



Weathering the storm: How does firm oil price uncertainty exposure impact green innovation in times of geopolitical tensions

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ARTICLE INFO

Keywords:

Green innovation
Oil price uncertainty
Geopolitical tensions
Supply chain alliances
Supply chain efficiency

ABSTRACT

This study examines the impact of oil price uncertainty sensitivity on corporate green innovation, in times of geopolitical tensions. Using manually collected import and export data at the destination country-firm level from China Customs Dataset, we construct the unique measure of firm-level geopolitical tensions of Chinese listed companies received from foreign supply chain partners. Our results reveal that firms with higher exposure to oil price uncertainty are more likely to engage in green innovation. Importantly, geopolitical tensions significantly and positively moderate the relationship between corporate oil price uncertainty exposure and green innovation efforts, with the effect being particularly pronounced in the context of geopolitical tensions originating from customer countries. Further analysis reveals that domestic supply chain alliances and supply chain efficiency mitigate firms' urgency for green innovation. Finally, we find that the effects of oil price uncertainty and geopolitical tensions on green innovation are more pronounced in firms with higher international exposure, and greater competitive pressures.

1. Introduction

In the context of growing demands for environmental sustainability, green innovation has emerged as a crucial strategy for firms to navigate uncertain environments. Green innovation involves not only technological advancements aimed at reducing carbon emissions and pollution but also the adoption of renewable energy sources to decrease reliance on unsustainable resources (Xu et al., 2021; Shao et al., 2021). This study examines the impact of firms' sensitivity to oil price uncertainty (OPU exposure), particularly during periods of geopolitical tension, on green innovation, guided by three primary motivations.

Firstly, frequent fluctuations in international crude oil prices have prompted investigations into how oil price uncertainty impacts economic activities and financial market development (Amin et al., 2023; Maghyereh and Abdoh, 2020; Elder and Serletis, 2009; Koirala and Ma, 2020). Our study focuses on firm-level exposure to OPU, captured by OPU beta, which reflects the sensitivity of a firm's stock return to unexpected changes in oil price volatility. Studying firm-level exposure to OPU is particularly important because macro-level uncertainty metrics often mask heterogeneous firm responses. As emphasized in the literature on risk exposure (e.g., Nagar et al., 2019; Yang and Yang, 2021), firms differ significantly in how external shocks transmit into their

operations and strategic decisions. OPU beta captures this heterogeneity by quantifying each firm's specific vulnerability or sensitivity to oil price volatility, thus offering a more granular perspective on how energy-related uncertainty may shape firm behaviour. This focus is consistent with the broader literature on firm-specific risk exposures to macroeconomic shocks (e.g., Phan et al., 2019; Zhang and Broadstock, 2020). In addition, existing literature presents mixed results regarding the impact of OPU on investment decisions. Dutta et al. (2020) suggests that rising OPU may prompt green investment as firms seek alternative, sustainable energy sources, while others (e.g., Amin et al., 2023; Yang and Song, 2023) find that uncertainty generally discourages innovation investment by increasing firms' operational costs. Despite these efforts, limited attention has been given to how OPU exposure, as a time-varying firm-specific risk factor, influences strategic decisions such as green innovation.

Secondly, geopolitical tensions have increasingly triggered reactions through global supply chains, significantly affecting corporate decisions (Zhang et al., 2024). Geopolitical conflicts can lead to logistical delays (Güray et al., 2025), trade barriers (Fan et al., 2024), or retaliatory policies that ripple across interconnected supply chains (Meunier and Nicolaidis, 2019). Using manually collected import and export data at the destination country-firm level from the China Customs Dataset, we

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develop a unique measure of geopolitical tensions faced by Chinese listed companies through their foreign supply chain partners. As China is deeply embedded in the global manufacturing network, disruptions to upstream suppliers or downstream markets can directly impact domestic firms' operations and strategic planning. Our evidence, generated from the measure of geopolitical tension spill-over from foreign supply partners, is expected to add unique insights to geopolitical risk studies.

Thirdly and importantly, firms must navigate various risks in an increasingly uncertain global environment, which creates more complex challenges. Examining the influence of OPU exposure during geopolitical tensions on green innovation provides valuable insights into how firms manage multiple firm-level uncertainties to maintain sustainability. Geopolitical risk reflects the broad uncertainty generated by events such as military tensions, trade disputes, and sanctions (Caldara and Iacoviello, 2022). In recent years, geopolitical risk has become a major uncertainty that amplifies firms' risk perception and alters investment behaviour (Handley and Limão, 2017; Baker et al., 2016). For example, the 2022 Russia-Ukraine conflict sharply increased both geopolitical and trade policy uncertainty, triggering raw material supply shocks and export restrictions that disrupted Chinese manufacturing firms linked to European and Russian markets (Zhang et al., 2023). We expect that the influence of geopolitical tensions from foreign suppliers will amplify the influence of OPU beta. Therefore, studying the impact of firm-specific geopolitical tensions on the relationship between OPU exposure and green innovation can provide critical insights into the strategic drivers of sustainability transitions.

China's status as the world's largest net oil importer and second-largest oil consumer positions it uniquely at the nexus of oil market dynamics and firm behaviour (Yang and Song, 2023). The National Bureau of Statistics of China highlights that the nation's dependency on oil imports has been escalating, surpassing 70 % in 2018, thereby making Chinese firms particularly susceptible to oil price shocks (National Bureau of Statistics, 2019). Additionally, China has consistently been one of the largest exporters in the world. As of 2022, China accounted for approximately 14.42 % of global exports, making it the world's largest exporter (WTO, 2023). Given their extensive involvement in global trade and supply chains, Chinese firms face a complex and transnational set of geopolitical risks, making the Chinese market an ideal case for studying how geopolitical risks are transmitted through supply chains and influence corporate behaviour. Furthermore, China's recent vigorous promotion of green development, with substantial investments in green innovation by both the government and enterprises, provides a rich empirical foundation for examining the role of green innovation in responding to external uncertainties.

Using data from Chinese listed firms from 2007 to 2016,¹ our empirical analysis demonstrates that firms with higher OPU beta significantly increase both the quantity and quality of their green innovation during periods of heightened geopolitical tensions. This finding underscores that, when confronted with oil price volatility and geopolitical risks, firms can strategically leverage green innovation to mitigate operational uncertainties and ensure long-term sustainability. Robustness checks, including the use of alternative measures and strict fixed effects controls, validate the reliability of these results. Furthermore, our analysis highlights that the positive impact of OPU beta on green innovation is particularly pronounced in the context of geopolitical tensions originating from supplier countries.

Further analysis indicates that the impact of OPU beta and geopolitical risks on green innovation is more pronounced in firms with a higher proportion of international business, or greater competitive pressures. Firms with a higher proportion of international business are more exposed to global market volatility (Campos et al., 2023), making them more sensitive to disruptions caused by geopolitical risks and oil

price fluctuations. This exposure could drive firms to adopt proactive strategies, such as investing in green innovation, to mitigate potential risks and maintain their competitive edge in international markets. Firms operating under intense competitive pressures are incentivized to innovate rapidly to differentiate themselves and capture market opportunities (Di Dio and Correani, 2020), particularly when external uncertainties create openings for market leadership. These dynamics collectively illustrate how firm-level characteristics interact with external shocks to influence the adoption of green innovation as a strategic response.

We also find a moderating effect of domestic supply chain alliance and supply chain efficiency on our baseline results. While supply chain alliances provide stability and operational resilience (Philsoophian et al., 2021), they may also be associated with a reduced urgency for green innovation. This could reflect the stabilizing role these factors play, which allows firms to focus on maintaining their current operations rather than immediately pursuing long-term innovation strategies. Similarly, supply chain efficiency, by optimizing resource utilization and streamlining operations, enhances firms' ability to withstand disruptions and minimize costs (Kamalahmadi et al., 2022). However, this focus on efficiency could inadvertently shift attention away from long-term innovation strategies, as firms may prioritize short-term operational stability and cost management over proactive green innovation initiatives.

The contributions of this paper are threefold. First, existing studies primarily focus on the impact of oil price fluctuations on firm behaviour, such as Amin et al. (2023) and Yang and Song (2023), which indicate that oil price uncertainty reduces innovation investment. Our study examines how varying degrees of firm-level sensitivity to oil price volatility affects green innovation. In addition, we examine the interacted impact of OPU beta and the weighted geopolitical risk of firm suppliers' and customers' countries on corporate green innovation. This adds new evidence to the findings of Lee et al. (2023), who investigate the impact of global geopolitical tensions on innovation of Chinese firms. Our study provides new insights into the motivations behind corporate green innovation in uncertain environments, indicating that firms navigate multiple risks through green innovation to improve sustainability.

Second, this study contributes to ongoing debates on corporate investment behaviour under uncertainty. While traditional real options theory posits that firms often delay or reduce investments in uncertain environments to preserve strategic flexibility for the future (Cooper and Priestley, 2011), strategic growth theory offers a contrasting view. According to Kulatilaka and Perotti (1998), uncertainty, when coupled with competitive pressures, can incentivize firms to invest proactively in growth opportunities to secure first-mover advantages and deter competitors. Our findings provide empirical support for this perspective, demonstrating that firms facing both oil price volatility and geopolitical risks increase green innovation investments. These results extend the applicability of strategic growth theory, highlighting how firms strategically leverage innovation as a means of responding to external uncertainties while positioning themselves for long-term growth.

Third, this research advances the understanding of the role of supply chain dynamics in moderating the relationship between external uncertainties and green innovation. Specifically, we reveal that domestic supply chain alliances and supply chain efficiency act as critical moderating factors. While OPU exposure and geopolitical risks drive firms to enhance green innovation, the stability and resources provided by domestic supply chain alliances reduce firms' dependency on vulnerable international supply chains, thereby diminishing the urgency for green innovation. Similarly, supply chain efficiency fosters operational stability and resource optimization, also tempering the need for green innovation. Our findings expand Hsieh et al. (2018), which highlight the importance of domestic supply chain collaboration in securing resources, and Kamalahmadi et al. (2022), which emphasize the dual role of supply chain efficiency in enhancing stability and

¹ Our sample period ends in 2016 due to the data on importing and exporting of Chinese firms are only available up to 2016.

Table 1
Descriptive statistics.

Panel A Descriptive statistics of key variables						
	(1)	(2)	(3)	(4)	(5)	(6)
	N	Mean	Standard deviation	Minimum	Median	Maximum
<i>OPUbeta</i>	25,652	0.036	0.037	0.000	0.024	0.171
<i>GPRC</i>	25,652	0.033	0.118	0.000	0.000	1.172
<i>GPRS</i>	25,652	0.024	0.108	0.000	0.000	1.130
<i>Patent</i>	25,652	0.369	0.738	0.000	0.000	6.608
<i>Invention</i>	25,652	0.122	0.403	0.000	0.000	5.602
<i>Utility</i>	25,652	0.308	0.667	0.000	0.000	6.155
<i>Citation</i>	25,652	0.021	0.211	0.000	0.000	6.489
<i>CIvention</i>	25,652	0.019	0.189	0.000	0.000	5.209
<i>CUtility</i>	25,652	0.015	0.154	0.000	0.000	6.163
<i>F.Patent</i>	25,593	0.426	0.783	0.000	0.000	6.609
<i>F.Invention</i>	25,593	0.136	0.423	0.000	0.000	5.545
<i>F.Utility</i>	25,593	0.360	0.715	0.000	0.000	6.188
<i>F.Citation</i>	25,593	0.026	0.239	0.000	0.000	6.295
<i>F.CIvention</i>	25,593	0.021	0.203	0.000	0.000	5.407
<i>F.CUtility</i>	25,593	0.018	0.174	0.000	0.000	5.765
<i>MTB</i>	25,652	0.633	0.246	0.001	0.639	1.463
<i>Growth</i>	25,652	0.117	0.280	-0.557	0.105	0.989
<i>ROA</i>	25,652	0.065	0.130	-0.495	0.070	0.360
<i>Size</i>	25,652	22.000	1.234	19.860	21.850	25.620
<i>Lev</i>	25,652	0.452	0.208	0.053	0.452	0.878
<i>Cash</i>	25,652	0.153	0.121	0.013	0.119	0.631
<i>RDSales</i>	25,652	0.003	0.010	0.000	0.000	0.076
<i>Board</i>	25,652	2.151	0.201	1.609	2.197	2.708
<i>Indep</i>	25,652	0.372	0.052	0.333	0.333	0.571
<i>Big4/10</i>	25,652	0.473	0.499	0.000	0.000	1.000
<i>Top1</i>	25,652	0.353	0.149	0.096	0.334	0.742
<i>SOE</i>	25,652	0.441	0.497	0.000	0.000	1.000

Panel B Number of firms by industry		
Industry Name	Firm Count	Share (%)
Agriculture, Forestry, Animal Husbandry & Fishery	42	1.28
Mining	76	2.32
Manufacturing	2255	68.96
Electricity, Heat, Gas & Water Production	114	3.49
Construction	94	2.87
Wholesale & Retail Trade	169	5.17
Transport, Storage & Postal Services	105	3.21
Accommodation & Catering Services	8	0.24
Information Transmission, Software & IT	34	1.04
Finance	117	3.58
Real Estate	58	1.77
Leasing & Business Services	45	1.38
Scientific Research & Technical Services	58	1.77
Water Conservancy, Environment & Public Facilities	1	0.03
Resident Services, Repair & Other Services	10	0.31
Education	13	0.40
Health & Social Work	56	1.71
Culture, Sports & Entertainment	15	0.46
Total	3270	100

Panel C Number of manufacturing firms by subsector.		
Industry name	Firm number	Proportion
Agricultural and Sideline Food Processing	49	2.17 %
Food Manufacturing	46	2.04 %
Beverage Manufacturing	43	1.91 %
Textile Industry	36	1.60 %
Apparel Manufacturing	36	1.60 %
Leather Products	10	0.44 %
Wood Processing	7	0.31 %
Furniture Manufacturing	23	1.02 %
Paper Manufacturing	26	1.15 %
Printing Industry	12	0.53 %
Cultural & Educational Goods	18	0.80 %
Petroleum Processing	15	0.67 %
Chemical Raw Materials	233	10.33 %
Pharmaceutical Manufacturing	225	9.98 %
Chemical Fiber Manufacturing	23	1.02 %
Rubber Products	72	3.19 %
Plastic Products	88	3.90 %
Non-Metallic Minerals	35	1.55 %

(continued on next page)

Table 1 (continued)

Panel C. Number of manufacturing firms by subsector.		
Industry name	Firm number	Proportion
Ferrous Metal Smelting	74	3.28 %
Non-Ferrous Metal Smelting	58	2.57 %
Metal Products	122	5.41 %
General Equipment	202	8.96 %
Specialized Equipment	129	5.72 %
Automotives Manufacturing	47	2.08 %
Railway/Aerospace Equipment	228	10.11 %
Electrical Machinery	335	14.86 %
Computer/Communications Equipment	43	1.91 %
Instrument Manufacturing	15	0.67 %
Other Manufacturing	5	0.22 %
Total	2255	100 %

Panel A of this table presents the descriptive statistics of the key variables in the sample. Panel B shows the distribution of firms across different industries in the sample. Panel C further reports the number of firms in each sub-sector within the manufacturing industry, based on the first three digits of the CSRC industry classification code. The sample consists of firms listed on the SHSE and SZSE from 2007 to 2016. The total sample includes 3270 firms, 25,652 observations. Detailed definitions of variables are presented in Appendix A.

constraining flexibility. By integrating these insights, our study provides a nuanced understanding of how supply chain dynamics shape corporate innovation strategies.

2. Literature and hypothesis development

2.1. Impact of oil price uncertainty

Under the highly energy-dependent global economy, the impact of oil price volatility on corporate decision-making has attracted significant academic attention. OPU not only influence firms' investment behaviours but also affect their profitability and stimulate innovation in clean energy technologies. Existing studies explore how oil price volatility shapes corporate investment and profitability decisions under uncertainty. The influence of oil price volatility on corporate investment decisions is particularly pronounced. [Henriques and Sadorsky \(2011\)](#) demonstrate a U-shaped relationship between OPU and corporate investment, indicating that firms are more inclined to invest under either extremely low or extremely high oil price volatility. Similarly, [Alaali \(2020\)](#), in a study of investment behaviours of UK firms, finds that oil price volatility introduces uncertainty, resulting in a nonlinear relationship between OPU and investment spending. Specifically, firms display a U-shaped investment response, adjusting their strategies to diversify risks ([Alaali, 2020](#)).

Beyond investment decisions, oil price volatility significantly impacts corporate profitability, especially in energy-intensive sectors like oil and gas. [Lyócsa and Todorova \(2021\)](#) find that oil price volatility is a key determinant of stock price fluctuations in the oil and gas exploration and production industry, directly influencing profitability expectations. This insight aids firms in developing risk management strategies to navigate market instability. [Narayan and Sharma \(2014\)](#) further reveal that oil price volatility serves as a predictor of stock return volatility, enabling investors to devise trading strategies and achieve higher returns during periods of heightened oil price volatility.

With growing global attention to sustainability, the effect of oil price volatility on green innovation has garnered increasing interest. [Fazlollahi and Ebrahimijam \(2017\)](#) indicate that oil price volatility enhances the market appeal of clean energy firms, driving more investment into the sector. Although the short-term impact of oil price volatility on the clean energy market is limited, its long-term effects are significant ([Fazlollahi and Ebrahimijam, 2017](#)), underscoring the importance of oil price volatility in clean energy investment. Additionally, [Ji and Fan \(2012\)](#) highlight the strengthened spillover effects of oil price volatility on non-energy commodity markets following the financial crisis, intensifying the linkages between clean energy and traditional energy markets. This relationship suggests that oil price volatility not only influences firms' financial conditions but also encourages them to pursue

long-term green investment and risk mitigation strategies.

One of the primary drivers of green innovation prompted by oil price volatility is the threat it poses to the stability of future energy supplies, which compels firms to increase investment in energy technologies and innovation to reduce reliance on traditional fossil fuels. [Ebrahim et al. \(2014\)](#) argue that oil price uncertainty drives firms to focus more on the sustainability of energy supplies, especially during periods of high oil prices, demonstrating a potential causal link between OPU and green innovation. Similarly, [Alhassan's \(2019\)](#) research, based on data from the Gulf Cooperation Council (GCC) markets, indicates that oil price volatility not only impacts short-term financial decisions but may also encourage companies to adopt more strategic investment approaches, including exploring long-term green technology solutions. These findings highlight how oil price volatility exerts financial pressures while simultaneously incentivizing firms to seek innovative energy solutions and drive green innovation.

2.2. Geopolitical risks and their disruptive effects on supply chain relationships

Geopolitical crises profoundly affect supply chains, presenting both significant challenges and opportunities for firms to adapt strategically. [Schotter and Thi My \(2013\)](#) highlight that suppliers in underdeveloped regions are particularly vulnerable to geopolitical uncertainties due to their limited resources and technical capabilities, often becoming the weakest links in supply chains. Such vulnerabilities frequently lead to supply interruptions and financial strain, hampering firms' ability to maintain consistent operations. Similarly, [Liu and Ning \(2023\)](#) reveal that global supply chain tensions exacerbate material shortages and increase import costs, forcing firms to bear higher expenses to secure essential raw materials. This diminishes their competitiveness in international markets, further intensifying the adverse effects of geopolitical risks.

However, these disruptions also compel firms to reassess their operational strategies and leverage innovation to mitigate vulnerabilities. [Sabahi and Parast \(2020\)](#) argue that innovation enhances firms' resilience to supply chain disruptions by fostering capabilities such as agility, knowledge sharing, and flexibility, which are particularly valuable in uncertain environments. [Roscoe et al. \(2022\)](#) further demonstrate that firms redesigning their supply chains in response to geopolitical disruptions often adopt strategies that promote sustainability and resilience, such as diversifying supplier bases and investing in green technologies. These approaches not only reduce dependency on high-risk suppliers but also align with broader environmental objectives. Additionally, [Jabbarzadeh et al. \(2018\)](#) highlight that integrating resilience strategies with green practices enables firms to address both operational risks and environmental challenges, positioning crises as

Table 2
Pairwise Pearson correlation coefficients.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
1																
(1) OPUbeta	-0.022***															
(2) GPRC	-0.045***	1														
(3) GPRS	-0.057***	-0.053***	1													
(4) Patent	0.130***	0.039***	0.197***	1												
(5) Citation	0.136***	0.057***	0.145***	-0.007	1											
(6) MTB	-0.200***	-0.047***	0.033***	0.009	-0.023***	1										
(7) Growth	0.012**	-0.004	0.025***	0.005	-0.069***	0.336***	1									
(8) ROA	-0.054***	0.006	0.016**	0.046**	0.535***	0.062***	0.133***	1								
(9) Size	0.084***	-0.126**	-0.059***	0.011*	0.319***	0.024***	-0.175***	0.418***	1							
(10) Lev	-0.071***	-0.080***	0.102***	0.011*	-0.189***	0.029***	0.183***	-0.198***	-0.091***	1						
(11) Cash	0.014**	0.044***	-0.037***	-0.004	-0.086***	-0.007	-0.032***	-0.012**	0.040***	0.040***	1					
(12) RDSales	0.029***	-0.008	0.071***	0.020**	0.150***	0.012*	0.051***	0.231***	-0.036***	-0.036***	-0.048***	1				
(13) Board	-0.053***	0.004	0.025***	0.007	0.150***	0.012*	0.051***	0.231***	0.150***	0.150***	-0.493***	0.028***	1			
(14) Indep	0.022***	-0.015**	-0.015**	0.004	-0.025***	-0.001	-0.027***	0.018***	-0.017***	0.007	0.025***	-0.013**	0.039***	1		
(15) Big4/10	0.082***	-0.015**	-0.024***	0.035**	0.031***	-0.008	0.032***	0.172***	-0.041***	0.005	-0.072***	0.024***	0.032***	0.059***	1	
(16) Top1	-0.056***	0.011*	0.014**	0.009	0.152***	0.039***	0.154***	0.215***	0.032***	0.034***	-0.072***	0.024***	0.032***	0.059***	0.032***	1
(17) SOE	-0.051***	-0.046***	-0.014**	-0.009	0.182***	-0.042***	-0.020**	0.274***	0.260***	-0.067***	-0.071***	0.274***	-0.082***	-0.049***	-0.082***	0.208***

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

potential catalysts for innovative solutions. Together, these findings underscore the transformative potential of geopolitical crises, driving firms toward long-term innovation strategies that enhance their resilience, competitiveness, and sustainability.

2.3. How uncertainty drives firms toward green innovation

Strategic growth theory posits that under high uncertainty, firms may choose to invest proactively to secure competitive advantages, particularly in industries characterized by intense competition and rapid change (Kulatilaka and Perotti, 1998). This perspective highlights that uncertainty can reduce the value of waiting and incentivize firms to invest early to pre-empt competitors. For example, Van Vo and Le (2017) demonstrate that firms in competitive industries are more likely to increase R&D investments during uncertain periods, recognizing the potential to establish first-mover advantages and mitigate risks associated with delayed actions. Kulatilaka and Perotti (1998) argue that uncertainty encourages proactive investments, as firms aim to capture larger market shares and deter rivals by leveraging growth opportunities. Chen et al. (2005) illustrate how firms in dynamic and uncertain markets, succeed by adopting adaptive investment strategies that align with both external market shifts and internal growth objectives.

Green innovation requires significant initial investment but provides firms with opportunities to reduce reliance on traditional energy sources and secure long-term operational sustainability. Ebrahim et al. (2014) find that firms adopt innovative, energy-independent technologies to reduce dependence on unstable fossil fuel markets and mitigate resource-related risks. Fazlollahi and Ebrahimijam (2017) show that oil price uncertainty also drives market interest in clean energy, as firms seek sustainable alternatives to maintain operational stability. Green innovation serves as a strategic response, enabling firms to reduce dependence on traditional energy sources and enhance operational sustainability. High OPU exposure is likely to push firms to invest in renewable energy technologies and adaptive strategies to stabilize operations and future-proof their business. Based on the above analysis, we propose the following hypothesis:

Hypothesis 1a. OPU exposure positively influences corporate green innovation.

In contrast, real options theory posits that uncertainty often deters investment, as firms delay committing resources to irreversible projects to maintain strategic flexibility (Cooper and Priestley, 2011). Real options theory views investment opportunities as analogous to financial options, highlighting that when investments are largely irreversible and future conditions are unclear, managers have the valuable option to wait for more information to be available (Dixit and Pindyck, 1994). Under oil price volatility, this dynamic may cause firms to hesitate in pursuing green innovation, which typically involves long-term commitments and substantial upfront costs. Bloom (2009) shows that when uncertainty spikes, firms tend to “pause” or cut back on investment in the short term.

Existing studies provide evidence on how OPU influences corporate innovation. Alaali (2020) indicates that heightened oil price uncertainty reduces capital expenditure as firms prioritize financial flexibility over long-term innovation. Moreover, Narayan and Sharma (2014) show that OPU increases costs for firms by disrupting financial planning and cash flow predictability, thereby discouraging investment in innovation. Hasan et al. (2022) find that under volatile energy markets, firms focus on cost control and risk mitigation rather than committing to high-risk initiatives like green innovation. This view aligns with the premise that in uncertain environments, firms with higher OPU exposure might forgo potentially transformative projects to preserve resources for immediate operational needs (Bloom, 2009; Wang et al., 2019). Based on the above discussion, we propose the following hypothesis:

Hypothesis 1b. OPU exposure negatively influences corporate green innovation.

Table 3
Impact of OPUBeta on firm green innovation in times of geopolitical tensions.

	(1)	(2)	(3)	(4)	(5)	(6)
	<i>F. Patent</i>	<i>F.Citation</i>	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Patent</i>	<i>F.Citation</i>
<i>OPUBeta</i>	1.984*** (8.182)	0.602*** (6.308)	1.766*** (7.250)	0.220*** (2.739)	1.864*** (7.643)	0.446*** (4.652)
<i>GPRC</i>			-0.249*** (-5.490)	-0.269*** (-7.363)		
<i>OPUBeta * GPRC</i>			7.498*** (4.993)	13.149*** (7.608)		
<i>GPRS</i>					-0.379*** (-7.201)	-0.220*** (-5.384)
<i>OPUBeta * GPRS</i>					6.936*** (3.838)	10.974*** (5.216)
<i>MTB</i>	-0.011 (-0.277)	0.029*** (3.115)	-0.012 (-0.311)	0.022** (2.405)	-0.010 (-0.267)	0.025*** (2.728)
<i>Growth</i>	0.007 (0.422)	0.007 (1.152)	0.005 (0.341)	0.005 (0.796)	0.006 (0.399)	0.005 (0.907)
<i>ROA</i>	0.126*** (2.834)	0.024** (2.286)	0.123*** (2.765)	0.019* (1.822)	0.126*** (2.848)	0.024** (2.318)
<i>Size</i>	0.211*** (19.097)	0.007*** (3.037)	0.212*** (19.171)	0.010*** (4.044)	0.211*** (19.174)	0.008*** (3.309)
<i>Lev</i>	0.073* (1.650)	0.017 (1.539)	0.074* (1.659)	0.023** (2.034)	0.071 (1.609)	0.022* (1.947)
<i>Cash</i>	-0.030 (-0.549)	-0.006 (-0.381)	-0.030 (-0.563)	-0.006 (-0.388)	-0.028 (-0.524)	-0.006 (-0.434)
<i>RDSales</i>	2.523*** (3.120)	0.291 (1.247)	2.516*** (3.118)	0.307 (1.349)	2.552*** (3.161)	0.287 (1.264)
<i>Board</i>	0.057 (1.161)	0.013 (1.109)	0.057 (1.175)	0.012 (1.053)	0.059 (1.202)	0.012 (1.075)
<i>Indep</i>	0.169 (0.963)	0.016 (0.346)	0.172 (0.977)	0.017 (0.373)	0.172 (0.978)	0.015 (0.336)
<i>Big4/10</i>	0.003 (0.227)	0.004 (1.021)	0.003 (0.224)	0.003 (0.879)	0.004 (0.240)	0.005 (1.156)
<i>Top1</i>	-0.103* (-1.807)	0.032** (2.055)	-0.106* (-1.867)	0.023 (1.484)	-0.104* (-1.831)	0.027* (1.787)
<i>SOE</i>	0.031 (1.554)	-0.003 (-0.676)	0.032 (1.637)	0.001 (0.152)	0.031 (1.549)	-0.001 (-0.212)
Constant	-4.488*** (-17.510)	-0.231*** (-3.757)	-4.495*** (-17.554)	-0.268*** (-4.388)	-4.492*** (-17.556)	-0.240*** (-3.927)
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	25,593	25,593	25,593	25,593	25,593	25,593
Adjusted R ²	0.301	0.047	0.301	0.074	0.302	0.059

This table presents the impact of *OPUBeta* on firm green innovation productivity and quality, and the amplifying effect of geopolitical tensions. Column (1) and (2) reports the regression result between *OPUBeta* and one-year forward *Patent* and *Citation*, respectively. Columns (3) and (4) show the amplifying effects of geopolitical tensions from customer countries, while Columns (5) and (6) display the amplifying effects of geopolitical tensions from supplier countries, both on one-year forward *Patent* and *Citation*. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm level. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

The interplay between OPU and geopolitical risk (GPR) introduces compounded external pressures that significantly shape firms' strategic decisions regarding green innovation. While OPU reflects volatility in energy input costs that can disrupt firms' budgeting and operational planning (Alaali, 2020; Hasan et al., 2022), GPR contributes an additional layer of uncertainty by threatening global supply chain continuity, access to critical resources, and policy stability (Roscoe et al., 2022; Lee et al., 2023). When these two sources of uncertainty coexist, firms may perceive heightened strategic vulnerability. GPR may amplify the effect of OPU exposure by intensifying firms' concerns about long-term access to stable energy and material supplies, thereby reinforcing the urgency to invest in green technologies.

Existing studies suggest that GPR does not merely increase background uncertainty but has a direct influence on global energy volatility, especially in oil markets. Qin et al. (2020) show that geopolitical risks exert asymmetric effects on oil, gas, and heating oil prices under different market conditions, thereby making energy costs more unpredictable for firms. Similarly, Liu et al. (2021) find that GPR induces long-term energy price volatility, exacerbating planning uncertainty for energy-dependent firms. GPR has also been shown to influence oil prices and shipping costs simultaneously, disrupting both input markets and

global logistics networks (Khan et al., 2021). Therefore, for firms facing both high firm-level GPR and greater OPU exposure, green innovation becomes a proactive hedge that enables firms to manage the overlapping challenges of energy volatility and geopolitical disruption.

Hypothesis 2. Geopolitical risk positively amplifies the relationship between oil price uncertainty exposure and corporate green innovation.

3. Research design

3.1. Data and sample

Our initial sample comprises all Chinese companies listed on the A-share market of the Shanghai and Shenzhen Stock Exchanges from 2007 to 2016. Basic information about these listed firms and the relevant financial data were sourced from the China Stock Market and Accounting Research (CSMAR) database. Patent data were obtained from the website of the Chinese National Intellectual Property Administration. Data on firms' overseas customers and suppliers were collected from China Customs. Oil price data were gathered from the U.S. Energy Information Administration, while data related to global geopolitical

Table 4
Robustness test: Controlling for multiple fixed effects.

	(1)	(2)	(3)	(4)	(5)	(6)
	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Patent</i>	<i>F. Citation</i>
<i>OPU</i> _{beta}	0.640*** (3.355)	0.544*** (3.423)	0.540*** (2.684)	0.191** (2.093)	0.571*** (2.971)	0.387*** (2.830)
<i>GPRC</i>			-0.111** (-2.465)	-0.227*** (-4.515)		
<i>OPU</i> _{beta} * <i>GPRC</i>			2.602*** (3.015)	9.924*** (4.643)		
<i>GPRS</i>					-0.150*** (-2.880)	-0.198*** (-4.861)
<i>OPU</i> _{beta} * <i>GPRS</i>					2.970*** (2.376)	8.029*** (4.365)
Constant	-3.516*** (-5.490)	-0.076 (-1.023)	-3.510*** (-5.472)	-0.090 (-1.146)	-3.523*** (-5.479)	-0.088 (-1.151)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Province*Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry*Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	25,400	25,400	25,400	25,400	25,400	25,400
Adjusted R ²	0.618	0.249	0.618	0.262	0.618	0.254

This table replicates the baseline regression from Table 3, substituting firm-province-year fixed effects for the original model. The control variables are the same as in Table 3. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the industry level. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

Table 5
Robustness test: Subsamples with positive *GPRC* or *GPRS* observations.

	(1)	(2)	(3)	(4)
	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Patent</i>	<i>F. Citation</i>
<i>OPU</i> _{beta}	1.304** (2.255)	2.508*** (5.943)	1.502** (1.976)	1.945*** (3.561)
<i>GPRC</i>	-0.451*** (-8.316)	-0.102*** (-2.996)		
<i>OPU</i> _{beta} * <i>GPRC</i>	8.144*** (4.508)	2.810** (2.028)		
<i>GPRS</i>			-0.314*** (-5.422)	-0.101*** (-2.679)
<i>OPU</i> _{beta} * <i>GPRS</i>			6.369*** (3.028)	4.481** (2.537)
Constant	-4.582*** (-8.421)	-2.287*** (-6.065)	-3.551*** (-6.431)	-1.709*** (-3.747)
Controls	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	3940	3940	2414	2414
Adjusted R ²	0.239	0.163	0.224	0.156

This table reruns the baseline regression from Table 3, using only the subsample with positive *GPRC* or *GPRS* observations. The control variables are the same as in Table 3. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm level. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

risk and country-specific geopolitical risk were extracted from the Economic Policy Uncertainty website. We excluded the following: (1) financial firms, (2) special treatment (ST) firms, and (3) observations with missing information required for variable construction. To mitigate the impact of outliers, all continuous variables were winsorized at the 1 % and 99 % levels. Our final sample consists of 3270 listed firms, amounting to 25,652 firm-year observations.

3.2. Firm's exposure to oil price uncertainty risk

To measure a firm's exposure to OPU, we employ a two-step approach. First, following Sadorsky (2008), we measure month-level oil price uncertainty as the standard deviation of daily West Texas Intermediate (WTI) oil price returns over a given month. This approach captures the volatility of oil prices, reflecting market uncertainty. The formula for calculating OPU is expressed as follows:

$$OPU_t = \sqrt{\frac{1}{N-1} \sum_{d=1}^N (r_d - E(r_d))^2} \cdot \sqrt{N} \tag{1}$$

where r_d represents the daily oil price returns of trading day d and N represents the number of trading days in month t . This measure of OPU has been widely adopted in recent studies, including those by Amin et al. (2023), Hasan et al. (2022), and Maghyereh and Abdoh (2020).

Second, to assess a firm's exposure to OPU, we draw on the methodology of Peng et al. (2023). Specifically, we compute a firm's OPU-beta (*OPU*_{beta}) based on Fama-French three-factor model. The model estimates the sensitivity of a firm's stock returns to changes due to OPU, as follows:

$$r_{i,t} = \alpha + \beta_{OPU} \cdot OPU_t + \beta_M \cdot MKT_t + \beta_S \cdot SMB_t + \beta_H \cdot HML_t + \epsilon_t \tag{2}$$

where $r_{i,t}$ is the return of firm i at time t ; MKT_t , SMB_t , and HML_t are the market, size, and value factors from the Fama-French three-factor model, respectively; β_{OPU} captures firms' sensitivity to OPU, referred to as the OPU-beta; ϵ_t is the error term. We compute β_{OPU} using a 60-month rolling window regression approach. The absolute value of β_{OPU} is used as the firm's OPU exposure (*OPU*_{beta}), capturing the extent to which a firm is affected by OPU.

3.3. Aggregated geopolitical tensions of customer/supplier countries adjusted by trade volume

The country-specific Geopolitical Risk Index, developed by Caldara and Iacoviello (2022), measures the intensity of geopolitical risks on a country-specific basis using automated text-search results from major global newspapers. The GPR index is constructed from articles published in 11 newspapers: the Chicago Tribune, the Daily Telegraph, Financial Times, The Globe and Mail, The Guardian, the Los Angeles Times, The New York Times, USA Today, The Wall Street Journal, and The Washington Post. The index is calculated by counting the number of articles related to adverse geopolitical events each month, expressed as a share of the total number of news articles. The automated search covers eight categories: War Threats, Peace Threats, Military Buildups, Nuclear Threats, Terror Threats, Beginning of War, Escalation of War, and Terror Acts. For 44 advanced and emerging countries, the country-specific GPR index is calculated by counting the monthly share of newspaper articles from 1985 to 2022 that both meet the criterion for inclusion in the

Table 6
Robustness test: Using manufacturing subsample.

	(1)	(2)	(3)	(4)	(5)	(6)
	<i>F. Patent</i>	<i>F.Citation</i>	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Patent</i>	<i>F.Citation</i>
<i>OPUbeta</i>	2.316*** (7.956)	0.765*** (6.038)	2.048*** (6.977)	0.279*** (2.644)	2.197*** (7.453)	0.600*** (4.632)
<i>GPRC</i>			-0.207*** (-4.180)	-0.274*** (-6.921)		
<i>OPUbeta * GPRC</i>			7.006*** (4.339)	12.875*** (7.079)		
<i>GPRS</i>					-0.334*** (-5.879)	-0.196*** (-4.425)
<i>OPUbeta * GPRS</i>					5.023*** (2.554)	9.261*** (4.308)
Constant	-5.345*** (-14.940)	-0.360*** (-3.615)	-5.366*** (-15.005)	-0.419*** (-4.229)	-5.352*** (-14.980)	-0.375*** (-3.764)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16,315	16,315	16,315	16,315	16,315	16,315
Adjusted R ²	0.293	0.062	0.294	0.086	0.294	0.069

This table presents the baseline regression results based on the subsample of manufacturing firms only. The industry fixed effect is the subsector fixed effect within the manufacturing industry. The control variables are the same as in Table 3. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm level. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

global GPR index and mention the name of the country or its major cities.

To assess the impact of geopolitical risk from the countries where a company’s overseas clients or suppliers are located, we adjust this metric by weighting it according to the proportion of business conducted with these clients or suppliers. Specifically, in Eq. (3), we calculate the proportion of trade value (import and export) from each client *k* in country *j* relative to the firm *i*’s total trade value with all clients ($p_{ijk,t}$). We then multiply this proportion by the geopolitical risk of the respective client’s country *j*. Next, we aggregate the geopolitical risk from all client countries for each firm-year, resulting in the firm’s Client Geopolitical Risk (*GPRC*). Similarly, based on Eq. (4), we calculate the Supplier Geopolitical Risk (*GPRS*) from the countries where the suppliers are located.

$$GPRC_{i,t} = \sum p_{ijk,t} * GPR_{j,t} \tag{3}$$

$$GPRS_{i,t} = \sum p_{ijk,t} * GPR_{j,t} \tag{4}$$

3.4. Green innovation

To evaluate a firm’s green innovativeness, we adopt the methodology outlined by Amin et al. (2023) and construct two primary measures of firm innovation. The first measure is the natural logarithm of one plus the total number of patent applications filed by a firm each year that were eventually granted. In line with Griliches et al. (1986), we use the application year of a patent instead of its grant year, as the application year more accurately reflects the actual time of the firm’s innovation activities.

While the number of patents per firm-year is commonly used in innovation studies, this measure may not necessarily capture the significance of new inventions. For example, it treats all patents equally, regardless of whether they are revolutionary or incremental. To address this issue, we follow Bradley et al. (2017) to assess the significance of patents by employing a second proxy for innovation productivity. This second measure captures a patent’s influence, quantified as the natural logarithm of one plus the number of non-self-citations each green patent receives. To measure a firm’s green innovation, we consider only citations received within three years after the patent is granted, as green patents can continue to accumulate citations throughout the sample period. Green patents are specified based on the green inventory patent classification scheme published by the World Intellectual Property

Organization (WIPO).

3.5. Control variables

We control for many variables that may explain green innovation. The controls include market to book value (*MTB*), annual growth rate of sales revenue (*Growth*), return on assets (*ROA*), firm size (*Size*), leverage ratio (*Leverage*), ratio of net cash flows from operating activities to total assets (*Cash*), research and development investment to total sales (*RDSales*), board size (*Board*), board independence (*Independence*), auditing quality (*Big4/10*), state control (*SOE*), and ownership of the largest shareholder (*Top1*). The variable definitions are presented in Appendix A.

3.6. Model specification

To examine impact of firms’ sensitivity to oil price uncertainty, and supply chain geopolitical risk spillover on firm green innovation, we use the following regression model:

$$GreenInno_{i,t+1} = \beta_0 + \beta_1 OPUbeta_{i,t} + \beta_2 OPUbeta_{i,t} * GPR_{i,t} + \sum_k \beta_k Controls_{k,i,t} + \epsilon_{i,t} \tag{5}$$

where *GreenInno*_{*i,t+1*} represents one-year forward of the two green innovation measures *Patent* and *Citation*. *GPR*_{*i,t*} are the two measures of geopolitical tensions from customer countries (*GPRC*) and supplier countries (*GPRS*), respectively. *OPUbeta*_{*i,t*} represents the measure of firm in year *t*. Following the approach of previous studies on firm green innovation, such as Hu et al. (2023) and He et al. (2022), we include a set of firm characteristics as control variables, acknowledged as significant determinants of firm green innovation. These variables comprise 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*), and state ownership (*SOE*). We include industry fixed effects to control unobservable industry-level and macroeconomic factors. Year-fixed effects are also included in all regressions to account for variations and trends across different years, helping to mitigate the influence of time-related factors on green innovation. Appendix A presents the variable definitions.

Table 7
Impact of OPUbeta and geopolitical tensions on green invention and utility patents.

Panel A. Impact on green innovation productivity						
	(1)	(2)	(3)	(4)	(5)	(6)
	<i>F.Invention</i>	<i>F.Utility</i>	<i>F.Invention</i>	<i>F.Utility</i>	<i>F.Invention</i>	<i>F.Utility</i>
<i>OPUbeta</i>	0.821*** (6.084)	1.773*** (8.119)	0.738*** (5.472)	1.618*** (7.370)	0.741*** (5.431)	1.663*** (7.587)
<i>GPRC</i>			-0.088*** (-3.541)	-0.186*** (-4.448)		
<i>OPUbeta * GPRC</i>			2.833*** (2.872)	5.327*** (3.786)		
<i>GPRS</i>					-0.205*** (-5.519)	-0.309*** (-6.327)
<i>OPUbeta * GPRS</i>					4.904*** (3.656)	6.607*** (3.911)
<i>MTB</i>	-0.046** (-2.313)	0.026 (0.725)	-0.047** (-2.352)	0.025 (0.706)	-0.047** (-2.335)	0.026 (0.719)
<i>Growth</i>	-0.017* (-1.827)	0.010 (0.700)	-0.017* (-1.879)	0.009 (0.639)	-0.017* (-1.871)	0.010 (0.667)
<i>ROA</i>	0.001 (0.045)	0.157*** (3.884)	-0.000 (-0.000)	0.155*** (3.832)	0.001 (0.054)	0.158*** (3.897)
<i>Size</i>	0.099*** (15.229)	0.175*** (17.425)	0.099*** (15.318)	0.175*** (17.467)	0.099*** (15.281)	0.175*** (17.491)
<i>Lev</i>	0.008 (0.327)	0.091** (2.306)	0.008 (0.340)	0.091** (2.306)	0.008 (0.323)	0.091** (2.289)
<i>Cash</i>	0.051* (1.675)	-0.045 (-0.944)	0.050* (1.668)	-0.046 (-0.957)	0.051* (1.693)	-0.044 (-0.925)
<i>RDSales</i>	2.328*** (4.352)	1.360* (1.938)	2.326*** (4.352)	1.353* (1.932)	2.340*** (4.373)	1.381** (1.971)
<i>Board</i>	0.054** (1.974)	0.038 (0.860)	0.054** (1.980)	0.038 (0.873)	0.055** (2.003)	0.039 (0.891)
<i>Indep</i>	0.265*** (2.818)	0.111 (0.681)	0.266*** (2.826)	0.113 (0.693)	0.266*** (2.832)	0.113 (0.691)
<i>Big4/10</i>	0.011 (1.391)	-0.004 (-0.268)	0.011 (1.387)	-0.004 (-0.269)	0.011 (1.413)	-0.003 (-0.253)
<i>Top1</i>	-0.044 (-1.414)	-0.086* (-1.682)	-0.045 (-1.461)	-0.088* (-1.725)	-0.045 (-1.458)	-0.087* (-1.713)
<i>SOE</i>	0.023** (2.180)	0.023 (1.311)	0.024** (2.238)	0.024** (1.374)	0.024** (2.206)	0.023 (1.324)
Constant	-2.266*** (-14.123)	-3.717*** (-16.041)	-2.269*** (-14.166)	-3.721*** (-16.070)	-2.269*** (-14.157)	-3.721*** (-16.080)
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	25,593	25,593	25,593	25,593	25,593	25,593
Adjusted R ²	0.163	0.273	0.163	0.273	0.164	0.274

Panel B Impact on green innovation quality						
	(1)	(2)	(3)	(4)	(5)	(6)
	<i>F.CInvention</i>	<i>F.CUtility</i>	<i>F.CInvention</i>	<i>F.CUtility</i>	<i>F.CInvention</i>	<i>F.CUtility</i>
<i>OPUbeta</i>	0.448*** (4.928)	0.380*** (5.890)	0.159** (2.237)	0.160*** (2.872)	0.326*** (3.515)	0.278*** (4.303)
<i>GPRC</i>			-0.167*** (-4.741)	-0.133*** (-5.242)		
<i>OPUbeta * GPRC</i>			9.919*** (6.696)	7.540*** (6.504)		
<i>GPRS</i>					-0.168*** (-5.134)	-0.156*** (-5.112)
<i>OPUbeta * GPRS</i>					8.668*** (5.086)	7.115*** (4.592)
<i>MTB</i>	0.030*** (3.780)	0.012* (1.956)	0.023*** (3.043)	0.007 (1.177)	0.027*** (3.418)	0.010 (1.570)
<i>Growth</i>	0.007 (1.427)	0.002 (0.470)	0.006 (1.114)	0.001 (0.166)	0.006 (1.202)	0.001 (0.245)
<i>ROA</i>	0.015* (1.717)	0.023*** (2.957)	0.011 (1.272)	0.019*** (2.605)	0.015* (1.733)	0.023*** (2.993)
<i>Size</i>	0.005*** (2.583)	0.005** (2.303)	0.007*** (3.619)	0.006*** (3.106)	0.006*** (2.843)	0.005** (2.496)
<i>Lev</i>	0.005 (0.561)	0.023*** (2.595)	0.010 (1.125)	0.027*** (3.002)	0.009 (0.956)	0.026*** (2.901)
<i>Cash</i>	0.004 (0.260)	-0.007 (-0.674)	0.004 (0.281)	-0.006 (-0.669)	0.003 (0.218)	-0.007 (-0.714)
<i>RDSales</i>	0.269 (1.615)	0.152 (0.894)	0.288* (1.757)	0.165 (0.993)	0.265 (1.636)	0.151 (0.903)
<i>Board</i>	0.014 (1.534)	0.010 (1.094)	0.013 (1.437)	0.009 (1.024)	0.014 (1.503)	0.010 (1.076)

(continued on next page)

Table 7 (continued)

	Panel B Impact on green innovation quality					
	(1)	(2)	(3)	(4)	(5)	(6)
	<i>F.CInvention</i>	<i>F.CUtility</i>	<i>F.CInvention</i>	<i>F.CUtility</i>	<i>F.CInvention</i>	<i>F.CUtility</i>
<i>Indep</i>	0.007 (0.194)	-0.008 (-0.239)	0.007 (0.196)	-0.008 (-0.238)	0.007 (0.181)	-0.009 (-0.248)
<i>Big4/10</i>	0.003 (0.815)	0.007*** (2.590)	0.002 (0.657)	0.007** (2.477)	0.003 (0.935)	0.008*** (2.714)
<i>Top1</i>	0.025* (1.727)	0.026** (2.336)	0.017 (1.224)	0.020* (1.824)	0.021 (1.478)	0.023** (2.105)
<i>SOE</i>	-0.002 (-0.550)	-0.005 (-1.327)	0.001 (0.206)	-0.003 (-0.694)	-0.001 (-0.136)	-0.004 (-0.961)
Constant	-0.173*** (-3.553)	-0.146*** (-2.955)	-0.207*** (-4.223)	-0.171*** (-3.485)	-0.180*** (-3.720)	-0.152*** (-3.074)
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	25,593	25,593	25,593	25,593	25,593	25,593
Adjusted R ²	0.038	0.038	0.060	0.055	0.048	0.047

This table presents the impact of *OPUbeta* and geopolitical risks from suppliers/customers on the quantity and quality of different types of green innovation. In Panel A, the primary outcome variables are the forward one-period natural logarithm of the number of invention patents and utility model patents. Panel B displays the forward one-period natural logarithm of citations for invention patents and the count of utility model patents. The independent and control variables align with those in Table 3. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm level. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

4. Empirical results

4.1. Descriptive statistics and correlation matrix

Table 1 Panel A presents the descriptive statistics of the key variables. The minimum and maximum values of the *Patent* variable are 0 and 6.608, respectively, with a standard deviation of 0.738. For the *Citation* variable, the minimum and maximum values are 0 and 6.489, with a standard deviation of 0.211. These statistics indicate a significant variation in the number of patent applications and citations among firms in our sample. The mean value of *OPUbeta* is 0.036, with a minimum of 0.000, a maximum of 0.171, and a standard deviation of 0.037. This suggests that while most firms exhibit low sensitivity of returns to oil price uncertainty, there is substantial variation across firms. The mean values of *GPRC* and *GPRS* are 0.033 and 0.024, respectively, with standard deviations of 0.118 and 0.108. This indicates considerable variation in the geopolitical risk, weighted by overseas business volume, from the countries of both clients and suppliers across firms, with the risk from customer countries being greater than that from supplier countries. Panel B presents the distribution of firms across industries in our sample. As shown, manufacturing firms account for the largest proportion, comprising 68.96 % of the total sample. Given this dominance, we further classify manufacturing firms into sub-industries based on the first three digits of the China Securities Regulatory Commission Industry Code. The detailed breakdown is presented in Panel C, which shows the number and proportion of firms in each manufacturing subsector. As Panel C illustrates, manufacturing firms in sectors such as Electrical Machinery (14.86 %), Chemical Raw Materials (10.33 %), Pharmaceutical Manufacturing (9.98 %), Railway and Aerospace Equipment (10.11 %), and General Equipment (8.96 %) represent a substantial portion of the sample. This indicates that the manufacturing firms in our dataset are not only numerous but also relatively diverse across subsectors.

Table 2 provides the correlation matrix for the main variables used in our analysis. The correlation coefficients between the independent variables are relatively small, suggesting that multicollinearity is not a serious issue in this study.

4.2. Firm OPU exposure, geopolitical tensions and firm green innovation

Table 3 presents the baseline results of the impact of OPU sensitivity on green innovation output and quality during times of geopolitical tensions, based on Eq. (3). The coefficients of *OPUbeta* in Columns (1)

and (2) are both positive and statistically significant at the 1 % level. This indicates that a firm's sensitivity to oil price uncertainty positively influences both its green innovation output and quality. The economic significance of the coefficients for *OPUbeta* in Columns (1) and (2) indicates that a 1 standard deviation increase in a firm's sensitivity to oil price fluctuations is associated with an 17.23 % increase in green innovation output and an 85.67 % improvement in green innovation quality.

In Columns (3) through (6), the coefficient of *OPUbeta* remains significantly negative at the 1 % level. The interaction terms *OPUbeta***GPRC* and *OPUbeta***GPRS* are significantly positive at the 1 % level, indicating that during geopolitical tensions, firms more sensitive to OPU are more likely to enhance green innovation. This finding is consistent with the strategic growth theory, suggesting that firms increase investments to seek alternatives when facing risks.

Geopolitical crises transmitted through supply chains may have different impacts depending on whether they originate from suppliers or customers. Comparing the results in Columns (3) and (4) with those in Columns (5) and (6) of Table 3 reveals that the coefficient of *GPRC***OPUbeta* is bigger than that of *GPRS***OPUbeta*. This indicates that firms with higher oil price uncertainty exposure are more inclined to enhance their innovation levels when geopolitical risks affect their customer countries, compared to when such risks impact their supplier countries. This finding is consistent with the results of Fan et al. (2024), who find that geopolitical conflicts in customer countries negatively affect cross-border supplier-buyer relationships. However, suppliers with stronger innovation capabilities are better able to maintain these relationships and mitigate transactional losses (Fan et al., 2024).

To ensure the robustness of our baseline regression results, we incorporate firm-year fixed effects to account for potential confounding factors within the dataset. Specifically, Table 4 presents the results of the baseline regression model with the inclusion of firm, province×year, and industry×year fixed effects. This adjustment addresses unobserved firm-specific, time-varying, and regional varying characteristics that might otherwise introduce bias into the analysis, enhancing the reliability of the findings.

A proportion of Chinese listed firms may not have foreign supply chain partners, which could dilute the overall results. To address this, we re-examine the impact of OPU exposure on corporate green innovation using a subsample consisting only of observations with positive *GPRC* or *GPRS* values. Specifically, we exclude observations where *GPRC* or *GPRS* equals zero and rerun the baseline regression. The results, presented in Table 5, remain consistent with those of the baseline regression.

Table 8
The impact of green patents on firm value under the dual influence of GPR and OPU.

Panel A The impact of green patent on Tobin's Q.				
	F.TobinQ		F2.TobinQ	
	(1)	(2)	(3)	(4)
	With dual impact	Without dual impact	With dual impact	Without dual impact
Patent	0.069** (2.196)	0.112 (1.433)	0.301*** (10.366)	0.161 (1.357)
Growth	-0.160 (-0.994)	0.041 (0.228)	-0.267** (-2.045)	0.288 (0.626)
ROA	0.101 (0.131)	-0.045 (-0.055)	-0.272 (-0.495)	0.183 (0.209)
Size	-0.623*** (-7.342)	-0.796*** (-8.502)	-0.675*** (-9.605)	-0.827*** (-7.652)
Lev	0.541 (0.825)	1.502** (2.391)	0.341 (0.674)	1.019* (1.957)
Cash	0.538 (1.152)	3.896* (1.760)	0.716** (1.981)	4.484 (1.281)
RDSales	4.029* (1.783)	-0.370 (-0.132)	3.404 (1.545)	0.078 (0.016)
Board	0.338 (0.665)	-0.804 (-0.799)	0.270 (0.698)	-1.653 (-0.964)
Indep	1.706 (1.097)	1.499 (1.102)	1.132 (0.945)	1.037 (0.533)
Big4/10	0.010 (0.153)	0.270 (1.591)	0.020 (0.363)	0.495 (1.504)
Top1	0.158 (0.979)	-1.169*** (-2.809)	0.406*** (2.806)	-1.233* (-1.927)
SOE	0.141 (1.229)	-0.231** (-2.370)	0.057 (0.638)	-0.285** (-2.448)
Constant	13.837*** (18.605)	20.010*** (6.032)	15.221*** (21.863)	22.830*** (4.128)
Industry FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	5494	15,230	5366	12,811
Adjusted R ²	0.149	0.042	0.214	0.035

Panel B The impact of green patent citation on ROA				
	F.ROA		F2.ROA	
	(1)	(2)	(3)	(4)
	With dual impact	Without dual impact	With dual impact	Without dual impact
Patent	0.007*** (2.823)	0.003 (1.369)	0.006** (2.024)	0.003 (1.294)
MTB	-0.162*** (-15.001)	-0.148*** (-17.690)	-0.127*** (-10.837)	-0.109*** (-11.189)
Growth	0.087*** (12.309)	0.068*** (14.374)	0.057*** (7.677)	0.033*** (6.650)
Size	0.032*** (12.988)	0.027*** (14.499)	0.022*** (7.755)	0.021*** (9.858)
Lev	-0.057*** (-4.610)	-0.059*** (-5.811)	-0.057*** (-3.738)	-0.046*** (-4.194)
Cash	0.087*** (6.547)	0.138*** (11.542)	0.085*** (5.831)	0.117*** (8.976)
RDSales	-0.329** (-2.413)	-0.740*** (-5.604)	-0.415** (-2.221)	-0.726*** (-4.512)
Board	0.010 (0.956)	0.011 (1.267)	0.019 (1.625)	0.008 (0.852)
Indep	-0.042 (-1.124)	-0.024 (-0.842)	-0.030 (-0.743)	-0.057* (-1.753)
Big4/10	0.004 (1.256)	0.004 (1.365)	0.004 (1.130)	-0.000 (-0.025)
Top1	0.050*** (3.895)	0.115*** (11.616)	0.066*** (4.604)	0.105*** (9.323)
SOE	-0.029*** (-6.615)	-0.010*** (-2.796)	-0.024*** (-4.993)	-0.008** (-2.059)
Constant	-0.546*** (-10.019)	-0.495*** (-12.588)	-0.392*** (-6.400)	-0.372*** (-8.271)
Industry FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	5793	15,130	5685	12,045
Adjusted R ²	0.231	0.146	0.153	0.105

This table examines the impact of green patents on firm value under the dual influence of GPR and OPU exposure. Panel A presents the effects of green patents on Tobin's Q (*TobinQ*) at year $t + 1$ and $t + 2$. Panel B shows the effects on return on assets (*ROA*) at year $t + 1$ and $t + 2$. Columns (1) and (3) report results for the subsample subject to the dual effect, identified by the value $OPUBeta \times GPRC$ or $OPUBeta \times GPRS$ greater than 0. Columns (2) and (4) present results for the subsample not affected by the dual effect. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at the firm level. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

Table 6 reports the robustness of the baseline findings by restricting the analysis to manufacturing firms only, addressing the issue that the green innovation response to *OPUBeta* may differ across manufacturing firms in sectors. Columns (1) to (6) present results from different model specifications, progressively incorporating interactions with measures of geopolitical tensions (*GPRC* and *GPRS*). The interaction terms $OPUBeta \times GPRC/GPRS$ are significantly positive in Columns (3) to (6) implying that firms exposed to both OPU and geopolitical tensions are more likely to innovate green technologies, potentially as a risk-mitigation strategy.

Furthermore, we explore the impact of OPU exposure and geopolitical tensions on the output and quality of different types of patents produced by firms. The results are presented in Table 7. Panel A of Table 7 displays the effects of *OPUBeta*, *GPRC*, and *GPRS* on the output of green invention patents and utility model patents, while Panel B highlights the impact on the quality of these patents.

The results reveal that the effects of $OPUBeta \times GPRC$ and $OPUBeta \times GPRS$ on the output of invention patents are lower than their effects on utility model patents. However, the quality of invention patents is significantly higher than that of utility model patents. This suggests that while geopolitical tensions and oil price uncertainty may stimulate a greater quantity of utility model patents due to their relatively lower development costs and shorter innovation cycles, firms prioritize the development of higher-quality invention patents when addressing long-term strategic goals and uncertainties.

Our baseline results show that firm-level OPU exposure and GPR significantly promote green innovation, the ultimate goal of such innovation is often to enhance long-term firm performance (Porter and Linde, 1995). Therefore, it is important to examine whether green innovation driven by external uncertainty can translate into tangible improvements in corporate outcomes. We conduct an additional analysis to test whether green innovation can improve firm performance under the pressures of OPU exposure and heightened geopolitical tensions involving foreign supply partners. Specifically, we examine the impact of green innovation on two measures of firm performance, e.g., Tobin's Q and return on assets (ROA), under the dual influence of OPU exposure and GPR. We conduct a heterogeneity analysis by dividing the sample into two groups: firms subject to both OPU and GPR shocks (i.e., with the value of $OPUBeta \times GPRC$ or $OPUBeta \times GPRS$ is greater than 0) and firms not affected by the dual influence (i.e., with the value of $OPUBeta \times GPRC$ or $OPUBeta \times GPRS$ equals 0).

As reported in Table 8, Panel A shows that green innovation significantly improves Tobin's Q in both the $t + 1$ and $t + 2$ year for firms under the dual influence. Panel B further demonstrates that green patents are positively associated with ROA, again only for the subsample exposed to both OPU exposure and GPR. In contrast, these effects are statistically insignificant in the unaffected group. These findings reinforce the practical relevance of our study by showing that green innovation enhances firm value especially under extremely heightened external uncertainties. This is consistent with prior literature (e.g., Xie et al., 2015; Chen et al., 2022), suggesting that green innovation strengthens firm competitiveness and supports long-term value creation under volatile external environments. While in environments lower external uncertainties the impact of green innovation could be relatively less recognized by stakeholders, therefore adding insignificant value to firm performance. In addition, when the external environment is relatively stable, the urgency to hedge against risks, such as policy shifts or

Table 9
Mechanism analysis: Government green subsidy.

	(1)	(2)	(3)	(4)	(5)
	<i>F. Patent</i>	<i>F. Citation</i>	<i>GreenSubsidy</i>	<i>F. Patent</i>	<i>F. Citation</i>
<i>OPUBeta</i>	1.984*** (8.182)	0.602*** (6.308)	0.034** (2.002)	1.997*** (7.828)	0.636*** (6.155)
<i>GreenSubsidy</i>				0.534*** (3.655)	0.160** (2.169)
Constant	-4.488*** (-17.510)	-0.231*** (-3.757)	0.068*** (4.534)	-4.949*** (-17.411)	-0.252*** (-4.086)
Controls	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Observations	25,593	25,593	21,745	21,697	21,697
Adjusted R ²	0.301	0.047	0.061	0.312	0.050
Sobel Test				4.208***	3.906***

This table presents the mediation effects of government green subsidy on the relationship between *OPUBeta* and corporate green innovation. *GreenSubsidy* is measured as green subsidy received from governments divided by total assets. The control variables are the same as in Table 3. All regressions include industry and year fixed effects. Standard errors are robust and clustered at the firm level, with t-statistics shown in parentheses. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

Table 10
The impact of domestic supply chain alliances.

	(1)	(2)	(3)	(4)
	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Patent</i>	<i>F. Citation</i>
<i>OPUBeta</i>	1.761*** (7.232)	0.220*** (2.738)	1.859*** (7.624)	0.446*** (4.647)
<i>GPRC</i>	-0.250*** (-5.507)	-0.270*** (-7.364)		
<i>OPUBeta * GPRC</i>	7.527*** (5.009)	13.156*** (7.609)		
<i>OPUBeta * GPRC* Alliance</i>	-3.172*** (-6.186)	-1.384*** (-7.173)		
<i>GPRS</i>			-0.379*** (-7.208)	-0.220*** (-5.385)
<i>OPUBeta * GPRS</i>			6.955*** (3.846)	10.981*** (5.217)
<i>OPUBeta * GPRS* Alliance</i>			-1.324** (-2.526)	-1.060*** (-6.417)
<i>Alliance</i>	0.011** (2.510)	-0.000 (-1.051)	0.010** (2.471)	-0.000 (-1.219)
Constant	-4.487*** (-17.508)	-0.268*** (-4.387)	-4.485*** (-17.512)	-0.240*** (-3.929)
Controls	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	25,593	25,593	25,593	25,593
Adjusted R ²	0.302	0.074	0.302	0.059

This table examines the moderating effect of firms' domestic supply chain alliances on the impact of *OPUBeta* and geopolitical factors on green innovation. *Alliance* represents the natural logarithm of the number of suppliers/customers with whom the firm has established strategic partnerships domestically. The control variables are the same as in Table 3. t-statistics are reported in parentheses. Standard errors are robust and clustered at the firm level. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

resource volatility, is reduced, so firms may not experience immediate market advantages or risk mitigation benefits from green innovation.²

4.3. Mechanism analysis: Government green subsidies

Governments often respond to rising external uncertainties, for instance energy market shocks, by providing green subsidies to guide firms toward sustainable practices and mitigate long-term risks (Xing et al., 2022). In this study, governments are more likely to support firms

Table 11
The impact of supply chain efficiency.

	(1)	(2)	(3)	(4)
	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Patent</i>	<i>F. Citation</i>
<i>OPUBeta</i>	1.768*** (7.252)	0.221*** (2.753)	1.863*** (7.634)	0.444*** (4.641)
<i>GPRC</i>	-0.245*** (-5.449)	-0.265*** (-7.361)		
<i>OPUBeta * GPRC</i>	19.812*** (3.069)	30.304*** (3.818)		
<i>OPUBeta * GPRC* Efficiency</i>	-2.613** (-2.049)	-3.651** (-2.371)		
<i>GPRS</i>			-0.389*** (-7.366)	-0.233*** (-5.545)
<i>OPUBeta * GPRS</i>			18.724*** (3.010)	26.596*** (4.088)
<i>OPUBeta * GPRS* Efficiency</i>			-2.371** (-2.015)	-3.179*** (-2.775)
<i>Efficiency</i>	-0.018*** (-3.137)	-0.000 (-0.416)	-0.018*** (-3.134)	-0.001 (-0.777)
Constant	-4.391*** (-17.070)	-0.263*** (-4.282)	-4.391*** (-17.069)	-0.235*** (-3.812)
Controls	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	25,593	25,593	25,593	25,593
Adjusted R ²	0.302	0.077	0.303	0.061

This table investigates the moderating effect of firms' supply chain efficiency on the impact of *OPUBeta* and geopolitical factors on green innovation. *Efficiency* is defined as the natural logarithm of 365/firm's inventory turnover ratio. The control variables are the same as in Table 3. t-statistics are reported in parentheses. Standard errors are robust and clustered at the firm level. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

with greater OPU exposure, aiming at encouraging green technological transitions. Therefore, we performed a three-step mediation test using government green subsidies, measured as green subsidies received from governments divided by total assets, as the mediating variable. In the first step analysis (Columns (1) and (2) in Table 9), we regress the outcome variables (*F. Patent* and *F. Citation*) on the explanatory variable (*OPUBeta*), re-presenting the baseline findings as a benchmark for comparison. In the second step analysis (Column (3)), we regress *OPUBeta* on the measure of government green subsidy, *GreenSubsidy*. Columns (4) and (5) include *GreenSubsidy* as a mediator in the model. The coefficient on *GreenSubsidy* is positive and significant for both green innovation measures. After including *OPUBeta* in the regression,

² We appreciate the suggestions provided by the anonymous reviewer.

Table 12
Reliance on overseas business.

	High international business				Low international business			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>F. Patent</i>	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Citation</i>	<i>F. Patent</i>	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Citation</i>
<i>OPU</i> β <i>^*</i> <i>GPRC</i>	6.387*** (3.785)		12.526*** (6.579)		-0.332 (-0.133)		0.550 (1.388)	
<i>OPU</i> β <i>^*</i> <i>GPRS</i>		6.773*** (2.984)		12.391*** (4.585)		2.005 (0.821)		0.384 (0.882)
Constant	-5.635*** (-14.959)	-5.612*** (-14.920)	-0.476*** (-4.138)	-0.420*** (-3.647)	-3.113*** (-10.329)	-3.122*** (-10.358)	0.013 (0.626)	0.015 (0.727)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12,954	12,954	12,954	12,954	12,637	12,637	12,637	12,637
Adjusted R ²	0.327	0.328	0.101	0.093	0.272	0.273	0.011	0.011

This table shows the analysis with the sample split into two groups based on the median percentage of overseas revenue in total revenue. The control variables are the same as in Table 3. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at firm level. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

Table 13
Impact of competitive pressure.

	High competition				Low competition			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	<i>F. Patent</i>	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Citation</i>	<i>F. Patent</i>	<i>F. Patent</i>	<i>F. Citation</i>	<i>F. Citation</i>
<i>OPU</i> β <i>^*</i> <i>GPRC</i>	12.294*** (5.789)		20.829*** (8.035)		0.899 (0.477)		0.559 (1.437)	
<i>OPU</i> β <i>^*</i> <i>GPRS</i>		11.020*** (4.395)		18.188*** (5.375)		1.141 (0.476)		0.214 (0.604)
Constant	-5.090*** (-13.918)	-5.081*** (-13.909)	-0.493*** (-4.865)	-0.456*** (-4.547)	-3.946*** (-12.714)	-3.961*** (-12.772)	-0.020 (-0.501)	-0.017 (-0.421)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	13,035	13,035	13,035	13,035	12,556	12,556	12,556	12,556
Adjusted R ²	0.329	0.328	0.172	0.150	0.295	0.296	0.022	0.022

This table divides the sample into high competition and low competition sub-samples based on the median value of Herfindahl-Hirschman Index (HHI). The control variables are the same as in Table 3. *t*-statistics are reported in parentheses. Standard errors are robust and clustered at firm level. *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively.

GreenSubsidy remains positively significant, indicating that government green subsidies serve as a channel through which firms respond to oil price uncertainty by investing in green initiatives. The Sobel test result indicates that the mediating effect of green subsidy is significant. Thus, firm with higher exposure to OPU are more likely to receive greater green subsidies, which in turn fosters their green innovation.

4.4. Moderating effects of supply chain perspectives

While we find that external shocks such as oil price volatility and geopolitical risks directly influence firms' innovation strategies, the role of supply chain structures in mediating these effects remains underexplored. Supply chain dynamics, particularly their ability to absorb or amplify external uncertainties, may critically shape firms' green innovation responses. Investigating this perspective provides a foundation for understanding the mechanisms through which firms navigate complex external pressures and adjust their innovation strategies accordingly.

4.4.1. Domestic supply chain strategic alliances

Domestic supply chain strategic alliances refer to collaborative partnerships between a firm and its domestic suppliers, customers, or other domestic supply chain stakeholders, aimed at achieving mutual operational benefits such as improved resource accessibility, enhanced bargaining power, and increased operational resilience (Monczka et al.,

1998). Domestic supply chain alliances play a crucial role by providing firms with stable supply sources, facilitating resource pooling, and enabling more effective risk-sharing mechanisms within domestic markets (Hsieh et al., 2018). By maintaining strong domestic alliances, firms can mitigate risks arising from international supply chain disruptions and geopolitical tensions, allowing them to better cope with external uncertainties (Roscoe et al., 2022).

Our empirical analysis suggests that OPU exposure and geopolitical conflicts pose significant external pressures on firms, thereby encouraging them to engage in green innovation as a strategic hedge. Domestic supply chain alliances, by enhancing organizational stability and providing secure access to critical resources, could shape the effects of these external pressures. Specifically, stronger domestic alliances might reduce firms' immediate incentives for green innovation by alleviating external pressures and stabilizing operations in the short run.

To empirically examine this moderating role, we define the variable *Alliance* as the natural logarithm of the number of domestic supply chain strategic partnerships maintained by each firm. Interaction terms between OPU exposure (*OPU* β), geopolitical risks (*GPRC* and *GPRS*), and *Alliance* are included in our baseline regression. As shown in Table 10, we find significantly negative interaction terms, indicating that domestic supply chain alliances indeed buffer external pressures, thereby diminishing the urgency to pursue immediate green innovation. This highlights the nuanced theoretical role of domestic alliances. While providing necessary stability and resource access, they may

concurrently reduce the urgency for proactive, riskier strategic actions like green innovation. This finding underscores the complexity in balancing supply chain stability and innovative momentum under uncertainty.

4.4.2. Supply chain efficiency

Supply chain efficiency refers to a firm's capability to optimize the utilization of its resources, streamline operational processes, and minimize costs across the entire supply chain (Kamalahmadi et al., 2022). A primary indicator of supply chain efficiency is inventory turnover, reflecting how effectively firms manage inventory levels and resource flows to reduce holding costs and enhance responsiveness. Theoretically, supply chain efficiency can significantly influence firm strategic behaviour under conditions of external uncertainty. While efficiency facilitates stable operations and reduced operational costs, it might also encourage firms to maintain conservative resource allocation strategies (Wiengarten et al., 2016).

In the face of OPU exposure and geopolitical risks, efficient supply chains help firms absorb external shocks by offering greater operational flexibility and cost-saving mechanisms. However, highly efficient supply chains may also reduce immediate pressures for strategic change, including green innovation, by enabling firms to withstand short-term disruptions without the need for transformative adjustments. Efficiency-driven operational stability is beneficial, while it may inadvertently lower incentives for firms to adopt proactive, long-term innovation initiatives especially when involving higher upfront costs and risks.

We measure *Efficiency* as the natural logarithm of 365 divided by the firm's inventory turnover ratio. Including interaction terms ($OPU\beta * GPRC * Efficiency$ and $OPU\beta * GPRS * Efficiency$) in our baseline regression, we find (as reported in Table 11) that supply chain efficiency negatively shapes the relationship between external uncertainties and green innovation. Specifically, higher supply chain efficiency reduces the urgency for green innovation investment, as firms prioritize short-term cost optimization and operational stability over the immediate pursuit of innovation. However, we also emphasize that efficient supply chains provide firms the strategic flexibility to selectively and deliberately pursue green innovation in a more controlled, long-term-oriented manner. This nuanced theoretical interpretation deepens our understanding of how operational efficiency interacts with external uncertainties to shape corporate innovation strategies.

4.5. Motivation behind firms' adoption of green innovation strategies

4.5.1. The dependence on international markets

We then analyze the motivations behind firms' adoption of green innovation strategies. Geopolitical risks differ from other macroeconomic uncertainties caused by government policies and domestic business environments, as it focuses more on international conflicts and political tensions. Existing research (e.g., Roberts et al., 2019) indicates that such risks often have a significant impact on international trade. Compared to the relatively stable domestic market, international markets are particularly vulnerable to geopolitical tensions, leading to increased fragility in global supply chains and market demand. Therefore, for firms with a higher proportion of international business, facing high OPU beta and geopolitical risks from supply chain countries, they are more likely to adopt green innovation as a strategy to mitigate these external shocks. Firms with a higher proportion of international business are more dependent on global markets and international supply chains, which significantly increases their risk exposure when dealing with oil price fluctuations and geopolitical risks (Campos et al., 2023). Particularly for firms highly sensitive to OPU, geopolitical tensions can further exacerbate cost uncertainty, transmitting through global supply chains to impact firm operations. This dual uncertainty makes firms with higher international business exposure more reliant on innovation strategies, especially green innovation, to reduce dependence on fossil fuels and

mitigate the impact of energy cost volatility on their global operations.

To test this conjecture, we divided firms into two groups based on the median of their international business proportion: firms with a higher proportion of international business than the median and those with a lower proportion. The estimation results in Table 12 show that the impact of $OPU\beta$ and geopolitical tensions is more pronounced for firms with a higher proportion of international business. This result suggests that, when faced with high OPU beta and geopolitical risk, firms with significant international business are more likely to increase their investment in green innovation to reduce uncertainty in their global operations and maintain competitiveness. Thus, firms with a high proportion of international business, given their greater exposure to global market uncertainties such as oil price uncertainty and geopolitical risks, are more inclined to adopt green innovation as a strategy to address these challenges.

4.5.2. Competitive pressure

Competitive pressure typically arises from intense competition among firms in the market, especially in resource-constrained industries and highly saturated markets (Giachetti, 2016). When facing strong competition, firms often need to continuously improve product quality, reduce costs, and enhance operational efficiency to maintain their market position (Di Dio and Correani, 2020). However, in the context of increasing OPU exposure and geopolitical risks, the external environment becomes more complex and unpredictable. This uncertainty not only impacts a firm's operating costs and market demand but can also influence its overall strategic layout through the supply chain (Cao et al., 2020; Roscoe et al., 2020). In such a scenario, firms facing higher competitive pressure may be more inclined to pursue green innovation as a means of gaining a new competitive edge. Green innovation can help firms reduce their dependence on fossil fuels, mitigate the negative effects of energy cost volatility on production and operations, and enhance their sustainable development image, meeting the growing demand from consumers and investors for environmentally friendly products and services (Wurlod and Noailly, 2018). Thus, we conjecture that in environments with highly competitive pressure, firms may be more motivated to engage in green innovation to address OPU and geopolitical risks, thereby maintaining or improving their market position in a competitive landscape.

To test this conjecture, we group the sample firms based on the median of the Herfindahl Index to distinguish between high and low competitive pressure environments. We then analyzed the impact of OPU beta and geopolitical risks on green innovation under these conditions. The results, presented in Table 13, show that in the highly competitive pressure subgroup, OPU beta and geopolitical risks significantly promote green innovation. This finding supports our hypothesis that when faced with higher competitive pressure, firms are more likely to increase their investment in green innovation to respond to external uncertainties and maintain their competitiveness.

5. Conclusion

This study examines the interplay between oil price uncertainty exposure, geopolitical risks, and corporate green innovation, providing novel insights into how firms respond strategically to external uncertainties. Our findings demonstrate that firms with greater sensitivity to oil price uncertainty are more likely to engagement in green innovation, particularly during periods of intensified geopolitical tensions. The amplifying effect of geopolitical crises are especially pronounced when these tensions originate from customer countries, highlighting the role of supply chain vulnerabilities in shaping innovation strategies.

Additionally, we observe a negative moderating effect of domestic supply chain alliances and supply chain efficiency on our baseline results. While domestic supply chain alliances and supply chain efficiency provide stability and operational resilience (Philsoophian et al., 2021), they may also reduce the urgency for green innovation. This effect likely

reflects the stabilizing role these factors play, enabling firms to prioritize maintaining current operations rather than immediately pursuing long-term innovation strategies. Similarly, supply chain efficiency enhances firms' resilience by optimizing resource utilization and streamlining operations, allowing them to withstand disruptions and minimize costs (Kamalahmadi et al., 2022). However, our results indicate that supply chain efficiency can inadvertently divert urgent attention from green innovation, as supply chain efficiency enables firms to emphasize short-term operational stability and cost management over proactive investments in green innovation initiatives.

Our findings offer significant implications for both corporate strategy and policymaking. For firms, the results emphasize the importance of green innovation, particularly in uncertain environments where green innovation can serve as a key tool for achieving competitive advantage and long-term sustainability. Policymakers, on the other hand, should recognize the role of supply chain dynamics in addressing external uncertainties. Efforts to enhance domestic supply chain alliances and efficiency should be accompanied by incentives that encourage firms to

maintain innovation intensity. Moreover, targeted policies that alleviate financial constraints. Which in turn promote green innovation in energy-sensitive and internationally active firms can help ensure that innovation continues to thrive, even under volatile conditions. These insights provide a comprehensive framework for navigating the complexities of geopolitical and economic uncertainty while advancing sustainability goals.

CRediT authorship contribution statement

Kai Huang: Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation. **Jing Chi:** Supervision. **Jing Liao:** Supervision. **Mui Kuen Yuen:** Supervision.

Declaration of competing interest

No potential conflict of interest was reported by the authors.

Appendix A. Variable description

Variable	Description
<i>Patent</i>	Natural logarithm of one plus the total number of green patent applications filed by a firm in the given year that were eventually granted.
<i>Invention</i>	Natural logarithm of one plus the total number of green invention patent applications filed by a firm in the given year that were eventually granted.
<i>Utility</i>	Natural logarithm of one plus the total number of green utility patent applications filed by a firm in the given year that were eventually granted.
<i>Citation</i>	Natural logarithm of one plus the number of non-self-citations each green patent receives within three years after it is granted.
<i>CIvention</i>	Natural logarithm of one plus the number of non-self-citations each green invention patent receives within three years after it is granted.
<i>CUtility</i>	Natural logarithm of one plus the number of non-self-citations each green utility patent receives within three years after it is granted.
<i>OPUbeta</i>	According to Peng et al. (2023), the annual firm exposure to OPU is calculated based on monthly data through the FAMA three-factor model. We take its absolute value.
<i>GPRC</i>	This variable represents the cumulative geopolitical risk faced by the countries of firm <i>i</i> 's customers during year <i>t</i> . The annual geopolitical risk index for each country is obtained from the work of Caldara and Iacoviello (2022).
<i>GPRS</i>	This variable represents the cumulative geopolitical risk faced by the countries of firm <i>i</i> 's suppliers during year <i>t</i> . The annual geopolitical risk index for each country is obtained from the work of Caldara and Iacoviello (2022).
<i>MTB</i>	The ratio of market value to its book value of equity.
<i>Growth</i>	Change in sales between years <i>t</i> and <i>t-1</i> .
<i>ROA</i>	Return on assets, calculated as net profit after tax/total assets.
<i>Size</i>	The natural logarithm of total assets.
<i>Lev</i>	Total liabilities scaled by total assets.
<i>Cash</i>	Cash and cash equivalents scaled by total assets.
<i>RDSales</i>	R&D expenses scaled by total sales.
<i>Board</i>	The natural logarithm of the total number of directors on the board.
<i>Indep</i>	The proportion of independent directors to the total number of directors on the board.
<i>Big4/10</i>	A dummy variable equals one if the auditor of the firm is one of international "Big4" or "Domestic 10" audit firms, and zero otherwise.
<i>Top1</i>	The largest shareholding ratio.
<i>SOE</i>	A dummy variable equals one if the ultimate controller of a firm is a government agency or a state-owned enterprise, and zero otherwise.
<i>Alliance</i>	The natural logarithm of the number of suppliers/customers with whom the firm has established strategic partnerships domestically.
<i>Efficiency</i>	The natural logarithm of 365/firm's inventory turnover ratio.
<i>HHI</i>	The variable Herfindahl-Hirschman Index (<i>HHI</i>) represents the degree of industry competition. It is calculated as the sum of the squares of the market shares of all firms within the industry, with higher values indicating lower competition and greater market concentration.

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eneco.2025.109050>.

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