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The global geopolitical-energy uncertainty index and total factor productivity: New evidence from firm-level analysis☆

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ABSTRACT

This paper examines the impact of the global geopolitical-energy uncertainty (GEU) on firm-level total factor productivity, considering variation across countries, industries, and firm sizes. Employing the novel GEU index proposed by Dang et al. (2024a) and firm-level annual data from 2001 to 2023, we find strong evidence that the GEU index negatively affects firm productivity. There is heterogeneity in the GEU index's impact. Firms in developed countries such as the US, UK, France, and Germany are more negatively affected, whereas Canadian firms show a positive response. Energy-intensive firms and smaller firms experience stronger negative impacts. Mechanism analysis further demonstrates that both firm level characteristics and macroeconomic energy conditions shape productivity responses to GEU. Higher profitability reduces the negative impact of GEU shocks, while higher cost intensity and higher global energy prices amplify the adverse effects, increasing productivity losses. Our baseline results remain robust under different robustness checks. The paper's findings offer guidance for firms to develop effective strategies to manage risks during periods of heightened geopolitical-energy uncertainty.

1. Introduction

Energy is a critical strategic resource underpinning economic growth (Wen et al., 2019). Acheampong et al. (2021), for instance, provide empirical evidence showing a strong positive association between economic growth and energy consumption. Within the broader energy context, oil stands out as a particularly important source due to its widespread use in various economic activities, having strategic importance for national and global economies. However, due to its scarcity, the spatial separation between demand and supply, and its low elasticity of demand, oil price uncertainties can disrupt investment decisions, industrial production and dampen overall economic activities (Elder and Serletis, 2010; Jo, 2014; Peersman and Van Robays, 2012). According to Hamilton (2003) and Charfeddine et al. (2020), oil price uncertainties have significant detrimental effects on economic growth on both national and global scales.

It is also important to note that oil price stability is highly susceptible to geopolitical risks. Empirical evidence suggests that geopolitical risks drive up energy price volatilities, amplify precautionary behaviors, and restrict the availability of oil energy for productive use (Liu et al., 2019; Mei et al., 2020; Wang et al., 2021). This heightened volatility, in turn, is detrimental to firms' productivity (Liu et al., 2024; Ren et al., 2023b). In fact, Mignon and Saadaoui (2024) demonstrate that positive shocks of geopolitical risks can raise concerns over supply chain disruptions and induce expectations for oil supply shortages, thereby constraining business operations and reducing production capacity. Generally, geopolitical risks can reduce firm investment and innovation, inhibiting productivity growth (Caldara and Iacoviello, 2022; Nguyen et al., 2022).

On the other hand, literature also find evidences that oil prices and volatilities have significant negative and positive, respectively, causal effects on geopolitical risk (Ivanovski and Hailemariam, 2022). Abdel-Latif and El-Gamal (2019) and Su et al. (2021) document significant

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interactions between oil price and geopolitical risks and demonstrate bidirectional casual linkages between the two risk factors. More recent studies reinforce this interdependence, showing that geopolitical instability drives oil markets through both supply and demand channels, while energy volatility simultaneously feeds back into geopolitical risk dynamics (Jiao et al., 2023).

Taken together, existing literature offers three key insights: (1) both geopolitical and oil price risks have significant impacts on productivity; (2) these two risk factors influence each other in a bidirectional manner; and (3) geopolitical risk exerts influence on productivity both directly and indirectly through its impact on oil prices, while oil price risk may hinder productivity both directly and indirectly via influencing geopolitical risk.

Building on the evidence that geopolitical and oil price risks are closely interrelated and jointly influence firm productivity, it becomes clear that examining these risks in isolation may overlook important interactions. As prior studies have largely analyzed geopolitical and energy risks separately, often neglecting their combined impact, an integrated approach is necessary. To this end, we employ the novel global geopolitical-energy uncertainty (GEU) index developed by Dang et al. (2024a), which jointly captures geopolitical and energy uncertainty. Dang et al. (2024a) show that the GEU index is highly responsive to major geopolitical tensions and energy shocks, and that it has strong explanatory power for global energy price volatility, sectoral stock market performance, and key macroeconomic indicators across both developed and developing economies. While its relevance has been established at the global, national, and sectoral levels, its implications for firm-level productivity remain unexplored. This study seeks to address this gap in the literature by investigating the GEU index's impact on firm productivity, thereby offering new insights into the risk-productivity nexus. In this way, we move beyond prior studies that treat geopolitical and energy risks separately, offering the first firm-level evidence on their joint productivity effects.

By examining the combined effects of geopolitical and energy risks through the GEU index, our study centers on firm productivity as the key outcome of interest. Krugman (1997) asserts that "*Productivity isn't everything, but in the long run it is almost everything*". Similarly, Syverson (2011) argued that "…*another robust finding in the literature—virtually invariant to country, time period, or industry—is that higher productivity producers are more likely to survive than less efficient industry competitors*". Therefore, our study focuses on the vital importance of geopolitical and energy risks for firm productivity although they have profound economic implications in other aeras, such as supply chain stability, product competitiveness, capital costs, investment decisions, and strategic planning. As noted by Syverson (2011), "*productivity is quite literally a matter of survival for businesses*". While geopolitical and energy risks may affect investment and other firm decisions, our analysis is not an investment specification. Compared to investment, which represents one possible short-run adjustment channel (Bloom, 2009), productivity captures the broader and more persistent efficiency implications (Krugman, 1997). Hence, we explicitly focus on firm productivity (TFP) as the primary outcome variable, since it directly reflects firms' efficiency and long-term performance. We argue that understanding the GEU index's impact on firm productivity is essential for firms to assess risk exposure, formulate mitigation strategies, and sustain productivity. This consideration is particularly crucial for firms in energy-intensive industries under the background of escalating geopolitical and energy market uncertainties.

Theoretically, GEU may adversely affect firm productivity through several mechanisms. First, an increase in the GEU index, by construction reflecting both geopolitical and energy uncertainty, represents the type of uncertainty that, as Bloom (2009) argues, raises the option value of waiting and induces firms to postpone their hiring and investments, thereby reducing resource reallocation and causing a significant drop in productivity growth. Accordingly, firms with higher investment intensity appear to be particularly sensitive, as uncertainty tends to trigger delays of capital expenditures, slowing down their productivity growth. Second, firms with heavier cost structures appear more vulnerable (Bernard et al., 2006; Kling et al., 2021), since higher costs undermine competitiveness and magnify exposure to shocks. Third, at the macro level, GEU shocks often operate through energy price shocks, which raises input costs and leads firms to scale down capacity utilization, resulting in short-term productivity losses (André et al., 2023).

Overall, this study employs the comprehensive global geopolitical-energy uncertainty (GEU) index of Dang et al. (2024a) to examine its effects on firm-level productivity across various industries and countries around the world over the period from 2001 to 2023. The study pursues following specific objectives. First, we examine the overall impact of the GEU index on firm productivity (TFP). Second, we investigate cross-country heterogeneity in this relationship. Third, we compare differential responses between energy-intensive versus less energy-intensive firms and between smaller versus larger firms. Finally, we explore potential mechanisms through which GEU affects firm productivity. Unlike previous studies which focus on the individual impacts of either geopolitical risk or energy risk, the present study takes a holistic approach to investigating the combined influence of both risk factors. By utilizing the new GEU index which integrates geopolitical risks alongside energy market uncertainties, we aim to provide new evidence to enhance understanding of their joint effects on productivity.

The study makes two contributions to literature. *First*, to the best of our knowledge, this is the first study to examine the impact of geopolitical-and-energy risk on firm-level productivity, using the comprehensive GEU index developed by Dang et al. (2024a) and a large sample of firms from different industries worldwide. *Second*, the study contributes to the productivity literature by providing new evidence demonstrating that the GEU index is a significant determinant of firm productivity. We measure productivity using total factor productivity (TFP), which is widely recognized as a key determinant of firm-level economic growth (Tian and Twite, 2011), and a critical indicator of firm's efficiency in converting input factors into outputs (Dang et al., 2024b).

Several key findings are observed from our study. First, an increase in the GEU index has a significant negative impact on firm-level productivity across the entire sample. Second, the productivity response to the GEU index varies across firms depending on their characteristics, the energy intensity of their industries, and their country of origin. Specifically, a rise in the GEU index has a significant negative influence on productivity of the firms in France, Germany, the UK, and the US, while a significant positive impact is observed for Canadian firms.[1] Furthermore, smaller firms and those operating in energy-intensive industries have stronger negative responses than their larger counterparts and those in less energy-intensive industries. Third, both firm-level characteristics and macroeconomic energy conditions determine the extent to which GEU shocks affect productivity. Mechanism analysis shows that more profitable firms are better able to withstand GEU shocks, while firms with higher cost intensity experience larger productivity losses. Capital expenditure generally enhances productivity, but this positive effect is weakened during periods of heightened uncertainty, consistent with the notion that firms delay investment under high GEU period. At the macro level, higher global energy prices amplify the negative impact of GEU, highlighting the role of energy costs as a key transmission channel.

The remainder of this paper proceeds as follows. A literature review is presented in Section 2, followed by discussions of research methodology and data presented in Section 3. We present and discuss empirical results in Section 4 and report the results for robustness tests in Section 5

[1] Of these five nations, Canada is the only net oil exporter. These results are consistent with Peersman and Van Robays (2012) who find that economic activity responses to oil shocks are different for net oil-importing countries and net oil-exporting countries.

shows. Section 6 concludes our study.

2. Literature review

This section presents an overview of the relevant literature, focusing on three key areas: energy uncertainty and geopolitical risk, their interactions, and the implications of these risks for productivity.

2.1. Energy uncertainty and geopolitical risk

Foundational studies emphasize the macroeconomic consequences of oil price uncertainty. Elder and Serletis (2010) show that such uncertainty can overshadow investments, depress consumption, and reduce aggregate output measured by real GDP. Similarly, Peersman and Van Robays (2012) extend this by showing that such effects are heterogeneous across countries, with net energy importers experiencing persistent declines in economic activity. Furthermore, Elder (2019) shows that heightened oil price volatility disproportionately affects energy-intensive industries. These findings highlight the broader macroeconomic importance of oil price volatility and have motivated subsequent studies to explore the specific channels through which it transmits to the real economy. For instance, Gao et al. (2022) argue that rising volatility induces precautionary inventory-taking, which reduces oil available for production, hampers investment and consumption, lowers employment opportunities, and dampens overall economic activity. Extending the evidence to a cross-country perspective, Dang et al. (2023) provide systematic cross-country evidence that energy uncertainty hampers economic activity across sectors. Together, this stream of work demonstrates that uncertainty in energy markets transmits to the real economy through multiple channels, from inventories to sectoral production and cross-country dynamics.

Building on these macro-level insights, later contributions extend the focus to financial markets and firm-level outcomes. Kilian and Park (2009) and Xiao et al. (2018) show that oil price uncertainty reduces stock market returns, especially in bearish markets. Whereas earlier studies emphasized aggregate outcomes, Phan et al. (2020) provide micro-level evidence that oil price uncertainty negatively impacts firm performance, thereby bridging the missing firm-level perspective. Firms respond to such uncertainty by increasing their cash holdings (Zhang et al., 2020), delaying or discouraging merger and acquisition activities (Barrows et al., 2023), and reducing innovation (Amin et al., 2023; Yang and Song, 2023). This evidence underscores that energy-related uncertainty does not only suppress aggregate activity but also reshapes firm-level decision-making and performance.

Parallel to this energy-focused literature, geopolitical risk has emerged as another key uncertainty factor. Caldara and Iacoviello (2022) pioneered a textual-based index of geopolitical risk, demonstrating its explanatory power for GDP growth and firm investments. Employing the geopolitical risk index of Caldara and Iacoviello (2022), subsequent studies extend these findings by showing significant effects on firms' idiosyncratic volatility and firm value (Pringpong et al., 2023; Ren et al., 2023a). Moreover, this line of work extends beyond aggregate indicators, with recent evidence highlighting sectoral and asset-class channels, such as spillovers to defense firms through sentiment and capital flows (Klein, 2024).

2.2. Interactions of energy uncertainty and geopolitical risk

A growing body of research has recognized the interdependence of energy markets and geopolitical conditions. Early evidence suggests that geopolitical risk drives oil prices and their volatility (Antonakakis et al., 2017; Bouoiyour et al., 2019; Liu et al., 2019). Consistent with this, Mei et al. (2020) document increased oil price volatility under geopolitical tensions, while Su et al. (2021) find positive oil price responses to geopolitical risk shocks. Beyond this one-directional view, more recent studies emphasize feedback effects, implying a two-way interaction between energy markets and geopolitical conditions. For instance, Ivanovski and Hailemariam (2022) report that oil prices and volatility exert significant causal effects on geopolitical risk. Meanwhile, more recent studies have in turn emphasized the reverse channel, showing that geopolitical instability can also drive oil markets, such as Jiao et al. (2023) who demonstrate that geopolitical shocks affect oil markets through both supply and demand channels. Taken together, these findings underscore the interconnectedness between energy uncertainty and geopolitical risk.

2.3. Uncertainties/risks and firm productivity

The productivity literature emphasizes how uncertainty impedes firms' efficiency. Bloom (2009, 2014) and Bloom et al. (2018) argue that heightened uncertainty raises the option value of waiting, causing firms to delay investment and hiring. Such delays slow resource reallocation and reduce productivity growth. Empirical studies corroborate this theoretical channel. For instance, Choi et al. (2018) show that higher aggregate uncertainty reduces productivity growth, particularly in industries dependent on external financing. Related studies document negative effects of climate and policy-related uncertainties on productivity at both the firm (Ren et al., 2022) and regional levels (Dai and Zhu, 2024).

Moving from general uncertainty to energy-specific risks, recent work documents that oil price uncertainty significantly lowers firm productivity. For instance, Ren et al. (2023b) and Liu et al. (2024) provide evidence that oil price uncertainty negatively impacts firm-level productivity. By contrast, research directly linking geopolitical risk to productivity remains limited. Caldara and Iacoviello (2022) report a negative impact of geopolitical risk on expected total factor productivity across 18 emerging economies. However, the authors do not explore the underlying mechanisms. Nguyen et al. (2022) fill this void by showing that geopolitical risk hampers productivity growth through slower technological progress and reduced per-capita income.

To summarize, prior studies establish strong links between oil price uncertainty and macroeconomic activity, firm-level outcomes, and financial markets, as well as between geopolitical risk and investment, valuation, and sectoral performance. Moreover, recent contributions underscore the mutual interactions between energy uncertainty and geopolitical risk. However, these insights remain fragmented, as most studies treat the two risks separately and only limited evidence connects them to productivity outcomes. In particular, firm-level productivity effects—where uncertainty may be most consequential for long-term competitiveness—have not been systematically analyzed. Thus, unlike earlier studies that consider geopolitical and energy risks separately, we provide novel firm-level evidence on how these risks jointly affect productivity. Motivated by this gap, the present study hypothesizes that heightened global geopolitical–energy uncertainty, as captured by the GEU index of Dang et al. (2024a), exerts a negative effect on firm-level total factor productivity.

3. Methodology and data

3.1. Methodology

In this study, we investigate how firm-level productivity is affected by the global geopolitical-energy uncertainty index (i.e., the GEU index). This index is developed by Dang et al. (2024a), measuring the risks/uncertainties from both geopolitical tensions and the energy markets at the global scale. The index is constructed using a text-based approach and based on the Economist Intelligence Unit's global reports. There are three components in the GEU index, including the geopolitical risk sub-index, the energy-related sub-index and economic policy uncertainty sub-index. Those three sub-indices are combined together to make up the final GEU index using the principal component analysis (PCA). The details of this approach are presented in Appendix C.

Our model is based on previous empirical studies on the determinants of firm productivity to develop the regression models (Dang et al., 2024b; Ding et al., 2016; Ren et al., 2023b; Ren et al., 2022; Zhang et al., 2023). Eq. (1) presents our baseline regression model.

$$TFP_{i,t} = \varphi_e + \omega_t + \beta_1 GEU_t + M_{i,t}\gamma + \varepsilon_{i,t} \tag{1}$$

where i and t represent firm and year, respectively. φ_e controls for firm fixed effects, or industry[2] fixed effects, or country[3] fixed effects. ω_t captures year fixed effects. *TFP* represents firm productivity (or the total factor productivity). Similar to Dang et al. (2024b), we estimate the total factor productivity employing the method proposed by Wooldridge (2009) for our baseline analyses. *GEU* stands for the global geopolitical-energy uncertainty index developed by Dang et al. (2024a), which is our primary variable of interest. *M* is the matrix of control variables that include (i) *Firm_size*, measured by the natural logarithm of total assets; (ii) *Liquidity*, measured by the natural logarithm of (1 + ((current assets – current liabilities) / total assets)); and (iii) *Growth*, the growth opportunities of firms, measured by the natural logarithm of Price-to-Book ratio. The inclusion of those control variables in our regression models is in line with previous empirical studies on productivity at firm level, such as Tian and Twite (2011), Ding et al. (2016), and Li and Su (2022).

In Section 4.1, we adopt regression model (1) for the full sample as well as for different selected economies to examine the heterogeneity of the GEU index's impact on firm productivity at the country level. We also decompose our full sample into two sub-samples, including (i) energy-intensive industries[4] and (ii) less energy-intensive industries. Accordingly, we examine whether the GEU index exerts a significantly different effect on the productivity of firms from energy-intensive industries compared to firms from less energy-intensive industries. To serve that purpose, we perform the regression model as in Eq. (2).

$$TFP_{i,t} = \varphi_e + \omega_t + \alpha_1 GEU_t + \alpha_2 Energy\_intensive_i + \alpha_3 GEU_t{}^*Energy\_intensive_i + M_{i,t}\delta + \varepsilon_{i,t} \tag{2}$$

where *Energy_intensive* is a dummy variable that takes the value of 1 for industries that are considered as energy intensive, including Basic Materials, Energy, Industrials, and Utilities, and 0 otherwise.

Also in Section 4.1, we based on the median of *Firm_size* to categorize all firms in our sample into two sub-samples, including (i) smaller firms and (ii) larger firms. We want to check whether the impact of GEU index on firm productivity is different between smaller and larger firms in our sample (see Eq. (3)).

$$TFP_{i,t} = \varphi_e + \omega_t + \theta_1 GEU_t + \theta_2 Smaller\_firm_i + \theta_3 GEU_t{}^*Smaller\_firm_i + M_{i,t}\vartheta + \varepsilon_{i,t} \tag{3}$$

where *Smaller_firm* is a dummy variable, representing smaller firms in our sample. The median of *Firm_size* is used as a threshold to divide our full sample into smaller firms and larger firms. Accordingly, *Smaller_firm* equals to 1 if *Firm_size* is smaller than or equal to the median of *Firm_size*, and 0 otherwise.

To strengthen the credibility of our empirical analysis, we complement the baseline regressions with a range of identification, placebo, and robustness tests. Specifically, we employ two-step system GMM estimations and an event-study difference-in-differences framework as identification tests (Sub-section 4.3). We further conduct placebo analyses, including alternative-shock replacements (using GPR and EPU indices), future-shock tests with leads of the GEU index, and circular time-shift exercises that misalign the timing of shocks (Appendix A). For robustness, we re-estimate the results using alternative productivity measures (Levinsohn–Petrin and Olley–Pakes), alternative estimation approaches (linear mixed model and Hausman–Taylor) (Section 5), as well as the panel impulse response function and demeaned interaction terms following Balli and Sørensen (2013) (Appendix B). Together, these additional analyses ensure that our findings are not driven by spurious correlations, reverse causality, or model specification choices.

3.2. Data

We employ the global geopolitical-energy uncertainty index proposed by Dang et al. (2024a) as our variable of interest. The global economic policy uncertainty index (EPU) of Baker et al. (2016) and the global geopolitical risk index of Caldara and Iacoviello (2022) are obtained from the website www.policyuncertainty.com. Apart from those uncertainty indices, all annual firm-level data are collected from Refinitiv Workspace (formerly Refinitiv Eikon). Due to data availability, our ultimate sample includes 1042 firms from 30 countries[5] with 6886 firm-year observations over the period from 2001 to 2023. Our final sample include 10 industries: Basic Materials, Consumer Discretionary, Consumer Staples, Energy, Health Care, Industrials, Real Estate, Technology, Telecommunications, and Utilities. Financial industry is excluded from our ultimate sample as this industry has substantially different financial reporting practices (Chen et al., 2019).

The descriptive statistics of variables employed in our study are presented in Table 1A. As can be seen from Table 1A, we find that the mean of firm productivity measures (i.e., *TFP_Wrdg*, *TFP_LP*, and *TFP_OP*) is not quite different from the mean of estimated firm productivity from previous studies (Dang et al., 2024b; Figal Garone et al., 2020; Fiorini et al., 2021; Nakatani, 2023; Tian and Twite, 2011), implying that our estimations of firm productivity appear reliable. The correlation matrix is presented in Table 1B, showing the cross correlations ranging from −0.299 to 0.288. It implies that no significant multicollinearity is found among explanatory variables in our study. Furthermore, we also perform the panel unit root tests (i.e., the augmented Dickey-Fuller and Phillips-Perron) and find that all variables employed in the regression models are stationary.

4. Empirical results

4.1. The GEU index and firm-level productivity

In this section, we employ the panel regression model as in Eq. (1) to investigate how firm productivity responds to the GEU index. The regression results in case of full sample are presented in Table 2. As can be seen, the GEU index has a statistically significant negative impact on firm productivity across different model specifications in which we control for different fixed effects,[6] including firm fixed effects, year fixed effects, firm-year fixed effects, industry-year fixed effects, and country-year fixed effects. This result is in line with previous studies such as Bloom (2009), Bloom (2014), and Ren et al. (2022) who argue that

[2] Including: Basic Materials, Consumer Discretionary, Consumer Staples, Energy, Health Care, Industrials, Real Estate, Technology, Telecommunications, and Utilities.

[3] Including: Australia, Austria, Belgium, Brazil, Canada, China, Cyprus, Denmark, Finland, France, Germany, Hong Kong, India, Ireland, Italy, Japan, Malaysia, Netherlands, New Zealand, Norway, Pakistan, Philippines, South Africa, South Korea, Spain, Sweden, Switzerland, United Kingdom, United States, Vietnam.

[4] Industries categorized as energy intensive include Basic Materials, Energy, Industrials, and Utilities.

[5] Including: Australia, Austria, Belgium, Brazil, Canada, China, Cyprus, Denmark, Finland, France, Germany, Hong Kong, India, Ireland, Italy, Japan, Malaysia, Netherlands, New Zealand, Norway, Pakistan, Philippines, South Africa, South Korea, Spain, Sweden, Switzerland, United Kingdom, United States, Vietnam.

[6] The Hausman test confirms that a fixed effects model is more appropriate for our panel data.

Table 1
Summary statistics.

A. Descriptive statistics						
Variable	Observation	Mean	Median	Standard deviation	Min	Max
Firm's output	6886	18.253	18.315	2.515	8.987	25.024
Capital input	6886	20.01	20.119	2.648	8.987	26.431
Labor input	6886	7.968	8.013	2.309	0.000	13.175
Intermediate input	6886	19.962	19.981	2.623	8.006	27.326
TFP_Wrdg	6886	2.327	2.397	1.010	−5.136	7.120
TFP_LP	6886	2.030	2.093	1.001	−5.357	7.025
TFP_OP	6886	4.149	4.196	1.082	−3.154	9.053
GEU	6886	−0.044	0.154	0.883	−1.979	1.550
Firm_size	6886	21.028	21.044	2.398	13.472	27.300
Liquidity	6886	0.131	0.122	0.175	−1.493	0.754
Growth	6886	0.557	0.545	0.983	−14.117	6.876
Energy_intensive	6886	0.530	1.000	0.499	0.000	1.000
Smaller_firm	6886	0.500	0.500	0.500	0.000	1.000
GPR	6886	4.621	4.592	0.229	4.348	5.172
EPU	6886	4.942	4.847	0.475	4.140	5.771
B. Correlation matrix						
	TFP_Wrdg	*GEU*	*Firm_size*	*Liquidity*	*Growth*	
TFP_Wrdg	1.000					*TFP_Wrdg*
GEU	−0.008	1.000				*GEU*
Firm_size	0.288	0.092	1.000			*Firm_size*
Liquidity	0.180	−0.007	−0.299	1.000		*Liquidity*
Growth	0.285	0.110	0.077	−0.080	1.000	*Growth*

Notes: *Firm's output* is the natural logarithm of operating income. *Capital input* is the natural logarithm of net fixed assets. *Labor input* is the natural logarithm of number of employees. *Intermediate input* is the natural logarithm of total costs excluding depreciation and amortization. *TFP_Wrdg* is the estimated firm productivity using Wooldridge (2009)'s method. *TFP_LP* is the estimated firm productivity using Levinsohn and Petrin (2003)'s method. *TFP_OP* is the estimated firm productivity using Olley and Pakes (1996)'s method. *GEU* is the global geopolitical-energy uncertainty index proposed by Dang et al. (2024a). *Firm_size* stands for the natural logarithm of total assets. *Liquidity* is the natural logarithm of (1 + ((current assets – current liabilities) / total assets)). *Growth* stands for growth opportunities of firms, measured by the natural logarithm of Price-to-Book ratio. *Energy_intensive* is a dummy variable, which is 1 for industries that are energy intensive (i.e., Basic Materials, Energy, Industrials, and Utilities) and 0 otherwise. *Smaller_firm* is a dummy variable, which is 1 for firms with *Firm_size* that is less than or equal the median of *Firm_size* in the sample, and 0 otherwise. *GPR* stands for the global geopolitical risk index of Caldara and Iacoviello (2022). *EPU* is the global economic policy uncertainty index (EPU) of Baker et al. (2016).
Firm's output, *capital input*, *labor input*, and *intermediate input* are employed to estimate the total factor productivity (or firm productivity) based on the Wooldridge (2009)'s method for the baseline analysis, and the methods of Olley and Pakes (1996) and Levinsohn and Petrin (2003) in the robustness tests.

Table 2
The impact of GEU index on firm-level productivity (baseline results).

	(1)	(2)	(3)	(4)	(5)
GEU	−0.083***	−0.054***	−0.070***	−0.063***	−0.080***
	(0.011)	(0.015)	(0.014)	(0.015)	(0.014)
Firm_size	0.160***	0.158***	0.192***	0.155***	0.142***
	(0.020)	(0.005)	(0.028)	(0.005)	(0.006)
Liquidity	1.571***	1.783***	1.581***	1.755***	1.662***
	(0.122)	(0.080)	(0.124)	(0.082)	(0.083)
Growth	0.281***	0.295***	0.288***	0.285***	0.373***
	(0.023)	(0.031)	(0.024)	(0.031)	(0.016)
Firm FE	Yes	No	Yes	No	No
Year FE	No	Yes	Yes	Yes	Yes
Industry FE	No	No	No	Yes	No
Country FE	No	No	No	No	Yes
N	6462	6886	6462	6886	6881
Adjusted R^2	0.532	0.248	0.534	0.279	0.310

Notes: Robust standard errors are presented within parentheses. ***, ** and * stand for the significance level of 1 %, 5 % and 10 %, respectively. The estimations are based on the model: $TFP_{i,t} = \varphi_e + \omega_t + \beta_1 GEU_t + M_{i,t}\gamma + \varepsilon_{i,t}$ (1). The dependent variable is *TFP_Wrdg*, estimated using Wooldridge (2009)'s method.

higher uncertainty leads to decreases in firm productivity (or productivity growth).

Next, we perform the same regression (1) for some selected countries in our sample to examine the heterogeneity in the GEU index's impact on firm productivity across different countries. Table 3 shows our regression results at the country level, which only presents the results of countries with a sufficient number of observations to perform the regression. As can be seen from Table 3, we find that 5/12 economies experiencing the significant negative impacts from the GEU index on firm-level productivity, including Finland, France, Germany, the UK, and the US. Interestingly, we note that Canada is the only economy witnessing a statistically significant positive effect from the GEU index. Canada appears to have relative geopolitical stability, compared to other European countries or the US that tend to be more directly impacted by geopolitical disruptions or conflicts. Indeed, Canada only shares its border with the US that is regarded as a stable and friendly neighbor. Additionally, Canada is far from the Middle East or Eastern Europe and hence, it has a buffer from different geopolitical tensions that might impact those regions. Meanwhile, European countries appear to be more exposed to geopolitical disruptions, especially due to the reliance of those economies on energy supplies from unstable country (such as Russia). Furthermore, although the US is not geographically near unstable regions, this country tends to get heavily involved in global geopolitical conflicts, given that the US is considered a global superpower, and it also replies on energy supplies from foreign sources. Apart from that, Canada's energy security is considered robust as it is among the countries with the most diverse mixes of energy sources across the globe. That country appears to be more energy self-sufficient due to a significant proportion of its own resources compared to other economies (Best et al., 2010).

Categorizing our sample into energy-intensive industries[7] versus less energy-intensive industries, we aim to investigate if there is any difference in the impact of the GEU index on firm productivity in industries that are more energy intensive. The results of regression model (2) are

[7] Industries categorized as energy intensive include Basic Materials, Energy, Industrials, and Utilities.

Table 3
The impact of the GEU index on firm-level productivity (for some selected countries in the sample).

	Austria		Belgium		Canada		Finland		France		Germany	
GEU	−0.095	−0.102	−0.118	0.010	0.105**	0.093*	−0.128*	−0.149	−0.075**	−0.058*	−0.136***	−0.116***
	(0.108)	(0.121)	(0.092)	(0.062)	(0.053)	(0.055)	(0.067)	(0.093)	(0.036)	(0.031)	(0.039)	(0.039)
Firm_size	0.099	−0.032	0.165***	0.224*	0.005	0.081	−0.021	0.143	0.154***	0.350***	0.133***	0.265***
	(0.075)	(0.303)	(0.045)	(0.119)	(0.030)	(0.113)	(0.070)	(0.184)	(0.023)	(0.052)	(0.015)	(0.096)
Liquidity	1.613**	1.597**	1.824***	3.515***	0.887**	1.014*	0.333	1.544*	1.832***	2.210***	1.612***	1.342***
	(0.688)	(0.723)	(0.518)	(0.673)	(0.380)	(0.550)	(0.642)	(0.785)	(0.380)	(0.338)	(0.147)	(0.200)
Growth	0.347**	0.296	0.398***	0.134	0.213**	0.154	0.571***	0.436***	0.371***	0.269***	0.523***	0.455***
	(0.164)	(0.186)	(0.103)	(0.082)	(0.098)	(0.153)	(0.108)	(0.103)	(0.038)	(0.043)	(0.038)	(0.057)
Industry-year FE	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Firm-year FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	142	141	264	259	299	282	133	117	1324	1292	969	937
Adjusted R^2	0.269	0.295	0.313	0.514	0.266	0.418	0.418	0.481	0.275	0.499	0.338	0.504
	Italy		Japan		Spain		Sweden		UK		US	
GEU	−0.103	−0.094	−0.152	−0.123	−0.058	−0.068	−0.080	−0.015	−0.132***	−0.109***	−0.103***	−0.066**
	(0.103)	(0.109)	(0.105)	(0.102)	(0.072)	(0.072)	(0.068)	(0.089)	(0.032)	(0.030)	(0.029)	(0.031)
Firm_size	0.266***	−0.062	0.188*	0.992***	0.105***	0.358***	0.166***	−0.304	0.207***	0.072	0.118***	0.135**
	(0.086)	(0.152)	(0.095)	(0.212)	(0.038)	(0.136)	(0.030)	(0.210)	(0.016)	(0.062)	(0.013)	(0.065)
Liquidity	0.735	0.779	2.628***	4.722***	1.585***	2.112***	2.119***	4.512***	2.017***	1.160***	1.292***	1.668***
	(0.695)	(0.598)	(0.361)	(1.604)	(0.386)	(0.465)	(0.409)	(1.005)	(0.204)	(0.317)	(0.187)	(0.333)
Growth	0.134	0.192	0.525***	0.632***	0.258***	0.197*	0.266*	0.131	0.381***	0.297***	0.361***	0.327***
	(0.102)	(0.165)	(0.099)	(0.147)	(0.077)	(0.111)	(0.135)	(0.137)	(0.031)	(0.039)	(0.035)	(0.043)
Industry-year FE	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Firm-year FE	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	241	232	177	110	318	315	146	122	1095	1056	1445	1367
Adjusted R^2	0.193	0.302	0.422	0.681	0.256	0.278	0.309	0.483	0.309	0.529	0.295	0.535

Notes: Robust standard errors are presented within parentheses. ***, ** and * stand for the significance level of 1 %, 5 % and 10 %, respectively. We present the estimation results only for countries with a sufficient number of observations to perform the regression. The estimations are based on the model: $TFP_{i,t} = \varphi_e + \omega_t + \beta_1 GEU_t + M_{i,t}\gamma + \varepsilon_{i,t}$ (1). The dependent variable is *TFP_Wrdg*, estimated using Wooldridge (2009)'s method.

Table 4
The impact of the GEU index on firm-level productivity (energy-intensive industries versus less energy-intensive industries).

	(1)	(2)	(3)
GEU	−0.033	−0.067***	−0.058***
	(0.021)	(0.018)	(0.019)
Energy_intensive	−0.218***	−0.191***	−0.188***
	(0.022)	(0.021)	(0.021)
*GEU*Energy_intensive*	−0.047**	−0.050**	−0.051**
	(0.024)	(0.023)	(0.023)
Firm_size	0.162***	0.145***	0.147***
	(0.005)	(0.006)	(0.006)
Liquidity	1.810***	1.696***	1.698***
	(0.080)	(0.082)	(0.082)
Growth	0.288***	0.359***	0.360***
	(0.030)	(0.016)	(0.016)
Year FE	Yes	No	Yes
Country FE	No	Yes	Yes
N	6886	6881	6881
Adjusted R^2	0.260	0.317	0.318

Notes: Robust standard errors are presented within parentheses. ***, ** and * stand for the significance level of 1 %, 5 % and 10 %, respectively. The estimations are based on the model: $TFP_{i,t} = \varphi_e + \omega_t + \alpha_1 GEU_t + \alpha_2 Energy\_intensive_i + \alpha_3 GEU_t{*}Energy\_intensive_i + M_{i,t}\delta + \varepsilon_{i,t}$(2). The dependent variable is *TFP_Wrdg*, estimated using Wooldridge (2009)'s method. *Energy_intensive* is a dummy variable that takes the value of 1 for industries that are considered as energy intensive, including Basic Materials, Energy, Industrials, and Utilities, and 0 otherwise. The dummy variable "*Energy_intensive*" gets absorbed when firm fixed effects or industry fixed effects are employed because it is fully collinear with those fixed effects. Hence, we do not present the estimation results of firm fixed effects or industry fixed effects.

shown in Table 4. As can be seen, the GEU index is found to exert stronger significant negative effects on firm productivity in case of energy-intensive industries, indicated by the statistically significant negative coefficients of the interaction term *GEU*energy_intensive*. This finding is in line with Elder (2019) who finds that energy-intensive industries experience significant negative effects from the oil price uncertainty. This finding implies that firms from energy-intensive industries need to take the GEU index as a significant determinant of their total factor productivity, and thus they need to have appropriate measures to avoid the negative impacts from the geopolitical-energy uncertainties on their productivity.

Based on the median of *Firm_size*, we categorize all firms in our sample into two sub-samples, including (i) smaller firms and (ii) larger firms. We aim to investigate whether the impact of GEU index on firm productivity is different between smaller and larger firms in our sample. Estimation results are presented in Table 5.

Looking at Table 5, we note that firms with smaller firm size appear to witness greater adverse impact from the geopolitical-energy uncertainties, indicated by the statistically significant negative coefficient of the interaction term *GEU* Smaller_firm* (−0.059) in column (1) of

Table 5
The impact of the GEU index on firm-level productivity (smaller firms versus larger firms).

	Full sample	Less energy-intensive industries	Energy-intensive industries
	(1)	(2)	(3)
GEU	−0.039**	−0.019	−0.060***
	(0.016)	(0.025)	(0.020)
Smaller_firm	−0.016	−0.026	0.009
	(0.046)	(0.088)	(0.049)
GEU Smaller_firm*	−0.059***	−0.046	−0.080***
	(0.021)	(0.032)	(0.028)
Firm_size	0.191***	0.230***	0.137***
	(0.030)	(0.043)	(0.042)
Liquidity	1.589***	1.690***	1.468***
	(0.124)	(0.175)	(0.177)
Growth	0.287***	0.226***	0.368***
	(0.024)	(0.029)	(0.034)
N	6462	2989	3473
Adjusted R^2	0.535	0.551	0.515

Notes: Robust standard errors are presented within parentheses. ***, ** and * stand for the significance level of 1 %, 5 % and 10 %, respectively. Firm-year fixed effects are controlled in all models.
The estimations are based on the model: $TFP_{i,t} = \varphi_e + \omega_t + \theta_1 GEU_t + \theta_2 Smaller\_firm_i + \theta_3 GEU_t{*}Smaller\_firm_i + M_{i,t}\vartheta + \varepsilon_{i,t}$ (3). The dependent variable is *TFP_Wrdg*, estimated using Wooldridge (2009)'s method. *Smaller_firm* is a dummy variable, which equals to 1 if *Firm_size* is smaller than or equal to the median of *Firm_size*, and 0 otherwise.

Table 5. When decomposing our full sample into "Less energy-intensive industries" and "Energy-intensive industries", we find that only the firm productivity from "Energy-intensive industries" (column (3)) experiences a statistically significant effect with the coefficient of −0.080, meanwhile no significant impact is found in case of "Less energy-intensive industries" (column (2)). These findings suggest that the GEU index tends to have significantly more negative impacts on the productivity of smaller firms, particularly those in energy-intensive industries.

4.2. Mechanism analysis: firm characteristics and energy price channels

To investigate the potential channels through which the GEU index affects firm productivity, we estimate interaction models between the GEU index and firm- or energy-related characteristics. Specifically, we standardize a set of firm-level variables, including profitability (EBIT/total assets), cost intensity (total costs/total assets), and capital expenditure ratio (capital expenditure/total assets). Also, measures of energy price changes (log returns of global energy price index[8] and West Texas Intermediate (WTI) spot crude oil price[9]) are included to represent energy price exposure. The general empirical model is as in Eq. (4).

$$TFP_{i,t} = \mu_i + \omega_t + \gamma_1 GEU_t + \gamma_2 Z_{i,t} + \gamma_3 GEU_t{*}Z_{i,t} + M_{i,t}\delta + \varepsilon_{i,t} \quad (4)$$

where $Z_{i,t}$ stands for the standardized firm characteristic (Panel A-Table 6) or energy price exposure (Panel B-Table 6). Firm and year fixed effects (μ_i and ω_t) are included to control for unobserved heterogeneity across firms and over time. γ_3 is the coefficient of interest, which captures whether the sensitivity of firm productivity ($TFP_{i,t}$) to GEU shocks varies systematically with firm characteristics or energy price dynamics.

While the regressions in Eq. (4) identify the average effects of GEU through firm characteristics and energy prices, they do not reveal how these mechanisms vary across different levels of the underlying variables. To address this limitation, we compute and plot the marginal effects of GEU with respect to firm productivity at different values of profitability, cost intensity, capex ratio, and energy price changes. In other words, Fig. 1 illustrates $\partial TFP/\partial GEU = \beta_1 + \beta_3 \times Z$, where Z denotes the standardized firm or energy variable, thereby providing a more nuanced picture of the heterogeneous responses along the distribution of firm characteristics and energy price exposures.

Table 6 presents the results of mechanism analysis (Eq. 4). Panel A considers firm characteristics, such as profitability, cost intensity, and investment intensity, as potential mechanisms, while Panel B explores the role of energy prices as a macro-level transmission channel. As shown in Table 6A, the positive and significant interaction

Table 6
Mechanism Analysis: Firm Characteristics and Energy Prices.

Panel A. Firm level mechanism			
	(1)	(2)	(3)
GEU	−0.055***	−0.070***	−0.075***
	(0.013)	(0.014)	(0.014)
Profitability	0.301***		
	(0.034)		
*GEU*Profitability*	0.122***		
	(0.021)		
Cost_intensity		−0.037	
		(0.036)	
*GEU*Cost_intensity*		−0.019*	
		(0.011)	
Capex_ratio			0.046***
			(0.017)
*GEU*Capex_ratio*			−0.017
			(0.011)
Firm_size	0.172***	0.184***	0.173***
	(0.026)	(0.028)	(0.031)
Liquidity	1.323***	1.585***	1.627***
	(0.122)	(0.123)	(0.143)
Growth	0.222***	0.288***	0.294***
	(0.022)	(0.024)	(0.024)
N	6405	6462	6163
Adjusted R^2	0.580	0.535	0.533

Panel B. Energy price mechanism		
	(1)	(2)
GEU	−0.072***	−0.072***
	(0.015)	(0.015)
Global_energy	−0.059***	
	(0.012)	
*GEU*Global_energy*	−0.027*	
	(0.015)	
WTI		−0.054***
		(0.012)
*GEU*WTI*		−0.021
		(0.018)
Firm_size	0.207***	0.206***
	(0.031)	(0.031)
Liquidity	1.544***	1.542***
	(0.132)	(0.133)
Growth	0.326***	0.322***
	(0.025)	(0.024)
N	5739	5739
Adjusted R^2	0.544	0.542

Notes: Robust standard errors are presented within parentheses. ***, ** and * stand for the significance level of 1 %, 5 % and 10 %, respectively. Firm-year fixed effects are controlled in all models. The estimations are based on the model: $TFP_{i,t} = \mu_i + \omega_t + \gamma_1 GEU_t + \gamma_2 Z_{i,t} + \gamma_3 GEU_t{*}Z_{i,t} + M_{i,t}\delta + \varepsilon_{i,t}$ (4). The dependent variable is *TFP_Wrdg*, estimated using Wooldridge (2009)'s method. *Profitability* is the standardized (EBIT/Total Assets). *Cost_intensity* is the standardized (Total costs/Total assets). *Capex_ratio* is the standardized (Capital expenditure/Total assets). *Global_energy* is the standardized return of Global price of Energy index. WTI is the standardized return of Spot crude oil price: West Texas Intermediate.

[8] Obtained from Federal Reserve Economic Data: https://fred.stlouisfed.org/series/PNRGINDEXM.

[9] Obtained from Federal Reserve Economic Data: https://fred.stlouisfed.org/series/WTISPLC

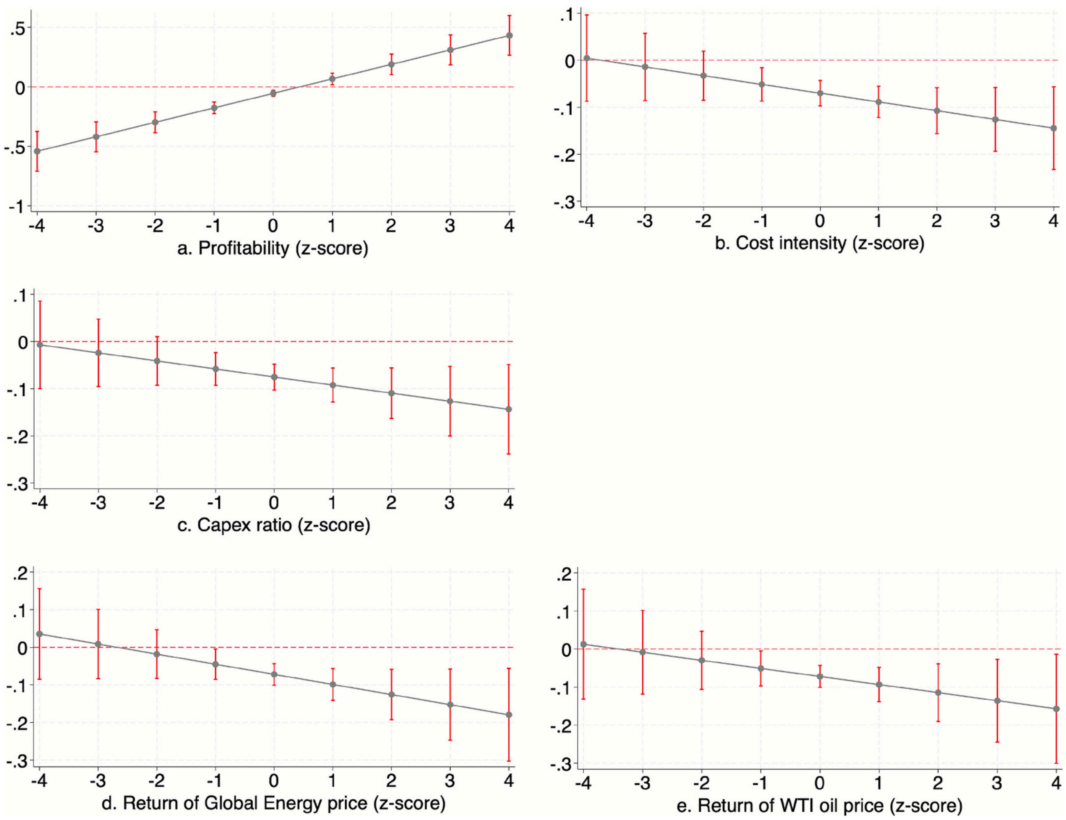


Fig. 1. Marginal effects of the GEU index on firm productivity, conditional on firm characteristics and energy prices. Notes: Vertical red bars represent the 95 % confidence intervals. The y-axis in each panel reports the effect of the GEU index on firm productivity, while the x-axis shows the standardized value of the corresponding channel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

*GEU*Profitability indicates that more profitable firms are better able to withstand GEU shocks. Fig. 1a illustrates this channel: the marginal effects of GEU turn less negative and eventually positive at higher profitability levels, highlighting the buffer role of earnings capacity.* Since profitability and productivity tend to be positively linked *(*Bottazzi et al., 2008*;* Foster et al., 2008*)*, higher profitability can be viewed as reflecting greater productivity and efficiency, which in turn enhances firms' resilience to GEU shocks. Cost intensity also emerges as a relevant channel, as the negative interaction term (*GEU*Cost_intensity*) indicates that firms with heavier cost structures suffer stronger productivity losses from GEU shocks. Fig. 1b supports this evidence, as the marginal effect of GEU on firm productivity becomes increasingly negative with rising cost intensity. This evidence is consistent with prior findings that higher costs undermine firm outcomes (Bernard et al., 2006; Kling et al., 2021), suggesting that cost burdens magnify the vulnerability of firms to external shocks. When examining capital expenditure (*Capex_ratio*), the statistically significant positive coefficient indicates that firms with higher capital spending tend to achieve greater productivity. In normal times, industries that invest more in capital assets are better able to leverage innovation, leading to higher total factor productivity (Ma et al., 2022). However, the interaction term between GEU and the capital expenditure ratio (*GEU*Capex_ratio*) is statistically insignificant. Despite this, the negative sign of the coefficient suggests that during periods of heightened uncertainty, the positive effect of capital investment may be weakened or dampened. This finding is consistent with Bloom (2009, 2014) and Bloom et al. (2018)'s argument that, under conditions of high uncertainty, firms tend to delay investment, meaning that capital expenditures no longer translate directly into productivity gains. Fig. 1c supports this interpretation by showing a downward-sloping and statistically significant marginal effect, indicating that as the capex ratio increases, the adverse impact of GEU on firm productivity becomes stronger.

Turning to energy prices, Table 6B indicates that global energy price amplifies the detrimental effect of GEU, as reflected in the negative and significant interaction term (*GEU*Global_energy*). Similarly, although the interaction between GEU and WTI is statistically insignificant, its coefficient is still negative. Fig. 1d and e further demonstrate this mechanism, showing that the marginal effect of GEU index on firm productivity becomes more adverse as global energy price return and WTI return rise, underlining the importance of energy price as a macro transmission channel. Consistent with this evidence, André et al. (2023) document that energy price shocks lead firms to scale down capacity utilization, which results in short-term declines in their productivity.

4.3. Identification tests

4.3.1. Two-step system generalized method of moments (GMM)

In this sub-section, we perform identification tests to validate our baseline findings. First, we re-estimate our baseline regressions using a two-step system generalized method of moments (GMM) estimation. The system GMM is recommended in panel settings where endogeneity may arise (Nickell, 1981). Proposed by Arellano and Bover (1995) and Blundell and Bond (1998), this approach helps address potential biases from fixed effects in short panels while mitigating endogeneity concerns (Canh et al., 2020). Additionally, the Windmeijer (2005) finite-sample corrected standard errors are estimated to ensure more reliable inference.

Table 7 reports the two-step system GMM results. The lagged dependent variable is positive and significant, confirming the persistence of firm productivity. The significant and negative effect of the GEU index in column (1) confirm our findings from Table 2, while the adverse and significant interaction terms (i.e., *GEU*Energy_intensive* and *GEU*Smaller_firm*) in columns (2) and (3) remain consistent with results from Tables 4 and 5. Especially, the diagnostic tests (including AR(2),

Table 7
Identification tests: Two-step system GMM.

	(1)	(2)	(3)
TFP_Wrdg(t-1)	0.428***	0.529***	0.278***
	(0.106)	(0.178)	(0.048)
GEU	−0.043**	0.520**	0.778
	(0.017)	(0.257)	(0.502)
Energy_intensive		0.644	
		(0.551)	
*GEU*Energy_intensive*		−0.987**	
		(0.446)	
Smaller_firm			0.092
			(0.091)
GEU Smaller_firm*			−1.662*
			(0.997)
Firm_size	0.096***	0.062*	0.130***
	(0.020)	(0.035)	(0.019)
Liquidity	1.019***	0.746**	1.273***
	(0.202)	(0.308)	(0.163)
Growth	0.221***	0.210***	0.222***
	(0.029)	(0.045)	(0.047)
N	5844	5844	5844
Number of groups	618	618	618
Number of instruments	37	47	34
Arellano-Bond test for AR(1)	$z = -5.68$, $p < 0.001$	$z = -4.41$, $p < 0.001$	$z = -10.00$, $p < 0.001$
Arellano-Bond test for AR(2)	$z = 1.60$, $p = 0.110$	$z = 1.47$, $p = 0.142$	$z = -1.50$, $p = 0.133$
Hansen test	$\chi^2(12) = 10.26$, $p = 0.593$	$\chi^2(20) = 21.51$, $p = 0.368$	$\chi^2(7) = 1.67$, $p = 0.976$
Difference-in-Hansen test (levels)	$\chi^2(1) = 0.16$, $p = 0.687$	$\chi^2(4) = 4.29$, $p = 0.369$	$\chi^2(2) = 0.30$, $p = 0.863$

Notes: Robust (Windmeijer-corrected) standard errors are presented within parentheses. ***, ** and * stand for the significance level of 1 %, 5 % and 10 %, respectively. The dependent variable is *TFP_Wrdg*, estimated using Wooldridge (2009)'s method. Year fixed effects are controlled. Diagnostic tests: Arellano–Bond AR (1) and AR(2) tests check for serial correlation in first-differenced residuals; the Hansen test assesses the joint validity of instruments; and the Difference-in-Hansen test evaluates the exogeneity of instrument subsets.

Hansen, and Difference-in-Hansen) further confirm the validity of the instruments, supporting the robustness of our baseline findings.

4.3.2. Event-study analysis using difference-in-differences

To help address endogeneity concerns by assessing pre-trends and dynamics, we implement an event-study specification within a two-way fixed-effects difference-in-differences (TWFE DiD) framework, following Autor (2003), as an additional identification test of our baseline results. We define 2015 as the event year because the GEU index shows a clear shift around this time. Specifically, the average value of the GEU index before 2015 is negative (mean ≈–0.55), whereas it rises sharply after 2015 (mean ≈ 0.58), with higher peaks. This pattern indicates a significant increase in geopolitical-energy uncertainty starting from 2015, making it a natural cutoff point for our event-study analysis. This year also corresponds with major real-world developments that heightened geopolitical and energy risk for the period after it. Notably, energy markets became more volatile following the 2014–2015 oil price collapse, driven by OPEC production decisions, U.S. shale growth, and fluctuating global demand. Geopolitical tensions escalated, including ongoing conflicts in the Middle East, the Syrian civil war, and instability in Iraq and Libya, as well as continued Russia-West confrontations related to Ukraine and European energy security. In addition, the 2015 Paris Agreement (COP21) introduced uncertainty regarding carbon pricing, emissions targets, and the timing and stringency of climate and energy policies. In this analysis, energy-intensive firms are the treatment group, and non-energy-intensive firms are the control group. The event-study analysis is based on the regression as in Eq. (5).

$$TFP_{i,t} = \mu_i + \omega_t + \sum_{k=-8,k\neq-1}^{8} \beta_k (D_i \times 1\{t - t_0 = k\}) + M_{i,t}\delta + \varepsilon_{i,t} \tag{5}$$

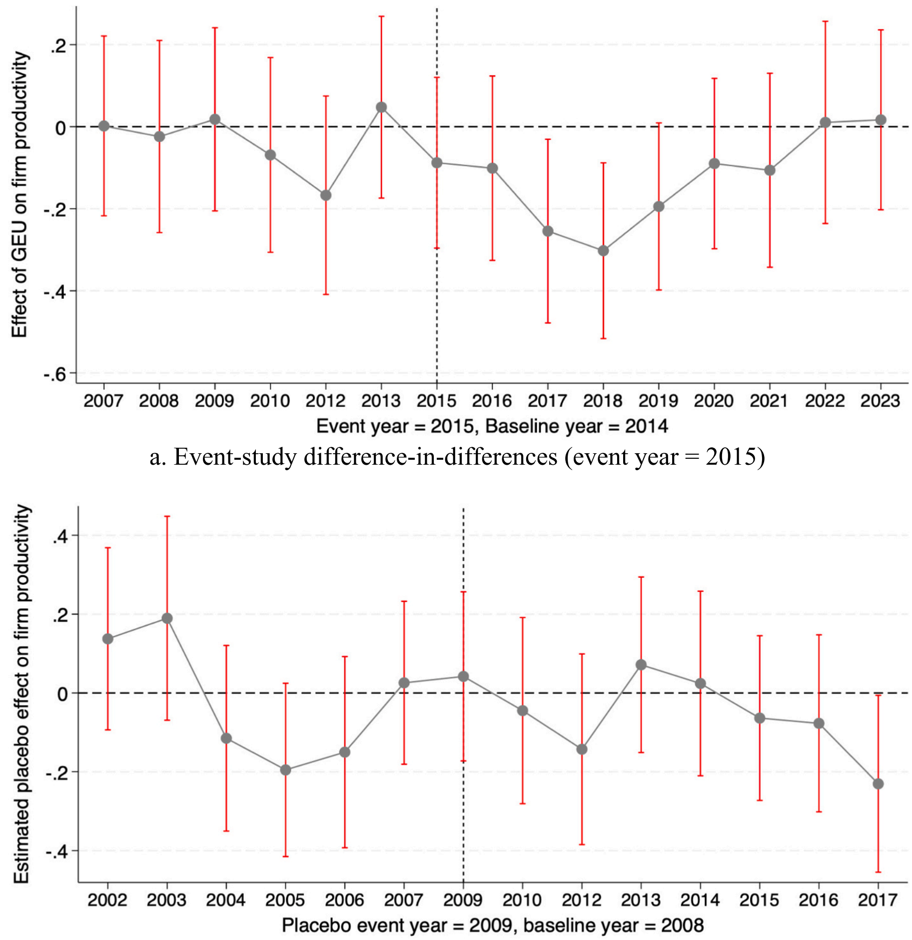
where $t_0 = 2015$ is the event year. k is the relative year to the event year, which is $\in [-8,8]$ excluding the baseline year 2014 ($k = -1$). D_i is the treatment indicator, which equals 1 for energy-intensive firms and 0 otherwise. β_k is the treatment effect at relative year k. $1\{t - t_0 = k\} = \begin{cases} 1, & t - t_0 = k \\ 0, & t - t_0 \neq k \end{cases}$.

The main event-study analysis is illustrated in Fig. 2a. Besides, to further validate our findings, we also conduct a placebo event-study using Eq. (5) but re-centering the event year at 2009 (baseline 2008) (see Fig. 2b). Insignificant placebo estimates would indicate that the main results (in Fig. 2a) are not driven by spurious correlations or arbitrary timing.

As illustrated in Fig. 2a, firm productivity shows no significant differences between treated and control groups prior to 2015, consistent with the parallel trend assumption. After the onset of GEU shocks in 2015, the coefficients turn negative, with the most pronounced significant declines during 2017–2018. Indeed, between 2017 and 2018, energy markets became more volatile due to OPEC production changes, U. S. shale growth, and conflicts in the Middle East, including U.S. sanctions on Iran. At the same time, trade tensions between the U.S. and China and unclear energy policies added further uncertainty. This suggests that heightened geopolitical-energy uncertainty exerted a significant and adverse impact on firm TFP, even though the magnitude of the effect fluctuates in subsequent years.

To further validate this result, Fig. 2b applies a placebo test with a fake event year of 2009. The absence of statistically significant effects (in Fig. 2b) around the placebo event (2009) reinforces that the post-2015 decline (in Fig. 2a) is not driven by spurious correlations or pre-existing trends. Overall, the evidence highlights that GEU shocks represent a genuine source of productivity loss for firms, and the placebo test enhances confidence in the identification strategy.

To formally assess the validity of the event-study specification in Fig. 2, we conduct joint F-tests on the interaction coefficients from Eq. (5) (see Table 8). Panel A reports a **parallel-trends test** for the actual event year 2015 by testing whether pre-event coefficients (2007–2013, baseline 2014) are jointly equal to zero. Panel B provides a **placebo test** by re-centering the model at a fake event year 2009 (baseline 2008) and testing whether post-2009 coefficients (2010–2017) are jointly zero. As shown in Table 8, both tests yield insignificant F-statistics, implying that neither the pre-2015 coefficients nor the placebo post-2009 coefficients are statistically different from zero. These results are consistent with the evidence in Fig. 2, confirming that the parallel-trends assumption holds



a. Event-study difference-in-differences (event year = 2015)

b. Placebo event-study difference-in-differences (fake event year = 2009)

Fig. 2. Event-study analysis using a two-way fixed-effects difference-in-differences framework. Notes:Vertical red bars represent the 95 % confidence intervals. Fig. 2a shows the event-study estimates around the actual event year (2015), while Fig. 2b reports a placebo test for Fig. 2a using a fake event year (2009). The baseline year (2014 in Fig. 2a, 2008 in Fig. 2b) is normalized to zero and therefore not shown. The GEU index is unavailable for 2011, so estimates for that year are also not displayed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 8
Event-study DiD identification tests: parallel trends and placebo.

Panel	Test type	Null hypothesis	F-stat	*p*-value
A. Pre-treatment (2015 event)	Parallel-trends test (2007–2013, baseline 2014)	All pre-event interaction terms = 0	0.70	0.649
B. Post-treatment (fake 2009 event)	Placebo test (2010–2017, baseline 2008)	All placebo interaction terms = 0	1.49	0.166

and that the observed productivity decline after 2015 is unlikely to be explained by spurious correlations. Together, Fig. 2 and Table 8 confirm the validity of our identification strategy.

5. Robustness tests

In this section, we use two different measures of firm-level total factor productivity as proposed by Levinsohn and Petrin (2003) and Olley and Pakes (1996) along with alternative regression models (including the linear mixed model and Hausman-Taylor model) to check the robustness of our baseline results in Section 4.

The linear mixed model (or linear mixed-effects model), an augmented version of simple linear model, comprises of both fixed factors and random factors in the model (Duchateau and Janssen, 1997; Verbeke and Molenberghs, 2000). In other words, this model can control for both fixed effects and random effects. As such, it is regarded as a versatile tool for efficiently addressing research questions (Oberg and Mahoney, 2007). Indeed, Oberg and Mahoney (2007) argue that the linear mixed model could model the within-subject correlation and weigh the estimation process so that it might allow subjects with more information and less variable information to contribute more to the analysis. Meanwhile, proposed by Hausman and Taylor (1981), the Hausman-Taylor model is considered to allow the correlation between some regressors with random individual effects. A major benefit of the Hausman-Taylor estimator is that it enables the estimation of time-invariant variables which are dropped by the fixed effects models (Baltagi, 2023). Especially, previous studies suggest that this model could be employed as a treatment for endogeneity (Fetai, 2018; Gardebroek and Lansink, 2003; Lu et al., 2018).

As can be seen from Table 9, the estimation results confirm the significantly adverse effects of the GEU index on firm productivity as indicated by the statistically significant negative coefficients of "GEU" in Table 9A. Additionally, the statistically significant negative coefficients of the interaction term "*GEU*Energy_intensive*" in Table 9B confirm that energy-intensive firms' productivity witnesses more negative impact from the GEU index, compared to less energy-intensive firms. Similarly, findings from Table 9C validate our baseline results regarding the more negative impacts of the GEU index on the productivity of smaller firms.

Beyond above robustness checks, we also implement a set of

Table 9
Robustness test: The impact of the GEU index on firm-level productivity (using alternative methods and alternative measures of firm productivity).

Panel A. Full sample

	Wooldridge (2009)			Levinsohn and Petrin (2003)			Olley and Pakes (1996)		
	Firm - Year fixed effects	Linear mixed model	Hausman-Taylor model	Firm - Year fixed effects	Linear mixed model	Hausman-Taylor model	Firm - Year fixed effects	Linear mixed model	Hausman-Taylor model
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
GEU	−0.070***	−0.092***	−0.082***	−0.069***	−0.091***	−0.081***	−0.073***	−0.094***	−0.081***
	(0.014)	(0.012)	(0.014)	(0.014)	(0.012)	(0.014)	(0.014)	(0.012)	(0.014)
Firm_size	0.192***	0.154***	0.161***	0.174***	0.136***	0.146***	0.209***	0.207***	0.191***
	(0.028)	(0.010)	(0.029)	(0.028)	(0.010)	(0.029)	(0.028)	(0.011)	(0.030)
Liquidity	1.581***	1.878***	1.572***	1.580***	1.874***	1.572***	1.650***	2.192***	1.649***
	(0.124)	(0.130)	(0.190)	(0.125)	(0.131)	(0.191)	(0.123)	(0.138)	(0.192)
Growth	0.288***	0.375***	0.282***	0.288***	0.369***	0.282***	0.285***	0.360***	0.280***
	(0.024)	(0.021)	(0.039)	(0.024)	(0.021)	(0.039)	(0.024)	(0.022)	(0.040)
N	6462	6886	6886	6462	6886	6886	6462	6886	6886
Adjusted R^2	0.534	–	–	0.525	–	–	0.581	–	–

Panel B. Energy-intensive industries

	Wooldridge (2009)			Levinsohn and Petrin (2003)			Olley and Pakes (1996)		
	Country - Year fixed effects	Linear mixed model	Hausman-Taylor model	Country - Year fixed effects	Linear mixed model	Hausman-Taylor model	Country - Year fixed effects	Linear mixed model	Hausman-Taylor model
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
GEU	−0.058***	−0.067***	−0.057***	−0.055***	−0.065***	−0.056***	−0.057***	−0.068***	−0.054***
	(0.019)	(0.018)	(0.020)	(0.020)	(0.018)	(0.020)	(0.020)	(0.018)	(0.021)
Energy_intensive	−0.188***	−0.184***	−0.338***	−0.200***	−0.196***	−0.361***	−0.160***	−0.167***	−0.387***
	(0.021)	(0.045)	(0.054)	(0.021)	(0.046)	(0.055)	(0.021)	(0.049)	(0.059)
*GEU*Energy_intensive*	−0.051**	−0.047**	−0.047*	−0.052**	−0.047**	−0.047*	−0.052**	−0.048**	−0.050**
	(0.023)	(0.023)	(0.025)	(0.023)	(0.023)	(0.025)	(0.023)	(0.024)	(0.025)
Firm_size	0.147***	0.156***	0.158***	0.124***	0.138***	0.143***	0.164***	0.208***	0.189***
	(0.006)	(0.010)	(0.029)	(0.006)	(0.010)	(0.029)	(0.006)	(0.011)	(0.030)
Liquidity	1.698***	1.902***	1.567***	1.660***	1.898***	1.567***	1.822***	2.213***	1.644***
	(0.082)	(0.130)	(0.190)	(0.083)	(0.131)	(0.191)	(0.085)	(0.138)	(0.192)
Growth	0.360***	0.370***	0.282***	0.354***	0.364***	0.282***	0.346***	0.356***	0.280***
	(0.016)	(0.021)	(0.039)	(0.016)	(0.021)	(0.039)	(0.016)	(0.022)	(0.039)
N	6881	6886	6886	6881	6886	6886	6881	6886	6886
Adjusted R^2	0.318	–	–	0.295	–	–	0.378	–	–

Panel C. Smaller firms

	Wooldridge (2009)			Levinsohn and Petrin (2003)			Olley and Pakes (1996)		
	Firm - Year fixed effects	Linear mixed model	Hausman-Taylor model	Firm - Year fixed effects	Linear mixed model	Hausman-Taylor model	Firm - Year fixed effects	Linear mixed model	Hausman-Taylor model
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
GEU	−0.039**	−0.058***	−0.055***	−0.038**	−0.056***	−0.053***	−0.041***	−0.058***	−0.054***
	(0.016)	(0.014)	(0.015)	(0.016)	(0.014)	(0.015)	(0.016)	(0.014)	(0.015)
Smaller_firm	−0.016	−0.018	−0.017	−0.014	−0.015	−0.016	−0.016	−0.007	−0.024
	(0.046)	(0.055)	(0.064)	(0.046)	(0.055)	(0.064)	(0.046)	(0.056)	(0.063)

(*continued on next page*)

Table 9 (*continued*)

Panel C. Smaller firms

	Wooldridge (2009)			Levinsohn and Petrin (2003)			Olley and Pakes (1996)		
	Firm - Year fixed effects	Linear mixed model	Hausman-Taylor model	Firm - Year fixed effects	Linear mixed model	Hausman-Taylor model	Firm - Year fixed effects	Linear mixed model	Hausman-Taylor model
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
GEU Smaller_firm*	−0.059***	−0.070***	−0.059**	−0.060***	−0.070***	−0.060**	−0.060***	−0.075***	−0.062**
	(0.021)	(0.023)	(0.025)	(0.021)	(0.023)	(0.025)	(0.021)	(0.024)	(0.025)
Firm_size	0.191***	0.151***	0.167***	0.173***	0.133***	0.152***	0.208***	0.206***	0.206***
	(0.030)	(0.014)	(0.026)	(0.030)	(0.014)	(0.026)	(0.031)	(0.015)	(0.027)
Liquidity	1.589***	1.875***	1.588***	1.588***	1.872***	1.588***	1.658***	2.189***	1.671***
	(0.124)	(0.130)	(0.190)	(0.125)	(0.131)	(0.191)	(0.123)	(0.137)	(0.192)
Growth	0.287***	0.374***	0.282***	0.287***	0.368***	0.282***	0.284***	0.359***	0.282***
	(0.024)	(0.021)	(0.039)	(0.024)	(0.021)	(0.039)	(0.024)	(0.022)	(0.040)
N	6462	6886	6886	6462	6886	6886	6462	6886	6886
Adjusted R^2	0.535	–	–	0.526	–	–	0.581	–	–

Notes: Robust standard errors are presented within parentheses. ***, ** and * stand for the significance level of 1 %, 5 % and 10 %, respectively.
The estimations in Panel A are based on the model: $TFP_{i,t} = \varphi_e + \omega_t + \beta_1 GEU_t + M_{i,t}\gamma + \varepsilon_{i,t}$ (1).
The estimations in Panel B are based on the model: $TFP_{i,t} = \varphi_e + \omega_t + \alpha_1 GEU_t + \alpha_2 Energy\_intensive_i + \alpha_3 GEU_t{*}Energy\_intensive_i + M_{i,t}\delta + \varepsilon_{i,t}$ (2)
The estimations in Panel C are based on the model: $TFP_{i,t} = \varphi_e + \omega_t + \theta_1 GEU_t + \theta_2 Smaller\_firm_i + \theta_3 GEU_t{*}Smaller\_firm_i + M_{i,t}\vartheta + \varepsilon_{i,t}$ (3).
Smaller_firm is a dummy variable, which equals to 1 if *Firm_size* is smaller than or equal to the median of *Firm_size*, and 0 otherwise.

placebo/falsification and robustness tests reported in Appendix A and B. Specifically, Appendix A examines placebo specifications by replacing GEU with alternative global uncertainty indices (GPR and EPU), using future GEU values (t + 1, t + 2) to rule out reverse causality, and performing circular time-shift tests that misalign the true timing of shocks. Appendix B provides further robustness checks by re-estimating the effects through the panel impulse response function framework and by employing demeaned interaction terms following Balli and Sørensen (2013). Across all these tests, the placebo specifications yield no significant effects, as expected, whereas the additional robustness checks consistently reproduce the negative impacts of GEU observed in the baseline regressions. This evidence confirms that our main results are not driven by spurious correlations, model specification choices, or alternative estimation strategies. Taken together, these tests reinforce the robustness and credibility of our baseline findings.

6. Conclusions and implications

Employing GEU index proposed by Dang et al. (2024a), this study explores the impact of the global geopolitical-energy uncertainty on total factor productivity at the firm level. The results show that higher GEU negatively affects firm productivity, with effects that vary across countries, industries, and firm sizes. Smaller firms and those operating in energy-intensive industries are more adversely affected, while firms with higher profitability are less impacted. Additionally, firms with higher cost intensity experience larger productivity losses under GEU, and rising global energy prices intensify the negative effects.

The findings suggest several important implications. From a firm perspective, smaller firms and those operating in energy-intensive industries should focus on strengthening operational resilience to mitigate the impact of high geopolitical-energy uncertainty. This could include improving cost management and diversifying energy sources. Also, maintaining profitability and having appropriate investment strategies are essential. Special attention should be given to firms operating in countries or sectors (energy insensitive industries) particularly exposed to GEU. From a policy perspective, governments can help enhance productivity by ensuring stability in energy markets, promoting the development and use of sustainable energy sources, and encouraging firms to adopt energy-efficient technologies and practices. Policies should also consider industry and firm characteristics to ensure they effectively address the impacts of geopolitical-energy uncertainty.

Although this study provides valuable evidence on the effects of GEU on firm productivity, it relies on annual firm-level data, which may not fully capture firms' short-term adjustments. Furthermore, while TFP is a key measure of efficiency, other dimensions of firm performance could also be examined. Future research could explore higher-frequency data and additional firm-level strategies to mitigate the impact of geopolitical-energy uncertainty.

CRediT authorship contribution statement

Tam Hoang Nhat Dang: Writing – original draft, Resources, Methodology, Formal analysis, Data curation. **Faruk Balli:** Writing – review & editing, Supervision, Methodology. **Hatice Ozer Balli:** Supervision, Resources, Methodology, Formal analysis. **Mei Qiu:** Writing – original draft, Methodology, Formal analysis, Data curation. **Hannah Nguyen:** Supervision, Methodology, Investigation.

Appendix A. Placebo/falsification tests

To ensure that our baseline findings are not driven by spurious correlations or reverse causality, we conduct a series of placebo tests. Table A1 examines the GEU-energy intensity interaction, while Table A2 focuses on the GEU-small firm interaction. In each case, we implement three falsification strategies. *First*, we replace the GEU index with alternative global uncertainty measures (i.e., global geopolitical risk - GPR and global economic policy uncertainty - EPU) (see Panel A). *Second*, we use future GEU values (t + 1, t + 2), which by construction cannot affect current firm productivity; any significance would indicate reverse causality (see Panel B). *Finally*, we perform circular time-shift tests by re-assigning the whole GEU series to future years (k = 1–4), which breaks the true timing of shocks (see Panel C). The lead test checks if future shocks predict today's outcomes, while the time-shift test checks if mis-aligned shocks spuriously reproduce the baseline pattern. These placebo specifications follow the same baseline regressions in Eqs. (2) and (3), with only minor modifications to the shock variable.

Across all specifications in Panel B and C of Table A1 and A2, the placebo interaction terms are statistically insignificant, supporting the validity of our identification strategy. For Panel A of Table A1, only the GEU–energy intensive interaction (column (1)) has a significant and negative impact on firm productivity, whereas the GPR–energy intensive (column (2)) and EPU–energy intensive (column (3)) interactions are insignificant. This indicates that the GEU index provides a more consistent explanation of energy-intensive firms' productivity responses compared to GPR and EPU. Similarly, in Panel A of Table A2, only the GEU–smaller firm interaction (column (1)) exerts a significant adverse effect on firm TFP, suggesting that the productivity of smaller firms may be more sensitive to GEU, compared to other uncertainty indices. Generally, the more consistent and robust effects of GEU across specifications support the interpretation that GEU is the primary source of the adverse productivity impacts.

Table A1
Placebo/falsification tests for the GEU-energy intensity interaction.

Panel A. Alternative-shock placebo test				
	(1)	(2)		(3)
Index	−0.058***	−0.381***		0.027
	(0.019)	(0.077)		(0.064)
Energy_intensive	−0.188***	−0.861**		−0.178***
	(0.021)	(0.417)		(0.023)
*Index*Energy_intensive*	−0.051**	0.148		−0.020
	(0.023)	(0.090)		(0.082)
Control variables	Yes	Yes		Yes
N	6881	6881		5844
Adjusted R^2	0.318	0.317		0.322
Panel B. Future-shock placebo test				
	(1)		(2)	
$GEU_{(t+1)}$	−0.096***			
	(0.023)			
$GEU_{(t+2)}$			−0.070***	
			(0.024)	
Energy_intensive	−0.196***		−0.196***	
	(0.022)		(0.022)	
$GEU_{(t+1)}$*Energy_intensive*	−0.012			
	(0.028)			
$GEU_{(t+2)}$*Energy_intensive*			0.020	
			(0.028)	
Control variables	Yes		Yes	
N	5844		5225	
Adjusted R^2	0.326		0.331	
Panel C. Circular time-shift placebo test				
	(1)	(2)	(3)	(4)
GEU_k1	0.002			
	(0.020)			
GEU_k2		0.015		
		(0.022)		
GEU_k3			0.044**	
			(0.020)	
GEU_k4				0.034
				(0.023)
Energy_intensive	−0.180***	−0.201***	−0.197***	−0.190***
	(0.021)	(0.023)	(0.023)	(0.024)
*GEU_k1*Energy_intensive*	−0.039			
	(0.025)			
*GEU_k2*Energy_intensive*		−0.003		
		(0.027)		
*GEU_k3*Energy_intensive*			0.033	
			(0.026)	
*GEU_k4*Energy_intensive*				0.041
				(0.029)
Control variables	Yes	Yes	Yes	Yes
N	6542	6241	5974	5664
Adjusted R^2	0.314	0.313	0.320	0.313

Notes: Robust standard errors are presented within parentheses. ***, ** and * stand for the significance level of 1 %, 5 % and 10 %, respectively. We note that the dummy variable "*Energy_intensive*" gets absorbed when firm fixed effects are employed because it is perfectly collinear with those fixed effects. As such, country-year fixed effects are controlled in models instead of firm-year fixed effects. For Panel A, "*Index*" stands for GEU, GPR or EPU. The estimation in column (1) is based on Eq. (2), while the variable *GEU* in Eq. (2) is replaced with *GPR* and *EPU* in the estimations of column (2) and (3), respectively. $GEU_{(t+1)}$ and $GEU_{(t+2)}$ are one- and two-year leads of the GEU index. *GEU_k1 to GEU_k4* denote the index shifted forward by 1–4 years as placebo shocks.

Table A2
Placebo/falsification tests for the GEU-smaller firm interaction.

Panel A. Alternative-shock placebo test

	(1)	(2)	(3)
Index	−0.039**	−0.321***	0.061
	(0.016)	(0.060)	(0.046)
Smaller_firm	−0.016	−0.382	−0.040
	(0.046)	(0.390)	(0.051)
*Index*Smaller_firm*	−0.059***	0.079	−0.070
	(0.021)	(0.085)	(0.071)
Control variables	Yes	Yes	Yes
N	6462	6462	5739
Adjusted R^2	0.535	0.535	0.537

Panel B. Future-shock placebo test

	(1)	(2)
$GEU_{(t+1)}$	−0.068***	
	(0.018)	
$GEU_{(t+2)}$		−0.035*
		(0.018)
Smaller_firm	−0.009	−0.010
	(0.048)	(0.050)
$GEU_{(t+1)}$**Smaller_firm*	−0.000	
	(0.026)	
$GEU_{(t+2)}$**Smaller_firm*		0.006
		(0.025)
Control variables	Yes	Yes
N	5739	5177
Adjusted R^2	0.528	0.538

Panel C. Circular time-shift placebo test

	(1)	(2)	(3)	(4)
GEU_k1	0.020			
	(0.015)			
GEU_k2		0.030*		
		(0.015)		
GEU_k3			0.070***	
			(0.015)	
GEU_k4				0.045***
				(0.017)
Smaller_firm	−0.018	−0.045	−0.032	−0.015
	(0.048)	(0.050)	(0.049)	(0.052)
*GEU_k1*Smaller_firm*	−0.032			
	(0.022)			
*GEU_k2*Smaller_firm*		−0.005		
		(0.023)		
*GEU_k3*Smaller_firm*			0.011	
			(0.022)	
*GEU_k4*Smaller_firm*				0.027
				(0.025)
Control variables	Yes	Yes	Yes	Yes
N	6129	5838	5561	5258
Adjusted R^2	0.539	0.535	0.549	0.543

Notes: Robust standard errors are presented within parentheses. ***, ** and * stand for the significance level of 1 %, 5 % and 10 %, respectively. Firm-year fixed effects are controlled in models. For Panel A, "*Index*" stands for GEU, GPR or EPU. The estimation in column (1) is based on Eq. (3), while the variable *GEU* in Eq. (3) is replaced with *GPR* and *EPU* in the estimations of column (2) and (3), respectively. $GEU_{(t+1)}$ and $GEU_{(t+2)}$ are one- and two-year leads of the GEU index. *GEU_k1 to GEU_k4* denote the index shifted forward by 1–4 years as placebo shocks.

Appendix B. Additional robustness checks

B.1. Robustness tests using the panel impulse response function

Apart from the regression models presented in Section 5.1, in this section, we employ the panel impulse response function to explore whether one shock from the GEU index might lead to significant decreases in firm productivity or not. Looking at Fig. B1 where we use the impulse response analysis with different measures of total factor productivity, we note that one shock from the GEU index leads to a statistically significant decrease in firm productivity (Fig. B1a). Moreover, one shock from the interaction term "*GEU*Engery_intensive*" also leads to significant drops in the productivity at firm level (Fig. B1b). Those findings confirm our baseline results in Table 2 and Table 4.

As can be seen from Fig. B1c where we perform the impulse response functions with the impulse of "*GEU*Smaller_firm*", it is noted that the interaction term "*GEU*Smaller_firm*" significantly reduces different measures of firm productivity. Such findings confirm our baseline results regarding the GEU index' impact on the productivity of smaller firms presented in Table 5.

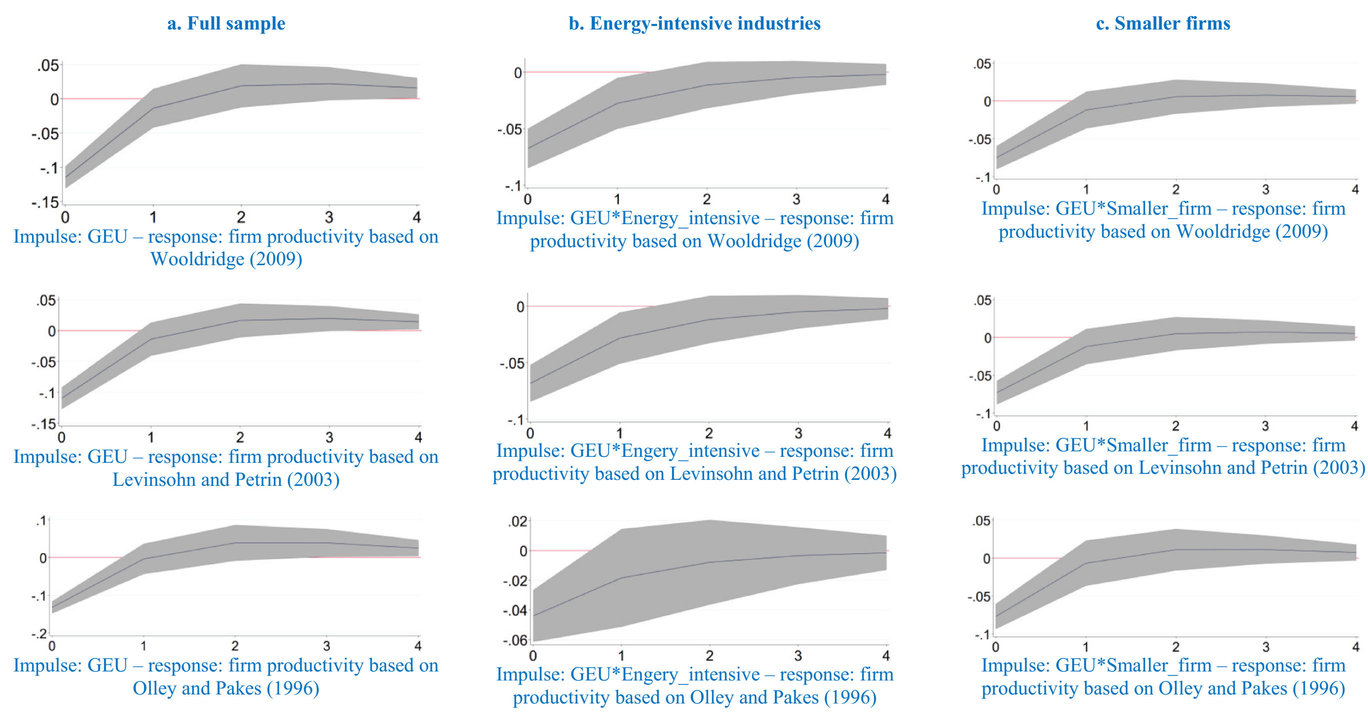


Fig. B1. Robustness test: Panel impulse response analysis.
Notes: The analysis is based on the 95 % confidence interval.

B.2. Robustness tests using the demeaned interaction term by Balli and Sørensen (2013)

In this section, we employ the demeaned interaction term proposed by Balli and Sørensen (2013). This corrected interaction term is suggested to help reduce the spurious estimations in the model. Following Balli and Sørensen (2013), we re-estimate our regression models with the demeaned interaction terms as in Equation (b1) and (b2).

$$TFP_{i,t} = \varphi_e + \omega_t + \alpha_1 GEU_t + \alpha_2 Energy\_intensive_i + \alpha_3 Demean\_GEU_t{*}Energy\_intensive_i + M_{i,t}\delta + \varepsilon_{i,t} \quad \text{(b1)}$$

$$TFP_{i,t} = \varphi_e + \omega_t + \theta_1 GEU_t + \theta_2 Smaller\_firm_i + \theta_3 Demean\_GEU_t{*}Smaller\_firm_i + M_{i,t}\vartheta + \varepsilon_{i,t} \quad \text{(b2)}$$

where $Demean\_GEU = GEU - \overline{GEU}$, and $\overline{GEU}$ stands for the mean of GEU.

As can be seen from Table B1, the coefficients of the demeaned interaction terms in Panel A and B are both statistically significant and negative across different model specifications. Such results confirm our baseline findings that firm productivity from energy-intensive firms and smaller firms are more negatively affected by the GEU index.

Table B1
Robustness test: Using the demeaned interaction term by Balli and Sørensen (2013).

Panel A. Energy-intensive industries	Country - Year fixed effects	Linear mixed model	Hausman-Taylor model
	(1)	(2)	(3)
GEU	−0.048**	−0.067***	−0.057***
	(0.020)	(0.017)	(0.020)
Energy_intensive	−0.186***	−0.184***	−0.326***
	(0.045)	(0.045)	(0.054)
*Demean_GEU*Energy_intensive*	−0.044*	−0.050**	−0.046*
	(0.024)	(0.023)	(0.025)
Control variables	Yes	Yes	Yes
N	6886	6886	6886
Adjusted R^2		–	–

Panel B. Smaller firms	Firm - Year fixed effects	Linear mixed model	Hausman-Taylor model
	(1)	(2)	(3)
GEU	−0.038**	−0.062***	−0.058***
	(0.019)	(0.013)	(0.015)
Smaller_firm	−0.013	−0.017	−0.012
	(0.064)	(0.055)	(0.064)
Demean_GEU Smaller_firm*	−0.061**	−0.066***	−0.055**
	(0.026)	(0.024)	(0.025)
Control variables	Yes	Yes	Yes
N	6886	6886	6886
Adjusted R^2	0.095	–	–

Notes: Robust standard errors are presented within parentheses. ***, ** and * stand for the significance level of 1 %, 5 % and 10 %, respectively.
The estimations in Panel A are based on the model: $TFP_{i,t} = \varphi_e + \omega_t + \alpha_1 GEU_t + \alpha_2 Energy\_intensive_i + \alpha_3 Demean\_GEU_t{*}Energy\_intensive_i + M_{i,t}\delta + \varepsilon_{i,t}$ (4).
The estimations in Panel B are based on the model: $TFP_{i,t} = \varphi_e + \omega_t + \theta_1 GEU_t + \theta_2 Smaller\_firm_i + \theta_3 Demean\_GEU_t{*}Smaller\_firm_i + M_{i,t}\vartheta + \varepsilon_{i,t}$ (5).

Appendix C. Principal Component Analysis (PCA) approach

The principal component analysis (PCA) approach, first introduced by Hotelling (1933), is a technique that reduces the dimensionality of data while retaining the maximum possible variance. The method transforms a set of correlated variables into a smaller number of uncorrelated principal components, which capture the essential structure of the data (Fu et al., 2021; Luo et al., 2022). Each component is assigned weights based on the intrinsic characteristics of the indicators, ensuring that the resulting components are free from subjective influence (Zou et al., 2023).

The procedure follows three main steps. **First**, each sub-index is standardized using Z-score normalization to remove biases from scale differences:

$$z_{ij} = \frac{x_{ij} - \overline{\mu}_j}{\sigma_j} \quad \text{(c1)}$$

where x_{ij} is the raw value i of sub-index j (where $j = 1, 2, 3$), $\overline{\mu}_j$ and σ_j are its mean and standard deviation.

Second, the correlation matrix is calculated and decomposed into eigenvalues and eigenvectors.

Finally, principal components are ranked by their explained variance, and those with eigenvalues greater than one are retained (Amuakwa-Mensah et al., 2018; Zou et al., 2023). The selected eigenvectors then serve as weights for constructing the composite GEU index.

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2025.109054.

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