Do Markets Price Changes in Economic Oil Reserves?*

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Abstract

Currently proven oil reserves are largely excessive from a climate standpoint, raising concerns about the potential financial mispricing of carbon assets. This paper studies how large oil companies' financial valuation reflects the size of their economic oil reserves. To this end, we exploit changes in firms' economic oil reserves induced by oil-price variations, and we examine the relation between these reserve changes and firms' stock returns. Economic theory predicts that firm value is convex in the output price when price affects quantities. We exploit this prediction to extend the conventional analysis of firms' financial exposure to changes in the oil price, separating the intensive margin (economic reserves held constant) and the extensive margin (changes in economic reserves). First, we empirically validate that financial market movements are consistent with the extensive margin effect of the oil price. Second, we exploit fundamental reserve data to estimate the economic reserves' sensitivity to the oil price (RSP). Third, we show that our new metric explains a risk premium, accounting for up to half the industry's average cost of capital. This means that the risk associated with more sensitive economic reserves is material to investors who demand compensation from oil companies for the possibility of oil assets' reassessment.

Keywords: Economic oil reserves; Stranded assets; Oil price risk; Risk premium.

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1 Introduction

Currently proven oil reserves are largely excessive from a climate standpoint. According to resource specialists, about a third of these are incompatible with the global carbon budgets that would limit global warming to 1.5°C or even 2°C (McGlade and Ekins, 2015; Welsby et al., 2021; Trout et al., 2022), representing several hundred billion US dollars in discounted exploitation profits (Semieniuk et al., 2022). The apparent inconsistency between oil companies' assets and governmental climate policy objectives raises two concerns. The first one, obviously, is the failure to achieve governments' stated objectives—e.g., the Paris Agreement's nationally determined contributions—whose causes have been extensively studied by the environmental and resource economics literature. Our analysis deals with the second concern: The potential financial mispricing of carbon assets.

Financial regulators—e.g., Mark Carney's repeated warnings as Governor of the Bank of England[1]—economists (Stern and Stiglitz, 2021), and environmental NGOs—see, e.g., Carbon Tracker and LSE Grantham Research Institute's (2013) and Carbon Tracker's (2022) reports on the so-called "carbon bubble" due to "unburnable" carbon assets—have questioned whether financial markets adequately assess carbon assets. Now more than ever, the high level of uncertainty about future climate action calls for a careful management of investors' exposure to the risk of fossil fuel reserves reassessment—see, e.g., *The Financial Times*, March 7, 2025.[2] Although financial markets' imperfect assessment of carbon assets is often presumed or feared, this hypothesis remains untested. It is so despite the fact that the price mechanism through which excessive carbon assets are deemed unprofitable is a cornerstone of the energy transition (Van der Ploeg and Rezai, 2020a,b; Chen et al., 2023).[3]

In this paper, we study how large oil companies' financial valuation reflects the size of economic oil reserves. To this end, we exploit monthly changes in firms' economic oil reserves induced by oil-price variations, and we examine the relation between these reserve changes and firms' stock returns. We show how investors' behavior reflects the effect of the oil price on economic quantities. Moreover, our results suggest a risk premium associated with the sensitivity of economic reserves with respect to the oil price, specific to each company depending on its reserves' structure. This premium results in a penalty on firms that are the most exposed to the risk of reserve reassessment.

In reality, oil companies mainly consist of a portfolio of resource assets, each with an assessed amount of oil reserves producible at some costs. For a given oil price, we define economic reserves as the amount of these assets whose exploitation revenues at current prices

[1] See, e.g., *The Guardian*, October 13, 2014, on the risk of fossil fuel asset mispricing. Similar concerns have motivated the US Securities and Exchange Commission to regularly clarify reporting requirements for oil and gas companies over the past decade.

[2] Available at: `https://www.ft.com/content/47461362-1e18-4f2b-9336-142faf53b311`.

[3] Whether it is driven by carbon penalties or by the promotion of clean energy sources, climate policy is hoped to make the exploitation of fossil fuels less profitable, leading to the stranding of existing uneconomic reserves.

exceed development and exploitation costs.[4] Reserves are commonly assessed under current market conditions, partly because of the unpredictability of future oil prices[5]—e.g., the US Securities and Exchange Commission (SEC) requires that economic reserves be assessed using the 12-month historical average of oil prices.[6] When the oil price becomes lower, the value of oil companies' resource assets decreases both because, at the "intensive margin," exploited reserves are expected to generate less revenue, and because, at the "extensive margin," fewer reserves remain economic.

For example, in June 2020, ExxonMobil warned the SEC that if oil prices remained around $40 per barrel, around 20% of its reserves would become uneconomic. In general, ExxonMobil is exposed to oil price changes at the intensive margin, i.e., to the extent of its economic reserves. In the 2020 period of low oil profitability, however, the company was also exposed at the extensive margin, because, with many assets with break-even prices around 40$ per barrel, its economic reserves were particularly sensitive.

Our analysis rests on the theoretical microeconomic decomposition of the effect of a firm's output price on its profits. The first-order effect of the price is given by Hotelling's Lemma, indicating that a firm is exposed to a small price change up to its supply. The second-order effect of the price is due to the adjustment in supply, which explains the convexity of profits with respect to the price. This simple decomposition carries over to the adjustment of economic reserves to the current oil price. On the one hand, the first-order linear effect captures the "intensive margin" explained above. On the other hand, the second-order quadratic effect isolates out the role of adjustments in economic reserves specific to the "extensive margin," our main channel of interest.

Based on this, our approach is to extend the standard, linear Capital Asset Pricing Model (CAPM) to the convex effect specific to the extensive margin. We obtain a new, non-linear regression model relating firms' stock returns to oil price changes, along with other factors traditionally used to explain stock returns—e.g., market risk and other Fama-French factors. The structural interpretation of this model attributes the model's convexity to variation in economic oil reserves with the oil price: the coefficient of the quadratic term captures the elasticity of economic oil reserves with respect to the oil price.

Our estimation approach relies on several assumptions. First, we assume that companies' reserves, their structure, and sensitivity are exogenous. The actual structure of oil companies' reserves appears to be determined by their acquisition history. Over the period that we

[4]Equivalently, in the language commonly used by industry participants, economic reserves correspond to oil assets with break-even prices below the market price, where one asset's break-even price is the leverage cost of extraction, the per-barrel cost, inclusive of development expenditures.

[5]In a famous study, Alquist et al. (2013) consider a wide range of out-of-sample forecasting methods for the price of oil, concluding that there is no evidence of significant accuracy gains with respect to the no-change forecast. Moreover, Conlon et al. (2024) finds that combinations of forecasts for the end-of-month oil prices are not more accurate than the no-change forecast either.

[6] The SEC requires the reporting of "proved reserves," defined as quantities of oil estimated with reasonable certainty to be economically producible under existing economic and technological conditions.

review, the companies' reserve structure is very inert, despite some limited transactions. Second, we assume that price variations are exogenous. We do not explain these variations. We hold that Western oil companies in our sample take the oil price as given. The oil price may be managed at the level of the OPEC+ cartel. Yet, it frequently varies, mainly due to demand-side shocks (Kilian, 2009). In fact, our strategy is to combine the inertia of oil companies' reserves structure with the frequency of exogenous oil price changes.

Our empirical analysis covers the period 1990-2020 and focuses on the 18 largest companies active in the US, producing more than 1% of the country's oil output (BP, ExxonMobil, Chevron, etc).

We estimate our augmented asset-pricing model in two different ways. In the first, we only exploit financial or price information. We find that the quadratic term specific to economic reserves' adjustment is significantly different from zero. Moreover, based on our structural interpretation of the model, we show how estimated parameters can be combined to reveal the sensitivity of economic reserves that is consistent with observed financial movements. We find that the "implied" elasticity of economic reserves with respect to the oil price lies around 3.

Then, we use fundamental reserve and ownership data to measure each company's economic reserves' sensitivity to the price, a new metric that we call RSP (Reserves' Sensitivity to Price). We rely on data from the Rystad UCube Database (Rystad Energy, 2024), the most comprehensive dataset of oil fields covering all oil assets worldwide owned by the companies in our sample. For each company and year, we build the marginal cost of exploiting the assets they control, and estimate the RSP as a local elasticity around each month's price. We obtain a panel of RSP measures, one for each company and each month.

In the second estimation of our model, the convexity of the relation between stock returns and oil returns is partly attributed to the role of the RSP, in line with theory. It is in this setting that we observe an RSP premium: Firms with more sensitive economic reserves exhibit higher stock returns.

The financial interpretation of this result goes as follows. A higher RSP means reserves are more sensitive to oil price fluctuations, including the risk that assets become stranded. Microeconomic theory indicates that the RSP captures the curvature of the profit-price relation. Asset-pricing theory holds that, for investors, this means greater exposure to oil price risk, which they require compensation for.

Quantitatively, our results indicate that investors' concern for the sensitivity of economic reserves explains up to half an oil company's cost of capital. To sum up, our results indicate that the vulnerability of oil companies' economic reserves to the oil price is material to investors. Theory suggests that this is because more sensitive reserves augment oil companies' exposure to the oil price risk.

2 Related literature and contribution

We are not the first to examine how the oil industry is affected by fluctuations in oil prices. Asset-pricing analysis has long estimated oil companies' exposure to the oil price risk, among other factors, by estimating the linear relation between oil price changes and stock returns—see, e.g., Parsons (2013)' review. To our knowledge, however, this paper is the first to examine the sensitivity of carbon assets to price changes and to show that the resulting risk of economic reserve adjustments is material to investors.

In this section, we explain how our methods, results, and estimates contribute to the various fields of economic research.

Resource economics. In general, this paper adds to the empirical literature concerned with the factors affecting natural resource production. Among other examples, Bohn and Deacon (2000) examine the effect of ownership risk on countries' oil use and management; Arezki et al. (2017) estimate the effect of reserve discoveries on domestic investment and macroeconomic variables; Ahlvik et al. (2026) estimate the effect of country-level extraction tax changes on oil production and development. We contribute to this literature by examining another factor affecting the oil industry: The structure of oil reserves and the risk of their reassessment.

Moreover, our study provides a new empirical measure of the elasticity of economic reserves with respect to the oil price (RSP) that captures the exposure to the risk of reassessment. Interestingly, we find that our estimates have desirable statistical properties, making them useful for empirical research on the oil industry's response to the energy transition.

Asset pricing. Our empirical approach is inspired by the time-honored finance literature on asset pricing estimating businesses' exposure to systemic risks—Merton (1973), Fama and French (1996), Fama and French (2015)—including analyses of the oil price risk—see, e.g., Parsons' (2013) review and examples of applications therein. Our contribution to this literature is methodological: We extend its conventional model—relating oil price changes to stock returns linearly—by adding a theory-based quadratic component that captures price-induced quantity changes, showing that the extensive margin effect of oil price changes increases exposure to the oil price risk. In this respect, our methodological contribution resembles Borenstein and Farrell (2007) study on gold mining: Their paper also exploits the theoretical convexity of firm value in prices and financial data to examine the industry's efficiency. Our main methodological novelty is to exploit our structural extension of the financial model to examine the specific role of changes in economic reserves.

Climate-related risks. At the intersection of the environmental economics literature and the finance literature, recent studies also examine how markets price climate-related risks.

For example, Krueger et al. (2020) survey investors' perception of climate risks, including the belief that financial valuation does not fully integrate these risks.

Close to the spirit of this paper, Bolton and Kacperczyk (2021) and Bolton and Kacperczyk (2023) establish a "carbon premium" at the global level, positively associating firms' CO2 emissions with realized stock returns; their results suggest that this premium is because more polluting firms are more exposed to the risk of transition, against which investors require a compensation. Consistently, Hengge et al. (2023) find that unanticipated carbon price increases cause negative abnormal—unexplained by traditional factors—stock returns. Atilgan et al. (2024) revisit Bolton and Kacperczyk (2023) and find that polluting firms' stock returns are not only associated with realized stock returns but also with earning surprises. This suggests that the carbon premium at least partly results from outperformance, e.g., the fact that polluting firms were less penalized than expected. In the case of biodiversity risk, Coqueret et al. (2024) address the above interpretation ambiguity by exploiting expected stock returns estimated by Chabi-Yo et al. (2023).

By contrast with this literature, we directly examine the structure of carbon assets and we rely on the theoretical prediction for how the sensitivity of oil reserves amplifies the oil price risk. Our robust evidence of an RSP premium is not prone to an ambiguous interpretation of realized stock returns both because it is consistent with theory, and because our RSP measure of reserves' structure could hardly explain outperformance.

Supply-side climate policies. Finally, our results' implications are related to the literature on the supply-side climate policies initiated by Harstad (2012)—see also, e.g., Asheim et al. (2019). Indeed, our analysis shows that financial markets already penalize oil producers for the risk of assets' adjustment and suggests that future public policies making oil exploitation less profitable will be amplified by higher costs of capital.

Also motivated by the apparent excessive investment in oil reserve development, Coulomb et al. (2025) suggest that efforts to develop more reserves be regulated. Besides insufficient carbon pricing, which is a sufficient justification for exploration regulation, we find no evidence of mispricing of oil assets.

3 Theoretical preliminaries

To start with, we examine how a firm's profit is affected by the price of its output, through both the intensive and extensive margins. For parsimony, we rely on a textbook static model in this section. Shortly below, with technical details in the appendix, we explain how the implications of this simplifying setup carry over to a firm exploiting a resource over time.

Let a profit-maximizing firm produce a single output in quantity x at a marginal cost $MC(x)$, differentiable and strictly increasing, taking as given the output price $p > 0$. We

assume $MC(0) < p$ so that some production is warranted. Its profit function is:

$$\pi(p) = \max_x px - \int_0^x MC(v)\ dv. \tag{1}$$

By Hotelling's Lemma, the effect of an infinitesimal change in price p is given by $\pi'(p) = x(p)$, where $x(p) \equiv MC^{-1}(p)$ is the firm's supply. The Lemma yields a linear relation between price changes and profit changes:

$$\Delta\pi = \beta\Delta p, \tag{2}$$

where $\Delta\pi = \pi'(p)/\pi(p)$, $\Delta p = dp/p$, and $\beta \equiv \frac{px(p)}{\pi(p)}$.

Since theoretical infinitesimal changes in prices leave supply unchanged, the linear relation 2 between changes in prices and changes in value captures the impact of the price at the intensive margin. In practice, for example, financial studies estimate a linear relation between price fluctuations and changes in value. Its coefficient, coined the "oil β" (see, e.g., Parsons (2013)), measures oil companies' exposure to variations in the oil price.

By contrast, we obtain a more general approximation of price changes by taking the second-order Taylor expansion of the profit function. It yields:

$$\underbrace{\Delta\pi \approx \overbrace{\beta\Delta p}^{\text{Intensive margin}}}_{\text{Traditional model}} + \overbrace{\frac{1}{2}\beta\rho(\Delta p)^2}^{\text{Extensive margin}}, \tag{3}$$

where the second term, absent in 2, now captures the effect of price fluctuations on supply through the elasticity $\rho \equiv \frac{px'(p)}{x(p)}$.

This more general expression highlights that the often-estimated linear β coefficient captures the first-order effect of prices on value, the intensive margin. It also shows that the second-order component of price changes captures changes in supply, at the extensive margin, and isolates out the elasticity of supply as a measure of this margin.

This parsimonious model brings up a simple insight that we will directly use to extend the standard financial analysis of oil companies' exposure to changes in economic resources. This application of the decomposition formula 3 relies on the following interpretation: The output price p is the current oil price, at which all current reserves will be evaluated; $MC(x)$ is the marginal cost of exploiting current reserves; $x(p)$ is the amount of current reserves that are economic at current conditions; and ρ is the elasticity of economic reserves to the current price or, equivalently, the elasticity of the inverse of the marginal extraction cost of current reserves.

In Appendix B, we present a model in which an oil company maximizes long-run profit from heterogeneous reserves produced over time. In line with the usual practice, we assume that future reserves are evaluated at the current price. We obtain a decomposition equation identical to 3, relating stock returns, oil price changes, and the elasticity of economic oil reserves.

4 Capital asset pricing model with price-induced quantity changes

The conventional Capital Asset Pricing Model (CAPM) and its multifactor extensions allow the estimation of the linear relation between fluctuations in market prices and stock returns. For oil companies, the "oil beta" coefficient indicates how fluctuations in the oil price relate to fluctuations in companies' market value. The empirical model we will estimate is a simple extension of the CAPM, inspired by the second-order decomposition in 3 of the effect of the output price on market value, as per intensive and extensive margins.

4.1 Financial market data

We assemble a panel that relates oil companies to monthly financial information. The period under review is 1990-2020. We select companies that are traded on the New York Stock Exchange (NYSE) with a share of proven and probable reserves above 1% of total oil companies' reserves—based on data from Rystad Energy, as detailed in the next section. This selection includes eighteen companies[7] representing the so-called "Big Oil," accounting for about 90% of oil reserves. For each month, each firm is associated with its stock returns in excess of the risk-free (13-week Treasury-bill rate) monthly rate. Finally, each month is associated with Fama-French factors, including market returns, and with the rate of change in Brent crude end-of-month prices, all taken as monthly rates.

4.2 Does the extensive margin matter?

As in the traditional CAPM, we estimate the linear influence of fluctuations in oil prices (intensive margin), along with other standard factors that explain stock returns—resulting in the Fama-French 3 or 5-factor models. Our model extends the traditional asset pricing models by adding a second-order component of fluctuations in oil prices that features the effect of prices on quantities sold (extensive margin).

Estimating equation. We estimate the following model:

$$\Delta V_{it} - r_t = \beta \Delta p_t + \frac{1}{2}\beta\rho(\Delta p_t)^2 + X_t'\phi_i + \tau_y + \tau_i + \nu_{it}, \tag{4}$$

where ΔV_{it} is firm i's stock returns in month t, r_t is the risk-free rate, Δp_t are percentage changes in the oil price, X_t is a vector of market factors, ϕ_i a vector of firm-specific parameters, τ_y and τ_i are year- and firm-fixed effects, and ν_{it} is an idiosyncratic shock assumed orthogonal to oil prices.

[7]They are British Petroleum (BP), Canadian Natural Resources (CNRL), Chevron, CNOOC, ConocoPhillips, Ecopetrol, Eni, Equinor, ExxonMobil, Inpex, Occidental Petroleum, Petrobras, Petronas, Qatar Petroleum, Repsol, Shell, Sinopec, and Total Energies.

Table 1: Mean parameter estimates from financial data and "implied" sensitivity for top oil companies

	(1)	(2)	(3)	(4)	(5)	(6)
Oil return	0.228***	0.229***	0.238***	0.239***	0.241***	0.241***
	(0.031)	(0.031)	(0.030)	(0.030)	(0.028)	(0.028)
Squared oil return	0.288***	0.286***	0.309***	0.308***	0.361***	0.360***
	(0.073)	(0.073)	(0.071)	(0.071)	(0.070)	(0.070)
Implied RSP	2.520***	2.504***	2.593***	2.581***	2.998***	2.982***
	(0.760)	(0.765)	(0.711)	(0.716)	(0.714)	(0.719)
Fixed effects	*Year*	*Firm + Year*	*Year*	*Firm + Year*	*Year*	*Firm + Year*
Asset model	*CAPM*	*CAPM*	*F-F 3*	*F-F 3*	*F-F 5*	*F-F 5*
Obs.	2,843	2,843	2,843	2,843	2,843	2,843
R^2	0.349	0.349	0.387	0.388	0.405	0.406

*** $p < 0.01$. *Notes:* Standard errors clustered by firm. For the Implied RSP, standard errors are obtained using the Delta method. "F-F 3" and "F-F 5" denote Fama-French 3 and 5-factor models.

For our purpose, the formulation in 4 focuses on fluctuations in oil prices, rather than other market factors. For example, the traditional CAPM "beta coefficient" is the parameter in ϕ_i multiplied by market returns. Our formulation, moreover, makes use of the property that the coefficient of squared oil price changes is, theoretically, proportional both to the oil beta, the coefficient of oil price changes, and to the sensitivity of quantities to price changes.

We estimate the coefficient β of the first-order effect of oil price changes and the coefficient $(1/2)\beta\rho$ of their second-order effect as means at the sector level. We now present our regression results.

Results. In Table 1, we present estimates of our two main coefficients, β of oil price changes, and $(1/2)\beta\rho$ of squared oil price changes, as well as the quantity sensitivity ρ that they would imply. We consider six specifications that vary the sets of market factors—market returns only (CAPM) or three or five Fama-French factors—and fixed effects. These results show that the key coefficients are significantly different regardless of the specification. The coefficient of oil price fluctuations, the "oil beta," aligns with recent studies.

Closer to our interest, the positive coefficient of the quadratic term is in line with the theoretical convexity of profits. This curvature of the relationship between price fluctuations and market values may be interpreted as reflecting the extensive margin effect of price changes, i.e., through changes in economic quantities. At least, it shows that financial markets co-movements with oil price fluctuations are consistent with price-induced changes in producible quantities.

Were the curvature of the relation between price fluctuations and stock returns fully attributed to changes in economic resources, our estimates would indicate an implied estimate for ρ of around 3. In other words, on average, markets behave *as if* a 1% increase in oil

prices was increasing economic reserves by 3%. This interpretation would also be consistent with the conventional CAPM interpretation: The convexity of the relation between oil price changes and changes in values increases oil companies' exposure to the oil price risk, calling for greater compensation of investors.

That said, this simple model does not allow us to properly identify the role of changes in economic oil resources associated with changes in prices.

5 Estimation of oil companies' elasticity of economic reserves from reserve data

In this section, we examine oil companies' reserves to measure how sensitive economic reserves are to changes in prices. We will use the obtained measures in the next section to revisit financial movements.

5.1 Reserve data

We assemble a panel including the same eighteen oil companies with annual data on their reserves, including information about profitability. The period under review here is 1990–2020. For each year, each company is associated with all its assets (i.e., active licenses, fields, or discoveries) reported in the Rystad Energy's UCube Global Asset-Level Oil and Gas Database; this includes quantities of proven plus probable (2P) oil reserves, weighted by the asset's share owned by the firm, and their estimated break-even price. The break-even price is calculated as the oil price at which the total value of the extracted oil (considering the projected prices and production profiles) equals the sum of all costs (CAPEX, OPEX, etc.) over the life of the asset, discounted to their present value. While its estimation methodology is proprietary, Rystad Energy is a leading data provider for the industry, and their estimation takes into account detailed information about the quality of oil reserves within each asset, including the expected rate of production over the lifetime of the asset and its recoverable volume of oil. For every asset, we take the most recently updated estimate of the break-even price.

To our knowledge, Rystad Energy's data is the most comprehensive one as far as oil companies' reserves are concerned. Its coverage is virtually exhaustive, including 84 oil-producing countries around the world that, together, own 99.5% of the global oil reserves (EIA, 2020). Recent papers use the same data to quantify, for example, climate supply-side policies (Ahlvik et al., 2026) and the social efficiency of oil extraction (Coulomb et al., 2026).

Taking assets' levelized costs of extraction (LCOE) as a proxy for marginal costs of production, this dataset allows us to construct oil companies' marginal costs of producing current reserves at current technological conditions. Figure I shows these marginal cost curves for year 2020. The fact that these curves cross indicates that the structure of reserves

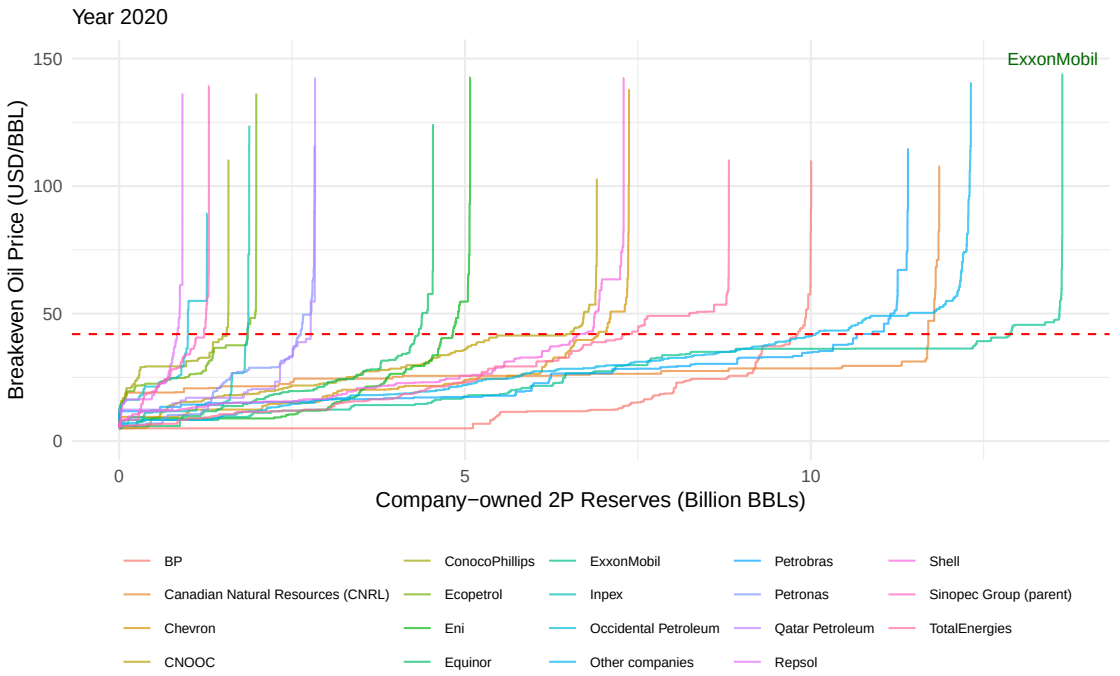


Figure 1: 2020 marginal cost curves

can vary dramatically across companies, irrespective of their size. For instance, our dataset captures the vulnerability of Exxon-Mobil's reserves around $40 per barrel, in line with our introductory example.

We focus the analysis on assets' heterogeneity in their profitability as captured by break-even prices; that is, besides this heterogeneity, we treat all of a company's assets are homogeneous. This is a simplifying assumption because, in reality, assets differ by their quality. Break-even price estimates, however, reflect some dimensions of these quality differences.

For a given current oil price, companies' marginal production cost curves indicate economic reserves, which we define as the amount of their reserves that are economically exploitable at current conditions, regardless of when their extraction would take place. In this analysis, we use end-of-month Brent oil prices to inform current prices, which we then compare to break-even prices as indicated in the constructed marginal cost curves.

We then estimate the elasticity of economic reserves with respect to the current oil price, i.e., our measure of the instantaneous vulnerability of an oil company's reserves to the risk that they become uneconomic. In terms of the marginal extraction costs of current reserves, the elasticity of economic reserves to the oil price is the elasticity of the inverse of the marginal cost to economic reserves.

5.2 Estimation of oil companies' reserves sensitivity to the oil price (RSP)

Ordering reserves by increasing marginal costs and accumulating their quantities yields the step function shown in Figure 1. A visual inspection of the resulting curve after a log-log transformation (that is, applying logs to cumulative quantities and costs) shows that the edges of the steps do not align, thus suggesting that the elasticity of economic reserves varies along the marginal cost curve. However, the notion of local elasticity in this piecewise representation is not well-defined. To measure local elasticities, we adopt a nonparametric approach with a smooth approximation using locally weighted linear regressions, or LOESS (Cleveland, 1979). [8]

The data for each curve consists of J pairs (q_j, c_j), where q_j is the total economic reserves with marginal cost below or equal to cj. Let f represent the function mapping $\log c$ to $\log q$. The LOESS approach locally approximates f with a linear function at a given point z by solving

$$\min_{\eta_0(z),\eta_1(z)} \sum_{j=1}^{J} K_h\left(z, \log c_j\right)\left[\log q_j - \eta_0(z) - \eta_1(z)\log c_j\right]^2,$$

where K_h is a kernel function with bandwidth h that weights observation j depending on the distance between z and c_j. The approximation is then given by $\hat{f}(z) = \hat{\eta}_0(z) + \hat{\eta}_1(z)z$. In this formulation, we are interested in the local slope ($\hat{\eta}_1$) estimated at the log of the current oil price ($z = \log p_t$), which approximates the local elasticity of economic reserves, or RSP.

The goal of this estimation is to obtain local derivatives at a single point per period and company. For this reason, we pick a practical bandwidth equal to the largest one-year variation in oil prices observed in the sample ($46.56/bbl), so that the estimated RSP captures sensitivity within a plausible range around the current price. Although the bandwidth can be considered large for normal years[9], this choice allows for enough flexibility to capture substantial shifts in local slopes, as illustrated below.

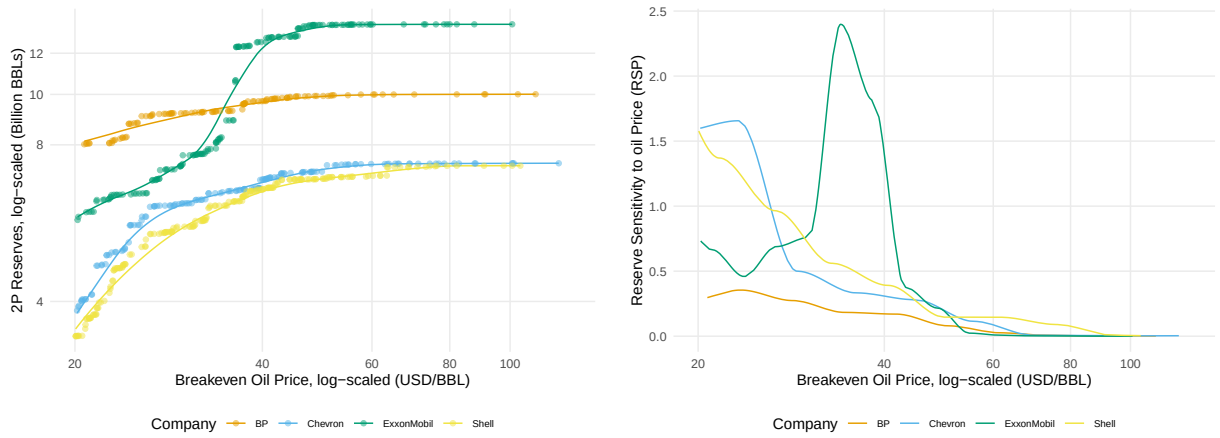
5.3 Results

Panel (a) in Figure II displays the data points on cumulative reserves at various costs of extraction and the smooth approximation of the underlying curve in log scale. This panel indicates that slopes vary not only across companies but, most significantly, at different levelized extraction costs. Panel (b) shows that information directly by plotting the value of the first derivative at each price point and illustrates the fact that slopes can vary substantially.

[8] Alternatively, one could use finite difference methods to calculate local derivatives. However, due to the uneven and occasionally sparse distribution of data points, we found that the resulting derivatives were noisy and unstable, and therefore favored a smoothing approach.

[9] For reference, the sample mean of absolute yearly price change is $10.92/bbl.

For example, the elasticity of Exxon-Mobil's economic reserves peaks around $40 per barrel, in line with our introductory example.



(a) Kernel-smooth inverse (log-log) LRMCs

(b) Local first derivatives

Figure 2: 2020 examples of local elasticities of economic reserves

Our approach allows the estimated RSP values to capture the heterogeneity displayed in Figure II at the company-month level. In Appendix D, we show that our RSP measures not only vary significantly across companies but also increase dramatically as the oil price declines. This property substantiates the concern that the energy transition will make oil companies' assets increasingly vulnerable, as oil production will become less profitable. We also show that RSP measures are independent of companies' size. This statistical property makes our new measure useful to empirical research on the behavior of the oil industry in the face of its economic vulnerability.

In the rest of this paper, we examine how financial markets integrate these measures into their reactions to oil price changes.

6 Evidence of an RSP premium

We now revisit the relation between stock returns and oil price fluctuations, in the spirit of Section 3. By contrast with that section, however, we exploit the obtained RSP measures and their variations across companies and months.

6.1 Estimating equation

To isolate the market response to firm-time variations in the sensitivity of economic reserves, besides the average convexity of the response to oil price changes, we extend Section 3's estimating equation to deviations in firm-month RSP.

	Excess returns
Estimated parameters	
γ_0	0.236**
	(0.090)
γ_1	0.143**
	(0.049)
Model	F-F 5 factor
Fixed effects	Firm + Year
Observations	3,333
R^2	0.302

** $p < 0.05$.
Standard errors clustered by company.
Mean $\beta_i \approx 0.175$, $\bar{\rho} \approx 0.9$.

Table 2: Mean parameter estimates with RSP deviations

Formally, we estimate the following model:

$$\Delta V_{it} - r_t = \beta_i \Delta p_t + \gamma_0 (\Delta p_t)^2 + \gamma_1 (\rho_{it} - \bar{\rho}) \times (\Delta p_t)^2 + X_t' \phi_i + \tau_y + \tau_i + \nu_{it}, \tag{5}$$

where the coefficient β_i captures firm-level (first-order) exposure to oil price fluctuations, γ_0 captures the average response to squared oil price changes, and γ_1 isolates the specific role of RSP firm-month deviations from the global mean.

6.2 Results

We use the method of least squares with standard errors clustered at the company level. We include the five Fama-French factors as controls, along with firm- and year-fixed effects.

In Table II, we present estimates of our two sector-level coefficients of interest, γ_0 and γ_1.

Our results indicate that, in addition to the average role of squared price changes captured by γ_0, variations in our RSP measures across firms and months significantly contribute to explaining heterogeneity in stock returns. These results are complementary to Section 4's analysis of the relation between stock returns and oil price fluctuations: They point to the sensitivity of economic reserves as an explanation for the second-order reaction of stock returns to oil price fluctuations, in line with theory. More precisely, given the RSP global average of $\bar{\rho} \approx 0.9$, our estimates imply that when the RSP is twice the global average, it increases the contribution of squared oil changes by 55%.

The usual finance interpretation of CAPM estimation holds: Our results show a risk premium to the interaction between the sensitivity of oil reserves and oil price fluctuations. Indeed, according to the asset pricing theory, higher risk is associated with greater expected

returns. The new factor that our analysis identifies, the vulnerability of economic reserves, increases expected returns because it increases risk. Here, the risk comes from fluctuations in oil prices. In line with the theoretical impact of the output price on profit (Section 3), the risk here is augmented by the extensive margin. Greater expected returns follow because investors require compensation against this augmented risk.

Our results show that RSP variations generate economically significant, sometimes large, risk premia. Estimates reported in Table II imply that the average risk premium generated by squared price changes is 38 basis points per month (bp/m).[10] When companies have an RSP 2 percentage points higher than the average—for example, Figure III of Appendix D shows this happens in periods of moderate oil prices—the risk premium is augmented by about $46bp/m$. This represents more than half the industry's average excess returns of $86bp/m$.

7 Conclusion

In this paper, we have examined the financial role of the sensitivity of economic oil reserves. To this end, we have extended the conventional financial analysis of risk exposure to obtain a new testable model of how oil price fluctuations affect oil companies through changes in economic reserves. We find that investors behave in a way that is neatly consistent not only with the intensive-margin effect of oil prices captured by traditional analyses, but also with the extensive-margin effect untested until now. Our results provide robust evidence of an RSP premium associated with the vulnerability of oil reserves. This premium depends on both the companies' reserve structure and the oil price. In periods of moderate oil prices, this premium can account for more than half of their excess stock returns.

This risk premium can be explained as follows. According to economic theory, the sensitivity of economic oil reserves captured by our RSP measure increases oil companies' exposure to oil price fluctuations. According to the asset pricing theory, this augmented risk exposure translates into greater expected returns because markets require compensation.

For oil companies, the RSP premium amounts to a supply-side penalty: Investors penalize oil companies through their cost of capital for the risk that their reserves become uneconomic and stranded. Our results indicate that this penalty increases as oil production becomes less profitable, because lower oil prices increase the sensitivity of oil reserves. A crucial implication of our analysis is that, given the oil industry's excessive reserves, demand-side climate action should be significantly amplified by the RSP premium.

Besides our methodological contribution and the contribution of our results to the literature on energy-related risks and stranded assets, this research also provides a new RSP measure of reserves' sensitivity. Our company-month RSP estimates may be directly useful for empirical studies of the oil industry for several reasons. First, by capturing the extensive-

[10]The industry average squared price change is 0.016, to be multiplied by γ_0.

margin effect of oil price fluctuations, the RSP measure is theoretically complementary to traditional measures of oil companies' exposure. Second, it features significant variations across companies and over time, independently of companies' size, a desirable property for comparison purposes—See Appendix D for more details.

The reaction of oil companies to situations in which their reserves are more vulnerable goes beyond the scope of our paper. Nevertheless, our sample of RSP estimates of oil reserves' vulnerability may be a useful asset for future research in this direction.[11]

[11]For example, preliminary results show that our RSP measure correlates with oil companies' investment, including efforts in political influence.

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Appendix to "Do Markets Price Changes in Economic Oil Reserves?"

April 30, 2026

A Proof of Equation 3

Consider a small change in the price from p to $p + dp$. The second-order Taylor expansion of the value function 1 gives the following approximation of this function at price $p + dp$:

$$\pi(p + dp) \approx \pi(p) + pi'(p)dp + \frac{1}{2}pi''(p)(dp)^2.$$

Denoting $d\pi = \pi(p + dp) - \pi(p)$ the change in the value function associated with the change in the price, we obtain: $d\pi = \pi'(p)dp + \frac{1}{2}\pi''(p)(dp)^2$. Dividing all terms by π, it follows: $\Delta\pi = \frac{\pi'(p)}{\pi(p)}dp + \frac{1}{2}\frac{\pi''(p)}{\pi(p)}(dp)^2$. Making use of Hotelling's Lemma, we have $\pi'(p) = x(p)$ and $\pi''(p) = x'(p)$. Using the notations of the text, we obtain directly Equation 3.

B An isomorphic model of oil exploitation over time

In this section, instead of the purposely simple static model of Section III, we present a dynamic model of resource exploiting. Under the assumptions of this model, we obtain a prediction identical to 3, relating current price changes, the sensitivity of economic oil reserves, and stock returns.

We consider an oil company i at time t, endowed with heterogeneous reserves. The company plans to exploit reserves over time under a current price assumption in such a way as to maximize the stream of its future profits.

We model reserve heterogeneity as captured by the break-even prices data that we exploit, indicating the *current marginal cost* of producing currently existing reserves. Accordingly, we assume that the long-run marginal cost of exploiting (cumulative) economic reserves, expressed in present value is increasing, denoted by:

$$MC_{it}(Q).$$

For mathematical convenience, we further make the usual assumption that $MC_{it}(Q)$ is differentiable, unlike our discrete data. The cost function of economic reserves:

$$C_{it}(Q) = \int_{s \geq t} MC_{it}(Q)dQ$$

In line with the usual assessment of economic oil reserves of oil—see, e.g., the US SEC requirements in Footnote 6—we assume that future profits are evaluated under a current price assumption. Formally, this means that reserve units are evaluated as if each would fetch a unit present-value revenue equal to the current price, regardless of when it will be exploited. An empirical justification of this practice is to invoke that, as documented by Alquist et al. (2013) and by Anderson et al. (2013), real long-term price expectations for oil and oil products are relatively well approximated by a random walk.

Accordingly, we assume that although future prices are uncertain, given the current price p_t, their common expectation in present-value terms is:

$$\mathbb{E}\left[p_s|p_t\right] = p_t.$$

Based on these assumptions, and further assuming risk neutrality, we adhere to Hotelling's valuation principle. At date t, firm i maximizes the future discounted stream of its expected profits, by choice of extraction quantities x_{it}, generating a current market value:

$$V_t(p_t, \gamma_{it}) = \max_{(x_{is})_{s\geq t}, \bar{Q}_{it}} \sum_{s\geq t} \mathbb{E}\left[p_s|p_t\right] x_{is} - C_{it}(\bar{Q}_{it}) + \text{NOP},$$

under the constraint that economic reserves are planned long-run cumulative extraction:

$$\bar{Q}_{it} = \sum_{s\geq t} x_{is}.$$

In this formulation, discounting is implicit since revenues and costs are expressed in present-value terms. Moreover, we introduce NOP to capture expected "non-oil profits," assumed independent of the oil price.

The market value of the oil company at date t can be simplified to:

$$V_t(p_t, \gamma_{it}) = p_t \bar{Q}_{it} - C_{it}(\bar{Q}_{it}) + \text{non-oil profits},$$

which has the same form as the profit function in the static model of Section III. The same derivation as in the previous appendix allows us to obtain the effect of a change in the current oil price on stock returns:

$$\Delta V \simeq \beta \Delta p + \frac{1}{2}\beta\rho(\Delta p)^2,$$

where ρ is now elasticity of economic reserves, $\rho \equiv \frac{\bar{Q}'_{it}(p_t)p_t}{\bar{Q}_{it}(p_t)} = \frac{MC_{it}(\bar{Q}_{it})}{MC'_{it}(\bar{Q}_{it})\bar{Q}_{it}}$.

This model features the same properties as the static model of Section III. First, the relation between oil returns and stock returns is convex. Its convexity reflects ρ, the elasticity of economic reserves. When prices are higher, β increases.

C More details on reserves data

Data Collection: Rystad Energy gathers data from various sources. This includes public sources such as company reports, filings, and presentations, as well as regulatory databases. They also utilize proprietary data obtained through partnerships, industry contacts, and field surveys. Their global network and access to numerous data sources enable them to compile a comprehensive dataset.

Asset-Level Analysis: For 2P reserves (Proven plus Probable), Rystad conducts an asset-level analysis. This involves examining individual oil fields or reservoirs for their geological characteristics, production levels, remaining reserves, and technological requirements. They assess each asset's technical data, operational status, and future development plans.

Estimating Breakeven Prices: Breakeven prices are calculated based on a combination of operational and financial metrics. This includes costs related to exploration, drilling, extraction, transportation, and other operational expenses. They also consider capital expenditures, overhead costs, and necessary returns on investment. For each asset, they estimate the oil price at which the total revenues from the asset would cover all these costs and expenditures, effectively determining the price at which the operation becomes profitable.

Economic and Market Considerations: Rystad's analysis also factors in broader economic and market variables such as global oil prices, market supply and demand dynamics, geopolitical factors, and environmental regulations. These factors can significantly influence the costs and revenues associated with oil assets.

Advanced Modeling and Analytics: Rystad employs advanced statistical models, simulations, and predictive analytics to process and analyze the collected data. This allows them to make informed estimates and forecasts about reserve sizes, production lifespans, and financial viability.

Regular Updates and Revisions: The oil and gas industry is dynamic, with frequent changes in market conditions, technological advancements, and regulatory environments. Rystad regularly updates their datasets and models to reflect these changes, ensuring their estimates remain relevant and accurate.

In summary, Rystad Energy's methodology for collecting data and estimating breakeven prices for oil assets involves a thorough analysis of extensive data from multiple sources, detailed asset-level examination, and sophisticated economic modeling. This approach enables them to provide accurate and comprehensive insights into the oil industry, crucial for businesses, investors, and policymakers.

D RSP estimates and properties

RSP estimates tend to decrease with the oil price. When the oil price is high, the sensitivity of reserves becomes zero, as reflected in the marginal cost curves. As oil production becomes

less profitable, however, the extensive margin plays a greater role.

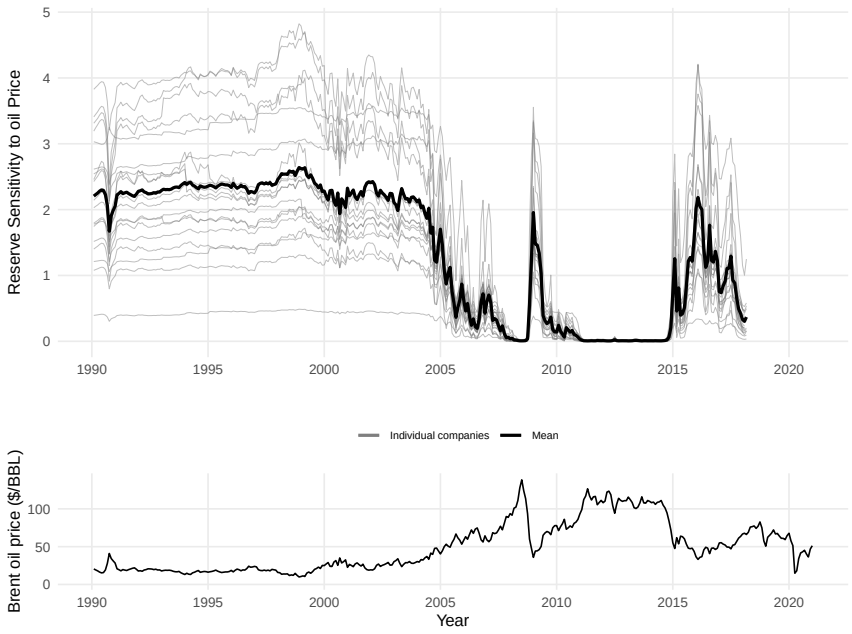


Figure 3: RSP variations across companies, price, and months

RSP estimnates are independent of companies' size. $Cor(RSP, Reserves) = -0.07$. This independence makes RSP a useful measure to compare oil reserves' vulnerability across companies

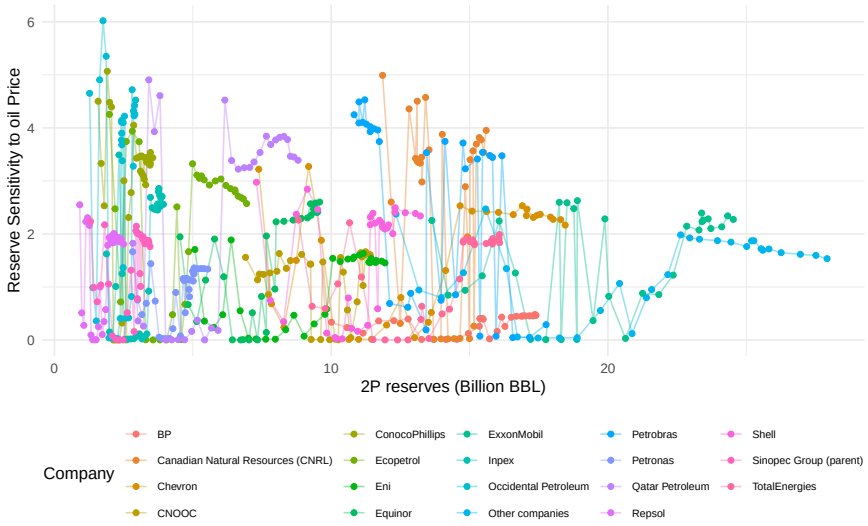


Figure 4: RSP variations with companies' reserves

Dependent variable: log(RSP)	Log-linear	Log-log
Brent price	***-0.064	
	(0.003)	
2P reserves	-0.013	
	(0.014)	
log(Brent price)		***-2.689
		(0.128)
log(2P reserves)		-0.142
		(0.111)
N	589	589
R^2	0.82	0.66

Note: SEs clustered by company.

Table 3: RSP variations with price and reserves