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Science and the stock market: Investors' recognition of unburnable carbon

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ABSTRACT

This paper documents the stock market's reaction to a 2009 paper in the *Nature* journal of science, which concluded that only a fraction of the world's existing oil, gas, and coal reserves could be emitted if global warming by 2050 were not to exceed 2 °C above pre-industrial levels. This *Nature* article is now one of the most cited environmental science studies in recent years. Our analysis indicates that this publication prompted an average stock price drop of 1.5% to 2% for our sample of the 63 largest U.S. oil and gas firms. Later, in 2012–2013, the press "discovered" this article, writing hundreds of stories on the grim consequences of unburnable carbon for fossil fuel companies. We show only a small negative reaction to these later stories, mostly in the two weeks following their publication. This limited market response contrasts with the predictions of some analysts and commentators of a substantial decline in the shareholder value of fossil fuel companies from a carbon bubble. Our paper discusses possible reasons for this discrepancy.

1. Introduction

On April 29, 2009, 17:15 GMT, Richard Black (2009), writing for the BBC, broke the headline "About three-quarters of the world's fossil fuel reserves must be left unused if society is to avoid dangerous climate change, scientists warn." That headline referred to two papers in the April 30, 2009 issue of *Nature* – Allen et al. (2009) and Meinshausen et al. (2009) – both of which concluded that if global warming by 2050 were not to exceed 2 °C above pre-industrial levels, then strict limits on the total carbon budget through that date would be required. The latter study went one step further and predicted that to meet such goal, less than one-half of the world's proved economically recoverable oil, gas, and coal reserves could be emitted during 2007–2050. What these studies meant, especially Meinshausen et al. (2009), was that without major changes in business practices and government policy much of the world's fossil fuel would be stranded and, therefore, potentially worthless under the climate change scenarios examined. At the time, however, the scientists and the media[1] seemingly ignored a key implication, namely, that if the burning of fossil fuel were greatly limited under a 2 °C climate solution, this could trigger a sharp reduction in energy firms' valuations because their financial statement reserves make up a significant part of that value (Harris and Ohlson, 1987; Qurin et al., 2000). Following the initial BBC story, however, both *Nature* papers drew little attention from the financial media and, otherwise, stayed in relative obscurity.[2]

In the passage of time since, however, a very different situation has emerged. Thomson Reuters' *Web of Science* now ranks Meinshausen et al. (2009) as one of the most cited environmental studies in recent years, placing it in the top 0.1% of science papers published in 2009; and the results and implications are now also well known to a much

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[1] For listing of media reports coincident with the April 30, 2009 issue of *Nature*, see sites.google.com/a/primap.org /www/nature/nature_presscoverage.

[2] For example, of the 741 Google Scholar cites for Meinshausen et al. (2009) through September 30, 2013, only 64 occurred in 2009, and of these most were made by fellow scientists.

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larger audience due, in part, to reports by Leaton (2011), Spedding et al. (2013), Redmond and Wilkins (2013), and popular press articles such as McKibben (2012) and *The Economist* (2013). Leaton et al. (2013) have updated the remaining carbon budget from 2007–2050 to 2013–2050 and paint an even gloomier picture for the energy industry. For example, the updated data indicate that the world's listed fossil fuel (oil, gas, and coal) firms have the equivalent of 1541 gigatons of CO_2 in their proved and potential reserves, but their customers can burn safely only 269 (225) gigatons for temperatures to have a 50% (80%) chance of not rising by more than 2 °C above pre-industrial levels (Leaton et al., 2013, 15); and, with present trends, this remaining carbon budget will be spent well before 2050.[3] These more recent figures imply that 82% (1-(269÷1541)) of firms' proved fossil fuel reserves could eventually be unburnable.[4] In financial terms, and assuming accurate data, the potential cost is daunting. According to Spedding et al. (2013), the combination of reduced oil and gas prices (from lower demand) and unburnable fossil fuel reserves places at risk some 40% to 60% of the market capitalization of the world's top 200 energy companies. With a total year end 2012 market capitalization of about $4 trillion (Leaton et al., 2013), this could translate to a substantial wealth loss for these firms' shareholders, thereby bursting what some analysts and commentators have termed a carbon bubble from the mispricing of fossil fuel reserves. The Spedding et al. (2013) report, however, cautions that investors "have yet to price in such a risk, perhaps because it seems so long term."[5]

This paper examines when and whether the stock market might have recognized the potential loss of value to energy company shareholders due to unburnable carbon, which, in this paper, we define as the economic value of the excess of a firm's prove economically recoverable oil, gas, and coal reserves over those reserves consistent with stabilizing global temperature increases at an acceptable level, such as less than 2 °C.[6] On the one hand, we might expect investors to respond rationally to all available information in pricing their securities, including significant results from science, in our case, the aforementioned *Nature* publication. Under such rational response hypothesis, we predict a negative price reaction as early as April 29, 2009, when the BBC first published its story about Allen et al. (2009) and Meinshausen et al. (2009). On the other hand, financial experts offer various explanations of why capital markets might respond biasedly and slowly to adverse news about future returns, for example, based on media inattention (Dyck and Zingales, 2003), investor bias (Bernhardt et al., 2006; Hirshleifer, 2001; Welch, 2000), hard-to-process information (Kumar, 2009), proprietary cost (Healy and Palepu, 2001; Verrecchia, 2001), and poor communication by scientists (Revell, 2013). These and other explanations offer an alternative view, which we call the lagged response hypothesis, which predicts an additional and possibly more negative (and delayed) response to news stories following the *Nature* articles. We reason this could occur if the financial and popular media increasingly publicize the earlier scientific results as newsworthy and/or investors respond to the updated scientific evidence, which might place more relevance on the earlier results, in this case, the possibility that unburnable carbon could adversely affect the share value of energy firms.[7] In discussing the earlier *Nature* articles, the media may have also contributed to the public's understanding of the science by introducing "unburnable carbon" as an easy-to-understand metaphor for the fossil fuel carbon on company balance sheets that would threaten their market value under policies to limit global temperature increases to less than 2 °C. Both the rational response and lagged response hypotheses also encompass the null hypothesis of no response; that is, we might observe no systematic response to unburnable carbon regardless of the sequence of the news or events, possibly because of the uncertain and long-term nature of the increased investment risk or from offsetting benefits ignored or underemphasized by the news media.[8]

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[3] More recent estimates by the IPCC's Fifth Assessment Report (IPCC, 2013) suggest a world carbon budget of 1119 gigatons of CO_2 for a greater than 50% chance of temperatures rising to less than 2 °C (including reductions for non-CO_2 radiative forcings). We calculate this number for the 50% scenario as follows: IPCC (2013, 1113) indicates a total carbon budget of 1210 gigatons since 1870. Net of non-CO_2 radiative forcings over the same period, this results in a total carbon budget of 820 gigatons. But 515 gigatons of carbon were emitted in 1870–2011. This leaves 305 gigatons of carbon or 1119 (305×3.67) gigatons of CO_2 remaining to be emitted after 2011. Since only about 27% of the remaining amount would be burnable as oil, gas, or coal (Leaton, et al., 2013), this amount is much less than the proved and potential fossil fuel reserves sitting on firms' balance sheets of 1541 gigatons of CO_2. For similar data on the CO_2 budget, see IEA (2014).

[4] This 82% estimate, however, applies to oil, gas, and coal firms. An analysis of the distribution of fossil fuel reserves by McGlade and Ekins (2015, 189) suggests unburnable reserves of 33% and 49% of total reserves for oil and gas, respectively. Moreover, the overall percentage for U.S. oil and gas firms is generally lower given the proximity of their reserves to demand centers. For example, based on Exxon-Mobil's 2013 disclosures of proved developed and undeveloped oil reserves (2013 Form 10-K Part 1, Item 2), the combined percentage of unburnable reserves given the percentages in McGlade and Ekins (Table 1, p. 189) is 17% for 2 °C without Carbon capture and sequestration (CCS).

[5] Amid these stories about how unburnable carbon might affect oil and gas companies' valuations, over the same time period, public interest continued to grow around topics such as the role of anthropogenic (man-made) carbon emissions in the stabilization of radiative forcing from global temperature increases. Discussions often centered on a desirable target level of global emission concentration (e.g., CO_2 stabilization at 450 ppm) and/or international actions to meet the target such as cap-and-trade, carbon capture, use of negative emission investments, and clean technology. If covered by the media from an investor standpoint, those discussions often focused on (a) which sectors, notably energy, might be most exposed to carbon regulation such as cap-and-trade and (b) the nature of the transformation of the energy sector worldwide under a global agreement to cap carbon emissions. One early press report (March 11, 2008) used the term "unburnable" as a reserve category, although this was primarily in the context of proposals to reduce carbon use consistent with a desired level of global CO_2 concentration to limit global warming (e.g., news.bbc.co.uk/2/hi/science/nature/7287572.stm). On the other hand, the scientific literature on climate change has mostly ignored the term, until quite recently (e.g., McGlade and Ekins, 2015; also note 4). For example, a search of the term "unburnable carbon" in the many hundreds of published climate change research papers between 2007 and 2013 supported by the Tyndall Centre for Climate Change Research produces the result "no items found" (www.tyndall.ac.uk/biblio). In addition, while Spedding et al. (2013) raise unburnable carbon as a significant energy company valuation issue, Spedding et al. (2008), which pre-dates the 2009 *Nature* articles, makes no reference to the term or similar phrase.

[6] While few scientific articles use the term "unburnable" or "stranded" carbon (note 5), Meinshausen et al. (2009, p. 1158) clearly imply such a concept by referring to (a) budgeted GHG emissions consistent with policies to stabilize global temperature increases to an acceptable level, such as less than 2 °C, and (b) the GHG emissions in "proven economically recoverable oil, gas and coal reserves." A precise definition of "unburnable carbon" requires further specification, however; in particular, a statement of (i) the time horizon of the GHG emission budget, at least initially, (ii) whether the concept shall be viewed as an emission quantity or a measure of economic value, (iii) an emission policy objective, (iv) the emissions that would be produced, such as from proved economically recoverable reserves or from proved and provable reserves, within the stated time horizon in the absence of a policy objective, and (v) the level of disaggregation, such as at the company, industry, or economy-wide level. For the present analysis, we assume that rational investors would have anchored their response on the *Nature* article, as it was in the public domain at the time. That article considered a budget horizon of 2050 relative to proved economically recoverable oil, gas, and coal reserves and a 2 °C policy objective. While not discussed in the 2009 *Nature* articles, rational investors, also, would have considered the potential loss of shareholder value of unburnable carbon (rather than the physical residual carbon) at the company level by discounting the future net value of residual carbon to the present, conditional on their expectations of future firm performance, governmental policies, efforts to mitigate, and technological change. We recognize, however, that investors' response to the subsequent news stories could have been affected by firm-related analyses (e.g., Leaton, 2011), new results such as those based on an extended budget horizon to 2100 (IPCC, 2001; McCollum et al., 2014), an evolving definition of fossil fuel reserves, and possible future short- and long-term policy changes within the horizon that could change the emission budget (and mix of fossil fuels) to meet the temperature change policy objective (Bauer et al., 2013, 2015).

[7] As a possible example of the lagged response hypothesis, Huberman and Regev (2001) document a small positive response to a *Nature* article of November 27, 1997 about a scientific advance in cancer therapy, but it was not until a May 3, 2008 story in the *New York Times* that the breakthrough garnered widespread attention, prompting a much more significant reaction in the next few days.

[8] By potentially affecting the future demand for fossil fuel, unburnable carbon news could increase oil price uncertainty, thereby inducing firms to postpone current investment, which could negatively affect firm value. Effects on firm value from oil price uncertainty, however, can depend on whether future oil prices and firms' output increase or decrease in response to governments' and others' actions to constrain carbon emissions in the fossil fuel sector (Elder and Serletis, 2010; Rahman and Serletis, 2011).

Investors' recognition of unburnable carbon is important for two key reasons. First, it is important to shed light on how and when stock prices might reflect significant results from science, since a delay or miscommunication could create profitable arbitrage opportunities for the more informed. Second, it is essential to understand the media's role, for while unburnable carbon may be a compelling story with worrisome implications for many, rational investors would "see through" the metaphor and analyze and consider all potential future scenarios for the firms they analyze, including hard-to-value strategic options. Some would have offsetting effects on firm value; for instance, those resulting from governments' energy policies to lower the costs of carbon capture and sequestration and/or to require firms to decarbonize in other ways. Changes in firms' plans and strategies designed to mitigate the risks associated with unburnable carbon, such as by investing in more profitable alternative energy sources with lower emissions and/or adopting more informative risk disclosures, would also have offsetting effects. Collectively, our findings regarding a possible stock price reaction to unburnable carbon news offer an evidence-based counterbalance to those media scenarios that perhaps infuse more emotion and politics into climate change than is appropriate or reasonable.[9]

To test our hypotheses, we examine oil and gas firms in the *Datastream Energy Index*, which comprises 72 U.S. firms in Global Industry Classification Standard code 10120 (comprising the sub-codes Integrated Oil and Gas, and Oil and Gas Exploration and Production). The constraint that we require daily stock price data from CRSP for the study period then reduces our final sample to 63 firms. Our data show that these firms include the largest oil and gas firms in the United States, and most disclose significant oil and gas reserves in their financial statements. Of all U.S. oil and gas firms, these should be the most exposed to redundant reserves and, hence, the risk of unburnable carbon. We use this sample to conduct an event study of the relationship between energy firms' daily excess stock returns and news stories about unburnable carbon.[10]

We start with the BBC's April 29, 2009 story about the *Nature* articles (also reported on the same day as a Dow Jones News Service environmental capital blog) and then use Factiva to identify all news items through May 31, 2013 that might reasonably relate to unburnable carbon based on key words and phrases (listed in Section 3).[11] We identify other events and factors that help us calibrate investors' response to news about unburnable carbon, such as earnings announcements, SEC filings, and news about a proposed carbon tax. As additional factors, we control for crude oil price changes and use the number of energy industry news stories unrelated to unburnable carbon on the same day as an overall measure of daily information intensity. As discussed in Section 3, our event study approach faces some unique challenges, in particular, the feature that we study news stories (e.g., the *Nature* publication) common to all energy firms. So when we control for changes in crude oil prices and energy news in general we may be removing some of the effects we seek to detect. With too few controls, we may incorrectly attribute a price response to news about unburnable carbon when none in fact occurred (type 1 error); with too many controls, we may incorrectly conclude a lack of response to unburnable carbon when one in fact may have occurred but is obscured by the controls (type 2 error).

We report the following key results. First, we find a mean excess stock price drop of 1.5% to 2% in the three-days around the *Nature* publication date. Because we control for oil price changes and observe a low intensity of other crude oil and natural gas stories in the same three-day window, this response reflects a low type 2 error, namely, that an investor response unrelated to the *Nature* article might explain the result. This response also exceeds the mean price drop around a well-publicized news story about a possible carbon tax on fossil fuel companies (carbon tax news–the variable *CarbonTaxDum*) (−0.52%). Second, the subsequent media stories about unburnable carbon in 2012–2013 do not associate with a statistically significant negative excess price response over days -1 to 1 around the news dates, declining only minimally on average (−0.02%). Third, firms with proved reserves on their balance sheets dropped more than firms without a disclosure (−0.09%), suggesting that investors conditioned their response on a factor unique to unburnable carbon. Fig. 1 illustrates these results by showing the mean excess stock price change in response to the different unburnable carbon news events. These excess stock price changes are the estimated coefficients from a regression of the daily stock return over event days −1 to 1 on the different news events with controls for the Fama–French risk factors and other variables. Eq. (2) in Panel B of the appendix states the "event-day" regression model, and regression 3 of Table 2 shows the results in Fig. 1 in more detail.

We also examine investors' recognition of unburnable carbon using a "calendar-day" regression model, where we benchmark the stock price response to the different news events using all calendar day stock returns in the study period. We state this model as Eq. (3) in Panel B of the appendix. Because we use all calendar days in the model, we can not only test for an initial response to the 2012–2013 unburnable carbon news stories but, also, whether investors might have responded over an extended window, which we specify as trading days −1 to 10 (and −1 to 5) days relative to news day 0. Fig. 2 shows the coefficients from a regression of daily stock return over all calendar days in the study period with unit (dummy) variables for the news event days and controls for the Fama–French risk factors and other variables. Using the data in regression 4 of Table 3, investors responded significantly and negatively to the *Nature* article (−0.84%) and news of a possible carbon tax (−0.56%). Investors also responded significantly and negatively to the 2012–2013 unburnable news stories (*OtherNewsDays*) over days −1 to 10 (−0.13%) but not days −1 to 1 (Fig. 1); thus, indicating a significant delayed response rather than a rapid response to those stories. For firms potentially affected by the 2012–2013 unburnable news stories that also disclosed proved reserves, stock prices declined even further over days −1 to 10 (−0.16%). But we would expect this additional negative response because the proved reserves store much of the unburnable carbon.

The statistically significant three-day price reactions to unburnable carbon news are small economically, however. For example, Fig. 3 shows that, based on the coefficients from the regression results in Fig. 1, the price reactions aggregate to a shareholder loss of $23.3 billion or 2.14% of market capitalization ($1.089 trillion as of fiscal year end 2013). This small but statistically detectable stock market response to unburnable carbon stands in contrast with the prediction of some analysts and commentators of a substantial decline in the shareholder value of fossil fuel firms from stranded carbon (e.g., Spedding et al., 2013). Finally, Fig. 4 shows that of the aggregate loss of $23.3 billion, $16.5 billion results from the price drop around the *Nature* article

[9] For example, McKibben (2012) writes: "We know how much we can burn, and we know who's planning to burn more. Climate change operates on a geological scale and time frame, but it's not an impersonal force of nature; the more carefully you do the math, the more thoroughly you realize that this is, at bottom, a moral issue; we have met the enemy and they is [sic.] Shell."

[10] We compute excess returns based on the Fama and French (1993) model, which adjusts daily raw stock returns for risk premia from the market as a whole (*Mkt-RF*), company size (*SML*), and expected earnings growth (*HML*).

[11] We choose the cutoff date of May 31, 2013, as it follows the end of the first quarter of 2013 by two months, by which time most of the popular press stories tied to the original *Nature* articles had been written. Regarding the start date for our analysis, a natural question is whether investors might have recognized unburnable carbon as a firm valuation issue earlier than the *Nature* articles. While we are not aware of the mention of "unburnable carbon" earlier in science and news publications (see, also, notes 5, 6. and 15), the IPCC's Third Assessment Report (IPCC, 2001) does refer to excess fossil fuel reserves. However, Fig. SPM.2 of the summary for policy makers on mitigation (IPCC, SPM-Mitigation, 2001) also shows that "the carbon in proven conventional oil and gas reserves, or in conventional oil resources, is much less than the cumulative carbon emissions associated with stabilization of carbon dioxide at levels of 450 ppm." (IPCC, SPM-Mitigation, 2001, 4). Hence, from a financial standpoint, if oil and gas investors had read IPCC (2001), even taking into account the political authority of that report, they would likely have showed little concern for unburnable carbon in the oil and gas industry. Rather, if at all, their focus would have been coal.

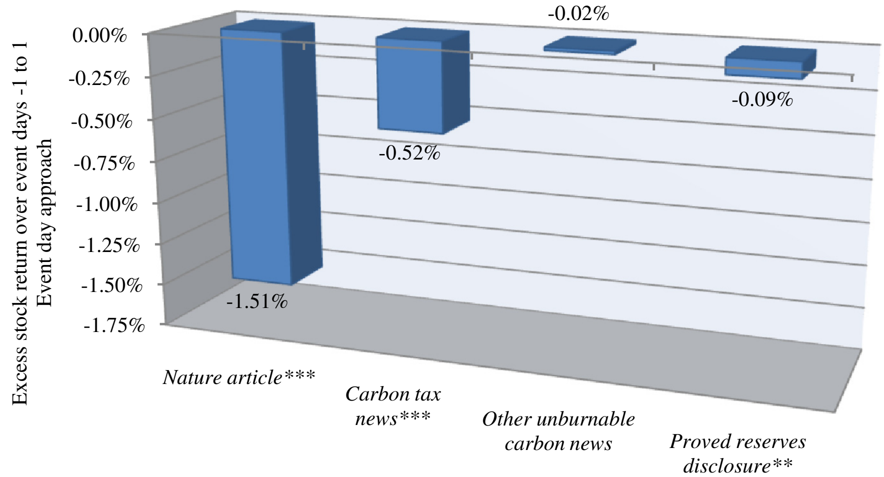

Fig. 1. Coefficients from a regression of daily stock return over event days −1 to 1 on the unburnable carbon news events (*Nature* article, carbon tax news, other unburnable carbon news) with controls for the Fama–French risk factors, proved reserves disclosure, and other variables. All variables are defined in Panel A of the appendix. Eq. (2) in Panel B of the appendix specifies the regression model. *** = significant at <.001, ** = significant at <.05, and * = significant at <.1, using a two-tailed t test versus the null of zero.

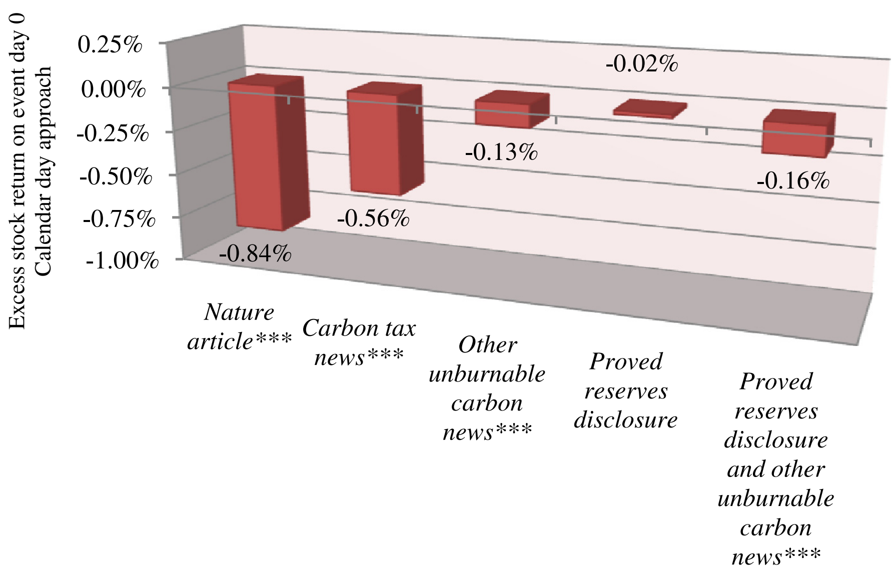

Fig. 2. Coefficients from a regression of daily stock return over all calendar days in the study period on the unburnable carbon news events (*Nature* article, carbon tax news, other unburnable carbon news) with controls for the Fama–French risk factors, proved reserve disclosure, and other variables. ***–significant at <.0001 using a two-tailed t test versus the null of zero.

(71%), with the remaining price drop resulting from news about a proposed carbon tax ($5.7 billion) and news stories in 2012–2013 about unburnable carbon ($1.2 billion). We find it interesting that, while one of the most cited environmental science studies in recent years seems to have had a limited but clear sway with investors in U.S. oil and gas stocks, the unburnable carbon stories that dominated the news media in 2012–2013 had an almost imperceptible impact – about one-tenth of one percent ($1179 ÷ $1,088,615) of firm value according to our regression-based calculations. Later sections detail the regressions and discuss explanations of this result.[12]

[12] An alternative analysis would consider the overall effect on oil and gas firms' stock prices of unburnable carbon under assumed climate change scenarios; and several studies take that approach (e.g., Ansar et al., 2013). We do not take that approach in this paper, as our focus is on the, arguably, lethargic propagation of the unburnable carbon findings, initially in the 2009 *Nature* article and then later in media reports in 2012–2013. Section 4 comments on the potential for investors to recognize the effects of unburnable carbon on firm value earlier than 2009.

Section 2 identifies the prior literature and develops the main testable predictions. Section 3 describes the sample and data. Section 4 summarize the results and sensitivity tests, respectively. Section 5 concludes and discusses limitations. An appendix specifies the regression models and variables and states the data sources.

2. Prior literature and research hypotheses

Despite a plethora of stock market studies on a wide range of news events and announcements (see Beyer et al. (2010) for a review), surprisingly absent are findings on breakthrough publications in science. Some scientific journals publish discoveries with important implications for capital allocation and investors' returns. Yet the market's response could be quite limited if science publishes hard-to-process information, perhaps because the researchers have few incentives explain the implications of their results or wish to keep the results confidential. In addition, results-oriented investors may have little interest in discoveries that have uncertain and distant payoffs, as the present value of the

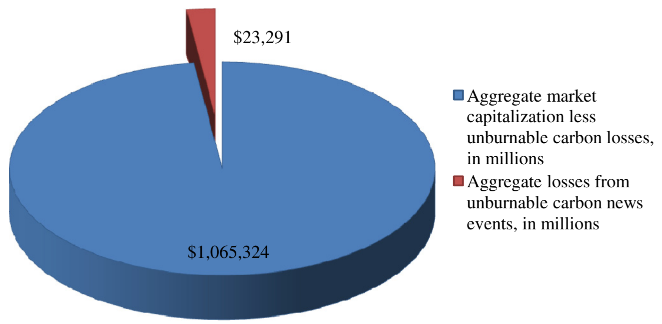

Fig. 3. Aggregate dollar losses of $23,291 million from unburnable carbon new events based on the coefficients in Fig. 1 for the "event-day" regression model (Eq. (2) in Panel B of the appendix) relative to the aggregate market capitalization of our oil and gas firm sample of $1,088,615 ($23,291 plus $1,065,324) million.

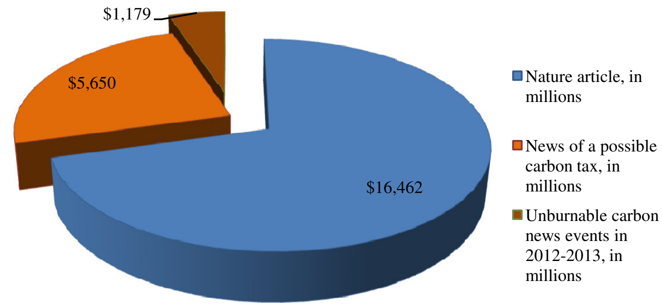

Fig. 4. Aggregate dollar losses of $23,291 million from unburnable carbon news events split into losses from the *Nature* article ($16,642 million), news of a possible carbon tax ($5650 million), and all unburnable news stories in 2012–2013 ($1179 million).

cash flows from such (optional) future investments would be small relative to the present value of current and projected operations. Huberman and Regev (2001) document a $3.375 increase in Entremed's stock price around November 28, 1997, when *Nature* published an article on the discovery of a cancer-curing drug by that firm. It was not until May 4, 1998 that the stock price jumped dramatically, over a few days, by $39.75 (from $12.06 to $51.81) following a *New York Times* story. Huberman and Regev (2001) conclude that this later response was an overreaction, as the *New York Times* and other media used the same information as in the original *Nature* article.[13] That study, therefore, documents an initial response, which the authors describe as rational, followed by an overreaction from increased media attention.[14] On the other hand, the stock market might overreact to an initial scientific result, perhaps with the help of the media, and correct itself later based on a more rational and complete assessment of the evidence. Hill et al. (1991) document that a Utah university news conference on March 23, 1989 announcing that scientists had produced sustainable energy from cold fusion increased palladium prices by 25% over announcement days −2 to 14 following a worldwide media frenzy. Those prices, however, dropped to pre-announcement levels in the next few months as the impossibility of limitless energy from low temperature nuclear fusion became evident through additional and more credible channels.

Given these studies, what might we expect about investors' response to the *Nature* articles suggesting unburnable carbon? Since Factiva shows that the initial articles did trigger some mention of unburnable carbon in the popular press, this might suggest the rational response hypothesis; namely, that we should observe a limited but negative investor reaction, but not a biased one or an overreaction potentially inspired by media attention. On the other hand, because of heightened interest in unburnable carbon by the financial and popular media beginning in 2012, much of which predicted dire consequences for the fossil fuel industry, we might expect a stronger media-driven negative response to these later stories, even though they might have added little new information to the basic results from science. This would be consistent with the delayed response hypothesis and the results reported in Huberman and Regev (2001) and Tetlock (2007). However, the delayed response hypothesis assumes the myopic behavior of investors, as they focus on the news stories only (which tend to be highly correlated) rather than the broader array of all information, including information from firms and governments regarding their actions and policies undertaken or to be undertaken, in this case, to mitigate the impact of unburnable carbon. For example, rational investors might consider not only governments' possible policies to require firms to internalize carbon cost, redistribute carbon taxes, and/or underwrite carbon capture and sequestration (CCS), but, also, firms' plans and strategies to mitigate the risks associated with unburnable carbon, such as by investing in more profitable alternative energy sources with lower emissions or by expanding the information set, for instance, through more informative risk disclosures in published financial reports. To the extent that these plans, strategies, and possible government actions have offsetting effects on shareholder value, we would expect a less negative response under the rational or delayed response hypotheses; although media bias (Groseclose and Milyo, 2005) suggests that we would not expect the press to discuss the full array of offsetting factors, so a delayed and biased response could still occur. Finally, we entertain a third possibility of no reaction to either the initial publication or the later news stories, which essentially is the null hypothesis for the delayed and rational response hypotheses. It could be entirely rational, for example, for investors to register no reaction to the initial and later news about the effects of unburnable carbon if the consequences for firms were so uncertain and remote and/or that they expected full mitigation from government policies or through their own actions.

3. Sample and data

We start with 72 oil and gas firms comprising the *Datastream Energy Index* and then select firms registered with the SEC and with stock price and financial data available from CRSP and Datastream and Compustat, respectively (63 firms). Next, we access Factiva to identify 246 print media stories on 142 days relating to unburnable carbon by using the following search terms: unburnable and bubble, two degrees celsius (2 °C), 560 or 450 ppm (parts per million), 565 gigatons, 2795 gigatons, Meinshausen, Carbon Tracker, and HSBC and carbon bubble. We then eliminate stories on weekends since we cannot ascribe a daily stock price reaction to those days. This produces a final sample of 88 unburnable carbon news stories by 59 different print media sources. Apart from the initial *Nature* publication in April 2009, all but one of the remaining stories occurs between March 23, 2012 and March 5, 2013 (our cutoff date). Because much else could be disclosed each of those days, we control for other information in our formal tests of investor response (Section 4).

Fig. 5 compares the frequencies of unburnable carbon news with all news stories over days −1 to 1 relating to crude oil and natural gas markets, also extracted from Factiva. This figure shows that media interest in unburnable carbon began around March 2012 and peaked in January–February 2013. On the other hand, Fig. 5 shows a reasonably stable pattern for crude oil and natural gas news stories over the study period, other than a spike in April 2011 relating mostly to worldwide attention to an unpopular proposal by the Australian government for a corporate carbon tax (116 stories on April 11 and 840 for the month). While not an unburnable carbon story, we include this newsworthy carbon tax news event in the regression analysis to help benchmark the impact of the more directed unburnable carbon stories – initially in *Nature* and then later in 2012–2013. Fig. 5 also indicates a very

[13] Entremed's stock price eventually dropped to $24.875 on November 12, 1998, when it became known that other laboratories could not replicate the original *Nature* result.

[14] See, Dyck and Zingales (2003), Tetlock (2007), Barber and Odean (2008) and Fang and Peress (2009) for studies that document evidence of media bias in pricing stocks.

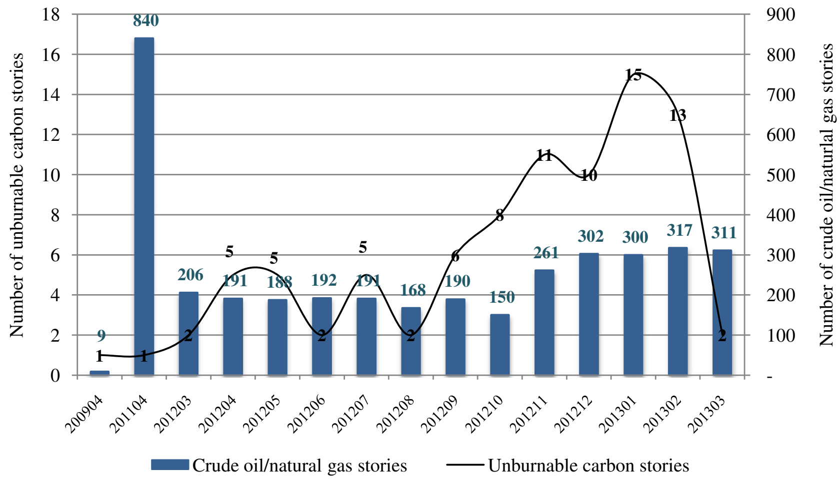

Fig. 5. The black line represents the number of unburnable carbon stories including the *Nature* publication (y-axis on left), and the blue bars represent the number of crude oil/natural gas stories by month (y-axis on right). Source: Factiva. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

small number of crude oil and natural gas stories around the date of the *Nature* publication, which means that this event should have low potential for contamination by other oil and gas stories on the same day (low type 2 error).[15]

Table 1 provides additional summary statistics for the sample based on quarterly observations over fiscal years 2008–2012. As expected, our sample mostly consists of large (mean total assets (*TA*) = $18.615 billion and mean market capitalization (*MKTVL*) = $17.558 billion), profitable (mean earnings per share as reported (*ESPAR*) = $1.00 and mean earnings per share after extraordinary items (*ESPBA*) = $0.14), and productive firms (mean sales to total assets (*REVTA*) = 0.18). These firms also invest substantially in new projects (mean capital expenditures to total assets (*CAPTA*) = 0.16). However, investors view these firms as riskier than most because of higher market risk (mean beta (*RBETA*) = 1.44) and financial leverage (mean debt to equity ratio (*LEVRG*) = 0.82). Additionally, we observe that the sample appears well governed (mean governance score (*CGVSC*) = 73.20%) but ranks low on environmental performance (mean environmental score (*ENVSC*) = 32.57%). We also split the sample into firms with and without proved reserve disclosure, which is also a proxy for high and low exploration costs (since exploration would be immaterial for firms without reserve disclosure). This analysis (untabulated) show that our sample combines larger oil and gas exploration firms (*TA*) with higher capital expenditures (*CAPTA*) (75% of the sample) and smaller oil and gas service firms with lower capital expenditures (25% of the sample). As such, our combined sample reflects considerable heterogeneity in terms of firm size and capital investment projects. Both groups, however, are similarly well covered by financial analysts (*ANALYST*), trade frequently (*LGMKT*), and have similar governance (*CGVSC*), economic (*ECNSC*), and environmental pillar (*ENVSC*) scores. Clearly, we study a non-random sample, in this case, a heterogeneous though mostly large set of U.S. oil and gas firms with higher than average market risk. However, as we indicated at the outset, these firms should disclose (and most did disclose) significant uptapped oil and gas reserves in their financial statements. This means a higher likelihood that stock prices would be affected by investors' perceptions of the effects of unburnable carbon and not other factors (reduces type 2 error).

[15] We also used directEDGAR to conduct a search of the SEC filings of our 63-firm sample based on the same search terms used to search Factiva for news stories. Interestingly, this search indicated that no companies had such disclosures. As such, we are reasonably certain that despite a possible risk of unburnable carbon for oil and gas firm asset values on the balance sheet or in supplemental disclosures, these companies assumedly deemed that the implications of unburnable carbon did not rise to the level of a material disclosure.

4. Results

4.1. Main results

As a preliminary analysis, we first conduct separate cross-sectional regressions of R_j on *RF*, *Mkt-RF*, *SMB*, *HML* (Fama and French, 1993), and percentage change in the spot price for crude oil (Chen et al., 1986) over event days −1 to 1 for each of the three news events: April 30, 2009 (*Nature* publication date), April 11, 2011 (first potential post-*Nature* mention of unburnable carbon but dominated by carbon tax news), and all unburnable carbon news stories in 2012–2013 combined. Model 1 in Panel B of the appendix specifies the regressions. Under the rational response hypothesis, we expect a negative stock price reaction coincident with the news event. Untabulated results show mostly negative mean excess returns (the alpha coefficients in the regressions) on days −1 to 1 for all three events (results available on request). Also consistent with a rational response, the day −1 to 1 mean excess return for the 2012–2013 stories is more negative for firms with proved reserve disclosures. But this is what we would expect given that the response to unburnable carbon should vary positively with disclosed reserves. In sum, preliminarily, the data suggest a possible negative market reaction related to unburnable carbon occurring on event days −1 to 1. However, in the case of the *Nature* publication, the April 11, 2011 carbon tax event, and the later stories, much other information could be affecting the daily excess returns. Recall that these are one-off news events for all firms, and our research design does not randomize the effects of these news items. We correct for this aspect of our research design by introducing additional controls into the excess returns calculation, which we do in two ways.

The first way conducts a cross-sectional regression in event time (time *t* is relative to an event date), where we focus on two narrow windows, namely, day 0 and days −1 to 1, and control for energy company news on those same days, as such factors might also drive investors' returns. Specifically, in addition to the Fama–French risk factors as per model 1, for each sample company, we select four proxies for the intensity of other news available to investors based on the number of Dow Jones newswire stories from Factiva on (a) corporate news generally, (b) crude oil and natural gas markets, (c) earnings, and (d) analysts' comments and recommendations. While this is not a complete set of other information, these data arguably cover several significant drivers of stock price, especially earnings and analysts' news. Stated formally as model 2 in Panel B of the appendix, this model also controls for daily percentage change in oil prices, another driver of energy company stock returns.

Table 2 presents the results of the event-day regressions, summarized as follows. Each of the Fama–French risk factors (*RF*, *Mkt-RF*, *SMB*, *HML*) and *PercentageChangeOilPrice* significantly explain daily stock

Table 1
Sample descriptive statistics.

Variable	Unit	Mean	Median	Percentile 25	Percentile 75	Standard deviation	No. obs. (min)
LEVRG	Fraction	0.82	0.53	0.29	0.86	4.08	224
REVTA	Fraction	0.18	0.08	0.05	0.13	0.33	224
CAPTA	Fraction	0.16	0.12	0.07	0.18	0.22	224
EPSBA	Dollars	0.14	0.27	−0.12	0.91	2.00	224
EPSAR	Dollars	1.00	0.85	−0.36	3.36	4.84	224
TA	Dollars, millions	18,615	3505	1443	9777	47,073	224
LOGTA	Natural log of *TA*	8.28	8.16	7.27	9.19	1.74	224
LGMKT	Natural log of market value	8.04	7.87	6.82	9.21	1.75	224
RBETA	Number	1.44	1.32	1.01	1.87	0.62	224
SHREQ	Dollars, millions	9273	1347	531	4572	24,448	224
MKTVL	Dollars, millions	17,558	2951	986	10,409	53,644	224
CGVSC	Percent (100 = 100%)	73.20	72.52	62.93	84.25	14.51	224
ECNSC	Percent (100 = 100%)	50.91	48.60	27.81	71.68	25.71	224
ENVSC	Percent (100 = 100%)	32.57	16.90	12.31	45.66	27.99	224

Note: Panel A of the appendix defines and states the data source of the variables.

returns. For example, regression 1 shows an average *Mkt-RF* coefficient of 1.3086, which is approximately the same as mean *RBETA* in Table 2 (of 1.44); and regressions 1–4 show sensitivities of stock return to oil price changes (oil price "beta") of about 18.6% to 24%, which are also highly significant and positive (Kolodziej et al., 2014). In addition, the regression coefficients on the news intensity variables mostly show that energy company stock returns relate in a very minor way to news stories in each of the four Factiva news categories.

We now comment on the test variables. First, we observe significantly negative coefficients for the *Nature* publication (*NatureArticleDum*), which range from −0.0152 (regression 1) to −0.0202 (regression 4) with p-values of less than 0.0001. As this is a dummy variable, the coefficient represents the incremental percentage change in energy company stock price (from −1.52% to −2.02%) after controlling for all other factors, including coincident news. Second, the news stories on April 11, 2011 – which are mostly about the possibility of a corporate carbon tax – show significantly negative coefficients for (*CarbonTaxDum*), which range from −0.0050 (regression 2) to −0.0097 (regression 4) with p-values of less than 0.0001 Thus, our regression analysis confirms that an event which we would expect to negatively affect energy company stock prices does that. Third, focusing on the three-day window, we find negative coefficients for firms with proved reserve disclosures (*ProvedReserveDum*) (regressions 3 and 4); and when we interact the April 11, 2011 news stories with a dummy variable, which equals 1 for firms with reserve disclosure and 0 otherwise (*CarbonTaxDum***ProvedReserveDum*), the coefficient for this interaction effect is also significantly negative (regression 4). This is consistent with the notion that the negative effects of unburnable carbon and a

Table 2
Stock price response to unburnable news stories: Event day regressions.

Response window	Day 0	Day 0	Days −1 to 1	Sum of days −1 to 1
Regression no.	(1)	(2)	(3)	(4)
Intercept	−0.0008	0.0002	−0.0002	0.0138
Prob > |t|	0.1019 ns	0.8563 ns	0.6201 ns	<.0001 ***
RF	112.4071	265.9941	216.9264	1298.7089
Prob > |t|	0.27 ns	0.0178 **	0.0037 ***	<.0001 ***
Mkt-RF	1.3086	1.3130	1.4511	1.1182
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	<.0001 ***
SMB	0.2642	0.2021	0.1014	−0.1463
Prob > |t|	0.0033 ***	0.0267 **	0.1102 ns	0.4112 ns
HML	0.7811	0.7344	0.5265	0.3049
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	0.0891 *
PercentageChangeOilPrice	0.2203	0.2210	0.2400	0.1864
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	<.0001 ***
CarbonTaxDum	−0.0057	−0.0050	−0.0052	−0.0097
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	<.0001 ***
NatureArticleDum	−0.0152	−0.0154	−0.0151	−0.0202
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	0.0011 ***
ProvedReserveDum	0.0016	0.0005	−0.0009	−0.0046
Prob > |t|	0.0162 **	0.4545 ns	0.0489 **	0.0009 ***
CarbonTaxDum * *ProvedReserveDum*	−0.0044	−0.0040		−0.0078
Prob > |t|	0.0062 ***	0.014 **		0.0131 **
Corporate/Industrial News		<0.0001		<0.0001
Prob > |t|		0.0008 ***		0.7727 ns
Crude Oil/Natural Gas Product Markets	<0.0001		<0.0001	
Prob > |t|		<.0001 ***		<.0001 ***
EPSAR		<0.0001		<0.0001
Prob > |t|		0.0809 *		0.1964 ns
ANALYST	<0.0001		<0.0001	
Prob > |t|		0.0205 **		0.9435 ns
Adjusted R square	27.68%	28.12%	30.33%	8.16%
No. observations	5355	5355	15,687	5292

Notes: Regression nos. 1–4 summarize the event day regressions for model 2 of daily stock return or the sum of daily stock return over days −1 to 1 on unburnable carbon news stories, with controls for the Fama–French risk factors, oil price changes, and four information intensity measures. Panels A and B of the appendix define the variables and specifies the model, respectively. *** = significant at <.001, ** = significant at <.05, * = significant at <.1, and ns = not significant using a two-tailed *t* test versus a null of zero.

possible carbon tax increase the effects further for firms with proved reserve disclosure versus those without. Fourth, we show mostly insignificant intercept coefficients. This is a residual effect over all unburnable carbon event days not explained by the regressor variables. However, to the extent that we capture the effects of unburnable carbon and other price sensitive news with our regressor variables, we would not expect this to be significant. Finally, we note the number of observations for regressions 1, 2, and 4 derives from the sample of 63 firms times 85 event dates. The numbers are slightly smaller for regression 4 due to missing daily return observations for some firms.

Table 3 presents the results under the calendar-time approach (time t is a calendar day), which is our second way to analyze the unburnable carbon events.[16] Here we widen the window to include all trading days from December 16, 2008 (90 trading days prior to the Nature publication) to March 5, 2013 (end of the study period) and include dummy variables to indicate the presence of an event on calendar day t potentially related to unburnable carbon, which can be common for all sample firms or unique at the firm level and/or for subsets of the sample. This approach also includes the Fama–French risk factors (*RF*, *Mkt-RF*, *SMB*, *HML*) and *PercentageChangeOilPrice* as common factors that may affect firms differentially on each trading day. In addition, this approach allows us to include several other test or control variables such as earnings announcements (different days for each company), longer window responses to unburnable carbon news (days −1 to 5 and days −1 to 10), and company characteristics that differ over time and across firms such as size, environmental performance, which otherwise might influence the market's response to unburnable carbon news. This approach has the further advantage that the statistical tests of whether an unburnable carbon event has a significant impact on stock prices use the entire time series to infer the regression coefficients rather than only those days on which an event occurred.

Table 3 offers several observations. First, the Fama–French coefficients are broadly similar to those in Table 2. For example, the coefficients on *Mkt-RF* approximate 1.25 (versus 1.12 to 1.45 in Table 2); and the oil price betas for *PercentageChangeOilPrice* approximate 0.25 (versus 0.19 to 0.24 in Table 3). Second, several of the control variables are significant in the expected direction. The coefficient for *LOGTA* is significantly negative (larger firms reflect lower returns); the coefficient for the intensity of earnings news (*QE-1to1*) is significantly positive (higher intensity of earnings reports associates with positive news); and the coefficient for *ENVSC* is also significantly positive (better environmental performance associates with positive stock returns). Third, similar to Table 2, the April 11, 2011 event (*CarbonTaxDum*) is significantly negative but the interaction with *ProvedReserveDum* is not. Fourth, we observe significantly negative coefficients for *NatureArticleDum*, which exceed negatively the coefficients for *CarbonTaxDum*. These coefficients are less than those in Table 2, however, because of the additional controls in the model. We also find negative coefficients for *OtherNewsDays-1to5* and *ProvedReserveDum*, but these are not significant. However, when we extend the news event period to −1 to 10 days, the coefficients for both *OtherNewsDays-1to10* and *OtherNewsDays-1to10*ProvedReserveDum* are significantly negative. For example, regressions 2, 3, and 4 show that the combined effect on stock price of *OtherNewsDays-1to10* and *OtherNewsDays-1to10*ProvedReserveDum* is −0.29%, which while statistically significant is economically quite small. Hence, rather than an immediate response to the 2012–2013 unburnable carbon news stories, these results suggest a small, delayed response to those stories occurring mainly over 10 days following their release. This response is also predictably more negative for firms with disclosed reserves. Fig. 2, discussed earlier, shows the same result, since it is based on the same regressions.

In sum, as with the previous table, Table 3 shows a significant negative reaction to the *Nature* story but no similar initial response to the later (2012–2013) unburnable carbon news stories. However, we do find evidence of a statistically significant delayed reaction to the 2012–2013 stories in the next two weeks following their publication (*OtherNewsDays-1to10*), although that delayed response is economically quite small. In other words, while the evidence supports the delayed response hypothesis, we also find relatively small negative excess returns over days -1 to 10 that differ predictably on the basis of disclosure of proved reserves (*OtherNewsDays-1to10*ProvedReservesDum*).

While our finding of a more negative response for firms with proved reserve disclosure comports with investors responding to information about unburnable carbon (defined as the economic value of unburnable carbon on firms' balance sheets), reserve disclosure firms are also larger, in part, because they engage in significant oil and gas exploration. Larger firms, on average, though, have higher public information availability (Yohn, 1998), which means that investors anticipate more information prior to news announcements. So our finding of an incremental negative effect for proved reserve disclosure coincident with unburnable carbon news should make our findings conservative.[17]

Table 3
Stock price response to unburnable news stories: Calendar day regressions.

Response window	All days	All days	All days	All days
Regression no.	(1)	(2)	(3)	(4)
Intercept	0.0040	0.0010	0.0010	0.0041
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	<.0001 ***
RF	−49.8622	−51.8207	−51.8360	−52.1903
Prob > |t|	0.0127 **	0.0093 ***	0.0093 ***	0.0088 ***
Mkt-RF	1.2515	1.2504	1.2504	1.2509
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	<.0001 ***
SMB	0.2994	0.2968	0.2968	0.2983
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	<.0001 ***
HML	0.2015	0.2065	0.2065	0.2041
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	<.0001 ***
PercentageChangeOilPrice	0.2482	0.2475	0.2475	0.2476
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	<.0001 ***
CarbonTaxDum	−0.0064	−0.0056	−0.0056	−0.0056
Prob > |t|	<.0001 ***	<.0001 ***	<.0001 ***	<.0001 ***
NatureArticleDum	−0.0082	−0.0082	−0.0082	−0.0084
Prob > |t|	0.0218 **	0.0231 **	0.0231 **	0.0193 **
ProvedReserveDum	−0.0002	−0.0003	−0.0003	−0.0002
Prob > |t|	0.5274 ns	0.2996 ns	0.3000 ns	0.4741 ns
*CarbonTaxDum * ProvedReserveDum*	−0.0014		−0.0002	
Prob > |t|	0.4147 ns		0.9322 ns	
OtherNewsDays-1to5	−0.0003			
Prob > |t|	0.3401 ns			
OtherNewsDays-1to10		−0.0014	−0.0014	−0.0013
Prob > |t|		<.0001 ***	<.0001 ***	<.0001 ***
*ProvedReserveDum * OtherNewsDays-1to10*		−0.0015	−0.0015	−0.0016
Prob > |t|		0.0096 ***	0.0126 **	0.0066 ***
QE-1to1	0.0014			0.0013
Prob > |t|	0.0126 **			0.0133 **
LOGTA	−0.0004			−0.0004
Prob > |t|	<.0001 ***			<.0001 ***
ENVSC	<0.0001			<0.0001
Prob > |t|	0.0509 *			0.0707 *
Adjusted R square	36.87%	36.86%	36.86%	36.90%
No. observations	65,331	65,331	65,331	65,331

Notes: Regression nos. 1–4 summarize the calendar day regressions for model 3 of daily stock return or the sum of stock return over days −1 to 1 on unburnable carbon news stories, with controls for the Fama–French risk factors, oil price changes, earnings announcements, total assets, and environmental performance. Panels A and B of the appendix define the variables and specifies the model, respectively. *** = significant at <.001, ** = significant at <.05, * = significant at <.1, and ns = not significant using a two-tailed t test versus a null of zero.

[16] This regression is shown as Eq. (3) in the appendix.

[17] Untabulated analysis also shows a stronger negative effect for non-reserve disclosure firms without controlling for size (*LOGTA*) in the regressions (Eq. (2) and (3)). This mostly reflects their small size, but the result could also reflect a negative signaling effect from non-reserve disclosure (assuming investors expected disclosure).

4.2. Additional tests

Given we study oil and gas firms, a logical next question asks whether a similar response might have occurred for U.S. coal companies. Using the same event study approach, we find no negative investor response around the same unburnable carbon news stories for 29 of the 31 firms comprising the Dow Jones U.S. Coal Index. Several factors could explain this result. First, coal firm valuation analyses tend to link more to projected rates of coal production and current profitability rather than to potential coal resources underground and future profitability, the latter which can be highly uncertain. This leads investors to apply high equity and credit discount rates, thereby making their assessments of the resources underground (potentially extractable in the future) less sensitive to mispricing. Second, coal firm valuations would have reacted earlier to CO_2 climate change constraints in general; in that, while environmental regulations constraining the use of coal have been accelerating, they date back more than three decades (e.g., the Clean Air Act, 42 U.S.C. §7401 et seq. 1970). In addition, scientific discussion regarding the future of coal under climate policy constraints varies significantly, depending on the time horizon. For example, Bauer et al. (2015) suggest coal's marginal profit rate is already limited and, thereby, coal loses the least monetarily in the short term (to 2030) and long term (to 2100), as opposed to oil and gas which suffer the largest economic losses under climate change stabilization policies on fossil fuel markets, especially in the later part of the century (2030–2100). Second, the news media stories we study focus far more on unburnable carbon regarding oil and gas than coal reserves. More complete evidence, however, on these and other unexplored issues regarding the response of coal firm valuations to news about unburnable carbon is best gathered through additional research. Such research would consider variables such as changes in coal demand and coal prices, carbon limitation and reduction policies, and specific actual and proposed regulations directed at the coal industry.

Because we analyze all media stories about unburnable carbon (identified through Factiva) over the 2009–2013 period, we essentially examine the entire population of news stories potentially relevant to investors' assessments of oil and gas firms' market value. This means that the regression coefficients show the average response coefficients for this sample over the study period, and do not generalize to other industries or sectors. However, from the perspective of studying a population, some contend that researchers should refine their analysis when they study common events, because company A's response to an event on day t may not be independent of company B's response on event day t, especially if A and B operate in the same industry. When events cluster on common dates, this can reduce the number of independent residuals in the regression, which is an assumption of the test statistics we use. As a sensitivity test, we estimate the regressions in Tables 2 and 3 based on standard errors for coefficient significance that adjust for clustering. Untabulated analysis shows that when we cluster at the company level (extreme clustering), none of the test statistics for the unburnable carbon news stories is significant at $p < .05$, although we would expect this given that the effective number of excess return observations for each event date is one (not 63). However, when we cluster by asset quintile or reserve disclosure quintile (which is a less extreme way to partition the excess return observations into potentially unrelated groups), the coefficients for *NatureArticleDum* in Tables 2 and 3 and *OtherNewsDays-1to10* in Table 3 continue to be negative and significant (at $p < .05$).

We also face a design issue when some events cluster in time, namely, day t could be day 0 for event X and, say, day −2 for event Y for the same company. With overlapping days, under the event day or calendar day approaches, this creates spatial correlation in the regression residuals, which can also influence the regression standard errors. To avoid overlap, we make an assumption about an event a particular day might relate to. Given an overlap, we could assign the minimum event day to day t (day −2 in the example above) or the maximum event day to day t (day 0 in the example above). The regressions in Tables 2 and 3 adopt the minimum event day assumption. However, we obtain similar results for our regression test variables when we adopt the maximum event day assumption. The results in Table 3 are also robust to the inclusion of 8-K and 10-K filing dates, company attributes such as corporate governance, and different classifications of media news intensity based on filters available through Factiva.

5. Conclusions and discussion

This paper studies whether the stock market recognized the significance of the Meinshausen findings contemporaneous with the 2009 *Nature* publication and/or whether the market might have responded later, and perhaps biasedly, in conjunction with heightened media attention. For the *Nature* publication, we show results most consistent with the rational response hypothesis, namely, that despite the relative obscurity of the *Nature* article, stock prices declined by 1.5% to 2.0% (depending on the model to estimate expected stock returns) over days −1 to 1 around the April 30, 2009 publication date. This limited yet negative change stands in contrast to the claims of many of a substantial potential loss of energy companies' shareholder value. From a research design standpoint, the small number of news releases around April 30, 2009 also means that we can more likely link the −1.5% to −2.0% stock price response to information in the publication rather than media bias or unrelated stories. Moreover, any such bias would also have been predictably small, as research indicates that the least media bias occurs for low visibility events relating to firms with high public information availability (Dyck and Zingales, 2003).

We then test for a reaction around the dates of the news reports in 2012–2013, which could be biased, as the later press stories introduced little new information beyond the *Nature* articles; or an unbiased rational response to new information, for example, because new analysis made it clearer which energy firms faced stranded carbon assets and/or updated the global carbon budget for new levels of temperature change. Our results for the 2012–2013 press stories comport more with the former view, as they show no stock price movement – positive or negative – in days −1 to 1 but, rather, a statistically significant but economically small delayed negative reaction over the next 10 trading days. We tested for a reaction on day 0, days −1 to 1, and days −1 to 10 (allowing for a multi-day response) and whether the reaction might be more negative for firms with significant reserves and found a systematic response that increased negatively for the longer event window and firms with disclosed reserves. However, while negative, this evidence does not support the predictions of many that recognition of unburnable carbon might prompt a substantial reduction in the shareholder value of fossil fuel firms, although it does suggest that the media may have prompted a small negative price reaction over the next two weeks.

Why might we have observed only a limited negative stock price reaction to the scientific results that McKibben (2012) concludes "add up to global catastrophe" and that, also, have sparked considerable interest in campaigns for institutions to divest themselves of fossil fuel companies (e.g., Ansar et al., 2103)? Others have issued similar assertions, such as "fossil-fuel investments are destined to lose their economic value."[18] While none of the following explanations is entirely new, the collective views of energy company shareholders and investors as expressed through stock price changes provide an important counterbalance to the mostly one-sided predictions of the popular and financial press, in particular, those that espouse a carbon pricing bubble.

First, investors would consider alternatives such as the use of carbon capture and sequestration (CCS) (Chu and Majundar, 2012; Gale, 2004; Global CCS Institute, 2014) and CO_2 enhanced oil recovery (EOR) (Gozalpour et al., 2005; National Energy Laboratory, 2010) which could be beneficial for unburnable carbon (e.g., assuming sufficient prices for carbon and oil and gas) by allowing fossil fuel production

[18] online.wsj.com/news/articles/SB10001424052702304655104579163663464339836.

(e.g., by power companies) to continue by storing carbon emissions from the extraction process (CCS) (Elliot and Celia, 2012) or by injecting the carbon underground as a well stimulation technique (EOR). While these new technologies may increase the costs of extraction, the added production expense is generally immaterial to profitability on the basis of net present per barrel value except under very low oil price scenarios. The oil industry itself remains optimistic that it will be able to continue to extract its reserves profitably using CCS technologies.[19] There are also indications that some governments could share a proportion of the cost for CCS. In Canada, for example, which would not like to see its massive oil sands reserves wind up as stranded assets, government subsidies may cover up to 60% of the $1.35 billion costs to add CCS regarding a Shell Canada, Chevron Canada, and Marathon Oil Sands joint production project.[20]

Second, investors would anticipate governments' energy policies, which might provide economic incentives in the form of tax reductions for firms to internalize the cost externalities of unburnable carbon; although given the high requirement for mobility and the difficulty of quickly replacing hydrocarbon-based fuels in transportation, the timing of when governments might respond to scientific information about climate change and implement strict carbon restrictions on oil remains uncertain. But regardless of whether governments impose tax costs or offer benefits, the longer it takes governments to set policies to restrict or replace the use of carbon-based fuels, the smaller the impact such policies would have on today's stock prices for oil and gas companies. In pricing energy stocks, rational investors would also generally have difficulty in projecting how policies that affect future demand for reserves will ultimately influence future energy prices (which can be highly uncertain under any scenario and not just under a future where carbon emissions will be constrained) and, thus, it is reasonable to suppose that many investors would be reluctant to make substantial portfolio adjustments based on the modeling of uncertain price competition points for various energy commodities.[21] Investors, moreover, would be increasing reluctant to make such portfolio adjustments based on horizons of more than 20–30 years (e.g., to 2100), as at such future points conjecture replaces uncertainty and present values trend rapidly to zero. Investors' anticipation of governments' policies on unburnable carbon also means that countries rather than companies or investors might bear more cost.[22] This factor may also help explain the limited impact of unburnable carbon on firm value.

Third, investors would be skeptical about whether the demand for oil and gas can actually be pared back within an economically meaningful horizon, regardless of the need to lessen carbon emissions; and may be assuming that more carbon reduction or stranding will come from less clean alternatives such as coal.[23] For example, the International Energy Agency (IEA, 2014) forecasts that oil demand will rise to 104 million barrels per day by 2040, up from 90 million in 2013, with almost all of the net growth coming from the transport sector in emerging economies. Over 90% of all fuel used in the transport sector is petroleum-based. Moreover, to date, there are few commercially available substitutes for petroleum based fuels for vehicles; and those that exist, mainly biomass, electricity, and hydrogen, are not yet in wide deployment. This reality renders the demand for oil relatively inelastic in both the short and medium term; and a large-scale transition to other non-oil fuels would take decades. The IEA, for example, anticipates that road transport for freight and personal mobility will be responsible for 75% of future oil in transportation use, and the global passenger vehicle fleet is expected to double in the coming decades to 1.7 billion by 2035 (IEA, 2011).

A fourth possible explanation could relate to investors' dearth of information in companies' financial statements. In the United States, the SEC (2010) requires all material risks and uncertainties to be disclosed about climate change. Yet after taking a comprehensive search of the most recent 10-K filings of the firms in our sample, we could find no mention of unburnable carbon or an equivalent phrase (based on the same search terms used to search for news media articles in Factiva). Proposals by private-sector groups for climate change risk disclosures in financial statements related to stranded assets (e.g., Asset Owners' Disclosure Project, aodproject.net; Institutional Investors Group on Climate Change, globalinvestorcoalition.org; Carbon Asset Risk Initiative, www.ceres.org), however, may change the present disclosure imbalance.

A final possible explanation relates to the effects of potential media bias, in which prior work suggests should be small, as energy stocks are largely held by institutional investors, trade in efficient markets, and their prices reflect a wide range of investment strategies with relatively few constraints. Our results are consistent with this view, as they show a small but detectable delayed reaction to the 2012–2013 stories.

We cannot rule out the possibility of a carbon bubble, however, as market prices in the past have grossly deviated from the underlying fundamentals, as in the case of the dotcom bubble of 2000 (Olek and Richardson, 2003) and earlier episodes. Drastic action by governments and regulators such as a prohibition on fossil fuel production on a global basis, or the imposition of a very strict cap on global carbon emissions within the framework of a truly workable carbon market, might be two such long-tail events that could burst this potential bubble.

Our results are not without limitations. First, the effects we document do not extrapolate to global energy markets, as we study only U.S. oil and gas firms, which hold only a fraction of the world's unburnable carbon. The large majority is held in coal reserves or in oil and gas reserves owned by central governments or national oil companies (up to 80% by some estimates), whose stakeholders and profit incentives differ greatly from those of the U.S. companies we study (Jaffe and Soligo, 2010). In other words, much of the risk of unburnable carbon lies with countries rather than companies. In addition, we may have underestimated the impact of unburnable carbon news, as our models

[19] In its 2010 World Energy Outlook, the International Energy Agency (2010) notes that "cutting emissions sufficiently to meet the 2 degrees C goal would require a far-reaching transformation of the global energy system." However, the agency forecasts that "carbon capture and storage (CCS) plays an important role…" in such scenarios, especially in the power generation sector. Specifically, under its 2 °C scenario, the IEA estimates that CCS will provide 14% of cumulative emission reductions between 2015 and 2050 compared to a business as usual scenario. On the other hand, the use of CCS may have only limited relevance because most of the oil-related carbon will be combusted in vehicles' motors. McCollum and Yang (2009) counterbalance this view contending that fossil fuel demand will continue for transportation, especially for air and marine travel. World population and miles traveled per person will also increase substantially through 2050. What this suggests is that while it will still be difficult to capture carbon from oil-based transportation, CCS will become increasingly important for electric and biomass transportation. Hence, in the larger picture of meeting the 2 °C threshold, CCS will be potentially important and relevant not because of gasoline combustion, but because of the need to decarbonize electricity and biofuels, which will be used increasingly for land transportation.

[20] Shell Canada, Chevron Canada, and Marathon Oil Sands in 2012 announced Alberta Government approval of the $1.35 billion Quest CCS project, which will gather CO_2 emissions from an oil sands upgrading project in Canada and pipe the carbon to a site 80 km away for storage underground. Government subsidies will cover the majority of the project cost ($745 million), with the industry partners covering mainly the cost of construction of the CCS facilities. In 2015, the U.S. Department of Energy also agreed to participate in this project (https://sequestration.mit.edu/tools/projects/quest.html).

[21] This horizon issue may also explain the limited impact on stock prices of divestment campaigns, which research suggests associate with little permanent impact on target company valuations. See Ansar et al. (2013) for a review of this literature.

[22] For example, Bauer et al. (2013) find that the loss of present value of companies' rents from stranded fossil fuel assets to stabilize climate at less than 2 °C above preindustrial levels would be more than offset by gains to emission allowance owners, a portion of which could be redistributed though market mechanisms or climate change policy to compensate fossil fuel companies for stranded asset losses.

[23] Carbon constraints may also raise the demand for natural gas in the intermediate term as is happening currently in the United States in light of coal regulations. Combustion of natural gas for power generation typically results in 50% less CO_2 emissions than coal.

of excess change in stock price extract the influence of market returns, crude oil price changes, and news events about the crude oil and gas markets generally, all of which could reflect some anticipatory and antecedent impacts about how unburnable carbon might affect shareholder value. This could be especially the case if investors' beliefs that carbon policies will lower demand and thereby oil and gas prices are the main mechanism under which unburnable carbon affects oil and gas firm valuation. Lastly, while we document the average response effects of unburnable carbon on U.S. fossil fuel firms based on past and present events, those effects may not generalize to future news stories, as today's events could change tomorrow's government policies and firms' investment plans in ways that even a crystal ball could not anticipate.

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Appendix A

Panel A: Definition and source of variables

Variable	*Description*	*Source*
ANALYST	1 if analyst comment or recommendation on day *t*, otherwise 0.	IBES
CAPTA	Quarterly capital expenditure ÷ quarterly total assets	Research Insight
CarbonTaxDum	1 for day 0 (or days −1 to 1) around April 11, 2011, otherwise zero	Factiva
CGVSC	Corporate governance pillar score	Asset 4
Corporate/Industrial News	1 for days −1 to 1 around corporate/industrial news, otherwise 0.	Factiva
CrudeOil/	1 for days −1 to 1 around crude oil market news, otherwise 0.	Factiva
NaturalGasProductMarkets	1 for days −1 to 1 around natural gas product market news, otherwise 0.	Factiva
ECNSC	Economic pillar score	Asset 4
ENVSC	Environmental pillar score	Asset 4
EPSAR	Quarterly earnings per share as reported	Worldscope
EPSBA	Quarterly earnings per share including extraordinary items	Research Insight
HML	Fama–French earnings growth factor	Ken French web site
LEVRG	Debt ÷ common equity	Research Insight
LGMKT	Natural log of quarterly market value traded	Research Insight
LOGTA	Natural log of quarterly total assets	Research Insight
Mkt-RF	Return on U.S. market value-weighted equity index in excess of risk free rate	Ken French web site
MKTVL	Market value of stock at fiscal year end	Research Insight
NatureArticleDum	1 for day 0 (or days −1 to 1) around April 30, 2009, otherwise zero	Factiva
OtherNewsDays-1to10	1 for days −1 to 10 around 2012–2013 unburnable carbon news, otherwise 0	Factiva
OtherNewsDays-1to5	1 for days −1 to 5 around 2012–2013 unburnable carbon news, otherwise 0	Factiva
PercentageChangeOilPrice	$(COP_t - COP_{t-1})/COP_{t-1}$, where COP_t = spot price of West Texas Intermediate crude	www.indexmundi.com/commodities
ProvedReserveDum	1 if Form 10-K contains disclosure of proved reserves, otherwise zero	SEC Edgar
QE-1to1	1 for days −1 to 1 around quarterly earnings announcement date, otherwise 0	Research Insight
RBETA	Beta	Research Insight
REVTA	Quarterly net sales ÷ quarterly total assets	Research Insight
RF	Daily one-month Treasury bill rate	Ken French web site
SHREQ	Quarterly shareholders' equity	Research Insight
SMB	Fama–French size factor	Ken French web site
TA	Quarterly total assets	Research Insight

Panel B: Regression models

(1) Cumulative daily excess returns around unburnable carbon news stories

To examine the relationship between excess returns and unburnable carbon news stories, we estimate daily excess returns using a Fama–French model (1993) as shown in Eq. (1).

$$r_{it} = RFt + \alpha + \beta_1(Mkt_t - RF_t) + \beta_2 SMB_t + \beta_3 HML_t + \beta_4 PercentageChangeOilPrice_t + \varepsilon_{it} \quad (1)$$

The intercept term, α, reflects the amount that firm U.S. oil and gas firms outperform/under-perform the market on a risk-adjusted basis on the event day (excess return). *RF* is the daily one-month Treasury bill rate. The independent variables are as follows: Mkt_t–RF_t = the return on a U.S. market value-weighted equity index (*Mkt*) in excess of the monthly T-bill rate on day t (*RF*); SMB_{it} (Small Minus Big) = the average return on the small-cap portfolio minus the average return on the large-cap portfolio (size factor); HML_{it} (High Minus Low) = the average return on the high book-to-market portfolio minus the average return on the low book-to-market portfolio (earnings growth factor); and $PercentageChangeOilPrice_t = (COP_t - COP_{t-1})/COP_{t-1}$, the percentage change in the spot price of West Texas Intermediate crude oil over day *t*.

(2) Stock price response to unburnable carbon news stories: Event day regressions

This model regresses daily stock returns, r_{it} in event time, for the 63 U.S. oil and gas firms on our test variables, Fama–French risk factors, and other controls as shown in Eq. (2) below.

$$\begin{aligned} r_{it} = {} & RF_t + \alpha + \beta_1(Mkt_t - RF_t) + \beta_2 SMB_t + \beta_3 HML_t + \beta_4 PercentageChangeOilPrice_t + \beta_5 CarbonTaxDum_t + \beta_6 NaturePublicationDum_t \\ & + \beta_7 ProvedReserveDum_i + \beta_8 CarbonTaxDum_t * ProvedReserveDum_{it} + \beta_9 Corporate/IndusrialNews_t \\ & + \beta_{10} CrudeOil/NaturalGasProductMarket_t + \beta_{11} EPSAR_{it} + \beta_{12} ANALYST_{it} + \varepsilon_{it} \end{aligned} \quad (2)$$

The Fama–French risk factors and percentage change in oil price are as previously specified. $NaturePublicationDum_t$ = one for days −1, 0, and 1 around the Nature article on April 30, 2009, and zero otherwise; and where day 0 is one of three news story publication dates; $CarbonTaxDum_t$ = one for days −1, 0, and 1 around the spike in unburnable carbon new stories on April 11, 2011, and zero otherwise; $NaturePublicationDum_t$ = one for days −1, 0, and 1 around the *Nature* articles on April 30, 2009, and zero otherwise; $ProvedReserveDum_{it}$ is a binary variable, equal to one when the Form 10-K contains disclosure of proved reserves, and zero otherwise; $CarbonTaxDum_t * ProvedReserveDum_i$ = the interaction of carbon tax news and proved reserves; $Corporate/IndustrialNews_t$ = one for days −1, 0, and 1 around corporate/industrial news, and zero otherwise; $CrudeOil/NaturalGasProductMarket_t$ = one for days −1,0, and 1 around crude oil market news and zero otherwise; $EPSAR_{it}$ = quarterly earnings per share as reported by Worldscope; $ANALYST_{it}$ = one if an analyst comments or makes a recommendation on firm *i* on day *t*, and zero otherwise.

(3) Stock price response to unburnable carbon news stories: Calendar day regressions
This model regresses daily stock returns, r_{it} in calendar time, for the 63 U.S. oil and gas firms on our test variables, Fama–French risk factors, and other controls and as shown as Eq. (3) below.

$$\begin{aligned} r_{it} = {} & RF_t + \alpha + \beta_1(Mkt_t - RF_t) + \beta_2 SMB_t + \beta_3 HML_t + \beta_4 PercentageChangeOilPrice_t + \beta_5 CarbonTaxDum_t + \beta_6 NaturePublicationDum_t \\ & + \beta_7 ProvedReserveDum_i + \beta_8 CarbonTaxDum_t * ProvedReserveDum_{it} + \beta_{13} OtherNewsDays{-}1\text{to}5_t + \beta_{14} OtherNewsDays{-}1\text{to}10_t \\ & + \beta_{15} OtherNewDays{-}1\text{to}5_t * ProvedReserveDum_i + \beta_{16} \mathrm{QE}{-}1\text{to}1_{it} + \beta_{17} LOGTA_{it} + \beta_{18} ENVSC_{it} + \varepsilon_{it} \end{aligned} \tag{3}$$

The newly-introduced independent variables are as follows: $OtherNewsDays - 1to5_t$ = one for days −1 to 5 around 2012–2013 unburnable carbon news, and zero otherwise; $OtherNewsDays - 1to10_t$ = one for days -1 to 10 around 2012–2013 unburnable carbon news, and zero otherwise; the interaction between unburnable carbon news and proved reserves; $QE - 1to1_{it}$ = one for days −1, 0, and 1 around quarterly earnings announcements, and zero otherwise; $LOGTA_{it}$ = Natural log of quarterly total assets; and $ENVSC_{it}$ = environmental pillar score.

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