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The systemic risk of US oil and natural gas companies[☆]

Massimiliano Caporin[a], Fulvio Fontini[b], Roberto Panzica[c,*]

[a] Department of Statistics, Universitá degli Studi di Padova, Italy
[b] Department of Economics and Management, Universitá degli Studi di Padova, Italy
[c] European Commission, Joint Research Centre, Italy

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ABSTRACT

We analyse the evolution of the systemic risk impact of oil and natural gas companies since 2000. This period is characterised by several events that affected energy source markets: the real effect of the global financial crisis, the explosion of shale production and the diffusion of the Covid-19 pandemic. The price of oil and natural gas showed extreme swings, impacting companies' financial situations, which, accompanied by technological developments in shale production, had an impact on the debt issuance and on the overall risk level of the oil and natural gas sector. By studying the systemic impact of oil and natural gas companies on risk in the financial market, measured by the ΔCoVaR, we observe that in the most recent decade, their role is sensibly increasing compared to 2000–2010, even accounting for the possible effect associated with the increase in companies' sizes. In addition, our results show evidence of a decreasing relevance of traditional drivers of systemic risk, suggesting that additional factors might be present. Finally, when focusing on the impact of Covid-19, we document its relevant role in fuelling the increase in the oil and natural gas companies' systemic impact.

1. Introduction

The oil and gas upstream production sector in the US has undergone a notable change in the last decade, propelled by the shale oil[1] and shale gas production boom. From 2000 to 2021, US crude oil yearly production doubled, from 2.13 to 4.08 gigabarrel per year (reaching a maximum of 4.48 in 2019), driven by the exploitation of shale fields, whose share in production shifted from less than 8% at the beginning of the sample to 65% in 2021. In the same period, natural gas production changed from 19.18 to 33.49 trillion cubic feet, and the share of shale gas moved from 30% to 86%. Production companies financed their growth, and the drilling activities engaging in bond issuance were rated with low grades by credit agencies. According to Moody's, at the beginning of 2020, North American oil and gas exploration and production companies had \$86 billion in debt, which will mature between 2020 and 2024, and pipeline companies have an additional \$123 billion in debt coming due over the same period.[2] Oil and gas companies are price takers in the global market for crude oil. This means that oil and gas companies that do not pursue risk management via hedging or other financial engineering activities can experience erratic or significant energy price volatility, which, in turn could impact their cash flows (Fusaro, 1998). Both oil and gas prices have experienced large variations over the past decades. For oil, the WTI spot price at Cushing (OK) (weekly, FOB, dollar per barrel - Source: Refinitiv) was 24.23 in January 2000, spiked up to 133.88 in August 2008, then went down to 16.55 in April 2020, and come back to 75.21 at the end of 2021. For natural gas, the Henry Hub spot price (weekly, dollars per MMbtu - Source: Refinitiv) started in our sample as low as 2.42, increased up to 13.42 (a 544% rise) in October 2005, then moved down to the minimum of 1.63 in June 2020, and again up to 3.76 at the end of December 2021, with at least 15 price spikes throughout the whole sample. Several local and worldwide factors have contributed to this, including geopolitical upheavals, the worldwide financial crisis of 2007/08, the Oil Glut of 2014, the increasing concern about climate

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* Corresponding author.
E-mail addresses: massimiliano.caporin@unipd.it (M. Caporin), fulvio.fontini@unipd.it (F. Fontini), roberto.panzica@ec.europa.eu (R. Panzica).

[1] From here onward, we shall use the term 'shale' as synonymous of 'tight' for both oil and gas, as this has become common in the economic literature, even though they have specific meanings.

[2] https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/moody-s-oil-gas-drillers-face-daunting-debt-wall-in-next-4-years-57196039

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change and importance of decarbonisation, and the COVID-19 outbreak, to name just a few. In addition, the shale boom has played a crucial role, shortening the payback time of upstream investments but also increasing companies' risk exposure. This has strongly impacted the financial stability of oil and gas companies: from 2015, the number of fallen angels has been increasing.[3] The lesson of the financial crisis of 2007/08 is that idiosyncratic shocks can aggregate each other and become systemic under precise conditions. For instance, Acemoglu et al. (2012) show that aggregate fluctuations may originate from microeconomic shocks to firms, while Gabaix (2011) shows that individual firm shocks do not average out if the distribution of the firm size is fat-tailed. Therefore, it is of the utmost importance to study the extent to which turmoil in the oil and gas sector can fuel a new financial crisis and threaten the stability of the financial system. In this paper, we try to provide an answer to this research question.

We investigate the systemic risk of oil and natural gas sector by looking at its evolution over time and at the determinants of the indicator put forward in Adrian and Brunnermeier (2016), the Delta Conditional Value-at-Risk ($\Delta CoVaR$). The advantage of the $\Delta CoVaR$ is that it enables us to determine the impact of each oil and gas company on a proxy of the financial market (the system) conditional on the distress in the company. Moreover, this methodological approach allows us to control for possible state variables when building the indicator and to correlate the estimated indicators in the cross-section of oil and natural gas companies with possible risk and impact drivers. This second step is of particular interest, as it enables us to identify the drivers of the rise in the oil and gas sector's systemic risk.

The study focuses on a panel of US companies active from 2000 to 2021 in the oil and gas production sector[4] and accounts for the role played by a selection of risk drivers, including both market-wide and company-specific variables. Two sub-periods are specified, 2000–2010 and 2011–2021, taking into account the evolution of the shale extraction and the structural break identified in the oil prices by Caporin et al. (2019). The analysis shows that company size plays a relevant non-linear role in shaping the company's impact on the systemic risk of the market: in the first sub-period, only large companies had an impact on the systemic risk, but in the second period, the impact was expanded to small companies as well. Our empirical findings suggest to the policy-makers that potential regulations should not neglect small and medium firms in designing policies aimed at containing the systemic risk of US oil and natural gas sector. Robustness checks confirm the findings. This result confirms the role played by shale extraction in changing the risk structure of oil and gas companies and, through this, its importance as a driver of systemic risk. Differently, the role of debt issuance is negligible.

The paper is structured as follows. In Section 2, we review the related literature and we present an overview of the US corporate debt market by sector. In Section 3, we review the methodology for computing the systemic risk measure ($\Delta CoVaR$), while in Section 4, we describe the data we use in the empirical analysis. In Section 5, we investigate the drivers used for predicting the $\Delta CoVaR$ measure, and in Section 6, we gather the empirical results and our inferences. We close the paper with a robustness analysis, in Section 7, and with final remarks in Section 8.

2. Literature background and institutional framework

The global challenges faced by the US oil and natural gas sector are becoming increasingly complex. In this respect, it is crucial to investigate the drivers affecting oil and natural gas companies and whether the sector is resilient enough to avoid threatening financial stability. Sadorsky (2001) shows that exchange rates, crude oil prices and interest rates have large and significant impacts on stock price returns in the Canadian Oil and Natural Gas industry. Faff and Brailsford (1999) document a positive and significant impact of oil prices on Australian oil and gas industry equity returns, as well as El-Sharif et al. (2005) who find that gas and oil price have positive effects on UK oil and gas companies. The rig counts have also been studied, taking into account their technology as well as their importance as indicators of the industry's health (Apergis et al., 2021). Nevertheless, drilling is capital-intensive since companies must finance their investment, which inevitably brings about other elements of risk. Howard and Harp Jr. (2009) suggest that, for a complete evaluation of the risk, company characteristic such as ratios and debt should be taken into account with the drivers mentioned before.

The transition to a lower-carbon economy could make the future of oil and natural gas firms more gloomy and uncertain. From this angle, according to Diaz-Rainey et al. (2021), transition risks could affect the oil and natural gas sectors. These include the following: (i) higher costs in finding and extracting new oil and gas reserves; (ii) low oil prices, as found by Basher et al. (2018); (iii) the falling cost of renewable energy generation; (iv) the switch to electric vehicles, underpinned by technological improvements to batteries and decreasing vehicle and battery costs; (v) environmental-minded investors affecting demand for petrochemicals (see Fama and French, 2007) and (vi) carbon pricing and taxation schemes. Diaz-Rainey et al. (2021) found that the signing of the Paris Agreement had a large negative impact on the oil and gas sector. Monasterolo and De Angelis (2020) found that the after the Paris Agreement, high carbon stocks became less appealing for investors. An eventual and realistic contraction of oil and natural gas demand could reduce the cash flows and the margin of profit for these firms, which are already in distress.

The characterisation of systemic risk, its definition and the identification of methodologies for its estimation is one of the most debated topics in the financial economics and econometrics literature since the advent of the global financial crisis. Following part of the literature, we define systemic risk as an event or a circumstance that could threaten the stability of the financial system. From the measurement point of view, the econometric literature includes several different methodologies that might be considered for the purpose of monitoring the systemic riskiness of a sector by looking at market data. We refer the reader to the survey by Benoit et al. (2017) for a review of the most relevant systemic risk measures. In this vein, Adrian and Brunnermeier (2016) introduced $\Delta CoVaR$ to evaluate the systemic risk of single companies when they enter into a distress state. We chose this measure for our analyses as it allows for the introduction of covariates that, in our setting, will have a relevant role, as we will show in the following sections. Lupu et al. (2021) found that European energy companies enhanced systemic risk spillovers during 2008, early 2009, and 2020. Within the oil and gas sector, the $\Delta CoVaR$ has been used in Khalifa et al. (2021) to evaluate the role of oil in driving the systemic risk of the Gulf Cooperation Countries' financial markets, while Tiwari et al. (2020) used $\Delta CoVaR$ and MES to show that oil price dynamics contribute significantly more to G7 stock market returns during volatile times than during stable times.[5] Ouyang et al. (2022) analyse the relationship between the oil price and the systemic risk under different market conditions, decomposing the oil price in negative and positive price, and finding that the oil price impact on systemic risk is asymmetric under medium and high risk conditions. Moreover, they show that systemic risk is only negatively influenced by

[3] https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/s-p-global-fallen-angels-count-surges-to-highest-since-2015-58071556

[4] This also includes companies that provide upstream support activities, as explained in the data section.

[5] In this respect, Mensi et al. (2017) and Liu and Gronwald (2017) analyse the dependence structure between crude oil prices and major regional developed stock markets and oil and gas sector.

oil-specific demand shocks. Furthermore, the impact of oil price shocks on systemic risk decreased during the pandemic.[6] Reboredo (2015) uses a copula approach to spot the dependence among systemic risk, oil price and renewable sector. The paper shows that oil and renewable energy markets are positively correlated, that is, they are coupled in such a way that they crash and boom together. The finding on systemic risk indicates that oil price dynamics significantly contributes around 30% to downside and upside risk of renewable energy companies. We differ from Kerste et al. (2015), who compute the expected fraction of failing firms in one sector given the firms' default *within* and *between* sectors, and we are closer to Adrian and Brunnermeier (2016) who investigate how oil and natural gas firm losses, measured by Value-at-Risk could have an impact on the broader economy defined by market losses; we leave the risk spillover among sectors to further research. Al-Jarrah et al. (2021) show that traditional models fail to capture the systemic risk of small–middle size banks operating in the Gulf Cooperation Council since they have high levels of economies of scale. In this respect, analysing the systemic risk spillover of the US oil and gas sector is crucial, given the strong dependence on oil prices and the failure of traditional drivers to capture systemic risk. Bond holders could also amplify the spillover on the financial system by withdrawing their position, given the high credit risk of these securities, especially if driven by herding behaviour during market turmoil. Differently from the cited literature, we investigate the relationship between the losses of US oil and natural gas companies, and the systemic risk. We focus on the role played by the shale revolution, on the one hand, and the relationship between systemic risk and the size of firms, on the other hand. Our analysis offers a picture to the systemic risk drivers of the oil and natural gas sector, which might be impacted negatively by the forthcoming energy transition towards clean technologies. Thus, the study can provide support to policy regulators by showing how much incremental additional negative shocks on this sector would increase the systemic risk.

To assess, from a systemic risk perspective, the importance of the US oil and natural gas sector within the US debt market, we retrieve from Dealogic DCM the amount at issuance of US bonds. The most active issuers in the US bond market are governmental issuers and financial corporations.[7] In particular, in the period 2000–2010 the amount of bonds issued by financial corporations was 15.3 trillion dollars (T\$), followed by the government, with 7.3 T\$, and non-financial corporations, reaching a total of 3.4 T\$. The debt structure changed after 2010: financial institutions substantially reduced the issuances from 2011–2020. The government led the issuance, with roughly 19 T\$, followed by financial corporations at 9.3 T\$, while non-financial companies add up to 7.7 T\$. The amount at issuance increased from the first (2000–2010) to the second (2011–2020) period as a consequence of the behaviour of the Federal Reserve, which kept down the interest rate. Fig. 1 shows the breakdown of the amount at issuance by global industry group for each period. The oil and natural gas companies raised capital of 251 Bn \$ in the first period, the fifth sector by issued volume. In the second period, we observe a generalised expansion of bonds' issuance, especially for oil and natural gas firms, which increased the amount of issuance by 134%, reaching 589 Bn \$, the fifth sector in terms of amount issued.

The financial importance of the oil and gas sector can also be evaluated by looking at its relative rating compared to the other sectors. Fig. 2 reports the weighted rating at the sector level. The oil and natural gas sector was less creditworthy in the first period (2000–2010), with a rating averaging at 9.1, which decreases to 8.6 in the second period (2011–2020).[8] The evidence presented above about the large amount of debt issued and the low level of creditworthiness of US companies active in the oil and gas sector confirms the importance of undertaking a systemic evaluation. This will allow us to determine how potential risks that originate in the oil and gas sector could spread throughout the entire financial system, affecting its stability. We pursue this line of research by first reviewing the methodology and then we move to the empirical evidence.

3. Methodology

From a methodological point of view, the $\Delta CoVaR$ is estimated with a two-step procedure. Let us denote by X_t^i the losses at time t for company i, where losses are obtained as the negative of stock price returns. Moreover, X_t^{system} is the system loss at time t, and M_t a vector of state variables at time t. The first step in the $\Delta CoVaR$ estimation is the estimation by means of quantile regression (Koenker, 2005) of the two linear models

$$X_t^i = \alpha_q^i + \gamma_q^i M_{t-1} + \epsilon_{q,t}^i \tag{1}$$

$$X_t^{system} = \alpha_q^{system|i} + \gamma_q^{system|i} M_{t-1} + \beta_q^{system|i} X_t^i + \epsilon_{q,t}^{system|i} \tag{2}$$

where the subscript q identifies the estimated quantile, and the superscript $system \mid i$ highlights the coefficients account for the dependence of the system on oil company i. Following the standard practice, for the system, we consider the quantiles $q = 0.99$ and $q = 0.95$, i.e., the 1% and 5% upper tails of losses, while for the company, we consider the same quantiles of the system and we also add the median one, i.e., $q = 0.50$.

Given the estimated coefficients, we compute the value-at-risk of the company, i.e. $VaR_{q,t}^i$,

$$VaR_{q,t}^i = \hat{\alpha}_q^i + \hat{\gamma}_q^i M_{t-1}, \quad q = 0.5, 0.95, 0.99, \tag{3}$$

and the q conditional-value-at-risk of the system when the company's i losses are set at their τ quantile, namely $CoVaR_{q,t}^{system|i,\tau}$:

$$CoVaR_{q,t}^{system|i,\tau} = \hat{\alpha}_q^{system|i} + \hat{\gamma}_q^{system|i} M_{t-1} + \hat{\beta}_q^{system|i} VaR_{\tau,t}^i \tag{4}$$
$$\{q,\tau\} = \{(0.99, 0.99), (0.95, 0.95), (0.99, 0.50), (0.95, 0.50)\}.$$

Finally, building on the estimated risk measures, we compute the impact on the system of the distress in company i. This distress is associated with the company return moving from the median level of losses to an upper quantile of losses. $\Delta CoVaR_{q,t}$ equals

$$\begin{aligned}\Delta CoVaR_{q,t}^{system|i} &= (CoVaR_{q,t}^{system|i,q} - CoVaR_{q,t}^{system|i,0.5}) \\ &= \hat{\beta}_q^{system|i}(VaR_{q,t}^i - VaR_{0.50,t}^i),\end{aligned} \tag{5}$$

with the usual choices for the quantile level, i.e. $q = 0.95$ or $q = 0.99$.

The $\Delta CoVaR_{q,t}^{system|i}$ is expressed in the unit of measure adopted for losses, i.e. percentages, but it is also interesting to show its monetary value. For this purpose, the risk measure is multiplied by a proxy of the company size, expressed in US Dollars, leading to the monetary Delta CoVar: $\Delta^{\$}CoVaR_{q,t}^{system|i}$. We report the results of $\Delta^{\$}CoVaR_{q,t}^{system|i}$ in Section 7.2. The evaluation of $\Delta CoVaR_{q,t}^{system|i}$ provides insights into the company-specific systemic risk, and by comparing this risk measure over time and in the cross-section in a panel of companies, we identify changes in the level and dispersion of risk. Moreover, we specify the drivers of the oil and gas company's systemic risk and infer potential sources of risk that can lead to an increase in the overall systemic risk.

[6] In our study, the oil price assumes a secondary role as it might impact the margin of the US oil and natural gas companies; this is related to the oil price effect on the number of producing wells, as stated by US energy information administration agency report: www.eia.gov/petroleum/wells/pdf/full_report.pdf.

[7] Municipal and sovereign bonds are included under the label *government*.

[8] The rating score is defined as the weighted average of companies' ratings, with weights given by the amount at issuance. The rating is computed by considering the most important credit agencies (Standard & Poor, Moody's and Fitch). The rating score of investment bonds varies from 1 to 10. The maximum creditworthiness is defined by 1, the lowest grade, just before the *junk bonds*, by 10.

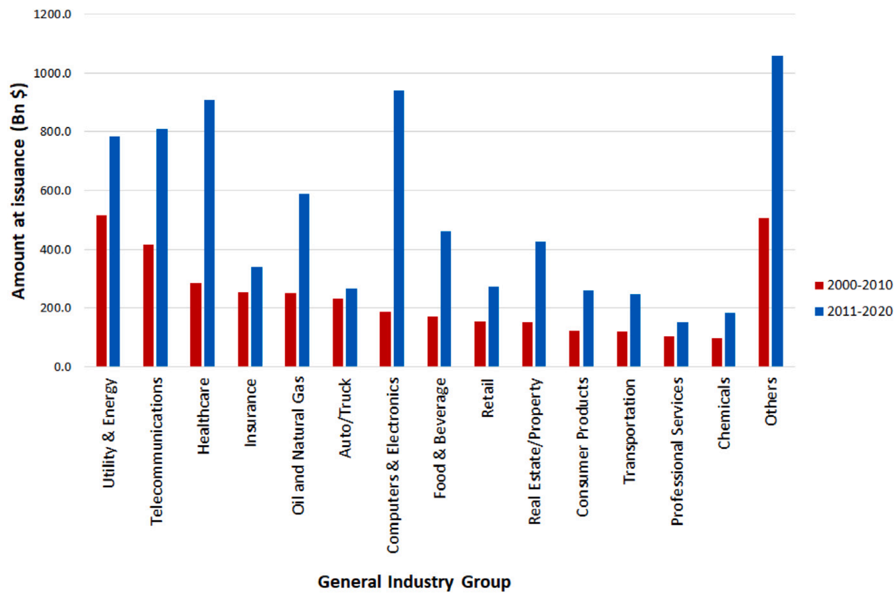

Fig. 1. US non-financial corporation bond issuances.
Note: The figure reports the amount at issuance issued by the US non-financial corporation aggregated in general industry group in 2000–2010 (red bar) and 2011–2020 (blue bar). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: Dealogic DCM.

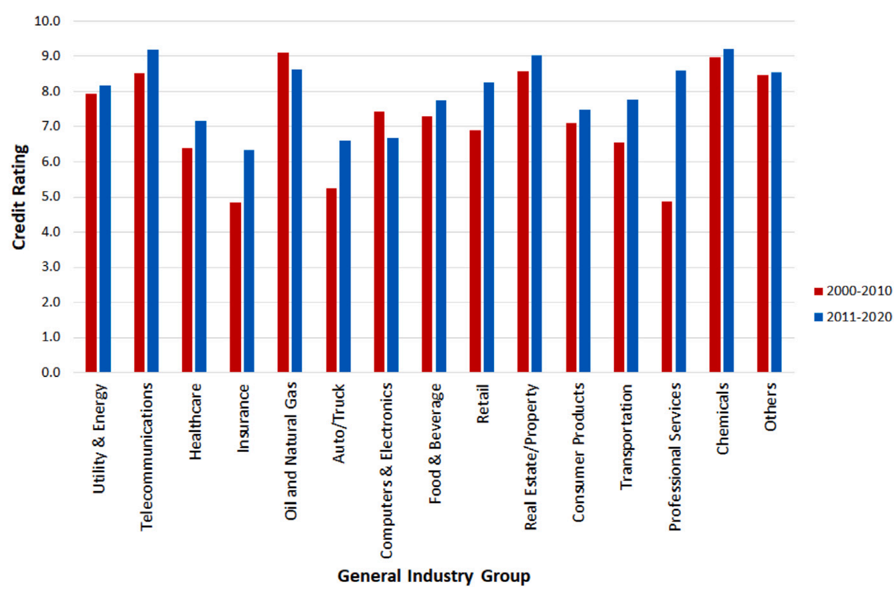

Fig. 2. US non-financial corporation credit ratings.
Note: The figure reports the credit rating of the general industry group of US non-financial corporation respectively in 2000–2010 (red bar) and 2011–2020 (blue bar). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: Dealogic DCM.

4. Data and preliminary analyses

We downloaded US oil and natural gas companies' stock returns, weekly-based, from Refinitiv/Eikon. The sample covers, according to the NACE 4-digit classification, the following economic activities (NACE code in parentheses): extraction of crude petroleum (06.10), extraction of natural gas (NACE) (06.20), support activities for petroleum and natural gas extraction (NACE) (09.10).[9] The time horizon spans from January 2000 to December 2021. Fig. 3 exhibits the price of Crude Oil-West Texas Intermediate and the price of natural gas (Henry Hub Spot price) over time. Given their strong dependence with the cash flows of the oil and natural gas companies, we associate Fig. 3 with the number of US-listed companies in the oil and natural gas sector in Fig. 4. Overall, the number of public oil and natural gas companies raised in 2000, dropped after the global financial crisis in 2008 and

[9] The NACE 4-digit classification is retrieved from Refinitiv/Eikon. We include the support activity sector in the sample because of the strong link between companies providing support activities and the oil and gas companies. This has been reinforced by the shale boom: to cultivate shale fields, the support activities include providers of a collection of equipment (such as high-pressure pumps, blenders and storage facilities) known as *frac spread*, which is needed for both shale oil and gas extraction.

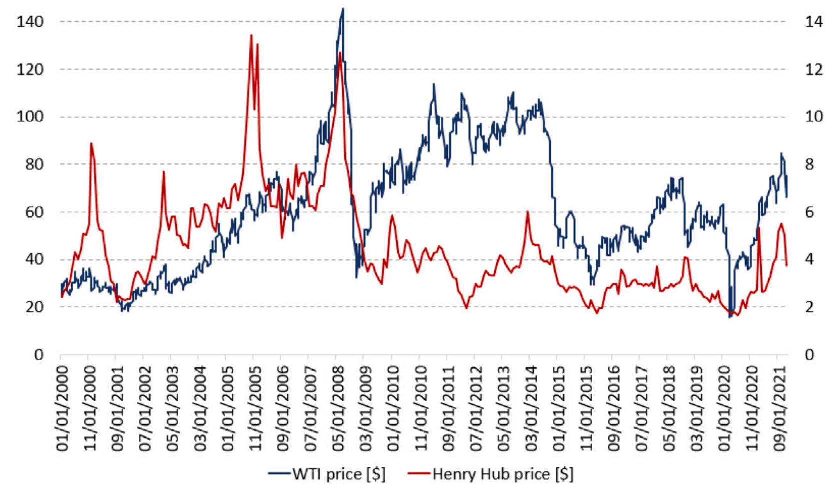

Fig. 3. WTI price and Henry Hub price.
Note: The figure reports on the left *y*-axis, the price of WTI (dollars per barrel), defined by the red line, and on the right *y*-axis the Henry Hub Spot price of natural gas (dollars per MMbtu) over time from 2000 to December 2021. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

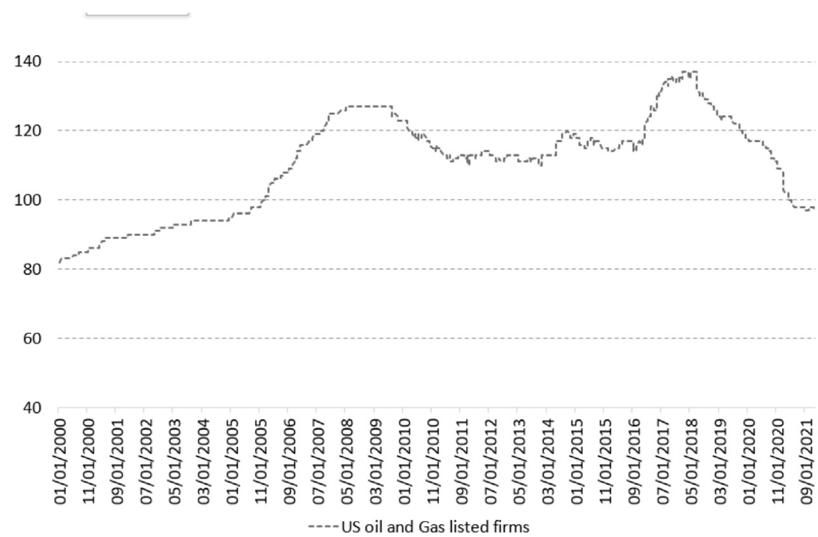

Fig. 4. Number of US oil and natural gas firms. Note:The figure reports the number of US oil and natural gas firms over time from 2000 to December 2021 (dashed line).

reached a maximum of 137 in 2018; finally, the number plummeted to 97 at the end of 2021 (Fig. 4). The first drop might be related to the consequences of the global financial crisis; the more recent contraction in active companies is due to the COVID-19 outbreak and its impact on the real economy. The entire sample is thus characterised by two sub-samples including, first a phase of moderate increase in the number of companies, a second phase with a steeper increase in the companies, and then a third phase with a drop.

The evolution of the number of companies can also be associated with the margin that oil and natural gas firms have on their cost, which depends on the oil and gas prices. Periods of drops in oil and natural gas prices are coupled with reductions in the number of firms. By combining the patterns in the number of active companies and the patterns in the oil and gas prices, we decided to analyse separately the sub-samples 2000–2010 and 2011–2021; such a choice is also coherent with the evidence in Caporin et al. (2019) that identity a structural break in the oil price time series, located at the beginning of 2011.

We first proceed to a filtering step on the downloaded stock return series: we consider all the companies that, in the time period considered, are characterised by the presence of non-missing values for at least two years (100 consecutive observations). Such a choice excludes companies active from 2010 to 2010, or from 2011 to 2021, for short periods of time and, at the same time, keeps track of all firms that entered or left the market during the time period considered. Our sample is thus composed by 127 listed companies in 2000–2010 and 165 firms in 2011–2021.[10]

Table 1 reports the number of firms by sector (NACE 4-digit code) and period and some descriptive statistics of their market capitalisation. Notably, in the first period, 57% of the firms belong to the extraction of crude oil, followed by firms involved in support activities, at 27%, and finally by those focused on the extraction of gas, at 16%. The composition remains roughly unchanged in the second period, even though we observe an increasing number of firms. In addition, the

[10] Although the chosen selection criteria might potentially exclude companies that entered the market before 2010 and that were active for less than two years, both in the first and in the second sample, no company falls into this category. A total of 73 companies entering the market before 2010 were active for less than two years in the first sample and for more than two years in the second sample; they have been included in the second sample only. Finally, there were 35 companies that entered the market before 2010 and were active for more than two years in the first sample and for less than two years in the second sample. They have been included in the first sample only.

Table 1
Firms descriptive statistics by NACE code 4-digits.

NACE code 4-digits	Nfirms	%	Mean	Std	Median	Q10	Q90
07-01-2000 31-12-2010							
			Market cap [M$]				
Extraction of crude petroleum (NACE) (06.10)	71	56.69	3363	9298	471	49	8381
Extraction of natural gas (NACE) (06.20)	21	16.54	4347	5474	2125	74	14079
Support activities for petroleum and natural gas extraction (NACE) (09.10)	34	26.77	3636	10241	992	73	6735
07-01-2011 31-12-2021							
			Market cap [M$]				
Extraction of crude petroleum (NACE) (06.10)	90	54.55	5087	11857	1005	82	15693
Extraction of natural gas (NACE) (06.20)	34	20.61	5132	5496	3711	319	10791
Support activities for petroleum and natural gas extraction (NACE) (09.10)	41	24.85	4304	14224	995	92	5087

Notes: The table reports the number of firms (absolute value and percentage) and the weekly market capitalisation averaged across time expressed in millions of dollars (M$). We compute, over the cross-section, mean, standard deviation, median, and 10% and 90% quantiles.

number of firms belonging to the extraction of natural gas increased more than those active in the extraction of crude oil and support activities. If we focus on the market capitalisation, we observe that it rises in the second period. Firms that belong to the extraction of natural gas are larger than those that are part of the other sectors. Table 1 reports the mean, standard deviation, median and 10% and 90% quantiles of the weekly market capitalisation, averaged over time.[11] The high standard deviation and the discrepancy between the average and the mean show evidence of the relevant heterogeneity in the sectors' market value. Firms that belong to the extraction of natural gas, have the highest median in the first period, reaching a value of $2125 million, followed by firms in the supporting activities, with a value of $992 million, and extraction of crude oil firms, with $471 million. If we look at the mean, the ranking of the market value remains unchanged. In the second period, the extraction of the crude oil sector increased its dimension, moving to the second highest market cap, with $5087 million, on average. The extraction of natural gas remains the largest sector, with a median capitalisation equal to $5132 million. Notably, focusing on the difference between the mean and median and on the market value dispersion, we see that companies involved in the extraction of crude oil and in support activities are more heterogeneous that the gas extraction companies.

Sadorsky (2001) has shown that exchange rates, crude oil prices and interest rates each have large and significant impacts on stock price returns in the Canadian oil and natural gas industry. To consider these effects in the analysis of the systemic risk of US oil and natural gas companies, we select the following state variables to be included in Eqs. (3) and (5). First, we use *Tbill3M*, which is the change in the three-month Treasury Bill rates. This variable measures the attractiveness of the risk-free rate in the US economy. Then, we include *Term_spread_10Y3M*, a measure of term spread, computed as the difference between the 10-year bond yield and the three-month Treasury Bill rate. The term spread measures the slope of the bond yield curve. Further, we include *Credit_spread*, which is the difference between the ICE Bank of America BBB US corporate index and the Treasury 10-year bond yield. The credit spread monitors the additional risk faced by investors when buying corporate debt in place of a safer government debt. In addition, we introduce Ret_{MKT}, the Standard & Poor's 500 market index return, and Ret_{WTI}, the West Texas Intermediate (WTI) crude oil price return. We also add $Price_{WTI} - Price_{BRE}$, the difference between the WTI and the European Brent oil prices. The difference measures the disagreement in oil price between the two most predominant world oil benchmarks.[12] To monitor the market stress, we introduce *Δ VIX*, the change in the Russell volatility index, defined as the implied volatility of a synthetic at-the-money option of the Russell 2000 index. Finally, to take into account the demand of urban consumers, we introduce *Inflation rate*, a measure of the average monthly change in the prices for goods and services paid by urban consumers. A detailed description of the variables and their sources is reported in the Appendix, Table 10.

For the analyses, the sample is split into two time periods: the first spans from 07-01-2000 to 31-12-2010, the second from 07-01-2011 to 31-12-2021. This aims at evaluating the role played by the shale oil and gas boom and is coherent with the findings in Caporin et al. (2019), who identify a structural break located in early 2011 by studying the long-run relationship in the WTI-Brent oil time series.[13]

Table 2 reports the descriptive analysis of the state variables in the two time periods. Except for *Tbill3M*, which is approaching zero, moving from -9.1×10^{-5} in the first period to -1.3×10^{-6} in the second period, *Term_spread_10Y3M*, *Ted_spread* and *Credit_spread*, on average, register a contraction in the second period. By contrast, Ret_{MKT} increases (from 0.0001 to 0.0027). Ret_{WTI} shrinks its average value from 0.0022 to −0.0003, while *Δ VIX* and $Price_{WTI} - Price_{BRE}$ increase their average, reaching a value of −0.0009 and 0.0849 during the second period, compared to −0.0120 and −0.0373, respectively, in the first period. The inflation rate drops from 0.0903 in the first period to 0.0722 in the second. All variables are leptokurtic except for *Term_spread_10Y3M*.

Table 3 reports the summary statistics for the market equity losses X_t^i and for the risk measures of the oil and natural gas firms in the two periods. The time series of each firm are first averaged, and then the mean, standard deviation, median and 10% and 90% quantiles are calculated cross-sectionally. Both $VaR_{q,t}^i$ and $\Delta CoVaR_{q,t}^i$ are obtained by running the quantile regressions in Eqs. (3), (5) and (5), at quantiles 0.99 and 0.95. We also report $VaR_{q,t}^{Sys}$, the financial system's value-at-risk, again at quantiles 0.99 and 0.95. The last two columns report the number of firms used in the corresponding period and the number of weeks in each period, respectively.

In the first period (2000 – −2010), the oil and natural gas firms register negative losses (gains) equal to −0.002, on average (−2.9%

[11] We first average over time the weekly market capitalisation of the various companies and then proceed to evaluate the descriptive statistics over the cross-section.

[12] Traditionally WTI and Brent jointly comoved, with an average 3 dollars per barrel premium in favour of WTI. The spread widened in 2011 and returned to its average long-term value in 2014. Several factors contributed to the widening of the gap, including upstream oil supply constraints in the US. The variable introduced aims at taking into account possible impacts on systemic risks of these factors.

[13] Caporin et al. (2019) identify a break at the beginning of February 2011. We set here the break date at the beginning of 2011 to be able to transform the data frequency into quarterly data. See Section 5.

Table 2
State variable summary statistics.

	07-01-2000 to 31-12-2010					
	Mean	Std	Kurtosis	Skewness	Min	Max
Tbill3M	−9.1E−05	0.0013	17.524	−1.200	−0.0080	0.0083
Term_spread_10Y3M	0.0012	0.0179	2.194	−0.378	−0.0296	0.0318
Ted_spread	0.0053	0.0051	15.666	2.950	0.0010	0.0425
Credit_spread	0.0200	0.0122	8.874	2.263	0.0063	0.0722
Ret_{MKT}	0.0001	0.0275	9.764	−0.849	−0.2002	0.1141
Ret_WTI	0.0022	0.0573	7.993	−0.369	−0.3122	0.3594
$Price_{WTI} - Price_{BRE}$	−0.0373	0.0475	4.408	0.202	−0.2022	0.1733
ΔVIX	−0.0120	3.2334	14.585	0.654	−19.2400	24.8100
Inflation rate	0.0903	0.1620	10.988	−1.418	−0.7684	0.6750
	07-01-2011 to 31-12-2021					
	Mean	Std	Kurtosis	Skewness	Min	Max
Tbill3M	−1.3E−06	0.0005	135.756	−8.003	−0.0087	0.0022
Term_spread_10Y3M	0.0004	0.0080	2.245	−0.160	−0.0167	0.0188
Ted_spread	0.0028	0.0015	15.777	2.438	0.0003	0.0146
Credit_spread	0.0156	0.0048	7.560	1.476	0.0084	0.0455
Ret_{MKT}	0.0027	0.0222	12.015	−1.052	−0.1620	0.1146
Ret_WTI	−0.0003	0.0601	26.183	0.666	−0.3689	0.6028
$Price_{WTI} - Price_{BRE}$	0.0849	0.0668	4.423	0.495	−0.2153	0.3671
ΔVIX	−0.0009	3.4249	10.685	0.652	−18.7400	23.0300
Inflation rate	0.0722	0.1215	7.831	−1.206	−0.5128	0.3320

Notes: The table shows the weekly-based descriptive statistics of state variables. First we average the weekly-based time series, across time and then we compute the distribution. The table reports the mean, standard deviation, skewness, kurtosis, minimum and maximum value of the state variable distribution.

Table 3
Summary statistics for estimated risk measures.

	07-01-2000 31-12-2010												
	Mean	Std	Median	Q10	Q90		Mean	Std	Median	Q10	Q90	# firms	Obs
X_t^i	−0.002	0.004	−0.003	−0.006	0.003	X_t^i	−0.002	0.004	−0.003	−0.006	0.003	127	573
$VaR_{99,t}^i$	0.218	0.120	0.183	0.113	0.351	$VaR_{95,t}^i$	0.124	0.057	0.113	0.073	0.174	127	573
$\Delta CoVaR_{99,t}$	0.033	0.017	0.035	0.011	0.053	$\Delta CoVaR_{95,t}$	0.018	0.009	0.019	0.005	0.028	127	573
$VaR_{99,t}^{Sys}$	0.067	0.009	0.068	0.055	0.080	$VaR_{95,t}^{Sys}$	0.039	0.005	0.039	0.034	0.045	127	573
Market Cap (M$)	3599	9003	654	56	8411	Market Cap (M$)	3599	9003	654	56	8411	127	574
	07-01-2011 31-12-2021												
	Mean	Std	Median	Q10	Q90		Mean	Std	Median	Q10	Q90	# firms	Obs
X_t^i	0.003	0.007	0.002	−0.002	0.012	X_t^i	0.003	0.007	0.002	−0.002	0.012	165	573
$VaR_{99,t}^i$	0.228	0.122	0.200	0.129	0.358	$VaR_{95,t}^i$	0.130	0.049	0.121	0.078	0.185	165	573
$\Delta CoVaR_{99,t}$	0.025	0.014	0.025	0.008	0.039	$\Delta CoVaR_{95,t}$	0.013	0.006	0.013	0.005	0.021	165	573
$VaR_{99,t}^{Sys}$	0.051	0.008	0.051	0.040	0.061	$VaR_{95,t}^{Sys}$	0.030	0.004	0.030	0.025	0.037	165	573
Market Cap (M$)	4901	11480	1081	107	14396	Market Cap (M$)	4901	11480	1081	107	14396	164	574

The table reports the summary statistics of the market equity losses X_t^i and the systemic risk measures $VaR_{q,t}^i$, $\Delta CoVaR_{q,t}^i$ and the financial system value at risk $VaR_{q,t}^{Sys}$ at quantiles 99 and 95 percent. First we average the weekly time series across time and then we compute the distribution.

in terms of annualised average percentage). On the contrary, in the second period (2011 – –2021), the losses rise to 0.003 (3.8% in terms of annualised average percentage). On average, Var_{95}^i at firm level equals 0.124, which is roughly comparable with the Var_{95}^i of the second period, 0.130. Additionally, the Var_{99}^i rises from 0.218 to 0.228. The effect is more pronounced looking at the median; both VaR_{99}^i and VaR_{95}^i increase over time, from 0.183 to 0.200 and from 0.113 to 0.121, respectively. $\Delta CoVaR_{95}$ does not change across the two periods (0.018 vs. 0.013). The same considerations apply to the results looking at the 0.99 quantile (0.033 vs. 0.025). Finally, looking at the market capitalisation, we note that firms decisively increase their magnitude across two periods, from $3599 million to $4901 million, on average.[14]

5. ΔCoVaR and its predictors over time

In this section, we investigate the drivers affecting the cross-sectional dispersion of the $\Delta CoVaR$ in the two periods under study. In the fashion of Adrian and Brunnermeier (2016), we use as predictors the state variables and some institutional characteristics. This larger set of risk predictors has a crucial role: systemic risk arises in normal times and thus predictors can act as early-warning indicators. Since both firm characteristics and potentially relevant state control variables have lower frequencies, following Adrian and Brunnermeier (2016), we aggregate $\Delta CoVaR$ at the quarterly level. Specifically, starting from weekly $\Delta CoVaR_{q,t}^{system|i}$ we generate a weekly panel of $\Delta^{\$}CoVaR_{q,t}^{system|i}$ by multiplying each company-specific risk measure by the market capitalisation of the conditioning institution i at time t and then we normalise it by the cross-sectional average of market equity at time t.[15] Finally, we obtain quarterly figures of $\Delta CoVaR_{q,t}^{system|i}$ by averaging over the weekly observations within each quarter.

$\Delta CoVaR_{q,t}^{system|i}$ becomes our dependent variable, which is regressed over lagged state variables, M_{t-1}, and lagged firm characteristics, X_{t-1}. Note that the predictors are all lagged by a single quarter. The specification we adopt is the following:

$$\Delta CoVaR_{q,t}^{system|i} = a + cM_{t-1} + bX_{t-1} + \eta_t \quad (6)$$

[14] For what concerns state variables, we do not comment on their role in the evaluation of the risk indicators at both the company and the market levels. They are included in the analyses just to account for the overall economy state.

[15] We use as the dependent variable $\Delta CoVaR_{q,t}^{system|i}$ in the baseline model. Table 7 exhibits the results by using $\Delta^{\$}CoVaR_{q,t}^{system|i}$ as the dependent variable.

Table 4
Summary statistics for estimated risk measures, state variables and company characteristics at quarterly level.

Panel A	Q1 2000–Q4 2010									
Variables	N	mean	sd	skewness	kurtosis	p25	p50	p75	min	max
$\Delta CoVaR99$	4,470	0.034	0.024	2.034	11.130	0.019	0.030	0.044	0.000	0.276
$\Delta CoVaR95$	4,472	0.018	0.012	1.867	9.119	0.009	0.016	0.023	0.000	0.106
$\Delta CoVaR^{\$}99$	4,470	0.041	0.125	10.960	203.100	0.001	0.005	0.028	0.000	3.478
$\Delta CoVaR^{\$}95$	4,472	0.025	0.079	8.645	111.900	0.000	0.003	0.016	0.000	1.641
var99	4,529	0.213	0.160	3.463	25.920	0.118	0.168	0.255	0.019	2.544
var95	4,529	0.120	0.077	2.563	14.470	0.072	0.099	0.142	0.005	0.959
Tbill3M	9,416	−0.001	0.005	−1.119	3.658	−0.002	0.000	0.002	−0.014	0.006
Ted_spread	9,416	0.005	0.005	2.128	8.150	0.002	0.004	0.006	0.002	0.025
Credit_spread	9,416	0.020	0.012	2.146	8.116	0.013	0.017	0.024	0.007	0.063
Oil	9,416	0.006	0.022	2.237	10.970	−0.005	0.002	0.012	−0.031	0.106
Ret_WTI	9,416	0.029	0.187	−1.947	10.330	−0.031	0.052	0.121	−0.814	0.342
Inflation Rate	9,416	1.165	1.322	−2.379	11.750	0.833	1.349	1.835	−5.012	3.323
Henry Hub_ret	9,416	0.010	0.224	−0.243	2.282	−0.155	0.041	0.190	−0.465	0.391
size	4,675	20.090	2.291	−0.195	2.719	18.460	20.230	21.700	11.780	25.690
debt	4,428	10.430	4.746	−1.232	3.411	9.089	12.050	13.650	0.000	17.170
ROA	4,432	0.055	3.048	−36.400	1376.000	0.038	0.089	0.148	−115.000	7.724
ROE	4,432	5.051	55.820	13.070	195.400	0.077	0.203	0.331	−300.000	976.300
$\Delta NRIGS_{\%}$	9,416	0.010	0.119	−1.379	4.960	−0.028	0.035	0.083	−0.368	0.184
Panel B	Q1 2011–Q4 2021									
Variables	N	mean	sd	skewness	kurtosis	p25	p50	p75	min	max
$\Delta CoVaR99$	4,853	0.025	0.014	1.439	10.630	0.016	0.025	0.033	0.000	0.162
$\Delta CoVaR95$	4,840	0.014	0.007	0.793	4.799	0.009	0.014	0.018	0.001	0.059
$\Delta CoVaR^{\$}99$	4,845	0.034	0.075	3.704	19.610	0.001	0.006	0.024	0.000	0.730
$\Delta CoVaR^{\$}95$	4,832	0.022	0.053	4.215	24.660	0.001	0.003	0.014	0.000	0.557
var99	4,991	0.225	0.124	3.739	38.970	0.149	0.197	0.272	0.033	2.428
var95	4,991	0.129	0.059	1.949	13.390	0.089	0.117	0.156	0.018	0.833
Tbill3M	9,416	0.000	0.002	−2.317	11.380	0.000	0.000	0.001	−0.010	0.004
Ted_spread	9,416	0.003	0.001	0.402	2.237	0.002	0.003	0.004	0.001	0.005
Credit_spread	9,416	0.016	0.004	0.634	2.951	0.012	0.015	0.018	0.009	0.027
Oil	9,416	0.005	0.024	−0.371	3.405	−0.011	0.007	0.022	−0.066	0.053
Ret_WTI	9,416	−0.004	0.256	−1.639	9.285	−0.085	0.026	0.127	−1.093	0.651
Inflation Rate	9,416	1.334	1.385	0.611	5.097	0.848	1.253	1.803	−2.200	5.250
Henry Hub_ret	9,416	0.005	0.171	0.299	2.567	−0.115	−0.003	0.094	−0.307	0.394
size	5,131	20.660	2.190	−0.227	2.605	19.240	20.760	22.220	12.770	25.750
debt	4,501	11.710	4.670	−1.598	4.522	10.860	13.350	14.660	0.000	17.470
ROA	4,545	0.136	1.946	30.600	993.800	−0.017	0.043	0.095	−2.123	63.570
ROE	4,545	1.484	18.020	17.940	374.100	−0.030	0.096	0.231	−6.340	438.500
$\Delta NRIGS_{\%}$	9,416	−0.017	0.216	−1.519	5.638	−0.046	0.021	0.110	−0.779	0.328

Notes: The table reports each variable and the descriptive statistics in two sub-periods: from January 2000 to December 2010, reported in panel A, and from January 2011 to December 2021, reported in panel B. Data are quarterly based. The descriptive statistics comprehend the mean, standard deviation, skewness, kurtosis, quantile at 25%, median, quantile at 75% , minimum and maximum values of the state variable distribution.

The state variables and the firm controls that are included in the regression are summarised in Table 10. The firm characteristics we take into account are the following:

- $VaR_{q,QPYYYY-QPYYYY}$: the time series of quarterly losses at the q% quantile, obtained by averaging the weekly observation within the quarter. The weekly VaR is estimated by using (3). The time horizon is defined by the quarter QP = Q1, …,Q4 and the year YYYY;
- *Size*: computed as the logarithm of the market capitalisation;
- *Debt*: computed as the logarithm of the total debt;
- *ROA*: the ratio between *operating income* and *total asset income*;
- *ROE*: the ratio between *operating income* and *common equity*;
- $\Delta NRIG_{\%}$: the percentage variation in the number of active oil rigs.

We also define two alternative specifications in Eq. (6) by interacting *VaR* with *Size* as Eq. (7) and interacting *VaR* with $Size^2$ as in Eq. (8).

$$\Delta CoVaR^{system|i}_{q,t} = a + b_1 VaR_{q,t-1} + b_2 Size_{t-1} + b_3 VaR_{q,t-1} \times Size_{t-1} + \mathbf{b}'_X \mathbf{X}_{t-1} + \mathbf{c}'_M \mathbf{M}_{t-1} + \eta_t \tag{7}$$

$$\Delta CoVaR^{system|i}_{q,t} = a + b_1 VaR_{q,t-1} + b_2 Size_{t-1} + b_3 VaR_{q,t-1} \times Size_{t-1} + b_4 Size^2_{t-1} + b_5 VaR_{q,t-1} \times Size^2_{t-1} + \mathbf{b}'_X \mathbf{X}_{t-1} + \mathbf{c}'_M \mathbf{M}_{t-1} + \eta_t \tag{8}$$

The two alternative specifications are crucial for spotting possible non-linearities that could affect the dependent variable. Table 4 reports the summary statistics of $\Delta CoVaR$ and VaR at the 0.99 and 0.95 quantiles, and of the firm characteristics. We focus on the two periods, $Q12000--Q42010$ and $Q12011--Q42021$, to identify the impact of the oil and gas sector's structural and technological changes in the relation between predictors and systemic risk measures.

The average value of $\Delta CoVaR$ at 95% and 99% remains constant from the first period values, from 0.018 and 0.034 to 0.014 and 0.025 in the second period. The same considerations hold for $\Delta CoVaR^{\$}$ at 95% and 99%. The average of VaR at 95% and 99%, slightly rises from 0.120 and 0.213 in the first period to 0.129 and 0.225 in the second period; the effect is stronger for the median. *Tbill3M* is bounded to zero across the two periods. *Ted_spread* moves from 0.005 in the first period to 0.003 in the second. Similarly, *Credit_spread* reduces to 0.016 in the second period, from 0.02. The oil and natural gas industry portfolio (*Oil*) remains constant across the two periods, at 0.005. The first period sees a lower inflation rate compared to the second one, decreasing from 1.16 to 1.33. Ret_{WTI} falls from 0.03 to −0.04, while $Ret_{HenryHub}$ spurred its value from 0.01 to 0.005. If we focus on firm variables, *Size* remains constant to 20 across the two periods, while the average of *Debt* rises in the second period to 11.7 from 10.4. *ROA* raises to 0.136 in the second period, demonstrating an opposite behaviour with

Table 5
VaR^i as predictor of $\Delta CoVaR^i$ — Baseline model.

Variables	Δ_CoVaR99 Q1 2000–Q4 2010	Δ_CoVaR95 Q1 2000–Q4 2010	Δ_CoVaR99 Q1 2011–Q4 2021	Δ_CoVaR95 Q1 2011–Q4 2021
Panel A	Eq. (6): Baseline			
$VaR_{99,QPYYYY-QPYYYY}$	0.0253*		0.0494***	
	(0.014)		(0.006)	
$VaR_{95,QPYYYY-QPYYYY}$		0.0405***		0.0422***
		(0.011)		(0.004)
Size	−0.0004	−0.0000	0.0004*	0.0001
	(0.000)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	3,580	3,540	3,320	3,325
Number of firms	105	104	123	123
R2	0.565	0.605	0.362	0.378
Adj R2	0.563	0.603	0.360	0.375
Panel B	Eq. (7): Baseline $+b3VaR_{q,t-1} \times Size_{t-1}$			
$VaR_{99,QPYYYY-QPYYYY}$	−0.1577***		−0.0558*	
	(0.055)		(0.029)	
$VaR_{99,QPYYYY-QPYYYY}$ *Size	0.0100***		0.0053***	
	(0.004)		(0.002)	
$VaR_{95,QPYYYY-QPYYYY}$		−0.2879***		−0.1073***
		(0.028)		(0.026)
$VaR_{95,QPYYYY-QPYYYY}$ *Size		0.0184***		0.0075***
		(0.002)		(0.001)
Size	−0.0036***	−0.0029***	−0.0010**	−0.0010***
	(0.001)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	3,580	3,540	3,320	3,325
Number of firms	105	104	123	123
R2	0.590	0.675	0.371	0.397
Adj R2	0.588	0.674	0.368	0.394
Panel C	Eq. (8): Baseline $+b3VaR_{q,t-1} \times Size_{t-1} + b_4 Size^2_{t-1} + b_5 VaR_{q,t-1} \times Size^2_{t-1}$			
$VaR_{99,QPYYYY-QPYYYY}$	0.3465**		0.1532	
	(0.135)		(0.161)	
$VaR_{99,QPYYYY-QPYYYY}$ *Size	−0.0479***		−0.0165	
	(0.015)		(0.016)	
$VaR_{99,QPYYYY-QPYYYY}$ $*Size^2$	0.0016***		0.0006	
	(0.000)		(0.000)	
$VaR_{95,QPYYYY-QPYYYY}$		0.0127		0.1077
		(0.120)		(0.159)
$VaR_{95,QPYYYY-QPYYYY}$ *Size		−0.0156		−0.0144
		(0.013)		(0.016)
$VaR_{95,QPYYYY-QPYYYY}$ $*Size^2$		0.0010***		0.0006
		(0.000)		(0.000)
Size	−0.0067	−0.0102***	0.0011	0.0009
	(0.006)	(0.002)	(0.004)	(0.002)
$Size^2$	0.0001	0.0002***	−0.0001	−0.0000
	(0.000)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	3,580	3,540	3,320	3,325
Number of firms	105	104	123	123
R2	0.611	0.695	0.372	0.398
Adj R2	0.609	0.694	0.369	0.395

Notes: The table reports the results of the fixed effect panel regression relative to the entire sample. Panel A shows the coefficients of interest defined by Eq. (6). Panel B reports the coefficients of interest, defined by Eq. (7) by introducing the interaction between *VaR* and *Size*. Panel C exhibits the coefficients of interest as in Eq. (8) by interacting *VaR* and $Size^2$. The control variable parameters are given, respectively, in Tables 14, 15 and 16. Standard errors clustered by firm are in parentheses. *** p<0.01, ** $p < 0.05$, * $p < 0.1$.

respect to *ROE*, which sinks to 1.4; this reminds us of the importance of using both firms' profitability indicators in the analyses. The number of rig percentage changes $\Delta NRIGS_{\%}$ slumps in the second period to −0.017. Overall, a preliminary evaluation of the data features of the two samples shows differences, which depend on the changes in the oil and natural gas production structure, and notably the increased shale oil production, but also on the variation in the financial system risk dominated in the first period by the global financial crisis, while the end of the second period suffers from the effect of the first wave of the COVID-19 pandemic.

6. The drivers of systemic risk in oil and natural gas companies

Table 5 reports the panel regression results for two periods, Q1 2000–Q4 2010 and Q1 2011–Q4 2021.[16] We stress that all the drivers are lagged by one quarter, coherently with Eq. (6). Since we are dealing

[16] The table shows only the coefficients for the variables of interest. The complete regressions that include all the control variable coefficients are reported in the Appendix; see Tables 14, 15, and 16, respectively.

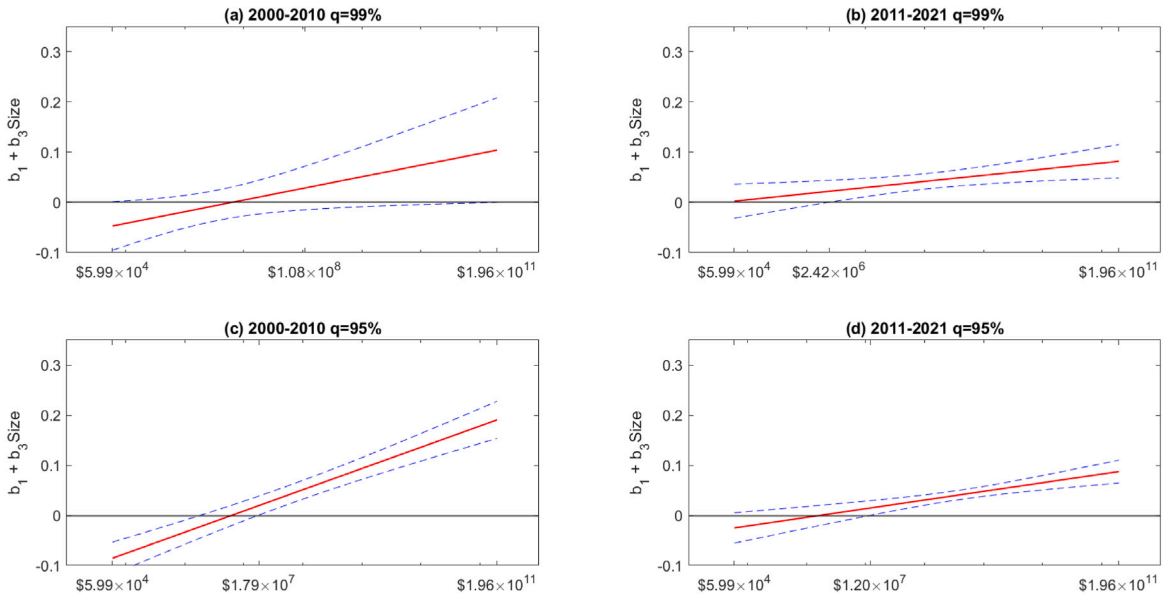

Fig. 5. Impact of size on VaR: Linear interaction.
Note:The figure shows the pattern of the joint coefficient $b_1 + b_3 Size_{t-1}$ (red line) with respect to $Size$. The blue dashed lines represent the confidence interval at 99%.

with panel estimates, we control for the time-invariant heterogeneity by resorting to a fixed effect estimator. The standard errors are clustered by firm. Table 5 panel A shows that the VaR at the 99% and 95% levels has a lower impact on $\Delta CoVaR$ in the first period than in the second. In the second period, the VaR at 99%, on average, affects $\Delta CoVaR$ with a magnitude equal to 4.9%; the effect is, roughly, the double of the first period. On the contrary, if we look at the 95% VaR, the impact is only slightly increasing.

Looking at the control variables (reported in Table 14 in the Appendix), *Ted_spread*, *Credit_spread* and *Inflation rate* have a positive and significant impact on $\Delta CoVaR$ in all periods. *Tbill3M* is negative and significant for $\Delta CoVaR$ at 95% and 99%, but only in the second period, with coefficients roughly equal to −0.44 in both cases. The impact of the oil and natural gas sector (*Oil*) changes across two periods: in the first period, it has a positive effect on $\Delta CoVaR$, but the effect is lower and negative in the second period. Ret_{WTI} and $Ret_{HenryHub}$ have a negative and significant impact on $\Delta CoVaR$ at 95% and 99%; in particular $Ret_{HenryHub}$ is significant in all periods, while Ret_{WTI} is relevant only in the second period. Our results are in line with Ouyang et al. (2022) since Ret_{WTI} has a negative and significant relationship with the systemic risk measures before COVID-19.

Looking at firm's characteristics, *Size* has a limited, positive impact on $\Delta CoVaR$, but only at 99% in the second period. *Debt* is mildly positive and significant only in the first period. *ROE* has an oscillating impact: the sign of *ROE* changes at different quantile levels. Finally, $\Delta NRIGS_{\%}$ negatively affects $\Delta CoVaR$ at 95% and 99%, but only in the first period. Interestingly, a positive trend of $\Delta NRIGS_{\%}$ shows that the extraction business is expanding. Therefore the cash flow of that activity rewards the shareholders, thus reducing the systemic risk associated with that business.

The system risk is not impacted by the company size. However, the company contribution to the systemic risk might change in the cross-section of companies according to their size, thus impacting on the relation between the company risk measure and the systemic risk measure. Therefore, the relevance of the company risk measure's impact on the systemic risk might be modulated by the company size. To test this, we report in Panel B the coefficients interacting VaR with *Size*. The interaction term is positive and significant, while the two variables alone, VaR and *Size*, have a negative and significant impact on $\Delta CoVaR$. This signals that the size of the companies, *per se*, reduces the systemic risk, while the company's own risk, weighted by the company size, raises the systemic risk, since the company's risk increases the systemic risk, and the bigger the company, the bigger the effect. However, the overall impact is difficult to identify by simply looking at estimated coefficients, as it also depends on the company's size. Fig. 5 helps to visualise the overall impact of the company risk on the systemic risk; the overall effect is due to the interaction between VaR and *size* for different levels of $Size$: the figure reports the estimated value (red lines) and the 95% confidence interval (blue dashed lines) of $b_1 + b_3 Size_{t-1}$. The left side of the figure, plots (a) and (c), reports the coefficient for the first period: the joint impact is not significant when VaR is at 99%, but the effect is significant if the quantile is 95% and the company size is greater than M$17.9. In the second period, the overall impact is smaller, but it is significant at 99% and at 95% when the company size goes above M$2.4 and M$12.0, respectively. To evaluate possible non-linearities in the indirect effect of the company size on the systemic risk, we interact VaR with both $Size$ and $Size^2$. Panel C reports the regression results. As in the previous case, we compute the composite impact (now equal to $b_1 + b_3 Size_{t-1} + b_5 Size^2_{t-1}$) and the 95% confidence interval (see Fig. 6). The left side shows the pattern for the first sample, 2000–2010. The effect is non-significant only for the smallest firm included in the sample, and this holds for both VaR cases, i.e., for the 99% and 95%VaR. The coefficient is positive and significant only for firms with a size greater than M$884 (a) and M$14.7 (c). The right part of the figure reports the joint impact in 2011–2021. The effect is significant for those firms with a $Size$ greater than M$2.1 and at a 99% quantile (b). By contrast, in plot (d), the effect is positive and significant after a threshold level of M$9.82. In summary, the graphs show that $Size$ plays a relevant role in VaR, but only for large size firms in the first period. In the second period, the impact is more widespread in the cross-section of companies. This is highlighted by the reduction in the size threshold above which we detect a significant and increased impact of the size-modulated company risk on the systemic risk index.[17]

[17] One possible reason is that the introduction of the shale technology into the US oil and natural gas sector boosted the number of firms in the second period. Consequently, the contribution on $\Delta CoVaR$ of each firm is lower in the second period because it is spread out on a higher number of firms.

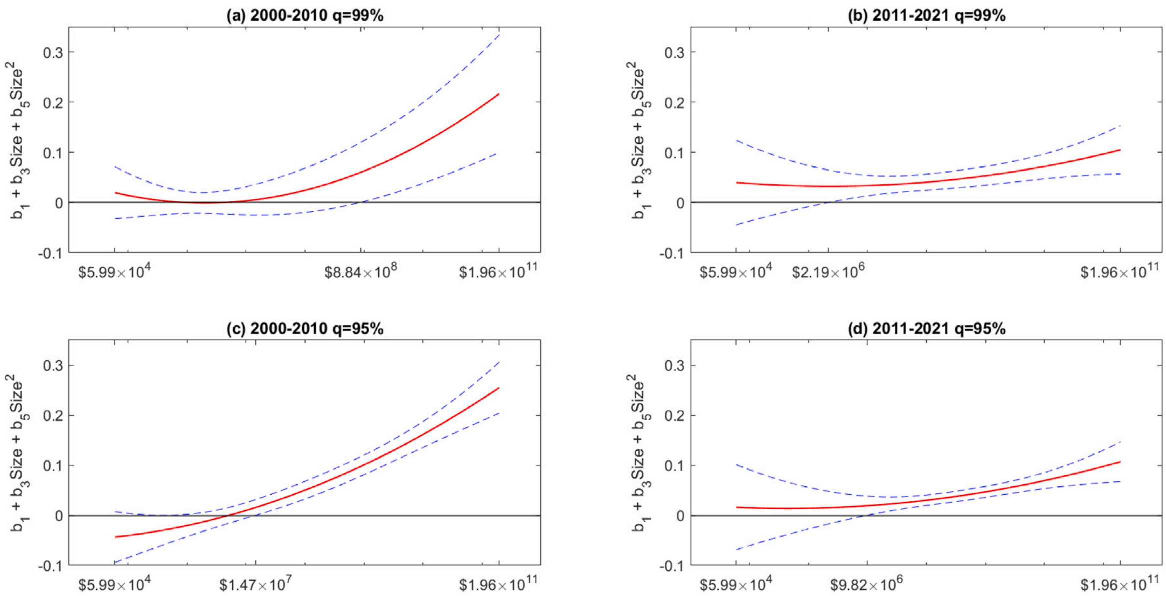

Fig. 6. Impact of size on VaR: Quadratic interaction.
Note: The figure shows the pattern of the joint coefficient $b_1 + b_3 Size_{t-1} + b_5 Size^2_{t-1}$ (red line) with respect to $Size$. The blue dashed lines represent the confidence interval at 99%.

7. Sensitivity analyses and robustness checks

7.1. Oil, gas and supporting activities

The sample of firms considered in the analysis belongs to three subsectors, as reported in Table 1. We investigate here the extent to which the effect on $\Delta CoVaR$ varies across the sub-groups, to detect whether the results are also impacted by the main companies' activity. Panel A of Table 6 shows the regression coefficients, considering only firms in the extraction of crude oil sector. The results indicate that VaR has a significant and stronger impact on $\Delta CoVaR$ in the second period, looking at extreme risks (99% quantile). The effect is the opposite, considering the VaR at 95%. In both periods, the coefficients are significant. Panels B and C show the regression coefficients for firms belonging to the extraction of natural gas and support activities, respectively. In both cases, the VaR is economically and statistically significant only in the second period, showing that these firms are sensibly more risky than in the first period. Particularly, the VaR at the 99% quantile has the highest magnitude across time and subgroup, with a value of 0.07.

7.2. Dollar-valued systemic risk

In this section, we verify that our results do not depend on the scale of the dependent variable, and consider the effect of VaR on $\Delta CoVaR^{\$}$ as computed in Adrian and Brunnermeier (2016). The difference with Eq. (6) is that the risk measure is now multiplied by a proxy for of the company size expressed (usually) in US Dollars, leading to $\Delta^{\$} CoVaR^{system|i}_{q,t}$. Therefore, the dependent variable is weighted by the firm size. The empirical findings in Table 7 report a sharp difference in terms of the impact of VaR on $\Delta CoVaR^{\$}$ across two periods. The results corroborate our finding in Table 5. The risk metric is not significant in the first period, while the coefficients become significant, and equal to 0.05 and 0.07, for VaR at 99% and 95%, respectively, in the second period. The coefficients in Table 5 are the sensitivities of $\Delta CoVaR^{\$}$ with respect to the characteristics expressed in decimal units. For example, the coefficient of 0.0504 on the VaR_{99} in the second period implies that an increase in an institution's VaR (say, from 0.05 to 0.06) is associated with an increase in $\Delta CoVaR^{\$}$ of 0.0504 decimal points of quarterly market equity losses at 99%. Second, the variable *Size* is positively significant in all periods and for all quantiles.

7.3. Balanced panel

In this section, we test our findings by replicating them with a more balanced panel. Two alternative specifications are adopted: first, the *balanced case*, in which we choose the listed firms that, in the time period considered, are characterised by the presence of missing values less than 20% of the time. In this case, we consider firms possessing available observations for more than 80% of the time horizon. In the second specification, termed *strong balanced*, only listed firms that have been running their business in both periods are included in the sample. The results are collected in Table 8. The first four columns show that the VaR at 95% and 99% has a positive and significant effect on $\Delta CoVaR$, and that the effect is stronger in the second period. By contrast, in the *strong balanced* case, the VaR has a positive and significant impact on $\Delta CoVaR$, but the impacts seems reduced from the first to the second period, even though the magnitude is higher than the baseline results in Table 5. Since, in the *strong balanced* case, the sample of companies does not change over time, it includes only those firms who survived the different shocks across the years. At first glimpse, we could incur in a survivorship bias, since we are selecting those firms with solid characteristics with respect to the others.[18] If we look at the descriptive statistics for these firms, they are in line with the baseline case, and the *Debt* surged from 10.59 to 11.65. The profitability ratios are in line with the baseline case, across two periods. For instance, on average, ROE plummeted from 12.54 to 3.6; the ROA rose to 0.3 from 0.2 in the second period and showed contrasting behaviour with the ROE. VaR at 95% (99%) surged to 0.121 (0.212) from 0.109 (0.189). Only the evolution of *Size* differs from the baseline, as it increases from 20.48 to 21.65. Finally, the $\Delta CoVaR$ at 95% (99%) of these firms declines across the two periods from 0.019 (0.037) to 0.015 (0.026). Since the drivers' patterns are comparable with the baseline case, we suspect that the exclusion of newborn oil and gas firms can provide a different picture of the systemic risk of the US oil and natural gas sector.

7.4. Removing the COVID outbreak

To corroborate our results, we replicate the regressions, excluding from the sample the period after the COVID-19 outbreak (from Q1

[18] Survivorship bias is well-know in the mutual funds literature; for further details, please see Rohleder et al. (2011).

Table 6
VaR^i as predictor of $\Delta CoVaR^i$ — NACE 4-digit breakdown.

Panel A	Extraction of Oil			
Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021
$VaR_{99,QPYYYY-QPYYYY}$	0.0318*		0.0467***	
	(0.016)		(0.009)	
$VaR_{95,QPYYYY-QPYYYY}$		0.0446***		0.0329***
		(0.013)		(0.005)
Size	−0.0006	0.0001	0.0002	−0.0000
	(0.000)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	1,961	1,961	1,872	1,877
Number of firms	57	57	67	67
R2	0.549	0.567	0.322	0.357
Adj R2	0.546	0.564	0.317	0.352
Panel B	Extraction of natural gas			
Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021
$VaR_{99,QPYYYY-QPYYYY}$	0.0105		0.0719***	
	(0.018)		(0.005)	
$VaR_{95,QPYYYY-QPYYYY}$		0.0191		0.0571***
		(0.024)		(0.006)
Size	−0.0008	0.0000	0.0008	0.0004
	(0.001)	(0.000)	(0.001)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	526	526	546	546
Number of firms	16	16	23	23
R2	0.666	0.647	0.403	0.349
Adj R2	0.658	0.638	0.389	0.333
Panel C	Support activities			
Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021
$VaR_{99,QPYYYY-QPYYYY}$	0.0121		0.0401***	
	(0.024)		(0.007)	
$VaR_{95,QPYYYY-QPYYYY}$		0.0375		0.0532***
		(0.028)		(0.008)
Size	0.0006	0.0000	0.0008**	0.0004*
	(0.001)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	1,093	1,053	902	902
Number of firms	32	31	33	33
R2	0.586	0.677	0.473	0.464
Adj R2	0.581	0.673	0.465	0.456

Notes: The table reports the results of the fixed effect panel regression. Panel A, in particular frames the analysis for those firms belonging to the extraction of crude petroleum (NACE 06.20). Panel B reports the results for the extraction of natural gas firms (NACE 06.20). Finally, Panel C reports the results for those firms operating as support of the oil and natural gas extraction(NACE 06.20).

2020 to Q4 2021). With this further robustness, we control for the possibility that our results may be driven by the turbulence induced by the pandemic. The results are collected in Table 9. The empirical findings show that after the exclusion of COVID-19, the VaR has a positive and significant effect on $\Delta CoVaR$, and the effect is stronger if compared with the results in Table 5. For the VaR at 99% (95%) (column I and IV in Table 9), we note that it has an impact equal to 0.061 (0.056) on $\Delta CoVaR$. Columns II and V report the coefficients when we interact VaR with *Size*. The variables VaR and *Size* have a negative and significant impact on $\Delta CoVaR$. In contrast, their interaction is positive and significant, as in Table 14. Fig. 7 shows the relation between the composite effect across different $Size$ levels. Graphs (a) and (b) report the coefficients' evolution when VaR is at 99% and 95%. The joint effect is significant for firm sizes greater than M$2.6 and M$1.62, respectively. The impact is comparable with graphs (b) and (d) in Fig. 5.

Panel C reports the regression results when we interact VaR with $Size$ and $Size^2$. The left plots of Fig. 8 have already been reported in Section 6. The effect of size is significant only for firms greater than M$884 (a) and M$14.7 (c) (99% and 95% quantiles). The right part of the panel reports the joint coefficient for the second period. It is always significant, considering that the risk is measured with the quantile at 99%. Nevertheless, when we look at the quantile at 95%, the effect is significant for those firms with $Size$ values greater than M$1.2 (see panel (d)). Surprisingly, if we compare the 2011–2021 period in Figs. 5 and 6 with 2011–2019 in Figs. 7 and 8, the latter graphs have a sharper slope. Summarising the main finding, the results are confirmed even if we exclude the COVID-19 period. Indeed, the sensitivity to the size is further increased.[19] A possible explanation is that the COVID-19 impacted the relation between companies' risk and systemic risk, leading to a structural break. After the pandemic outbreak, a systemic event, the entire economy was affected, and in relative terms, other sectors have contributed more to the overall systemic risk, thus lowering the impact of the oil and gas sector. Therefore, by excluding the COVID-19 period from the analysis, our results are confirmed and even stronger than those previously reported.

[19] As a further robustness check, we also compute the regression in Eqs. (6), (7) and (8) by taking into account the period 2020–2021. The results are not significant.

Table 7
VaR^i as a predictor of dollar $\Delta CoVaR^i$.

Variables	$\Delta\_CoVaR99^{\$}$ Q12000–Q42010	$\Delta\_CoVaR95^{\$}$ Q12000–Q42010	$\Delta\_CoVaR99^{\$}$ Q12011–Q42021	$\Delta\_CoVaR95^{\$}$ Q12011–Q42021
$VaR_{99,QPYYYY-QPYYYY}$	−0.0187		0.0504**	
	(0.026)		(0.023)	
$VaR_{95,QPYYYY-QPYYYY}$		−0.0078		0.0692**
		(0.034)		(0.026)
Ted_spread	1.8695**	1.2029**	1.3127*	0.5011
	(0.921)	(0.516)	(0.744)	(0.452)
Credit_spread	0.9207***	0.5070***	0.4093	0.2853
	(0.309)	(0.182)	(0.299)	(0.190)
Tbill3M	−0.4173***	−0.2176***	−0.5097	−0.5745
	(0.115)	(0.079)	(0.545)	(0.437)
Oil sector return	0.3370***	0.1992***	−0.0307*	−0.0257**
	(0.104)	(0.058)	(0.017)	(0.011)
Inflation rate	0.0031*	0.0020**	0.0026***	0.0020***
	(0.002)	(0.001)	(0.001)	(0.001)
Size	0.0107***	0.0063***	0.0114***	0.0072***
	(0.004)	(0.002)	(0.003)	(0.002)
Debt	−0.0007	−0.0005	0.0000	−0.0000
	(0.001)	(0.000)	(0.000)	(0.000)
ROA	−0.3388	−0.2073	−0.2948	0.0420
	(0.356)	(0.222)	(0.459)	(0.246)
ROE	−0.0011	−0.0007	−0.0229	−0.0030***
	(0.001)	(0.000)	(0.026)	(0.001)
RET_{WTI}	−0.0015	−0.0002	−0.0084***	−0.0039**
	(0.003)	(0.002)	(0.003)	(0.002)
$RET_{HenryHub}$	−0.0083	−0.0047	−0.0042	−0.0046**
	(0.006)	(0.003)	(0.003)	(0.002)
$\Delta NRIGS_{\%}$	0.0182***	0.0107***	−0.0044	−0.0016
	(0.005)	(0.004)	(0.003)	(0.002)
Constant	−0.1972**	−0.1161**	−0.2223***	−0.1408***
	(0.083)	(0.049)	(0.063)	(0.041)
Observations	3,580	3,540	3,320	3,325
Number of firms	105	104	123	123
R2	0.0654	0.0703	0.0638	0.0548
Adj R2	0.0620	0.0669	0.0601	0.0511

Notes: The table reports all the coefficients of the fixed effect panel regression. The dependent variable in Eq. (6) is computed using the methodology of Adrian and Brunnermeier (2016), where $\Delta CoVaR$ is multiplied by a proxy for the company size expressed (usually) in US Dollars. Standard errors are clustered by firm in parentheses. *** p<0.01, ** $p < 0.05$, * $p < 0.1$.

Table 8
VaR^i as predictor of $\Delta CoVaR^i$ — Balanced panel.

Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021
	Balanced				Strong Balanced			
$VaR_{99,QPYYYY-QPYYYY}$	0.0237		0.0471***		0.0604**		0.0507***	
	(0.016)		(0.006)		(0.027)		(0.007)	
$VaR_{95,QPYYYY-QPYYYY}$		0.0404***		0.0467***		0.0661***		0.0512***
		(0.013)		(0.005)		(0.019)		(0.006)
Size	−0.0006**	−0.0001	0.0003	0.0001	−0.0002	0.0001	0.0002	−0.0001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,117	3,077	2,240	2,245	1,651	1,651	1,608	1,639
Number of firms	75	74	56	56	39	39	39	40
R2	0.553	0.589	0.380	0.352	0.594	0.635	0.417	0.373
Adj R2	0.551	0.587	0.377	0.348	0.590	0.632	0.413	0.368

Notes: The table reports the results of the fixed effect panel regression relative to the entire sample defined by Eq. (6). In this table, we test two alternative specifications. The columns under 'Balanced' represent the coefficients for those listed firms that have non-missing observations for at least 80% of the period of time considered. The 'strong balanced' case reports the coefficients for the same firms in both periods. Standard errors clustered by firm are in parentheses. *** p<0.01, ** $p < 0.05$, * $p < 0.1$.

7.5. Alternative specifications

Finally, we define two alternative specifications of Eq. (6) by interacting *VaR* with *debt* as in Eq. (9) and interacting *VaR* with $Debt^2$ as in Eq. (10). This allows us to test whether the debt structure of the oil and gas companies has an effect similar to that of the companies' size in modulating the impact of the companies' risk on the systemic risk.

$$\Delta CoVaR_{q,t}^{system|i} = a + b_1 VaR_{q,t-1} + b_2 Debt_{t-1} + b_3 VaR_{q,t-1} \times Debt_{t-1} + \mathbf{b}_X' \mathbf{X}_{t-1} + \mathbf{c}_M' \mathbf{M}_{t-1} + \eta_t \tag{9}$$

$$\Delta CoVaR_{q,t}^{system|i} = a + b_1 VaR_{q,t-1} + b_2 Debt_{t-1} + b_3 VaR_{q,t-1} \times Debt_{t-1} + b_4 Debt_{t-1}^2 + b_5 VaR_{q,t-1} \times Debt_{t-1}^2 + \mathbf{b}_X' \mathbf{X}_{t-1} + \mathbf{c}_M' \mathbf{M}_{t-1} + \eta_t \tag{10}$$

Although *Debt* weakly affects $\Delta CoVaR$ only in the first period, we investigate whether the company's contribution to the systemic risk may change according to their debt burden. The company's sensitivity to systemic risk could change according to its debt structure. For this reason, we test the coefficient interacting VaR and $Debt$. Table 11 in panel A shows the results according to Eq. (9). The interaction term is positive and significant in all cases except for VaR_{99} in the second period. The variable *Debt* is negative and significant in all periods. The effect is decisively lower than the interaction term and the VaR coefficient. In this respect, Fig. 9 reports the overall effect. In particular, it includes the estimated value (red line) and the 99% confidence interval (blue dashed line) showing that the composite coefficient $b_1 + b_3 Debt_{t-1}$ varies slightly in the first period with increasing *Debt* and

Table 9
VaR^i as predictor of $\Delta CoVaR^i$ — Removal of the COVID-19 outbreak period.

Variables	Q12011–Q42019					
	Δ_CoVaR99			Δ_CoVaR95		
	I	II	III	IV	V	VI
$VaR_{99,QPYYYY-QPYYYY}$	0.0614***	−0.0824**	0.6517***			
	(0.007)	(0.035)	(0.195)			
$VaR_{99,QPYYYY-QPYYYY}$ *Size		0.0074***	−0.0686***			
		(0.002)	(0.021)			
$VaR_{99,QPYYYY-QPYYYY}$ *$Size^2$			0.0019***			
			(0.001)			
$VaR_{95,QPYYYY-QPYYYY}$				0.0565***	−0.0785**	0.1605
				(0.005)	(0.031)	(0.160)
$VaR_{95,QPYYYY-QPYYYY}$ *Size					0.0067***	−0.0177
					(0.002)	(0.017)
$VaR_{95,QPYYYY-QPYYYY}$ *$Size^2$						0.0006
						(0.000)
Size	−0.0001	−0.0019***	0.0151***	0.0001	−0.0008***	0.0017
	(0.000)	(0.001)	(0.005)	(0.000)	(0.000)	(0.002)
$Size^2$			−0.0004***			−0.0001
			(0.000)			(0.000)
Controls and Constant	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,782	2,782	2,782	2,782	2,782	2,782
Number of firms	118	118	118	118	118	118
R2	0.340	0.361	0.372	0.347	0.362	0.363
Adj R2	0.337	0.357	0.369	0.344	0.358	0.359

Notes: The table reports the results of the fixed effect panel regression in Eq. (6) by excluding the first two quarters of 2020 (COVID Outbreak). Clustered standard errors are in parentheses. *** p<0.01, ** $p < 0.05$, * $p < 0.1$.

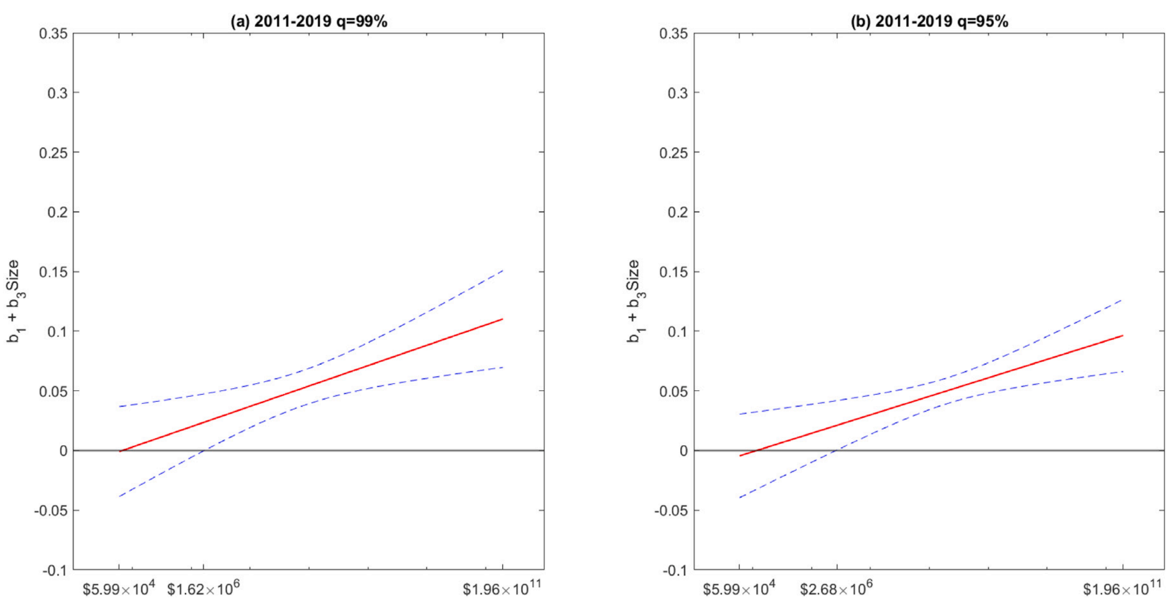

Fig. 7. Impact of size on VaR: Linear interaction without COVID-19 period.
Note:The figure shows the pattern of the joint coefficient $b_1 + b_3 Size_{t-1}$ (red line) with respect to $Size$. The blue dashed lines represent the confidence interval at 99%.

remains constant in the second period. The results look the same when we add the quadratic interaction, as in Eq. (10). VaR coefficients are significant only in the second period. The interaction term with *Debt* is significant only in the first quarter with $VaR_{95\%}$. The relation between the composite coefficient $b_1 + b_3 Debt_{t-1} + b_5 Debt^2_{t-1}$ and *Debt* is reported in Fig. 10: in panel (c), we observe a positive and significant relation. Finally, we also consider a comprehensive specification in which we combine *Size* and *Debt*, according to (11) and (12). The results are reported in Table 12. Table 13 includes the results when we exclude the interaction given by the coefficient b_6 in Eq. (11) and the interactions given by the coefficients b_9 and b_{10} in Eq. (12).

$$\Delta CoVaR^{system|i}_{q,t} = a + b_1 VaR_{q,t-1} + b_2 Size_{t-1} + b_3 VaR_{q,t-1} \times Size_{t-1} + b_4 Debt_{t-1} + + b_5 VaR_{q,t-1} \times Debt_{t-1} + b_6 VaR_{q,t-1} \times Size_{t-1} \times Debt_{t-1} + \mathbf{b}'_X \mathbf{X}_{t-1} + \mathbf{c}'_M \mathbf{M}_{t-1} + \eta_t \tag{11}$$

$$\Delta CoVaR^{system|i}_{q,t} = a + b_1 VaR_{q,t-1} + b_2 Size_{t-1} + b_3 VaR_{q,t-1} \times Size_{t-1} + b_4 VaR_{q,t-1} \times Size^2_{t-1} + + b_5 Size^2_{t-1} + b_6 Debt_{t-1} + b_7 VaR_{q,t-1} \times Debt_{t-1} + b_8 VaR_{q,t-1} \times Debt^2_{t-1} + b_9 VaR_{q,t-1} \times Size_{t-1} \times Debt_{t-1} + + b_{10} VaR_{q,t-1} \times Size^2_{t-1} \times Debt^2_{t-1} + \mathbf{b}'_X \mathbf{X}_{t-1} + \mathbf{c}'_M \mathbf{M}_{t-1} + \eta_t \tag{12}$$

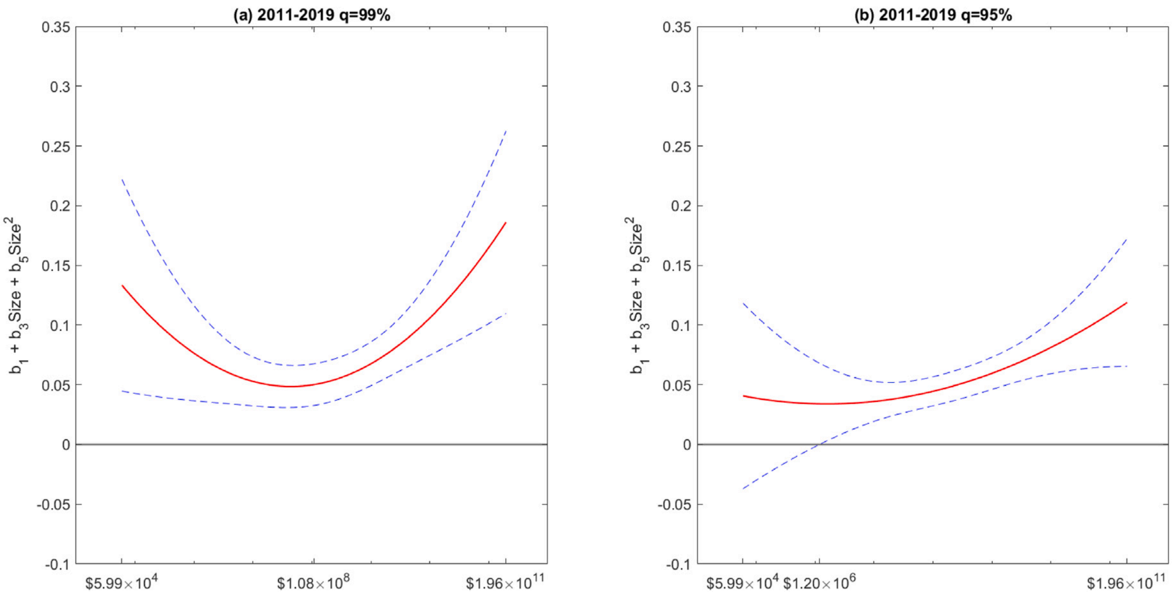

Fig. 8. Impact of size on VaR: Quadratic interaction without COVID-19 period.
Note: The figure shows the pattern of the joint coefficient $b_1 + b_3 Size_{t-1} + b_5 Size^2_{t-1}$ (red line) with respect to $Size$. The blue dashed lines represent the confidence interval at 99%.

Although the overall effect is complex, Table 12 shows in Panel A and Panel B that the adjusted R^2 is comparable with Panels B and C in Table 5. The same holds for Table 13.

8. Conclusion and policy implications

This paper contributes to the literature on systemic risk by providing an empirical analysis of the impact of the US oil and natural gas sector on systemic risk. The diffusion of shale production from 2011 onward has impacted US oil and natural gas companies, raising their debt and increasing their level of risk. We show that the company's losses, as summarised by the VaR at 95% and 99%, have contributed to systemic risk (in the sense that they are $\Delta CoVaR$ predictors). This effect has been higher in the second period, when oil and gas supply has been mostly driven by shale. Additional results highlight that the size of the company has indeed played a role in the systemic risk, but mostly through the indirect impact on the companies' own risk. Moreover, this effect depended non-linearly on the size of the company and has become smaller in the second period, showing that small companies in the oil and gas sector have also started contributing to the systemic risk after the shale production boom.

Robustness checks confirm these findings. The effect is stronger and the difference between the two periods is higher when we change the measure to compute $\Delta CoVaR$, expressing it in monetary terms. Looking at each sub-sector individually (namely, extraction of oil, extraction of gas and supporting activities, respectively), we show that the natural gas extraction and the support activities sector are the subgroups for which the impact on $\Delta CoVaR$ is higher and for which the difference across the two periods are more relevant, compared to the oil sector. The results are still valid if we take into account a balanced sub-panel of firms composed only of companies with available observations more than 80% of the time and also when we exclude the COVID-19 period from the analysis.

Our empirical findings suggest that the losses of US oil and natural gas companies have a boosting impact on the systemic risk, and consequently could threaten the stability of the financial system. These results have interesting policy implications if applied to the current geopolitical framework. Since 2022, the Russia–Ukraine war changed the economic context we had become accustomed to before and during the COVID19 pandemic. The oil price (WTI) and gas price (Henry Hub) from the end of 2020 soared 40% and 34% to the end of 2022, respectively. This had positive impact on the oil and gas companies which have increased their margins and potentially increased their net worth. Nonetheless, the next future is gloomy for these companies, since the European Union strategy is to become independent from fossil fuel by 2035,[20] and to reach the carbon neutrality by 2050.[21]. We cannot exclude that other countries could mimic the European Union long-run policies. This could indirectly affect the balance-sheet of the oil and gas companies by shrinking the demand of oil and gas. The negative spillovers could be severe if they will not be adequately offset by the internal demand of fossil fuel, or by some other economies not implementing green policies. Besides, the future of oil and gas companies also depends on the grade of commitment of the US environmental policy in regulating highly polluting firms, decreasing dependence on fossil fuels, and meeting Paris Agreement objectives. Although the Consolidated Appropriations Act (CAA) of 2021, which included provisions aimed at decreasing greenhouse gas emissions such as the Energy Act of 2020, was approved by the US administration, the majority leadership in both the House and the Senate in the 117th congress have called for whole-of-chamber approach to tackle climate change. Among these proposals, there is the legislation intended to affect the climate change mitigation that may also increase climate resilience or reduce GHG emissions.[22] Our results aim at warning the legislators that in case of an abrupt transition to a low carbon economy, a possible negative spillovers from the oil and natural gas sector could arise, and it will lead to an increase in the systemic risk, calling for appropriate risk sterilisation policies.

At the same time, the legislator should consider the systemic risk in energy policies tailored at sector level since the transition would

[20] The European climate law makes reaching the EU's climate goal of reducing EU emissions by at least 55% by 2030 a legal obligation. Within the Fit for 55 package, the Commission proposed to revise rules on CO2 emissions for cars and vans. The proposal introduces increased EU-wide reduction targets for 2030 and sets a new target of 100% for 2035. For further details please see https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

[21] EU countries are committed to achieving climate neutrality by 2050, delivering on the commitments under the Paris Agreement, for further details please see https://www.consilium.europa.eu/en/policies/green-deal/.

[22] For further details see https://crsreports.congress.gov/product/pdf/R/R46947.

induce the restructuring of the energy sector. As hydrocarbons would play a lesser role in the energy mix, it becomes important to account for the effect of this change on systemic risk while designing policies. To this end, it would be beneficial to couple energy transition measures with prudential policies that take into account the ex-ante and ex-post $\Delta CoVaR$ of the companies active in each energy sector. It is worth noting that a similar relationship between the technological change in the energy upstream sector (that lead to the shale boom) and the systemic risk, can occur also for other technological changes in the energy upstream sector, such as the one induced by the diffusion of renewable energy sources. The impact on the systemic risk of investments in renewable energy sources calls for specific analyses that shed new light on the interdependency between energy companies and systemic risk. Our findings can also be of interest for investors who seek to plan investments or restructure their business activities. They can utilise our measure of the contribution to systemic risk stemming from the oil and gas sector.

Finally, if we focus on the role of the company's size, the link with the systemic risk suggests that energy regulatory policies will also have a spillover effect on the systemic risk. This aspect is often underrated in the development of sectoral policies, highlighting the need for a prudent approach when designing policies that influence the size and market share of companies in primary energy sectors. For instance, the policymakers could design policies aim to extend requirements currently imposed on large enterprises to medium and small-sized companies, based on the results of systemic risk tests that periodically measure sectorial $\Delta CoVaR$. This approach is comparable to the regulation of European financial institutions. Nevertheless, there should be an a priori evaluation of the potential effects of such policies, given the non-linear relationship between company size and systemic risk. In this respect, our results would represent a relevant starting point and the methodology we designed could be adopted as a tool for policy impact assessments on the systemic risk.

CRediT authorship contribution statement

Massimiliano Caporin: Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Supervision. **Fulvio Fontini:** Writing – original draft, Writing – review & editing, Methodology. **Roberto Panzica:** Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing.

Appendix

See Tables 11–16 and Figs. 9 and 10.

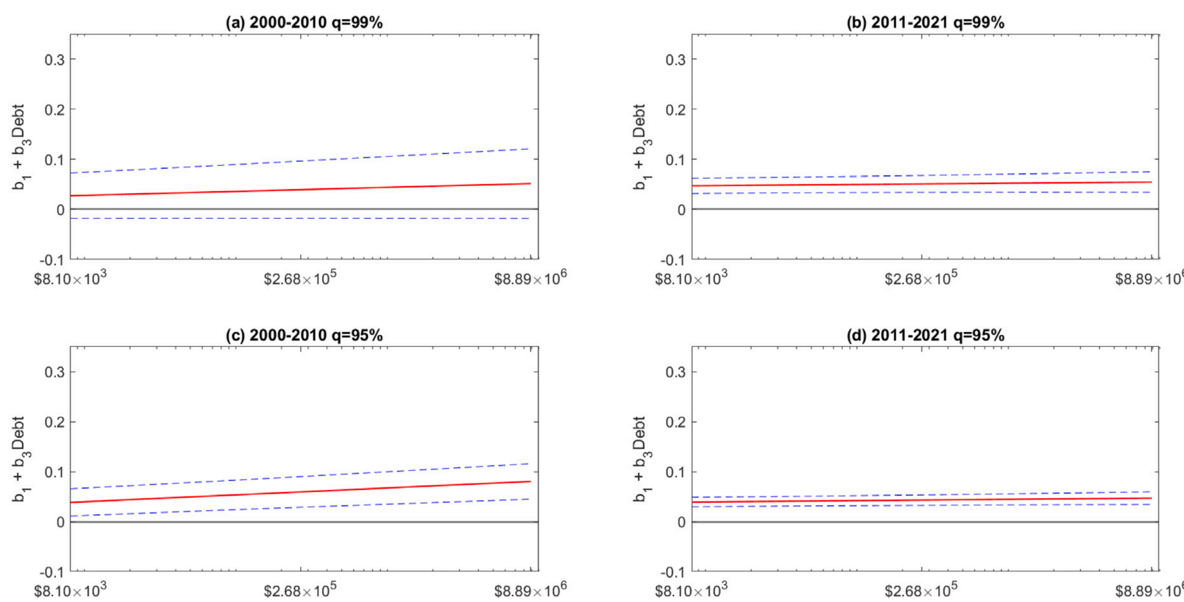

Fig. 9. Impact of debt on VaR: Linear interaction.
Note:The figure shows the pattern of the joint coefficient $b_1 + b_3 Debt_{t-1}$ (red line) with respect to $Debt$. The blue dashed lines represent the confidence interval at 99%.

Table 10
Variable definitions and sources.

N	Code	Description	Source	Frequency
1	Tbill3M	Three-month Treasury bill rate changes	Refinitiv	Week/quarter
2	Term_spread_10Y3M	Difference between the composite 10-year bond yield	Refinitiv	Week/quarter
		and the three-month bill rate	Refinitiv	Week/quarter
3	Ted_spread	Difference between the three-month LIBOR rate	Refinitiv	Week/quarter
		and the three-month secondary market Treasury bill rate.		
4	Credit_spread	Difference between ICE Bank of America BBB US Corporate Index	Refinitiv	Week/quarter
		and treasury 10-year bond yield		
5	Ret_{MKT}	Standard and Poor 500 Market Index return	Refinitiv	Week/quarter
6	Ret_{WTI}	Crude Oil-West Texas Intermediate return	Refinitiv	Week/quarter
7	$Ret_{HenryHub}$	United States, Natural Gas, Prices, Henry Hub Spot, USD	Refinitiv	Week/quarter
8	$Price_{WTI} - Price_{BRE}$	Difference between the Crude Oil-West Texas Intermediate price	Refinitiv	Week/quarter
		and European Brent oil		
9	Δ VIX	Russel volatility index change	Refinitiv	Week/quarter

(continued on next page)

Table 10 (*continued*).

N	Code	Description	Source	Frequency
10	Inflation Rate	Changes of all urban consumers, United States city average	Refinitiv	Week/quarter
11	Oil	Petroleum and natural gas industry portfolio return	French library	quarter
12	Debt	Natural logarithm of all interest bearing and capitalised lease obligations.	Refinitiv	year
13	Size	Natural logarithm of market capitalisation	Refinitiv	year
14	ROA	Ratio between Operating Income and Total Asset	Refinitiv	year
15	ROE	Ratio between operating income and common equity	Refinitiv	year
16	$\Delta NRIGS_{\%}$	Weekly census change in percentage of the number of oil drilling rigs actively exploring for or developing oil or natural gas in the U.S.	Baker Hughes North American Rotary	Week/quarter

Table 11
VaR^i as predictor of $\Delta CoVaR^i$ — The role of *Debt*.

Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021
Panel A	Eq. (9): Baseline $+b_3 VaR_{q,t-1} \times Debt_{t-1}$			
$VaR_{99,QPYYYY-QPYYYY}$	−0.0038		0.0372***	
	(0.009)		(0.009)	
$VaR_{99,QPYYYY-QPYYYY}$ *Debt	0.0035**		0.0011	
	(0.001)		(0.001)	
$VaR_{95,QPYYYY-QPYYYY}$		−0.0154		0.0292***
		(0.011)		(0.006)
$VaR_{95,QPYYYY-QPYYYY}$ *Debt		0.0060***		0.0011**
		(0.001)		(0.000)
Debt	−0.0007*	−0.0007***	−0.0002	−0.0002**
	(0.000)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	3,580	3,540	3,320	3,325
Number of firms	105	104	123	123
R2	0.582	0.642	0.364	0.380
Adj R2	0.580	0.640	0.362	0.377
Panel B	Eq. (10): Baseline $+b_3 VaR_{q,t-1} \times Debt_{t-1} + b_4 Debt^2_{t-1} + b_5 VaR_{q,t-1} \times Debt^2_{t-1}$			
$VaR_{99,QPYYYY-QPYYYY}$	−0.0005		0.0379***	
	(0.011)		(0.009)	
$VaR_{99,QPYYYY-QPYYYY}$ *Debt	0.0004		−0.0001	
	(0.004)		(0.002)	
$VaR_{99,QPYYYY-QPYYYY}$ $*Debt^2$	0.0002		0.0001	
	(0.000)		(0.000)	
$VaR_{95,QPYYYY-QPYYYY}$		0.0069		0.0322***
		(0.011)		(0.006)
$VaR_{95,QPYYYY-QPYYYY}$ *Debt		−0.0074***		−0.0017
		(0.003)		(0.002)
$VaR_{95,QPYYYY-QPYYYY}$ $*Debt^2$		0.0010***		0.0002
		(0.000)		(0.000)
Debt	0.0002	0.0010**	−0.0001	0.0000
	(0.001)	(0.000)	(0.001)	(0.000)
$Debt^2$	−0.0001	−0.0001***	−0.0000	−0.0000
	(0.000)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	3,580	3,540	3,320	3,325
Number of firms	105	104	123	123
R2	0.583	0.659	0.365	0.382
Adj R2	0.581	0.658	0.362	0.379

Notes: The table reports the results of the fixed effect panel regression relative to the entire sample. Panel A reports the coefficients of interest defined by Eq. (7) by introducing the interaction between *VaR* and *Debt*. Panel C exhibits the coefficients of interest as in Eq. (8) by interacting *VaR* and $Debt^2$. The control variable parameters given, respectively in Table 14, 15 and 16. Standard errors clustered by firm are in parentheses. *** p<0.01, ** $p < 0.05$, * $p < 0.1$.

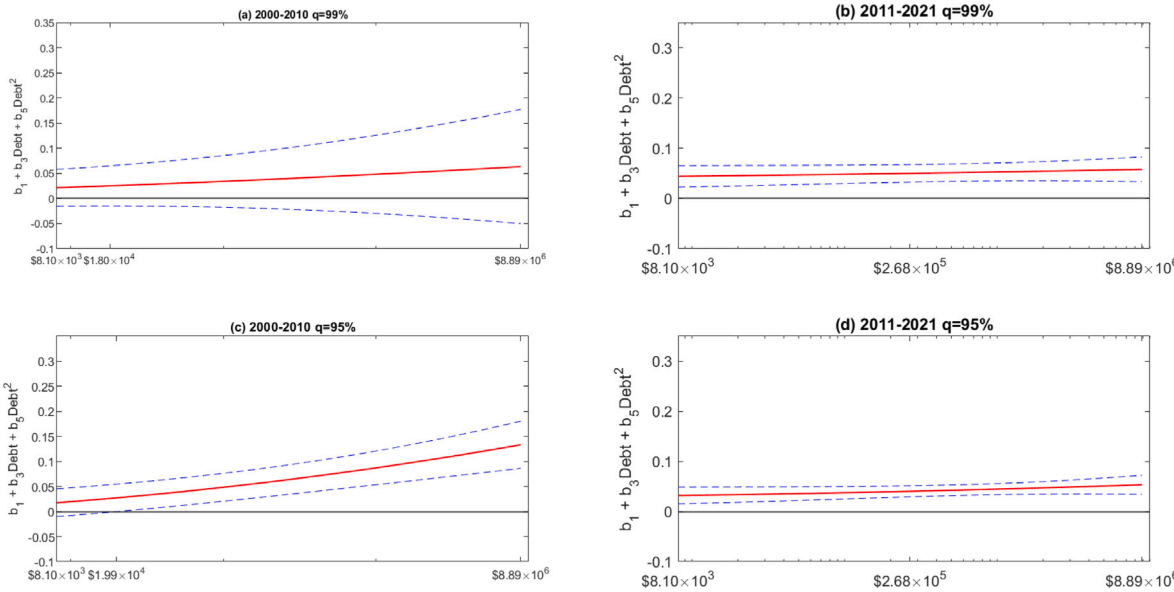

Fig. 10. Impact of debt on VaR: Quadratic interaction.
Note: The figure shows the pattern of the joint coefficient $b_1 + b_3 Debt_{t-1} + b_5 Debt^2_{t-1}$ (red line) with respect to $Debt$. The blue dashed lines represent the confidence interval at 99%.

Table 12
VaR^i as predictor of $\Delta CoVaR^i$ — The role of $Size$ and $Debt$.

Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021
Panel A: Eq. (11)				
$VaR_{\tau,QPYYYY-QPYYYY}$	−0.0170	−0.1244*	−0.0023	−0.0911**
	(0.066)	(0.070)	(0.044)	(0.040)
$VaR_{\tau,QPYYYY-QPYYYY}$ *Size	0.0012	0.0077*	0.0023	0.0068***
	(0.004)	(0.004)	(0.002)	(0.002)
$VaR_{\tau,QPYYYY-QPYYYY}$ *Debt	−0.0112*	−0.0103*	−0.0043	−0.0018
	(0.006)	(0.005)	(0.004)	(0.004)
$VaR_{\tau,QPYYYY-QPYYYY}$ *Size*Debt	0.0007**	0.0007**	0.0002	0.0001
	(0.000)	(0.000)	(0.000)	(0.000)
Size	−0.0024**	−0.0025***	−0.0008	−0.0009***
	(0.001)	(0.001)	(0.001)	(0.000)
Debt	0.0004	−0.0009	0.0001	0.0002
	(0.002)	(0.001)	(0.001)	(0.001)
Size*Debt	−0.0000	0.0000	−0.0000	−0.0000
	(0.000)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	3,580	3,540	3,320	3,325
Number of firms	105	104	123	123
R2	0.600	0.693	0.373	0.397
Adj R2	0.598	0.691	0.369	0.394
Panel B : Eq. (12)				
$VaR_{\tau,QPYYYY-QPYYYY}$	0.7064**	0.3889*	−0.1766	0.2156
	(0.336)	(0.226)	(0.254)	(0.357)
$VaR_{\tau,QPYYYY-QPYYYY}$ *Size	−0.0880**	−0.0526*	0.0199	−0.0262
	(0.038)	(0.027)	(0.028)	(0.038)
$VaR_{\tau,QPYYYY-QPYYYY}$ $*Size^2$	0.0027**	0.0018**	−0.0004	0.0009
	(0.001)	(0.001)	(0.001)	(0.001)
$VaR_{\tau,QPYYYY-QPYYYY}$ *Debt	−0.0252	−0.0305**	0.0131	−0.0018
	(0.024)	(0.013)	(0.016)	(0.017)
$VaR_{\tau,QPYYYY-QPYYYY}$ $*Debt^2$	0.0007	0.0011**	−0.0010	−0.0002
	(0.001)	(0.001)	(0.001)	(0.001)
$VaR_{\tau,QPYYYY-QPYYYY}$ *Size *Debt	0.0017	0.0017**	−0.0004	0.0003
	(0.001)	(0.001)	(0.001)	(0.001)
$VaR_{\tau,QPYYYY-QPYYYY}$ $*Size^2*Debt^2$	−0.0000	−0.0000**	0.0000	−0.0000
	(0.000)	(0.000)	(0.000)	(0.000)

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Table 12 (*continued*).

Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021
Size	0.0025	−0.0031	−0.0077	0.0041
	(0.007)	(0.004)	(0.007)	(0.005)
$Size^2$	−0.0002	0.0000	0.0002	−0.0001
	(0.000)	(0.000)	(0.000)	(0.000)
Debt	0.0067	0.0042***	−0.0046	0.0016
	(0.005)	(0.002)	(0.004)	(0.002)
$Debt^2$	−0.0002	−0.0002**	0.0003*	−0.0000
	(0.000)	(0.000)	(0.000)	(0.000)
Size*Debt	−0.0004*	−0.0002***	0.0002	−0.0001
	(0.000)	(0.000)	(0.000)	(0.000)
$Size^2 * Debt^2$	0.0000	0.0000**	−0.0000	0.0000
	(0.000)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	3,580	3,540	3,320	3,325
Number of firms	105	104	123	123
R2	0.617	0.702	0.375	0.402
Adj R2	0.615	0.700	0.371	0.398

Notes: The table reports the results of the fixed effect panel regression relative to the entire sample. Panel A reports the coefficients of interest defined by Eq. (11) by introducing in the model the interaction between *VaR* and *Size*, *VaR* and *Debt* and, *Size* and *Debt*. Panel B exhibits the coefficients of interest as in Eq. (12) by adding to the interaction in panel A the second-order interaction *VaR* and $Size^2$, *VaR* and $Debt^2$d an, $Size^2$ and $Debt^2$. Standard errors clustered by firm are in parentheses. *** p<0.01, ** $p < 0.05$, * $p < 0.1$.

Table 13
VaR^i as predictor of $\Delta CoVaR^i$, an alternative specification - The role of $Size$ and $Debt$.

	Q12000–Q42010	Q12000–Q42010	Q12011–Q42021	Q12011–Q42021
Panel A: Eq. (11) after the removal of b_6				
$VaR_{\tau,QPYYYY-QPYYYY}$	−0.1394***	−0.2666***	−0.0538*	−0.1099***
	(0.047)	(0.029)	(0.029)	(0.027)
$VaR_{\tau,QPYYYY-QPYYYY}$ *Size	0.0081***	0.0156***	0.0051***	0.0078***
	(0.003)	(0.002)	(0.002)	(0.001)
$VaR_{\tau,QPYYYY-QPYYYY}$ *Debt	0.0021	0.0032***	0.0002	−0.0003
	(0.002)	(0.001)	(0.001)	(0.000)
Size	−0.0030***	−0.0024***	−0.0009**	−0.0011***
	(0.001)	(0.000)	(0.000)	(0.000)
Debt	−0.0003	−0.0003***	−0.0000	0.0000
	(0.000)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes
Observations	3,580	3,540	3,320	3,325
Number of firms	105	104	123	123
R2	0.595	0.684	0.371	0.397
Adj R2	0.594	0.683	0.368	0.394
Panel B: Eq. (12) after the removal of b_9 and b_{10}				
$VaR_{\tau,QPYYYY-QPYYYY}$	0.2961**	−0.0059	0.1916	0.1487
	(0.139)	(0.120)	(0.165)	(0.160)
$VaR_{\tau,QPYYYY-QPYYYY}$ *Size	−0.0453***	−0.0135	−0.0220	−0.0205
	(0.016)	(0.013)	(0.017)	(0.016)
$VaR_{\tau,QPYYYY-QPYYYY}$ $*Size^2$	0.0016***	0.0008**	0.0007*	0.0008*
	(0.000)	(0.000)	(0.000)	(0.000)
$VaR_{\tau,QPYYYY-QPYYYY}$ *Debt	0.0067	0.0014	0.0038*	0.0046**
	(0.004)	(0.003)	(0.002)	(0.002)
$VaR_{\tau,QPYYYY-QPYYYY}$ $*Debt^2$	−0.0005	0.0001	−0.0003*	−0.0004***
	(0.000)	(0.000)	(0.000)	(0.000)
Size	−0.0065	−0.0094***	0.0024	0.0018
	(0.005)	(0.002)	(0.004)	(0.002)
$Size^2$	0.0001	0.0002***	−0.0001	−0.0001
	(0.000)	(0.000)	(0.000)	(0.000)
Debt	−0.0014	−0.0002	−0.0009*	−0.0008***
	(0.001)	(0.000)	(0.001)	(0.000)
$Debt^2$	0.0001	−0.0000	0.0001*	0.0001***
	(0.000)	(0.000)	(0.000)	(0.000)
Controls and Constant	Yes	Yes	Yes	Yes

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Table 13 (*continued*).

	Q12000–Q42010	Q12000–Q42010	Q12011–Q42021	Q12011–Q42021
Observations	3,580	3,540	3,320	3,325
Number of firms	105	104	123	123
R2	0.616	0.700	0.374	0.401
Adj R2	0.614	0.699	0.370	0.398

Notes: The table reports the results of the fixed effect panel regression relative to the entire sample. Panel A reports the coefficients of interest defined by Eq. (11) by introducing in the model the interaction between *VaR* and *Size* and, *VaR* and *Debt*. Panel B exhibits the coefficients of interest as in Eq. (12) by adding to the interaction in panel A the second-order interaction *VaR* and $Size^2$ and, *VaR* and $Debt^2$. Standard errors clustered by firm are in parentheses. *** p<0.01, ** $p < 0.05$, * $p < 0.1$.

Table 14
The predictors of $\Delta CoVaR$ — All drivers.

Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021	Δ_CoVaR99 Q12011–Q42019	Δ_CoVaR95 Q12011–Q42019
$VaR_{99,QPYYYY-QPYYYY}$	0.0253*		0.0494***		0.0614***	
	(0.014)		(0.006)		(0.007)	
$VaR_{95,QPYYYY-QPYYYY}$		0.0405***		0.0422***		0.0565***
		(0.011)		(0.004)		(0.005)
Ted_spread	1.0060***	0.5004***	1.0903***	0.5630***	0.4012**	0.1798**
	(0.142)	(0.073)	(0.143)	(0.076)	(0.182)	(0.085)
Credit_spread	0.4473***	0.1829***	0.0894*	0.0604**	0.1270**	0.1191***
	(0.064)	(0.027)	(0.052)	(0.024)	(0.052)	(0.024)
Tbill3M	−0.0500*	−0.0036	−0.4471***	−0.4483***	−0.2918***	−0.1284***
	(0.028)	(0.014)	(0.077)	(0.051)	(0.091)	(0.045)
Oil sector return	0.2197***	0.1322***	−0.0444***	−0.0280***	−0.0415***	−0.0267***
	(0.015)	(0.008)	(0.004)	(0.002)	(0.004)	(0.002)
Inflation rate	0.0021***	0.0014***	0.0015***	0.0010***	0.0019***	0.0012***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Size	−0.0004	−0.0000	0.0004*	0.0001	−0.0001	0.0001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Debt	0.0002*	0.0002*	0.0000	−0.0000	0.0000	−0.0000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ROA	0.2156*	0.0184	0.0412	0.1042**	0.0625	0.0005
	(0.126)	(0.108)	(0.064)	(0.040)	(0.103)	(0.047)
ROE	−0.0002*	0.0004***	−0.0025**	0.0002***	0.0000	−0.0001
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)
RET_WTI	−0.0011	0.0001	−0.0061***	−0.0031***	−0.0043***	−0.0024***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
Henry Hub_ret	−0.0035***	−0.0023***	−0.0059***	−0.0038***	−0.0061***	−0.0038***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
$\Delta NRIGS_{\%}$	0.0146***	0.0086***	−0.0005	−0.0003	−0.0012*	−0.0008**
	(0.001)	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)
Constant	0.0157**	0.0026	0.0020	0.0039	0.0136**	0.0044*
	(0.007)	(0.004)	(0.005)	(0.002)	(0.006)	(0.002)
Observations	3,580	3,540	3,320	3,325	2,782	2,782
Number of firms	105	104	123	123	118	118
R2	0.565	0.605	0.362	0.378	0.340	0.347
Adj R2	0.563	0.603	0.360	0.375	0.337	0.344

Notes: The table reports all the coefficients of the fixed effect panel regression defined by Eq. (6). Standard errors clustered by firm are in parentheses. *** p<0.01, ** $p < 0.05$, * $p < 0.1$. Results are reported for the sub-samples of the main results as well as for the sub-samples adopted in the robustness check with separate analyses for the COVID-19 period.

Table 15
The predictors of $\Delta CoVaR$ — Interaction with $Size$.

Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021	Δ_CoVaR99 Q12011–Q42019	Δ_CoVaR95 Q12011–Q42019
$VaR_{99,QPYYYY-QPYYYY}$	−0.1577***		−0.0558*		−0.0824**	
	(0.055)		(0.029)		(0.035)	
$VaR_{99,QPYYYY-QPYYYY}$ *Size	0.0100***		0.0053***		0.0074***	
	(0.004)		(0.002)		(0.002)	
$VaR_{95,QPYYYY-QPYYYY}$		−0.2879***		−0.1073***		−0.0785**
		(0.028)		(0.026)		(0.031)
$VaR_{95,QPYYYY-QPYYYY}$ *Size		0.0184***		0.0075***		0.0067***
		(0.002)		(0.001)		(0.002)

(*continued on next page*)

Table 15 (*continued*).

Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021	Δ_CoVaR99 Q12011–Q42019	Δ_CoVaR95 Q12011–Q42019
Size	−0.0036***	−0.0029***	−0.0010**	−0.0010***	−0.0019***	−0.0008***
	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
Ted_spread	1.0080***	0.3847***	1.1527***	0.6632***	0.3951**	0.2087***
	(0.159)	(0.048)	(0.140)	(0.072)	(0.157)	(0.077)
Credit_spread	0.3746***	0.1028***	0.0464	0.0185	0.0880*	0.1015***
	(0.082)	(0.020)	(0.055)	(0.020)	(0.049)	(0.022)
Tbill3M	0.0285	0.0636***	−0.4603***	−0.4633***	−0.2960***	−0.1349***
	(0.031)	(0.012)	(0.076)	(0.051)	(0.089)	(0.044)
Oil sector return	0.2066***	0.1219***	−0.0448***	−0.0290***	−0.0422***	−0.0269***
	(0.014)	(0.008)	(0.004)	(0.002)	(0.004)	(0.002)
Inflation rate	0.0022***	0.0015***	0.0015***	0.0010***	0.0019***	0.0012***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Debt	0.0002	0.0001	0.0000	−0.0000	0.0000	−0.0000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ROA	0.1947**	−0.0124	0.0449	0.0883**	0.0309	−0.0125
	(0.096)	(0.061)	(0.057)	(0.039)	(0.102)	(0.045)
ROE	−0.0002**	0.0003***	−0.0028**	0.0004***	0.0002	−0.0000
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)
RET_WTI	−0.0013*	0.0007	−0.0060***	−0.0032***	−0.0036***	−0.0022***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
Henry Hub_ret	−0.0037***	−0.0024***	−0.0059***	−0.0039***	−0.0059***	−0.0038***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
$\Delta NRIGS_{\%}$	0.0144***	0.0087***	−0.0007	−0.0005*	−0.0013*	−0.0009**
	(0.001)	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)
Constant	0.0790***	0.0582***	0.0302***	0.0270***	0.0498***	0.0227***
	(0.013)	(0.005)	(0.009)	(0.004)	(0.010)	(0.005)
Observations	3,580	3,540	3,320	3,325	2,782	2,782
Number of firms	105	104	123	123	118	118
R2	0.590	0.675	0.371	0.397	0.361	0.362
Adj R2	0.588	0.674	0.368	0.394	0.357	0.358

Notes: The table reports all the coefficients of the fixed effect panel regression defined by Eq. (7). The table reports the coefficients by introducing the interaction between *VaR* and *Size*. Standard errors clustered by firm are in parentheses. *** p<0.01, ** $p < 0.05$, * $p < 0.1$.

Table 16
The predictors of $\Delta CoVaR$ — Interaction with $Size$ and $Size^2$.

Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021	Δ_CoVaR99 Q12011–Q42019	Δ_CoVaR95 Q12011–Q42019
$VaR_{99,QPYYYY-QPYYYY}$	0.3465**		0.1532		0.6517***	
	(0.135)		(0.161)		(0.195)	
$VaR_{99,QPYYYY-QPYYYY}$ *Size	−0.0479***		−0.0165		−0.0686***	
	(0.015)		(0.016)		(0.021)	
$VaR_{99,QPYYYY-QPYYYY}$ $*Size^2$	0.0016***		0.0006		0.0019***	
	(0.000)		(0.000)		(0.001)	
$VaR_{95,QPYYYY-QPYYYY}$		0.0127		0.1077		0.1605
		(0.120)		(0.159)		(0.160)
$VaR_{95,QPYYYY-QPYYYY}$ *Size		−0.0156		−0.0144		−0.0177
		(0.013)		(0.016)		(0.017)
$VaR_{95,QPYYYY-QPYYYY}$ $*Size^2$		0.0010***		0.0006		0.0006
		(0.000)		(0.000)		(0.000)
Size	−0.0067	−0.0102***	0.0011	0.0009	0.0151***	0.0017
	(0.006)	(0.002)	(0.004)	(0.002)	(0.005)	(0.002)
$Size^2$	0.0001	0.0002***	−0.0001	−0.0000	−0.0004***	−0.0001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Ted_spread	0.8640***	0.2987***	1.1537***	0.6672***	0.4076***	0.2097***
	(0.152)	(0.039)	(0.139)	(0.071)	(0.154)	(0.075)
Credit_spread	0.3388***	0.0933***	0.0418	0.0169	0.0655	0.0997***
	(0.083)	(0.018)	(0.054)	(0.020)	(0.048)	(0.021)
Tbill3M	0.0511	0.0687***	−0.4690***	−0.4656***	−0.3147***	−0.1382***
	(0.032)	(0.012)	(0.076)	(0.051)	(0.086)	(0.043)
Oil sector return	0.2067***	0.1236***	−0.0453***	−0.0294***	−0.0430***	−0.0270***
	(0.015)	(0.008)	(0.004)	(0.002)	(0.004)	(0.002)
Inflation rate	0.0021***	0.0015***	0.0015***	0.0010***	0.0019***	0.0012***

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Table 16 (*continued*).

Variables	Δ_CoVaR99 Q12000–Q42010	Δ_CoVaR95 Q12000–Q42010	Δ_CoVaR99 Q12011–Q42021	Δ_CoVaR95 Q12011–Q42021	Δ_CoVaR99 Q12011–Q42019	Δ_CoVaR95 Q12011–Q42019
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Debt	0.0002	0.0001	0.0000	−0.0000	0.0000	−0.0000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ROA	0.2446**	0.0271	0.0581	0.0904**	0.0124	−0.0094
	(0.095)	(0.058)	(0.062)	(0.039)	(0.097)	(0.045)
ROE	−0.0001	0.0004***	−0.0028**	0.0004***	0.0000	−0.0000
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)
RET_WTI	−0.0016**	0.0006	−0.0060***	−0.0031***	−0.0034***	−0.0021***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
Henry Hub_ret	−0.0038***	−0.0024***	−0.0059***	−0.0038***	−0.0058***	−0.0038***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
$\Delta NRIGS_{\%}$	0.0142***	0.0086***	−0.0007	−0.0005*	−0.0013*	−0.0009**
	(0.001)	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)
Constant	0.1132*	0.1279***	0.0100	0.0083	−0.1176**	−0.0017
	(0.058)	(0.023)	(0.046)	(0.024)	(0.050)	(0.024)
Observations	3,580	3,540	3,320	3,325	2,782	2,782
Number of firms	105	104	123	123	118	118
R2	0.611	0.695	0.372	0.398	0.372	0.363
Adj R2	0.609	0.694	0.369	0.395	0.369	0.359

Notes: The table reports all the coefficients of the fixed effect panel regression defined by Eq. (8). The table reports the coefficients by introducing the interaction between VaR and *Size* and VaR and $Size^2$. Standard errors clustered by firm are in parentheses. *** p<0.01, ** $p < 0.05$, * $p < 0.1$.

References

Acemoglu, D., Carvalho, V.M., Ozdaglar, A., Tahbaz-Salehi, A., 2012. The network origins of aggregate fluctuations. Econometrica 80 (5), 1977–2016.

Adrian, T., Brunnermeier, M.K., 2016. CoVaR. The Am. Econ. Rev 106 (7), 1705.

Al-Jarrah, I.M.W., Al-Abdulqader, K., Hammoudeh, S., 2021. How do bank features and global crises affect scale economies? Evidence from the banking sectors of oil-rich GCC emerging markets. Emerg. Markets Finan. Trade 57 (3), 891–913.

Apergis, N., Ewing, B.T., Payne, J.E., 2021. The asymmetric relationship of oil prices and production on drilling rig trajectory. Resour. Policy 71, 101990.

Basher, S.A., Haug, A.A., Sadorsky, P., 2018. The impact of oil-market shocks on stock returns in major oil-exporting countries. J. Int. Money Finance 86, 264–280.

Benoit, S., Colliard, J., Hurlin, C., Pérignon, C., 2017. Where the risks lie: a survey on systemic risk. Rev. Finance 21 (1), 109152.

Caporin, M., Fontini, F., Talebbeydokhti, E., 2019. Testing persistence of WTI and brent long-run relationship after the shale oil supply shock. Energy Econ. 79, 21–31.

Diaz-Rainey, I., Gehricke, S.A., Roberts, H., Zhang, R., 2021. Trump vs. Paris: The impact of climate policy on US listed oil and gas firm returns and volatility. Int. Rev. Financ. Anal. 76, 101746.

El-Sharif, I., Brown, D., Burton, B., Nixon, B., Russell, A., 2005. Evidence on the nature and extent of the relationship between oil prices and equity values in the UK. Energy Econ. 27 (6), 819–830.

Faff, R.W., Brailsford, T.J., 1999. Oil price risk and the Australian stock market. J. Energy Finan. Develop 4 (1), 69–87.

Fama, E.F., French, K.R., 2007. Disagreement, tastes, and asset prices. J. Financ. Econ. 83 (3), 667–689.

Fusaro, P.C., 1998. Energy Risk Management: Hedging Strategies and Instruments for the International Energy Markets. McGraw Hill Professional.

Gabaix, X., 2011. The granular origins of aggregate fluctuations. Econometrica 79 (3), 733–772.

Howard, A.W., Harp Jr., A.B., 2009. Oil and gas company valuations. Bus. Valuat. Rev 28 (1), 30–35.

Kerste, M., Gerritsen, M., Weda, J., Tieben, B., 2015. Systemic risk in the energy sector—Is there need for financial regulation? Energy Policy 78, 22–30.

Khalifa, A., Caporin, M., Costola, M., Hammoudeh, S., 2021. Systemic risk for financial institutions in the major petroleum-based economies: The role of oil. Energy J. 42, 247–274.

Koenker, R., 2005. Quantile Regression. Cambridge University Press.

Liu, J., Gronwald, M., 2017. Oil price systemic risk for the oil and gas industry: A copula-CoVaR approach. Available At SSRN 2998196.

Lupu, R., Călin, A.C., Zeldea, C.G., Lupu, I., 2021. Systemic risk spillovers in the European energy sector. Energies 14 (19), 6410.

Mensi, W., Hammoudeh, S., Shahzad, S.J.H., Shahbaz, M., 2017. Modeling systemic risk and dependence structure between oil and stock markets using a variational mode decomposition-based copula method. J. Bank. Financ. 75, 258–279.

Monasterolo, I., De Angelis, L., 2020. Blind to carbon risk? An analysis of stock market reaction to the Paris agreement. Ecol. Econom. 170, 106571.

Ouyang, Z.-s., Liu, M.-t., Huang, S.-s., Yao, T., 2022. Does the source of oil price shocks matter for the systemic risk? Energy Econ. 109, 105958.

Reboredo, J.C., 2015. Is there dependence and systemic risk between oil and renewable energy stock prices? Energy Econ. 48, 32–45.

Rohleder, M., Scholz, H., Wilkens, M., 2011. Survivorship bias and mutual fund performance: Relevance, significance, and methodical differences. Rev. Finance 15 (2), 441–474.

Sadorsky, P., 2001. Risk factors in stock returns of Canadian oil and gas companies. Energy Econ. 23 (1), 17–28.

Tiwari, A.K., Trabelsi, N., Alqahtani, F., Raheem, I.D., 2020. Systemic risk spillovers between crude oil and stock index returns of G7 economies: Conditional value-at-risk and marginal expected shortfall approaches. Energy Econ. 86, 104646.