Heliyon 10 (2024) e28215

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

# COVID-19 pandemic, Russia-Ukraine conflict and shale gas development: Evidence from fractional integration

Sakiru Adebola Solarin [a], Carmen Lafuente [b], Luis A. Gil-Alana [c,*], María Goenechea [b]

[a] *Faculty of Business, Multimedia University, Melaka, Malaysia*
[b] *Universidad Francisco de Vitoria, Madrid, Spain*
[c] *University of Navarra, NCID and DATAI, Pamplona, Spain, and Universidad Francisco de Vitoria, Madrid, Spain*

ARTICLE INFO

*Keywords:*
Shale gas production
COVID-19 pandemic
Russia-Ukraine war
Persistence

ABSTRACT

Although there are papers on the persistence of energy series including the persistence of shale gas, the impact of recent developments such as the Covid-19 pandemic and Russia-Ukraine conflict have been rarely explored in the existing literature**.** This paper examines the structure of shale gas production in the U.S. by looking at the degree of persistence across different areas, with the aim to determine if shocks in the series are permanent or transitory. Using fractional integration methods (which unlike the conventional methods, allow for the determination of the persistence of energy and non-energy series in a robust manner), and different subsamples that include the Covid-19 pandemic and the Russia-Ukraine war, our results indicate that there is a substantial decrease in the integration order in the total shale gas production in the U.S. as well as in four other plays-Haynesville, Permian, Utica and Eagle Ford. However, no differences are observed with respect to the Russia-Ukraine war. There is another group of four series (Marcellus, Niobrara-Codell, Woodford and Rest of US 'shale') with a very small reduction in the degree of persistence and another group of three series with almost no reduction at all in the order of integration (Barnett, Mississippian and Fayetteville). Several implications in terms of policy are reported at the end of the manuscript.

## 1. Introduction

Shale gas, which is an unconventional gas that is produced from impermeable shale (mostly) through hydraulic fracturing, confers several benefits to an economy. It is an additional source of energy with abundant, useful and environment-friendly characteristics. Shale gas production fosters energy security (since it is produced locally) and helps to meet demand shocks and decrease price volatility. Expansion of shale gas can lead to increased supply of energy, and ultimately leading to cheap energy prices for both residential and industrial users. The increased share of natural gas (because of rising shale activities) in the energy mix at the expense of coal or oil produces less $CO_2$ emissions [1].

In fact, it has been one of the most important economic events of the 21st century, specifically, the extraction of natural shale gas in the United States, because it was previously thought to be impossible or uneconomical. This has been made possible by the combination of horizontal drilling and hydraulic fracturing that can extract huge amounts of natural gas from impermeable shale formations. There have been some studies reviewing shale gas production opportunities in the U.S. and assessed their possible evolution and

---

* Corresponding author. University of Navarra Faculty of Economics and ICS, E-31080, Pamplona, Spain.
*E-mail address:* alana@unav.es (L.A. Gil-Alana).

https://doi.org/10.1016/j.heliyon.2024.e28215
Received 9 November 2023; Received in revised form 26 February 2024; Accepted 13 March 2024

challenges [2].

Although shale gas is a recent development (relative to conventional gas production), shale has experienced shocks triggered by both financial and non-financial crises, just as the remaining sectors in an economy. For instance, the coronavirus disease pandemic (COVID-19) outbreak at the end of 2019 has caused several economic setbacks including decrease in demand for goods and services due to precautious consumption behaviour, decline in volume of production activities, and rising unemployment rates in different countries. COVID-19 pandemic has also adversely impacted the energy sector such as the shale gas industry. With falling energy prices during the epidemic, the shale industry experienced inadequate cash flow and the outlook for several shale companies with huge leverage profile looked bleak as some shale firms sought bankruptcy protection [3]. Unlike in 2014–16, the pandemic caused the shale firms to have few prospects to sell upstream assets as a mechanism to raise capital or service debt. The reduction in the price of oil also implies that firms that used reserve-based lending faced a dramatic review in their debt value [3].

The ongoing Russia-Ukraine conflict has also been reported to have negative effect on the shale gas industry. The conflict has caused several countries to introduce sanctions on imports of energy products from Russia including natural gas. The conflict has caused cost push inflation across the world, which has led to increase in cost of production, especially transportation cost. Price cap has been introduced during the crisis to reduce the price of energy products and decrease the possibility of Russia using income from energy sales to continue to fund the war, [4]. This action is a disincentive to energy production including the production of shale gas. The crisis has also caused reallocation of resources as many countries have intervened in the war through financial and non-financial resources. Shale industry is still developing and requires resources for research and development activities as well acquisition of new technologies to improve production. Potentials of cyberattacks on production facilities including energy facilities have also increased as a result of the ongoing war. Russia's prolonged war with Ukraine has increased risks of cyberattacks for oil and gas companies. Besides causing the closures of production plants, cyberattacks cause inability to meet production targets. Even when attacks have not occurred, continuous expectations of potential cyber-attacks have negative impact on production.

This is not surprising given the strategic nature of the two major countries involved in the conflict. Russia is one of the two main natural gas producers in the globe and has the biggest gas reserves in the globe. In 2021 the natural gas production for the country was 762 billion cubic meters of natural gas, and the exportation reached about 28% of the produced gas through pipeline [5]. The European countries imported about 40% of its natural gas from Russia in 2019, [6].

It is necessary to examine if these impacts will be permanent or temporary on the shale gas production. One way to determine the nature of the shock is through the testing of the persistence of shale gas production before and during the crises. Persistence is a measure of the duration of the effects of a shock to a particular series. If shale gas is persistent, shocks to shale gas will have a permanent effect. In the case of national output and the shale gas production being significantly linked (and when shale gas is persistent), shocks arising from the shale gas industry is likely spread to other sectors in the economy. Moreover, the magnitude of the persistence in the shale gas production is a essential issue for the net gas exporting economies. Gas production serves as a foreign exchange creating commodity for such economies. For example, if shale production is persistent and subsequently there is a decrease in gas supply, gas exporting economies will undergo a situation where incomes from gas exports will not quickly return back to their previous state and that supplementary sources of income are required to maintain the same level of income ([7]). Any change in the persistence of a series before and during an event of crisis implies that such crisis will affect the persistence of such series and serious government and business interventions will be needed to reduce any negative consequence of such event on the series.

There are papers that have examined the effect of COVID-19 pandemic on several energy series ([8,9]) and as well as papers on the impact of Russia-Ukraine conflict on several energy series ([10,11]**.** There also few papers that have examined the persistence of shale gas production such as [7]. However, according to our knowledge, none of the previous papers have examined the persistence COVID-19 pandemic or Russia-Ukraine conflict on shale gas production.

The aim of this paper is to examine the persistence of shale gas production in United States. It extends the extant literature by investigating the shocks of both COVID-19 pandemic or Russia-Ukraine war on shale gas production. The other addition of this paper is the application of fractional integration, which is a relatively new method in this field and allows for a more open dynamic specification than the standard structures based on integer differentiation. We are not aware of any of the previous studies that has used fractional integration approach to test Russia-Ukraine war on shale gas production. In fact, the standard literature when answering these two questions relies on unit root tests, testing if the series under investigation are stationary I(0), and thus being with low persistence and transitory shocks, or, if alternatively, they are nonstationary I(1), being highly persistence and with shocks having permanent effects. By permitting for fractional integration, we allow for a richer dynamic, allowing us study cases of series which are nonstationary though still mean reverting, with shocks disappearing by themselves in the long run.

The focus on the United States is a result of numerous reasons. The United States has the major economy in the globe and one of the biggest energy-consuming countries. In addition to Canada, Argentina and China, United States is one of the few nations that produce shale gas on a commercial basis ([12]). Although the United States produces diverse forms of energy, the dramatic increase in gas production can be partially credited to the development shale gas. Total gas production increased from 50.038 billion cubic feet per day in 2000 to 88.373 billion cubic feet per day in 2020, and further increased to 90.38 billion cubic feet per day in 2022 ([5]). Shale gas production was 3.01 billion cubic feet per day, 73.11 billion cubic feet per day, 77.56 billion cubic feet per day and 78.84 billion cubic feet per day in January 2000, December 2020, December 2021 and August 2022, respectively, [13].

## 2. Literature review

The literature review is divided into three sections: one section focusses on the persistence on energy series, a second one focusses on the forecasting of shale gas and the third one analyses the studies published about the consequences of the shocks arising from

Covid-19 and Russia-Ukraine conflict on different economics series.

### 2.1. Studies on the persistence of energy series

There are several studies that consider energy consumption or production stationarity ([14]). Relating the persistence of energy consumptions [15,16], have to be mentioned. While these authors adopted a Lagrange Multiplier unit root test [17], used a non-linear test. Apart from that, other authors have focused their studies on this issue, analyzing the situation in several countries in different periods.

On the other hand, there are studies focusing on the stationarity of energy production such as [18–21]. In recent years, other studies about this issue have been published [22]. investigate how shocks affect disaggregated energy consumption in Turkey for the period 1970 to 2016 and the persistence of shocks. For that study, they use not only a set of conventional unit root tests but also a recently developed Fourier panel test. As a result of it, their empirical findings were the nonstationary of that disaggregated energy use and the permanence of the effects of possible shocks on energy consumption in Turkey. According to Ref. [23], researchers and policymakers should examine the time series properties of energy and environmental series because there is a very close relationship between energy, environment, and the real economy. In another recent paper [24], examined the stationarity of fourteen series of monthly prices of energy commodities in the period 1980–2020. Their results indicate that most of the series analysed are trend stationary.

### 2.2. Studies on the forecasting of shale gas

Besides, there are studies about the monthly shale gas production forecast in EEUU according to ARIMA model and nonlinear metabolic grey model. They show how changes in shale gas production directly affect U.S. natural gas production and indirectly affect the global gas market [25].

This prediction is also studied by a novel mixture of the nonlinear grey model and Arima's linear residual correction is also used to predict shale oil production in the U.S. In such a investigation is established that, since the U.S. shale gas boom has affected the global oil market, it is important to predict U.S. shale production to see how the global oil market will evolve [26].

In this regard, it is important to assess the sustainability of shale gas production and it has been studied based on the WSR methodology and the diffuse matter element extension model, studying the case of China. This is, given that shale gas production has a very relevant effect on the global energy transformation, it is important to analyse the sustainable development of shale gas production as it is essential to achieve an efficient, ecological and long-term use of its energy. For that purpose, the WSR (Wuli-Shili-Renli) methodology is used to determine a comprehensive indicator system for assessing the sustainability of the shale gas industry [27].

The sustainability of the shale gas industry has also been studied through the combination of the DPSIRM model and the RAGA-PP techniques, in particular, by analysing the empirical cases of Sichuan y Chongqing, China. The model in particular was applied for an empirical analysis of the sustainability of this energy source in these territories of China where more than 90% of Chinese shale gas is produced. The results show that water scarcity, water pollution and pipe network density were the main factors influencing sustainable development. Geological conditions, market risks and core technology are factors that have the least impact on the sustainable development of shale gas in these Chinese territories [28].

The combination of the multi-level DPSIR framework, PPFCI technique and RAGA algorithm has also assessed the sustainable development potential of the shale gas industry in China [29].

### 2.3. Studies analyzing shocks arising from Covid-19 and Russia-Ukraine conflict

Regarding the studies published about the consequences of the shocks arising from Covid-19 and Russia-Ukraine conflict on different economic series, one of the relevant papers is that of [30] that studies if there is any adjustment in the level or trend of food prices in weak countries after the Covid-19 pandemic and the Russia-Ukraine war. They found that in the absence of COVID-19 and the Russia-Ukraine war, the price level trend would have been much lower in weak nations. In the same line, another study [8], analyzes the relationship between energy sources, clean and dirty, and energy metals from COVID-19 pandemic on. As a result of the investigation, after the COVID-19 pandemic, there has been a deep increase in connectedness. However, it is asymmetric at the lower and upper quantiles because the dependence among the variables at the upper quantiles is stronger than in the lower quantiles. The empirical results reveal a switch in the net connectedness indexes of energy metals and clean energy since January 2021. All these results have relevant implications in certain conditions for investors and policy makers for energy and metal ([9]). Finally [11], examined the influence of Russia -Ukraine War on the global energy and food security. According to that paper, the level of this detailed influence is not clear, and they propose new methods to study it. The authors recommend strengthen the enhance production capacity and energy types in order to avoid the effect of Russia-Ukraine conflict and take into account small countries in Africa and Asia to manage the risk.

## 3. Methodology

Testing of persistence of shale gas can be connected to the theory of energy transition. According to the theory, countries are likely to move to sources of energy that generate less emissions from sources of energy that generate more emissions as such countries experience technological advances and better economic conditions ([31]). Energy transition involves efforts aimed at moving from non-renewable energy sources (which also includes natural gas) to renewable energy sources (such as biomass, solar energy, and wind energy) ([31]). Energy transition can also involve the substitution of low-carbon fuel such as natural gas for higher content fossil fuels inclusive of oil and coal to decrease emissions. In this case, gas and specifically shale gas production or consumption is expected to persist in order for such efforts to have long term effects. This is because persistence implies that shocks to shale gas production will have a long-term impact on gas availability, [7].

Fractional integration seems to be a very useful methodology to determine if shocks in a time series (inclusive of shale gas production) have a transitory or a permanent nature. This methodology consists of differentiating a number of times, say d, the time series to render it stationary I(0) and this number d being real, it may be a fractional value. Thus, a time series, $\{x_t, t = 1, 2, \ldots\}$ is said to be integrated of order d, and denoted as I(d) if it can be expressed as

$$(1-B)^d x_t = u_t \quad t = 1, 2, \ldots, \tag{1}$$

where $B$ is the backshift (sometimes called lag, L) operator and $u_t$ is a short memory process $I(0)$. Note that by using a Binomial expansion, the polynomial in the left-hand side in (1) can be expressed as follows:

$$(1-B)^d = \sum_{j=0}^{\infty} \binom{d}{j} (-1)^j B^j = 1 - dB + \frac{d(d-1)}{2} B^2 - \ldots, \tag{2}$$

implying that

$$(1-B)^d x_t = x_t - d x_{t-1} + \frac{d(d-1)}{2} x_{t-2} - \ldots, \tag{3}$$

and thus, the parameter d becomes a crucial term to determine the degree of persistence in the data, higher the value of d is, the higher the dependence between the observations. In this context, mean reversion occurs if $d < 1$; the series is non-stationary if $d \geq 0.5$, and stationary if $0 < d < 0.5$. Moreover, as we have mentioned in other parts of the manuscript, fractional integration is more general and flexible than the classical approaches that simply consider $d = 0$ for the stationary ARMA case of $d = 1$ for the nonstationarity ARIMA model. These two cases can be considered as particular cases of interest in the I(d) specification. Since in this paper we deal with monthly data, and they are seasonally unadjusted, the simplest and best fitting definition for this type of data is a monthly AR(1) process defined as follows:

$$u_t = \rho u_{t-12} + \varepsilon_t, \tag{4}$$

where $\rho$ is the seasonality indicator and $\varepsilon_t$ is a white noise process.

The estimation of the parameters of interest is based on the Whittle function expressed in the frequency domain as in Refs. [32,33]. In fact, we use a testing approach based on the Lagrange Multiplier (LM) principle that is very appropriate in the context of fractional integration, providing us with confidence intervals of values of $d_o$ where the null hypothesis of $d = d_o$ cannot be rejected. This approach is very interesting, firstly, because it does not impose stationarity, and do can be any real value, including thus values above 0.5. Moreover, the limiting distribution of the test statistic is standard normal, and this asymptotic behavior holds whether or not the model incorporates deterministic terms like an intercept or a linear trend. Another nice feature of this approach is that it is the most efficient method in the Pitman sense against local alternatives, which has special interest in the context of fractional values for do. The functional form of the test is available in many of the numerous empirical applications conducted and based on [33], for example, in Refs. [34–37], and more recently, in Refs. [38–40] among many others. The codes for the implementation of this procedure are available from the authors upon request.

## 4. Data

The monthly figures for shale gas have been provided from the *Energy Information Administration* (EIA)[1] for the period January 2000 to August 2022. The data refer to shale gas production in several places in the U.S., the Barnett (TX), Eagle Ford (TX), Haynesville (LA&TX), Marcellus (PA, WV, OH & NY), Permian (TX & NM), Utica (OH, PA & WV), Niobrara-Codell (CO & WY), Bakken (ND & MT), Woodford (OK), Mississippian (OK), Fayetteville (AR) and Rest of US 'shale'. Since the data is on resource generation in the United States and it is also provided by a United States agency (The Energy Information Administration (EIA)), the reliability on the data is high. This is because United States' agencies (like many agencies in the developed countries) are known to provide reliable datasets in the globe. The paper in Ref. [7] is among the studies that have successfully used the same dataset.

Shale gas production involves extracting natural gas from shale formations using hydraulic fracturing (fracking). The EIA gathers data on U.S. shale gas production, including extraction volumes, well locations, and trends over time ([41]). This production method has had a substantial impact on natural gas supply, influencing energy markets and contributing to the U.S. energy independence in recent decades. In this research, we work with the gas production of the first day of each month measured in billion cubic feet per day

---

[1] The Energy Information Administration (EIA) is a U.S. government agency tasked with collecting and analyzing energy-related statistical information. It provides accurate and objective data on energy production, consumption, imports, exports, and prices to inform the public, policymakers, and stakeholders. The EIA's reports and analyses play a crucial role in shaping energy policies, investments, and strategic planning in the United States ([59]).

(bcf/day)

The objectives of this work are to analyse the persistence of shale gas production in the U.S., and to examine the effects of shocks of both COVID-19 pandemic and Russia-Ukraine conflict on shale gas production. For this reason, the data sample has been divided into three subsamples.

- First subsample whit a total of 240 observations: it starts at January 2000 and ending at December 2019 (COVID pandemic).
- Second subsample with a total of 267 observations: from January 2000 to February 2022 (Russia-Ukraine war).
- Third subsample with a total of 272 observations: from January 2000 to August 2022 (latest available data of the series).

The shale gas production in the United States from January 2000 to August 2022 generally exhibits an increasing trend. However, as observed in Fig. 1, there is a change in slope sign during the first year of the COVID-19 pandemic. From 2021 onwards, the sign returns to positive until the last analysed period. The overall production of shale gas continues to grow since 2021, albeit at a slower pace than in previous months, and no significant changes are observed due to the conflict between Russia and Ukraine.

Fig. 2 and Table 1 show the production of shale gas on four dates of interest for the research objective: January 2000 (initial data of the series); ending at December 2019 (first subsample); ending at February 2022 (second subsample), and ending at August 2022 (third subsample).

Total shale gas production has increased, as we observed when discussing Fig. 1, in each of the subsamples tested. This increase is due to the observed increase in production of Haynesville (LA&TX), Marcellus (PA, WV, OH&NY), Permian (TX&NM), Bakken (ND&MT), Woodford (OK) and Mississippian (OK); In the rest of the series there is a slight decrease in production.

However, in terms of average growth rate, it is observed in Table 2 that all series reduce their growth rate in each of the subsamples considered. The reduction in the growth rate is significantly greater in the second subsample (post-COVID data) than in the third (post-Russia-Ukraine conflict data). In the second subsample the decrease in the rate of shale gas production ranges from 1.12 points from Fayetteville (AR) and 0.04 points from Permian (TX & NM). In the third subsample, after the beginning of the Russia-Ukraine war, reduction in production rates ranges from 0.004 to 0.19 points.

## 5. Empirical results

The model examined in this paper is based on the following expression:

$$y_t = \alpha + \beta + t + x_t, (1 - B)^d x_t = u_t, u_t = \rho u_t - 12 + \varepsilon_t. \tag{5}$$

where $y_t$ is the series under observation; α and β are the intercept (or constant) and the linear time trend and are unknown parameters; B suggests the backshift operator such that $Bx_t = x_{t-1}$; $x_t$ represents the regression errors, and it is assumed to be integrated of order d or I(d), denoting that $u_t$ is integrated of order 0 (I(0)); furthermore, as earlier stated, given the seasonal (monthly) dimension of the series, the disturbance term $u_t$ is assumed to have a monthly (seasonal) AR(1) process, while ρ is the seasonality index, and $\varepsilon_t$ follows a white noise process.

We present the results with data ending at December 2019 (in Tables 3 and 4); ending at February 2022 (in Tables 5 and 6) and data ending at August 2022 (in Tables 7 and 8).

In Tables 3, 5 and 7 we provide the estimation of “d" of equation (5) under three assumptions or scenarios. In a first scenario we assume that the equation has no deterministic terms (or in other words, with $\alpha = \beta = 0$); in a second scenario we consider that the model has a constant term ($\alpha \neq 0$ and $\beta = 0$); and finally, we estimate “d" in a model that has a constant term and a linear trend ($\alpha \neq$

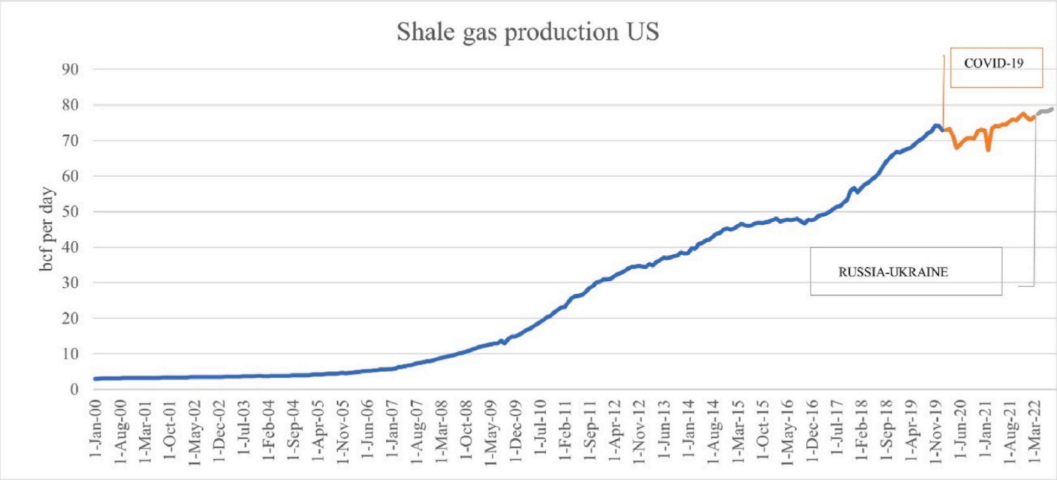

**Fig. 1.** Shale gas production United States (billion cubic feet per day).

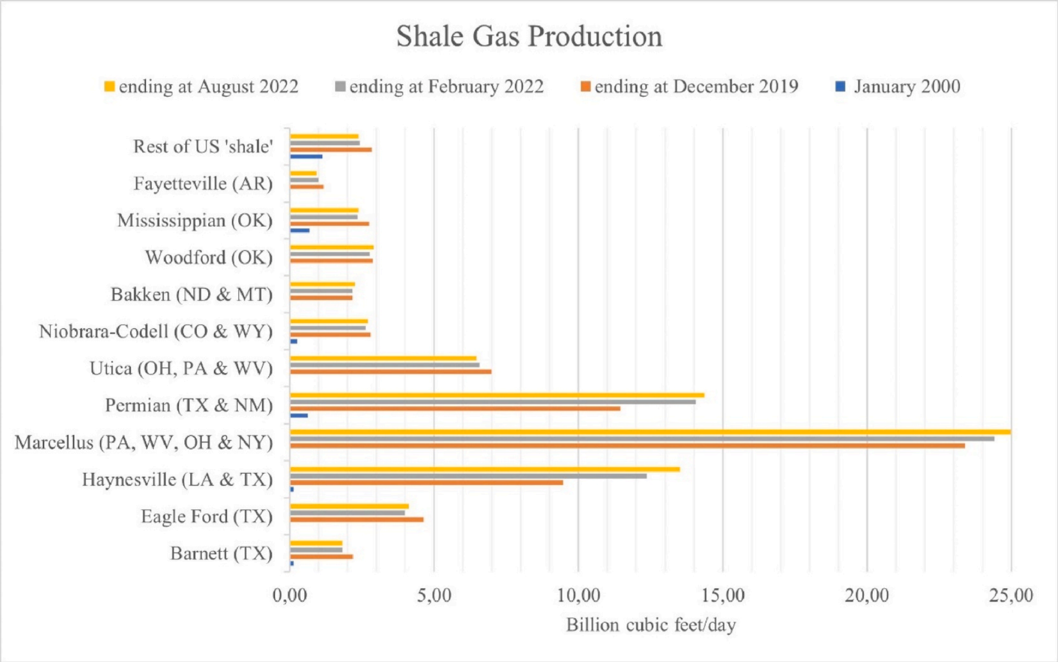

**Fig. 2.** Shale gas production in several places in the U.S (bcf per day).

**Table 1**
Shale gas production in several places in the US and total US(bcf per day).

| PRODUCTION (Billion Cubic feet/day) | January 2000 | ending at December 2019 | ending at February 2022 | ending at August 2022 |
|---|---|---|---|---|
| Barnett (TX) | 0.13 | 2.18 | 1.82 | 1.83 |
| Eagle Ford (TX) | 0.00 | 4.65 | 3.99 | 4.12 |
| Haynesville (LA & TX) | 0.14 | 9.47 | 12.37 | 13.51 |
| Marcellus (PA, WV, OH & NY) | 0.00 | 23.40 | 24.41 | 24.98 |
| Permian (TX & NM) | 0.63 | 11.46 | 14.06 | 14.36 |
| Utica (OH, PA & WV) | 0.00 | 6.98 | 6.57 | 6.48 |
| Niobrara-Codell (CO & WY) | 0.26 | 2.80 | 2.63 | 2.71 |
| Bakken (ND & MT) | 0.01 | 2.18 | 2.18 | 2.25 |
| Woodford (OK) | 0.01 | 2.87 | 2.78 | 2.90 |
| Mississippian (OK) | 0.69 | 2.76 | 2.35 | 2.38 |
| Fayetteville (AR) | 0.00 | 1.18 | 0.99 | 0.94 |
| Rest of US 'shale' | 1.13 | 2.84 | 2.43 | 2.38 |
| Total | 3.01 | 72.77 | 76.58 | 78.84 |

**Table 2**
Average growth rate (in %).

| | ending at December 2019 | ending at February 2022 | ending at August 2022 |
|---|---|---|---|
| Barnett (TX) | 1.17 | 0.98 | 0.97 |
| Eagle Ford (TX) | 5.10 | 4.51 | 4.44 |
| Haynesville (LA & TX) | 1.77 | 1.69 | 1.69 |
| Marcellus (PA, WV, OH & NY) | 4.35 | 3.92 | 3.86 |
| Permian (TX & NM) | 1.21 | 1.17 | 1.15 |
| Utica (OH, PA & WV) | 4.29 | 3.82 | 3.74 |
| Niobrara-Codell (CO & WY) | 1.00 | 0.87 | 0.87 |
| Bakken (ND & MT) | 2.14 | 1.92 | 1.90 |
| Woodford (OK) | 2.42 | 2.16 | 2.13 |
| Mississippian (OK) | 0.58 | 0.46 | 0.46 |
| Fayetteville (AR) | 8.70 | 7.58 | 7.39 |
| Rest of US 'shale' | 0.38 | 0.29 | 0.27 |
| Total | 1.34 | 1.22 | 1.21 |

0 and $\beta \neq 0$). In the latter case if $\alpha$ and $\beta$ are statistically significant we will choose the model with intercept and linear trend, while if only the parameter $\alpha$ is significant, we will choose the model with intercept. Tables 4, 6 and 8 show the results of the estimated models for each subsample, once we have selected the most appropriate of the three proposed scenarios.

Results with data ending at December 2019 (that is, before the starting of Covid-19) are reported across Tables 3 and 4 There is one series displaying mean reversion (Woodford (OK), with an estimated value of d equal to 0.90); for a group of five series (Marcellus (PA, WV, OH & NY), Utica (OH, PA & WV), Niobrara-Codell (CO & WY), Bakken (ND & MT) and Mississippian (OK), the unit root null hypothesis (i.e., $d = 1$) cannot be rejected; and this hypothesis is rejected in favor of $d > 1$ in the remaining cases: Barnett (TX), Eagle Ford (TX), Haynesville (LA & TX), Permian (TX & NM), Fayetteville (AR), Rest of US 'shale' and Total. The time trend coefficient is significantly positive in the majority of the cases, the exceptions being Barnett (TX), Eagle Ford (TX), Haynesville (LA & TX), Fayetteville (AR) and Rest of US 'shale', where the trend is found to be insignificant.

Results with data ending at February 2022 (that is, before the war in Ukraine) are presented in Tables 5 and 6 There are two series now showing mean reversion: Permian (TX & NM) and Woodford (OK). For the rest of the series the estimates of d are equal to or higher than 1. The time trend coefficient is significantly positive in eight out of the thirteen series examined, the same as in the previous subsample except Bakken where the time trend is now insignificant.

Results with data ending at August 2022 (Tables 7 and 8) are very similar to those ending at February 2022 with two series showing mean reversion Permian (TX & NM) and Woodford (OK), and the rest of the series with the estimates of d being equal to or higher than 1. The time trend is significantly positive in the same series as in the previous case along with Bakken (ND & MT). Thus, the only series where the time trend coefficient is insignificant are Barnett (TX), Eagle Ford (FX), Fayetteville (AR) and Rest of US 'shale'.

Comparing the results across subsamples (Table 9), we observe that there is a substantial decrease in the order of integration if the post-Covid data are used in five series: Eagle Ford (TX), Haynesville (LA & TX), Permian (TX & NM), Utica (OH, PA & WV) and Total. However, no differences are observed with respect to the Ukrainian-Russian war. There is another group of four series (Marcellus (PA, WV, OH & NY), Niobrara-Codell (CO & WY), Woodford (OK) and Rest of US 'shale') where we observe a very small reduction in the degree of persistence and another group of three series with almost no reduction at all in the order of integration (Barnett (TX), Mississippian (OK) and Fayetteville (AR).

As a robustness approach, we also employ other methods of fractional integration. In particular, we implemented the maximum likelihood parametric approach in Ref. [42] and the semiparametric log-periodogram method described in Ref. [43] and improved later in Refs. [44,45]. Though there were some slightly variations in the estimated values of d, qualitatively the same conclusions were obtained in all cases.

We can compare the results obtained in this work with others based on different techniques. Thus, we also conducted the analysis on the thirteen series for the three sample sizes with the classical unit root tests [46–48] and the results (not reported) supported the unit roots in all cases. This is not surprising given the high level of persistence in the data; however, these approaches do not allow to consider fractional degrees of differentiation and do not permit cases of mean reversion in the context of nonstationary data; moreover, these classical unit roots methods have very low power under fractional alternatives as was demonstrated in numerous papers such as in Refs. [49–51].

## 6. Discussion of the results

The foregoing results have generally shown that the shale gas production in the United States is highly persistent which is consistent with the results of [7]. However, the results differ from the output of [52], which provides evidence for stationarity of renewable production in the United States. The empirical results also indicate that COVID-19 epidemic led to a substantial reduction in the order of integration in the total shale production as well as four other series- Haynesville, Permian, Utica and Eagle Ford. According to Ref. [13], these four plays are among the largest ones in the United States as they occupy the second, third, fifth and sixth positions, respectively in terms of production. They also collectively account for about 37% of the total shale gas production in the United States.

**Table 3**

Estimates of d based on the model given by Equation (5). Data ending at December 2019.

| Series | No deterministic terms | An intercept | An intercept and a linear time trend |
|---|---|---|---|
| Barnett (TX) | 1.16 (1.11, 1.23) | **1.15 (1.12, 1.23)** | 1.14 (1.11, 1.23) |
| Eagle Ford (TX) | **1.21 (1.15, 1.28)** | 1.21 (1.15, 1.28) | 1.21 (1.15, 1.28) |
| Haynesville (LA & TX) | 1.44 (1.38, 1.51) | **1.45 (1.39, 1.52)** | 1.45 (1.39, 1.52) |
| Marcellus (PA, WV, OH & NY) | 0.99 (0.94, 1.05 | 0.99 (0.94, 1.05) | **0.99 (0.94, 1.06)** |
| Permian (TX & NM) | 1.16 (1.08, 1.25) | 1.19 (1.12, 1.27) | **1.21 (1.13, 1.30)** |
| Utica (OH, PA & WV) | 1.04 (0.98, 1.11) | 1.04 (0.98, 1.11) | **1.04 (0.98, 1.11)** |
| Niobrara-Codell (CO & WY) | 1.10 (1.03, 1.17) | 1.05 (0.99, 1.13) | **1.06 (0.99, 1.14)** |
| Bakken (ND & MT) | 1.02 (0.97, 1.09) | 1.03 (0.97, 1.09) | **1.03 (0.97, 1.10)** |
| Woodford (OK) | 0.92 (0.87, 0.99) | 0.92 (0.87, 0.99) | **0.90 (0.83, 0.99)** |
| Mississippian (OK) | 1.00 (0.94, 1.08) | 1.05 (0.99, 1.12) | **1.05 (0.99, 1.12)** |
| Fayetteville (AR) | **1.06 (1.01, 1.12)** | 1.06 (1.01, 1.12) | 1.06 (1.01, 1.12) |
| Rest of US 'shale' | 1.02 (0.95, 1.09) | **1.07 (1.01, 1.13)** | 1.07 (1.01, 1.13) |
| Total | 1.15 (1.09, 1.21) | 1.17 (1.12, 1.24) | **1.19 (1.13, 1.26)** |

In parenthesis the confidence bands of the non-rejection values of d, and in bold, the selected specification for each series in relation with the deterministic terms.

**Table 4**
Estimated coefficients based on the results in Table 3 Data ending at December 2019.

| Series | d (95% band) | Intercept (tv) | Time trend (tv) | SEA. |
|---|---|---|---|---|
| Barnett (TX) | 1.15 (1.12, 1.23) | 0.129 (1.88) | – | 0.114 |
| Eagle Ford (TX) | 1.21 (1.15, 1.28) | – | – | 0.134 |
| Haynesville (LA & TX) | 1.45 (1.39, 1.52) | 0.140 (1.70) | – | −0.055 |
| Marcellus (PA, WV, OH & NY) | 0.99 (0.94, 1.06) | −0.1.01 (−2.38) | 0.0975 (6.03) | 0.529 |
| Permian (TX & NM) | 1.21 (1.13, 1.30) | 0.884 (8.38) | 0.0684 (3.01) | 0.222 |
| Utica (OH, PA & WV) | 1.04 (0.98, 1.11) | −0.029 (−2.26) | 0.0347 (3.92) | 0.539 |
| Niobrara-Codell (CO & WY) | 1.06 (0.99, 1.14) | 0.248 (7.71) | 0.0112 (3.97) | 0.204 |
| Bakken (ND & MT) | 1.03 (0.97, 1.10) | 0.006 (2.28) | 0.0083 (4.55) | 0.143 |
| Woodford (OK) | 0.90 (0.83, 0.99)* | −0.012 (−2.25) | 0.0126 (6.83) | 0.067 |
| Mississippian (OK) | 1.00 (0.94, 1.08) | 0.679 (16.09 | 0.0087 (2.49) | 0.121 |
| Fayetteville (AR) | 1.06 (1.01, 1.12) | – | – | 0.139 |
| Rest of US 'shale' | 1.07 (1.01, 1.13) | 1.133 (17.21) | – | 0.143 |
| Total | 1.15 (1.09, 1.21) | 2.832 (7.21) | 0.2846 (4.25) | 0.322 |

The values in parenthesis in column 2 are confidence bands for d; those in columns 3 and 4 are the corresponding t-values of the estimates coefficients for the intercept and the time trend. * means evidence of mean reversion.

**Table 5**
Estimates of d based on the model given by Equation (5). Data ending at February 2022.

| Series | No deterministic terms | An intercept | An intercept and a linear time trend |
|---|---|---|---|
| Barnett (TX) | 1.15 (1.10, 1.20) | **1.15 (1.10, 1.20)** | 1.15 (1.10, 1.20) |
| Eagle Ford (TX) | **1.12 (1.06, 1.19)** | 1.12 (1.06, 1.19) | 1.12 (1.06, 1.19) |
| Haynesville (LA & TX) | 1.19 (1.14, 1.25) | 1.19 (1.14, 1.25) | **1.20 (1.14, 1.26)** |
| Marcellus (PA, WV, OH & NY) | 0.99 (0.93, 1.06) | 0.99 (0.93, 1.06) | **0.98 (0.92, 1.06)** |
| Permian (TX & NM) | 0.89 (0.83, 0.97) | 0.89 (0.83, 0.96) | **0.87 (0.81, 0.95)** |
| Utica (OH, PA & WV) | 0.97 (0.90, 1.05) | 0.97 (0.90, 1.05) | **0.97 (0.90, 1.05)** |
| Niobrara-Codell (CO & WY) | 1.03 (0.97, 1.13) | 1.04 (0.98, 1.13) | **1.04 (0.98, 1.13)** |
| Bakken (ND & MT) | **1.09 (0.95, 1.34)** | 1.09 (0.95, 1.34) | 1.09 (0.95, 1.34) |
| Woodford (OK) | 0.87 (0.82, 0.94) | 0.87 (0.82, 0.94) | **0.86 (0.80, 0.93)** |
| Mississippian (OK) | 1.01 (0.94, 1.09) | 0.99 (0.93, 1.06) | **0.99 (0.93, 1.06)** |
| Fayetteville (AR) | **1.05 (1.00, 1.10)** | 1.05 (1.00, 1.10) | 1.05 (1.00, 1.10) |
| Rest of US 'shale' | 1.02 (0.96, 1.10) | **1.03 (0.97, 1.09)** | 1.03 (0.97, 1.09) |
| Total | 1.00 (0.95, 1.06) | 1.01 (0.96, 1.07) | **1.01 (0.95, 1.08)** |

In parenthesis the confidence bands of the non-rejection values of d, and in bold, the selected specification for each series in relation with the deterministic terms.

**Table 6**
Estimated coefficients based on the results in Table 5. Data ending at February 2022.

| Series | d (95% band) | Intercept (tv) | Time trend (tv) | SEA. |
|---|---|---|---|---|
| Barnett (TX) | 1.15 (1.10, 1.20) | 0.129 (1.87) | – | 0.118 |
| Eagle Ford (TX) | 1.12 (1.06, 1.19) | – | – | 0.088 |
| Haynesville (LA & TX) | 1.20 (1.14, 1.26) | 0.115 (1.71) | 0.0431 (1.64) | 0.016 |
| Marcellus (PA, WV, OH & NY) | 0.98 (0.92, 1.06) | −0.100 (−2.34) | 0.0922 (5.72) | 0.498 |
| Permian (TX & NM) | 0.87 (0.81, 0.95)* | 0.784 (2.60) | 0.0723 (5.89) | 0.222 |
| Utica (OH, PA & WV) | 0.97 (0.90, 1.05) | −0.029 (−1.16) | 0.0250 (2.62) | 0.552 |
| Niobrara-Codell (CO & WY) | 1.04 (0.98, 1.13) | 0.249 (1.98) | 0.0088 (3.04) | 0.064 |
| Bakken (ND & MT) | 1.09 (0.95, 1.34) | – | – | 0.004 |
| Woodford (OK) | 0.86 (0.80, 0.93)* | −0.013 (−2.21) | 0.0108 (5.69) | 0.123 |
| Mississippian (OK) | 0.99 (0.93, 1.06) | 0.608 (2.31) | 0.0062 (1.70) | 0.064 |
| Fayetteville (AR) | 1.05 (1.00, 1.10) | – | – | 0.140 |
| Rest of US 'shale' | 1.03 (0.97, 1.09) | 1.133 (15.84) | – | 0.189 |
| Total | 1.01 (0.95, 1.08) | 2.745 (3.73) | 0.759 (5.83) | 0.236 |

The values in parenthesis in column 2 are confidence bands for d; those in columns 3 and 4 are the corresponding t-values of the estimates coefficients for the intercept and the time trend. * means evidence of mean reversion.

The results obtained from applying fractional integration confirm the information provided by the basic data treatment: on one hand, the overall growth of shale production in the US; and on the other hand, the impact of COVID-19 initially altering the trend direction, only to later return to a positive trend, though with production growth rates lower than those pre-pandemic (Refer to Fig. 1 and Table 2)

The rationales for such change in the persistence of total shale gas production in the United States are numerous. One of the reasons could be attributed to the investment decisions taken by shale companies during the initial periods of the COVID-19 epidemic, [53].

**Table 7**
Estimates of d based on the model given by Equation (5). Data ending at August 2022.

| Series | No deterministic terms | An intercept | An intercept and a linear time trend |
|---|---|---|---|
| Barnett (TX) | 1.15 (1.10, 1.20) | **1.15 (1.10, 1.20)** | 1.15 (1.10, 1.20) |
| Eagle Ford (TX) | **1.11 (1.06, 1.18)** | 1.11 (1.06, 1.18) | 1.11 (1.06, 1.19) |
| Haynesville (LA & TX) | 1.19 (1.13, 1.25) | 1.19 (1.13, 1.25) | **1.19 (1.14, 1.25)** |
| Marcellus (PA, WV, OH & NY) | 0.98 (0.92, 1.05) | 0.98 (0.92, 1.05) | **0.98 (0.92, 1.05)** |
| Permian (TX & NM) | 0.89 (0.83, 0.96) | 0.89 (0.83, 0.96) | **0.87 (0.80, 0.95)** |
| Utica (OH, PA & WV) | 0.97 (0.91, 1.06) | 0.97 (0.91, 1.06) | **0.97 (0.91, 1.06)** |
| Niobrara-Codell (CO & WY) | 1.03 (0.97, 1.12) | 1.04 (0.98, 1.13) | **1.04 (0.98, 1.13)** |
| Bakken (ND & MT) | 0.96 (0.87, 1.11) | 0.96 (0.87, 1.11) | **0.96 (0.86, 1.11)** |
| Woodford (OK) | 0.86 (0.81, 0.93) | 0.87 (0.81, 0.93) | **0.85 (0.79, 0.93)** |
| Mississippian (OK) | 0.99 (0.93, 1.06) | 0.99 (0.94, 1.05) | **0.99 (0.93, 1.06)** |
| Fayetteville (AR) | **1.04 (0.99, 1.10)** | 1.04 (0.99, 1.10) | 1.04 (0.99, 1.10) |
| Rest of US 'shale' | 1.02 (0.96, 1.09) | **1.03 (0.98, 1.09)** | 1.03 (0.98, 1.09) |
| Total | 1.00 (0.95, 1.07) | 1.01 (0.96, 1.07) | **1.01 (0.95, 1.08)** |

In parenthesis the confidence bands of the non-rejection values of d, and in bold, the selected specification for each series in relation with the deterministic terms.

**Table 8**
Estimated coefficients based on the results in Table 7- Data ending at August 2022.

| Series | d (95% band) | Intercept (tv) | Time trend (tv) | SEA. |
|---|---|---|---|---|
| Barnett (TX) | 1.15 (1.10, 1.20) | 0.129 (1.89) | – | 0.118 |
| Eagle Ford (TX) | 1.11 (1.06, 1.18) | – | – | 0.093 |
| Haynesville (LA & TX) | 1.19 (1.14, 1.25) | 0.112 (1.68) | 0.0480 (1.82) | 0.012 |
| Marcellus (PA, WV, OH & NY) | 0.98 (0.92, 1.05) | −0.101 (−2.32) | 0.0923 (5.85) | 0.493 |
| Permian (TX & NM) | 0.87 (0.80, 0.95)* | 0.783 (2.61) | 0.0731 (6.07) | 0.235 |
| Utica (OH, PA & WV) | 0.97 (0.91, 1.06) | −0.028 (−1.15) | 0.0244 (2.56) | 0.562 |
| Niobrara-Codell (CO & WY) | 1.04 (0.98, 1.13) | 0.249 (6.52) | 0.0088 (3.15) | 0.066 |
| Bakken (ND & MT) | 0.96 (0.86, 1.11) | 0.003 (−2.06) | 0.0082 (2.67) | −0.003 |
| Woodford (OK) | 0.85 (0.79, 0.93)* | −0.015 (−2.24) | 0.0110 (6.15) | 0.137 |
| Mississippian (OK) | 0.99 (0.93, 1.06) | 0.680 (11.42) | 0.0061 (1.82) | 0.066 |
| Fayetteville (AR) | 1.04 (0.99, 1.10) | – | – | 0.149 |
| Rest of US 'shale' | 1.03 (0.98, 1.09) | 1.134 (15.83) | – | 0.159 |
| Total | 1.01 (0.95, 1.08) | 2.741 (3.76) | 0.279 (5.99) | 0.237 |

The values in parenthesis in column 2 are confidence bands for d; those in columns 3 and 4 are the corresponding t-values of the estimates coefficients for the intercept and the time trend. * means evidence of mean reversion.

**Table 9**
Summary results of persistence.

| Series | December 2019 | February 2022 | August 2022 |
|---|---|---|---|
| Barnett (TX) | 1.15 (1.12, 1.23) | 1.15 (1.10, 1.20) | 1.15 (1.10, 1.20) |
| Eagle Ford (TX) | 1.21 (1.15, 1.28) | 1.12 (1.06, 1.19) | 1.11 (1.06, 1.18) |
| Haynesville (LA & TX) | 1.45 (1.39, 1.52) | 1.20 (1.14, 1.26) | 1.19 (1.14, 1.25) |
| Marcellus (PA, WV, OH & NY) | 0.99 (0.94, 1.06) | 0.98 (0.92, 1.06) | 0.98 (0.92, 1.05) |
| Permian (TX & NM) | 1.21 (1.13, 1.30) | 0.87 (0.81, 0.95)[a] | 0.87 (0.80, 0.95)[a] |
| Utica (OH, PA & WV) | 1.04 (0.98, 1.11) | 0.97 (0.90, 1.05) | 0.97 (0.91, 1.06) |
| Niobrara-Codell (CO & WY) | 1.06 (0.99, 1.14) | 1.04 (0.98, 1.13) | 1.04 (0.98, 1.13) |
| Bakken (ND & MT) | 1.03 (0.97, 1.10) | 1.09 (0.95, 1.34) | 0.96 (0.86, 1.11) |
| Woodford (OK) | 0.90 (0.83, 0.99)[a] | 0.86 (0.80, 0.93)[a] | 0.85 (0.79, 0.93)[a] |
| Mississippian (OK) | 1.00 (0.94, 1.08) | 0.99 (0.93, 1.06) | 0.99 (0.93, 1.06) |
| Fayetteville (AR) | 1.06 (1.01, 1.12) | 1.05 (1.00, 1.10) | 1.04 (0.99, 1.10) |
| Rest of US 'shale' | 1.07 (1.01, 1.13) | 1.03 (0.97, 1.09) | 1.03 (0.98, 1.09) |
| Total | 1.15 (1.09, 1.21) | 1.01 (0.95, 1.08) | 1.01 (0.95, 1.08) |

[a] means evidence of mean reversion.

The several lockdowns announced during the pandemic provided opportunities for many shale companies to massively divested from fossil fuels including shale gas and dramatically cut costs. Another reason for such a result was the labor shortage experienced during COVID-19 epidemic. The jobs-to-workers gap in the shale industry of the United States during the pandemic was estimated at about 20,000 people ([54]). The labor shortages negatively affected the ability of shale gas companies to drill plays for shale gas production.

The dividend policies of the shale companies can also explain the impact of COVID-19 on the sector. Shale operators pulled off a stunning business reversal: reining in capital spending and ploughing the windfall from a buoyant market into dividends and share buybacks. The transformation has made the sector the Standard and Poor's best performer for the past two years — but only at the expense of growth and investment in new drilling activities ([53]). Another reason for the impact of COVID-19 is the rise in cost of production, especially during pandemic. The average cost to drill a shale well grew from $7.3 million in 2019 to $9 million in 2022. The price of drilling 100 feet increased from $75,000 in 2020 to $100,000 in 2021 ([53]). According to the basic theory of supply, the increase in cost of production negatively affects production and supply.

The results further show that the Russia-Ukraine war has not generally affected the persistence of shale gas production in the country. This result is also reflected in the initial statistical analysis. The total gas production is not affected by the conflict between Russia and Ukraine (see Figs. 1 and 2). All regions (except Fayeteville, AR, and the rest of the US) increase their production in the third analysed subsample, during the period from the end of February 2022 (start of the conflict) to the end of August 2022 (see Table 1).

This is not surprising given that United States does not depend too much on gas from Russia. The country is reliant on neighboring countries for most of its gas imports. For instance, in 2021, about 99% of United States gas imports came from Canada ([54]). In addition, the United States has a huge amount of gas reserves and as such has been undaunted by possible reduction in the supply of Russia gas. United States' natural gas proved reserves have rose almost each year since 2000. Major advances in natural gas exploration as well as production technologies contributed to the expansion of natural gas production and reserves [54]. The gas varieties produced in the two countries are not perfect substitutes.

The failure to find a significant impact of Russia-Ukraine war on the shale gas production in United States can also be attributed to the availability of nearer and possibly cheaper alternative gas to European countries that were the major consumers of Russia. Germany, which was the Europe's largest consumer of Russian gas (but has cancelled the Nord Stream 2 gas project) can import additional gas from Denmark, Britain, the Netherlands and Norway through pipelines. Nigeria and Azerbaijan are also major natural gas producing nations. Algeria produces more than 100 billion cubic meters of natural gas per year ([55,56]).

## 7. Concluding comments

In this paper, we have looked at data of shale gas production in several places in the U.S., including Barnett (TX), Eagle Ford (TX), Haynesville (LA&TX), Marcellus (PA, WV, OH & NY), Permian (TX & NM), Utica (OH, PA & WV), Niobrara-Codell (CO & WY), Bakken (ND & MT), Woodford (OK), Mississippian (OK), Fayetteville (AR) and Rest of US 'shale'. Using fractional integration methods, we have examined the degree of integration of the series across different subsamples that include the Covid-19 pandemic and the Russia-Ukraine war.

The results can be summarized as follow: First we observe large degrees of integration in all series, with values close to 1 or superior to 1, implying high levels of persistence. Generally, we observe a reduction in the degree of dependence as time goes by being more marked because of Covid-19 pandemic, while the Russia-Ukraine war has almost produced no effect on this feature. Mean reversion is detected in very few cases: Woodford with data ending before the pandemic, and this location along with Permian if the 2021 and 2022 are included in the analysis.

The implication of the foregoing results is that COVID-19 pandemic has substantially disrupted the production of total shale gas production as well as in few big plays-Haynesville, Permian, Utica and Eagle Ford-in United States. An implication of the foregoing results is that successful policies used to boost shale gas production in the pre-COVID-19 period were not adequate during the pandemic and might not be adequate in case of outbreak of similar health crisis.

Hence, there is a need to roll out policies that will ensure mergers are easier in shale gas especially during crisis. This will ensure sick shale gas companies can easily merge with healthy ones, especially big oil and gas companies. An example was Chesapeake Energy, which filed for bankruptcy in June 2020 as its performance nosedived during the COVID-19 pandemic. The company (based in Oklahoma City) was one of the leaders in the shale breakthrough more than a decade ago. The policies on mergers should be introduced as early as possible in order minimized the disruption caused by COVID-19 pandemic on shale gas production.

A horizontal merger system (which involves shale gas firms which are into selling similar products or services and in the same market come together to dominate market share) can be adopted in the process of merger. This form of merger should generate improved financial capacity to invest on long-term basis, better efficiencies of scale, improved technical excellence, and the consolidation of multiple fragmented holdings. Bureaucratic bottleneck and funding might be served as challenge but this can be overcome with adequate planning. The differences in the coefficients of persistence and the differences in the changes in the coefficients imply that one size fits all approach might not be appropriate for all the plays. Hence, companies associated with plays that witnessed greater changes in the coefficients of persistence should receive more attention as they might have been more affected by the pandemic.

There is a need to introduce policies that will ensure that companies re-invest profit during health crisis. Incentives that ensure dividend policies of shale gas companies favors the re-investment of profits during health crisis should introduced as this will increase funding for drilling activities. The shale sector requires huge investment to ensure that production remains steady. Unlike conventional oil production, output from newly drilled shale wells plummets after a year or so of operation. To hold output, steady each year, companies must keep drilling more wells.

Another implication of the results is that the Russia-Ukraine war has not substantially affected shale gas production in the United States. The non-significant impact of Russia-Ukraine war on shale gas production implies that United States is yet to take adequate advantage of the stoppage of imports of Russia gas into usual consumer of Russia gas especially the European countries. Hence, there is a need to continue to improve horizontal drilling and hydraulic fracturing technologies that will ensure that volumes of shale gas can be produced at a lower cost. For the shale gas reservoir with high permeability, enlarging the hydraulic fractures length is likely to yield greater production, [57]. Hence this will make shale gas produced in the United States more competitive in the global gas market. More tax incentives can be introduced to ensure that shale gas can produced at a lower cost. Tax incentives may include a cut in tax payable on any from shale gas profits for a feasible period. The central government has several tax measures, but these can be expanded.

There is also a need to improve the speed at which produced gas are transported to buying countries, especially the European Union. Liquefaction and regasification processes should be improved so that gas will be deliver as fast as possible. As it appears that there is still currently space in European regasification receiving terminals to import more liquefied natural gas, more supply from United Stets will not be out of place.

This study has two major limitations. The study has only focused on shale gas production in United States. Although the United States is the largest shale gas producer, China, Mexico, and Canada are also producers of shale gas. In the meantime, the results obtained in the paper should be generalizable to other shale producers such as Canada and Mexico. This is because the gas industries in these countries share very similar characteristics as the United States. Like the United States, they do not depend much on either Russia or Ukraine for gas and as such changes in gas production in either Russia or Ukraine do not substantially affect production in Mexico, and Canada. The result might be different for China as it is one of the foremost buyers of Russian gas. Thus, a similar evaluation can be conducted in these countries to analyse how the pandemic and Russia-Ukraine war have affected their shale gas production. The knowledge of the effect of specific policies or events during the pandemic or the war on shale gas production has not been examined. Investigating the impact of specific events will improve our understanding of the nature of shale gas industry during crisis. From a methodological viewpoint, a further limitation of the present work is its linear modelling. Non-linear approaches can be implemented within the fractionally integrated structure, especially noting that these two issues (non-linearities and fractional integration) are very much related (see, e.g., Ref. [57]). Some deterministic nonlinear models have been already implemented in the literature (see, e.g. Ref. [58], and based on the Chebyshev polynomials in time), while stochastic nonlinear I(d) models still need to be further developed. Work in all these lines are now in progress.

## Data availability

Data are available from the authors upon request. They are also available at the repository DADUN from the University of Navarra.

## CRediT authorship contribution statement

**Sakiru Adebola Solarin:** Methodology, Investigation, Data curation. **Carmen Lafuente:** Validation, Supervision, Formal analysis. **Luis A. Gil-Alana:** Writing – original draft, Methodology, Investigation. **María Goenechea:** Visualization, Validation, Supervision, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

[1] S.A. Solarin, M.O. Bello, The impact of shale gas development on the US economy: evidence from a quantile autoregressive distributed lag model, Energy 205 (2020) 118004, https://doi.org/10.1016/j.energy.2020.118004.

[2] Q. Wang, X. Chen, A.N. Jha, H. Rogers, Natural gas from shale formation–the evolution, evidence and challenges of shale gas revolution in United States, Renew. Sustain. Energy Rev. 30 (2014) 1–28, https://doi.org/10.1016/j.rser.2013.08.065.

[3] International Energy Agency, World Energy Investment, 2020. https://www.iea.org/reports/world-energy-investment-2020. (Accessed 20 December 2022).

[4] W. Roeger, P.J. Welfens, Gas price caps and electricity production effects in the context of the Russo-Ukrainian War: modeling and new policy reforms, Int. Econ. Econ. Pol. 19 (2022) 645–673, https://doi.org/10.1007/s10368-022-00552-7.

[5] BP Statistical Review World Energy Review, BP Statistical Review World Energy Review, 2022. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html. (Accessed 20 December 2022).

[6] Nature, What the War in Ukraine Means for Energy, Climate, and Food, 2022. https://www.nature.com/articles/d41586-022-00969-9. (Accessed 20 December 2022).

[7] S.A. Solarin, L.A. Gil-Alana, C. Lafuente, An investigation of long range reliance on shale oil and shale gas production in the US market, Energy 195 (2020) 116933, https://doi.org/10.1016/j.energy.2020.116933.

[8] C. Chen, S.R. Haupert, L. Zimmermann, X. Shi, L.G. Fritsche, B. Mukherjee, Global prevalence of post-coronavirus disease 2019 (COVID-19) condition or long COVID: a meta-analysis and systematic review, J. Infect. Dis. 226 (9) (2022) 1593–1607, https://doi.org/10.1093/infdis/jiac136.

[9] B. Ghosh, L. Pham, T. Teplova, Z. Umar, COVID-19 and the quantile connectedness between energy and metal markets, Energy Econ. 117 (2023) 106420, https://doi.org/10.1016/j.eneco.2022.106420.

[10] B. Steffen, A. Patt, A historical turning point? Early evidence on how the Russia-Ukraine war changes public support for clean energy policies, Energy Res. Social Sci. 91 (2022) 102758, https://doi.org/10.1016/j.erss.2022.102758.

[11] X.Y. Zhou, G. Lu, Z. Xu, X. Yan, S.T. Khu, J. Yang, J. Zhao, Influence of Russia-Ukraine war on the global energy and food security, Resour. Conserv. Recycl. 188 (2023) 106657, https://doi.org/10.1016/j.resconrec.2022.106657.

[12] G.F. Feng, Q.J. Wang, Y. Chu, J. Wen, C.P. Chang, Does the shale gas boom change the natural gas price-production relationship? Evidence from the US market, Energy Econ. 93 (2021) 104327, https://doi.org/10.1016/j.eneco.2019.03.001.

[13] Energy Information Administration. U.S, Energy Facts - Energy Explained, 2022. https://www.eia.gov/energyexplained/?page=us_energy_home. (Accessed 20 December 2022).

[14] P.K. Narayan, R. Smyth, Are shocks to energy consumption permanent or temporary? Evidence from 182 countries, Energy Pol. 35 (1) (2007) 333–341, https://doi.org/10.1016/j.enpol.2005.11.027.

[15] M. Shahbaz, N. Khraief, M.K. Mahalik, K.U. Zaman, Are fluctuations in natural gas consumption per capita transitory? Evidence from time series and panel unit root tests, Energy 78 (2014) 183–195, https://doi.org/10.1016/j.energy.2014.09.080.

[16] F. Fallahi, M. Karimi, M.C. Voia, Persistence in world energy consumption: evidence from subsampling confidence intervals, Energy Econ. 57 (2016) 175–183, https://doi.org/10.1016/j.eneco.2016.04.021.

[17] S. Solarin, Assessing the effectiveness of the policies to boost hydropower consumption, Int. J. Energy Sect. Manag. 9 (2) (2015) 136–155, https://doi.org/10.1108/IJESM-03-2014-0004.

[18] P.K. Narayan, S. Narayan, R. Smith, Are oil shocks permanent or temporary? Panel data evidence from crude oil and NGL production in 60 countries, Energy Econ. 30 (3) (2008) 919–936, https://doi.org/10.1016/j.eneco.2007.07.005.

[19] S. Maslyuk, R. Smyth, Non-linear unit root properties of crude oil production, Energy Econ. 31 (1) (2009) 109–118, https://doi.org/10.1016/j.eneco.2008.09.004.

[20] C.P. Barros, L.A. Gil-Alana, J.E. Payne, An analysis of oil production by OPEC countries: persistence, breaks, and outliers, Energy Pol. 39 (1) (2011) 442–453, https://doi.org/10.1016/j.enpol.2010.10.024.

[21] H.H. Lean, R. Smyth, Are fluctuations in US production of renewable energy permanent or transitory? Apll. Energ. 101 (2013) 483–488, https://doi.org/10.1016/j.apenergy.2012.06.022.

[22] S. Erdogan, G. Akalin, O. Oypan, Are shocks to disaggregated energy consumption transitory or permanent in Turkey? New evidence from Fourier panel KPSS test, Energy 197 (2020) 117174, https://doi.org/10.1016/j.energy.2020.117174.

[23] C. Magazzino, Testing the stationarity and converge of CO2 emissions series in MENA countries, Int. J. Energy Sect. Manag. 13 (4) (2019) 977–990, https://doi.org/10.1108/IJESM-09-2018-0008, 2019.

[24] M. Landajo, M.J. Presno, P. Fernández González, Stationarity in the prices of energy commodities. A Nonparametric Approach, Energies 14 (11) (2021) 3324, https://doi.org/10.3390/en14113324.

[25] Q. Wang, S. Li, R. Li, M. Ma, Forecasting US shale gas monthly production using a hybrid ARIMA and metabolic nonlinear grey model, Energy 160 (2018) 378–387, https://doi.org/10.1016/j.energy.2018.07.047.

[26] Q. Wang, X. Song, R. Li, A novel hybridization of nonlinear grey model and linear ARIMA residual correction for forecasting US shale oil production, Energy 165 (2018) 1320–1331, https://doi.org/10.1016/j.energy.2018.10.032.

[27] Q. Wang, S. Li, Shale gas industry sustainability assessment based on WSR methodology and fuzzy matter-element extension model: the case study of China, J. Clean. Prod. 226 (2019) 336–348, https://doi.org/10.1016/j.jclepro.2019.03.346.

[28] Q. Wang, L. Zhan, Assessing the sustainability of the shale gas industry by combining DPSIRM model and Raga-PP techniques: an empirical analysis of Sichuan and Chongqing, China, Energy 176 (2019) 353–364, https://doi.org/10.1016/j.energy.2019.03.158.

[29] Q. Wang, X. Yang, Evaluating the potential for sustainable development of China's shale gas industry by combining multi-level DPSIR framework, PPFCI technique and Raga algorithm, Sci. Total Environ. 780 (2021) 146525, https://doi.org/10.1016/j.scitotenv.2021.146525.

[30] S. Diop, S. Asongu, The Impact of Covid-19 and Russia-Ukraine War on Food Prices in Fragile Countries: Misfortunes Never Come Singly, European Xtramile Centre of African Studies (EXCAS), 2022, https://doi.org/10.2139/ssrn.4210418. WP/22/055.

[31] C. Gürsan, V. de Gooyert, The systemic impact of a transition fuel: does natural gas help or hinder the energy transition? Renew. Sustain. Energy Rev. 138 (2021) 110552 https://doi.org/10.1016/j.rser.2020.110552.

[32] R. Dahlhaus, Efficient parameter estimation of self-similar processes, Ann. Stat. 17 (4) (1989) 1749–1766, https://doi.org/10.1214/aos/1176347393.

[33] P.M. Robinson, Efficient tests of nonstationary hypotheses, J. Am. Stat. Assoc. 89 (1994) 1420–1437, https://doi.org/10.2307/2291004.

[34] L.A. Gil-Alana, P.M. Robinson, Testing of unit roots and other nonstationary hypothesis in macroeconomic time series, J. Econom. 80 (2) (1997) 241–258.

[35] L.A. Gil-Alana, Mean reversion in the real exchange rates, Econ. Lett. 69 (3) (2000) 285–288, https://doi.org/10.1016/S0165-1765(00)00318-9.

[36] L.A. Gil-Alana, B. Henry, Testing of fractional cointegration in macroeconomic time series, Oxf. Bull. Econ. Stat. 65 (4) (2003) 517–529, https://doi.org/10.1111/1468-0084.t01-1-00048.

[37] J. Cunado, L.A. Gil-Alana, F. Perez de Gracia, A test for rational bubbles in the NASDAQ stock index: a fractionally integrated approach, J. Bank. Finance 29 (10) (2005) 2633–2654, https://doi.org/10.1016/j.jbankfin.2004.10.003.

[38] M. Abbritti, L.A. Gil-Alana, Y. Lovcha, A. Moreno, Term structure persistence, J. Financ. Econom. 14 (2) (2016) 331–352, https://doi.org/10.1093/jjfinec/nbv003.

[39] M. Martin-Valmayor, L.A. Gil-Alana, J. Infante, Energy prices in Europe. Evidence of persistence across markets, Resour. Pol. 82 (2023) 103546, https://doi.org/10.1016/j.resourpol.2023.103546.

[40] F. Furuoka, L.A. Gil-Alana, O. Yaya, E. Aruchunan, A.E. Ogbonna, A new fractional integration approach based on neural network nonlinearity with an application to testing unemployment hysteresis, Empir. Econ. (2024) forthcoming.

[41] Energy Information Administration, in: Natural Gas Explained, 2023. https://www.eia.gov/energyexplained/natural-gas/imports-and-exports.php. (Accessed 3 February 2023).

[42] F. Sowell, Maximum likelihood estimation of stationary univariate fractionally integrated time series models, J. Econom. 53 (1–3) (1992) 165–188, https://doi.org/10.1016/0304-4076(92)90084-5.

[43] J. Geweke, S. Porter-Hudak, The estimation and application of long memory time series models, J. Time Ser. Anal. 4 (1983) 221–238, https://doi.org/10.1111/j.1467-9892.1983.tb00371.x.

[44] P.M. Robinson, Log-periodogram regression of time series with long range dependence, Ann. Stat. 23 (3) (1995) 1048–1072, https://doi.org/10.1214/aos/1176324636.

[45] C.S. Kim, Peter C.B. Phillips, Log Periodogram Regression: the Nonstationary Case, October, Cowles Foundation, 2006. Discussion Paper No.1587 SSRN, https://ssrn.com/abstract=937915.

[46] D.A. Dickey, W.A. Fuller, Distributions of the estimators for autoregressive time series with a unit root, J. Am. Stat. Assoc. 74 (366) (1979) 427–481.

[47] P.C.B. Phillips, P. Perron, Testing for a unit root in time series regression, Biometrika 75 (1988) 335–346.

[48] G. Elliot, T.J. Rothenberg, J.H. Stock, Efficient tests for an autoregressive unit root, Econometrica 64 (1996) 813–836.

[49] F.X. Diebold, G.D. Rudebush, On the power of Dickey- Fuller tests against fractional alternatives, Econ. Lett. 35 (1991) 155–160.

[50] U. Hassler, J. Wolters, On the power of unit root tests against fractional alternatives, Econ. Lett. 45 (1) (1994) 1–5.

[51] D. Lee, P. Schmidt, On the power of the KPSS test of stationarity against fractionally-integrated alternatives, J. Econom. 73 (1) (1996) 285–302.

[52] C.C. Lee, O. Ranjbar, C.C. Lee, Analyzing the hysteresis properties and growth stability of renewable energy production of the US, Appl. Econ. 53 (24) (2021) 2752–2770, https://doi.org/10.1080/00036846.2020.1869168.

[53] S. Diop, S. Asongu, The Impact of Covid-19 and Russia-Ukraine War on Food Prices in Fragile Countries: Misfortunes Never Come Singly, European Xtramile Centre of African Studies (EXCAS), 2022, https://doi.org/10.2139/ssrn.4210418. WP/22/055.

[54] C. Gürsan, V. de Gooyert, The systemic impact of a transition fuel: does natural gas help or hinder the energy transition? Renew. Sustain. Energy Rev. 138 (2021) 110552 https://doi.org/10.1016/j.rser.2020.110552.

[55] Jerolmack, C., Westervelt, A. The Enduring Myth of America's "Molecules of Freedom". Available at: https://www.ft.com/content/60747b3b-e6ea-47c0-938d-af515816d0f1 (accessed on February/3/2023).

[56] D. Brower, M. McCormick, What the End of the US Shale Revolution Would Mean for the World, 2023. https://slate.com/news-and-politics/2022/04/ukraine-war-american-fracking-natural-gas-exports-russia.html. (Accessed 3 February 2023).

[57] D. Li, Y. Wang, B. Zeng, Q. Lyu, X. Zhou, N. Zhang, Optimization of the shale gas reservoir fracture parameters based on the fully coupled gas flow and effective stress model, Energy Sci. Eng. 9 (5) (2021) 676–693, https://doi.org/10.1002/ese3.852.

[58] F.X. Diebold, A. Inoue, Long memory and regime switching, J. Econom. 105 (1) (2001) 131–159, https://doi.org/10.1016/S0304-4076(01)00073-2.

[59] Energy Information Administration, About Energy Information Administration (EIA), 2023. https://www.eia.gov/about/. (Accessed 4 January 2024).