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Geopolitical Risk and National Green Economic Efficiency: Evidence from G20 Member Countries

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Abstract

This study uses the data of G20 countries from 2000 to 2022 as samples to examine the impact of geopolitical risk on the green economic efficiency. We use the Super-SBM model to measure the green economic efficiency of each country. Our results show that the rise of geopolitical risk significantly reduces the green economic efficiency of G20 members reflecting the negative impact of external uncertainty on international climate cooperation and environmental performance. The heterogeneity analysis finds that geopolitical risks are significantly negatively correlated with the green economic efficiency of countries in developed economies, but the effect is not significant in emerging economies that indicating that the impact mechanism of countries with different institutional soundness and development levels is different. The mechanism analysis reveals that geopolitical risks will aggravate the country's concerns about energy security, promote the increase in fossil fuel consumption, and then inhibit the improvement of the country's green economic efficiency; and geopolitical risks also cause exchange rate fluctuations to lead to increasing trade costs and restricting green investment. In addition, foreign direct investment alleviates the negative impact of geopolitical risks by promoting technology spillovers and capital inflows. Overall, this study provides a new perspective for coping with climate change; and provides suggestions for policy makers and relevant scholars in the field of environmental economics.

Keywords: geopolitical risk; green economic efficiency; G20 countries; super SBM-model; global uncertainties

1. Introduction

With the development of the economy, the negative impact of environmental pollution on various countries has become increasingly obvious, and governments of various countries have gradually realised that responding to climate change is crucial to the development of the country and even the region [1]. Under the global climate governance framework, countries have begun to promote energy transition and reduce greenhouse gas emissions, but in the complex international environment, the realisation of green transition and sustainable development is still facing many difficulties. In recent years, the global political and economic landscape has become increasingly turbulent, and geopolitical risks have continued to rise under the impetus of war conflicts, trade frictions, supply chain crises and anti-globalisation trends [2–5]. These external uncertainties are reshaping the global governance landscape and are already complicating countries' efforts to meet the Sustainable Development Goals [6]. In the existing studies, most of them focus on the influencing factors of green transformation and green economic development within a single economy, while there are very few studies on a broader scale. Therefore, in order to continuously promote the sustainable development of the global economy, and in the context of increasing geopolitical risks, it is particularly important to explore the influencing factors of the efficiency of green economies in different countries.

Green economic efficiency is widely used to assess a country's progress in green transition and sustainable economic development. It reflects the use of energy, labour, and capital, together with actions taken to mitigate climate change. Addressing climate change is a global issue. However, the increase in geopolitical risks has a significant negative impact on climate and energy policies [7–10]. Moreover, rising geopolitical risks have reduced the effectiveness of cross-country collaboration and raised the costs of international coordination, which in turn undermines climate cooperation [11,12]. Although we have learned about the impact of geopolitical risks on climate, such specific studies particularly those examining green economic efficiency remain rarely discussed. We reviewing extensive literature, we found that existing research on green economic efficiency remains confined to China. It is worth noting that climate change as a global issue，discussing it within a broader countries are necessary [13,14]. These studies have not yet expanded to a broader national level, and no research has explored the mechanisms influencing global green economic efficiency.Given the limited scholarly exploration of national green economic efficiency, our research aims to fill this gap by discussing its potential impact mechanisms from multiple perspectives.

In summary, this study uses data from 19 countries of the G20 economy as the research sample, and measure the green economic efficiency of each country from 2000 to 2022. It is worth noting that the main contributions of this study are as follows: First, this study is the first to use the Super-SBM model to measure the green economic efficiency of G20 countries, which can provide more accurate efficiency evaluation results compared with the traditional DEA method. Second, we have confirmed that the increase in geopolitical risk will significantly reduce the green economic efficiency of G20 countries. Third, we found that the negative impact of geopolitical risk on the green economic efficiency of countries is significantly different in developed economies and emerging economies. Fourth, this study is the first to reveal the transmission path of geopolitical risk and green economic efficiency - geopolitical risk has a negative impact on green economic efficiency by increasing the consumption of fossil energy in a country and causing the depreciation of the local currency. At the same time, we found that foreign direct investment can alleviate this negative impact to a certain extent. These findings expand the theoretical boundaries of environmental economics and provide new perspectives for policymakers. Overall, geopolitical risks negatively affect a country's green economic efficiency through mechanisms such as hindering energy transitions and causing exchange rate fluctuations. Understanding the impact of geopolitical risks on a country's green economic efficiency is crucial for leaders and policymakers to consider the effects of geopolitical risks when formulating climate policies, which is of great significance for a country's sustainable development.

The remainder of this paper is organised as follows: Section 2 reviews the literature and proposes the hypotheses; Section 3 describes the research design, including the empirical model, sample selection, and variable definitions; Section 4 presents a series of empirical results; and Section 5 discusses the conclusions and policy implications of this study.

2. Literature Review and Theoretical Hypothesis

2.1. Geopolitical Risks and Green Economic Efficiency

Green economic efficiency represents a country's ability and determination to achieve economic output while taking into account environmental protection and climate change, and is an important indicator for measuring a country's sustainable economic development [15,16]. This indicator reflects the degree of coordination between the economy and the environment, and also reflects a country's comprehensive ability in terms of institutional implementation, policy stability, and technological absorption and innovation. However, the increasing trend of anti-globalisation and geopolitical frictions in recent years have made the external environment for green transformation increasingly complex, and the efficiency of the green economy is facing multiple shocks. Countries have made many commitments to address climate change and have made many efforts in carbon emission reduction and energy transition. However, under the background of anti-globalisation, the economic development of countries has been impacted to varying degrees, and the fulfilment of environmental protection commitments faces many obstacles.

Resource dependence theory suggests that when a country is highly dependent on external resources in terms of energy or key technologies, the rise of geopolitical risks will exacerbate uncertainty, thereby hindering the process of green transformation. Zeraibi et al. (2025a) showed that there was a negative correlation between geopolitical risk and renewable energy in G7 countries [17], suggesting that geopolitical tensions may inhibit the input of clean energy. For specific industries, manufacturing remains a major driver of economic activity in G20 countries and prior studies report a U-shaped association between manufacturing agglomeration and green economic efficiency: moderate agglomeration may help reduce environmental pollution, and industrial structure acting as an important mediating channel [18,19]. Therefore, promoting renewable energy to support the green transformation of industrial structures is crucial. However, heightened geopolitical risks may inflict exogenous shocks on industrial structures, thereby impacting the progress of their transformation.

In addition, geopolitical risks also affect the efficiency of the green economy by influencing financial instruments. A study by Mertzanis et al. (2025) on cross-border financial markets indicates that the rise in geopolitical risks has, to a certain extent, driven the growth in the issuance of green bonds [20]. However, further research has found that geopolitical risks have a negative impact on the prices of green bonds [21]. A study on the BRICS countries also points out that there is a connection between green investment and green economic growth [22]. As an important tool for attracting green investment, changes in the green bond market will affect the scale of green investment, which is a key driver of green economic growth. Geopolitical risks may affect green economic efficiency by shaping clean-energy deployment, industrial restructuring, and the functioning of green financial markets.

From an institutional perspective, rising geopolitical risk often coincides with greater policy uncertainty. Institutional theory suggests that geopolitical instability can weaken the continuity and effectiveness of policy implementation. Evidence from the United States links climate policy uncertainty to lower green innovation [23], but the broader empirical picture is mixed. Using data from G20 economies, Wang et al. (2020) show that governments often mobilise additional resources to cope with external uncertainty and, in the name of energy security, support sustainable energy development [24]. In contrast, evidence from China indicates that economic policy uncertainty is positively associated with green economic efficiency, with market mechanisms acting as an important moderator [25]. Overall, these studies suggest that cross-country differences in institutional quality, fiscal capacity, industrial structure, and reliance on external resources can shape both the direction and the magnitude of the effect of geopolitical risk on green economic efficiency. Such divergences precisely highlight the necessity of systematically examining the overall impact of geopolitical risks on green economic efficiency in a broader context.

Based on this, we propose the following hypothesis

H1: *Geopolitical risk has a negative impact on the green economic efficiency of countries.*

2.2. Geopolitical Risk, Foreign Direct Investment and Green Economic Efficiency

Since the era of globalization, attracting foreign direct investment has been an important means for many countries to promote economic development. Through this source of capital, host countries can obtain opportunities to develop infrastructure and promote international exchanges and cooperation [26]. In recent years, with the concept of sustainable development deeply rooted in people's hearts, governments of all countries have attached more and more importance to achieving a win-win situation for the environment and the economy while attracting investment. Therefore, many scholars have begun to explore the role mechanism of foreign direct investment in the process of achieving sustainable development goals. Existing studies have shown that FDI affects a country's

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energy consumption through multiple channels, including by affecting corporate expansion, technology development, and market allocation, thereby affecting energy demand [27,28]. However, the rise of the anti-globalisation trend and the emergence of geopolitical tensions have brought new uncertainties and challenges to the cross-border flow of foreign direct investment, which also makes it necessary to explore the mechanism of foreign direct investment affecting the green economic efficiency of countries in this context.

First, the global value chain theory points out that the intervention of foreign direct investment can enable the host country to share the fruits of technological progress from other countries, promote capital inflows, create employment opportunities, and achieve technology sharing, so that unbalanced development areas can enjoy the fruits [29–31]. Shinwari et al. (2024) found that the inflow of foreign direct investment in countries along the Belt and Road positive affects the energy consumption and promoted the development of the green economy [32]. Some scholars believe that the capital and technological advantages brought by foreign investment help developing countries achieve sustainable development goals and fulfil their environmental governance commitments. For example, some studies have shown that foreign direct investment can reduce the environmental costs behind economic development [33]. Empirical analysis of East Asian economies has also found that FDI has a positive impact on the green growth process [34]. From the perspective of the pollution halo hypothesis, the technological progress brought about by the increase in foreign direct investment is conducive to promoting the development of green technology in the host country [35].

However, some studies hold the opposite view. Some scholars believe that some developed countries may transfer high-pollution and high-energy-consumption production links to host countries with lower environmental standards through foreign investment, thereby evading their own environmental regulatory responsibilities. In this case, foreign direct investment may be detrimental to the sustainable development of the host country. The literature has revealed the association between increased FDI and rising carbon emissions. For example, Abbas et al. (2023) found in their study of South Africa that every 1% increase in foreign direct investment would lead to an average increase of 0.03% in local per capita carbon emissions, supporting the pollution haven hypothesis, and pointed out that its impact on carbon emissions would also spread to neighbouring areas [36]. Obviously, the increase in carbon emissions will damage the green economic development of a country. It can be seen that the impact of FDI on environmental performance is not one-sidedly positive, and it is possible to weaken the efficiency of the green economy due to the introduction of high-polluting industries.

In addition, there is increasing evidence that the impact of FDI on a country's sustainable development is mainly determined by the quality of the host country's institutions [37,38]. Institutional quality is considered one of the key factors affecting the shape of the Environmental Kuznets Curve (EKC). In emerging economies, the impact of FDI on green economic efficiency is more complex due to the uncertainty of environmental policies and regulations. It is worth noting that the rise in geopolitical risks tends to exacerbate macroeconomic and policy uncertainties, which may lead to further turbulence in the institutional environment, thereby affecting the actual effect of FDI. For example, geopolitical tensions may reduce investor confidence and decrease investment inflows to host countries, which will weaken the host countries' access to green technologies and funds. Unstable institutional and policy environments may also prevent the full realisation of the positive effects of FDI. In summary, under the impact of geopolitical risks, the transmission mechanism of FDI affecting green economic efficiency is complex and changeable, and the existing research has not formed a consistent conclusion.

Based on this, we propose the following hypothesis

H2: *Foreign direct investment weakens the impact of geopolitical risk on the efficiency of the green economy.*

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2.3. Geopolitical Risks, Fossil Energy Consumption and Green Economic Efficiency

Fossil energy consumption has long been regarded as an important indicator to measure a country's energy development level and economic growth stage, and it is also an important influencing factor of green economic efficiency [39]. As the global climate change problem continues to intensify, the international community has reached a broad consensus on reducing dependence on fossil energy, promoting the transformation of energy structure, and achieving sustainable development goals [40]. However, the fundamental role of fossil energy in economic growth, industrial operation and social stability makes countries often affected by path dependence and institutional constraints when promoting green transformation. Given the economy's continued reliance on fossil fuels, the energy transition is unlikely to proceed rapidly and must contend with industrial-structure lock-in. A large number of studies have pointed out that factors such as the degree of trade openness, the level of technological innovation, tax policies, and government subsidies will significantly affect a country's energy consumption structure, and these factors are closely related to the complex and volatile geopolitical environment [41–44]. With the deepening of globalization, the industrial division of labour and energy cooperation between countries have been continuously strengthened, and many countries have formed a high degree of external dependence on the supply of key energy sources, which makes geopolitical risks an important exogenous factor affecting the energy structure and green economic efficiency [45,46].

Existing studies generally believe that geopolitical risks affect the performance of green development by affecting energy security and then forcing countries to adjust their energy structure. First, the rise in geopolitical risk will increase the uncertainty of energy supply. For countries that are highly dependent on imported oil and gas, external conflicts, policy changes, and transportation disruptions directly threaten energy security [47,48]. Energy security theory points out that when the external environment is unstable, countries tend to adopt a "conservative energy strategy", that is, increase fossil energy reserves and increase the production capacity of traditional fossil energy in their own countries to ensure the stability of economic operation. This strategy helps reduce the risk of energy supply in the short term, but the direct result is an increase in fossil energy consumption, which inhibits the improvement of the efficiency of the green economy. Therefore, geopolitical risks, by triggering concerns about energy security, make policymakers tend to delay the pace of reducing dependence on fossil energy, affecting the process of green transformation.

In addition, geopolitical tensions can also indirectly affect the green energy transition by hindering international cooperation. Shen and Yang (2024) argue that escalating geopolitical conflicts often trigger protectionist responses in the energy sector [49]. These include tighter controls on the export of, and cross-border collaboration in, key renewable-energy technologies to avoid strategic resources falling under external control. Such steps may bolster national security in the short term, but they can also narrow international exchanges in green technologies and, in turn, slow progress towards a green economy. Trade theory indicates that international conflicts and political tensions increase the cost of cross-border transactions, weaken energy cooperation and green technology exchanges among countries, and slow down the global diffusion of green technologies.

Based on this, we make the following hypothesis

H3: *Geopolitical risk increases fossil energy consumption and reduces the green economic efficiency of countries.*

2.4. Geopolitical Risks, Exchange Rates and Green Economic Efficiency

As an important macroeconomic variable, the exchange rate has a significant impact on the green economic growth of a country. Exchange rate fluctuations affect almost all industries and influence economic operations and the green transformation process through various channels. On the one hand, exchange rate fluctuations are directly related to the relative prices of import and export commodities: a depreciation of the local currency will increase import costs, while an appreciation will have the opposite effect. This price change will affect the introduction cost of clean energy

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technology and equipment, as well as the expectations of enterprises and consumers on energy prices, thus affecting the development of green economy [50]. On the other hand, exchange rate fluctuations also affect cross-border investment and capital flows, which in turn affect the financing environment for domestic green projects. In the context of today's increasingly complex global political and economic landscape, geopolitical risks have brought great uncertainty to exchange rates. Yilmazkuday (2025) studied 35 countries and found that geopolitical tensions often lead to greater depreciation of currencies for economies deeply integrated into global value chains. It can be seen that the exchange rates of highly open countries are more vulnerable to geopolitical events, and their green economic development may face greater uncertainty [51].

Exchange rate fluctuations caused by geopolitical risks mainly affect the efficiency of the green economy through capital flows and price effects. When geopolitical tensions are high, conflicts escalate, or the risk of sanctions increases, international capital tends to quickly shift to safe-haven assets, causing the currencies of some emerging markets or countries with high risk exposure to face greater depreciation pressure [52,53]. The depreciation of the local currency will significantly increase the import costs of the above-mentioned countries, making the introduction of renewable energy equipment, energy-saving technologies and other green production factors more expensive, thereby inhibiting the diffusion of clean technologies and industrial upgrading in the country. In addition, large exchange rate fluctuations can indirectly affect the efficiency of the green economy by affecting the government's fiscal capacity [54]. On the one hand, continuous currency depreciation will increase the burden of government debt denominated in foreign currencies, and the government may consume more fiscal resources to stabilise the exchange rate and repay debts. On the other hand, increased fiscal pressure will weaken the government's subsidies and support for green industries, affecting the investment in clean energy projects and environmental protection infrastructure [55]. In summary, the negative impact of exchange rate depreciation on the efficiency of the green economy is multi-layered: there are both cost increases and investment slowdowns at the micro level, and policy support at the macro level is weakened.

Based on this, we make the following hypothesis

H4: *Geopolitical risks cause currency devaluation, which in turn reduces the green economic efficiency of the country.*

Figure 1 shows the theoretical framework of this paper.

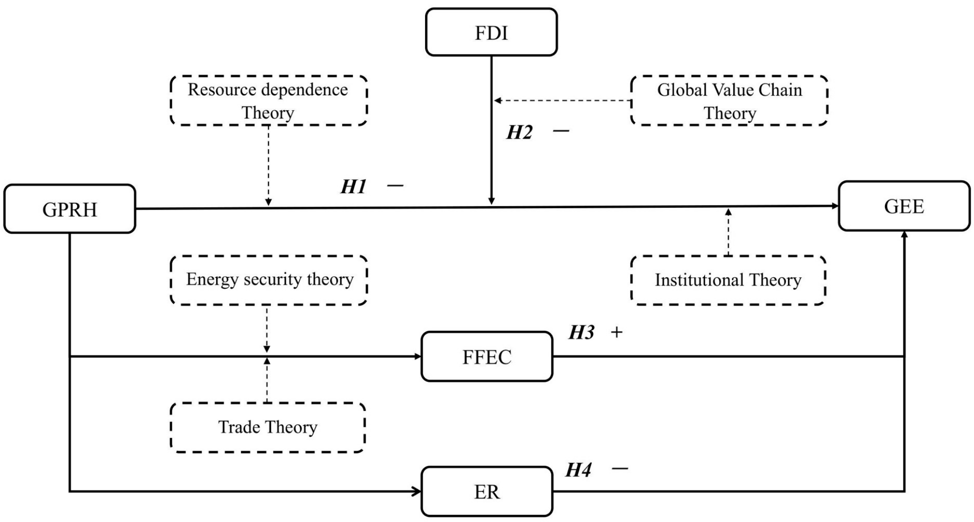

Figure 1. Theoretical Framework.

3. Research Design

3.1. Data and Variables

Based on the studies of Appiah-Otoo et al. (2023) and Luo et al. (2024), this study selected 19 G20 countries as samples (excluding the European Union) to examine the impact of geopolitical risks on the efficiency of the green economy from 2000 to 2022 [56,57]. The data mainly came from the World Bank WDI database. The WDI database developed by the World Bank has been widely recognised by the academic community and applied in many studies, and its data has high credibility. During the sample period, we used the two-sided 1% level winsorization treatment for the main variables to eliminate the impact of extreme values. The final sample contained 437 country-year panel observations.

3.1.1. Explanatory Variable: Geopolitical Risk (GPRH)

The core independent variable is geopolitical risk. This study uses the geopolitical risk index constructed by Caldara and Iacoviello (2022) for measurement [58]. The index quantifies geopolitical risk by counting the frequency of news reports involving events such as war threats, terrorist attacks, and diplomatic crises. The higher the value, the higher the level of geopolitical tension and uncertainty. This article selects the long-term geopolitical risk historical index (GPRH) in this study. The original data is published on a monthly frequency. In order to match the annual panel data, we take the arithmetic average of the monthly index for each country to obtain the annual geopolitical risk index from 2000 to 2022. The index has good comparability between countries and can comprehensively reflect the economic and environmental uncertainties brought about by major geopolitical events (such as conflicts, terrorist attacks, and diplomatic frictions) around the world. Figure 2 shows the trend of the GPRH index of the sample countries from 2000 to 2022.

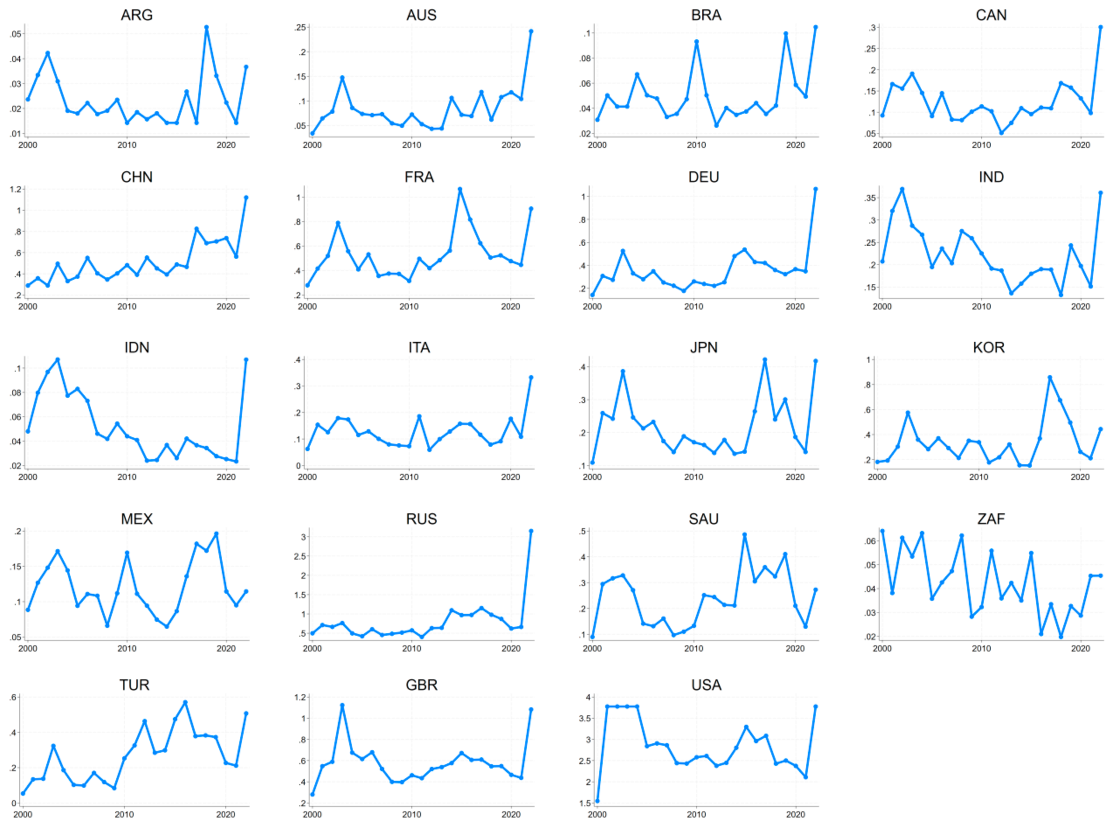

Figure 2. Geopolitical Risk Index of G20 Countries.

3.1.2. Explained Variable: Green Economic Efficiency (GEE)

In this paper, green economic efficiency (GEE) is taken as the dependent variable. In view of the limitations of radial and angular assumptions in the traditional data envelopment analysis (DEA) model, it is impossible to deal with slack variables and undesirable output. Therefore, based on the research of Tone (2002) [59], we use the super-slack measure (super-SBM) model including undesirable output to measure the green economic efficiency of G20 countries.

Suppose there are n decision-making units (DMUs). In this study, a DMU is defined as a "country-year" combination. Each DMU is characterized by q input variables$x \in R_{+}^{q}$, $u_1$desirable output variables $y_g \in R_{+}^{u1}$, and u_2 undesirable output variables $y^b \in R_{+}^{u2}$. The input matrix is defined as $X = [x_1, \cdots, x_n] \in R^{q \times n} > 0$, the desirable output matrix as $Y^g = [y_1^g, \cdots, y_n^g] \in R^{u_1 \times n} > 0$, and the undesirable output matrix as $Y^b = [y_1^b, \cdots, y_n^b] \in R^{u_2 \times n} > 0$. Based on the production possibility set $P = \{(x, y^g, y^b) | x \geq X\lambda, y^g \geq Y^g\lambda, y^b \leq Y^b\lambda, \lambda \geq 0\}$, the efficiency score in the SBM framework is formulated as follows:

$$\rho = min \frac{1 - \frac{1}{q}\sum_{i=1}^{q}\frac{s_i^-}{x_{i0}}}{1 + \frac{1}{u_1 + u_2}(\sum_{r=1}^{u_1}\frac{s_r^g}{y_{r0}^g} + \sum_{l=1}^{u_2}\frac{s_l^b}{y_{l0}^b})}$$

$$x_0 = X\lambda + s^-$$

$$y_0^g = Y^g\lambda - s^g$$

$$s^- \geq 0, s^g \geq 0, s^b \geq 0$$

In the above formula, x, y^g and y^b represent the input items, desirable output items and undesirable output items of the decision-making unit, s−, sg and sb represent the slack vectors of input, desirable output and undesirable output respectively, λ is the weight vector, and the subscript "0" in the model is the unit to be evaluated. When ρ=1, s^-, s^g and s^b are all 0, the decision-making unit is efficient: whenρ<1 it indicates that the decision-making unit has efficiency loss, and the input and output need to be further optimised at this time. Considering that the SBM model with undesirable output may have multiple decision-making units that are effective at the same time, that is, the efficiency values are all 1, which is not convenient for distinguishing and sorting these decision-making units. If multiple decision-making units are effective at the same time in the measurement results, the Super-SBM model with undesirable output needs to be used to solve the problem. Super-SBM can clearly identify various factors affecting the efficiency value, so as to improve the accuracy and rationality of efficiency measurement. The Super-SBM measurement formula is as follows:

$$\rho = min \frac{\frac{1}{q}\sum_{i=1}^{q}\frac{\bar{x}_i}{x_{i0}}}{\frac{1}{u_1 + u_2}(\sum_{r=1}^{u_1}\frac{\bar{y}_r^g}{y_{r0}^g} + \sum_{l=1}^{u_2}\frac{\bar{y}_l^b}{y_{l0}^b})}$$

$$\bar{x} \geq \sum_{i=1, i \neq 0}^{n} \lambda_i x_i \text{ , } \bar{y}^g \leq \sum_{i=1, i \neq 0}^{n} \lambda_i y_i^g$$

$$\bar{y}^b \geq \sum_{i=1, i \neq 0}^{n} \lambda_i y_i^b \text{ , } \bar{x} \geq x_0, \quad \bar{y}^g \leq y_0^g, \quad \bar{y}^b \geq y_0^b$$

$$\bar{y}^g \geq 0, \lambda \geq 0$$

In the formula, ρ represents the green economic efficiency. In addition, the following input and output variables are adopted in this study.

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Referring to the studies of Zhao et al. (2020a) and Kong et al. (2023), we selected the following input and output variables in the efficiency measurement [60,61]. The input factors were selected from three perspectives: energy input, labour input and capital input. Energy input is composed of energy consumption (kg of oil equivalent), labour input is reflected by the total number of labour force, and capital input is represented by the total amount of fixed capital formation. In terms of desirable output, GDP and forest coverage rate are regarded as ideal output. In terms of undesirable output, we focused on the emissions of harmful gases, and selected the total emissions of carbon dioxide (CO_2), the total emissions of methane (CH_4) and the total emissions of nitrous oxide (N_2O) as undesirable output. All the above data are from WDI. Table 1 lists the specific indicators used in the construction of the green economic efficiency index, Figure 3 shows the GEE gap of countries in 2022, and Figure 4 shows the change trend of GEE of countries from 2000 to 2022.

Table 1. Construction of the Green Economic Efficiency Indicator.

Type	Index	Specific Content
Investment	Energy input	Total energy consumption (kilograms of oil equivalent)
	Labour input	Total labour force
	capital investment	Gross fixed capital formation (constant 2015 US dollars)
Desirable output	Economic output	GDP (constant 2015 US dollars)
	Environmental optimization	Forest coverage rate (as a percentage of land area)
Undesirable output	Carbon dioxide	Total carbon dioxide (CO_2) emissions (excluding LULUCF, million tons of CO_2 equivalent)
	Methane	Total methane (CH_4) emissions (excluding LULUCF, million tons of CO_2 equivalent)
	Nitrous oxide	Total emissions of nitrous oxide (N_2O) (excluding LULUCF, million tons of CO_2equivalent)

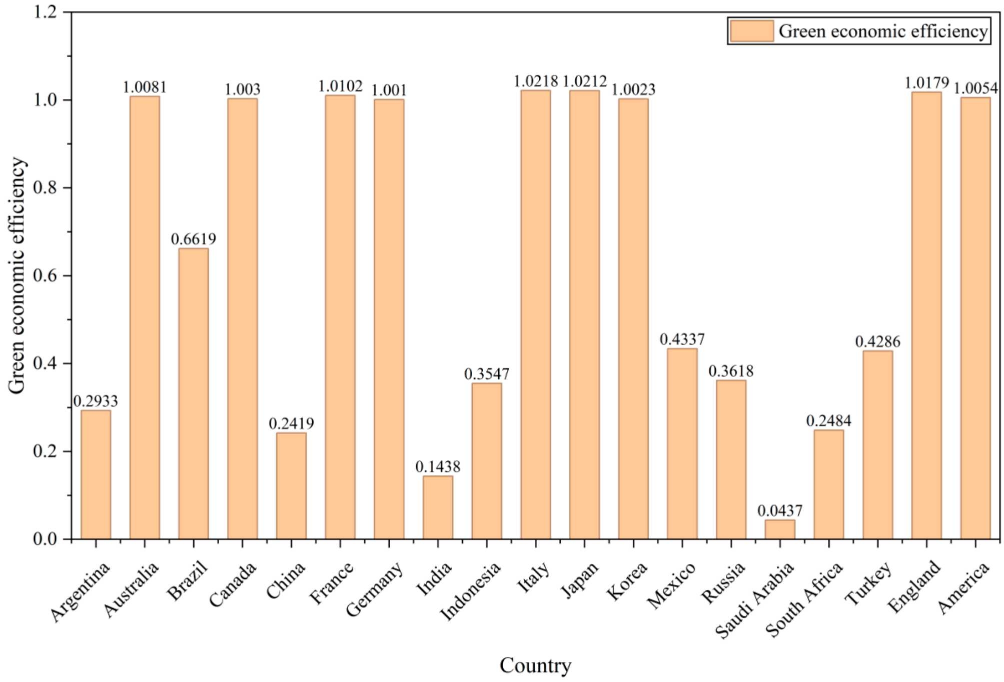

Figure 3. Green Economic Efficiency of G20 Countries in 2022.

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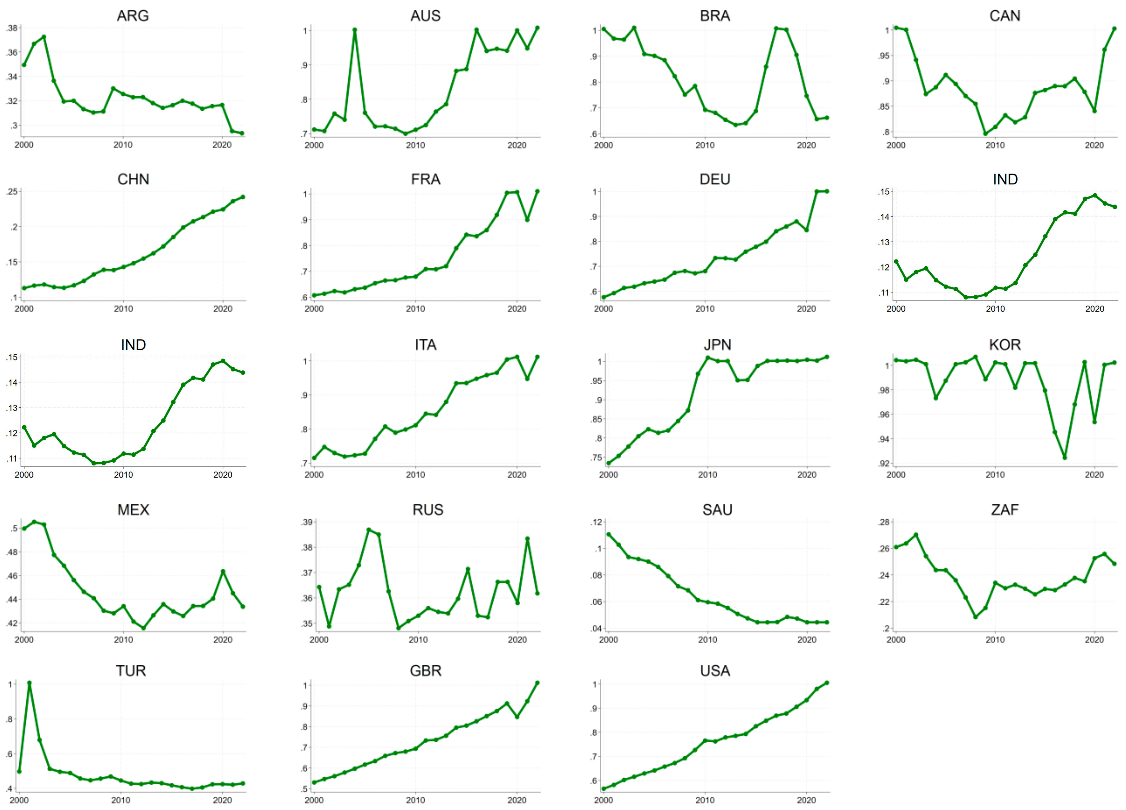

Figure 4. Green Economic Efficiency Trends in G20 Countries.

3.2. Control Variables

In order to control other factors that may affect the efficiency of green economy, this paper adds a series of control variables into the model. The level of economic development (AGDP) is measured by GDP per capita. The more developed the economy is, the more capital and technical resources the country usually has for clean production and energy efficiency improvement, and the better the environmental performance may be. Population density (PD) is expressed as the number of people per square kilometre. On the one hand, population density may lead to increased pressure on resources and environment, and on the other hand, it may improve the utilisation efficiency of infrastructure. The direction of its impact on the efficiency of green economy is uncertain. Macroeconomic stability is measured by the inflation rate (INF, expressed as the annual increase in the GDP deflator). Large swings in inflation can discourage investment in long-horizon green projects, whereas a more stable inflation environment tends to support the development of the green economy. In terms of trade openness (TRA), it is measured by the proportion of total trade (the sum of imports and exports) to GDP. The increase in trade volume can promote green efficiency through technology diffusion and international competition, but its impact may vary from country to country. The urbanisation rate (UP) is measured by the proportion of urban population to the total population. The urbanisation process is usually accompanied by the intensification of infrastructure and the improvement of resource allocation efficiency, and strengthens the public's awareness of environmental.

3.3. Mechanism Variables

In addition to the direct effect, this paper further examines the impact of geopolitical risk on green economic efficiency through the mediating effect of energy structure and the moderating effect of foreign direct investment.

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3.3.1. Mediating Variables: Fossil Fuel Energy Consumption Ratio (FFEC) and Exchange Rate (ER)

The fossil fuel energy consumption ratio (FFEC) is expressed as the percentage of fossil fuel energy consumption in primary energy consumption, reflecting the degree of cleanliness of a country's energy structure. Geopolitical tensions may prompt countries to adjust their energy mix by disrupting energy supply chains or energy price fluctuations. For example, high geopolitical risk may lead a country to rely more on its own fossil energy to ensure energy security, thereby increasing the proportion of fossil energy; in some cases, it may also promote the transformation of energy autonomy. However, over-reliance on fossil fuels is generally not conducive to improving the efficiency of the green economy, as its high carbon emissions will reduce ecological efficiency.

The exchange rate (ER) is expressed as the annual average exchange rate of the local currency against the US dollar (US dollar / local currency unit). ER reflects the stability of a country's currency value and the cost of international trade. Rising geopolitical risks often trigger the transfer of capital to safe-haven assets, causing large fluctuations in exchange rates, which directly impact the import costs of clean technologies and the financing capacity of green projects denominated in foreign currencies. For example, the depreciation of the local currency will raise the import prices of green energy-saving equipment and other products, and inhibit the willingness of enterprises to invest in green projects; drastic exchange rate fluctuations will also increase the repayment risk of cross-border green bonds and reduce the efficiency of resource allocation. Unstable exchange rates are generally not conducive to improving the efficiency of the green economy, because green technology innovation and promotion depend on a stable funding environment.

3.3.2. Moderating Variables

Foreign direct investment (FDI) is measured by net inflows (current US$). Foreign capital is not only a source of funds, but also an important channel for the diffusion of technology and the introduction of management experience. This paper argues that FDI may affect the relationship between geopolitical risk and green efficiency. On the one hand, the technology spillover effect brought by FDI helps to improve energy utilisation efficiency and environmental governance level, and to a certain extent, it alleviates the negative impact of geopolitical uncertainty on green development. On the other hand, geopolitical conflicts often hit investor confidence and inhibit foreign capital inflows, thus amplifying the adverse impact of geopolitical risks.

Table 2. Variable Definition.

Variable Types	**Variable Name**	**Variable Symbol**	**Variable Definition**
Independent variable	Geopolitical Risk Historical Index	GPRH	The geopolitical risk index (historical index) constructed by Caldara and Iacoviello (2022) is adopted to measure the geopolitical uncertainty of a country. The larger the index, the higher the risk.
Dependent variable	Green economic efficiency	GEE	The green economic efficiency index calculated based on the Super-SBM model, which integrates input factors, desirable outputs and undesirable outputs, indicates a higher green economic efficiency with a larger value.
Control variable	Per capita GDP	AGDP	Per capita GDP (in 2015 US dollars) is used to indicate the economic development level of a country.
	Population density	PD	Population density (people per square kilometer) reflects the degree of population spatial concentration.

	GDP deflator inflation rate	INF	The GDP deflator inflation rate (annual percentage) reflects the macro price level and economic stability.
	Trade volume	TRA	Trade openness, measured by the ratio of total imports and exports to GDP.
	The proportion of urban population to the total population	UP	The level of urbanisation is measured by the proportion of urban population to the total population.
	Total labour force participation rate	TLFP	Labour force participation rate, measured by the labour force participation rate of the population aged 15 and above (simulated ILO estimates).
Mediating variable	The percentage of fossil fuel energy consumption in total energy consumption	FFEC	The percentage of fossil fuel energy consumption in total energy consumption is used to indicate the degree of dependence on fossil energy in the energy structure.
	Exchange rate	ER	The annual average of the monthly exchange rate (US dollar/local currency unit).
Moderating variable	Net inflow of foreign direct investment	FDI	Net inflow of foreign direct investment (BOP basis, current US dollars) is used to measure the scale of foreign capital inflows.

3.4. Model

3.4.1. Main Regression Model

To investigate the impact of geopolitical risks on green economic efficiency (GEE) in G20 countries, we employ the following benchmark regression model:

$$GEE_{i,t} = \alpha_0 + \alpha_1 GPRH_{i,t} + \sum_{j=1} \beta_j Controls_{i,t} + \varepsilon_{i,t} \quad (1)$$

In the above model, i and t denote location and year, respectively. GEE represents green economic efficiency in a given year, while GPRH captures geopolitical risk. α_0 denotes the constant term, and $\varepsilon_{i,t}$ is the error term, $Controls_{i,t}$ refers to a set of control variables. Equation (1) incorporates both time and region fixed effects.

3.4.2. Mechanism Testing

As previously discussed, foreign direct investment and fossil fuel energy consumption may serve as key mechanisms through which geopolitical risks influence green economic efficiency. To examine these pathways, this study employs both mediating and moderating effect analyses. The corresponding econometric models are specified as follows

$$EEFC_{i,t} = \beta_0 + \beta_1 GFF_{i,t} + \beta_2 Controls_{i,t} + \varepsilon_{i,t} \quad (2)$$

$$ER_{i,t} = \beta_0 + \beta_1 GFF_{i,t} + \beta_2 Controls_{i,t} + \varepsilon_{i,t} \quad (3)$$

$$GEE_{i,t} = \gamma_0 + \gamma_1 GPRH_{i,t} + \gamma_2 FDI \times GPRH_{i,t} + \gamma_3 Controls_{i,t} + \varepsilon_{i,t} \quad (4)$$

4. Empirical Results

4.1. Descriptive Statistical Analysis

Table 3 reports the descriptive statistical results of the variables involved in the regression analysis. According to the information in Table 3, the average value of green economic efficiency

(GEE) is about 0.58, indicating that the overall green economic efficiency of the sample countries is at a medium level, and the difference between the minimum and maximum values is large, indicating that there are significant differences in the level of green economic efficiency among different countries. Geopolitical risk (GPRH) averages about 0.40. Its relatively large standard deviation and wide range indicate substantial cross-country variation over the sample period, in line with the rise in regional conflicts and terrorist incidents worldwide in recent years. Higher geopolitical risks often indicate a decline in investment and employment, and increase the risk of economic downturn. This phenomenon shows that geopolitical turmoil may weaken investment confidence and other channels, which is not conducive to the increase of green economic input and the improvement of efficiency.

As for the control variables, the mean of AGDP (GDP per capita) is relatively high, indicating that the sample includes both rich economies and underdeveloped countries; the mean and quartile difference of PD (population density) indicate that there are obvious differences in the population density of countries. The mean of INF (inflation rate) is moderate but the standard deviation is large, which means that the macroeconomic stability of different countries varies greatly. The mean of TRA (trade openness) shows that the sample countries have a moderate dependence on foreign trade, and the maximum value is close to or even exceeds 100%, which means that some economies are highly dependent on international trade. The mean of UP (urbanisation rate) is relatively high, that is, more than half of the population lives in cities, and the urbanisation level of countries varies significantly. The mean of TLFP (total labour force participation rate) is moderate, indicating that the overall labour force participation rate is moderate. In general, descriptive statistics show that there is sufficient discreteness between variables, which provides a reliable basis for subsequent regression analysis.

Table 3. Descriptive Statistical Analysis.

Variable	N	Mean	SD	p25	p75	Min	Max
GEE	437	0.580	0.306	0.326	0.860	0.0444	1.012
GPRH	437	0.397	0.651	0.0787	0.420	0.0142	3.776
AGDP	437	0.236	0.176	0.0833	0.380	0.00890	0.598
PD	437	0.141	0.149	0.0162	0.235	0.00260	0.529
INF	437	0.0613	0.0852	0.0156	0.0742	-0.0232	0.494
TRA	437	0.0517	0.0170	0.0402	0.0622	0.0219	0.0961
UP	437	0.736	0.151	0.684	0.823	0.289	0.919
TLFP	437	0.603	0.0582	0.575	0.644	0.469	0.729
FFEC	437	82.21	12.26	78.28	89.94	47.41	100
FDI1	437	0.0524	0.0767	0.00900	0.0569	-0.0171	0.381

4.2. Main Regression

In order to test the impact of geopolitical risk on green economic efficiency, this paper first conducted a benchmark regression analysis. Table 4 reports the main regression results of the impact of geopolitical risk on green economic efficiency. Column (1) is the regression result containing only the core explanatory variable GPRH and the double fixed effect, and column (2) adds all the control variables to form a complete model. According to the regression results, the GPRH coefficient is negative and significant at the 1% statistical level regardless of whether the control variables and fixed effects are added. The coefficients are -0.0885 and -0.1001, respectively, indicating that the increase in geopolitical risk will significantly reduce green economic efficiency. Therefore, the hypothesis H1 is confirmed. It can be seen that the increasing geopolitical uncertainty does constitute an obstacle to the green transformation process of the world's major economies.

Further examination of the estimated coefficients of the control variables in Table 4 reveals that the impact direction of most variables is consistent with expectations. In column (2), the AGDP coefficient is positive and significant, meaning that the higher the level of economic development, the higher the green economic efficiency of the country; the PD coefficient is positive and significant, indicating that the green economic efficiency of countries with higher population density is relatively

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higher; the INF coefficient is negative and significant, indicating that the decline in macroeconomic stability (i.e., the rise in inflation) is not conducive to green economic efficiency, which may be because high inflation weakens the ability to invest in environmental protection. The coefficient of TRA is not significant, indicating that the impact of trade on green efficiency varies from country to country; the UP coefficient is positive and significant, indicating that the increase in urbanisation can bring about economies of scale and more complete environmental protection infrastructure, thereby helping to improve green economic efficiency; the TLFP (total labour force participation rate) coefficient is negative and significant, which may mean that economies with high labour force participation are more dependent on traditional labour-intensive industries, which to some extent weakens the potential for improving green economic efficiency.

Table 4. Benchmark Regression Results.

	(1)	**(2)**
	GEE	GEE
GPRH	-0.0885***	-0.1001***
	(-4.0933)	(-5.9697)
AGDP		0.6541***
		(7.1214)
PD		0.6020***
		(6.6664)
INF		-0.3337***
		(-2.9764)
TRA		0.1543
		(0.2499)
UP		0.3782***
		(3.0634)
TLFP		-0.7172***
		(-3.7258)
_cons	0.6149***	0.5467***
	(44.4099)	(3.6101)
Time fixed effect	YES	YES
Location fixed effect	YES	YES
N	437	437
r2	0.0120	0.7634

t statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.3. Analysis of Mechanism Effect

4.3.1. Moderating Effect

We first examined the moderating effect of the interaction between foreign direct investment (FDI) and geopolitical risk (GPRH) on green economic efficiency (GEE). The regression results in column (1) show that the coefficient of the FDI*GPRH interaction term is positive and significant after its introduction, indicating that FDI has a significant moderating effect. In countries with higher levels of FDI inflows, the adverse impact of geopolitical risk on green economic efficiency is significantly reduced, and our hypothesis H2 is proved. Specifically, high levels of foreign direct investment can offset the negative impact of geopolitical risk to a certain extent, help the host country with the capital and technology it needs, and enhance economic resilience, thereby alleviating the inhibitory effect of geopolitical uncertainty on green economic efficiency.

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4.3.2. Test of the Mediating Effect

Columns (2) to (5) of Table 5 show the regression results of the mediating effect. First, column (2) shows the impact of geopolitical risk (GPRH) on the fossil fuel energy consumption rate (FFEC). The results show that the impact of GPRH on FFEC is positive and significant at the 1% statistical level, and its coefficient is 3.7992, indicating that the rise of geopolitical risk will significantly increase the proportion of fossil fuel energy consumption in the energy structure. Column (3) includes FFEC and GPRH in the regression of GEE at the same time. The results show that the impact of the two on GEE is significant at the 1% statistical level. The coefficient of FFEC is negative, indicating that the increase in fossil energy consumption will reduce the efficiency of the green economy. Geopolitical risks reduce the efficiency of the green economy by increasing the country's fossil energy consumption. Hypothesis H3 is confirmed.

Table 5. Mediation Analysis Results.

	(1)	(2)	(3)	(4)	(5)
	GEE	FFEC	GEE	ER	GEE
FFEC			-0.0078***		
			(-12.3030)		
ER					0.1651***
					(4.3399)
FDI	-1.1293***				
	(-5.9505)				
FDI*GPRH	0.4872***				
	(3.9063)				
GPRH	-0.1391***	3.7992***	-0.0704***	-0.0524**	-0.0914***
	(-5.2547)	(3.3767)	(-4.8569)	(-2.4356)	(-5.5324)
AGDP	0.7152***	3.3390	0.6802***	-0.1695	0.6821***
	(7.6125)	(0.5416)	(8.6801)	(-1.4366)	(7.5700)
PD	0.6463***	-13.7164**	0.4949***	0.1221	0.5819***
	(7.3721)	(-2.2628)	(6.3862)	(1.0521)	(6.5760)
INF	-0.4095***	32.6990***	-0.0784	0.1934	-0.3656***
	(-3.7598)	(4.3452)	(-0.8018)	(1.3430)	(-3.3255)
TRA	-0.1457	81.4457*	0.7900	-1.0652	0.3302
	(-0.2385)	(1.9644)	(1.4927)	(-1.3424)	(0.5451)
UP	0.2408*	5.3449	0.4199***	-1.0892***	0.5580***
	(1.8735)	(0.6450)	(3.9864)	(-6.8684)	(4.3695)
TLFP	-0.2332	-39.4463***	-1.0251***	0.0237	-0.7212***
	(-1.1373)	(-3.0526)	(-6.1729)	(0.0958)	(-3.8284)
_cons	0.4044***	95.4721***	1.2919***	0.9398***	0.3916**
	(2.6035)	(9.3915)	(9.0566)	(4.8308)	(2.5688)
Time fixed effect	YES	YES	YES	YES	YES
Location fixed effect	YES	YES	YES	YES	YES
N	437	437	437	437	437
R2	0.7827	0.3346	0.8283	0.4207	0.7740

t statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

In addition to the energy structure channel, exchange rate changes are also an important way for geopolitical risks to affect the efficiency of the green economy. Column (4) shows the impact of geopolitical risk (GPRH) on the exchange rate (ER). The results show that the impact of GPRH on ER is negative and significant at the 5% statistical level, indicating that when geopolitical risk rises, the exchange rate of the local currency shows a significant downward trend. Column (5) includes both

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ER and GPRH in the regression of GEE, and the results show that both are significantly correlated at the 1% statistical level. It can be seen that the rise of geopolitical risks will weaken the national green economic efficiency by disrupting the exchange rate. The decline of the exchange rate increases the uncertainty of the introduction and investment of green technology, which to some extent amplifies the negative impact of GPRH on GEE. This finding is consistent with hypothesis H4, which states that geopolitical risks cause currency depreciation and thus reduce the green economic efficiency of the country.

4.4. Heterogeneity Analysis

Although the benchmark regression reveals that the rise of geopolitical risk will significantly reduce the green economic efficiency of the overall G20 sample, the strength and significance of this relationship may vary due to the different stages of national development. There are systematic differences in the development level, technical capabilities, energy structure and resilience to external shocks of different countries, which may lead to different characteristics of the impact of geopolitical risks on green economic efficiency. With reference to the classification standards of the International Monetary Fund (IMF), we divide the G20 countries into developed countries (including the United States, Japan, Germany, the United Kingdom, France, Italy, Canada, Australia, and South Korea) and emerging economies (including China, India, Brazil, Russia, Indonesia, Mexico, Argentina, Turkey, Saudi Arabia, and South Africa), and conduct regression tests separately. Table 6 shows the regression results of different sample groups.

Table 6. Heterogeneity Analysis Results.

	(1)	**(2)**
	GEE	GEE
GPRH	-0.0307***	-0.0706
	(-3.1351)	(-1.3817)
AGDP	0.0053	-6.1721***
	(0.0327)	(-8.0155)
PD	0.1455*	0.7349
	(1.9733)	(1.0717)
INF	0.5877*	-0.0130
	(1.6546)	(-0.1067)
TRA	2.2829***	-2.9455***
	(4.2390)	(-3.0826)
UP	0.8061***	0.2260
	(3.9205)	(0.5496)
TLFP	-1.7735***	-0.1075
	(-5.8634)	(-0.2844)
_cons	1.1051***	0.8982*
	(10.5305)	(1.8825)
Time fixed effect	YES	YES
Location fixed effect	YES	YES
N	207	230
R2	0.8189	0.6884

t statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

The results in column (1) show the results of the developed countries group. The geopolitical risk has a significant negative impact on the green economic efficiency, with a coefficient of -0.0307, which is significant at the 1% statistical level. This result is consistent with the institutional theory. The increase of geopolitical risk increases the uncertainty of regional risk, which causes certain obstacles to the promotion of policies. The commitments made by developed countries in environmental protection and climate action may change due to the increase of uncertainty.

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In contrast, the coefficient of GPRH is negative but insignificant in the sample of emerging economies shown in column (2). This indicates that the direct impact of geopolitical risk on green economic efficiency is not obvious in emerging market countries, reflecting the significant heterogeneity between developed and emerging economies. This difference may stem from the differences between the two types of economies in terms of development stage, industrial structure, institutional completeness, and environmental governance capabilities. Therefore, the transmission path and intensity of geopolitical risks affecting the efficiency of the green economy vary depending on the characteristics of the country. Therefore, policy-making should take this heterogeneity into account: developed economies should attach importance to maintaining geopolitical stability to ensure the implementation of their environmental commitments, while emerging economies should focus on improving institutional construction and enhancing their resilience to external shocks.

4.5. Robustness Test

To ensure the reliability of the above conclusions, we designed a number of robustness tests.

4.5.1. Changing the Calculation Method of Explanatory Variables

We first changed the measurement method of the core explanatory variables, recalculated the geopolitical risk index (GPRH) using the geometric mean method, and used the new index for regression testing. The results are shown in column (1) of Table 7. After changing the measurement method, the coefficient of GPRH is still negative and significant at the 1% level, and the conclusion is consistent with the benchmark regression. This shows that the research conclusion is not affected by the change of the measurement method of the explanatory variable, and effectively excludes the interference of potential measurement errors.

Table 7. Robustness Tests.

	(1)	(2)	(3)	(4)	(5)
	GEE	GEE	GEE	GEE(q25)	GEE(q75)
GPRH1	-0.1065***				
	(-5.9181)				
GPRH		-0.1332***	-0.0978***	-0.0692***	-0.0714***
		(-4.5733)	(-6.3414)	(-6.7790)	(-4.8276)
AGDP	0.6568***	0.4398**	0.8063***	0.7658***	0.7526***
	(7.1402)	(2.5856)	(9.5993)	(8.4644)	(9.8690)
PD	0.6024***	0.7339***	0.6637***	0.5808***	0.6059***
	(6.6611)	(4.7666)	(7.7680)	(9.3814)	(7.3660)
INF	-0.3307***	0.4063*	-0.9098***	-0.3097***	-0.2536
	(-2.9467)	(1.8473)	(-9.0225)	(-4.3098)	(-1.1955)
TRA	0.1408	-0.2959	-1.6763***	1.6168***	0.5330
	(0.2270)	(-0.2519)	(-2.9188)	(3.5000)	(0.8709)
UP	0.3729***	0.3404*	0.5630***	0.4965***	0.1018
	(3.0147)	(1.8396)	(4.3058)	(5.0572)	(0.7924)
TLFP	-0.7154***	-0.6290*	-0.9667***	-1.2924***	-0.7607***
	(-3.7123)	(-1.8783)	(-4.9401)	(-8.4574)	(-3.1388)
_cons	0.5490***	0.5381**	0.6399***	0.6911***	0.9425***
	(3.6212)	(2.2163)	(4.1150)	(6.1545)	(4.3490)
Time fixed effect	YES	YES	YES	YES	YES
Location fixed effect	YES	YES	YES	YES	YES
N	437	190	247	437	437
R2	0.7630	0.6930	0.9001		
Pseudo R2				0.6804	0.5494

t statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

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4.5.2. Regression by Time Period

Furthermore, considering that the phased changes in the macro environment may have an impact on the results, we divided the sample period into two stages, 2000-2010 and 2010-2022, for regression. Column (2) of Table 7 shows the regression results for 2000-2010. The coefficient of GPRH is negative and significant at the 1% statistical level, indicating that geopolitical risks have had an adverse impact on green economic efficiency in the earlier period. After 2010, the global geopolitical tension further intensified (for example, the number of regional conflicts increased and the game between major powers was strengthened). Column (3) shows the regression results from 2010 to 2022. The results show that the coefficient of GPRH is significantly negative at the 1% statistical level in this stage, and the absolute value of the coefficient is slightly larger than that in the previous stage, which indicates that the negative impact of geopolitical risk on the efficiency of green economy is more prominent in the past decade. The above time-period test shows that the conclusions of this study remain robust under different international environments and time spans, and further supports the research hypothesis.

4.5.3. Replacing the Regression Model

In order to test the robustness of the model results, this paper uses the method of replacing the regression model to further analyse the regression relationship. We selected the 25% and 75% quantiles of the explained variable GEE for regression estimation to examine whether the impact of the explanatory variables was consistent at different conditional distribution levels. Columns (4) and (5) of Table 7 report the regression results of the 25% quantile and the 75% quantile, respectively. The estimation results under each quantile are basically consistent with the benchmark regression, indicating that the core explanatory variable of geopolitical risk maintains a significant negative impact in countries with low and high green economic efficiency. Specifically, the coefficient of GPRH is negative and significant at the 1% level in the regression of both the 25% quantile (low efficiency group) and the 75% quantile (high efficiency group). There is no difference in the direction of the impact of geopolitical risk shocks on countries with high green economic efficiency and countries with low green economic efficiency, both of which show a decline in green economic efficiency, further confirming the robustness of the benchmark conclusion.

4.6. Endogeneity Test

If there is an endogeneity problem between geopolitical risk (GPRH) and green economic efficiency (GEE), it will affect the empirical results of this study. Therefore, this paper uses the instrumental variable method and the lagged variable method to conduct the endogeneity test to solve the potential endogeneity problem.

First, in terms of instrumental variables, we used the dummy variable of "whether it is a permanent member of the UN Security Council" as the instrumental variable (IV). For the countries in the research sample, if it is a permanent member of the UN Security Council, the value of IV is 1, otherwise IV=0. The members of the UN Security Council have a prominent position in international politics. This identity is desirable to affect the level of geopolitical risk faced by the country, but it will not directly affect the country's green economic efficiency through other means. Therefore, this variable can be regarded as a reasonable instrumental variable to identify the causal effect of GPRH on GEE.

Columns 1 and 2 of Table 8 show the regression results of the endogeneity test using the instrumental variable method. Column 1 shows the regression results of the first stage. The results show that the instrumental variable is significantly related to GPRH, and its F value is greater than 10, which passes the weak instrumental variable test and verifies the effectiveness of our instrumental variable. In addition, the coefficient of IV is significantly positively correlated, indicating that the five permanent members of the Security Council generally bear higher geopolitical risks. Column 2 shows the regression results of the second stage. In the second stage regression, we replaced the original

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variable with the GPRH_hat predicted in the first stage. The results show that GPRH_hat is negatively correlated at the 1% statistical level, indicating that after correcting the potential endogeneity, the inhibitory effect of geopolitical risk on green economic efficiency is still valid, which is consistent with the benchmark regression conclusion, indicating that our main regression results are robust.

Secondly, considering the possible lag effect of the impact of geopolitical risk, we lagged the control variables and GPRH by one period respectively, and conducted regression analysis again. Columns (3) and (4) of Table 7 report the regression results of the control variables and the explanatory variables lagged by one period respectively. The results show that after the lag of one period, the coefficient of GPRH and its lag of one period is still negative and negatively correlated at the 1% statistical level, which means that the adverse impact of geopolitical risk on the efficiency of green economy is continuous and robust in the time dimension.

Table 8. Endogeneity Tests.

	(1)	(2)	(3)	(4)
	GPRH	GEE	GEE	GEE
IV	0.8545***			
	(15.3283)			
GPRH_hat		-0.2143***		
		(-8.0233)		
GPRH			-0.1020***	
			(-6.2340)	
GPRH_lag				-0.1115***
				(-6.4910)
AGDP	0.7013***	0.7358***	0.6870***	0.6739***
	(3.2550)	(8.1526)	(7.5274)	(7.4912)
PD	1.2121***	0.7680***	0.6422***	0.6294***
	(5.8746)	(8.2809)	(7.1809)	(7.0532)
INF	0.4321	-0.2929***	-0.2989**	-0.4358***
	(1.6314)	(-2.6903)	(-2.5707)	(-3.8065)
TRA	-10.1102***	-1.7461**	-0.1710	-0.3129
	(-7.3711)	(-2.5140)	(-0.2762)	(-0.5114)
UP	-0.7914***	0.2393*	0.3800***	0.3857***
	(-2.7350)	(1.9561)	(3.1364)	(3.1280)
TLFP	-2.2469***	-0.5397***	-0.6659***	-0.7372***
	(-4.3638)	(-2.8499)	(-3.4869)	(-3.9180)
_cons	2.2690***	0.6404***	0.5187***	0.5759***
	(6.1472)	(4.3351)	(3.4800)	(3.8539)
Time fixed effect	YES	YES	YES	YES
Location fixed effect	YES	YES	YES	YES
N	437	437	418	418
R2	0.7069	0.7780	0.7793	0.7838

t statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5. Conclusions

5.1. Results

This paper empirically tests the impact of geopolitical risk on green economic efficiency and its mechanism of action using panel data from G20 countries. The main conclusions are as follows: First, geopolitical risk significantly reduces green economic efficiency, and this conclusion still holds after a series of robustness tests. Second, the results of the mechanism analysis show that geopolitical risk indirectly weakens green economic efficiency through two channels: one is to lead to a higher

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proportion of fossil energy consumption, thereby hindering the transformation of the energy structure to renewable energy; the other is the depreciation of the exchange rate, which increases the uncertainty of trade and investment, thereby amplifying the adverse impact on green economic efficiency. Both of these mechanisms are statistically significant. In addition, in terms of the moderating effect, foreign direct investment (FDI) played a buffering role. In countries with high levels of FDI inflows, the inhibitory effect of geopolitical risk on green economic efficiency was significantly weakened. FDI helps to introduce advanced capital and technology, enhance economic resilience, and thus partially offset the impact of geopolitical uncertainty. Finally, the results of the heterogeneity analysis show that the impact on countries at different stages of development is different: in developed economies, the negative impact of geopolitical risk on green economic efficiency is more significant; while in emerging economies, the effect is not statistically significant, indicating that the latter may have different buffering mechanisms or impact paths when geopolitical risks intensify. The above conclusions still hold after a variety of robustness

5.2. Policy Recommendations

First, all countries should maintain peaceful and stable international cooperation relations and strive to alleviate the adverse impact of geopolitical tensions on the green transition. Developed countries should firmly fulfil their environmental and climate commitments when facing geopolitical risks, and avoid shaking long-term emission reduction and green transformation policies due to short-term uncertainties. Emerging economies should focus on improving the quality of institutions and policy continuity to enhance their adaptability and resilience to external shocks.

Second, we should actively promote the transformation of the energy structure, reduce excessive dependence on fossil energy, and improve energy autonomy in geopolitical turmoil by developing renewable energy, so as to reduce the constraints of geopolitical risks on the efficiency of the green economy from the source.

Thirdly, countries should encourage and utilise foreign direct investment in the green sector, introduce advanced technologies and funds, give full play to the positive role of FDI in buffering geopolitical shocks, and ensure that the diffusion of green technologies and the development of domestic green industries are not interrupted by external risks. Finally, maintaining macroeconomic and financial market stability is also a key measure. Policymakers should improve emergency mechanisms to stabilise exchange rates and investment expectations, and provide a stable external environment for green technology innovation and long-term carbon reduction projects.

5.3. Limitation

We acknowledge that this study still has some limitations. For example, there are limitations in the sample range and research design. The sample of this study comes from the G20 countries. Subsequent studies can extend the scope of analysis to more developing countries or a longer time span to examine whether the impact of geopolitical risks on green development is consistent or different at the national and regional levels. Future work could examine micro-level transmission channels and other potential drivers—such as domestic political stability and the characteristics of regional conflicts—to deepen understanding of how geopolitical uncertainty relates to green economic efficiency. Overall, our findings suggest that the international geopolitical environment has a measurable influence on green, high-quality development, and they offer empirical evidence that may inform policies aimed at advancing green transformation and sustainable development under external turbulence.

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