energies

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Movers and Shakers: Stock Market Response to Induced Seismicity in Oil and Gas Business

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Abstract: Investors increasingly need to account for concerns about non-financial performance and to consider the environmental impact of fossil fuel investment. We analyze how financial investors appreciate induced seismicity in oil and gas fields in the US and the Netherlands. We employ an event study to investigate the stock market reaction of investors in two fossil fuel majors, ExxonMobil and Royal Dutch Shell. We establish that stock market participants' response is positively but weakly related to induced seismicity with ExxonMobil. This suggests that markets might interpret this seismicity as a signal of future productivity. With Royal Dutch Shell, there is no significant association, suggesting that their investors do not specifically appreciate its externalities. We conclude that the externality of induced seismicity goes unpriced.

Keywords: induced seismicity; oil and gas majors; financial value; stock market; event study

Citation: Kallen, M.J.; Scholtens, B. Movers and Shakers: Stock Market Response to Induced Seismicity in Oil and Gas Business. *Energies* **2021**, *14*, 8051. https://doi.org/10.3390/en14238051

Academic Editor: Nuno Carlos Leitão

Received: 1 November 2021
Accepted: 24 November 2021
Published: 1 December 2021

1. Introduction

This paper analyzes how financial investors respond to induced seismicity. This is exploratory research, as this specific relationship has not been studied before. With this study, we aim at explaining why there might be a valuation effect and test whether this is indeed the case.

The extraction of fossil fuels can be accompanied by induced seismicity. The interest and concern regarding this seismicity has increased with the advent of unconventional exploration and exploitation of fossil minerals [1] and has become a matter for public concern [2]. The management of induced seismicity gets integrated in fossil fuel project appraisal [3,4]. In this study, the aim is to examine whether induced seismicity also influences the valuation of major oil and gas companies. To this extent, we analyze the stock market effects of induced seismicity in the Anadarko Basin, located in the state of Oklahoma in the US, and in the Slochteren field, located in the province of Groningen in the Netherlands. For these two regions, it is documented that drilling and fracking business operations have caused induced seismic activity ([5–7] for Oklahoma and [8,9] for Groningen). We investigate whether this induced seismicity can be associated with abnormal stock market returns of ExxonMobil and Royal Dutch Shell, two high-profile energy companies operating in both countries. We do not assume that these companies actually caused the seismicity. However, given they are both high profile companies operating in Groningen and Oklahoma, we assume financial analysts will keep track and are in the position to assess how induced seismicity could affect their value. Hence, it is the perception of the investor that is at the basis of the analysis of the relationship between induced seismicity and financial valuation. The financial investor perspective is relevant as companies require external funding for their operations. Their financial performance and prospects are assessed based on the development of their value. Increasingly, financial investors are under pressure from stakeholders to account for the externalities of their business [10]. For example, a social movement asks investors to divest from fossil fuel companies [11], which may have ramifications for their portfolio performance [12].

Our study takes an alternative perspective, namely the value relevance of induced seismicity. This complements other studies that investigate the influence of shocks on the valuation of oil and gas companies [13–15], but do not account for induced seismicity. Induced seismicity can affect the project operations, firm performance, and may have external effects. The first and last have previously been studied (e.g., [1,3], respectively), whereas little attention has been paid to the relationship with firm performance so far, let alone with market valuation. Induced seismicity may associate with firm value and, if so, with the stock market returns of companies in several ways: The appreciation of the expected discounted cash flows to the firm determines the value of the firm's stock. Then, we need to account for factors influencing expected costs and revenues, estimated project timing, and risk expectations. Important for our study is that we do not assume that the traders themselves actually feel the "microearthquakes", that the companies caused the specific earthquake, that the seismicity makes headlines, or that it immediately did result in damage. We do study how traders react to induced seismicity as they closely follow the firms they (consider to) invest in and have access to databases regarding corporate operations and performance. Induced seismicity will inform the traders regarding prospective operations, actions and firm value. In this regard, refs [3,4] show that management of seismicity affects firms' cash flows. Thus, although the economic effect might show in the long-run, the financial market perspective holds that financial investors immediately respond to relevant news about the firm and markets. This means that we can analyze the short-term response of these investors. We do so with the help of an event study (see Section 2).

Persistent damage to cultural heritage and real estate from the induced seismicity has led to fierce protests by the local community in Groningen and production may be halted prematurely [16]. Studies after unconventional drilling [6,17] find that project risks have increased in Oklahoma in relation to unconventional mining operations. Other studies [18,19] point at the perception of mining activity in relation to induced seismicity and find that perceived risks have increased. Such factors may have financial consequences for Royal Dutch Shell and Exxon Mobil, which might be accounted for by their investors. It is not necessarily the case that induced seismicity closely connects with these two firms; it is about how induced seismicity associates with investor appreciation of these companies. The companies' cash flows may be affected because there might be reparation costs and because exploitation renders additional revenues [17]. Changes in risk perception can also affect the time period during which fossil fuel can be extracted. Further, the reputation of the companies involved may be affected, which can have an impact on their perceived risk and translate into a modification of the discount rate [1,12,18]. Overall, the effect of induced seismicity on firm valuation is not straightforward and requires empirical investigation.

We study the relationship between induced seismicity and firm value with the help of an event study [20]. In an event study, the focus is on how financial investors' responses to an unexpected event compare to their expected ('normal') response in case the event would not have occurred. Induced seismicity is an unexpected event as earthquakes cannot be predicted [21]. Some studies investigate stock market effects of earthquakes and natural disasters in general using the event study methodology [22,23]. Both studies arrive at significantly negative abnormal returns on the event day. Ferreira and Karali [24] investigate how 24 major earthquakes affect 35 international financial markets and find these are resilient to shocks. In contrast, other studies [25,26] rely on much smaller samples, namely one earthquake and two hurricanes respectively. These studies also use the event study methodology and arrive at significant negative abnormal returns. Next to this method, there are alternative methods to study societal impact. For example, refs [27,28] rely on hedonic pricing. They use hazard maps and data for observed earthquakes to investigate if earthquake risks have a negative effect on housing rents. They find that property value discounts more than double after an earthquake due to severe underestimation of earthquake risks. As far as we are aware of, no other studies gauge the financial value relevance of induced seismicity.

Our exploratory study relates to this literature and uses hundreds of events. This sample size is substantially higher than the numbers used in the existing literature. Further, we investigate induced seismicity, which is thought to be less impactful than conventional seismicity from a geophysical perspective [5]. However, Grigolo et al. [29] suggest that the Mw 5.5 earthquake in Pohang (South Korea) is a possible case of induced seismicity, but this has not been confirmed yet. Therefore, we think there is merit in a systematic investigation of financial investors' response to induced seismicity as it informs about the business impact. We hypothesize that induced seismicity has a significant impact on the excess stock market returns. The null being that there is no impact. We test the hypothesis for the case of Royal Dutch Shell and Exxon Mobil and study induced seismicity in the Anadarko Basin and the Slochteren field. Furthermore, we compare the responses between both companies and locations. We find that investors in ExxonMobil show a positive response and those in Royal Dutch Shell do not change firm valuation in connection with the externality of induced seismicity. This suggests that financial market investors do not properly price induced seismicity.

The remainder of the paper is organized as follows. We first explain and motivate the event study methodology. Next, we detail the sampling procedure. Then, we present the results and engage in a comparison between the responses in the different countries and between the firms. The last section concludes.

2. Materials and Methods

We rely on the event study approach [20], which measures the impact of an event on firm value by examining the relationship between unexpected events and financial market data. This method builds on the assumption that, given rationality in the marketplace, the effects of an event will be immediately reflected in stock prices [30,31]. To this extent, the focus is on the abnormal returns, being the differential between actual and expected returns. To estimate expected returns, we use the market and risk adjusted returns model [20]. This model assumes a stable relation between the market and the security return. The relationship is estimated over an estimation window and this window has to be long enough to specify "expected" returns. In this study, we employ an estimation window of 100 days prior to the event date [22].

To derive abnormal returns, we first calculate actual daily returns as the change between the opening and closing price. As such, we are able to capture daily changes in stock prices resulting from news of unexpected quakes arriving at the market. Overnight returns are not analyzed; only the market response during the stock exchanges' opening hours. To calculate expected returns, we employ the market and risk adjusted returns model [20]. This model relates the stock market return of any given security to the return of the stock market portfolio as a whole and removes the portion of variation that is due to market volatility. Following [31], this provides an increased ability to detect event effects. The model is defined as

$$R_{it} = \alpha_i + \beta_i R_{mt} + \varepsilon_{it} \tag{1}$$

$$E(\varepsilon_{it} = 0) \tag{2}$$

$$var(\varepsilon_{it}) = \sigma_\varepsilon^2 \tag{3}$$

where R_{it} is the expected (normal) return for stock i at time t, R_{mt} is the return for the benchmark index m at time t, and ε_{it} the error term. The specific risk, or α_i, measures the amount that the stock has returned in comparison to the benchmark (general market) index it is compared with. The slope of the model, β_i, is calculated by relating the covariance of R_{it} and R_{mt} to the variance of R_{mt}. The beta measures the volatility of a stock's return in relation to a benchmark index and is an indication of its relative risk. The abnormal returns (AR_{it}) are calculated as the difference between the actual and expected (normal) returns.

The abnormal returns are then averaged to derive the average abnormal returns (AARs) in the event window as:

$$AAR_t = \frac{1}{N}\sum_{i=1}^{N} AR_{it} \quad (4)$$

where N is the number of events. As the aim of an event study is to establish whether there are average abnormal returns in the event window, we will test whether these significantly differ from zero. In addition, we also calculate and test cumulative average abnormal returns (CAARs). This is because "researchers test multiple-day periods because they believe that investors can receive new information on one day during the period but cannot determine exactly when" ([32], p. 51). To calculate the cumulative average abnormal returns, we first derive cumulative abnormal returns:

$$CAR_i(\tau_1, \tau_2) = \sum_{t=\tau_1}^{\tau_2} AR_{it} \quad (5)$$

The cumulative abnormal returns are summed abnormal returns in the event period from τ_1 to τ_2 for stock i. The cumulative average abnormal returns is calculated as:

$$CAAR(\tau_1, \tau_2) = \frac{1}{N}\sum_{i=1}^{N} CAR_i(\tau_1, \tau_2) \quad (6)$$

As many markets are characterized by high frequencies of missing returns due to non-trading, ref [31] point out that treating missing returns as zero would bias the results. Therefore, when an event occurs on a non-trading day, the stock price data of the first trading day is used (the day following the non-trading day). We use an event window of six days, namely from day 0 to day +5. Here, day 0 is the day on which the news regarding induced seismicity comes available to the market. This short period is chosen because we are interested in the immediate impact of seismicity as financial market participants are assumed to directly respond to news [33]. In addition, a relatively short event window helps avoid contaminating estimates with confounding factors [32].

To come to grips with induced seismicity, we study so called micro earthquakes, which relate to earthquakes with a minimum magnitude of 1.0 and a maximum magnitude of 3.9, as seen on the Richter scale. We want to point out that we assume that these micro earthquakes are equivalent to induced seismicity events. Of course, it is not possible to directly relate a specific earthquake to a specific and unique human action. However, the geophysical evidence detects a straightforward unidirectional relationship, both in the case of the Anadarko Basin [5–7], and the Slochteren field [8,9].

We want to use as much events as possible and therefore do not restrict ourselves to a particular time period. Given that we aim at a comparison and require geophysical and financial market data, we expect to lose some information, as the availability of the data is not synchronous. The data and stock market information for the companies and the induced seismicity used in this study is available at https://doi.org/10.34894/QWQ8SN.

We retrieve earthquake information regarding the Slochteren field from the KNMI database (http://rdsa.knmi.nl/dataportal), where earthquakes available from 26 December 1986 until 24 January 2020 is downloaded. This provides 1574 events. We deleted earthquakes with a magnitude smaller than, which reduced the sample size to 928. In case of overlap (i.e., two or more earthquakes within the event window), we omitted all these earthquakes from our sample as we cannot be sure where investors respond to [33]. This reduced the number of earthquakes to 519. The stock market data of Royal Dutch Shell and Exxon Mobil were available to us since March 2000. As a result, the number of events for the Netherlands was reduced to 423.

For the Anadarko Basin, the earthquake data is obtained from the USGS database (https://earthquake.usgs.gov/earthquakes/). We downloaded earthquakes with a minimum magnitude of 1.0 and a maximum of 3.9 from 1 March 2000 until 25 January 2020. This resulted in 13,087 events. To ensure no overlap in the event window of six days, a large number of events had to be deleted. This led to the removal of many earthquakes and resulted in the final number of 552 events. When investigating the response to overall induced seismicity in Groningen and Oklahoma, we could use a sample of 727 non-overlapping events.

For all stock market information, we rely on TR Eikon from Thomson Reuters, which is a proprietary database (https://eikon.thomsonreuters.com/index.html). We account for information about Royal Dutch Shell (RDS), The Hague, The Netherlands, and Exxon Mobil (XOM), Irving, TX, USA, between 1 March 2000 until 24 January 2020. We used the total return index, which accounts for dividend and stock splits. From this database, we also derive the corresponding benchmark index [31] for RDS, namely the Amsterdam Exchange Index (AEX), and the Dow Jones Industrial Average (DJI), the XOM benchmark. We control for confounding events regarding mergers and acquisitions, CEO transition, stock splits and profit warnings [20,33].

We tested for ARCH effects in the error term of Equation (1) and conclude there is none. Hence, we establish there is homoscedastic error variance. As we have a very short event window, we do not consider if returns covary with risk factors [30]. We provide descriptive statistics regarding the AARs in Tables A1–A3. These statistics suggest there is in many cases non-normal distribution of the abnormal returns. Hence, the hypothesis also requires non-parametric testing. Therefore, next to the conventional parametric tests, we will use non-parametric tests. For the former, we use a conventional t-test, and for the latter use the Generalized Sign Test [34]. This sign test compares the proportion of positive (or negative) abnormal returns around an event (event window) to the proportion from a period unaffected by the event (estimation window) and tests whether the number in the event window exceeds the number expected in the absence of abnormal performance. Further, it accounts for possible asymmetric return distributions under the null hypothesis. To compare performance differences between subgroups, we use the Mann-Whitney-Wilcoxon test and the Two-Sample Z-test. The first test compares two independent groups that do not require normally distributed samples. It examines whether a randomly selected value from one population will be less than or greater than a randomly selected from a second population. The two sample Z-Test compares whether the means of two groups are equal or not.

3. Results

3.1. Overall Results

Table 1 reports the average abnormal returns for the two companies in relation to the induced seismicity and shows the accompanying test statistics. For Royal Dutch Shell, it shows that there are no significant abnormal returns. Hence, we conclude stock market investors in Royal Dutch Shell do not to respond to induced seismicity. This finding does not support the hypothesis. This result contrasts with the findings for Exxon Mobil. Here, it shows that there are significant positive results on the event day (0.105%). This result also is significant from an economic point of view. The positive response can be motivated based on [17], who argues that investors in oil-and gas majors benefit from more production, which is accompanied by more induced seismicity. For day 2, there is a significant positive abnormal return (0.0008%). However, this result is not significant from an economic perspective and we do not reject the null. The difference between the two companies may be related to the different societal context where the two companies operate as well as in ownership composition. We leave this for further research.

Table 1. Average abnormal returns Royal Dutch Shell and Exxon Mobil—Slochteren and Anadarko induced seismicity combined (*df* = 726).

	Royal Dutch Shell			Exxon Mobil		
Day	**AAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**	**AAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**
0	−0.0004	0.3353	0.1834	**0.0010**	**0.0149**	**0.0022**
1	−0.0004	0.4933	0.2254	−0.0003	0.4211	0.2169
2	−0.0003	0.4383	0.4953	**0.0000**	0.349	**0.0348**
3	0.0009	0.3597	0.183	0.0000	0.3637	0.0977
4	−0.0007	0.0743	0.2105	−0.0004	0.1726	0.1759
5	0.0004	0.051	0.2032	−0.0002	0.4372	0.3135

Table 2 provides cumulative averaged abnormal returns for Royal Dutch Shell and Exxon Mobil regarding the 727 earthquakes. For Royal Dutch Shell, it shows there are no significant CAARs and there is no lagged response. For Exxon Mobil, the period from day zero to one suggests significant CAARs, but we regard them as just marginally relevant from an economic point of view given their very small size in terms of average abnormal returns. These findings confirm those in Table 1.

Table 2. Cumulative average abnormal returns Royal Dutch Shell and Exxon Mobil—Slochteren and Anadarko induced seismicity combined (*df* = 726).

	Royal Dutch Shell			Exxon Mobil		
Days	**CAAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**	**CAAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**
[0; 1]	0.0002	0.3960	0.2812	**0.0010**	0.0556	**0.0393**
[0; 3]	0.0003	0.3734	0.3067	0.0008	0.1709	0.3093
[0; 5]	0.0003	0.3968	0.1639	0.0004	0.3493	0.3633

3.2. Netherlands

Table 3 displays the AARs regarding 423 events of induced seismicity in the Slochteren field in the Netherlands. In the case of Royal Dutch Shell, there is a significant negative result on day 5 only. However, we do not regard this as support of the hypothesis, as investors are expected to come up with a more immediate response after an earthquake (see, e.g., [22,23]). For Exxon Mobil, the AAR on the event day is positive and significant (0.101%), also from an economic perspective. This is in line with the findings in Table 1, with the combined response to induced seismicity in the Netherlands and the US and may be explained following the line of reasoning by [17]. However, the results from the sign test suggest that AARs on day 3 are negative (0.06%) albeit marginally significant. This result is of limited economic significance.

Table 3. Average abnormal returns Royal Dutch Shell and Exxon Mobil—Slochteren induced seismicity (*df* = 422).

	Royal Dutch Shell			Exxon Mobil		
Day	**AAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**	**AAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**
0	0.0006	0.1697	0.2843	**0.0010**	**0.0176**	**0.0274**
1	0.0000	0.4430	0.4218	−0.0002	0.3735	0.4168
2	−0.0008	0.0976	0.3512	0.0000	0.4989	0.2401
3	0.0001	0.3988	0.2483	**−0.0006**	0.116	**0.0485**
4	−0.0011	0.0502	0.2276	−0.0004	0.2342	0.2148
5	**−0.0011**	**0.0472**	**0.0099**	0.0002	0.3714	0.3756

Table 4 provides cumulative abnormal returns for the two companies with induced seismicity in the Slochteren field. These returns are very small over the three different windows studied; in all cases they are less than 0.001. Compared to other studies [19,22–25], the response is much smaller. Table 4 also shows no statistical significance for either company. Hence, we conclude to reject the hypothesis that induced seismicity has valuation effects in these event windows.

Table 4. Cumulative average abnormal returns Royal Dutch Shell and Exxon Mobil—Induced seismicity in Slochteren (*df* = 422).

	Royal Dutch Shell			Exxon Mobil		
Days	**CAAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**	**CAAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**
[0; 1]	0.0007	0.2401	0.2203	0.0008	0.1405	0.0629
[0; 3]	0.0000	0.4991	0.3461	0.0002	0.4109	0.3756
[0; 5]	0.0000	0.4977	0.2459	0.0000	0.4869	0.3393

3.3. United States

Table 5 shows the financial investors' response to induced seismicity in the Anadarko Basin, Oklahoma, US. For Royal Dutch Shell, it appears that the AARs are negatively significant on day 2 and 5 of the event window (−0.0185% and 0.0390% respectively), supporting the hypothesis. Compared to the most closely related studies [22,24–26], this effect is relatively small and of limited significance from an economic point of view. This might result from the differences in intensity of earthquakes examined [18]. Table 5 also presents the results for ExxonMobil in Oklahoma. Investors respond positively (0.083%) to the events with this company. On day 2, there is a small significant negative response (−0.041).

Table 5. Average abnormal returns Royal Dutch Shell and Exxon Mobil—Induced seismicity in Anadarko Basin (*df* = 551).

	Royal Dutch Shell			Exxon Mobil		
Day	**AAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**	**AAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**
0	0.0001	0.3764	0.4052	**0.0008**	**0.0176**	**0.0002**
1	0.0002	0.3098	0.2514	0.0000	0.3735	0.3594
2	**−0.0002**	0.3016	**0.0268**	**−0.0004**	0.4989	**0.0043**
3	0.0001	0.3569	0.1038	0.0001	0.1160	0.3783
4	0.0003	0.1870	0.2004	−0.0005	0.2342	0.1977
5	**−0.0004**	0.1071	**0.0057**	−0.0002	0.3714	0.2776

To investigate whether there is a significant relation between earthquakes and excess stock market returns, we examine the cumulative abnormal returns of both companies in relation to induced seismicity in the Anadarko Basin. Table 6 shows that in the case of Royal Dutch, there is one statistically significant period where the CAAR is negative, based on the nonparametric test, namely from day zero to five [0; 5] (−0.0135%). From an economic point of view, this is a very small response and not significant. In the case of ExxonMobil, there are no significant results.

Table 6. Cumulative average abnormal returns Royal Dutch Shell and Exxon Mobil—Induced seismicity in Anadarko Basin (*df* = 551).

	Royal Dutch Shell			Exxon Mobil		
Days	**CAAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**	**CAAR**	***p*-Value (*t*-Test)**	***p*-Value (G. Sign)**
[0; 1]	0.0002	0.3058	0.3050	0.0008	0.1077	0.0917
[0; 3]	0.0005	0.2689	0.4052	0.0005	0.2689	0.3782
[0; 5]	**−0.0001**	0.4435	**0.0222**	−0.0002	0.4387	0.2482

3.4. Comparison

To examine whether Royal Dutch Shell and Exxon Mobil might respond differently to induced seismicity, we engage in the Mann-Whitney-Wilcoxon test and a Two-Sample Z-test. These results are reported in Tables A4–A6 in the Appendix A. From the Z-tests, it shows that the means of excess stock returns for both companies in all three samples are equal. This suggests that investors react in approximately the same way to induced seismicity. Furthermore, the non-parametric test results from the Mann-Whitney-Wilcoxon tests lead us to the conclusion that the oil- and gas giants have an equal distribution of ranks regarding excess stock returns and induced seismicity for the overall sample and the Slochteren subsample. However, regarding induced seismicity in the Anadarko Basin, investors of Royal Dutch Shell and Exxon Mobil respond in a significant different way on day zero. The AARs of day zero for Exxon Mobil are significantly positive whilst those of Royal Dutch Shell show no abnormal returns. Hence, in this context, investors in the US tend to appreciate Exxon Mobil stock in the case of induced seismicity, in contrast to investors in Royal Dutch Shell. However, the differential is economically insignificant (below 0.001%). This finding confirms results elsewhere in the literature as to how financial investors appreciate environmental news [35].

4. Conclusions

This study is exploratory research regarding the relationship between induced seismicity and the response from financial investors to firms connected with such seismicity. The purpose of this paper was to examine whether induced seismicity associates with excess stock market returns of oil and gas majors. We hypothesized that induced seismicity would be accompanied by a negative response from financial investors. We studied financial investors' response for Royal Dutch Shell and ExxonMobil regarding induced seismicity in the Anadarko Basin, Oklahoma, US, and in the Slochteren field, Groningen, the Netherlands. The sample covered more than 700 events.

We establish that induced seismicity in general does not seem to result in an economically significant response from financial investors and confirm the null hypothesis of no significant effect (see also [35]). Only in a few particular cases, we find there is an influence on excess stock market returns. The influence can be both negative and positive. More specifically, we detect a small significant negative response for Royal Dutch Shell in relation to induced seismicity in the Netherlands. However, this response does occur with a lag of about five days. Therefore, we conclude this does not provide convincing support for the hypothesis that induced seismicity in the Netherlands renders a significant response from the stock market regarding Royal Dutch Shell stock. With ExxonMobil, investors show a statistically significant but economically small positive response on the day the induced seismicity occurs. This somewhat surprising result may be explained by the fact that induced seismicity relates to an increase in operations that may be appreciated by investors. This result is in line with the study of Roach [17] about the relationship between earthquakes and the price of oil. We establish that stock market effects for induced seismicity are much smaller than those for natural seismicity are [22].

Comparing the two fossil fuel majors, we find that investors in ExxonMobil show a statistically significant different response from those in Royal Dutch Shell on the event day.

This might be associated with a difference in the investor base of the two companies. This is because the latter company is held more with European institutional investors who are more concerned with environmental issues than their US peers are and who operate under a regulatory regime that urges them to inform about non-financial risks [21]. However, even Royal Dutch Shell investors do not appear to depreciate the value of the firm in relation to induced seismicity in a significant extent. Therefore, we conclude that the externality of business-induced seismicity goes unpriced by financial investors in fossil fuel stocks.

These novel findings complement existing insights about the relationship between corporate activity and induced seismicity in other areas such as public perception of hydraulic fracturing [2,7], siting of energy systems [3,4], social perception [9], and valuation effects on housing [18]. In particular, they reveal that financial investors in general do not appreciate induced seismicity. This contrasts with their appreciation of high-impact seismic events [22,24,25]. It also contrasts with response by the public [2,9] and other stakeholders [3,4].

A caveat with our analysis is that we are not able to link business activity directly with individual earthquakes. This is due to the characteristics of geophysics. As such, we want to articulate that it is the investor's perception of the relationship between seismicity and business conduct that informs our study.

Author Contributions: Conceptualization, M.J.K. and B.S.; methodology, B.S.; validation, M.J.K. and B.S.; formal analysis, M.J.K.; investigation, M.J.K.; resources, M.J.K. and B.S.; data curation, M.J.K.; writing—original draft preparation, M.J.K.; writing—review and editing, B.S.; supervision, B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data and stock market information for the companies and the induced seismicity is available at https://doi.org/10.34894/QWQ8SN.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Descriptive statistics of the alpha, beta and average market and average abnormal returns regarding the induced seismicity in the US and the Netherlands in the estimation window (day -100 to day -1), (*df* = 726).

	Royal Dutch Shell			Exxon Mobil		
	α	β	AAR	α	β	AAR
Mean	0.0001	0.8180	0.0000	−0.0001	0.8890	0.0000
Median	0.0000	0.8031	0.0000	−0.0001	0.8806	0.0000
Standard Deviation	−0.0024	0.2402	0.0004	0.0009	0.1952	0.0004
Minimum	−0.0238	0.0294	−0.0011	−0.0026	0.2322	−0.0013
Maximum	0.0053	1.3846	0.0011	0.0043	1.4204	0.0015
Skewness	0.9925	0.2418	−0.0873	−0.7424	0.0813	0.1910
Kurtosis	3.0129	−0.5471	−0.0127	2.3787	0.0822	1.4547
Jarque-Bera Statistic	394.33	16.150	0.9371	238.18	1.0072	259.04

Table A2. Descriptive statistics of the alpha, beta and market and average abnormal returns regarding the induced seismicity in the Netherlands in the estimation window (day -100 to day -1), (*df* = 422).

	Royal Dutch Shell			Exxon Mobil		
	α	**β**	**AAR**	**α**	**β**	**AAR**
Mean	0.0001	0.7834	0.0000	0.0000	0.9013	0.0000
Median	0.0000	0.7548	0.000	−0.0001	0.9169	0.0000
Standard Deviation	0.0012	0.2266	0.0006	0.0009	0.1954	0.0005
Minimum	−0.0025	0.0294	−0.0015	−0.0023	0.2297	−0.0001
Maximum	0.0052	1.3597	0.0015	0.0046	1.3835	0.0011
Skewness	1.0580	0.3317	−0.2440	−0.9554	−0.3355	0.2964
Kurtosis	2.8133	−0.1512	−0.0254	2.4698	0.1738	−0.0366
Jarque-Bera Statistic	218.41	8.1632	8.1632	171.87	8.466	6.2153

Table A3. Descriptive statistics of the alpha, beta and average abnormal returns regarding the induced seismicity in the US in the estimation window (day -100 to day -1), (*df* = 551).

	Royal Dutch Shell			Exxon Mobil		
	α	**β**	**AAR**	**α**	**β**	**AAR**
Mean	0.0004	0.5198	−0.0002	−0.0003	0.9186	0.0003
Median	0.0001	0.5095	−0.0002	−0.0003	0.9422	0.0003
Standard Deviation	0.0014	0.1747	0.0002	0.0009	0.1933	0.0001
Minimum	−0.0228	−0.0218	−0.0007	−0.0026	0.3343	0.0000
Maximum	0.0069	0.9536	0.0003	0.0049	1.4276	0.0006
Skewness	1.1873	0.0286	0.2217	1.0545	−0.1460	−0.2052
Kurtosis	1.9658	−0.3840	−0.3841	4.8436	0.2391	−0.2038
Jarque-Bera Statistic	218.58	3.4687	3.4687	641.91	3.2753	7.2748

Table A4. Mann-Whitney-Wilcoxon test and the Two-Sample Z-test—Comparing Royal Dutch Shell and Exxon Mobil regarding the induced seismicity in the US and the Netherlands d (*df* = 726).

Day	*p*-Value (M.W.W. Test)	*p*-Value (Two Sample Z-Test)
0	0.1101	0.1010
1	0.4934	0.4444
2	0.3981	0.4533
3	0.4466	0.3099
4	0.3481	0.2730
5	0.1103	0.0875

Table A5. Mann-Whitney-Wilcoxon test and the Two-Sample Z-test—Comparing Royal Dutch Shell and Exxon Mobil regarding the induced seismicity in the Netherlands (*df* = 422).

Day	*p*-Value (M.W.W. Test)	*p*-Value (Two Sample Z-Test)
0	0.1880	0.2173
1	0.4915	0.3779
2	0.1943	0.1467
3	0.4883	0.1777
4	0.2802	0.196
5	0.0599	0.1394

Table A6. Mann-Whitney-Wilcoxon test and the Two-Sample Z-test—Comparing Royal Dutch Shell and Exxon Mobil regarding the induced seismicity in the US (*df* = 551).

Day	*p*-Value (M.W.W. Test)	*p*-Value (Two Sample Z-Test)
0	**0.0135**	0.0863
1	0.4341	0.3806
2	0.2173	0.3396
3	0.1763	0.3290
4	0.1418	0.0721
5	0.1071	0.3704

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