Economic Modelling 77 (2019) 21–33

Contents lists available at ScienceDirect

Economic Modelling

journal homepage: www.journals.elsevier.com/economic-modelling

Do shale gas and oil productions move in convergence? An investigation using unit root tests with structural breaks

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A R T I C L E I N F O

JEL classification:
K32
C23
C40

Keywords:
Shale gas
Shale oil
Natural gas
Structural breaks

A B S T R A C T

This paper investigates the long-run trends of shale gas and shale oil productions by applying univariate and panel Lagrange Multiplier (LM), GARCH-based, and PANICCA unit root tests to discover the mean-reverting behaviors. We employ monthly data from January 2007 to December 2016 of shale gas withdrawals and shale oil productions in the U.S. The empirical results both on specific state/oil well and panel data show that most structural breaks emerge around 2007–2011, during which shale energy was massively produced in the U.S. and the global financial crisis and energy shock occurred. Our results also indicate that most external shocks are transitory and the trends soon converge, and that cross-state/well factors have greater potential as temporary shocks than the state-specific/well-particular components. For robust analysis, we conduct additional LM tests of natural gas and crude oil productions for a comparison with the unconventional shale energy. The unit root test of Narayan and Popp (2010) on shale gas and shale oil productions help us to find more stationary evidence. Overall, we present powerful findings of the mean-reversion property and propose critical implications for authorities and market participants.

1. Introduction

Natural gas plays a significant role in the world energy market with its low production cost and strong operational flexibility (Burke and Yang, 2016). As an essential constituent of natural gas, both shale gas and shale oil are regarded as potential alternative energy resources with abundant, useful, and environment-kindly characteristics (Saussay, 2018). In the past 20 years, the productions of shale gas (hereafter, SGAS) and shale oil (hereafter, SOIL) have grown rapidly due to higher energy prices and the volatile output decline of traditional energy resources (Bilgili et al., 2016; Geng et al., 2016a).[1] Both SGAS and SOIL exploitation relieves the imbalance between natural gas as well as crude oil supply and demand and impacts national energy policies - for instance, import and export trade, tax revenue regulations, as well as financial distribution (Burke and Yang, 2016; Geng et al., 2016b). These factors have brought about a rise in the discussion in the literature about shale energy.

The United States is the only country in the world to exploit and produce SGAS and SOIL commercially on a large scale.[2] Though several other countries have abundant SGAS and SOIL resources, they lack drilling technologies, which directly lead to stagnating productions.[3] SGAS and SOIL producers in the U.S. developed horizontal drilling and hydraulic fracturing techniques at a considerable investment scope in the late-2000s and early-2010s, enabling a much lower drilling cost of shale energy there compared with natural gas drilling cost in other countries. The sharply increased productions brought great shocks to natural gas in 2011. In 2012, the U.S. Energy Information Administration (EIA) highlighted that, among the entire natural gas productions and supply, the share of SGAS and SOIL rose from approximately 0% in the 1990s to 25% and 34% until 2012, respectively. This indicates SGAS and SOIL have become the main components of U.S. energy consumption.

Due to the boom of SGAS and SOIL, the U.S. resumed the crude oil and natural gas exports in 2016 after a ban of nearly 40 years and announced

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[1] Shale oil is known as tight oil, shale-hosted oil, or light tight oil; please see https://en.wikipedia.org/wiki/Tight_oil.
[2] China also has abundant reserves of SGAS and SOIL, however, their relative data are not reported, and thus we cannot do any analysis.
[3] Other countries with abundant shale energy like China are Argentina, Mexico, Algeria, Brazil, and Russia. However, most of them lack drilling technology, which directly leads to stagnating production. For example, China possesses the largest shale reserves in the world, but the share of shale gas in China's entire natural gas production was less than 1% in 2012 (EIA, 2015).

https://doi.org/10.1016/j.econmod.2018.12.006
Received 12 September 2018; Received in revised form 3 December 2018; Accepted 25 December 2018
Available online 4 January 2019

it will become a net exporting region of gas in 2020 (Zhiltsov, 2017).[4] Energy resources are related to significant international interests and are coveted by all countries; many political conflicts have broken out over possessing more energy, such as the Persian Gulf War and frequent wars in the Middle East. This has brought greater research attention on the exploitation of SGAS and SOIL around the world. As SGAS and SOIL now play increasingly important roles in global energy supply, their long-run trends are of great importance, especially for policymakers and market participants.

We utilize both SGAS and SOIL as the main variables as this paper, because of their vital roles in current and future energy markets. In 2015, EIA reported that SGAS of the U.S. increased its output by over 50% every year during 2007–2012. SGAS and SOIL have garnered greater attention in the academic domain, with the existent literature focusing on drilling technology, extraction and production costs, energy price, employment, and income aspects (Paredes et al., 2015; Bilgen and Sarikaya, 2016; Bilgili et al., 2016; Saussay, 2018). As there is scant literature examining the economic and social factors of SGAS and SOIL, most studies have concentrated on total energy consumption and have contrary opinions about stationary property of energy consumption (Chang and Lee, 2008; Apergis and Tsoumas, 2011; Hasanov and Telatar, 2011; Golpe et al., 2012). According to the literature, stationarity denotes that the trends of variables commonly turn back to their long-run paths despite some temporary divergences.

Due to external shocks, structural breaks exist on the energy consumption path, and research analysis that does not consider structural breaks may cause bias and spurious rejections, resulting in confusing and uncertain implications to policy makers (Smyth, 2013; Shahbaz et al., 2014; Linn and Muehlenbachsn, 2018). The literature has argued that the trend of natural gas consumption may converge despite external structural breaks, and thus correctly mastering the properties of such breaks can provide useful information for authorities and market participants (Mishra and Smyth, 2014; Burke and Yang, 2016; Chen and Linn, 2017). Lee and Strazicich (2003, 2004) also highlighted that the efficiency of energy consumption tests can be greatly strengthened by endogenous structural breaks. Additionally, structural breaks can help test the time periods of historical issues and bring forth more accurate examination for the mean-reverting behaviors of energy variables (Friedl and Getzner, 2003; Stern et al., 2005). Multiple breaks should also be taken into consideration since extraordinary events may happen during data spans of over 20 years (Lanne and Liski, 2004; Chang et al., 2013).

As there are existing studies in the literature demonstrating the stationary property of natural gas and crude oil consumptions, what are the different points of SGAS and SOIL behaviors? We denote that a substitutional relationship exists in conventional natural gas/crude oil and unconventional shale gas/shale oil, respectively. Furthermore, the empirical results of the former do not represent the trend stationarity of SGAS and SOIL. Thus, for exploring the stationary behaviors of SGAS and SOIL under the structural breaks, it is vital to examine conventional gas and oil utilizations, as they deeply impact the fluctuating trend of the future energy market. Therefore, this paper explores the stationary property under structural breaks in the trends of SGAS and SOIL.

The purposes of this paper are to examine whether SGAS and SOIL sustain mean-reverting behaviors or not and then to note whether the impacts of external shocks to SGAS and SOIL are transitory or permanent,[5] under the consideration of stochastic convergence of structural breaks for the series of SGAS and SOIL in the U.S. The data of SGAS imply shale gas withdrawals from 16 states in the U.S. from January 2007 to December 2016, while data of SOIL denote shale oil productions from 14 shale oil wells in the U.S. over the same time interval. Advanced methods are adopted for the empirical analysis: the univariate minimum Lagrange Multiplier (LM) and panel unit root tests by Lee and Strazicich (LS, 2003, 2004) and Im et al. (2010); the univariate unit root test of Generalized AutoRegressive Conditional Heteroskedasticity (GARCH-based) by Narayan and Liu (NL, 2015); the panel unit root test in the Principal Components-based Panel analysis of Non-stationarity in Idiosyncratic and Common components (PANIC) and the Cross-section Average (CA), i.e. PANICCA which is proposed by Reese and Westerlund (RW, 2016)[6]; and finally, the NP test of Narayan and Popp (NP, 2010). All these tests present structural breaks.

We first utilize the traditional LM test without break and then employ univariate LS tests with one and two breaks. We additionally use the panel unit root test without and with breaks (Im et al., 2010) taking full samples as well as different group samples (lower and higher SGAS and SOIL), respectively.[7] To find more evidence for SGAS and SOIL trends' stationarity, we next utilize the Augmented Dickey-Fuller test (ADF-type) tests of the GARCH-based and PANICCA methods. For the robust analysis, we discuss the behaviors of the conventional energy of natural gas and crude oil, natural gas productions including and excluding SGAS, as well as crude oil productions. Lastly, we execute the NP test with two endogenous breaks on SGAS and SOIL. These tests further verify SGAS and SOIL trends' stationarity. We believe our findings offer useful implications for the energy industry, authorities, and market participants.

Our main contributions are as follows: Firstly, we are the first work to investigate the long-run behaviors of SGAS and SOIL, applying both time series and panel data unit root tests with structural breaks. We fill a gap in the literature by considering the stationary property of SGAS and SOIL in the U.S. and furthermore identify pivotal shocks, which can enhance our ability to predict SGAS and SOIL development trends. Secondly, we simultaneously consider without break, one-break, and two-break unit root tests, to provide more accurate results consistent with historical shocks and to identify what impact exogenous shocks have on SGAS and SOIL in the U.S. In addition, we are the first study to explore what influences are presented during the long-run trend of natural gas with and without shale gas, to further verify the important shocks of shale gas. Furthermore, we are the first to collect monthly data in the U.S. spanning 120 months for SGAS and SOIL and 312 months for natural gas and crude oil productions. Since the U.S. is the only country to exploit and produce shale gas commercially and the behaviors of shale oil and crude oil productions are vital to the energy market, our data present a more persuasive argument. We next apply univariate and panel LM, GARCH-based, PANICCA, and NP tests, and the structural breaks can greatly raise the efficiency of the tests, and are not necessary to simulate new critical values, which can hinge on the number of breakpoints and their locations. Finally, we offer various implications for the energy sector and for those with an interest in the critical status of SGAS and SOIL - for example, authorities, SGAS and SOIL investors as well as producers, and SGAS and SOIL consumers.

The remainder of this paper runs as follows. Section 2 gives a brief method introduction to the LM, GARCH-based, PANICCA, and NP tests with structural breaks and then introduces the data sources and basic descriptive statistics of SGAS and SOIL. Section 3 discusses experimental

[4] As the advanced technology of drilling shale energy were applied widely in the U.S., following the shale gas revolution and sharply increase productions of crude oil as well as natural gas, the U.S. has resumed to adjust the ban of exporting crude oil and natural gas energy to re-export the resources.

[5] Transitory means that the trends of economic variables show temporary deviations from the long-run paths, while permanent means the trends always turn back to their mean convergence behaviors.

[6] Reese and Westerlund (2016) connected the Principal Components-based Panel analysis of Non-stationarity in Idiosyncratic and Common components (PANIC) of Bai and Ng (2004, 2010) with the Cross-section Average (CA) of Pesaran et al. (2013).

[7] Since the literature has introduced univariate and panel LM unit root tests without and with structural breaks many times, the methodology will not be elaborated here. Through recent original literature or other utilizations, readers can understand LM unit root tests on gas consumption (related articles include Lean and Smyth, 2013, 2014; Shahbaz et al., 2014; Mishra and Smyth, 2014).

results and policy implications. Section 4 summarizes the major conclusions of this paper.

2. Methodology and variables

2.1. Methodology

This section sets up the empirical framework. The advanced unit root tests with structural breaks are utilized to analyze the stationary property of SGAS and SOIL. They include the LM univariate and panel tests (LS, 2003, 2004); Im et al. (2010), the NP test (2010), the GARCH-based test (NL, 2015), and the PANICCA test (RW, 2016).

Following LS (2003, 2004), we briefly describe below the LM unit root test process. They first take the data generating process (DGP) of three models developed by Perron (1989) into account, in which the third model contains the level and trend changes.

$$y_t = \alpha' Z_t + \varepsilon_t \ \varepsilon_t = \rho\varepsilon_{t-1} + \mu_t \tag{1}$$

Here, Z_t shows the exogenous variables, $\mu_t \sim iidN(0, \sigma^2)$, and under the null and alternative hypothesis, DGP includes breakpoints. Narayan (2006) presented that $Z_t = [1,\ t,\ D_{1t},\ DT_{1t}]$, when considering the one-break unit root test; while the two-break test indicates that $Z_t = [1, t, D_{1t}, D_{2t}, DT_{1t}, DT_{2t}]$, where $D_{jt} = 1$ for $t \geq T_{Bj} + 1, j = 1, 2$ and 0 otherwise; $DT_{jt} = t - T_{Dj}$ for $t \geq T_{Bj} + 1, j = 1, 2$ and 0 otherwise; and T_{Bi} indicates the structural breakpoints for an individual sample *i*.

With the regression based on the LM principle, LS (2003, 2004) highlighted that the t-statistics of the LM test can be evaluated.

$$\Delta y_t = \alpha' \Delta Z_t + \gamma \widetilde{S_{t-1}} + \sum_{1}^{k} \xi_i \Delta \widetilde{S_{t-i}} + \tau_t \tag{2}$$

Here, $\widetilde{S_{t-1}}$ presents the detrended series, and $\widetilde{S_t} = y_t - \widetilde{\psi_x} - Z_t \tilde{\varepsilon}, t = 2, \ldots, T$; $\tilde{\alpha}$ is a vector of coefficients in the regression of Δy_t on ΔZ_t; $\widetilde{\psi_x}$ is defined as $y_1 - Z_1\tilde{\alpha}$, where y_1 and Z_1 are the first observations of y_t and Z_t, respectively; $\Delta\widetilde{S_{t-i}}, j = 1, \ldots k$ is the augmented variable that achieves the autocorrelated error corrections. The null hypothesis, meaning a unit root with structural breaks, is accomplished by $\gamma = 0$, and $\tilde{\varsigma} = t$ statistics show the LM test statistics testing $\gamma = 0$. Therefore, the structural breaks can be confirmed endogenously through the LM test by applying a grid search.

$$LM_{\varsigma} = \inf_{\lambda} \tilde{\varsigma}(\lambda) \tag{3}$$

Here, $\lambda = T_{Bj}/T, j = 1, 2$, where the locations of the two breaks decide the critical values. For serial correlation, we determine the maximum lag is eight according to the specific approach developed by Ng and Perron (1995).

In order to confirm the breakpoints, we use the critical values given by LS (2003, 2004), such that all possible break dates pass over the trimming region $(0.1T, 0.9T)$, and T implies the sample size. We present the conclusions of the without break test for zero to one lags.[8] For the one breakpoint and two breakpoints, we choose the optimal lag from zero to eight lags according to the connection of each breakpoint.

The panel LM unit root test with structural breaks, which is developed by Im et al. (2010), is a new approach with invariant nuisance parameters and can decrease the size and location distortions of breaks. A more accurate test statistic on the nuisance parameter is attained as follows:

[8] The reason why we just report without break tests with zero and one results is that the without break tests are regarded as the basis analysis herein - our key point is the panel unit root test with structural breaks. Furthermore, zero and one results can reflect stationary trends without breaks.

$$\Delta U_{i,t} = \alpha_i' \Delta Z_{i,t} + \beta_i \widetilde{S_{i,t-1}} + \sum_{j=1}^{k} \delta_{ij} \Delta \widetilde{S_{i,t-j}} + \sigma_{i,t} \tag{4}$$

$$\tilde{S}_t^* = \begin{cases} \dfrac{T}{T_B} \tilde{S}_t, t \leq T_B \\ \dfrac{T}{T - T_B} \tilde{S}_t, T_B < t \leq T. \end{cases} \tag{5}$$

Utilizing equation (5) by replacing $\tilde{S}_{i,t-1}$ with $\tilde{S}^*_{i,t-1}$, Im et al. (2010) found the modified panel LM unit root test can be attained through the average standardized statistic:

$$\bar{t}_{N,T} = \frac{1}{N} \sum_{i=1}^{N} \tilde{\delta}^*_{i,T} \tag{6}$$

$$LM_{\tilde{\delta}^*} = \frac{\sqrt{N}\left(\bar{t}_{N,T} - \tilde{P}\left(\bar{t}_{N,T}\right)\right)}{\sqrt{\tilde{Q}\left(\bar{t}_{N,T}\right)}} \tag{7}$$

Here, $\tilde{P}(\bar{t}_{N,T})$ and $\tilde{Q}(\bar{t}_{N,T})$ are the average means and variances of $\bar{t}$. They also utilize the cross-section averages of lagged standards, as well as first-differences of the sample:

$$\Delta U_{i,t} = \alpha_i' \Delta Z_{i,t} + \beta_i \tilde{S}^*_{i,t-1} + \lambda \tilde{S}^*_{t-1} + \chi \Delta \tilde{S}^*_t + \sum_{j=1}^{k} \lambda_{ij} \Delta \tilde{S}^*_{t-j} + \sum_{j=1}^{k} \varphi_{ij} \Delta \widetilde{S_{i,t-j}} + \sigma_{i,t} \tag{8}$$

Here, $\tilde{S}^*_{t-1} = N^{-1} \sum_{i=1}^{N} \tilde{S}^*_{i,t-1}$ and $\Delta\tilde{S}^*_t = N^{-1} \sum_{i=1}^{N} \Delta\widetilde{S}^*_{i,t} = \tilde{S}^*_t - \tilde{S}^*_{t-1}$. Im et al. (2010) transformed the previous unit root test and indicated the panel test has greater power and more accurate break size and location than other LM univariate unit root tests.

Another unit root test with two structural breaks is the ADF-type one, i.e. the NP test (2010), whereby the structural break dates are chosen by maximizing the break dummy coefficient under significance. Characterized by the innovational-outlier type, and under the null and alternative hypotheses, the NP test considers the two structural breaks. Compared with size and power, as well as the precise estimation of the break locations, the NP test is much better than the LM one (Narayan and Popp, 2013). The most general specification model is as follows:

$$\begin{aligned} \Delta y_t = {} & \alpha + \beta t + \lambda_1 DU_{1t} + \delta_1 DT_{1t} + \omega_1 D(T_B)_{1t} + \lambda_2 DU_{2t} + \delta_2 DT_{2t} \\ & + \omega_2 D(T_B)_{2t} + \gamma y_{t-1} + \sum_{i=1}^{k} m_i \Delta y_{t-1} + \sigma_t \end{aligned} \tag{9}$$

Here, $D(T_B)_{jt} = 1$ for $t = T_{Bj} + 1, j = 1, 2$. By considering Model AA, $\delta_1 = \delta_2 = 0$ and the null hypothesis implies $\gamma = 0$ is realized by the t-statistic on $\tilde{\gamma}$. NP (2010) utilized a sequential grid search to estimate the break locations, whereby the maximizing significance allows for the break dummy coefficients.

To get more powerful evidence of the stationary property, we utilize the GARCH-based unit root model, including the time trend and two structural breaks, developed by NL (2015). Previous literature has claimed that energy series trends always fluctuate over time, accounting for conditional heteroscedasticity, which is a prominent property of most high frequency series. The GARCH-based unit root test offers better size and power properties than traditional tests, but it may be influenced by the series of mean, variance, and co-variance (Narayan et al., 2008). This indicates that external shocks, such as political and economic effects, provide a new equilibrium that brings about breaks into energy consumption and production. Therefore, assuming that the trend of energy variables is non-stationary, a trend-GARCH (1,1) unit root model with two-break test is proposed.[9]

$$y_t = \beta_0 + \beta_1 t + \lambda y_{t-1} + \sum_{i=1}^{k} D_i B_{it} + \delta_t \tag{10}$$

Here, $B_{it} = 1$ for $t \geq T_{Bi}$; otherwise $B_{it} = 0$; $T_{Bi}, i = 1, 2, 3 \ldots k$ presents the locations of structural breaks; and D_i shows the break dummy coefficient. We utilize the test of two structural breaks according to the Bai and Perron (BP, 2003) multiple structural break method. As the BP method claims that a two-break test is the most common from the maximum breaks, we utilize the two-break test in the SGAS and SOIL series.

We also note that δ_t is described as the GARCH (1,1), which relies on the first-order generalized autoregressive conditional heteroskedasticity model.

$$\delta_t = \phi_t \sqrt{\omega_t \omega_t = \gamma + \rho \delta_{t-1}^2 + \varphi \omega_{t-1}} \tag{11}$$

Here, $\gamma \succ 0, \rho \geq 0, \varphi \geq 0$, and ϕ_t represents a sequence, which means independently distributed random variables contain zero mean as well as unit variance.

We additionally estimate the unknown break locations, T_{Bi}, in Eq. (10), based on the maximum t-value of the break dummy coefficient D_i, $i = 1, 2$. Hence, the estimated break locations of $\hat{T}_{B1}$, $\hat{T}_{B2}$, i.e. the first and second break dates, are as follows:

$$\hat{T}_{B1} = \text{argmax}_{\hat{T}_{B1}} \left| t_{\hat{D}_1} (T_{B1}) \right| \tag{12}$$

$$\hat{T}_{B2} = \text{argmax}_{\hat{T}_{B2}} \left| t_{\hat{D}_2} \left(\hat{T}_{B_1}, T_{B2} \right) \right| \tag{13}$$

To analyze the break locations, whether from the common factors or idiosyncratic components, and to find that non-stationary information can help distinguish between the cross-state/well (common) factors and state-specific/well-particular (idiosyncratic) components of SGAS and SOIL, we also analyze whether non-stationarity is mostly caused by cross-state/well, or state-specific/well-particular factors, or both components. Furthermore, vital information can be transmitted to authorities, producers, market investors, and SGAS and SOIL consumers. Therefore, we finally verify the shale energy variables by applying the PANICCA test proposed by RW (2016). The data generating process (DGP) is given as[10]:

$$Y_{i,t} = \beta'_i D_{t,p} + \xi'_i G_t + \sigma_{i,t} \tag{14}$$

Here, $\sigma_{i,t}$ represents a specific unit of scalar idiosyncratic error, and G_t is a vector of common factors with $r \times 1$, which can be regarded as cross-state/well (common) factors to all the individuals; ξ_i is given as the corresponding vector of trends; and $D_{t,p}$ presents a vector polynomial trend with $D_{t,p} = (1, \ldots, t^P)'$ and $(p+1) \times 1$.

There are two situations: (i) a constant where $p = 0$; and (ii) a constant and trend where $p = 1$. Under the gradually increasing proof of the co-movements between shale gas/oil and natural gas prices, RW (2016) considered a vector of additional variables with the below GDP process:

$$X_{i,t} = \gamma'_i D_{t,p} + \rho'_i G_t + \tau_{i,t} \tag{15}$$

Here, $X_{i,t}$ is defined as a vector of additional variables with $m \times 1$, which is utilized to show the common factors of $Y_{i,t}$; and $\tau_{i,t}$ represents the corresponding idiosyncratic errors, which also formulate the DGP of combined variables.

$$Z_{i,t} = M'_i D_{t,p} + Q'_i G_t + E_{i,t} \tag{16}$$

[9] This is mainly cited from Narayan and Liu (2015).
[10] This is mainly cited from Reese and Westerlund (2016).

Here, $M_i = (\beta_i, \gamma_i)$, $Q_i = (\xi_i, \rho_i)$ following the $r \times (m+1)$ matrix dimension, and $E_{i,t} = (\sigma_{i,t}, \tau'_{i,t})'$. RW (2016) highlighted the elimination of any uncertainty function of $Z_{i,t}$, which is better than any proposed method of common factor models applied to estimate Eq. (16). They also estimated $\hat{\sigma}_{i,t} = \rho \hat{\sigma}_{i,t-1} + \varepsilon_{i,t}$ and $\hat{G}_t = \varsigma \hat{G}_{t-1} + \eta_t$ with the null hypothesis of $\varsigma_1 = \varsigma_2 = \ldots = \varsigma_N = 1$. Three t-statistics are defined by the unit root test of $\hat{\sigma}_{i,t}$ for $\varsigma = 0$ and $\varsigma = 1$, respectively, which can be proposed by the $P_{a,p}, P_{b,p}$ and $PMSB_p$ (Panel Modified Sargan-Bhargava) tests.

When $p = 0$:

$$P_{a,p=0} = \frac{\sqrt{NT}\left(\hat{\varsigma}_0^+ - 1\right)}{\sqrt{2\hat{\phi}_\varepsilon^4 \Big/ \hat{\omega}_\varepsilon^4}}; P_{b,p=0} = \frac{\sqrt{NT}\left(\hat{\varsigma}_0^+ - 1\right)}{\sqrt{\hat{\phi}_\varepsilon^4 \Big/ \left[\omega_\varepsilon N^{-1} T^{-2} \sum_{i=1}^N \left(\hat{\sigma}_{i,-1}^0\right)' \hat{\sigma}_{i,-1}^0\right]}}; \tag{17}$$

$$PMSB_{p=0} = \frac{\sqrt{N}\left(N^{-1}T^{-2}\sum_{i=1}^N \left(\hat{\sigma}_{i,-1}^0\right)' \hat{\sigma}_{i,-1}^0 - \hat{\omega}_\varepsilon^2/2\right)}{\sqrt{\hat{\omega}_\varepsilon^4 \Big/ 3}} \tag{18}$$

When $p = 1$:

$$P_{a,p=1} = \frac{\sqrt{NT}\left(\hat{\varsigma}_1^+ - 1\right)}{\sqrt{36\hat{\sigma}_\varepsilon^4 \hat{\phi}_\varepsilon^4 \Big/ 5\hat{\omega}_\varepsilon^8}}; P_{b,p=1} = \frac{\sqrt{NT}\left(\hat{\varsigma}_1^+ - 1\right)}{\sqrt{6\hat{\sigma}_\varepsilon^4 \hat{\phi}_\varepsilon^4 \Big/ \left[5\omega_\varepsilon^6 N^{-1} T^{-2} \sum_{i=1}^N \left(\hat{\sigma}_{i,-1}^0\right)' \hat{\sigma}_{i,-1}^0\right]}}; \tag{19}$$

$$PMSB_{p=1} = \frac{\sqrt{N}\left(N^{-1}T^{-2}\sum_{i=1}^N \left(\hat{\sigma}_{i,-1}^0\right)' \hat{\sigma}_{i,-1}^0 - \hat{\omega}_\varepsilon^2/6\right)}{\sqrt{\hat{\omega}_\varepsilon^4 \Big/ 45}} \tag{20}$$

The idiosyncratic components of the unit root hypothesis are accomplished by the $P_{a,p}, P_{b,p}$, and $PMSB_p$ test statistics, while $\hat{G}_{i,t}$ presents the common factors of the unit root hypothesis. The modified "filtered" MQ_f and the "corrected" MQ_c tests are developed to estimate at least two factors (Bai and Ng, 2004).

2.2. Variables

The empirical analysis adopts monthly data on shale gas from 16 states and daily data on shale oil from 14 oil wells in the U.S. for the period covering 2007–2016. The dataset is taken from EIA. The state samples include Arkansas, California, Colorado, Louisiana, Michigan, Mississippi, Montana, New Mexico, Ohio, North Dakota, Oklahoma, Pennsylvania, Texas, Virginia, West Virginia, and Wyoming, where shale gas is mainly produced in the U.S. The oil wells are Monterey, Austin Chalk, Granite Wash, Woodford, Marcellus, Niobrara-Codell, Wolfcamp, Bonespring, Spraberry, Bakken, Eagle Ford, Yeso & Glorieta, Delaware, and Utica. In Appendix, Fig. 1 shows the shale gas of different states. This study is the first to select the main areas of SGAS and SOIL in the U.S. as the sample. Following the data normalization method of Ponniah (2003), we choose to normalize the data with [0, 1], simplifying the calculation and inducing statistical distribution.

We also depict monthly shale gas in the U.S., with Fig. 2 showing the trend of shale gas for the 16 states. According to the diverse changes seen in Fig. 2, some characteristics among all the samples with structural

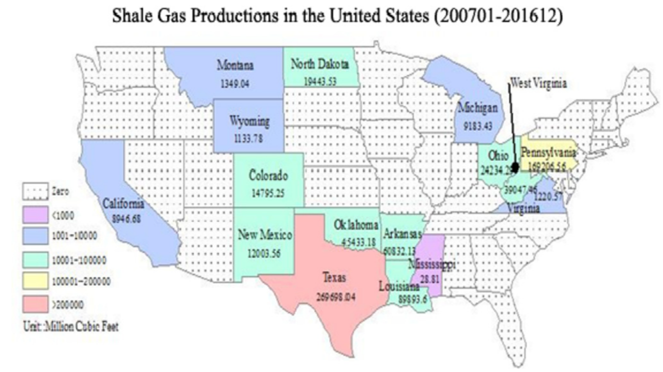

Fig. 1. The mean productions of shale gas in the United States, 2007M1-2016M12.

breaks can be found. For example, the New Mexico, Ohio, North Dakota, Oklahoma, Pennsylvania, Texas, West Virginia, and Wyoming plots exhibit an analogous increase throughout the whole time interval. Only two states, Michigan and Virginia, show downward trends. Arkansas, Colorado, and Louisiana have similar significant fluctuations around 2011–2014. Beginning in 2005, the shale gas boom helped the U.S. supply a large amount of natural gas. That is why sharp breakpoints emerge around 2011.

Fig. 3 depicts the 14 oil wells of the U.S., where we directly find some diversifications among the sample. For instance, the Niobrara-Codell, Bonespring, Spraberry, Bakken, and Eagle Ford plots present a similar increasing trend, in which the locations of the break arise during 2010–2016. The Austin Chalk, Marcellus, Yeso & Glorieta, and Delaware plots show sharp fluctuations in the observation period. The break dates are similar with the shale gas, caused by the shale boom in 2007.

We overall preliminarily use direct visual research to support the alternative hypotheses, which means the convergent characteristics of the SGAS and SOIL trends. To find more evidence, we observe the descriptive statistics for SGAS and SOIL (see Table 1). Texas has the highest mean, while the lowest one is for Mississippi. The median statistics present the same results. The highest standard deviation is in Pennsylvania, and the lowest is in Montana. Pennsylvania also has the largest interval of max and min statistics, while Mississippi has the smallest level. Thus, we find the well-developed states of shale gas are Texas and Pennsylvania, and that deviations in shale gas may relate to the structural breaks.

Table 1 also shows that Eagle Ford has the highest mean while Marcellus owns the lowest one. The highest median is in Bakken, and the lowest is in Utica. Eagle Ford has the highest standard deviation, while Austin Chalk has the lowest one. Moreover, Eagle Ford has the largest interval of max and min statistics. The deviations are consistent with the period of the shale boom.

3. Empirical results and implications

3.1. Univariate and panel LM unit root tests

3.1.1. Univariate unit root test without break

For convenient comparison, we start with the Schmidt and Phillips (SP, 1992) LM unit root test that does not consider structural breaks. Table 2 first reports the without break results utilizing the statistics of $Z(\rho)$ and $Z(\tau)$ for SGAS and SOIL. All results denote that the only stationary series are Michigan and Oklahoma. For SOIL, all the oil wells reject the alternative hypothesis. Amsler and Lee (1995) argued that the Schmidt and Phillips test (1992) might bring a biased and spurious result when structural breaks are not considered. Since energy consumption usually fluctuates due to many macroeconomic and political reasons, breakpoints should not be neglected as a vital characteristic, which is the main limitation of the SP test.

3.1.2. Univariate unit root test with one break

Considering the failure to accept the alternative hypothesis of the unit root test and in order to get more accurate evidence of mean convergence, we utilize the LS (2003, 2004) tests with structural breaks. Table 2 also shows the one-break tests of SGAS and SOIL, which present an intercept (Model A) as well as intercept and slope break (Model C).

The intercept model shows slightly more stationary evidence than the

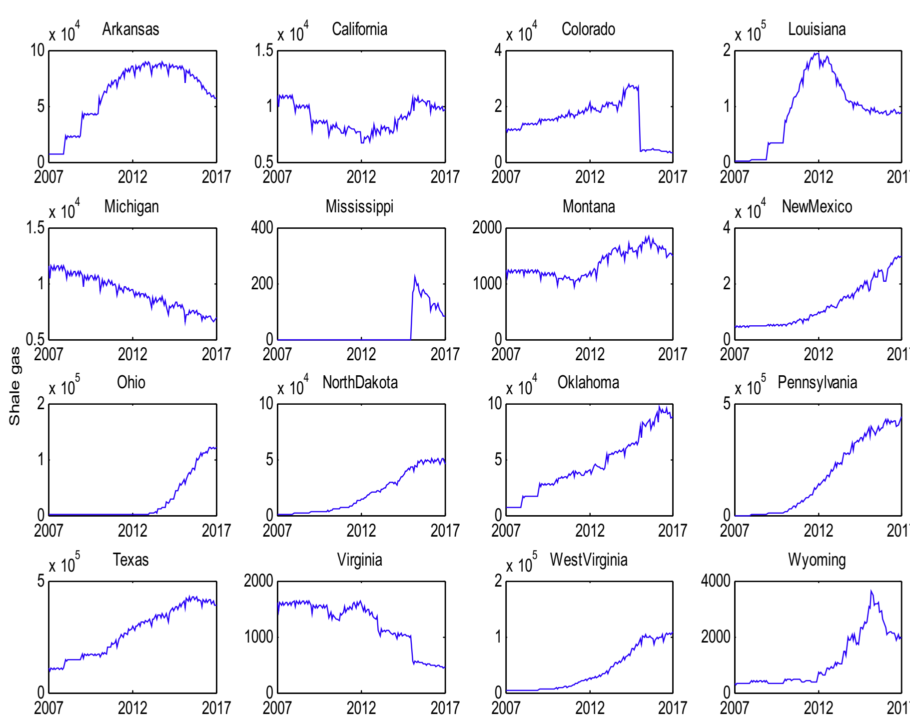

Fig. 2. Shale gas productions in the U.S., 2007M1-2016M12.

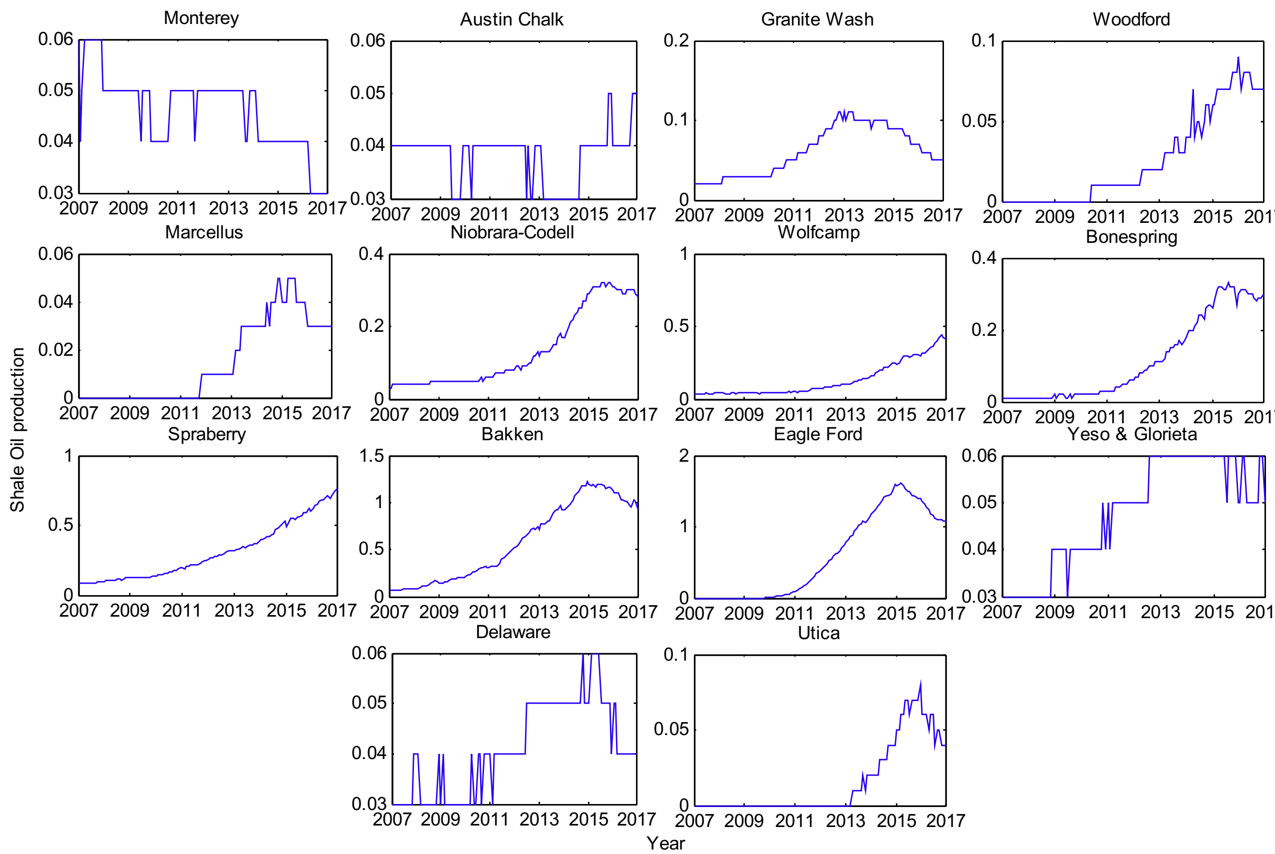

Fig. 3. Shale oil productions in the U.S., 2007M1D1-2016M12D1.

Table 1
Descriptive statistics.

Variables	Samples	Descriptive Statistics				
		Mean	Std.dev.	Median	Max	Min
SGAS	Arkansas	60832	26935	71295	89050	6448
	California	8947	1208	8665	10998	6637
	Colorado	14795	6715	15314	27683	3130
	Louisiana	89894	60449	91958	194801	1150
	Michigan	9183	1477	9195	11582	6515
	Mississippi	29	60	0	222	0
	Montana	1349	235	1239	1836	937
	New Mexico	12004	7811	9004	29931	4144
	Ohio	24234	39854	436	122485	1
	NorthDakota	19443	17874	13742	50949	541
	Oklahoma	45433	25880	39264	97370	6368
	Pennsylvania	169207	159796	127282	439209	0
	Texas	269698	107811	285897	426618	97020
	Virginia	1221	409	1384	1649	450
	West Virginia	39047	37140	23808	108063	3108
	Wyoming	1134	953	553	3627	299
SOIL	Monterey	0.046	0.007	0.050	0.060	0.030
	Austin Chalk	0.038	0.004	0.040	0.050	0.030
	Granite Wash	0.061	0.030	0.060	0.110	0.020
	Woodford	0.025	0.028	0.010	0.090	0
	Marcellus	0.014	0.016	0.010	0.050	0
	Niobrara-Codell	0.133	0.103	0.080	0.320	0.030
	Wolfcamp	0.128	0.117	0.070	0.440	0.030
	Bonespring	0.116	0.115	0.060	0.330	0.010
	Spraberry	0.307	0.195	0.255	0.760	0.090
	Bakken	0.580	0.410	0.515	1.220	0.070
	Eagle Ford	0.582	0.592	0.375	1.620	0
	Yeso &Glorieta	0.047	0.011	0.050	0.060	0.030
	Delaware	0.040	0.009	0.040	0.060	0.030
	Utica	0.015	0.023	0	0.080	0

Notes: Shale gas productions are measured in thousand cubic feet; Shale oil productions are measured in million cubic feet per day. Shale gas productions are abbreviated to SGAS, while shale oil productions are presented by SOIL. The sample of shale gas productions includes 16 states with abundant shale gas reserves, while 14 oil wells are utilized for the sample of shale oil productions.

Table 2
Univariate LM unit root test without a break, with one break, and with two breaks.

	Samples	Lag = 0		Lag = 1		Model A			Model C				Model AA					Model CC						
		Z(ρ)	Z(τ)	Z(ρ)	Z(τ)	TB	S_{t-1}	B_t	TB	S_{t-1}	B_t	D_t	TB_1	TB_2	S_{t-1}	B_{t1}	B_{t2}	TB_1	TB_2	S_{t-1}	B_{t1}	B_{t2}	D_{t1}	D_{t2}
SGAS	Arkansas	–	–	–	–	200805	–	–	201208	–	–	–	200912	201601	–	○	○	201105	201409	–	□	–	○	○
	California	–	–	–	–	201402	–	–	201302	–	–	○	200912	201402	–	○	–	201211	201601	–	–	○	□	□
	Colorado	–	–	–	–	201607	–	◊	201511	○	○	○	201409	201512	–	□	○	201511	201612	○	○	□	○	○
	Louisiana	–	–	–	–	201012	–	○	201012	–	○	–	200912	201306	–	○	□	201011	201309	–	◊	–	○	○
	Michigan	○	○	○	○	201305	○	–	201011	○	○	○	201305	201408	○	–	–	201401	201411	○	○	○	○	○
	Mississippi	–	–	–	–	201607	–	□	201511	○	○	○	201601	201607	–	◊	□	201511	201605	○	○	○	○	○
	Montana	–	–	–	–	201402	–	◊	201306	–	○	○	201306	201504	–	○	○	201109	201401	–	–	○	○	○
	New Mexico	–	–	–	–	201602	–	○	201206	–	○	–	201602	201604	–	○	□	201108	201409	□	–	○	□	○
	Ohio	–	–	–	–	201601	–	○	201211	–	–	–	201506	201605	–	○	□	201406	201607	○	○	–	–	○
	NorthDakota	–	–	–	–	201305	–	□	201501	–	□	○	201411	201605	–	○	□	201110	201601	◊	–	○	–	○
	Oklahoma	○	○	○	□	201502	–	–	201511	◊	–	○	201402	201512	◊	–	□	201201	201510	◊	◊	○	–	○
	Pennsylvania	–	–	–	–	201401	–	–	201405	–	◊	◊	201607	201611	–	○	○	201108	201412	–	–	○	○	–
	Texas	◊	◊	–	–	201202	–	–	201601	–	○	○	201511	201601	–	□	–	201202	201611	–	–	–	○	○
	Virginia	–	–	–	–	201512	–	○	201311	–	□	○	201312	201512	◊	○	○	201107	201311	–	–	□	□	○
	West Virginia	–	–	–	–	201612	–	○	201611	–	–	○	201608	201612	–	–	○	201212	201601	–	–	○	–	○
	Wyoming	–	–	–	–	201409	–	○	201505	–	–	○	201406	201409	–	○	○	201306	201601	◊	○	–	○	□
SOIL	Monterey	–	–	–	–	20110901	○	○	20100801	○	○	○	20100801	20110901	○	○	○	20100801	20130501	○	○	–	–	–
	Austin Chalk	–	–	–	–	20120601	□	○	20130501	○	–	□	20130201	20140801	○	○	○	20090901	20130301	□	◊	–	○	○
	Granite Wash	–	–	–	–	20131101	–	–	20111101	–	–	□	20080801	20131101	–	–	–	20100801	20130101	–	○	○	–	–
	Woodford	–	–	–	–	20140301	–	○	20140201	–	–	○	20131201	20140301	–	○	○	20111101	20151101	○	–	–	–	–
	Marcellus	–	–	–	–	20141101	–	□	20130101	–	–	○	20130201	20130501	–	○	○	20110701	20150601	○	–	○	□	○
	Niobrara-Codell	–	–	–	–	20120901	–	□	20130601	–	–	○	20120901	20151101	–	○	–	20120901	20141001	–	○	□	–	□
	Wolfcamp	–	–	–	–	20151201	–	○	20130201	–	–	○	20080301	20140801	–	◊	–	20101101	20130201	□	□	–	◊	○
	Bonespring	–	–	–	–	20150401	–	–	20130201	–	–	○	20150401	20151001	–	–	–	20111001	20150201	□	◊	○	□	–
	Spraberry	–	–	–	–	20141201	–	○	20120501	–	–	□	20141201	20150601	–	○	□	20100301	20130601	○	–	◊	○	○
	Bakken	–	–	–	–	20121201	–	○	20130601	–	□	□	20150501	20151101	–	–	–	20101001	20141201	◊	–	○	□	◊
	Eagle Ford	–	–	–	–	20151101	–	◊	20121001	–	–	◊	20140501	20150501	–	○	□	20100401	20131001	□	–	–	○	□
	Yeso&Glorieta	–	–	–	–	20150601	–	○	20120801	○	–	○	20101001	20101201	◊	○	○	20081001	20120701	○	–	○	○	□
	Delaware	–	–	–	–	20110201	–	◊	20150501	□	–	□	20081201	20151101	◊	○	○	20100501	20150701	○	◊	–	○	○
	Utica	–	–	–	–	20140201	–	◊	20140401	–	◊	○	20150601	20151201	–	○	○	20130301	20150101	□	○	–	◊	○

Notes: B_{t1} is the coefficient on the first break in the intercept; B_{t2} is the coefficient on the second break in the intercept. D_{t1} is the coefficient on the first break in the slope; and D_{t2} is the coefficient on the second break in the slope. '○', '□', and '◊' denote rejecting the null hypothesis of unit root with statistical significance at the 1%, 5%, and 10% levels, respectively. '-' denotes accepting the null hypothesis of unit root.

traditional unit root test, while providing less evidence than the intercept and slope model (see Table 2). We find that only Michigan rejects the null result of Model A, while Model C shows Colorado, Michigan, Mississippi, and Oklahoma passing the stationary property. The SGAS breaks are during the period 2010–2016.

Table 2 also reports that only Monterey and Austin Chalk reject the unit root hypothesis of Model A, while Model C adds 4 oil wells meeting the stationary trend. Based on these results, the much better method for the stationary trend test of SGAS and SOIL can be determined. For Model A and Model C, we choose the latter as a more powerful method. According to Sen (2003), Model C performs better than Model A when using the Monte Carlo simulation with unknown breakpoint dates. Overall, Model C performs better and gives more evidence for the mean-reverting behaviors. Moreover, after applying the one-break test, the null hypothesis for SGAS is rejected by one quarter of the sample, while the result of SOIL rejects nearly 29% of the sample.

3.1.3. Univariate unit root test with two breaks

The above tests still leave nearly 70% of SGAS and SOIL accepting the unit root tests with non-stationary conclusions. Table 2 further reports Model AA and Model CC and their structural break results. Model AA shows 3 out of 16 states rejecting the null test of non-stationarity, while Model CC shows that the number increases to 8, encompassing 50% of the states. Table 2 also shows that 4 out of 14 oil wells reject the null hypothesis of Model AA, while Model CC increases the number to 12, occupying 86% of the sample. The breakpoints focus on 2009–2016 since SGAS and SOIL have become important energy sources for the U.S. (the reasons for the shocks are listed later in this section).

The structural breaks of the LM unit root test concentrate in 2007–2011 and 2014–2016. The first set of breakpoints is around 2007–2011, which is not a surprise as the shale gas revolution had become a very significant component of the energy industry. Following the first horizontal well in the Barnett Shale play drilled by Devon Energy Company of the U.S. in 2002, SGAS and SOIL gradually expanded. As we can see, the shale gas revolution started in 2005 and added considerable scale in 2007.

The real breakthrough for shale gas occurred in 2008, which involves three aspects. First, the global financial crisis resulted in peak prices for hydrocarbons, while U.S. production achieved its highest growth rate. Expansionary fiscal policies were then implemented to stimulate the U.S. economy; for instance, the U.S. Federal Reserve (FED) implemented three quantitative easing programs (large-scale asset purchases) that also impacted European countries from December 2008 to October 2014. Second, industrial investments into SGAS and SOIL sharply increased, following the gradual drop in conventional gas and oil potential. Third and finally, continuous improvement in drilling technologies and new resource applications led to a large decrease in costs, which enabled SGAS and SOIL to be economic and beneficial. When the applied technologies improved in 2009, recoverable shale reserves in the U.S. rose sharply by 51% versus the previous year. By 2011, the U.S. cumulative gas output occupied 15% of the world's total. Under the sharp increase of SGAS and SOIL, U.S. companies decreased prices to a much lower level.

The other set of breakpoints focuses on 2014–2016 at the end of the series. Throughout the global financial crisis, SGAS and SOIL developments exhibited an increasing recovery phenomenon. However, from the global background in 2014, international crude oil prices sharply dropped by approximately 50%, as oil-producing countries accelerated their pace of oil output, and oil demand was restrained by the gradually slowdown of economies worldwide, bringing about an oversupply condition in the global market. Furthermore, the extraction of SGAS and SOIL resulted in three negative social effects: groundwater contamination, geological disruption, and noise pollution from production operations. Over the past five years, many reports have asserted that the hydraulic fracturing technology of SGAS and SOIL entails more risks than benefits to the development regions. Moreover, the cry of 'Not in My Back Yard' (NIMBY) increased in the U.S. (Saussay, 2018) and intensified, with some local authorities' policies set up to protect the surrounding residents. Below, we offer some potential reasons why the breakpoints occurred around 2014–2016.

3.1.4. Panel unit root test with up to two breaks

Based on the univariate LM unit root test, Im et al. (2010) asserted that the asymptotic distribution of a new panel LM unit root test cannot be impacted by structural breaks, with the new panel allowing breakpoints in both the intercept and slope. Additionally, the panel tests include both cross-sectional data and full span analyses, thus making the examination more accurate and comprehensive. The simulation research revealed that the panel unit root test is not only robust for structural breaks, but also has greater efficiency than the univariate test (Im et al., 2010). Therefore, to provide more evidence for the mean convergence trend, we utilize the LM panel unit root test without one break, with one break, and with two breaks according to Im et al. (2010).

We first examine the full span states of the mean reverting trend and then divide the samples into two groups, based on high and low levels of the average value (see Table 3). We discover that no matter for the full or divided spans, all shale states have stationary property with breaks. It also denotes both the traditional unit root test and the panel examination, with the groups of low and high quantities reporting significant conclusions. Again, the sample overall brings strong evidence of trend stationarity, implying that a temporary deviation exists and that it will always turn back to the long-run trend.

3.2. GARCH – based unit root test with structural breaks

Table 4 reports the NL trend – GARCH unit root test with two structural breaks. We utilize TB_1 and TB_2 as the first and second break date of the samples; T-statistic represents the *t*-test statistics for examining the unit root hypothesis, while alpha (α) and beta (b) imply the coefficient of the constant in the model. Moreover, we also report the half-life statistic, calculated as $\ln(0.5)/\ln(\alpha+\beta)$, which indicates how many months it takes to halve the influences of shocks. From Table 4, we find 11 out of 16 states reject the null hypothesis, and 7 out of 14 oil wells accept the alternative hypothesis. The locations of break dates are mostly around the periods of 2008–2011 and 2013–2016, which are nearly consistent with our earlier finding, whereby the breakpoints focus on 2007–2011 and 2014–2016.

3.3. PANICCA unit root test with idiosyncratic and common factors

Table 5 reports the RW PANICCA results. We examine the samples with the full panel and divided into two groups, i.e., low productions and high productions of SGAS and SOIL. According to Bai and Ng (2004, 2010), we utilize MQ statistics as the common factors, and the test statistics of $P_{a,p}$, $P_{b,p}$, and $PMSB_p$ are presented for the idiosyncratic component, respectively; $P = 0$ shows only a constant in the model, while $P = 1$ indicates both constant and trend results. As the addition of covariates can improve the powerfulness and preciseness of the outcome

Table 3
Panel LM unit root test without a break, with one break, and with two breaks.

Variables	Panels	Without break	One break	Two breaks
SGAS	Full Panel	◊	◊	○
	Low Group	○	○	○
	High Group	◊	¤	¤
SOIL	Full Panel	–	○	○
	Low Group	–	○	○
	High Group	–	¤	○

Notes: '○', '¤', and '◊' denote rejecting the null hypothesis of unit root with statistical significance at the 1%, 5%, and 10% levels, respectively. '-' denotes accepting the null hypothesis of unit root. Critical values for the panel LM unit root tests with structural breaks at the 10%, 5%, and 1% levels are respectively 1.282, 1.645, and 2.326.

Table 4
NL GARCH univariate test with two breaks.

Variables	Samples	TB_1	TB_2	T-stat	α	b	Half life
SGAS	Arkansas	200712	200812	−2.65	0.08	0.20	0.54
	California	200812	201403	-5.58^{c}	0.20	0.72	8.31
	Colorado	201312	201412	−1.90	0.70	0.80	1.71
	Louisiana	200812	201212	-13.43^{c}	0.20	0.60	3.11
	Michigan	200906	201112	-11.22^{c}	0.25	0.50	2.41
	Mississippi	201310	201412	-13.58^{c}	0.68	0.80	1.77
	Montana	201206	201403	-7.30^{c}	0.55	0.72	2.90
	New Mexico	201112	201512	-3.46^{a}	0.50	0.90	2.06
	Ohio	201311	201601	-4.62^{b}	0.69	0.91	1.47
	North Dakota	201102	201512	−0.71	0.42	0.90	2.50
	Oklahoma	201404	201411	-7.82^{c}	0.73	0.79	1.66
	Pennsylvania	201203	201303	−2.07	0.52	0.62	5.29
	Texas	201102	201304	-6.46^{c}	0.42	0.63	14.21
	Virginia	201212	201406	-5.12^{c}	0.60	0.75	2.31
	West Virginia	201305	201511	−0.82	0.64	0.88	1.66
	Wyoming	201110	201305	-5.43^{c}	0.48	0.64	6.12
SOIL	Monterey	20090601	20111201	-11.74^{c}	0.25	0.50	2.41
	Austin Chalk	20121001	20121201	-24.27^{c}	0.58	0.77	2.31
	Granite Wash	20080101	20100201	-5.21^{c}	0.11	0.32	0.82
	Woodford	20080701	20141201	0.00	0.16	0.80	16.98
	Marcellus	20111201	20130601	-16.18^{c}	0.50	0.65	4.96
	Niobrara-Codell	20120701	20131201	-4.20^{b}	0.56	0.70	3.10
	Wolfcamp	20080201	20140201	−2.24	0.12	0.72	3.98
	Bonespring	20141201	20151201	−2.76	0.80	0.90	1.31
	Spraberry	20081201	20141201	−0.06	0.20	0.80	0.69
	Bakken	20110601	20150801	-4.01^{a}	0.45	0.87	2.50
	Eagle Ford	20130501	20131201	0.00	0.64	0.80	1.90
	Yeso& Glorieta	20131001	20150801	-12.22^{c}	0.78	0.87	1.38
	Delaware	20110701	20130701	−2.83	0.46	0.76	3.49
	Utica	20140201	20150501	−1.97	0.72	0.84	1.56

Note: TB_1 and TB_2 mean the first and second break dates, respectively. [a], [b], and [c] represent statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 5
PANICCA test with one additional variable (natural gas price).

Variables	Panels	Common Factors				Idiosyncratic Component					
		P = 0		P = 1		P = 0			P = 1		
		MQ_f	MQ_c	MQ_f	MQ_c	$P_{a,p}$	$P_{b,p}$	$PMSB_p$	$P_{a,p}$	$P_{b,p}$	$PMSB_p$
SGAS	Full Panel	-118.413^{c}	−0.231	-119.201^{c}	-34.757^{c}	0.951	0.938	0.041	1.825	3.812	7.950
	Low Group	−1.195	-8.727^{c}	−1.195	-21.319^{c}	−3.488	−1.435	−0.714	0.739	0.924	0.680
	High Group	−1.198	−0.222	−1.199	-34.011^{c}	0.641	1.211	2.351	0.173	0.189	0.206
SOIL	Full Panel	-53.244^{c}	−6.431	-76.986^{c}	-17.162^{c}	2.704	1.869	−0.757	1.669	3.349	6.716
	Low Group	-60.560^{c}	−6.447	-77.299^{c}	-17.164^{c}	−0.303	−0.295	−0.029	0.093	0.091	−0.042
	High Group	-62.137^{c}	-13.916^{c}	-78.461^{c}	-23.473^{c}	0.812	2.012	4.676	2.402	3.237	1.282

Note: The MQ statistics represent the common factor; The test statistics of $P_{a,p}$, $P_{b,p}$, and $PMSB_p$ are valid for the idiosyncratic component; P = 0 shows only constant in the model, while P = 1 implies both constant and trend results. [a], [b], and [c] represent statistical significance at the 10%, 5%, and 1% levels, respectively.

(RW, 2016), we utilize natural gas prices from 2007M1–2016M12 as the additional variable in the PANICCA test.[11]

Table 5 implies that the stationarity is attributable to the common factors, indicating that the cross-state/well factors will lead to temporary shocks to SGAS and SOIL, and the trends will turn back to a mean-reversion property in the future. However, non-stationarity exists in the idiosyncratic component, which implies that the effects from state-specific or well-particular components will have permanent shocks to SGAS and SOIL, further presenting that non-stationarity of SGAS and SOIL mainly comes from the specific state or oil well. Furthermore, energy policy and investments need immediate adjustments by authorities and market participants.

3.4. Robust analysis

To get a more accurate result of stationarity, we first conduct a robust analysis, choosing the conventional energy natural gas production (hereafter, NGAS) and crude oil production (hereafter, COIL) from January 1991 to December 2016. We divide the sample of NGAS into two groups, shale gas included (SGINCLUDED) and shale gas excluded (SGEXCLUDED), respectively, to examine how shale gas influences the fluctuations to natural gas paths. Moreover, we take the crude oil production trend to compare with SOIL. The LM univariate and panel unit root tests with and without structural breaks are then utilized again.

Table 6 first shows the without break results in which just one-third of the sample rejects the without break tests (for both SGINCLUDED and SGEXCLUDED). It also reports the tests with structural breaks, whereby 7 states of SGINCLUDED reject the unit root tests, while only 6 states of SGEXCLUDED present the stationary property. We find that the results of SGINCLUDED perform better than those of SGEXCLUDED for the stationary property (see Table 8). Moreover, the structural breaks focus on 1997–2000, 2007–2011, and 2014–2016, which are periods of either the embryonic stage or the prosperous stage of shale gas. Thus, we claim that the addition of shale gas brings more structural breaks for natural gas. However, temporary deviations caused by shale gas do not change the long-run trend of natural gas, and the SGINCLUDED sample shows more stochastic convergence property than the SGEXCLUDED sample.

[11] The addition of covariates gets more accurate and powerful outcomes of the samples (Salisu, 2018).

Table 6
Univariate LM unit root test without a break, with one break, and with two breaks of the robust analysis (NGAS).

States	Without break		One break								Two breaks													
	SGINCLUDED	SGEXCLUDED	SGINCLUDED				SGINCLUDED				SGEXCLUDED							SGINCLUDED						
			TB	S_{t-1}	B_t	D_t	TB	S_{t-1}	B_t	D_t	TB_1	TB_2	S_{t-1}	B_{t1}	B_{t2}	D_{t1}	D_{t2}	TB_1	TB_2	S_{t-1}	B_{t1}	B_{t2}	D_{t1}	D_{t2}
Arkansas	–	–	200804	–	–	○	201008	–	–	–	200701	201203	–	–	–	◊	◊	200908	201003	–	○	–	○	○
California	◊	–	199907		◻	○	200106	–	◊	–	199802	200005	○	◊	–	◊	◻	199804	200702	–	–	◊	○	○
Colorado	○	○	201012	–	○	–	201310	–	–	◻	200811	201402	○	○	◊	○	○	201103	201402	–	–	–	○	◊
Louisiana	–	–	199807	–	○	–	199810	–	–	–	199612	199805	–	◊	–	–	◻	199611	199710	–	○	○	○	○
Michigan	○	○	199909	◻	–	○	200801	–	○	◊	199803	200902	○	○	–	○	○	199703	200702	–	○	–	○	○
Mississippi	○	○	199703	–	–	○	199703	–	–	○	200411	200901	–	–	◊	○	○	200311	200801	–	–	◊	○	○
Montana	–	–	200512	–	–	–	201002	–	–	○	199809	200909	–	○	◊	○	○	199805	200611	◊	◊	○	○	○
NewMexico	–	–	200802	◊	–	○	200802	◻	–	○	200802	201503	–	–	–	○	◻	199811	200702	◻	○	–	–	○
Ohio	–	–	201210	◻	–	○	200711	◻	–	○	201309	201505	○	–	○	–	○	200601	200902	○	○	◻	○	○
NorthDakota	–	–	201205	–	–	○	201012	–	◊	○	201106	201505	○	◊	○	–	○	200809	201312	–	–	○	–	○
Oklahoma	–	–	200408	–	◊	○	199901	–	○	○	199812	201504	◻	○	○	○	○	199411	201404	◊	◻	○	○	○
Pennsylvania	–	–	200911	–	–	○	201503	–	○	○	201009	201501	○	◻	○	○	○	201108	201212	○	◊	–	○	○
Texas	–	◊	200801	–	◻	○	200601	–	◻	○	199711	200803	–	–	–	○	○	199612	200808	–	○	○	–	○
Virginia	◻	○	201002	◻	–	◻	201102	◻	–	–	200310	201402	–	◊	◊	○	○	200210	200401	◻	○	○	○	○
WestVirginia	–	–	201201	–	–	○	201412	–	○	○	201010	201503	–	–	–	–	○	199910	201002	–	◊	–	○	○
Wyoming	–	–	200710	–	–	◊	200710	–	–	◊	199705	201101	–	–	○	–	–	199612	201001	–	–	○	–	–

Notes: '○', '◻', and '◊' denote rejecting the null hypothesis of unit root with statistical significance at the 1%, 5%, and 10% levels, respectively. '-' denotes accepting the null hypothesis of unit root.

Table 7
Univariate LM unit root test without a break, with one break, and with two breaks of the robust analysis (COIL).

States	Without break	One break				Two breaks						
		TB	S_{t-1}	B_t	D_t	TB_1	TB_2	S_{t-1}	B_{t1}	B_{t2}	D_{t1}	D_{t2}
Arkansas	○	200701	○	–	–	199401	199703	◻	–	–	○	○
California	○	201401	–	○	○	199806	201102	◻	–	–	○	–
Colorado	–	201006	–	–	○	201209	201401	–	–	–	–	○
Louisiana	○	200808	–	○	○	199402	200809	–	◻	–	○	◻
Michigan	○	200003	○	◻	○	200001	200010	○	◻	–	○	–
Mississippi	–	200703	–	◻	○	200509	200602	–	◻	–	○	◊
Montana	–	200402	–	–	○	200603	200703	–	–	–	–	◊
NewMexico	–	201101	–	○	○	199801	201102	–	○	○	○	○
Ohio	–	201302	○	–	○	200003	201306	○	–	–	○	○
NorthDakota	–	201102	–	–	○	201401	201403	○	–	○	○	○
Oklahoma	–	201101	–	○	○	201102	201307	–	–	◻	–	○
Pennsylvania	–	201301	–	○	○	201112	201206	–	◊	–	○	○
Texas	–	200906	–	–	○	200809	201310	○	–	○	○	○
Virginia	○	200111	○	–	○	200002	200111	○	○	○	○	○
WestVirginia	–	201211	◻	–	○	201306	201310	○	◊	◻	–	○
Wyoming	–	200601	–	◻	○	199406	199502	–	–	○	–	○

Notes: Same as Table 6.

Table 8
Panel LM unit root test without a break, with one break, and with two breaks of the robust analysis (NGAS and COIL).

Variables		Panels	Without break	One break	Two breaks
NGAS	SGINCLUDED	Full Panel	–	○	○
		Low Group	–	○	○
		High Group	–	○	○
	SGEXCLUDED	Full Panel	–	□	○
		Low Group	–	○	○
		High Group	–	–	○
COIL		Full Panel	□	○	○
		Low Group	○	○	○
		High Group	□	○	○

Notes: Same as Table 6.

From Tables 7–8, we also find the without break results of the stationary property of COIL perform better than those of SOIL, but the one- and two-break results do not. The break dates focus on the periods of 1997–1998 and 2000–2010, which are not consistent with the breakpoints of SOIL. Thus, considering structural breaks, the trend stationarity of SOIL is better than the COIL trend, and SOIL may be an alternative energy resource to ease the supply and demand issue of crude oil.

We also utilize the NP (2010) unit root test with two endogenous structural breaks to get more powerful evidence for the stationary trend of SGAS. This method has the key feature with an ADF-type innovational-outlier test, and under both the null and alternative unit root hypotheses, two structural breaks are allowed (Narayan and Popp, 2011). Considering the size and power, as well as the precise estimation of break locations, the NP test performs better than the LM test (Narayan and Popp, 2013). The results of NP test find more states (10 out of 16 states from Model AA and 12 out of 16 states from Model CC) accepting the stationary hypothesis than the LM test (see Table 9). We find more robust evidence for SGAS and SOIL developments and further implications for the energy market.

3.5. Policy implications

The empirical experiments above help us to explore the historical trends of SGAS and SOIL in the U.S. Overall, most evidence shows that SGAS and SOIL will turn back to their mean convergence in the long-run trend after temporary shocks, implying these shocks are not transmitted to any mean-reverting behavior. There are also some states that fail to support the stationarity of the SGAS and SOIL series. By considering other market participants, our findings help provide some motivations and suggestions for SGAS and SOIL policymakers, producers, market investors, and SGAS and SOIL consumers as we note below.

(1) For policymakers: The stationary property of the majority sample indicates that policymakers should not adopt an excessive energy policy or interfere with shale energy markets from the short-run perspective, since a stable policy is a critical factor for macroeconomic development. Contrarily, in those states having a non-stationary property, large-scale and long-term investments in SGAS and SOIL are needed.

(2) For producers: The stationary property reminds producers to not take any immediate action when the SGAS and SOIL markets fluctuate due to temporary changes. Furthermore, the stationary trends can also help SGAS and SOIL producers predict production amounts, thus helping to reduce profit risk (Chen and Linn, 2017). However, for states with non-stationary trends, SGAS and SOIL producers should adjust their strategies to timely adjust to market changes. We also propose that producers follow gas and oil market reports and adhere to local policies immediately, which can result in high efficiency for SGAS and SOIL.

(3) For market investors: As Chang and Lee (2008) asserted, the mean convergence of economic variables could enhance our ability to predict future trends. Various significant risks exist in energy exports and imports, and adjusting strategies in an immediate manner is essential to a country's energy security (Geng et al., 2017). Thus, the stationary results can help market investors understand future SGAS and SOIL developments, by predicting SGAS and SOIL trends under structure breaks. Additionally, hedging investment risk should also be targeted by risk-averse firms and investors and those with risk preferences. The stationary trend implies no excessive adjustments to investments are needed, while the non-stationary path means that changes should made in an immediate manner.

(4) For SGAS and SOIL consumers: By the stochastic convergence property, SGAS and SOIL consumers can infer the long-term price trend, and thus they can better arrange their consumption more properly, while at the same time promoting consumption activities and reducing consumption risks (Bilgen and Sarikaya, 2016). In addition, convergence can raise consumers' confidence on sustained and stable energy supplements, which in return can increase social stability. All this should benefit global household units.

Since the structural breaks are short-lived, and some powerful forces pull the SGAS and SOIL markets back to their equilibrium in the long run, the roles that policymakers, producers, investors, and consumers play are overall limited. As the full SGAS and SOIL series reflect the characteristic of mean-reverting behavior with temporary shocks, the SGAS and SOIL markets can be predicted to a better degree. Thus, market participants should master the hidden information and utilize it in their future investment strategies to try and grab more secure profits.

Because SGAS and SOIL have vital influences on demand and supply in the global energy market, we also suggest that authorities provide some form of sustainable support. First, while SGAS and SOIL are in their primary stages in the energy world, large amounts of funding for extraction technologies and drilling costs are needed. Hence, we suggest some monetary and fiscal policies, i.e. tax incentives and financial subsidies, to stimulate SGAS and SOIL developments (Chen and Linn, 2017). Furthermore, expansionary SGAS and SOIL policies can be proposed to benefit local economies. The stationary property of SGAS and SOIL implies that governments should continually put forward future strategies for SGAS and SOIL consumption, and related authorities should design energy policies following biannual reports on the SGAS and SOIL industries. These general SGAS and SOIL policies can help ensure gas utilization efficiency and reduce wastage of resources.

4. Conclusions

Investigating energy market issues has become one of the most interesting research fields and has drawn widespread attention from both the energy industry and market participants. This paper investigates the trend of shale gas and oil productions using several advanced unit root tests, in order to discover the mean reverting behaviors for variables and to find whether temporary or permanent changes exist in the long-run path from external shocks, using data on 16 states and 14 oil wells of

Table 9
NP unit root test with two breaks.

Variables	Model	Model AA						Model CC							
	Samples	TB_1	TB_2	K	S_{t-1}	B_{t1}	B_{t2}	TB_1	TB_2	K	S_{t-1}	B_{t1}	B_{t2}	D_{t1}	D_{t2}
SGAS	Arkansas	200712	200812	6	–	◇	–	200812	200912	6	○	○	□	□	–
	California	200901	201412	6	○	–	–	200901	201412	6	□	□	–	–	–
	Colorado	201412	201501	1	○	○	□	201312	201412	0	○	○	○	–	□
	Louisiana	200812	200912	3	○	○	□	200812	200912	3	–	–	–	○	□
	Michigan	200901	201501	5	○	○	○	200901	201501	7	○	◇	–	□	–
	Mississippi	201412	201509	6	◇	○	○	201412	201508	8	○	○	○	◇	◇
	Montana	201206	201404	1	◇	○	◇	201206	201404	1	□	○	–	–	–
	New Mexico	201412	201511	8	–	○	○	201412	201511	8	–	○	○	○	○
	Ohio	201406	201501	8	◇	○	○	201501	201509	8	◇	○	○	□	–
	North Dakota	201501	201507	8	–	○	–	201311	201501	6	–	○	–	–	–
	Oklahoma	201212	201412	8	◇	◇	–	201212	201412	8	□	–	–	□	◇
	Pennsylvania	201306	201505	7	–	–	□	201306	201505	4	◇	○	○	○	□
	Texas	200712	201006	2	–	–	○	201006	201401	8	□	◇	◇	○	◇
	Virginia	201212	201412	7	□	○	□	201212	201412	7	○	◇	–	○	◇
	West Virginia	201506	201510	3	–	○	○	201506	201510	3	□	–	□	○	○
	Wyoming	201306	201406	7	□	○	□	201406	201504	7	–	□	–	◇	–
SOIL	Monterey	20100801	20110801	4	◇	–	–	20100801	20130801	0	○	○	○	○	○
	Austin Chalk	20120601	20151001	0	□	○	○	20091101	20151001	0	□	□	□	–	–
	Granite Wash	20121101	20130101	0	–	○	○	20120301	20140101	0	◇	○	○	□	○
	Woodford	20140301	20140901	7	–	○	○	20140301	20141101	4	□	○	○	□	–
	Marcellus	20130501	20151201	7	–	○	–	20130201	20141201	7	□	□	–	○	–
	Niobrara-Codell	20120901	20140201	3	–	◇	◇	20120901	20140201	1	□	○	◇	○	○
	Wolfcamp	20150301	20151201	0	–	○	○	20140201	20150301	3	–	◇	□	–	□
	Bonespring	20150601	20151101	8	□	○	○	20150601	20151101	8	◇	○	○	○	○
	Spraberry	20141201	20151101	2	–	–	○	20140701	20141201	3	□	–	◇	○	○
	Bakken	20131101	20141201	6	–	–	–	20121201	20131101	7	–	–	◇	–	○
	Eagle Ford	20141101	20150301	7	–	○	□	20141101	20150301	7	□	◇	–	○	–
	Yeso & Glorieta	20150601	20151101	3	–	○	□	20090601	20150601	1	□	○	◇	□	○
	Delaware	20120601	20151101	0	○	○	○	20100301	20151101	0	○	○	○	○	□
	Utica	20150601	20151201	8	○	–	○	20150601	20151201	5	○	○	○	○	○

Notes: Same as Table 6.

the U.S. from January 2007 to December 2016.

The conclusion is that sharp shocks only have transitory influences on shale gas and shale oil productions, implying that production trends will ultimately turn back to their long-run equilibrium. When structural breaks are added, we are able to discover more stationary trends of shale gas and shale oil productions. In addition, temporary deviations of breakpoints imply that low efficiency may exist in policy and producer adjustments towards shale gas and shale oil consumption. We also note that shale gas and shale oil can facilitate the stationary property of natural gas and crude oil, and that cross-state/well factors perform better than the state-specific/well-particular components in the stationary trends. Based on these analyses, some useful implications for authorities and market participants are provided.

Since shale gas and shale oil have significant effects on global energy development, the conclusions herein may enrich shale energy investigations and promote related investments in the future. Moreover, the findings provide important implications for shale energy policy, investors, producers and consumers.

Acknowledgements

The authors acknowledge the financial support from the NSFC (Program No. 70972053, 71372173, 71672144) and the Research Fund for the National Soft Science Research Program (Program No. 2014GXS4D153) and the Doctoral Program of Higher Education (Program No.20126118110017); Also, this research was supported by the Science and Technology Research and Development Program of Shaanxi Province (Program No. 2017KRM059, 2017KRM057, 2014KRM28-2, 2012KRZ13); Scientific Research Program Funded by Shaanxi Provincial Education Department (Program No. 2015JZ021) and social science funding project of Shaanxi province (Project No. 12D231, 13D217), Key Projects of Social Science Planning of Xi'an (Project No. 17J85) and the Science and Technology Research Program of Xi 'an Technology Bureau (Project No. 2017111SF/RK005-(2), SF1225-2); base Project of Social and Science Technology Research Program of Shaanxi Provincial Education Department (Program No. 16JZ043). Chun-Ping Chang is also grateful to the Ministry of Science and Technology of Taiwan for financial support through grant MOST 106-2410-H-158-001.The authors are also very grateful to three anonymous reviewers and editor for their insightful comments that helped us sufficiently improve the quality of this paper.

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