shale gas production in international markets and in the world economy. Some of these works such as Chew (2014) show that these unconventional hydrocarbons are attractive because of their large areal extent and consequent low exploration risk and long, stable production life. However, their ultimate production volume is unlikely to match that of conventional oil and natural gas liquids (NGLs). Geographically, most occur in North America and Venezuela. Also, Hosseini and Shakouri (2016), using a system dynamics approach and simulation results, argue that unconventional oil can gain a considerable market share in the short run, although conventional oil will remain as the major source for the market in the long run. However, unconventional gas is more evenly distributed all over the world than unconventional oil, providing the prospect of security of supply for more countries. According to Chew (2014), the eightfold growth in shale gas production in recent years and the interest that this has created suggest that in the close future we will see significant shale gas production outside North America. This author also argues that environmental concerns may delay development but will probably prove to be insignificant because existing, largely standard, operating procedures already resolve the technical issues. Other authors such as Zou et al. (2016) have investigated the impact that the oil and unconventional gas revolution has had on the oil and gas world production. According to them, the growing demand for environmental policies will boost the consumption of new energy sources that will displace existing ones, although, due to the influence of different factors, it is difficult to predict the peaks of oil and gas production.

Regarding the influence of the production of unconventional hydrocarbons on the prices of gas and oil, Chiodi et al. (2016) indicate that a significant production of unconventional gas could lower the prices of natural gas and that the growing unconventional oil production has limited potential to lower oil prices.

The decrease in oil prices caused by the rise in non-conventional oil production, among other factors, has had a positive effect on global activity in the medium term (Baffes et al., 2015). Some observers attribute the general decrease in world oil prices since June 2014 to the expansion in production of shale oil (Kilian, 2016a). Benes et al. (2015) present a nonlinear econometric model on oil price behavior in the world market. They use annual data, from 1983 to 2011 and examine the global GDP, the global oil price and the global oil supply. Their model indicates a perceptible but small and transitory output effect. The increase in the industrial production of U.S. and the possible commercial consequences derived from this revolution have been investigated by various authors. Thus, for example, Kilian (2016b) opines that the rise in the production of shale oil in the U.S. has reduced the market for the crude oil exports from Arab oil producing countries.

There are also studies that specifically examine the development of shale gas in the U.S. Aruga (2016), for example, suggests that the U.S. shale gas revolution has not yet affected the international markets. On the other hand, shale gas production has become a significant part in the total gas production of the U.S. (Caporin and Fontini, 2017). Bilgili (2016) shows that industrial production is positively associated to the production of shale gas and the U.S. can use shale gas reserves to meet the energy demand. Finally, Feng et al. (2019) has shown that the development of shale gas has affected the relationship between the natural gas price and production.

3. Methodology

Long range dependence or strong dependence means that observations which are far distant in time are highly correlated, and there are many processes satisfying this property. Among them, a very popular one and very much used in econometrics is the one that belongs to the category of fractional integration. It means that the number of differences required in a process to render it stationary $I(0)$ is a fractional value.

Given a covariance stationary process $\{x_t,\ t = 0, \pm 1, \ldots\}$, it is said to be $I(0)$ if the infinite sum of all its autocovariances $\gamma_u = E[(x_t - Ex_t)(x_{t+u} - Ex_t)]$ is finite, i.e.,

$$\sum_{u=-\infty}^{\infty} |\gamma_u| < \infty. \qquad (1)$$

Then, a process is said to be integrated of order d or $I(d)$ if it can be represented as:

$$(1 - L)^d x_t = u_t, \quad t = 0, \pm 1, \ldots, \qquad (2)$$

where L is the lag operator $(L^k x_t = x_{t-k})$, and u_t is $I(0)$.[3] Using the Binomial expansion on the expression on L above, the equality in (2) can be expressed as

$$\left(\sum_{j=0}^{\infty} \psi_j L^j \right) x_t = u_t, \qquad t = 0, \pm 1, \ldots$$

$$\left(\sum_{j=0}^{\infty} \binom{d}{j} (-1)^j L^j \right) x_t = u_t, \qquad t = 0, \pm 1, \ldots$$

or, alternatively as

$$\left(1 - d\, L + \frac{d(d-1)}{2} L^2 - \ldots \right) x_t = u_t,$$

implying that

$$x_t = d\, x_{t-1} - \frac{d(d-1)}{2} x_{t-2} + \frac{d(d-1)(d-2)}{6} x_{t-3} - \ldots + u_t .$$

---

[3] An I(0) process is defined as a covariance stationary process when the infinite sum of the autocovariances is finite.

In other words, x_t is determined by its previous history, and the higher the value of d is, the higher the level of association is between observations distant in time. The differencing parameter d plays a very vital function as an indicator of the degree of persistence in the data. Also, this parameter is relevant from a statistical viewpoint. If d is positive but smaller than 0.5, x_t is still covariance stationary, but as d increases from 0.5, the series becomes more nonstationary, in the sense that the variance of the partial sums increases with d; from a policy perspective, $d < 1$ implies mean reversion, i.e., random shocks will have a temporary nature and disappear in the long run. On the other hand, if $d \geq 1$, there is no mean reversion and shocks will have a permanent nature, persisting forever.

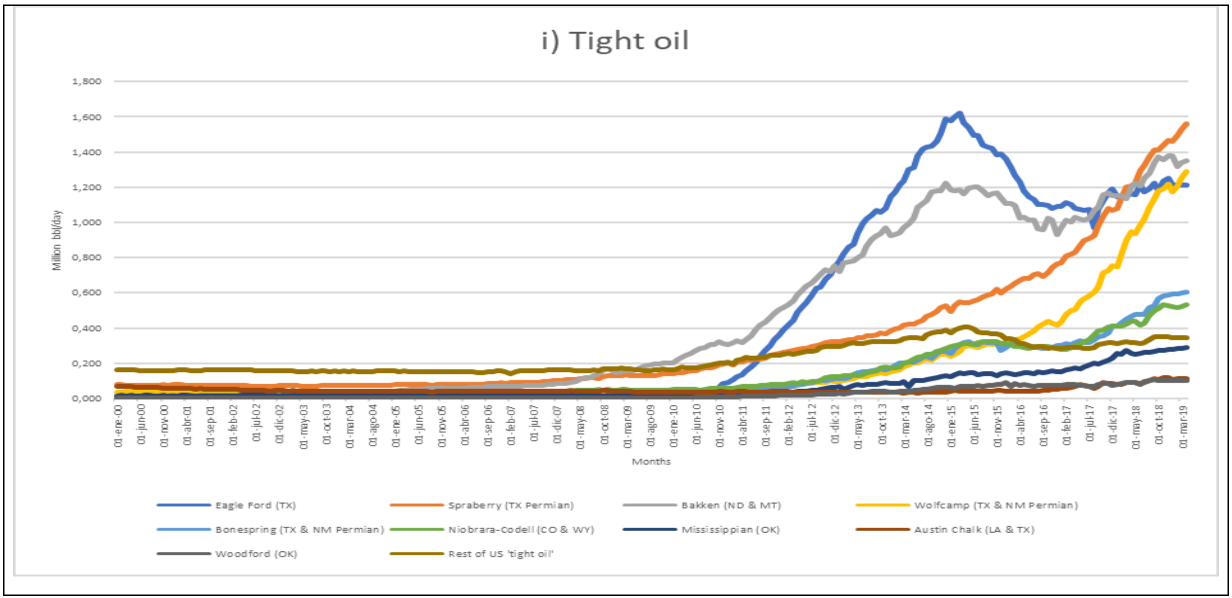
In this article a battery of methods will be used to estimate d, some of them based on parametric methods, while others use semiparametric or even nonparametric approaches. All of them will be based on the Whittle function in the frequency domain (Dahlhaus, 1989). For the parametric methods, a version of the tests of Robinson (1994) is used. This method will permit us to test any real value d in (2) under specific assumptions about the disturbance term u_t. Here the case of white noise u_t will be first implemented, but also autocorrelation in turn, using a non-parametric approach of dealing with autocorrelation based on the exponential spectral method of Bloomfield (1973). A semiparametric method (Robinson, 1995) where no functional form is imposed on u_t will also be employed.

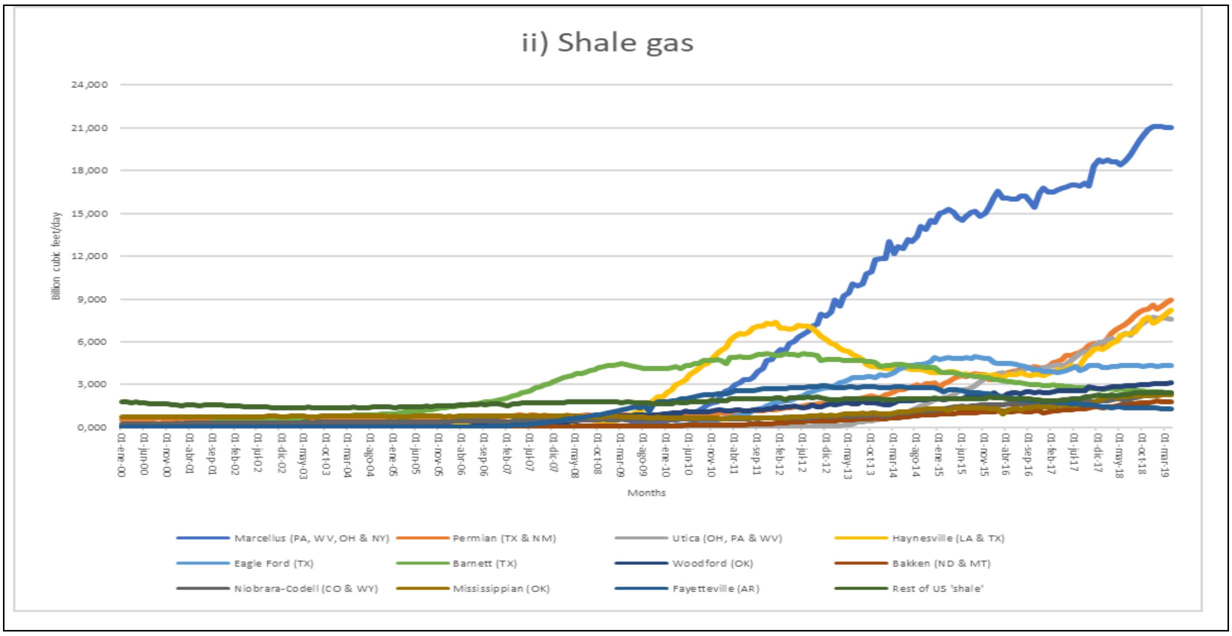
4. Data

The monthly data for the shale gas and oil plays have been generated from the *Energy Information Administration* for the period, January 2000 to April, 2019. Figure 1 shows the evolution of shale gas and oil production during the period under consideration. Bakken (ND & MT), Eagle Ford (TX) and Spraberry (TX Permian) are the biggest shale oil producers under the sample period. Wolfcamp (TX&NM) although a little later than the previous series, also has significant growth. On the other hand, Woodford (OK), Austin Chalk (LA & TX) and Mississippian (OK) have the smallest volume of shale oil production.

All series grow during the period considered, reaching maximum production in 2019 (except Eagle Ford and Rest of US) with maximum production in 2015. Shale gas series, in general, also grow throughout the sample period and the maximum production in each of the study areas corresponds to the last year of the sample period (2019), except in Barnett, Fayetteville, and Eagle Ford (maximum productions in 2011, 2012 and 2015 respectively). The extraction of shale gas in Marcellus started in 2005, since then the production has grown without interruption, reaching its maximum in 2019, surpassing the maximum production of Barnett, Haynesville, Permian and Utica, and becoming the main source of gas in the United States.

Figure 1: Production of shale oil and gas plays in the U.S. (2000-2019)





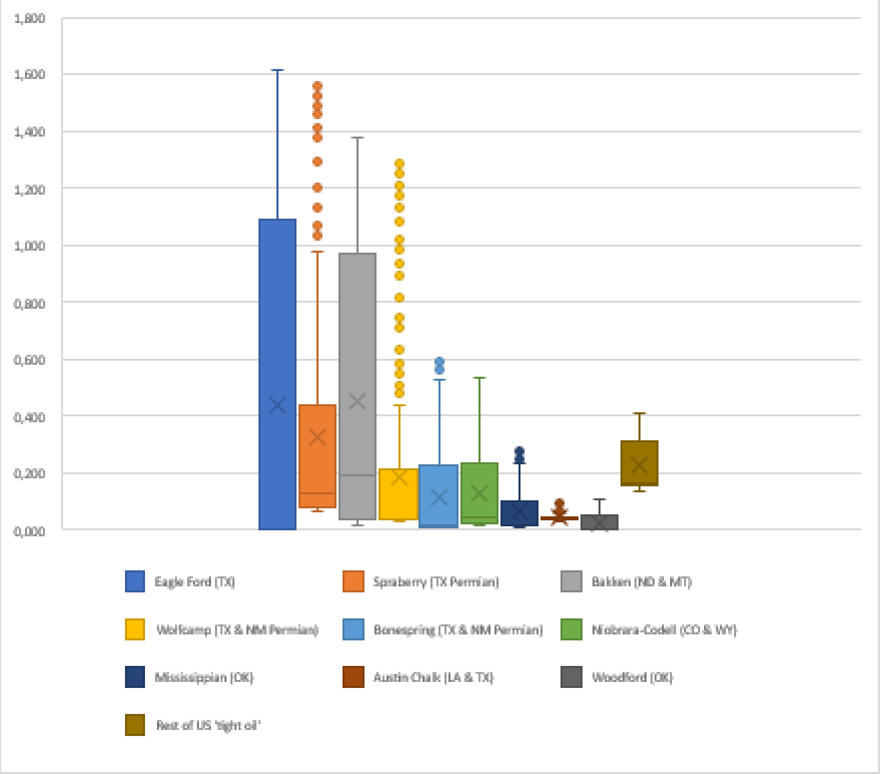
Note: AR is Arkansas; CO is Colorado; LA is Los Angeles; MT is Montana; ND is North Dakota; NM is New Mexico; OH is Ohio; Ok is Oklahoma; PA is Pennsylvania; TX is Texas; WV is West Virginia; WY is Wyoming.

The list and the descriptive analysis of the selected countries are presented in Table 1. Boxplot shows in terms of position measurements, the differences between the analyzed series. The importance of Eagle Ford (TX) and Bakken (ND&MT) in oil production is noted. As far as the shale gas series are concerned, production in Marcellus is significant (PA, WV, OH &NY). In average terms, Marcellus (PA, WV, OH & NY) are the biggest shale gas producers under the sample period. The maximum oil production averages are found in Bakken (ND&MT), Eagle Ford (TX) and Spraberry (TX Permian). The outliers of Spraberry (TX Permian) and Wolfcamp (TX&NM), referring to oil production maximums, show the irregularity of their series, which may lead to confusion in the interpretation of their trends. In this sense, the same is true in the production of shale oil in Permian (TX&NM) and Utica (OH, PA&WV).

Table 1: Descriptive statistics and boxplot of shale oil and gas plays in the U.S.

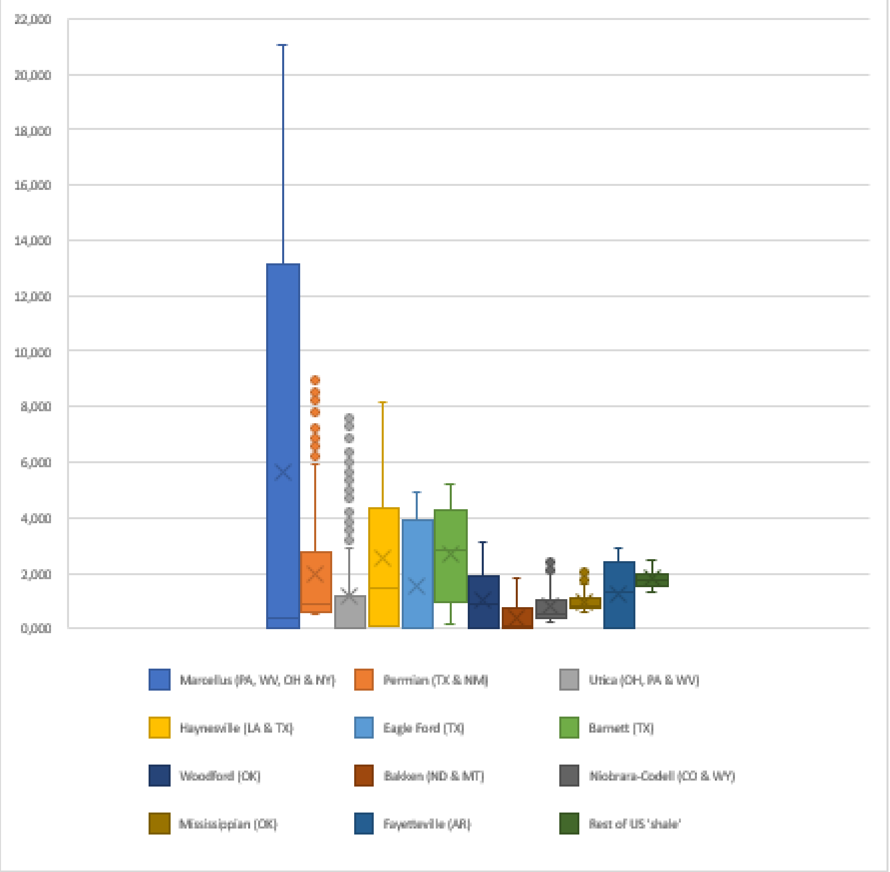
i) Tight oil

Austin Chalk (LA & TX)	
Mean	0.05
Maximm	0.12
Minimun	0.03
Bakken (ND & MT)	
Mean	0.45
Maximm	1.38
Minimm	0.02
Bonespring (TX & NM Permian)	
Mean	0.12
Maximm	0.61
Minimm	0.01
Eagle Ford (TX)	
Mean	0.44
Maximm	1.62
Minimm	0.00
Mississippian (OK)	
Mean	0.06
Maximm	0.29
Minimm	0.01
Niobrara-Codell (CO & WY)	
Mean	0.13
Maximm	0.54
Minimm	0.01
esto f US 'tight oil'	
Mean	0.23
Maximm	0.41
Minimm	0.14
Spraberry (TX Permian)	
Mean	0.33
Maximm	1.56
Minimm	0.07
Wolfcamp (TX & NM Permian)	
Mean	0.18
Maximm	1.29
Minimm	0.03
Woodford (OK)	
Mean	0.02
Maximm	0.11
Minimm	0.00



ii) Shale gas

Bakken (ND & MT)	
Mean	0.41
Maximm	1.85
Minimm	0.01
Barnett (TX)	
Mean	2.72
Maximm	5.22
Minimm	0.13
Eagle Ford (TX)	
Mean	1.56
Maximm	4.95
Minimm	0.00
Fayetteville (AR)	
Mean	1.21
Maximm	2.90
Minimm	0.00
Haynesville (LA & TX)	
Mean	2.56
Maximm	8.20
Minimm	0.07
Marcellus (PA, WV, OH & NY)	
Mean	5.64
Maximm	21.07
Minimm	0.00
Mississippian (OK)	
Mean	0.98
Maximm	2.32
Minimm	0.59
Niobrara-Codell (CO & WY)	
Mean	0.79
Maximm	2.39
Minimm	0.25
Permian (TX & NM)	
Mean	1.95
Maximm	8.92
Minimm	0.54
esto f US 'shale'	
Mean	1.79
Maximm	2.45
Minimm	1.35
Utica (OH, PA & WV)	
Mean	1.15
Maximm	7.70
Minimm	0.00
Woodford (OK)	
Mean	1.04
Maximm	3.11
Minimm	0.01



Note: AR is Arkansas; CO is Colorado; LA is Los Angeles; MT is Montana; ND is North Dakota; NM is New Mexico; OH is Ohio; OK is Oklahoma; PA is Pennsylvania; TX is Texas; WV is West Virginia; WY is Wyoming. The units are millions bbl/day in the case of i) (tight oil) and Billions cubic feet/day in the case of in ii) (shale gas).

5. Empirical results

Following authors such as Bhargava (1986), Schmidt and Phillips (1992) among others on the parameterization in unit roots models, the following linear model is used:

$$y_t \; = \; \alpha + \; \beta t \;\; + \;\; x_t \, , \qquad (3)$$

where y_t is each of the time series we observe; α and β are unknown coefficients referring to an intercept and a liner time trend, and x_t is defined as in equation (2), i.e., following an *I(d)* process. Thus, the model examined is:

$$y_t \; = \; \alpha + \; \beta t \;\; + \;\; x_t \, , \qquad (1 \, - L)^d \, x_t \;\; = \;\; u_t \, , \quad t \; = \; 1 \, , 2 \, , \ldots , \qquad (4)$$

testing the null hypothesis

$$H_o : \; d \;\; = d_o \, , \qquad (5)$$

for d_o-real values equal to -1, -0.99, … 1.99 and 2.

Tables 2 – 5 display the Whittle estimates of d for three set-ups, corresponding to the case of non-deterministic terms (2nd column), including a constant (in the 3rd column), and with a constant and a linear time trend (4th column), reporting also the 95% confidence intervals of the values of *d* where the null hypothesis cannot be rejected using Robinson's (1994) tests.

Tables 2 and 3 refer to the case of white noise errors, while Tables 4 and 5 allow for weak autocorrelation in the error term using the model of Bloomfield (1973). Values in bold in Tables 2 and 4 refer to the selected models for each series in relation to the deterministic terms[4], and once the models are selected, Tables 3 and 5 present their corresponding estimated coefficients.

Table 2: Estimated values of d under white noise errors

i) Tight oil			
Series	No terms	An intercept	A time trend
Austin Chalk (LA & TX)	1.00 (0.93, 1.09)	**0.98 (0.92, 1.07)**	0.98 (0.92, 1.07)
Bakken (ND & MT)	1.14 (1.08, 1.22)	1.14 (1.08, 1.22)	**1.15 (1.09, 1.23)**
Bonespring (TX & NM	1.16 (1.10, 1.22)	1.15 (1.10, 1.22)	**1.16 (1.11, 1.23)**
Eagle Ford (TX)	**1.28 (1.23, 1.34)**	1.28 (1.22, 1.34)	1.28 (1.23, 1.34)
Mississippian (OK)	0.98 (0.94, 1.03)	0.98 (0.94, 1.03)	**0.98 (0.93, 1.03)**
Niobrara-Codell (CO & WY)	1.31 (1.22, 1.43)	**1.31 (1.22, 1.44)**	1.32 (1.23, 1.44)
Rest of US 'tight oil'	1.03 (0.95, 1.13)	**1.15 (1.08, 1.24)**	1.15 (1.09, 1.24)
Spraberry (TX Permian)	1.25 (1.21, 1.31)	1.25 (1.21, 1.31)	**1.27 (1.23, 1.32)**
Wolfcamp (TX & NM Permian)	1.30 (1.25, 1.37)	1.29 (1.24, 1.37)	**1.30 (1.24, 1.36)**
Woodford (OK)	0.85 (0.81, 0.90)	0.85 (0.81, 0.90)	**0.83 (0.79, 0.88)**
ii) Shale gas			
Series	No terms	An intercept	A time trend
Bakken (ND & MT)	1.08 (1.03, 1.14)	1.08 (1.03, 1.14)	**1.08 (1.04, 1.15)**
Barnett (TX)	1.18 (1.13, 1.24)	**1.18 (1.14, 1.24)**	1.18 (1.14, 1.24)
Eagle Ford (TX)	**1.23 (1.18, 1.30)**	1.23 (1.18, 1.30)	1.24 (1.18, 1.30)
Fayetteville (AR)	**1.10 (1.06, 1.14)**	1.10 (1.06, 1.14)	1.10 (1.06, 1.14)
Haynesville (LA & TX)	**1.40 (1.34, 1.48)**	1.40 (1.34, 1.48)	1.40 (1.34, 1.48)
Marcellus (PA, WV, OH & NY)	1.07 (1.03, 1.12)	1.07 (1.03, 1.12)	**1.08 (1.03, 1.13)**
Mississippian (OK)	0.93 (0.87, 1.00)	0.89 (0.85, 0.95)	**0.89 (0.84, 0.95)**
Niobrara-Codell (CO & WY)	1.06 (1.00, 1.12)	1.06 (1.01, 1.12)	**1.06 (1.01, 1.13)**
Permian (TX & NM)	1.23 (1.17, 1.30)	1.23 (1.17, 1.30)	**1.24 (1.18, 1.31)**
Rest of US 'shale'	0.97 (0.89, 1.08)	**0.96 (0.90, 1.03)**	0.95 (0.89, 1.03)
Utica (OH, PA & WV)	1.23 (1.18, 1.29)	1.23 (1.18, 1.29)	**1.24 (1.19, 1.30)**
Woodford (OK)	0.90 (0.87, 0.95)	0.90 (0.86, 0.95)	**0.88 (0.83, 0.94)**

In bold, the selected models according to the deterministic terms.

---

[4] These models were selected by looking at the t-values of the coefficients on the do-differenced processes, noting that under H_o (5) the model in (4) can be expressed as $\tilde{y}_t = \alpha \tilde{1}_t + \beta \tilde{t}_t + u_t$, where $\tilde{y}_t = (1-L)^{d_o} y_t$; $\tilde{1}_t = (1-L)^{d_o}$; and $\tilde{t}_t = (1-L)^{d_o} t$, and u_t is I(0) by construction.

Table 3: Estimated coefficients for the selected models in Table 2

<table>
<tr><th colspan="4">i) Tight oil</th></tr>
<tr><th>Series</th><th>d (95% band)</th><th>Intercept (t-value)</th><th>Time trend (t-</th></tr>
<tr><td>Austin Chalk (LA & TX)</td><td>0.98 (0.92, 1.07)</td><td>0.0679 (20.90)</td><td>---</td></tr>
<tr><td>Bakken (ND & MT)</td><td>1.15 (1.09, 1.23)</td><td>0.0177 (1.95)</td><td>0.0054 (2.08)</td></tr>
<tr><td>Bonespring (TX & NM</td><td>1.16 (1.11, 1.23)</td><td>0.0073 (1.97)</td><td>0.0026 (2.37)</td></tr>
<tr><td>Eagle Ford (TX)</td><td>1.28 (1.23, 1.34)</td><td>---</td><td>---</td></tr>
<tr><td>Mississippian (OK)</td><td>0.98 (0.93, 1.03)</td><td>0.0137 (2.54)</td><td>0.0011 (3.67)</td></tr>
<tr><td>Niobrara-Codell (CO & WY)</td><td>1.31 (1.22, 1.44)</td><td>0.0149 (2.74)</td><td>---</td></tr>
<tr><td>Rest of US 'tight oil'</td><td>1.15 (1.08, 1.24)</td><td>0.1599 (30.18)</td><td>---</td></tr>
<tr><td>Spraberry (TX Permian)</td><td>1.27 (1.23, 1.32)</td><td>0.0747 (7.19)</td><td>0.0063 (2.39)</td></tr>
<tr><td>Wolfcamp (TX & NM</td><td>1.30 (1.24, 1.36)</td><td>0.0337 (2.97)</td><td>0.0056 (1.78)</td></tr>
<tr><td>Woodford (OK)</td><td>0.83* (0.79, 0.88)</td><td>-0.00012 (-0.40)</td><td>0.0004 (5.01)</td></tr>
<tr><th colspan="4">ii) Shale gas</th></tr>
<tr><th>Series</th><th>d (95% band)</th><th>Intercept (t-value)</th><th>Time trend (t-</th></tr>
<tr><td>Bakken (ND & MT)</td><td>1.08 (1.04, 1.15)</td><td>0.0084 (1.38)</td><td>0.0078 (3,46)</td></tr>
<tr><td>Barnett (TX)</td><td>1.18 (1.14, 1.24)</td><td>0.1289 (1.88)</td><td>---</td></tr>
<tr><td>Eagle Ford (TX)</td><td>1.23 (1.18, 1.30)</td><td>---</td><td>---</td></tr>
<tr><td>Fayetteville (AR)</td><td>1.10 (1.06, 1.14)</td><td>---</td><td>---</td></tr>
<tr><td>Haynesville (LA & TX)</td><td>1.40 (1.34, 1.48)</td><td>---</td><td>---</td></tr>
<tr><td>Marcellus (PA, WV, OH &</td><td>1.08 (1.03, 1.13)</td><td>-0.0660 (-1.20)</td><td>0.0894 (3,57)</td></tr>
<tr><td>Mississippian (OK)</td><td>0.89* (0.84, 0.95)</td><td>0.6941 (12.98)</td><td>0.0064 (3,16)</td></tr>
<tr><td>Niobrara-Codell (CO & WY)</td><td>1.06 (1.01, 1.13)</td><td>0.2504 (8.98)</td><td>0.0093 (3,76)</td></tr>
<tr><td>Permian (TX & NM)</td><td>1.24 (1.18, 1.31)</td><td>0.5291 (6.72)</td><td>0.0037 (2,15)</td></tr>
<tr><td>Rest of US 'shale'</td><td>0.96 (0.90, 1.03)</td><td>1.7849 (49.00)</td><td>---</td></tr>
<tr><td>Utica (OH, PA & WV)</td><td>1.24 (1.19, 1.30)</td><td>-0.0171 (-0.23)</td><td>0.0311 (1,93)</td></tr>
<tr><td>Woodford (OK)</td><td>0.88* (0.83, 0.94)</td><td>-0.0156 (-0.32)</td><td>0.0134 (7,66)</td></tr>
</table>

*: Evidence of mean reversion at the 5% level.

Starting with the results under the assumption of no autocorrelation, the time trend is significant in a number of cases. (Bakken, Bonespring, Mississippian, Spraberry, Wolfcamp and Woodford, for tight oil, and Bakken, Marcellus, Mississippian, Niobrara-Codell, Permina, Utica and Woodford in the case of shale oil). For the remaining cases, the intercept is sufficient to describe the deterministic terms. Looking at the estimated differencing parameter, *d*, in Table 3, for tight oil (Panel I), in seven out of the ten cases examined the estimates of d are statistically higher than 1; for two cases, the unit root cannot be rejected, and only for Woodford is there some evidence of mean reversion, with the value of *d* being statistically smaller than one. Looking at shale oil (Panel II), in nine out of the twelve cases *d* is higher than 1; for another one, the unit root null cannot be rejected, and for Mississippian and Woodford, a small degree of mean reversion is found in the data. Thus, according to these results, there is strong evidence of large degrees of persistence, and only for Woodford (in both tight and shale oil) and for Mississippian shale oil, is some small degree of mean reversion achieved.

Table 4: Estimated values of d under autocorrelated errors

i) Tight oil			
Series	No terms	An intercept	A time trend
Austin Chalk (LA & TX)	**0.94 (0.84, 1.07)**	0.93 (0.85, 1.01)	0.92 (0.85, 1.01)
Bakken (ND & MT)	**1.21 (1.11, 1.36)**	1.22 (1.11, 1.36)	1.23 (1.12, 1.37)
Bonespring (TX & NM Permian)	1.23 (1.15, 1.34)	**1.23 (1.14, 1.34)**	1.24 (1.16, 1.35)
Eagle Ford (TX)	**1.56 (1.44, 1.71)**	1.56 (1.44, 1.71)	1.56 (1.44, 1.71)
Mississippian (OK)	1.26 (1.17, 1.38)	**1.26 (1.18, 1.39)**	1.28 (1.19, 1.40)
Niobrara-Codell (CO & WY)	1.13 (1.05, 1.26)	1.14 (1.04, 1.25)	**1.14 (1.04, 1.28)**
Rest of US 'tight oil'	**1.02 (0.89, 1.19)**	1.20 (1.09, 1.34)	1.19 (1.08, 1.34)
Spraberry (TX Permian)	1.34 (1.27, 1.43)	**1.36 (1.29, 1.44)**	1.37 (1.30, 1.45)
Wolfcamp (TX & NM Permian)	**1.35 (1.28, 1.44)**	1.35 (1.28, 1.43)	1.38 (1.29, 1.44)
Woodford (OK)	1.06 (0.98, 1.15)	1.06 (0.99, 1.15)	**1.06 (0.98, 1.17)**
ii) Shale gas			
Series	No terms	An intercept	A time trend
Bakken (ND & MT)	1.11 (1.05, 1.20)	1.11 (1.05, 1.20)	**1.14 (1.06, 1.22)**
Barnett (TX)	**1.41 (1.32, 1.51)**	1.42 (1.33, 1.52)	1.41 (1.33, 1.52)

Eagle Ford (TX)	**1.43 (1.33, 1.56)**	1.43 (1.33, 1.56)	1.43 (1.34, 1.56)
Fayetteville (AR)	**1.36 (1.30, 1.44)**	1.36 (1.30, 1.44)	1.36 (1.30, 1.44)
Haynesville (LA & TX)	**1.46 (1.36, 1.58)**	1.46 (1.36, 1.59)	1.46 (1.36, 1.58)
Marcellus (PA, WV, OH & NY)	**1.25 (1.18, 1.36)**	1.25 (1.18, 1.36)	1.27 (1.20, 1.38)
Mississippian (OK)	**1.08 (0.98, 1.20)**	1.12 (1.03, 1.23)	1.12 (1.03, 1.23)
Niobrara-Codell (CO & WY)	1.15 (1.07, 1.26)	1.16 (1.09, 1.25)	**1.17 (1.09, 1.27)**
Permian (TX & NM)	1.27 (1.20, 1.37)	1.26 (1.20, 1.36)	**1.29 (1.21, 1.37)**
Rest of US 'shale'	**0.95 (0.81, 1.11)**	1.07 (0.96, 1.22)	1.07 (0.95, 1.23)
Utica (OH, PA & WV)	**1.34 (1.25, 1.47)**	1.34 (1.25, 1.47)	1.36 (1.27, 1.48)
Woodford (OK)	0.98 (0.93, 1.05)	0.98 (0.93, 1.05)	**0.98 (0.92, 1.06)**

In bold, the selected models according to the deterministic terms.

Table 5: Estimated coefficients for the selected models in Table 3

i) Tight oil			
Series	No terms	An intercept	A time trend
Austin Chalk (LA & TX)	0.94 (0.84, 1.07)	---	---
Bakken (ND & MT)	1.21 (1.11, 1.36)	---	---
Bonespring (TX & NM Permian)	1.23 (1.14, 1.34)	0.0075 (1.69)	---
Eagle Ford (TX)	1.56 (1.44, 1.71)	---	---
Mississippian (OK)	1.26 (1.18, 1.39)	0.0142 (2.97)	---
Niobrara-Codell (CO & WY)	1.14 (1.04, 1.28)	0.3099 (0.01)	0.0022 (2.99)
Rest of US 'tight oil'	1.02 (0.89, 1.19)	---	---
Spraberry (TX Permian)	1.36 (1.29, 1.44)	0.0752 (1.83)	---
Wolfcamp (TX & NM Permian)	1.35 (1.28, 1.44)	---	---
Woodford (OK)	1.06 (0.98, 1.17)	-3.3640 (-0.11)	0.0004 (1.67)
ii) Shale gas			
Series	No terms	An intercept	A time trend
Bakken (ND & MT)	1.14 (1.06, 1.22)	0.0092 (0.42)	0.0077 (2.69)
Barnett (TX)	1.41 (1.32, 1.51)	---	---
Eagle Ford (TX)	1.43 (1.33, 1.56)	---	---
Fayetteville (AR)	1.36 (1.30, 1.44)	---	---
Haynesville (LA & TX)	1.46 (1.36, 1.58)	---	---
Marcellus (PA, WV, OH & NY)	1.25 (1.18, 1.36)	---	---
Mississippian (OK)	1.08 (0.98, 1.20)	---	---

Niobrara-Codell (CO & WY)	1.17 (1.09, 1.27)	0.2521 (9.34)	0.0093 (2.21)
Permian (TX & NM)	1.29 (1.21, 1.37)	0.5299 (6.86)	0.0364 (1.69)
Rest of US 'shale'	0.95 (0.81, 1.11)	---	---
Utica (OH, PA & WV)	1.34 (1.25, 1.47)	---	---
Woodford (OK)	0.98 (0.92, 1.06)	-0.0047 (-0.06)	0.0134 (4.69)

*: Evidence of mean reversion at the 5% level.

Table 6: Estimates of d based on a semiparametric method

i) Tight oil			
Series	9	15	26
Austin Chalk (LA & TX)	> 1.500	> 1.500	1.201
Bakken (ND & MT)	1.477	> 1.500	1.362
Bonespring (TX & NM Permian)	> 1.500	> 1.500	> 1.500
Eagle Ford (TX)	> 1.500	> 1.500	> 1.500
Mississippian (OK)	1.485	1.434	1.455
Niobrara-Codell (CO & WY)	1.391	> 1.500	1.318
Rest of US 'tight oil'	1.201	> 1.500	1.457
Spraberry (TX Permian)	> 1.500	> 1.500	> 1.500
Wolfcamp (TX & NM Permian)	> 1.500	> 1.500	> 1.500
Woodford (OK)	1.414	1-273	1.193
ii) Shale gas			
Series	9	15	26
Bakken (ND & MT)	> 1.500	1.465	1.486
Barnett (TX)	> 1.500	> 1.500	> 1.500
Eagle Ford (TX)	> 1.500	> 1.500	1.469
Fayetteville (AR)	> 1.500	> 1.500	> 1.500
Haynesville (LA & TX)	> 1.500	> 1.500	> 1.500
Marcellus (PA, WV, OH & NY)	> 1.500	> 1.500	1.317
Mississippian (OK)	1.497	1.288	1.174
Niobrara-Codell (CO & WY)	1.421	> 1.500	1.365
Permian (TX & NM)	> 1.500	> 1.500	1.477
Rest of US 'shale'	1.011	1.224	1.172
Utica (OH, PA & WV)	> 1.500	> 1.500	> 1.500
Woodford (OK)	> 1.500	1.349	1.245

Next, in Tables 4 and 5, autocorrelated errors are permitted. For tight oil, the time trend is only required in the cases of Niobrara-Codell and Woodford, and for shale oil, the trend is significant in the cases of Bakken, Niobrara-Codell, Pernian and Woodford (in all cases the coefficients are positive). However, looking now at the estimated values of *d*, there is no sign of mean reversion in any single case, either in tight oil or in shale oil. The hypothesis of a unit root cannot be rejected for Austin Chalk and Woodford with tight oil, and for Rest of US and Woodford with shale oil. In all the other cases, d is found to be significantly higher than 1. Thus, little support of mean reversion is obtained in the results presented so far. Then, as a robustness method, a semiparametric method is implemented in which no specific model is imposed on the error term, simply allowing it to be *I(0)*. A "local" Whittle approach of Robinson (1995) is chosen here. The reason for this choice is that though there exist many other semiparametric methods (some of them in fact being extensions and improvements over Robinson, 1995) these generally require additional user-chosen parameters and the results are very sensitive to these numbers. In that sense, Robinson (1995) only requires a single bandwidth number.

Table 6 displays the results for a selected group of bandwidth numbers, $m = 9$ (which is approximately $T^{0.4}$), $m = 15$ ($T^{0.5}$) and $m = 26$ ($T^{0.6}$), where T is the sample size used. In general, large values for the estimates of *d* are observed, most of them being significantly higher than 1. Thus, there is no evidence of mean reversion with the semiparametric method, which is consistent with the parametric results based on autocorrelated errors.

6. Robustness checking

Since there was little production of unconventional oil and gas prior to 2007, we consider now data starting in January 2007, and the results in terms of the estimated values of d are presented in Table 7. Thus, it reproduces Table 2 but with data starting in January 2007. We see that the values are very similar to those using the whole sample size. In fact, the only qualitative difference takes place in the case of Mississippian in the tight oil, since the unit root null hypothesis could not be rejected with the whole dataset and is now rejected in favour of mean reversion (d < 1) with the data starting in January 2007. For all the other cases, the results are qualitatively very similar to those reported in Table 2 finding evidence of unit or explosive roots in the majority of the cases.

Table 7: Estimated values of d under white noise errors (data starting at 2007)

i) Tight oil			
Series	No terms	An intercept	A time trend
Austin Chalk (LA & TX)	0.98 (0.89, 1.12)	0.96 (0.88, 1.10)	**0.96 (0.87, 1.11)**
Bakken (ND & MT)	1.10 (1.01, 1.22)	1.11 (1.03, 1.23)	**1.11 (1.03, 1.23)**
Bonespring (TX & NM	1.10 (1.03, 1.20)	1.11 (1.04, 1.20)	**1.12 (1.04, 1.22)**
Eagle Ford (TX)	**1.27 (1.21, 1.36)**	1.27 (1.21, 1.36)	1.27 (1.20, 1.36)
Mississippian (OK)	0.92 (0.87, 0.99)	0.92 (0.87, 0.99)	**0.91 (0.84, 0.99)**
Niobrara-Codell (CO & WY)	1.27 (1.14, 1.45)	**1.30 (1.17, 1.48)**	1.31 (1.19, 1.49)
Rest of US 'tight oil'	1.01 (0.91, 1.15)	**1.17 (1.08, 1.29)**	1.17 (1.08, 1.29)
Spraberry (TX Permian)	1.20 (1.13, 1.28)	1.20 (1.14, 1.28)	**1.22 (1.16, 1.30)**
Wolfcamp (TX & NM Permian)	1.26 (1.19, 1.35)	1.25 (1.19, 1.35)	**1.27 (1.21, 1.37)**
Woodford (OK)	0.77 (0.70, 0.83)	0.78 (0.73, 0.89)	**0.70 (0.61, 0.80)**
ii) Shale gas			
Series	No terms	An intercept	A time trend
Bakken (ND & MT)	0.99 (0.92, 1.08)	0.99 (0.93, 1.08)	**0.99 (0.91, 1.10)**
Barnett (TX)	1.02 (0.94, 1.15)	**1.08 (1.02, 1.17)**	1.08 (1.02, 1.17)
Eagle Ford (TX)	1.23 (1.15, 1.31)	**1.22 (1.15, 1.31)**	1.22 (1.15, 1.31)
Fayetteville (AR)	1.08 (1.02, 1.15)	**1.07 (1.02, 1.14)**	1.07 (1.02, 1.14)
Haynesville (LA & TX)	**1.40 (1.32, 1.51)**	1.40 (1.32, 1.50)	1.39 (1.32, 1.50)
Marcellus (PA, WV, OH & NY)	0.97 (0.91, 1.05)	0.97 (0.92, 1.05)	**0.96 (0.89, 1.07)**
Mississippian (OK)	0.88 (0.80, 0.98)	0.86 (0.84, 0.93)	**0.84 (0.77, 0.92)**
Niobrara-Codell (CO & WY)	1.02 (0.95, 1.13)	1.01 (0.94, 1.10)	**1.01 (0.95, 1.11)**

Permian (TX & NM)	1.17 (1.09, 1.28)	1.18 (1.11, 1.28)	**1.20 (1.13, 1.30)**
Rest of US 'shale'	0.99 (0.88, 1.13)	0.97 (0.87, 1.11)	**0.97 (0.87, 1.10)**
Utica (OH, PA & WV)	1.18 (1.12, 1.28)	1.18 (1.12, 1.28)	**1.21 (1.14, 1.30)**
Woodford (OK)	0.69 (0.62, 0.81)	0.71 (0.67, 0.76)	**0.52 (0.41, 0.67)**

In bold, the selected models according to the deterministic terms.

Also, the possibility of non-linear trends is also taken into account. This is an important issue, noting that fractional integration and structural breaks are very intimated related issues (see, e.g., Diebold and Inoue, 2001). For this purpose, we use the approach developed in Cuestas and Gil-Alana (2016) that allows for fractional integration in the context of the Chebyshev polyonomials in time. We consider here the following model,

$$y_t \;=\; \sum_{i=0}^{m} \theta_i P_{iT}(t) \;+\; x_t\,; \qquad (1 \,-\, L)^d x_t \;=\; u_t, \qquad t \;=\; 1, 2, \ldots\,, \tag{6}$$

with m indicating the order of the Chebyshev polynomial $P_{i,T}(t)$ defined as:

$$P_{0,T}(t) \;=\; 1,$$

$$P_{i,T}(t) \;=\; \sqrt{2}\cos\left(i\pi(t-0.5)/T\right), \qquad t \;=\; 1, 2, \ldots, T; \qquad i \;=\; 1, 2, \ldots\,. \tag{7}$$

Hamming (1973) and Smyth (1998) present a detailed description of these polynomials in time, and Bierens (1997) and Tomasevic *et al.* (2009) argue that it is possible to approximate highly non-linear trends with rather low degree polynomials. Thus, if $m = 0$ the model contains an intercept, if $m = 1$ it also includes a linear trend, and if $m > 1$ it becomes non-linear - the higher m is the less linear the approximated deterministic component becomes.

Table 8 displays the estimates of d in (6) along with the Chebyshev coefficients, imposing m = 3, and using white noise errors. Thus, if the coefficients corresponding to θ_2 and/or θ_3 are statistically significantly different from zero we can conclude that the series display some non-linear structures. We observe in this table many significant non-linear coefficients. Starting with the tight oil, θ_2 is found to be significant in all except three series: Niobrara-

Codell, the rest of US and Wolfcamp. On the other hand, θ_3 is insignificant in the majority of the series, being significant only for Mississippian and Woodford. Looking now at shale gas, there are six series where both θ_2 and θ_3 are statistically significant; in another four series, one of the two coefficients is significant, and only for the Rest of the US the two coefficients are insignificant. Thus, evidence of non-linear structures is found in the majority of the cases examined. If we look now at the orders of integration of the series, evidence of mean reversion is found in two of the tight oil series (Mississippian and Woodford) and in four in the shale gas (Fayetteville, Marcellus, Mississippian and Woodford). In all the other cases, the estimates of *d* are equal to higher than 1 implying lack of mean reversion.

Table 8: Estimated values in a non-linear I(d) framework

i) Tight oil					
Series					
Austin Chalk (LA & TX)	0.95 (0.87, 1.04)	**0.065** **(3.21)**	-0.004 (-0.38)	**0.012** **(1.87)**	-0.006 (-1.39)
Bakken (ND & MT)	1.11 (1.03, 1.20)	0.395 (1.56)	**-0.428** **(-2.74)**	**0.141** **(2.05)**	0.022 (0.50)
Bonespring (TX & NM)	1.14 (1.08, 1.23)	0.094 (0.79)	-0.104 (-1.40)	**0.070** **(2.23)**	-0.026 (-1.34)
Eagle Ford (TX)	1.25 (1.19, 1.32)	0.349 (0.67)	-0.510 (-1.55)	**0.215** **(1.72)**	0.047 (0.63)
Mississippian (OK)	0.88 (0.83, 0.95)	**0.074** **(3.11)**	**-0.063** **(-4.52)**	**0.041** **(5.12)**	**-0.019** **(-3.51)**
Niobrara-Codell (CO & WY)	1.31 (1.21, 1.44)	0.062 (0.31)	-0.062 (-0.50)	0.050 (1.11)	-0.020 (-0.76)
Rest of US 'tight oil'	1.12 (1.05, 1.22)	**0204** **(2.69)**	-0.069 (-1.48)	0.021 (1.07)	0.016 (1.25)
Spraberry (TX Permian)	1.25 (1.19, 1.30)	0.153 (0.54)	-0.114 (-0.64)	**0.123** **(1.82)**	-0.062 (-1.53)
Wolfcamp (TX & NM Permian)	1.28 (1.22, 1.34)	-0.066 (-0.18)	0.047 (-0.20)	0.085 (1.03)	-0.059 (-1.21)
Woodford (OK)	0.61 (0.53, 0.70)	**0.025** **(7.07)**	**-0.029** **(-13.96)**	**0.016** **(10.20)**	**-0.004** **(-3.95)**
ii) Shale gas					
Series					
Bakken (ND & MT)	1.00 (0.93, 1.08)	**0.448** **(2.71)**	**-0.455** **(-4.59)**	**0.243** **(4.84)**	**-0.094** **(-2.82)**
Barnett (TX)	0.97 (0.90, 1.06)	**2.638** **(5.75)**	**1.209** **(4.41)**	**-1.014** **(-7.15)**	**0.453** **(4.73)**

Eagle Ford (TX)	1.17 (1.10, 1.25)	1.274 (1.19)	**-1.767** **(-2.63)**	**0.726** **(2.63)**	0.139 (0.80)
Fayetteville (AR)	0.76 (0.70, 0.83)	**1,061** **(8.29)**	**-0.960** **(-13.05)**	**-0.295** **(6.18)**	**0.517** **(14.56)**
Haynesville (LA & TX)	1.37 (1.31, 1.44)	-1.661 (-0.35)	0.710 (0.23)	-0.606 (-0.58)	**1.155** **(1.94)**
Marcellus (PA, WV, OH & NY)	0.92 (0.85, 0.99)	**5.394** **(4.03)**	**-6.541** **(-8.29)**	**3.185** **(7.36)**	-0.455 (-1.52)
Mississippian (OK)	0.78 (0.72, 0.86)	**1.035** **(6.96)**	**-0.313** **(-3.66)**	**0.245** **(4.48)**	**-0.164** **(-4.10)**
Niobrara-Codell (CO & WY)	0.99 (0.92, 1.08)	**0.837** **(3.96)**	**-0.498** **(-3.92)**	**0.231** **(3.61)**	**-0.143** **(-3.34)**
Permian (TX & NM)	1.22 (1.16, 1.29)	1.173 (0.64)	-0.776 (-0.66)	**0.760** **(1.67)**	-0.425 (-1.53
Rest of US 'shale'	0.94 (0.88, 1.03)	**2.045** **(9.26)**	**-0.247** **(-1.89)**	0.032 (0.45)	0.030 (0.63)
Utica (OH, PA & WV)	1.16 (1.10, 1.24)	1.279 (1.01)	-1.270 (-1.62)	**1.102** **(3.37)**	**-0.736** **(-3.60)**
Woodford (OK)	0.77 (0.69, 0.85)	**1.098** **(8.58)**	**-0.999** **(-13.55)**	**0.240** **(5.07)**	-0.013 (-0.37)

In bold, the selected models according to the deterministic terms.

7. Discussions of the results

The predominant evidence for persistence observed in the tested series is similar to the results of Lean and Smyth (2013) that also support persistence of an energy production series but contrary to the output of Narayan et al. (2008) and Barros et al. (2011) produce results in favour of stationarity or mean reversion of different energy production series. The results conform with the hypothesis of Hsu et al. (2008) which states that longer energy series are more likely to be more persistent. According to Hsu et al. (2008), shocks will result in a bigger deviation from the long-run equilibrium path, as it is tougher for large producers to swiftly return to long-run equilibrium. Bakken (ND & MT), Eagle Ford (TX) and Spraberry (TX Permian) are the biggest shale oil producers under the sample period and among the shale oil plays with evidence of more persistence as they produce larger orders of integration. Woodford (OK), Austin Chalk (LA & TX) and Mississippian (OK) have the smallest volume of shale oil production and are among the shale oil plays with lower persistence as they produce smaller coefficients. Marcellus (PA, WV, OH & NY), Barnett (TX) and Haynesville

(LA & TX) are the biggest shale gas producers under the sample period and among the shale gas plays with evidence of more persistence as they produce bigger coefficients. Bakken (ND & MT), Niobrara-Codell (CO & WY) and Mississippian (OK) have the smallest volume of shale gas production and are among the shale gas plays with lower persistence as they produce smaller coefficients.

The results conform with the hypothesis of Narayan et al. (2008) which states that production series with high volatility are likely to be more persistent. Eagle Ford (TX), Bakken (ND & MT) and Spraberry (TX Permian) are the most volatile plays under the sample period and among the shale oil plays with evidence of more persistence as they produce larger orders of integration. Austin Chalk (LA & TX), Woodford (OK) and Mississippian (OK) have the smallest volatility of shale oil production and are among the shale oil plays with lower persistence as they produce smaller degrees of integration. Marcellus (PA, WV, OH & NY), Barnett (TX) and Haynesville (LA & TX) and Utica (OH, PA & WV) are the most volatile plays under the sample period and among the shale gas plays with evidence of more persistence as they produce larger estimated values of *d*.

Our results are not consistent with the postulation of Maslyuk and Smyth (2009), which states that nations with large proven oil reserves will likely have stationary oil production as such countries would be capable of sustaining a consistent supply during political or economic turmoil. The U.S. has significant proven shale oil and shale gas resources and it is one of the richest countries in terms of both resources. The Marcellus shale is the biggest shale gas play in the country and it is valued to have around 141 trillion cubic feet of technically recoverable natural gas reserves. (Forbes, 2014).

The support for the persistence noticed in the analysed plays can be attributed to the nature of their trend paths. The plays displayed a consistent increase in production over the sample period, which can be attributed to the continuous increase in investment in the sector, favourable government policies and programs as well as ecological advances in the area of drilling and hydraulic fracturing, which have been useful in expanding shale oil and gas. Econometrically speaking, a series like the shale oil and gas series that have exhibited an increasing trend in the sample period is not likely to be stationary as its mean will be changing.

8. Conclusion

In this paper the degree of persistence of shale oil and shale gas production of several plays in the U.S. for the period, January, 2000 to April 2019 has been examined. For this purpose, the methods used were based on the concept of fractional integration which is more broadly encompassing than the conventional approaches premised on integer degrees of differentiation. Providing for fractional orders of integration permits us to test cases of nonstationarity though with mean reverting behaviour if the differencing parameter, *d*, is in the range of 0.5 and 1. The results suggest that most of the production series of the plays are persistent. The results further suggest that the degree of persistence is associated with the size and volatility of the plays. One of the implications of the results is that there is a hysteresis or path dependence in shale oil and gas production in the U.S., and therefore shocks resulting from new government policies concerning shale oil and gas in the U.S. will have lasting impacts on their production, signifying that policies aimed at changing the path of unconventional energy will be effective. These results can directly assist policy makers and investors interested in the unconventional energy market. The government needs to actively intervene in the market if there are negative shocks, especially natural disasters such as hurricanes, typhoons tornados, which often occur in the U.S. and have negative impacts on the production of unconventional energy sources. If the authorities fail to intervene, the reduction in unconventional energy, as a result of these disasters, is likely to be long term.

The U.S. has experienced several hurricanes and disasters over the past few years including Hurricane Harvey of 2017, which initially forced the Eagle Ford Rock Formation (shale oil and gas) in southern Texas to reduce output by up to 500,000 barrels per day (World View, 2017). The federal government responded in the same year with the introduction of several policies and programmes including the designation of $15 billion for Hurricane Harvey relief (among other spending actions). Similarly, the investors are likely to make desirable returns on their investment following a positive shock to unconventional sources energy such as the discovery of new and better drilling and fracking methods. Investors or businesses that possess significant market shares in the industry are likely to benefit most from such shocks

Second, as the shale oil and gas series are persistent, business cycle theories explaining output fluctuations as transitory departures from long-run growth (as activities in the energy sector can affect real income) lose their empirical support. The degree to which this happens is dependent on the dollar share of shale oil and gas in total output. This is because the business cycle theories expect the series in an economy to be stationary rather than being persistent as observed in this study.

Third, it will not be feasible to forecast the future values of shale oil and gas production by merely relying on their previous figures. Previous studies have forecasted shale oil and gas with past values serving as a key input in the analysis (Wang and Jiang, 2019). Organisations such as the Energy Information Administration and International Energy Agency have projected figures of shale oil and gas whilst relying on the current and past figures of the series.

Fourth, since the series are persistent, it is clear that not taking first differences in the shale oil and gas series before proceeding to the Granger causality test, may cause the series to be under-differenced. Using statistical methods such as ordinary least squares (OLS) to estimate an equation involving shale oil or shale gas could generate spurious estimates. The conventional diagnostic statistics which are utilised to evaluate OLS estimates will suggest a statistically significant relationship between the series when there is no such relationship and ultimately the procedure may yield inappropriate policy actions. However, it has to be noted that the persistence observed for unconventional energy production might not necessarily mean that there will be persistence in unconventional energy consumption. This is because energy carriers –which are convenient forms of stored energy - may deplete but energy consumption can continue by substitution of the carriers. Moreover, energy consumption figures usually exclude consumption from conversion of primary energy into secondary energy with the loss during the process of energy conversion.

Finally, the fact that non-linear structures of the form of the Chebyshev polynomials in time seem to be plausible in these data, indicates that non-linearities should be taken into account when modelling these and similar data. Nevertheless, even imposing non-linear structures, the orders of integration are high in all cases, indicating large degrees of persistence.

References

American Chemistry Council (2013). Shale gas, competitiveness, and new US chemical industry investment: An analysis based on announced projects. Available at https://www.americanchemistry.com/First-Shale-Study/ (accessed on 17 March 2019).

Arestis, P., & Sawyer, M. (2009). Path Dependency and Demand—Supply Interactions in Macroeconomic Analysis. In *Path dependency and macroeconomics* (pp. 1-36). Palgrave Macmillan, London.

Aruga, K. (2016). The US shale gas revolution and its effect on international gas markets. Journal of Unconventional Oil and Gas Resources, 14, 1-5.

Baffes, J., Kose, M. A., Ohnsorge, F., Stocker, M. 2015. The great plunge in oil prices: Causes, consequences, and policy responses. Policy Research Note No.1, World Bank.

Barros, C. P., Gil-Alana, L. A., & Payne, J. E. (2011). An analysis of oil production by OPEC countries: Persistence, breaks, and outliers. Energy Policy, 39(1), 442-453.

Barros, C. P., Gil-Alana, L. A., & Wanke, P. (2016). Energy production in Brazil: Empirical facts based on persistence, seasonality and breaks. Energy Economics, 54, 88-95.

Benes, J., Chauvet, M., Kamenik, O., Kumhof, M., Laxton, D., Mursula, S., & Selody, J. (2015). The future of oil: Geology versus technology. International Journal of Forecasting, 31(1), 207-221.

Bhargava, A. (1986). On the theory of testing for unit roots in observed time series, Review of Economic Studies, 53, 369-384.

Bierens, H.J., (1997). Testing the unit root with drift hypothesis against nonlinear trend Stationarity with an application to the US price level and interest rate", *Journal of Econometrics* 81, 29-64.

Bilgili, F., Koçak, E., Bulut, Ü., & Sualp, M. N. (2016). How did the US economy react to shale gas production revolution? An advanced time series approach. Energy, 116, 963-977.

Bloomfield, P. (1973). An exponential model in the spectrum of a scalar time series, Biometrika, 60, 217-226.

Cai, Y., & Menegaki, A. N. (2019). Fourier quantile unit root test for the integrational properties of clean energy consumption in emerging economies. Energy Economics, 78, 324-334.

Caporin, M., & Fontini, F. (2017). The long-run oil–natural gas price relationship and the shale gas revolution. Energy Economics, 64, 511-519.

Chew, K.J. (2014), The future of oil: unconventional fossil fuels, Philosophical Transactions: Mathematical, Physical and Engineering Sciences 372, Issue 2006.

Chiodi, A., Grargiulo, M., Gracceva, F., De Miglio, R., Spisto, A., Costescu, A & Giaccaria, S (2016), Unconventional oil and gas resources in future energy markets. A modelling analysis of the economic impacts on global energy markets and implications for Europe, JRC Science for Policy Report, European Comission.

Cuestas, J.C. and L.A. Gil-Alana, (2016), A non-linear approach with long range dependence based on Chebyshev polynomials, Studies in Nonlinear Dynamics and Econometrics 20, 57-94.

Dahlhaus, R. (1989) Efficient parameter estimation for self-similar process, *Annals of Statistics*, 17, 1749-1766.

Diebold, F.X. and A. Inoue (2001), Long memory and regime switching, Journal of Econometrics 105, 1, 131-159.

Energy Information Administration (2014) U.S. Energy Information Administration - EIA - Independent Statistics and Analysis Available at https://www.eia.gov/energyexplained/?page=us_energy_home (accessed on 17 May 2019).

Energy Information Administration (2019). U.S. Energy Facts - Energy Explained. Available at https://www.eia.gov/energyexplained/?page=us_energy_home (accessed on 17 May 2019).

Fallahi, F., Karimi, M., & Voia, M. C. (2016). Persistence in world energy consumption: Evidence from subsampling confidence intervals. Energy Economics, 57, 175-183.

Feng, G. F., Wang, Q. J., Chu, Y., Wen, J., & Chang, C. P. (2019). Does the shale gas boom change the natural gas price-production relationship? Evidence from the US market. Energy Economics, 1-25

Forbes (2014). Here's Why Marcellus shale play is so important for Chesapeake. Available at https://www.forbes.com/sites/greatspeculations/2014/09/26/heres-why-marcellus-shale-play-is-so-important-for-chesapeake/#58c48d536cc2 (accessed on 17 May 2019).

Hamming, R. W. “Numerical Methods for Scientists and Engineers”, Dover (1973).

Hosseini, S.H. & Shakouri, G.H. (2016), A study on the future of unconventional oil development under different oil price scenarios. A system dynamics approach, Energy Policy 91, 64-74.

Hsu, Y. C., Lee, C. C., & Lee, C. C. (2008). Revisited: are shocks to energy consumption permanent or temporary? New evidence from a panel SURADF approach. Energy Economics, 30(5), 2314-2330.

Hu, H., Wei, W., & Chang, C. P. (2019). Do shale gas and oil productions move in convergence? An investigation using unit root tests with structural breaks. Economic Modelling, 77, 21-33

Khraief, N., Omoju, O. E., & Shahbaz, M. (2016). Are fluctuations in electricity consumption per capita in Sub-Saharan Africa countries transitory or permanent?. Energy Strategy Reviews, 13, 86-96.

Kilian, L. (2016a). The impact of the shale oil revolution on US oil and gasoline prices. Review of Environmental Economics and Policy, 10(2), 185-205.

Kilian, L. (2016b). The impact of the fracking boom on Arab oil producers. CESifo Working Paper Series No. 5751, 1-40.

Le, M. T. (2018). An assessment of the potential for the development of the shale gas industry in countries outside of North America. Heliyon, 4(2), e00516.

Lean, H. H., & Smyth, R. (2013). Are fluctuations in US production of renewable energy permanent or transitory?. Applied Energy, 101, 483-488.

Male, F. (2019). Using a segregated flow model to forecast production of oil, gas, and water in shale oil plays. Journal of Petroleum Science and Engineering, 180, 48-61.

Maslyuk, S., & Dharmaratna, D. (2013). Impact of shocks on Australian coal mining. In Global energy policy and security(pp. 231-255). Springer, London.

Maslyuk, S., & Smyth, R. (2009). Non-linear unit root properties of crude oil production. Energy Economics, 31(1), 109-118.

Monge, M., Gil-Alana, L. A., & de Gracia, F. P. (2017). US shale oil production and WTI prices behaviour. Energy, 141, 12-19.

Narayan, P. K., & Smyth, R. (2007). Are shocks to energy consumption permanent or temporary? Evidence from 182 countries. Energy policy, 35(1), 333-341.

Narayan, P. K., Narayan, S., & Smyth, R. (2008). Are oil shocks permanent or temporary? Panel data evidence from crude oil and NGL production in 60 countries. Energy Economics, 30(3), 919-936.

Robinson, P.M. (1994). Efficient tests of nonstationary hypotheses, *Journal of the American Statistical Association* 89, 428, 1420-1437.

Robinson, P.M. (1995) Gaussian semi-parametric estimation of long range dependence, *Annals of Statistics* 23, 1630-1661.

Salisu, A. A., & Adediran, I. A. (2018). The US Shale Oil Revolution and the Behavior of Commodity Prices. Econometric Research in Finance, 3(1), 27-53.

Schmidt, P. and P. C. B. Phillips (1992). LM tests for a unit root in the presence of deterministic trends, Oxford Bulletin of Economics and Statistics, 54, 257-287.

Shahbaz, M., Khraief, N., Mahalik, M. K., & Zaman, K. U. (2014a). Are fluctuations in natural gas consumption per capita transitory? Evidence from time series and panel unit root tests. Energy, 78, 183-195.

Shahbaz, M., Tiwari, A. K., Jam, F. A., & Ozturk, I. (2014). Are fluctuations in coal consumption per capita temporary? Evidence from developed and developing economies. Renewable and Sustainable Energy Reviews, 33, 96-101.

Smyth, G.K. “Polynomial Aproximation”, John Wiley & Sons, Ltd, Chichester, (1998).

Smyth, R. (2013). Are fluctuations in energy variables permanent or transitory? A survey of the literature on the integration properties of energy consumption and production. Applied Energy, 104, 371-378.

Solarin, S. (2015). Assessing the effectiveness of the policies to boost hydropower consumption. International Journal of Energy Sector Management, 9(2), 136-155.

Solarin, S. A., & Lean, H. H. (2016). Are fluctuations in oil consumption permanent or transitory? Evidence from linear and nonlinear unit root tests. Energy Policy, 88, 262-270.

Tomasevic, N.M. and T. Stanivuk. “Regression Analysis and aproximation by means of Chebyshev Polynomial”, Informatologia no.42, 3, (2009): 166-172.

Wang, Q., & Jiang, F. (2019). Integrating linear and nonlinear forecasting techniques based on grey theory and artificial intelligence to forecast shale gas monthly production in Pennsylvania and Texas of the United States. Energy, 178, 781-803.

World Bank (2019). World Development Indicators. Available at www.data.worldbank.org (accessed on 17 May 2019).

World View (2017). U.S.: Hurricane Harvey’s Toll on Texas Energy. Available at https://worldview.stratfor.com/article/us-hurricane-harvey-s-toll-texas-energy (accessed on 17 May 2019).

Zou, C. Zhao, Q, Zhang, G & Xiong, B. (2016), Energy revolution: From a fossil energy era to a new energy era, Natural Gas Industry B 3, 1, 1-11.