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In the heat of the moment, secrets will out: Oil price uncertainty and firm green innovation disclosure

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A R T I C L E I N F O

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A B S T R A C T

This study investigates the relationship between oil price uncertainty and corporate green innovation disclosure behaviour. Drawing on a textual analysis of annual reports and social responsibility reports of Chinese listed companies, we construct a measure for the intensity of corporate green innovation disclosure. We find a significantly positive relationship between oil price volatility and the level of green innovation disclosure. This relationship remains robust after conducting robustness tests and addressing potential endogeneity. Further analysis reveals that this positive association is moderated by several firm-level factors, including environmental performance, legitimacy demands, and political connections. Additionally, the positive relationship is more pronounced in firms subject to higher regional environmental regulation intensity and market-based green initiatives. Our findings contribute new evidence to corporate sustainable development, demonstrating that energy uncertainty significantly influences information transparency in green innovation disclosure.

1. Introduction

The heightened interest in sustainability, particularly oil price uncertainty (OPU), has become a central topic in both academic and industrial discourse (Hu et al., 2023a). Existing literature underscores the profound impacts of oil price fluctuations on businesses, including higher operational costs, supply chain disruptions, exchange rate volatility, and energy policy uncertainty (Hu and Su, 2018; Smith & Jones, 2021). Heightened uncertainty may intensify stakeholders' concerns, thereby requiring companies to demonstrate their efforts in addressing these uncertainties through disclosures (Orij, 2010). While existing studies explore the impact of OPU on innovation commitment (Amin et al., 2023; Yang & Song, 2023), a gap remains in understanding how oil price fluctuations influence green innovation disclosure. This information is valuable to stakeholders and policymakers as it enhances transparency regarding innovation. This paper aims to explore how OPU influences corporate green innovation disclosure behaviour, revealing the motivations, challenges, and implications of these disclosures in the pursuit of sustainable development.

Oil price volatility creates uncertainties that affect firm profitability, valuations, and investment decisions (Henriques & Sadorsky, 2011), making it challenging for stakeholders to gauge a company's soundness. Firm green innovation disclosure is crucial for shaping stakeholder perceptions, boosting investor confidence, and ensuring regulatory compliance (Clarkson et al., 2008; Patten, 2002). In China, companies have the discretion to voluntarily disclose green innovation initiatives in their annual reports. According to

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proprietary cost theory, companies, when deciding on whether and when to disclose innovation information, balance the benefits of disclosure, such as gaining investor trust and improving reputation, against the concern to protect their competitive advantage (Berger & Hann, 2007; Imhof et al., 2022). While voluntary disclosure can showcase a company's green innovation efforts to the public, it may also expose sensitive research and development information to competitors. Thus, firms face the dilemma of whether, and to what extent, to voluntarily disclose their green innovation behaviour.

On one hand, OPU may reduce the level of green innovation disclosures. Disclosure might allow competitors to obtain key information, enabling them to take actions that could weaken the company's market position and competitiveness (Ellis et al., 2012). Moreover, since innovation projects often involve high uncertainty, disclosing innovation information may lead to inflated market expectations or concerns regarding the company's future performance. The failure of an innovation project could result in a significant decline in investor confidence (Greve, 2011). Additionally, disclosing green innovation during periods of high OPU may pose risks to stakeholders. While stakeholder theory indicates that voluntary disclosures can meet stakeholder demands, improve transparency, and demonstrate sustainability efforts (Phan et al., 2021), conflicting interests among stakeholders may compel firms to weigh the benefits of transparency against potential downsides.

Conversely, oil price uncertainty may increase green innovation disclosures, as explained by asymmetric information and signalling theories (Phan et al., 2021). OPU often leads to declines in corporate profitability, which can reduce shareholder returns and increase concerns regarding future financial performance (Song & Yang, 2022; Thi Huong Vuong et al., 2024). In response to these pressures, firms may increase green innovation disclosures as a strategic tool to mitigate stakeholder concerns. By providing transparency on sustainability initiatives, firms reduce information asymmetry and signal their commitment to long-term sustainable goals (López-Santamaría et al., 2021; Morellec & Schürhoff, 2011). Such disclosures are particularly effective in enhancing corporate credibility during periods of external uncertainty, helping to reassure stakeholders of the firm's capacity to manage sustainability risks (Stocken, 2000; Willems & Faulk, 2019). Furthermore, increased green innovation disclosures enable firms to showcase proactive efforts in addressing environmental challenges, thereby reinforcing stakeholder confidence in their ability to navigate future uncertainties (Orij, 2010).

Selecting China as the research context for examining OPU's impact on firm green innovation disclosure is grounded in several factors. Foremost, China's status as the world's largest net oil importer and second-largest oil consumer uniquely positions it at the nexus of oil market dynamics and firm behaviour. The National Bureau of Statistics of China highlights that the nation's dependency on oil imports has been rising, surpassing 70% in 2018, which makes Chinese firms particularly susceptible to oil price shocks (National Bureau of Statistics of China, 2018). Moreover, a lack of transparency in information is a major concern in Chinese financial market development. Information asymmetry, coupled with less mature regulatory and investor protection mechanisms, suggests that Chinese firms may exhibit distinct responses to oil price volatility compared to firms in more developed markets (Hu et al., 2022). Additionally, there is growing interest in exploring the relationship between oil prices and market dynamics within the Chinese context (Cong et al., 2008; Zeng et al., 2012). Although previous research has explored the link between oil price shocks and stock market fluctuations in China (Cong et al., 2008; Wei et al., 2019), the dynamic relationship between oil market shocks and firm disclosure behaviour remains underexplored. This gap presents a unique opportunity to contribute to the literature by examining how Chinese firms navigate the challenges posed by oil price volatility and the extent to which this influences their environmental claims and actions.

Utilising data from China's A-share market from 2008 to 2023, this study explores the relationship between OPU and firm green innovation disclosure. Based on a textual analysis of the annual reports and social responsibility reports of Chinese listed companies, we construct a measure for corporate green innovation disclosure, following Xie et al.'s (2019) method. The regression analysis indicates a significant positive relationship between OPU and the level of green innovation disclosures. To ensure robustness, additional tests control for economic policy uncertainty beta, firm fixed effects, and industry-province and firm-province fixed effects. Furthermore, to validate our findings, alternative measurements of OPU are adopted. We also employ lagged variable and instrumental variable approaches to rigorously address potential endogeneity.

We investigate moderating factors influencing the relationship between OPU and green innovation disclosure. Drawing on stakeholder and legitimacy theories, Goss and Roberts (2011) emphasise the importance of aligning corporate strategies with the interests of a broader range of stakeholders. Similarly, Deegan et al. (2000) argue that firms facing greater legitimacy demands are more likely to enhance legitimacy through disclosure mechanisms. Our findings indicate that both corporate environmental performance and legitimacy demands positively moderate the relationship between OPU and green innovation disclosure. In China's politically influenced environment, we also find that corporate political connections strengthen the positive relationship between OPU and green innovation disclosure. Furthermore, China's carbon trading pilot scheme, part of its broader strategy to combat climate change and reduce carbon emissions, as well as the stringency of regional environmental regulations, positively influence corporate green innovation disclosure.[1] These findings underscore the complex interplay between corporate responses to energy risks and the critical role of regulatory activism in promoting voluntary green innovation disclosure, enhancing informational transparency for both stakeholders and policymakers.

The contributions of this paper are fourfold. First, leveraging the context of OPU, our research provides new evidence in the debate on voluntary innovation disclosure by firms. According to proprietary cost theory, as suggested by studies such as Verrecchia (1993), Imhof et al. (2022), and Berger and Hann (2007), firms should protect their innovation information and avoid proactive disclosure to prevent leaks of confidential information and increased competition. Conversely, information asymmetry theory and signalling theory

[1] We thank the anonymous reviewer for these insights.

suggest that firms can signal their activities to the outside world through information disclosure, thereby mitigating information asymmetry between firms and stakeholders to gain trust and understanding (Pan et al., 2020). Our study fills a gap in the existing literature by supporting signalling theory. While previous studies have examined the relationship between OPU and patents (Amin et al., 2023; Yang & Song, 2023), the outcomes of innovation and innovation disclosure differ. First, patents are mandatory disclosures and are legally protected, while corporate innovation disclosures are voluntary and thus not protected due to their voluntary nature. Second, patents represent innovation output, whereas disclosures may include plans and progress on innovation. Interestingly, both Amin et al. (2023) and Yang and Song (2023) find that OPU reduces the number of patents and citations, yet we find that OPU increases firms' voluntary information disclosures related to green innovation. This finding not only provides new theoretical perspectives but also significant insights on corporate disclosure practices.

The second contribution of this study is expanding the existing literature on corporate voluntary disclosure in the context of heightened energy uncertainties, particularly regarding environmental responsibility. Oil price fluctuations heighten investor concerns regarding firms' exposure to energy-related risks (Maghyereh & Abdoh, 2020), and firms can alleviate these concerns through enhanced transparency from voluntary disclosures. While previous studies, such as those by Phan et al. (2021), Hasan et al. (2022b), and Benlemlih et al. (2024), have examined OPU's impact on corporate social responsibility (CSR) behaviour, their focus has primarily been on CSR or environmental performance overall. In contrast, our study explicitly centres on the disclosure of green innovation. Our study is unique, as oil price volatility directly affects the cost of oil, an essential input, creating uncertainties in profitability, valuations, and investment decisions (Henriques & Sadorsky, 2011). Such information asymmetry may heighten stakeholder concerns regarding firm transparency. Companies engage in voluntary disclosure not only to reduce information asymmetry between shareholders and management but also to lower their cost of capital (De Villiers & Van Staden, 2011). By releasing information transparently, companies signal their social commitments to external stakeholders, addressing concerns and enhancing credibility (Pan et al., 2020). Our findings provide new empirical evidence, demonstrating how firms respond to OPU by fostering green innovation disclosure, thereby advancing the understanding of corporate voluntary disclosure under conditions of energy uncertainty.

The third contribution of this study advances the ongoing debate on the impact of environmental reputation on corporate green innovation disclosure. Clarkson et al. (2008) suggest that companies are motivated to disclose 'good news' to distinguish themselves from firms with 'bad news', thus avoiding the adverse selection problem. As a result, firms with superior environmental reputations, due to proactive environmental strategies, are incentivised to voluntarily disclose more environmental information to inform investors and stakeholders (Clarkson et al., 2008). Similarly, studies by Zeng et al. (2012) and Huang and Kung (2010) indicate that firms with a stronger environmental reputation are more likely to disclose environmental information. Our findings show that the impact of OPU on green innovation disclosure is more significant for firms with stronger environmental commitments, as indicated by holding ISO environmental certifications and receiving higher third-party environmental ratings. This suggests that, when facing heightened energy uncertainties, firms with stronger environmental reputations are more likely to increase their green innovation disclosures in response to heightened stakeholder expectations. Our conclusions also differ from De Villiers and Van Staden's (2011) argument that firms with poor environmental reputations tend to disclose more environmental information, as well as from Nadeem's (2021) perspective on restorative justice in response to stakeholder pressure following corporate environmental violations.

Our results also provide new evidence on how regional policy orientation and market-based green initiatives promote corporate green innovation disclosure. In China, regional policy orientation plays a pivotal role in shaping firms' voluntary behaviours, closely linked to the nation's economic policy framework (Shen et al., 2020). Our findings reveal that the effect of OPU is more pronounced in firms located in regions with stronger environmental policy orientation. This finding aligns with Sun and Yang (2024), who find that government environmental target constraints can significantly drive firms' green innovation. Our study expands on this by focusing specifically on green innovation disclosure. Additionally, the carbon trading pilot scheme—a market-based effort to combat climate change and reduce carbon emissions—plays a crucial role in guiding corporate green strategies. We examine this scheme's moderating effect on the relationship between OPU and green innovation disclosure. Firms operating in carbon trading pilot regions are subject to stricter environmental regulations and are incentivised to adopt more sustainable practices to meet carbon reduction targets (Ren et al., 2024). Our findings show that firms in these pilot regions are more proactive in disclosing their green innovations when facing higher OPU.

The remainder of the study is organised as follows. Section 2 presents the literature review and hypothesis development. Section 3 reports the data, variable construction, and the regression model. Section 4 presents the empirical results and robustness tests. Section 5 concludes the study.

2. Literature review and hypothesis development

2.1. The economic impacts of oil price uncertainty

Previous literature has revealed the effects of oil prices and their uncertainty on macroeconomic and financial outcomes. Firstly, oil price volatility directly influences production costs and consumer spending (Koirala & Ma, 2020). As crude oil is an indispensable input in the production of most goods and services, an increase in its price raises the marginal cost of production while reducing consumers' spending capacity, thereby leading to a decrease in demand for corporate products (Pindyck, 1990). Moreover, fluctuations in oil prices are often linked to inflation or deflation, prompting central banks to adjust interest rates, which affects future firm cash flows and discount rates (Ferderer, 1996; Sadorsky, 1999).

Further research also demonstrates specific impacts of oil price uncertainty on macroeconomic factors, such as employment, income, consumption, labour flow, and output. Studies by Koirala & Ma (2020) reveal the impact of oil price uncertainty on the U.S.

unemployment rate, providing evidence of asymmetric effects of positive and negative oil price uncertainty shocks on rising unemployment rates. Supply-side effects induced by rising oil prices drive up production costs, slow economic growth, and reduce productivity (Brown & Yücel, 2002). Additionally, Maghyereh et al. (2019) show that oil market uncertainty negatively affected industrial output and document the asymmetric effects of oil price volatility on industrial production. Bashar et al. (2013) find that higher oil price uncertainty significantly reduced output and price levels. Ahmed and Wadud (2011) note that a positive shock to oil price uncertainty led to a decline in the consumer price index due to decreased purchasing power and disposable income. Herrera et al. (2019) argue that increased oil price uncertainty had a greater negative impact on employment flows in manufacturing than monetary policy uncertainty.

Existing research indicates that the impact of oil price fluctuations on firms is multifaceted, influencing profitability, investment decisions, financing conditions, and overall financial health. Bugshan et al., 2023 highlight that oil price volatility has a significant and negative impact on firm profitability, suggesting that future oil price uncertainty could profoundly influence corporate policies. At the investment level, Phan et al. (2019) observe that high oil price uncertainty increases the real option value of waiting, causing firms to delay investments until uncertainty resolves. This phenomenon is further supported by the adverse effects of oil price volatility on banks' lending capacities, as examined by Al-Khazali and Mirzaei (2017) and Lee and Lee (2019) in inefficient capital markets.

The broader impact of oil price uncertainty on firms' financial conditions has also drawn widespread attention. Fan et al. (2021), in studying the effects of market-oriented refined oil pricing reform on firm leverage, find a nonlinear relationship between oil price uncertainty and firm leverage, with trade credit and exacerbated financial distress risk as potential impact channels. Hasan et al. (2022a) also find that oil price uncertainty significantly affects short-term debt financing. Zhang et al. (2020) observe that oil price uncertainty increases firms' cash holdings, particularly when firm value increases, though this effect is mitigated for state-owned enterprises.

In the stock market, Park and Ratti (2008), Luo and Qin (2017), and Cunado and de Gracia (2014) all document the negative impact of oil price uncertainty on stock returns. Cunado and de Gracia (2014) suggest that the asymmetric impact of oil price uncertainty on stock returns can be explained by identifying the fundamental causes of oil price changes, whether demand- or supply-side. Additionally, Song and Yang (2022) demonstrate a negative correlation between oil price uncertainty and company performance, while Wong and Hasan (2021) find that oil demand shocks lead to increased stock repurchases, whereas oil supply shocks reduce dividends paid through stock repurchases, primarily driven by non-oil-producing companies. This implies that oil supply shocks create heightened uncertainty regarding companies' future growth potential.

2.2. The disclosure of green innovation under oil price uncertainty

Oil price uncertainty may exacerbate information asymmetry between firms and external stakeholders. Such uncertainty leads to delayed or altered investment decisions, especially in industries such as oil and gas, where companies with deeper market insights can manage risks more effectively than outside investors, widening the perceived risk gap (Maghyereh & Abdoh, 2020). Additionally, oil price volatility represents a source of uncertainty affecting the cost of a key input, oil, which creates further uncertainty regarding firm profitability, valuations, and investment decisions (Henriques & Sadorsky, 2011). This uncertainty makes it challenging for stakeholders to gauge a company's true health.

During periods of uncertainty, firms have incentives to provide insurance to the market about their stability by issuing new information (Assaf et al., 2023). Voluntary corporate disclosure serves as a key mechanism for reducing information asymmetry between firms and investors, and there is extensive research showing its effectiveness in managing risk and conveying information. For instance, signalling theory suggests that managers are motivated to send high-quality signals regarding performance and risk management system effectiveness to external investors, enabling them to adjust their valuation and risk perceptions accordingly (Lu et al., 2024). Research by Francis et al. (2008) demonstrates that voluntary disclosure significantly lowers the cost of capital, particularly for firms with higher earnings quality. Similarly, Jo and Kim (2007) show that increased disclosure frequency reduces incentives for earnings management by attracting investor attention, thereby improving earnings quality and enhancing liquidity.

Companies engage in voluntary disclosure not only to reduce information asymmetry between shareholders and management but also to lower the cost of capital (De Villiers & Van Staden, 2011). The uncertainty surrounding oil prices stems not only from market price fluctuations and raw material costs but also from changes in policy, competitive dynamics, and public opinion (Hasan et al., 2022b). Thus, voluntary disclosure becomes an effective tool for companies to signal transparency, align insider and outsider interests, and ultimately lower their cost of capital through increased transparency (Lu et al., 2024).

Oil price fluctuations also raise investor concerns regarding firms' exposure to energy-related risks (Maghyereh & Abdoh, 2020). According to information asymmetry and signalling theories, firms can signal their activities to external stakeholders through information disclosure, which mitigates information asymmetry, helping them gain trust and understanding (Pan et al., 2020). In response to higher expectations, firms with stronger reputations have greater incentives to voluntarily disclose information, signalling their commitment to transparency and adherence to higher social standards (Cao et al., 2012; Zeng et al., 2012). Moreover, companies can proactively disclose measures to address uncertainty rather than relying on reactive disclosure. Jog and McConomy (2003) argue that disclosing prospects through voluntary mechanisms can add value during periods of uncertainty. This proactive approach is particularly crucial during periods of market volatility, as it helps mitigate investor panic and fosters stakeholder trust (Lu et al., 2024). Proactive disclosures reach investors and other stakeholders quickly, emphasising a company's ongoing efforts, even at the planning stage. In green innovation, these disclosures may encompass not only innovation outcomes but also ongoing projects such as green technology development and energy efficiency improvements (Ho et al., 2023).

In markets such as China, where green innovation disclosure is not mandated, companies have the flexibility to decide the scope and nature of their disclosures (Xiang et al., 2020). This autonomy enables firms to control their narrative by reporting both ongoing and completed projects. Furthermore, China's policy environment, characterised by frequent changes and a focus on green development, increases the pressure on firms to engage in proactive disclosure. By doing so, companies can align with national sustainability policies, secure government support, and enhance social recognition (Xiang et al., 2020). Given the volatility of policy shifts, timely and transparent disclosures also help mitigate adverse market reactions (Hu et al., 2023b). Based on this analysis, we propose the following first hypothesis:

Hypothesis 1. Oil price uncertainty increases firm green innovation disclosure.

In contrast, heightened OPU may reduce the disclosure of green innovation. During periods of oil price fluctuation, disclosing green innovation may pose risks to stakeholders. While stakeholder theory suggests that firms use environmental disclosures to meet stakeholder demands, improve transparency, and demonstrate sustainability efforts (Phan et al., 2021), conflicting interests among stakeholders may compel firms to weigh the advantages of transparency against potential downsides. For instance, although investors may value insight into a company's strategies, disclosing green innovations could highlight high costs and long-term risks (Zhao et al., 2023). Rising oil prices reduce purchasing power and discretionary income, curbing consumption and reducing revenue (Baumeister et al., 2018). This uncertainty regarding future growth may trigger investor short-termism, leading to negative reactions to costly innovation activities. Furthermore, oil price fluctuations directly impact firms' operational costs and profitability, prompting them to be more cautious in these periods (Hamilton, 2009). Under such conditions, environmental initiatives may be considered less effective or beneficial in the short term, causing hesitation among both customers and suppliers (Murfield & Tate, 2017).

Moreover, proprietary cost theory suggests that disclosing sensitive innovation-related information can expose a firm's strategies to competitors, enabling them to counteract these strategies and thus eroding the firm's market position (Verrecchia, 1983). Green innovations often involve new, highly proprietary technologies and business models that are strategically significant. During periods of oil price uncertainty, competitors might actively seek new advantages, and disclosing green innovation strategies could inadvertently provide them with critical insights that allow them to imitate or counteract these innovations. Consequently, firms may opt to keep their information confidential, particularly in an uncertain oil price environment, to safeguard their competitive edge and maintain market share (Badia et al., 2021).

Furthermore, innovation projects often involve complex technical and market risks (Nanda & Rhodes-Kropf, 2017). For example, during periods of low oil prices, the cost advantage of traditional energy may overshadow the appeal of green energy projects, causing investors to question their economic viability. In such cases, disclosing green innovation information could lead to investor scepticism and increase the firm's financing and operational pressures. We expect that during periods of high OPU, disclosing green innovation information may heighten market concerns regarding the uncertainties associated with green innovation, particularly when these projects involve significant upfront investments and long-term technological development, both of which carry considerable uncertainty. Based on the above analysis, we propose the following hypothesis:

Hypothesis 2. Oil price uncertainty reduces firm green innovation disclosure.

3. Data and methodology

3.1. Sample

In this study, our sample initially consists of all non-financial A-share listed firms on the Shanghai Stock Exchange (SHSE) and Shenzhen Stock Exchange (SZSE) from 2008 to 2023. The starting year of 2008 was selected because China implemented the new accounting standards in 2007. We exclude firm-year observations with missing values, followed by firms listed on the stock exchange for less than 3 years. All continuous variables are winsorised at the top and bottom 1% to control for the possible disturbance of outliers. Our final sample includes 30,829 firm-year observations for 4532 firms. We collect firm-specific data from the China Stock Market & Accounting Research Platform (CSMAR) database and oil price data from the U.S. Energy Information Administration.

3.2. Variable description

3.2.1. Oil price uncertainty

The daily crude oil futures price of Brent is selected as a proxy for international crude oil prices, and we employ two measures to obtain metrics for OPU. The first measurement of OPU in our study is the standard deviation of daily oil price returns over 1 year, following Henriques and Sadorsky (2011):

$$OILVOL_t = \sqrt{\frac{1}{N-1}\sum_{d=1}^{N}(r_d - E(r_d))^2 * \sqrt{N}}$$

where r_d represents daily oil price returns for trading day d, and N represents the number of trading days in year t.

The second measurement of OPU in our study is the average of the daily conditional variance generated from a GARCH (1,1) model over 1 year, following Alaali (2020):

$$OILVAR_t = GARCH_t = \frac{1}{N}\sum_{d=1}^{N}\widehat{h_d}^2 * \sqrt{N}$$

where $\widehat{h_d}$ represents the fitted value of the conditional variance of trading day d from the GARCH (1,1) model, estimated using daily oil price returns r_d.

3.2.2. Firm green innovation disclosure

We employ the method of content analysis to analyse the textual information in corporate annual reports and social responsibility reports, aiming to construct a measure for corporate green innovation disclosure. Content analysis is a technical tool used for investigating published information (Tao et al., 2024; Xie et al., 2019; Yu & Jin, 2022). According to Xie et al. (2019), we quantify the level of corporate green innovation disclosure by constructing a composite index that includes five specific indicators (refer to Appendix A), designed to capture different dimensions of corporate green innovation.

Our analysis focuses on corporate CSR reports and annual reports, with particular attention to sections on environmental protection, sustainable development, and technological innovation. These sections typically contain voluntarily disclosed information regarding companies' environmental innovation initiatives. To ensure the accuracy and comprehensiveness of keyword selection, we refer to the coding methods of Xiang et al. (2020) and Mallin et al. (2013) and compile a set of keywords related to green innovation. This enables us to identify the extent of corporate disclosure on specific environmental innovation activities in the text analysis. The keywords for each indicator were carefully selected and calibrated to ensure they accurately reflect the company's innovation efforts in the respective areas. For instance, for the indicator 'Reducing resource and energy consumption and improving efficiency' (PROC1) in Appendix A, we selected the following 15 keywords: 'energy-saving technology', 'process optimisation', 'renewable energy', 'low-energy consumption', 'energy efficiency', 'resource optimisation', 'energy management system', 'green energy', 'carbon footprint reduction', 'waste heat recovery', 'energy conservation', 'smart grid', 'clean energy', 'cogeneration', and 'energy audit' (translated from Chinese). We first constructed a training sample to ensure these keywords are widely used terms that cover the key green innovation activities in this domain.

In the text analysis process, we combine coding with manual verification to conduct a quantitative analysis of the frequency of keyword occurrences in each report. Python is used to preprocess the text data related to environmental innovation. Specifically, we calculate the frequency of each keyword in the text and score each indicator according to the following rules: if the total frequency of keywords listed for a given indicator is 0 (i.e., there is no relevant description in the report), the score is 0; if the keywords appear 1–5 times, indicating only basic descriptions without detailed implementation information, the score is 1; if the keywords appear more than 5 times or there is a detailed description of specific implementation measures, effects, or technical applications, the score is 2. This scoring system is designed to differentiate the depth of corporate disclosure regarding green innovation, thus providing a more accurate reflection of the company's true extent of environmental innovation efforts.

3.2.3. Control variables

Following the approach of previous studies on firm disclosure, such as Flammer et al. (2021), we include a set of firm and CEO characteristics as control variables, which are recognised as significant determinants of firm disclosure. These variables include the market-to-book ratio (*MTB*), sales growth (*Growth*), return on assets (*ROA*), firm size (*Size*), leverage ratio (*Lev*), liquidity (*Cash*), R&D intensity (*RDSales*), board size (*Board*), board independence (*Indep*), auditor prestige (*Big410*), major shareholder ownership (*Top1*), state ownership (*SOE*), and market risk exposure (*Marketbeta*). Additionally, we include industry fixed effects to control unobservable industry-level and macroeconomic factors. Appendix B presents these variable definitions.

Table 1
Descriptive statistics.

	N	mean	sd	min	p25	p50	p75	max
OILVOL	30,829	0.296	0.076	0.169	0.240	0.303	0.310	0.551
OILVAR	30,829	0.008	0.002	0.005	0.006	0.007	0.009	0.013
GInoDis	30,829	0.327	0.413	0.000	0.000	0.000	0.667	2.000
MTB	30,829	1.924	1.259	0.866	1.197	1.515	2.122	8.631
Growth	30,829	0.116	0.296	−0.937	−0.043	0.091	0.232	1.527
ROA	30,829	0.047	0.097	−0.406	0.016	0.049	0.092	0.291
Size	30,829	22.240	1.264	20.040	21.320	22.030	22.940	26.060
Lev	30,829	0.413	0.200	0.057	0.254	0.405	0.558	0.896
Cash	30,829	0.159	0.120	0.011	0.072	0.126	0.210	0.595
RDSales	30,829	0.050	0.051	0.000	0.020	0.038	0.058	0.309
Board	30,829	2.107	0.194	1.609	1.946	2.197	2.197	2.639
Indep	30,829	0.378	0.054	0.333	0.333	0.364	0.429	0.571
Big410	30,829	0.514	0.500	0.000	0.000	1.000	1.000	1.000
Top1	30,829	0.332	0.144	0.087	0.221	0.309	0.426	0.721
SOE	30,829	0.292	0.455	0.000	0.000	0.000	1.000	1.000
Marketbeta	30,829	1.003	0.086	0.793	1.000	1.000	1.008	1.276

This table reports the descriptive statistics of the main variables used in the study. The sample consists of firms listed on the SHSE and SZSE from 2008 to 2023 (30,829 observations). Detailed definitions of variables are presented in Appendix B.

3.3. Summary statistics

Table 1 provides the descriptive statistics for the main variables, detailing means, standard deviations, and distribution data. The mean value of *GInoDis* is 0.327, with a minimum value of 0 and a maximum value of 2. Approximately 25% of the sample firms engage in voluntary green innovation disclosure. For *OILVOL*, the minimum, maximum, mean, and standard deviation values are 0.169, 0.551, 0.296, and 0.076, respectively, while for *OILVAR*, they are 0.008, 0.013, 0.008, and 0.002, respectively. These figures demonstrate that oil price returns exhibit significant fluctuations throughout the sample period.

The correlation coefficients of the key variables are reported in Table 2. The absolute values of the correlation coefficients between the other variables are relatively low, indicating multicollinearity is not a significant issue in our study.

4. Empirical results

4.1. Baseline regression result

In this study, our primary objective is to explore the impact of OPU on firms' innovation disclosure. Table 3 presents the estimated results from our analysis of OPU's effects on firm innovation disclosure. The coefficients of OPU in Columns (1) and (2) are positive and significant at the 1% level, demonstrating that OPU positively influences firm innovation disclosure. In terms of economic significance, for example, in Column (1) of Table 3, a 1 standard deviation increase in *OILVOL* leads to a decrease of 4.39% in the green innovation disclosure index (i.e., $(0.189 \times 0.076)/0.327 = 4.39\%$). This supports our positive association conjecture mentioned in Section 1. In times of uncertainty, firms have incentives to provide insurance to the market about their stability by issuing new information (Assaf et al., 2023). During periods of uncertainty, firms are incentivised to assure the market regarding their stability by issuing new information (Assaf et al., 2023). Oil price volatility heightens investor concerns regarding firms' exposure to energy-related risks (Maghyereh & Abdoh, 2020). By disclosing sustainability information, firms not only reduce information asymmetry but also signal their commitment to long-term environmental sustainability and risk management (López-Santamaría et al., 2021; Morellec & Schürhoff, 2011).

4.2. Robustness tests

In this section, we present several robustness tests to validate our main results. Specifically, we investigate whether the documented positive effect of OPU on firm innovation disclosure in Section 3.1 is robust to (1) controlling for multiple fixed effects, (2) controlling for other macroeconomic uncertainties, and (3) using an alternative proxy for oil price uncertainty.

In the baseline regression, we control for industry fixed effects, and following the research of Nguyen and Phan (2017) on economic policy uncertainty, the standard errors are clustered at the firm-year level. To further examine the robustness of our baseline regression results, this study employs a series of fixed effects controls to address potential confounders within the dataset. Specifically, Table 4 presents the outcomes of the baseline regression model, incorporating firm fixed effects. This adjustment aims to mitigate the influence of unobserved, firm-specific characteristics that could potentially bias the results. Table 5 extends the analysis by incorporating both industry-province and firm-province fixed effects, effectively controlling for systematic differences across firms, sectors, and regions that could influence the dependent variables. The results in Tables 4 and 5 show that OPU remains significantly and positively associated with firm green innovation disclosure after controlling for multiple fixed effects.

Existing studies have documented that several macroeconomic uncertainties can affect firm innovation disclosure. Therefore, one potential concern regarding our main results is that it may be other macroeconomic uncertainties, rather than OPU, that induce the increase in firm innovation disclosure. To address this concern, we check whether our main results are robust to including other macroeconomic uncertainties. Specifically, following Phan et al. (2021), we control for firm exposure to the China Economic Policy Uncertainty Index (EPU), as constructed by Baker et al., 2013. We calculate firm risk exposure by incorporating the natural logarithm of the EPU Index into the Fama-French Three-Factor Model, and we take the absolute value of EPU beta. The regression results controlling for EPU beta are shown in Table 6 (we exclude market beta due to collinearity concerns). The coefficients of OPU in Columns (1) and (2) are positive and significant at the 1% level, suggesting that OPU positively affects firm innovation disclosure. The results are consistent with the baseline, indicating that our main results are robust after controlling for other macroeconomic uncertainties.

To assess the robustness of our findings and address potential concerns regarding the measurement of oil price uncertainty, we examine whether our main results hold when employing an alternative proxy for this key variable. Specifically, we utilise the OPU calculated through the EGARCH model, enabling us to capture the dynamic nature of oil price volatility and its potential impact on the economic indicators under study. The results of this analysis, presented in Appendix C, complement our primary findings by providing an alternative measure of oil price uncertainty. Our findings, which remain significant across the alternative specifications, reinforce the robustness of our main results.

4.3. Analysis of endogeneity issue

To address potential concerns of reverse causality or contemporaneous relationships between OPU and voluntary green innovation disclosure, this study applies a lagged approach to both the independent and control variables. By incorporating a 1-year lag, we aim to capture the effects that oil price volatility may have on firm green innovation disclosure. This method helps mitigate endogeneity

Table 2
Pairwise Pearson correlation coefficients.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(1) *OILVOL*	1														
(2) *OILVAR*	0.784***	1													
(3) *MTB*	0.085***	0.098***	1												
(4) *Growth*	−0.087***	−0.048***	0.075***	1											
(5) *ROA*	−0.031***	−0.011***	−0.096***	0.335***	1										
(6) *Size*	−0.017***	−0.016***	−0.047***	0.050***	0.066***	1									
(7) *Lev*	0.048***	0.022***	0.401***	0.014**	−0.252***	0.489***	1								
(8) *Cash*	−0.033***	−0.009**	−0.084***	0.025***	0.196***	−0.213***	−0.416***	1							
(9) *RDSales*	−0.029***	0.013**	0.054***	−0.071***	−0.121***	−0.221***	−0.282***	0.189***	1						
(10) *Board*	0.023***	0.011**	−0.020***	0.018***	0.058***	0.249***	0.132***	−0.034***	−0.117***	1					
(11) *Indep*	−0.022***	−0.003***	0.022***	−0.016***	−0.035***	−0.004	−0.005	0.005	0.047***	−0.567***	1				
(12) *Big410*	−0.034***	−0.079***	−0.003	0.066***	0.097***	0.080***	0.002	0.010*	−0.025***	0.034***	0.002	1			
(13) *Top1*	−0.006	−0.012**	−0.082***	0.012**	0.162***	0.162***	0.015***	0.048***	−0.173***	0.013**	0.041***	0.088***	1		
(14) *SOE*	0.063***	0.031***	0.034***	−0.059***	−0.043***	0.363***	0.267***	−0.059***	−0.194***	0.265***	−0.057***	0.011*	0.214***	1	
(15) *Marketbeta*	−0.206***	−0.199***	0.011*	−0.019***	0.051***	−0.149***	−0.024***	0.094***	−0.021***	0.045***	−0.027***	−0.036***	0.048***	0.017***	1

This table reports the Pearson correlation coefficient. *t*-statistics are given in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 3
Baseline regression.

	(1)	(2)
	GInoDis	GInoDis
OILVOL	0.189***	
	(5.360)	
OILVAR		12.146***
		(4.291)
MTB	0.001	0.001
	(0.023)	(0.315)
Growth	−0.034***	−0.035***
	(-3.856)	(-3.758)
ROA	0.091*	0.093**
	(2.086)	(2.165)
Size	0.103***	0.102***
	(7.080)	(7.042)
Lev	−0.064***	−0.059***
	(-5.081)	(-5.914)
Cash	−0.006**	−0.004**
	(-2.143)	(-2.082)
RDSales	0.173*	0.169*
	(1.981)	(1.978)
Board	0.025**	0.026**
	(2.258)	(2.012)
Indep	0.093**	0.094**
	(2.076)	(2.095)
Big410	0.018***	0.018***
	(4.127)	(4.079)
Top1	0.075**	0.076**
	(2.663)	(2.714)
SOE	0.068***	0.068***
	(4.579)	(4.592)
Marketbeta	−0.177***	−0.162***
	(-3.811)	(-3.332)
Constant	−1.963***	−2.006***
	(-4.827)	(-5.498)
Industry FE	Yes	Yes
Observations	30,829	30,829
Adjusted R-squared	0.196	0.198

This table presents the impact of OPU on firm green innovation disclosure. Columns (1) and (2) respectively show the regression results with *OILVOL* and *OILVAR* as independent variables and *GInoDis* as the dependent variable, controlling for industry fixed effects. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

issues, providing a more reliable understanding of the causal impact of oil price uncertainty on firms' voluntary green innovation disclosures. Table 7 presents the results using a 1-year lag for both the independent and control variables. The results show that the association between the two OPU measurements and *GInoDis* remains significant, confirming the robustness of the baseline results.

To further address the endogeneity concern arising from the omission of macroeconomic variables and causality, we employ instrumental variable 2SLS estimation. Following the approach of Hasan et al. (2022a), we employ the geopolitical risks index (*GPR4c*) as the instrumental variable for oil price uncertainty. Geopolitical risks indirectly influence firm investment through their impact on oil price uncertainty, and prior studies have confirmed its significant role in influencing oil price uncertainty (Noguera-Santaella, 2016). However, the geopolitical risks index is not found to influence corporate green innovation disclosure. Therefore, it can be deemed as a strong instrument for OPU.

In the first stage, we regress the instrumental variables on each independent variable: *OILVOL* and *OILVAR*, respectively. The results are shown in Columns (1) and (2) of Table 8. *GPR4c* is positively related to *OILVOL* and *OILVAR* (with both coefficients statistically significant at the 1% level). The Cragg–Donald Wald F statistics for each test are 595.915 and 1989.649, which exceed the critical value, indicating that we can safely reject the weak instrumental variable hypothesis. The Kleibergen–Paap Wald rk LM statistics are significant at the 1% level, suggesting that the model is not under-identified. The fitted value of the first-stage regression is then collected and used as the main independent variable in the second-stage analysis. The results of the second-stage analysis are reported in Columns (3) and (4) of Table 8. The coefficients of fitted values are positive and statistically significant in both columns. Overall, our baseline results remain robust after addressing endogeneity employing the instrumental variable 2SLS estimation.

Table 4
Robustness test: Controlling for firm fixed effects.

	(1)	(2)
	GInoDis	GInoDis
OILVOL	0.091**	
	(2.190)	
OILVAR		6.878***
		(3.761)
MTB	−0.002***	−0.003
	(-3.691)	(-1.032)
Growth	−0.029**	−0.028**
	(-2.739)	(-2.300)
ROA	0.013	0.013
	(0.290)	(0.289)
Size	0.063***	0.062***
	(4.922)	(5.135)
Lev	−0.064	−0.072
	(-1.548)	(-1.263)
Cash	−0.025	−0.028
	(-0.570)	(-0.629)
RDSales	−0.108	−0.115
	(-1.091)	(-1.163)
Board	−0.072**	−0.071*
	(-2.168)	(-2.129)
Indep	−0.065	−0.064
	(-0.638)	(-0.628)
Big410	0.030***	0.034***
	(3.268)	(3.211)
Top1	−0.084*	−0.083*
	(-1.826)	(-1.792)
SOE	0.074***	0.073***
	(4.492)	(4.435)
Marketbeta	−0.253**	−0.242**
	(-2.344)	(-2.244)
Constant	−0.675**	−0.692**
	(-2.171)	(-2.731)
Firm FE	Yes	Yes
Observations	30,546	30,546
Adjusted R-squared	0.433	0.434

This table presents the robustness test, controlling for firm fixed effects. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

4.4. Factors shaping the influence of OPU on green innovation disclosures

Firms may have unique motivations for disclosing green innovations under external environmental pressures, which can be explained by various theories. In this section, we examine the factors influencing the impact of oil price uncertainty on green innovation disclosures.

4.4.1. Analysis of moderating factors on OPU and green innovation disclosures

There is an ongoing academic debate regarding whether companies with good reputations are more inclined to disclose information compared to those with poor reputations. Some studies, such as by Clarkson et al. (2008), argue that firms with superior reputations are motivated to disclose positive information to distinguish themselves from firms with negative news, thus avoiding adverse selection. Stakeholder theory, as advocated by scholars such as Bhandari and Javakhadze (2017) and Goss and Roberts (2011), emphasises the importance of aligning firm strategies with the interests of all stakeholders, beyond solely profit maximisation. This theory suggests that firms with stronger reputations, driven by societal and governmental demands for sustainability, may be more inclined to disclose green innovation efforts to meet stakeholder expectations. However, contrasting views, such as from De Villiers and Van Staden (2011), propose that firms with poorer reputations may disclose more information to address stakeholder concerns. Given this conflicting evidence, further research is required to clarify which types of firms are more likely to disclose.

To identify firms with stronger reputations in environmental initiatives, we refer to Liu et al. (2024) and Tu et al. (2024) and utilise the environmental sub-index from the Huazheng ESG Index to measure firm environmental performance. According to Bhandari and Javakhadze (2017), firms that prioritise stakeholder interests are expected to place greater emphasis on their CSR objectives. We introduce an interaction term between the two OPU measurements and a dummy variable, *HighCEP*. which takes the value of 1 if the firm's environmental performance score is above the industry-level median for the year, and 0 otherwise. The regression results, as shown in Table 9, indicate that both the *HighCEP* variable and the interaction term between OPU and *HighCEP* are positively associated

Table 5
Robustness test: Additional control for firm and province fixed effects.

	(1)	(2)	(3)	(4)
	GInoDis	GInoDis	GInoDis	GInoDis
OILVOL	0.179***		0.090**	
	(5.316)		(2.189)	
OILVAR		11.796***		6.878***
		(4.257)		(3.760)
MTB	0.001	−0.001	−0.002	−0.003
	(0.163)	(-0.195)	(-0.690)	(-1.031)
Growth	−0.035***	−0.035***	−0.029**	−0.028**
	(-6.870)	(-6.766)	(-2.738)	(-2.299)
ROA	0.093**	0.094**	0.013	0.013
	(2.187)	(2.265)	(1.290)	(1.289)
Size	0.102***	0.101***	0.063***	0.062***
	(7.028)	(6.989)	(4.920)	(5.133)
Lev	−0.061***	−0.057***	0.064***	0.072***
	(-5.960)	(-5.791)	(3.847)	(3.862)
Cash	−0.086**	−0.093**	−0.025	−0.028
	(-2.131)	(-2.072)	(-1.570)	(-1.629)
RDSales	−0.145	−0.142	−0.108	−0.115
	(-1.558)	(-1.559)	(-1.090)	(-1.163)
Board	0.026**	0.027**	0.072**	0.071*
	(2.416)	(2.470)	(2.167)	(2.128)
Indep	0.218**	0.219**	0.065**	0.064**
	(2.371)	(2.389)	(2.038)	(2.027)
Big410	0.044***	0.044***	0.033**	0.032**
	(4.911)	(4.868)	(2.268)	(2.211)
Top1	0.076**	0.077**	0.084*	0.083*
	(2.686)	(2.738)	(1.825)	(1.791)
SOE	0.074***	0.074***	0.074***	0.073***
	(5.031)	(5.027)	(4.490)	(4.433)
Marketbeta	−0.185***	−0.169***	−0.253**	−0.242**
	(-3.561)	(-3.381)	(-2.343)	(-2.243)
Constant	−1.942***	−1.986***	−0.675**	−0.692**
	(-4.783)	(-5.455)	(-2.170)	(-2.730)
Industry FE	Yes	Yes	No	No
Firm FE	No	No	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Observations	30,829	30,829	30,546	30,546
Adjusted R-squared	0.204	0.206	0.433	0.433

This table presents the robustness test, controlling for industry and province fixed effects in Columns (1) and (2), and firm and province fixed effects in Columns (3) and (4). *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

with green innovation disclosures at the 1% significance level. This suggests that firms with higher environmental engagement are more likely to disclose green innovations under conditions of oil price uncertainty, supporting the notion that firms that prioritise stakeholder interests are more responsive to external environmental pressures in the form of green innovation disclosures.

4.4.2. High legitimacy demand vs. low legitimacy demand

Legitimacy theory posits that organisations seek to manage public perception to avoid the risks associated with negative views of their actions, as highlighted by Dowling and Pfeffer (1975) and Lindblom (1994). To align with societal expectations or values and reduce legitimacy risks, organisations often adopt strategies that include disclosures. Oil price volatility may lead to heightened environmental regulation, as both governments and societies become more aware of the environmental impacts of energy consumption (Kang et al., 2019). This, in turn, encourages firms to enhance their green innovation disclosures to remain aligned with these evolving standards.

To understand the implications of legitimacy pressure for our baseline regression, we introduce an interaction term between the two OPU measurements and a dummy variable, *ISO14001*, which represents the possession of ISO14001 certification—a globally recognised marker of a firm's adherence to rigorous environmental management standards. The regression results, shown in Table 10, reveal that both the *ISO14001* and the interaction terms between OPU measurements and *ISO14001* are positively associated with green innovation disclosures at the 1% significance level. This suggests that firms with higher legitimacy demands, as indicated by the possession of ISO14001 certification, are more likely to disclose green innovations under conditions of oil price uncertainty. This finding supports our conjecture that firms facing higher expectations for legitimacy are more proactive in disclosing their green innovations in response to OPU.

Table 6
Robustness test: Controlling for *EPUbeta*.

	(1)	(2)
	GInoDis	GInoDis
OILVOL	0.192***	
	(9.211)	
OILVAR		12.406***
		(8.168)
MTB	−0.001	−0.001
	(-0.093)	(-0.258)
Growth	−0.034***	−0.034***
	(-6.809)	(-6.715)
ROA	0.083*	0.085*
	(1.825)	(1.917)
Size	0.104***	0.104***
	(7.282)	(7.220)
Lev	−0.170***	−0.164***
	(-5.241)	(-5.062)
Cash	−0.072**	−0.079**
	(-2.058)	(-2.208)
RDSales	−0.185	−0.180
	(-1.139)	(-1.112)
Board	0.051**	0.052**
	(2.386)	(2.250)
Indep	0.088**	0.090**
	(2.023)	(2.044)
Big410	0.018	0.018
	(1.099)	(1.062)
Top1	0.074	0.074
	(0.591)	(0.653)
SOE	0.067***	0.067***
	(4.468)	(4.496)
EPUbeta	0.421***	0.366***
	(3.750)	(3.729)
Constant	−2.168***	−2.195***
	(-6.176)	(-6.854)
Industry FE	Yes	Yes
Observations	30,829	30,829
Adjusted R-squared	0.196	0.197

This table presents the robustness test, controlling for the absolute value of *EPUbeta*. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

4.4.3. *The impact of policy connections*

Given China's unique institutional framework—characterised by state control over resources, a high degree of government ownership, and the prevalence of political ties among senior managers—political connections play a significant role in shaping business strategies (Li et al., 2015). For Chinese firms, obtaining political legitimacy is crucial, as political interference is a common feature of the Chinese business environment (Li & Zhang, 2010). These connections help firms negotiate and enforce contracts more effectively, allowing them to align closely with government expectations. This alignment helps safeguard their interests and bolsters their executives' political standing (Zhang et al., 2016). This dynamic is particularly relevant in the area of green innovation, where companies can enhance their corporate image and respond proactively to governmental expectations (Wang & Jiang, 2021). Thus, we conjecture that political connections may positively moderate firms' green innovation disclosure in times of uncertainty, as they allow firms to more adeptly navigate regulatory landscapes and demonstrate alignment with national goals.

Following Li et al. (2015), we introduce an interaction term between the two OPU measurements and a dummy variable, *PC*, which indicates whether a firm's board chairperson or CEO currently holds or has previously held a position in the central government, local government, National People's Congress, local people's congress, Chinese People's Political Consultative Conference, or local people's political consultative conference. The results, presented in Table 11, show that both the *PC* and its interaction terms with OPU are positively associated with green innovation disclosures at the 1% significance level. This finding supports our conjecture that political connections enhance firms' responsiveness to oil price uncertainty, encouraging them to more transparently disclose green innovation initiatives.

4.4.4. *The impact of regional environmental regulation intensity*

Social and institutional theories have long recognised that a country's institutional environment—including factors such as national culture, legal frameworks, and demographic diversity—plays a significant role in shaping managerial decision-making (Campbell, 2007). In the context of China, regional policy orientation plays a pivotal role in shaping firms' behaviours, which is

Table 7
Robustness check: Baseline regression with lagged independent variables.

	(1)	(2)
	GInoDis	GInoDis
L.OILVOL	0.023***	
	(4.157)	
L.OILVAR		3.151***
		(4.431)
L.MTB	0.006**	0.006**
	(2.476)	(2.306)
L.Growth	−0.018	−0.017
	(-1.068)	(-0.957)
L.ROA	0.108**	0.108**
	(2.791)	(2.781)
L.Size	0.103***	0.103***
	(7.285)	(7.249)
L.Lev	−0.093**	−0.091**
	(-2.901)	(-2.755)
L.Cash	0.009	0.008
	(0.218)	(0.205)
L.RDSales	0.119	0.118
	(1.217)	(1.222)
L.Board	0.026	0.026
	(0.986)	(0.998)
L.Indep	0.059	0.059
	(0.740)	(0.746)
L.Big410	0.031**	0.031***
	(2.945)	(3.022)
L.Top1	0.067**	0.067**
	(2.258)	(2.268)
L.SOE	0.059***	0.059***
	(3.878)	(3.876)
L.Marketbeta	−0.290***	−0.282***
	(-3.201)	(-3.168)
Constant	−1.803***	−1.825***
	(-4.726)	(-5.189)
Firm FE	Yes	Yes
Observations	25,076	25,076
Adjusted R-squared	0.189	0.180

This table presents the results of robustness checks for the baseline regression model, where all independent variables are lagged by 1 year. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

closely linked to the country's unique economic policy framework (Shen et al., 2020). Previous research indicates that regional environmental preferences are transmitted to firms through policy mechanisms (Lei et al., 2017), and stronger environmental policy intensity can exert pressure on firms to enhance their green and sustainable development practices (Lai et al., 2024). Cheng and Mao (2024) find that stringent administrative policies effectively stimulate firms to engage in environmental disclosure, reducing compliance risks while simultaneously enhancing their environmental reputation in the market. Similarly, Sun and Yang (2024) suggest that government-imposed environmental targets can be a significant driver of firms' green innovation. Based on this, we conjecture that the intensity of regional environmental regulations moderates the relationship between OPU and firms' green innovation disclosures.

We introduce an interaction term between the two OPU measurements and a dummy variable, *HighRERI*, which indicates whether the environmental regulation intensity in the firm's province is above the median for the year. The intensity of environmental regulation is measured by the ratio of completed industrial pollution control investment to the value added of the secondary industry in the province. The results, presented in Table 12, show that both *HighRERI* and its interaction terms with OPU are positively associated with green innovation disclosures at the 1% significance level. This suggests that firms operating in regions with stronger environmental regulations are more likely to disclose green innovations when faced with oil price uncertainty, highlighting the role of regulatory pressure in shaping firms' voluntary strategies.

4.4.5. The impact of carbon trading pilots

China's carbon trading pilot scheme, launched as part of its efforts to combat climate change and reduce carbon emissions, plays a crucial role in shaping corporate environmental strategies. After approval by the National Development and Reform Commission in 2011, the pilot scheme was introduced in 2013 across several major regions, including Beijing, Shanghai, Tianjin, Guangdong, and Shenzhen, with Chongqing and Hubei joining in 2014. These pilot regions serve as testing grounds for the national emissions trading

Table 8
Endogeneity test: IV test.

	First stage		Second stage	
	OILVOL	*OILVAR*	*GInoDis*	*GInoDis*
			(1)	(2)
GPR4c	0.198***	0.001***		
	(21.131)	(32.967)		
Fitted_ OILVOL			0.308***	
			(3.181)	
Fitted_ OILVAR				9.414**
				(2.194)
Constant	−0.001	−0.022	−0.458***	−0.458***
	(−0.004)	(−1.493)	(−8.103)	(−8.004)
Controls	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Observations	30,829	30,829	30,829	30,829
Adjusted R^2	0.680	0.664	0.713	0.714
Cragg-Donald Wald F statistic	595.915	1989.649		
Kleibergen-Paap Wald rk LM statistic	443.176***	1224.285***		

This table presents the endogeneity test using instrumental variable estimation, following Deng and Hao (2024). The average geopolitical risk index of the two largest consumers (the USA and China) and the two largest producers (Saudi Arabia and Russia) of crude oil in the world, namely GPR4c, is employed as the instrumental variable. Controls are the same as in Table 3 *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 9
The moderating effect of firm green performance.

	(1)	(2)
	GInoDis	GInoDis
OILVOL	0.060**	
	(2.374)	
OILVAR		5.239***
		(3.010)
HighCEP	0.088***	0.040***
	(5.245)	(2.725)
OILVOL HighCEP*	0.523***	
	(7.023)	
OILVAR HighCEP*		0.333***
		(5.314)
Constant	−2.009***	−2.005***
	(-12.828)	(-13.424)
Controls	Yes	Yes
Industry FE	Yes	Yes
Observations	30,829	30,829
Adjusted R2	0.243	0.244

This table reports the results of the regression as follows:

$$GInoDis_{i,t} = \beta_0 + \beta_1 OPU + \beta_2 OPU_t * HighCEP_{i,t} + \beta_2 HighCEP_{i,t} + \sum\nolimits_k \beta_k Controls_{k,i,t} + \epsilon_{i,t}$$

$HighCEP_{i,t}$ is a dummy variable that takes the value of 1 if the firm's environmental performance score is above the industry-level median for the year, and 0 otherwise. The measurement of the environmental performance score is collected from the environmental sub-index in the Huazheng ESG index. Controls are the same as in Table 3. Appendix B presents the detailed variable definitions. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

system, where firms receive emission allowances and can trade them on the carbon market (Liu & Zhang, 2019). Firms operating in pilot regions are subject to stricter environmental regulations and are incentivised to adopt more sustainable practices to meet carbon reduction targets (Ren et al., 2024). As a result, firms in these regions may be more proactive in disclosing their green innovations to align with regulatory requirements and gain competitive advantages in the low-carbon economy.

We introduce an interaction term between the two OPU measurements and a dummy variable, *Pilot*, which takes the value of 1 if the

Table 10
The moderating effect of ISO environmental certification.

	(1)	(2)
	GInoDis	GInoDis
OILVOL	0.112***	
	(3.912)	
OILVAR		4.706***
		(3.935)
ISO14001	0.233***	0.171***
	(10.498)	(7.243)
OILVOL ISO14001*	0.301***	
	(3.780)	
OILVAR ISO14001*		19.787***
		(6.133)
Constant	−1.973***	−1.973***
	(-18.511)	(-18.550)
Controls	Yes	Yes
Industry FE	Yes	Yes
Observations	30,829	30,829
Adjusted R2	0.277	0.279

This table reports the results of the regression as follows:
$GInoDis_{i,t} = \beta_0 + \beta_1 OPU + \beta_2 OPU_t{*}ISO14001_{i,t} + \beta_2 ISO14001_{i,t} + \sum_k \beta_k Controls_{k,i,t} + \epsilon_{i,t}$
$ISO14001_{i,t}$ is a dummy variable that takes the value of 1 if the firm holds an ISO14001 certificate, and 0 otherwise. Controls are the same as in Table 3. Appendix B presents the detailed variable definitions. t-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 11
The moderating effect of political connection.

	(1)	(2)
	GInoDis	GInoDis
OILVOL	0.115***	
	(3.413)	
OILVAR		11.064***
		(7.729)
PC	0.201***	0.139***
	(7.060)	(5.322)
OILVOL PC*	0.023***	
	(3.370)	
OILVAR PC*		2.491***
		(3.664)
Constant	−1.835***	−1.838***
	(-15.228)	(-15.426)
Controls	Yes	Yes
Industry FE	Yes	Yes
Observations	30,829	30,829
Adjusted R2	0.200	0.202

This table reports the results of the regression as follows:
$GInoDis_{i,t} = \beta_0 + \beta_1 OPU + \beta_2 OPU_t{*}PC_{i,t} + \beta_2 PC_{i,t} + \sum_k \beta_k Controls_{k,i,t} + \epsilon_{i,t}$
$PC_{i,t}$ is a dummy variable that takes the value of 1 if the firm's board chairperson or CEO is currently holding, or previously held a government position, and 0 otherwise. Controls are the same as in Table 3. Appendix B presents the detailed variable definitions. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

firm is located in a region included in the carbon trading pilot scheme in a given year, and 0 otherwise. The regression results, presented in Table 13, show that *Pilot* is positively associated with green innovation disclosures at the 1% significance level, indicating that firms in pilot regions are more likely to disclose green innovations. Furthermore, the interaction terms between OPU

Table 12
The moderating effect of regional environmental regulations.

	(1)	(2)
	GInoDis	GInoDis
OILVOL	0.157***	
	(3.946)	
OILVAR		9.340***
		(5.716)
HighRERI	0.024***	0.049***
	(4.428)	(2.692)
OILVOL HighRERI*	0.068***	
	(3.102)	
OILVAR HighRERI*		5.967**
		(2.322)
Constant	−1.952***	−1.983***
	(-16.460)	(-16.784)
Controls	Yes	Yes
Industry FE	Yes	Yes
Observations	30,829	30,829
Adjusted R2	0.156	0.158

This table reports the results of the regression as follows:
$GInoDis\_(i,t) = \beta_0 + \beta_1 OPU + \beta_2 OPU_t{*}HighRERI_{i,t} + \beta_2 HighRERI_{i,t} + \sum_k \beta_k Controls_{k,i,t} + \epsilon_{i,t}$
$HighRERI_{i,t}$ is a dummy variable that takes the value of 1 if the environmental regulation intensity in the firm's province is above the median for the year, and 0 otherwise. The intensity of environmental regulation is measured by the ratio of completed industrial pollution control investment to the value added of the secondary industry in that province. Controls are the same as in Table 3. Appendix B presents the detailed variable definitions. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 13
The moderating effect of carbon trading pilots.

	(1)	(2)
	GInoDis	GInoDis
OILVOL	0.215***	
	(5.929)	
OILVAR		13.282***
		(8.693)
Pilot	0.037***	0.035***
	(5.875)	(5.795)
OILVOL Pilot*	0.101**	
	(2.445)	
OILVAR Pilot*		3.707**
		(2.384)
Constant	−1.974***	−2.018***
	(-16.708)	(-17.106)
Controls	Yes	Yes
Industry FE	Yes	Yes
Observations	30,829	30,829
Adjusted R2	0.156	0.158

This table reports the results of the regression as follows:
$GInoDis_{i,t} = \beta_0 + \beta_1 OPU + \beta_2 OPU_t{*}Pilot_{i,t} + \beta_2 Pilot_{i,t} + \sum_k \beta_k Controls_{k,i,t} + \epsilon_{i,t}$
$Pilot_{i,t}$ is a dummy variable that takes the value of 1 if firm i is located in a region that has implemented a pilot carbon trading scheme in year *t*, and 0 otherwise. The pilot cities include Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong, and Shenzhen. Chongqing and Hubei joined the carbon trading pilot in 2014, while the other regions joined in 2013. Controls are the same as in Table 3. Appendix B presents the detailed variable definitions. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

measurements and *Pilot* are positively associated with green innovation disclosures at the 5% significance level. This result aligns with our conjecture and highlights the driving influence of market-based green initiatives on firms' green innovation disclosure.

5. Conclusion

The study highlights how firms adapt their voluntary disclosures on green innovation in response to energy uncertainties, specifically examining the impact of oil price uncertainty on corporate green innovation disclosures. We find a significantly positive relationship between these two variables of interest. By employing robust analysis techniques, including controlling for firm, industry, and province fixed effects, as well as addressing endogeneity using instrumental variable and lagged variable approaches, the results validate the robustness and reliability of the findings.

Additionally, this study finds that firms with higher environmental performance and greater legitimacy demands are more inclined to enhance their green innovation disclosures in the face of oil price uncertainty. The findings also show that corporate political connections strengthen this relationship. Furthermore, our results indicate that China's carbon trading pilot scheme and the stringency of regional environmental regulations positively moderate the relationship between OPU and green innovation disclosure, highlighting how regulatory frameworks can drive firms to align their strategies with broader environmental goals.

Overall, this research enriches the discourse on how firms navigate the dual challenges of oil price volatility and environmental sustainability, while also highlighting the nuanced role of internal governance mechanisms and external societal pressures in shaping corporate sustainability practices.

Author's opinions

All authors read and approved the final manuscript.

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Appendix A. The composition of indicators for corporate green innovation disclosure

Variables	Measurements	Data sources	Sources
GInoDis	PROC1. Aiming to reduce the consumption of resources and energy and improve resource and energy efficiency PROC2. Using recycled materials, recycling techniques, and environmental technologies PROC3. Applying environmental campaigns PROC4. Using pollution-control equipment PROC5. Adopting pollution-control projects and technologies	Firms' annual reports and corporate social responsibility reports	Frondel et al. (2007); Klassen & Whybark (1999); del Río González (2005); Zeng et al. (2010)

Appendix B. Variable description

Variable	Description
OILVOL	According to Yang and Song (2023), *OILVOL* is measured by the standard deviation of daily oil price returns for 1 year.
OILVAR	According to Yang and Song (2023), *OILVAR* is measured by the average of the daily conditional variance from the GARCH (1,1) model for 1 year.
OILVARE	*OILVARE* is measured by the average of the daily conditional variance from the EGARCH (1,1) model for 1 year.
GInoDis	According to Xie et al. (2019), the firm green innovation disclosure index is calculated from five sub-indicators. These sub-indicators are derived from text analysis of firm annual reports and social responsibility reports.
MTB	The ratio of market value to its book value of equity.
Growth	Change in sales between years *t* and *t*-1.
ROA	Return on assets, calculated as net profit after tax/total assets.
Size	The natural logarithm of total assets.
Lev	Total liabilities scaled by total assets.
Cash	Cash and cash equivalents scaled by total assets.
RDSales	R&D expenses scaled by total sales.
Board	The natural logarithm of the total number of directors on the board.
Indep	The proportion of independent directors to the total number of directors on the board.

(*continued on next page*)

(*continued*)

Variable	Description
Big410	A dummy variable equals one if the auditor of the firm is one of international 'Big4' or 'Domestic 10' audit firms, and 0 otherwise.
Top1	The largest shareholding ratio.
SOE	A dummy variable equals 1 if the ultimate controller of a firm is a government agency or a state-owned enterprise, and 0 otherwise.
Marketbeta	Based on monthly data, the annual market risk exposure of a firm is calculated through the FAMA three-factor model.
EPUbeta	According to Peng et al. (2023), the annual firm exposure to EPU is calculated based on monthly data through the FAMA three-factor model. We take its absolute value.
GPR4c	According to Deng and Hao (2024), the average geopolitical risk index of the two largest consumers (the USA and China) and the two largest producers (Saudi Arabia and Russia) of crude oil in the world. GPR4c is calculated using monthly geopolitical risk data constructed by Caldara and Iacoviello (2022) based on 10 newspapers beginning in 1985.
HighCEP	*HighCEP* is a dummy variable, which takes the value of 1 if the firm's environmental performance score is above the industry-level median for the year, and 0 otherwise. The environmental sub-index from the Huazheng ESG Index is used to measure firm environmental performance.
ISO14001	*ISO14001* is a dummy variable, which takes the value of 1 if the firm holds an ISO14001 certificate, and 0 otherwise.
PC	*PC* is a dummy variable that takes the value of 1 if the firm's board chairperson or CEO is currently holding, or previously held a government position, and 0 otherwise.
HighRERI	*HighRERI* is a dummy variable that takes the value of 1 if the environmental regulation intensity in the firm's province is above the median for the year, and 0 otherwise. The intensity of environmental regulation is measured by the ratio of completed industrial pollution control investment to the value added of the secondary industry in that province.
Pilot	*Pilot* is a dummy variable that takes the value of 1 if firm *i* is located in a region that has implemented a pilot carbon trading scheme in year *t*, and 0 otherwise. The pilot cities include Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong, and Shenzhen. Chongqing and Hubei joined the carbon trading pilot in 2014, while the other regions joined in 2013.

Appendix C. Redo baseline using alternative measure of OPU

	GInoDis
OILVARE	5.360***
	(7.213)
Constant	−1.931***
	(-4.943)
Controls	Yes
Industry FE	Yes
Observations	30,829
Adjusted R-squared	0.196

We recalculated our main independent variable of *OILVAR*, denoted as *OILVARE*. *OILVARE* is measured by the average of the daily conditional variance from the EGARCH (1,1) model for 1 year. Controls are the same as in Table 3. Appendix B presents the detailed variable definitions. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm-year level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

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