



The interaction of public–private partnership investment in energy and geopolitical risk in influencing carbon dioxide emissions in E7 countries

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Abstract

The recent geopolitical tensions are delaying government efforts to fight environmental degradation. This paper aims to examine how public–private partnership investment in energy reduces carbon emissions in E7 countries, a group that has witnessed rapid carbon emissions and frequent geopolitical risks. Utilizing the panel data of E7 countries from 1995 to 2019 and the recently developed panel quantile regression method, the paper reveals that while public–private partnership investment in energy serves as a solution for mitigating carbon emissions, geopolitical risk significantly escalates carbon emissions. In addition, geopolitical instability constraints the beneficial impact of public–private partnership investment in energy on carbon emissions reduction targets. The study also validates the existence of the Environmental Kuznets Curve hypothesis as well as the favorable roles of renewable energy, urbanization, and international trade in curbing carbon emissions. Based on the findings, the E7 governments are recommended to either ease the level of geopolitical insecurity or improve the strategies that a country responds to the geopolitical tension and manages its public–private partnership investment in energy.

Keywords Carbon emissions · Geopolitical risk · International trade · Public–private partnership investment · Green energy · Urbanization

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1 Introduction

Global warming, climate change, and environmental deprivation have been the most debatable concerns nowadays. These issues have underscored the need for the regulation of carbon emissions, as the main contributor of greenhouse gas emissions and the primary cause of global warming, climate change, and human diseases related to air pollution. While mitigating carbon emissions is imperative to achieve sustainable development, the data show the endless growth of global carbon emissions over the past two decades. Specifically, carbon emissions have increased by 1.89% per annum over the period 2001–2021, calling for conclusive policy actions to regulate its level effectively. Against this context, policymakers and researchers have engaged relentlessly in exploring the driving forces of growing carbon emissions and have detailed various determinants, ranging from economic, social, and technological, to political factors. Among these factors, two phenomena that have recently received much attention are Public–private partnership investment in energy (hereafter PPPIE) and geopolitical risk (hereafter GPR).

Investment in green energy projects is one of the most essential ways to achieve challenging environmental goals. However, as environmental quality is a public good, green energy projects, which have the characteristics of high up-front costs, long operating cycles, and high investment risk, have not received enough resources to develop to an economically efficient scale (Shahbaz et al., 2020). Moreover, the actions by governments to remove barriers to the development of private projects sometimes fail to attain the initial targets. Empirical evidence points out that most energy efficiency programs have not led to the desired outcomes and are not cost-effective (Arimura et al., 2012; Gillingham and Palmer, 2014). In this circumstance, the PPPIE may appear as a valid alternative to traditional public policies. Public–private partnership investment (hereafter PPPIE) refers to project-based collaboration among governments, for-profit firms and/or non-profit organizations. This form of collaboration allows the obliging parties to obtain more promising outcomes as compared to what could be expected if they perform alone. PPPIE overcomes the shrinkage of available public funds and makes it possible for the development of energy infrastructure in countries with high economic growth. The risk-sharing framework under the PPPIE allows cost minimization and market reforms while facilitating capacity building and knowledge transfer during the development and operation of energy projects. This, in turn, connects the project outcomes to sustainable development targets (Cheng et al., 2021; Yang et al., 2022). It explains how PPPIE model is theoretically linked to environmental sustainability (Buso & Stenger, 2018) as an efficient strategy to mitigate pollution emissions (Li & Ullah, 2022). The PPPIE model has been applied in many countries and its success in European Union is one of the sources of inspiration for other countries in the race for sustainable development. Specifically, the European Climate, Infrastructure and Environment Executive Agency (CINEA) which operates under the European Commission manages a public dashboard to provide information about all the projects related to climate and environment, energy, transport, mobility, and maritime. Those programs are entrusted by the European Commission and open to everyone to facilitate the necessary private and public investment. Besides the introduction of legal and institutional frameworks, funding for energy sustainability projects under the PPPIE is believed to successfully promote Europe's energy transition to a low-carbon society (European Commission website, n.d). However, in the empirical aspect, most existing literature indicates the harmful impact of PPPIE on environmental quality in selected countries and regions (Cheng et al., 2021; Gao et al., 2022; Gultom, 2021; Raza et al., 2021; Shahbaz et al., 2020), urging the researchers

to provide new insights on the reasons of such inefficiency. In this study, we argue that the inconsistent findings about the environmental impacts of PPPIE imply the existence of moderators in the PPPIE–environmental quality linkage which either fluctuates across periods or differs among countries.

Risks connected to terrorist attacks, war-related incidents, and international tensions are considered to be geopolitical risks. This could unavoidably worsen international relations and jeopardize national peace on both a national and global scale (Caldara and Iacoviello, 2022; Ghosh, 2022). This salient risk can affect the economic outlooks and socioeconomic decisions of relevant stakeholders, ranging from households, investors, and enterprises to governments and international organizations (Caldara & Iacoviello, 2018; Ghosh, 2022). GPR not only has negative effects on socioeconomic activities, but it also adversely influences environmental quality. Anser et al. (2021) theoretically suggest two opposing channels that link geopolitical uncertainty and environmental quality. The so-called “escalating effect” proposes that GPR restrains environmentally friendly engagements such as research and development activities, innovations, and the production and consumption of clean energies. Additionally, the geopolitical uncertainty could revert the energy transition process towards traditional and cheaper energy resources, which generate more pollutants. Concerning another indirect avenue, the business and financial deterioration due to high GPR forces enterprises to postpone or abandon their commitments to protecting the environment. However, the “mitigating effect” channel recommends a contrasting effect. The slower economic growth due to high uncertainties leads to the contraction of energy consumption, curtailing carbon emissions, especially those emitted from non-renewable energies. Moreover, a high level of geopolitical instability may drive capital flows and foreign direct investments away from emerging countries, then, reducing energy demand in these countries. Overall, GPR may either hold back or accelerate carbon emissions. Given this theoretical basis, the empirical studies indicate that GPR can either improve or deteriorate environmental quality (Adams et al., 2020; Anser et al., 2021; Bashir et al., 2023; Hashmi et al., 2022; Husnain et al., 2022). The findings depend largely on the proxies and measurements for GPR, e.g. terrorism, war, and political instability.

The theoretical framework of geopolitical risks reveals two key issues. First, the environmental impact of geopolitical risks is still inconclusive. Second, geopolitical risks, given either its “escalating effect” or “mitigating effect” could interfere with the extent to which PPPIE is geared towards and supports environmental sustainability goals. PPPIE, by its nature, is merely an investment which is uncertain regarding its outcomes and how the outcomes could make a significant improvement to the environmental quality as supposed. Because of the long-term nature of environmental issues and the complexity of PPPIE, the uncertainties caused by GPR and other political factors could dampen or even revert the beneficial impacts of PPPIE on the environment (Fredriksson & Wollscheid, 2013; Galilea & Medda, 2010). In this study, we propose at least four channels through which the environmental benefits of PPPIE may be hindered by the rise of geographical risk. First, either political risks or economic risks caused by geopolitical tension may activate rent-seeking behaviors among both authorities and economic actors that distort the decision-making of PPPIE (Drezner, 2011; Galtung, 1967; Lektzian, 2007). This could compound the damage to the deployment and results of the projects (e.g. the choice of technology, materials, project management, and risk sharing) given the inflexibility of the public–private partnership (Mota & Moreira, 2015). Second, uncertainty caused by geopolitical risks may divert the governments’ attention towards more urgent issues other than environmental controls (Madani, 2020) while gearing energy use towards traditional polluting yet cheaper sources (Anser et al.,

2021). As a result, there is little chance for the diffusion of PPPIE's outcomes (e.g. environmental-related technologies) through supply chains and the inter-sectoral linkages to create significant positive externalities to the environment. Third, stronger "rebound effects" under more green innovation following PPPIE could be witnessed during the periods of high geopolitical uncertainty. The reason is that due to the economic hardship caused by geopolitical risks, firms more likely reduce the costs of developing and adopting environmental-related technologies by using environmentally damaging inputs (also known as "brown" inputs) (Jenkins et al., 2011; Font Vivanco et al., 2014, 2015). Fourth, the positive externalities of PPPIE to green consumption may also be limited due to decreased income, rising unemployment, and dim economic outlooks caused by geopolitical tension. Nevertheless, there is a lack of empirical evidence regarding the involvement of GPR in mediating the relationship between PPPIE and environmental deprivation.

In response to those research gaps, this study aims to answer two research questions, including (1) how PPPIE and GPR influence the environment, and (2) how GPR affects the PPPIE—environmental quality nexus. In particular, the paper postulates that while PPPIE mitigates carbon emissions, GPR accelerates carbon emissions and dampens the beneficial effects of PPPIE. If these hypotheses are validated, they explain the reason for the unfavorable impact of PPPIE on environmental sustainability in emerging and developing countries that have been specified in previous studies.

To extract the empirical evidence on these issues, the context of Emerging 7 countries (hereafter E7) is chosen for the following reasons. First, E7 has become a globally giant player in terms of economic activities, energy consumption, and environmental impacts. It has recently surpassed G7 (short for Group of Seven countries) in terms of economic size. While in 2000, E7 and G7 accounted for 22.8% and 43.8% of global GDP (in purchasing power parity), the proportions changed to 36.5% and 30.9% in 2020, respectively. High economic growth demands huge energy production and consumption, unavoidably damaging the environment. According to BP (2022), the level of carbon emissions from E7 has increased by 4.1% per annum over the past two decades while that from G7 has decreased by 1.2% per annum, making the former replace the latter to become the largest contributor of carbon emissions. Achieving the goal of a low-carbon future is of paramount importance for the country group, which is among the most vulnerable to the effects of environmental degradation. Figure 1 shows that E7 contributed to 48.6% of 2020 global carbon emissions. Second, these countries are strong political powers with highly frequent geopolitical risks. The recent escalating economic, political, and military tensions between the USA and China, the Western world and Russia have far-reaching consequences for each competitor and the world. Not only does the strategic competition occur between E7 countries and the rest of the world, but E7 countries also suffer from border tensions with their neighbors (e.g. China and India) and internal geopolitical instability (e.g. Indonesia and Türkiye). In fact, the geopolitical risk indices of E7 countries are persistently higher than the world average (Anser et al., 2021). Third, the governments of E7 have encouraged PPPIE due to its expected benefits for energy production, energy efficiency, and environmental protection. This initiative can bridge the gap between energy demand and energy production while considering the environmental economic benefit–cost analysis. However, the amount of PPPIE in E7 plunged from 166.1 billion USD in 2011–2015 to 98.8 billion USD in 2016–2020. This 40.5% decline urgently requires the realignment of government policies to restore the investment and increase their efficiency in fulfilling their environmental commitments. Overall, the data show that the E7 bloc is among the most globally influential country groups based on its economic, geopolitical, and environmental status, providing

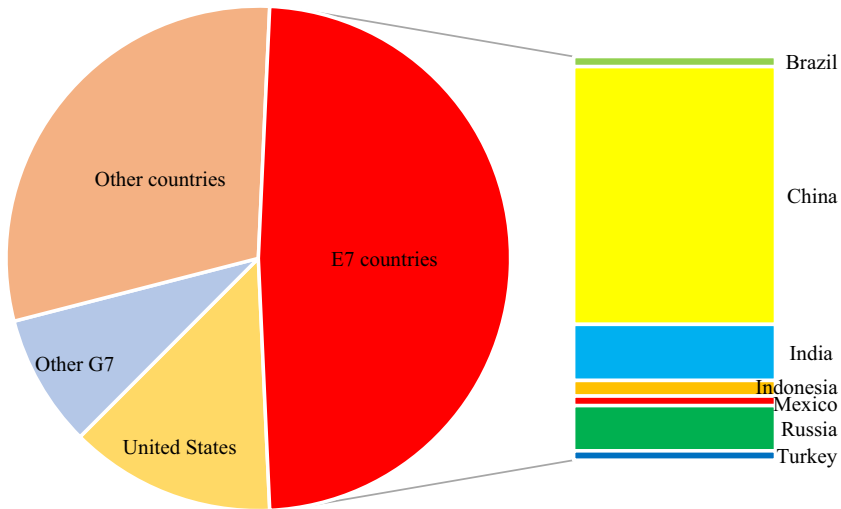


Fig. 1 Carbon emissions by countries. Source: BP Statistical Review of World Energy (2022)

an interesting context for conducting this empirical research. Due to the increasing importance of E7 countries in the global economy and energy and data availability, our sample encompasses E7 countries for the 1995–2019 period.

This empirical work contributes to the environmental economics literature in the following aspects. Foremost, it adds to the burgeoning research on the environmental effects of PPPIE, which has been considered a policy tool to resolve the problems of funding shortage and economic inefficiency of public investments in emerging countries. A number of studies have been documented in the literature that look at the contribution of public–private partnerships to environmental protection for either a single country (Anwar et al., 2021a, 2021b; Cheng et al., 2021; Shahbaz et al., 2020) or a group of chosen Asian or emerging countries (Alsagr & Hemmen, 2021; Gao et al., 2022; Kirikkaleli & Adebayo, 2021; Raza et al., 2021). However, no empirical evidence on E7 data has been investigated. Instead of focusing on a single country case as what has been done, we focus on the E7 to obtain more comprehensive and consistent results. Second, while previous works only document the consequences of PPPIE and GPR on the environment in isolation, this study provides the first empirical evidence of the moderating role of GPR as a possible reason for the less effective PPPIE in controlling carbon emissions in the E7 bloc. Understanding this linkage is strategically important given the increasing role of PPPIE in protecting the environment in the context that the world, especially E7 countries, has witnessed significant GPR in recent years. Another significant contribution lies in the methodological issue. Aggregation of the E7 countries' low-carbon future is a challenging task given their diverse circumstance and priorities. Each country has adopted its targets and reference points to specify its targets and different approaches for different sectors that are conditional on the current environmental problems. Thus, the present study utilizes the recently developed quantile regression estimator with non-additive fixed effects developed by Powell (2022), which is considered superior to conventionally adopted estimation techniques in contexts where individual and distributional heterogeneity exist. From the policymaking standpoint, the quantile regression supports the policy formulation process as it can relate the policy tools to the specific condition of environmental quality.

We divide the paper into five parts. The next section reviews the existing studies relevant to the relationship between PPPIE, GPR, and environmental quality. The third section describes the model construction, data, and estimation method. Estimation results are presented and discussed in the fourth section. Key conclusions and certain recommendations for policymakers are provided in the last section.

2 Brief literature review

The literature review is divided into two sub-sections. The impact of PPPIE on the sustainable environment is included in the first part, while the literature on the impact of geopolitical risk on environmental quality is highlighted in the second part.

2.1 Public–private partnership investments and carbon emissions

The importance of PPPI for technological innovation (Nisen et al., 2014), infrastructure (Ampratwum et al., 2022; Tsamboulas et al., 2013), and the health sector (Bonfim et al., 2018; Ferreira and Marques, 2021) is well documented in the literature. However, the PPPI literature related to environmental quality is quite limited in terms of quantity and inconsistent in terms of empirical findings. On the one hand, a small group of studies discovers the beneficial impacts of PPPI on the environment (Anwar et al., 2021a, 2021b; Buso & Stenger, 2018). For example, Buso and Stenger (2018) argue that in the context of high uncertainty, PPPI could be a wise strategy to foster the innovation and development of clean investments by efficiently addressing the contract incompleteness issue, mitigate operational constraints while improving performance. Anwar et al., (2021a, 2021b) examine the role of PPPI in the transport sector on carbon emissions discharged from transportation in China. The quantile autoregressive distributed lagged model indicates that PPPI has a favorable influence on air quality in high quantiles, e.g. 80th to 95th. Gao et al. (2022) explore the asymmetric influence of PPPIE on carbon emissions in selected Asia economies. While a positive variation in PPPIE benefits the environment in China and Türkiye over the long-run, it controls the environmental degradation in India, Indonesia, and Türkiye over the short-run.

On the other hand, most papers criticize PPPIE as the culprit of environmental degradation (Cheng et al., 2021; Raza et al., 2021; Shahbaz et al., 2020; Yang et al., 2022). Researching the environmental effects of PPPI in China remains to be an interesting topic. The impact of PPPIE and energy conservation on carbon emissions in China from 1991 to 2017 was examined by Cheng et al. in 2021. The empirical findings highlight the beneficial effect of PPPIE on carbon emissions and call for policymakers to increase the PPPI programs' effectiveness in terms of environmental quality. Similar results are reached by Shahbaz et al. (2020), who examine the connection between PPPIE and carbon emissions while taking the role of China's technological advancements into consideration. It is discovered that the PPPIE reduces environmental quality by raising carbon pollution between 1984 and 2018. According to Kirikkaleli and Adebayo (2021), PPPIE has a positive impact on India's consumption-based carbon pollution. To create a cleaner atmosphere, the authors advise that the nation increase its PPPI in renewable energy. Other studies analyze the PPPIE-environmental quality nexus in larger country groups. For instance, Raza et al. (2021) employ the non-parametric method to indicate PPPI as a strong determinant of carbon emissions in several Latin American and Asian countries. The harmful impact of PPPI

in non-renewable energy on carbon emissions follows a hump-shaped pattern over quantiles. Yang et al. (2022) evaluate the impact of PPPI on carbon emissions in E7 countries from 1995 to 2018. Given the heterogeneity implied in the dataset, the authors apply the method of moments of quantile estimation. Higher PPPIE is associated with higher carbon emissions with stronger effects in the case of more polluted countries.

2.2 Geopolitical risk and carbon emissions

In contrast to the literature on the PPPIE-environment nexus, there exists a plethora of works on the geopolitical tension and environmental sustainability relationship. Before the development of the GPR index by Caldara and Iacoviello (2022), empirical studies rely on different proxies to measure geopolitical risk, e.g. terrorism (Bildirici, 2020; Gokmenoglu et al., 2021), militarization (Bildirici, 2017; Jorgenson et al., 2010), and political instability (Abid, 2016; Kamah et al., 2021). The outcomes of these studies indicate that GPR can either increase or decrease carbon emissions. Nevertheless, such proxies do not fully capture the geopolitical events, do not cover real-time risks, and suffer from time inconsistency (Bouoiyour et al., 2019). The newly revealed GPR index by Caldara and Iacoviello (2022) is superior to other indicators in terms of event coverage, time consistency, and prediction ability (Anser et al., 2021; Husnain et al., 2022; Muhammad & Long, 2021).

A group of papers criticizes GPR as the primary cause of environmental damage. This argument is validated by Adams et al. (2020) who find that while GPR creates no significant consequence on air pollution in the short term, it dampens the environment in resource-rich economies by increasing air pollution in the long-run. In a similar vein, Anser et al. (2021) document that GPR escalates carbon emissions in BRICS nations. In a related attempt, Syed et al. (2022) note the latter distribution. While GPR raises air pollution at lower quantiles, it cuts down carbon emissions at the middle and higher quantiles.

Other studies find the beneficial impacts of GPR on environmental quality. For instance, Husnain et al. (2022) concludes that GPR tends to decrease carbon emissions and ecological footprint in E7 countries. Further, Hashmi et al. (2022) find that at the global level, GPR impedes carbon emissions significantly. Consistently, GPR is also found to strongly influence renewable energy production (Sweidan, 2021) and consumption (Alsagr & Hemen, 2021), thus, contributing to environmental sustainability. A recent paper written by Riti et al. (2022) indicates the presence of aggregation bias where the relationship between GPR and carbon emissions is positive at the aggregate level but negative at the country-specific level. Chu et al. (2022) find the potential heterogeneous influences of geopolitical risks on environmental quality across different countries. Another recent study by Chu et al. (2023) reveals that the promoting effect of geopolitical risk on the deployment of renewable energy is only found in high-income countries while adverse impacts of geopolitical uncertainty on renewables are witnessed within middle-income countries. Since renewable energy use has a negative association with carbon emissions (Doğan et al., 2021), this study also implies the potential heterogeneity in the geopolitical risk—environmental quality linkage.

2.3 The moderating role of geopolitical risk on the environmental impact of public–private partnership investments

Despite that PPPIE is established to alleviate carbon dioxide emissions by removing financial, operational, and psychological barriers to green innovation and clean investments,

it is uncertain whether such targets could be achieved (Anwar et al., 2021a, 2021b). The success of PPPIE may depend on some factors, including (1) whether PPPIE is properly directed to the development of environmentally-related technologies and sustainable projects as it is supposed, (2) whether outcomes of PPPIE are effectively applied in business practice, (3) the extent to which the “rebound effects” of green innovation occurs, and (4) the extent to which the positive externalities of PPPIE could be witnessed and expanded to the consumption sector. The rise of geopolitical risk could exert an influence on all of these factors and hence, interfere with the beneficial environmental impacts of PPPIE.

First, following Caldara and Iacoviello (2022), geopolitical risk may incorporate both political risks and economic risks that shake the peaceful course of international relations between countries (Wu et al., 2022). Those risks, in turn, constitute international drivers of corruption (OECD, 2012). In the context of political instability, power uncertainty may motivate the authorities to increase and gear fiscal expenditures towards rent-seeking activities other than productive work (Angelopoulos & Economides, 2008). Political instability is found to be associated with a higher level of corruption and distorted decisions of policymakers that harm economic performance in previous empirical works (Akçoraoğlu & Kaplan, 2017; Angelopoulos & Economides, 2008). In the same vein, economic sanctions (as a form of economic risk caused by geopolitical tension) are also found to trigger rent-seeking behaviors among both authorities and economic actors as a way to take advantage of the new condition (Lektzian, 2007). On the one hand, governments in the sanctioned states attempt to “stay in power” by “granting domestic contracts” (Lektzian, 2007). On the other hand, firms may resort to the “criminal route” to mitigate the repercussions of economic sanctions (Drezner, 2011; Galtung, 1967) or collect rents from the decreased competition during economic hardships (Drezner, 2011). At the same time, anti-corruption programs are more likely neglected during periods of political instability and economic pressure. Given the inflexibility of the public–private partnership (Mota & Moreira, 2015), the rent-seeking behaviors inspired by unexpected geographical risks may distort the choice of technology, materials, project management, and risk sharing, hence, hurting the effectiveness of PPPIE. In fact, even in normal settings, corruption is found to worsen environmental quality (Khalfaoui et al., 2023). During the geopolitical uncertainty periods, we expect that geopolitical risks may deteriorate the effectiveness of PPPIE by triggering higher levels of corruption.

Second, the environmental impacts of PPPIE are not limited to the immediate reduction of carbon emissions within the production stage of firms which are directly associated with the PPPIE (Yurdakul and Halim Kazan, 2020). Instead, PPPIE could generate positive externalities to the environment through the diffusion and knowledge spillovers of green technologies across supply chains and the inter-sectoral linkages (Green et al., 2012; Luzzini et al., 2015). The rise of geopolitical risks may disrupt this spillover process in two ways. On the one hand, under the “escalating effect”, economic uncertainty and hardships caused by GPR drive the energy transition towards more use of polluting energy sources and traditional production processes (that is cheaper) rather than the application of new green technologies and green inputs (as results of PPPIE’s outcomes) which may entail more costs and risks (Anser et al., 2021). On the other side of the coin, in the context of rising geopolitical risks, natural security problems such as unemployment and poverty are given more concern in the government agenda as compared to environmental issues (Madani, 2020). Moreover, the government even tend to weaken environmental controls as a tactic to help the business communities overcome challenging times caused by high geopolitical risks (Kolstad, 2016). The neglect of environmental regulation, the insufficient financial sources for green production practices among firms, and the high tendency of

rent-seeking behaviors of both authorities and economic actors (Angelopoulos & Economides, 2008; Daniel Drezner 2011; Lektzian, 2007), together, limit the motivations of applying results of PPPIE in practice. This further hinders the positive externalities of PPPIE to the environment.

Third, geopolitical risks may exaggerate the “rebound effects” of PPPIE. According to the systems thinking theory, we contend that PPPIE’s effects on the ecosystem should be evaluated in light of how it interacts with the entire socioeconomic system (Greening et al., 2000; Sterman, 2012). Despite the fact that PPPIE may promote green innovation and clean investments, the modifications to the energy market and infrastructure system that result from the adoption of green technologies may be able to capture the rebound effects of eco-innovation, which is the primary outcome of PPPIE, on the ecosystem. More specifically, as an outcome of increased energy efficiency and new environmentally favorable inputs, some conventional resources are now more affordable and are therefore in greater demand from manufacturers (Yang & Li, 2017). Additionally, “green” capital goods (with minimal environmental impact) as well as “brown” capital goods (with more detrimental environmental effects) are needed for the development and implementation of environmental-related technologies (Font Vivanco et al., 2014; Jenkins et al., 2011). In addition, it may require new infrastructure systems to be constructed to put green technologies into use (Font Vivanco et al., 2015). Given economic hardships during periods of geographical tension and the availability of the more polluting yet cheaper resources, a greater amount of “brown” inputs may be consumed to that serve the development and application of PPPIE’s outcomes. This would raise the total level of energy use and end up with more carbon dioxide emissions following the PPPIE.

Finally, the economic and social consequences of geopolitical risks may lead to decreased income, rising unemployment, and dim economic outlooks. This may drive the public away from green consumption towards more reliance on traditional polluting resources (Le & Hoang, 2022). This further restrains the favorable impacts of PPPIE in the consumption sector.

The review of existing literature related to PPPIE, GPR, and carbon emission reveals limited and inconsistent evidence on the relationship among them, which is an opportunity for further exploration. Based on the existing literature and our discussion, three hypotheses are suggested as follows:

- H1 PPPIE contributes to the control of carbon emissions.
- H2 GPR degrades environmental quality by increasing carbon emissions.
- H3 GPR significantly dampens the beneficial impact of PPPIE on carbon emissions.

3 Theoretical framework, data, and methodology

3.1 Theoretical background and model construction

In light of this context, it is essential to examine the impact of these economic and geopolitical factors on carbon emissions using a theoretical framework. This study embarks on the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model established by Dietz and Rosa (1997). Under this analytical setting, carbon emissions (C) is used as the dependent variable while the independent variables are public–private partnership investment in energy (P), geopolitical risk (G), and other

determining factors. In theory, PPPIE may be related to sustainable development because of its relevance in addressing rising energy demand while mitigating negative environmental externalities. It, thus, can be adopted as a policy tool for the government to tackle environmental degradation. However, recent studies suggest a positive linkage between PPPIE and carbon emissions in selected emerging economies like E7 countries, indicating that environmental quality is adversely affected by PPPIE. This harmful impact inspires us to test whether this paradox is caused by the increasing geopolitical uncertainties related to these countries over the last three decades.

This study follows the existing literature and exact the most prevalent factors utilized in the earlier empirical works (Anwar et al., 2021a, 2021b; Cheng et al., 2021; Jahanger et al., 2022; Riti et al., 2022; Xue et al., 2022). Specifically, affluence is represented by income per capita (Y) and trade openness (T), population is represented by urbanization (U), and technology is represented by renewable energy consumption (R). Following the Environmental Kuznets Curve (hereafter EKC) hypothesis framework, we include a squared term of income per capita (Y^2) into the carbon emissions function to explore whether the correlation between economic expansion and environmental deprivation follows a U-shape or inverted U-shape. International trade may alter environmental quality positively, negatively, or neutrally, depending on the combination of scale, technique, and composition effects (Antweiler et al., 2001; Li et al., 2015; Shahbaz et al., 2017). The effect of urbanization is expected to be negative based on the ecological modernization theory, which asserts the linkage between urbanization and green technologies, energy efficiency, public awareness, and preference for a cleaner environment (Ahmed and Wang, 2019; Xue et al., 2022). It is widely recognized that renewable energy sources have minimal carbon content, thereby raising far less carbon emissions than non-renewable energy sources (Zaidi et al., 2018). Based on such reasoning, we model the carbon emissions functions as follows:

$$C = f(P, G, Y, Y^2, T, U, R) \quad (1)$$

where C , P , G , Y , Y^2 , T , U , and R are carbon emissions, PPPIE, GPR, income per capita, squared of income per capita, trade openness, urbanization, and renewable energy, respectively. All variables, except for GPR as an index, are converted into natural-log form and Eq. (1) is rewritten in a linear regression formula as below:

$$C_{it} = \alpha_0 + \alpha_1 P_{it} + \alpha_2 G_{it} + \alpha_3 Y_{it} + \alpha_4 Y_{it}^2 + \alpha_5 T_{it} + \alpha_6 U_{it} + \alpha_7 R_{it} + \varepsilon_{it} \quad (2)$$

where α denotes the coefficient to be estimated, i and t characterize nation and time, respectively, and ε signifies the error term.

We enable the PPPIE and GPR to interact in the regression model to explore how geopolitical tension moderates the influence of public–private partnership investment on air pollution. Equation (3) includes the interaction variable between P and G to examine the latter's complementing influence on the connection between the former and carbon emissions. The following is Eq. (3):

$$C_{it} = \beta_0 + \beta_1 P_{it} + \beta_2 G_{it} + \beta_3 P_{it} G_{it} + \beta_4 Y_{it} + \beta_5 Y_{it}^2 + \beta_6 T_{it} + \beta_7 U_{it} + \beta_8 R_{it} + \varepsilon_{it} \quad (3)$$

The sign and significance level of the coefficient of interaction variable determine whether GPR amplifies or diminishes the environmental effect of PPPIE. Based on the above-suggested hypotheses, we expect $\beta_1 < 0$ if PPPIE is environmentally friendly (H_1), $\beta_2 > 0$ if GPR is not environmentally friendly (H_2) while $\beta_3 > 0$ if GPR dampens the beneficial impact of PPPIE on environmental quality (H_3).

3.2 Data

In this present study, we empirically analyze the roles of PPPIE and GPR in curbing carbon emissions along with income, renewable energy, urbanization, and international trade from 1995 to 2019 for E7 countries. The dependent variable, carbon emissions, is measured in kg per 2015 USD. Following the World Bank's definition, public–private partnership investment in energy is the value of commitments to energy projects, which have reached financial closure and directly or indirectly serve the public. We divide it by the gross domestic product to take into consideration the size of each E7 economy. The Caldara and Iacoviello (2022) geopolitical risk index is used to quantify geopolitical tension. The relative weighting of articles in prestigious journals that address geopolitical developments and the risks they present is calculated to create the index. The word search is divided into eight categories: war threats, peace threats, military threats, nuclear threats, terrorist threats, the beginning of a war, the rise of a war, and terrorist acts. With the exception of G , which is taken from the Economic Policy Uncertainty website, the other variables are acquired from the World Development Indicators database.

The time span, which is from 1995 to 2019, has been selected due to the following reasons. The first is the data availability across datasets. Although the World Development Indicators database provides the data for other variables from 1990, the data on PPPIE are supplied mostly from 1995, especially for the cases of Mexico, Russia, and Türkiye. The second motivation is the occurrence of the Covid-19 pandemic. In fact, while the latest data from two above-mentioned sources are up to 2021, we limit the research period to 2019 to separate the potential effects of the Covid-19 pandemic on the government and private's investment in energy. Akrofi and Antwi (2020), Hoang et al. (2021), Kuzemko et al. (2020) and Mofijur et al. (2021) conclude that Covid-19 pandemic generates various externalities on the commitments and actions of private and government sectors in supporting energy transition. Table 1 introduces the details of the analytical data set. Appendix 1 displays the movement of all variables in the studied period.

3.3 Cross-sectional dependence, unit root, and co-integration tests

Cross-sectional dependence is a common problem when analyzing panel data; it renders the traditional panel unit root and co-integration tests unreliable. Owing to the close social, political, and economic ties among the E7, observations from one nation may have a big impact on those from other nations. In order to address this issue, the mean correlation

Table 1 Variables, Explanation, Measurement, and Data source. *Source:* Authors' compilation

Variable	Description	Unit	Data sources
C	Carbon dioxide emissions	kg per 2015 USD	World Development Indicators
P	Public–private partnership investment in energy	% GDP	World Development Indicators
G	Geopolitical risk	index	Caldara and Iacoviello (2022)
Y	GDP per capita	constant 2015 USD	World Development Indicators
T	Trade openness	% GDP	World Development Indicators
R	Renewable energy	% energy consumption	World Development Indicators
U	Urban population	% population	World Development Indicators

between panel units is determined using the sophisticated technique created by Pesaran (2021). The test equation is as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij} \right) \quad (4)$$

here ρ_{ij} denotes the correlation efficient, T characterizes time dimension, and N symbolizes countries. Either strict cross-sectional independence or weak cross-sectional dependence is the null hypothesis.

The outcomes of the cross-sectional dependence test help to select a suitable unit root test method. If cross-sectional dependence exists, Pesaran (2007) suggests the adoption of the second-generation unit root test with the inclusion of cross-section averages of lagged levels and first differences of the individual series. The test equation is depicted as follows:

$$\Delta Y_{i,t} = \gamma_i + \gamma_i Y_{i,t-1} + \gamma_i \bar{X}_{t-1} + \sum_{l=0}^p \gamma_{il} \Delta \bar{Y}_{t-l} + \sum_{l=1}^p \gamma_{il} \Delta Y_{i,t-l} + \mu_{it} \quad (5)$$

where $\bar{X}_{t-1}$ and $\Delta \bar{Y}_{t-l}$ are the averages of cross sections. The test statistics is given as:

$$CIPS = N^{-1} \sum_{i=1}^n CADF_i \quad (6)$$

where $CADF_i$ shows the i th values of the cross-sectional augmented Dickey-Fuller in Eq. (5). According to the null hypothesis, every series is non-stationary.

To test for the incidence of a long-run connection between carbon emissions, PPPIE, geopolitical risk, and other control variables, the study adopts the Pedroni (1999, 2004) test. Based on a model where the AR parameter is either panel-specific or similar across the panels, the test statistics are computed. The panel-specific AR test statistics are referred to as "group-mean statistics" by Pedroni (1999, 2004), while the same-AR test statistics are called "panel co-integration statistics." The cross-sectional averages are first subtracted to alleviate the consequence of cross-sectional dependence (Levin et al., 2002).

3.4 Estimation method

When the error term has an identical distribution, a conditional mean of zero, and follows the normal distribution, the ordinary least squares (OLS) regression yields an unbiased and effective estimator. These presumptions, nevertheless, may not be realistic. When the majority of environmental and economic variables typically have non-normal distributions and outliers, OLS estimations can produce inaccurate findings. A quantile regression technique is proposed by Koenker and Bassett (1978) as a solution to the drawbacks of OLS estimation. First, by estimating parameters across the conditional distribution of the outcome variable, quantile regression enables a more thorough examination of the variables affecting environmental quality at various levels. Particular policy recommendations are made easier by this superiority. Secondly, quantile regression does not assume anything about the distribution of the target variable. When using conventional mean approaches, the statistical violation of normal distribution results in inconsistent estimation results. Third, because the quantile approach uses the median for estimation rather than the mean, it performs better when there are heavy distributions and outliers (Koenker, 2005). Fourth, this approach mitigates the issue of unobserved individual heterogeneity by enabling the

estimation of conditional heterogeneous covariance effects among variables within a nation (Canay, 2011; Powell, 2022).

Powell (2022) promotes the adoption of a panel quantile regression that maintains the non-separable error terms by using a "non-additive fixed effect." Furthermore, compared to other methods, Powell (2022)'s recommended method significantly reduces the number of estimated parameters by not measuring the individual fixed effects. This on-hand study adopts the generalized quantile regression estimator promoted by Powell (2022) with an instrumental variable setting to handle the possibility of endogeneity. Following the practice of Opoku and Aluko (2021) and Yang et al. (2022), it also assumes that all independent variables are endogenous and constitute the instrumental variable group. The Eq. (3) can be modeled as follows:

$$C_{it} = D'_{it}\gamma(U_{it}^*) \text{ with } U_{it}^* \sim (0, 1) \quad (7)$$

where C_{it} denotes the carbon emissions of nation i in year t ; D_{it} denotes the group of all independent variables, in Eq. (1); γ denotes the estimator of coefficients; U_{it}^* is the random error term. The model is dependent on the following for the country i in year t in the τ quantile:

$$P(C_{it} \leq D'_{it}\gamma(\tau) | D'_{it}) = \tau \quad (8)$$

The probability that the carbon emissions are less than the quantile function is equal to τ and similar for all explanatory variables, according to Eq. (5). To generate the parameters β , the generalized method of moments technique is used. Given its ability to deal with non-normal distribution and heterogeneity, several studies employ quantile regression approaches in environmental quality analysis (Chu et al., 2023; Opolu and Aluko, 2021; Ren et al., 2021). This paper follows their choice of estimation methodology and incorporates the roles of PPPIE, GPR, and other control variables in determining carbon emissions in E7 countries.

4 Results of empirical findings

4.1 Data descriptive

Table 2 presents the summary statistics for all variables. The mean value of carbon emissions is 0.736 kg per 2015 USD during the period 1995 to 2019. Across the sample, the minimum and maximum carbon emitters are Brazil (in 2009) and Russia (in 1996), respectively. India (in 2010) committed the highest value of public–private partnership investment to energy projects, up to 30 billion USD. This country also registered as the most sponsor for PPPIE if the amount is measured in relation to gross domestic product (1.767% GDP). Conversely, Russia (in 2005) spent the minimum value, only 3 million USD for PPPIE (equivalent to only 0.039% GDP). Several countries, e.g. Mexico, Russia, and Türkiye, did not invest in energy projects through PPP in the early years of the sample. For geopolitical tensions, the average value of the GPR index is 0.226 with a standard deviation of 0.236. Indonesia (in 2013) was the country with the lowest geopolitical uncertainty whereas the highest index belongs to Russia (in 2014).

Türkiye has the highest income among the sample as of 2019, followed by China and Russia. In contrast, India had the lowest income in 1995. Overall, the average income per

Table 2 Summary statistics and Correlation matrix

	<i>C</i>	<i>P</i>	<i>G</i>	<i>Y</i>	<i>R</i>	<i>U</i>	<i>T</i>
Mean	0.736	0.326	0.226	5922.919	26.194	59.817	45.133
Std. Dev	0.398	0.388	0.236	3396.154	15.898	19.789	14.490
Min	0.221	0.000	0.016	618.368	3.180	26.607	15.636
Max	1.911	1.767	1.141	12,006.820	54.484	86.824	96.186
Skewness	0.486	1.632	1.812	-0.212	0.143	-0.334	0.140
Kurtosis	2.148	5.128	6.231	1.547	1.504	1.593	3.232
Jarque-Bera	29.270	96.150	97.730	14.920	17.070	17.670	21.870
Correlation matrix							
<i>C</i>	1						
<i>P</i>	-0.237***	1					
<i>G</i>	0.573***	-0.336***	1				
<i>Y</i>	-0.523***	-0.152*	0.197**	1			
<i>R</i>	-0.143*	0.420***	-0.499***	-0.591***	1		
<i>U</i>	-0.672***	0.004	-0.066	0.904***	-0.351***	1	
<i>T</i>	0.110	-0.225***	0.133*	0.137*	-0.578***	-0.016	1

***, **, * show statistical significance at 1%, 5%, and 10%, respectively

capita is 5,923 USD with a standard deviation of 3,396. Indonesia has integrated extensively into the global economy by climbing from fourth to first place in terms of trade volume over gross domestic product whereas Brazil remains the least open country through the period 1995–2019. However, Brazil (in 2019) was recorded as the most urbanized country, followed by Mexico and Turkey. The statistics also reveal that the average renewable energy proportion is around 26.194%, significantly lower than the maximum value of 54.484% in India (in 1995). Nevertheless, the percentage of green energy in the total energy consumption of India has decreased to 32.930% (in 2019) as the economy grows considerably over the studied period. Rich in natural resources, Russia is a heavily non-renewable energy-dependent country with the proportion of renewable energy ranging from 3.180% to 3.871%.

The second part of Table 2 reports the correlation matrix for the chosen variables. The first column shows the pairwise connection between carbon dioxide emissions and its determinants. PPPIE, green energy, and urbanization indicate negative correlations (with environmental degradation) while GPR shows a meaningfully positive association. Trade openness displays a statistically insignificant correlation coefficient, although positive. A significantly negative association is observed between GPR and PPPIE, indicating that the movement of one variable is strongly related to the fluctuation of the other.

4.2 Results of cross-sectional dependence, unit root, co-integration tests

To explore the characteristics of the data, the presence of cross-sectional dependence is assessed by the adoption of Pesaran (2015) test. The results shown in Table 3 reject the null hypothesis of no cross-sectional dependence for all variables. As our data contain a inter-relation feature, the second-generation unit root test developed by Pesaran (2007)

Table 3 Cross-sectional dependence test

Variable	CD-test	corr	abs(corr)
<i>C</i>	7.82***	0.412	0.515
<i>P</i>	3.09***	0.158	0.301
<i>G</i>	3.91***	0.178	0.365
<i>Y</i>	17.91***	0.905	0.905
<i>R</i>	10.00***	0.519	0.629
<i>U</i>	19.44***	0.982	0.982
<i>T</i>	1.77*	0.075	0.476

***, **, * show statistical significance at 1%, 5%, and 10%, respectively

is applied. Table 4 shows that while the problem of unit root persists among the variables at level, the first difference transformation makes these variables stationary.

Table 5 displays the seven test statistics that were calculated using Pedroni (1999, 2004)'s co-integration test. The results of six of the seven tests, which strongly reject the null hypothesis that there is no co-integration, supporting the co-integration between the variables. The finding acknowledges that PPPIE, GPR, and other control variables maintain a co-integration relationship with respect to carbon emissions in E7 countries.

Table 4 Panel unit root test

Variable	<i>I</i> (0)	<i>I</i> (1)
<i>C</i>	2.079	−2.319***
<i>P</i>	−0.419	−7.264***
<i>G</i>	−3.199	−6.356***
<i>Y</i>	2.108	−2.067***
<i>R</i>	3.353	−2.878***
<i>U</i>	4.136	−1.311*
<i>T</i>	1.241	−8.117***

***, **, * show statistical significance at 1%, 5%, and 10%, respectively

Table 5 Panel co-integration test

H1: common AR coefficients (within-dimension)		H1: individual AR coefficients (between-dimension)	
Test	Statistics	Test	Statistics
Modified variance ratio	−3.889***		
Modified Phillips-Perron t	1.310*	Modified Phillips-Perron t	1.721**
Phillips-Perron t	3.308***	Phillips-Perron t	−1.360*
Augmented Dickey-Fuller t	4.695***	Augmented Dickey-Fuller t	0.075

***, **, * show statistical significance at 1%, 5%, and 10%, respectively

4.3 Results of panel quantile regression

The normality is examined through the quantile–quantile plot and the Skewness-Kurtosis test (Bera & Jarque, 1981). Quantile–quantile plot is a graphic tool that plots the distribution of variables against the theoretical normal distribution. As illustrated in Appendix 2, the variables come near to having a normal distribution in the center, but some of the observed points at the ends fall outside of the diagonal lines, indicating that the distribution is not normal. In addition, the Skewness-Kurtosis test in Table 6 shows that the distribution of residuals from estimating Eq. (2) is more skewed and more asymmetric than the normal distribution. Overall, the results of these two normality tests confirm the non-normal distribution of the panel data.

The connection between PPPIE and carbon emissions is graphically plotted as shown in Appendix 3, showing a sort of non-linear relationship. It suggests that the presence of non-normality and non-linear association actually justify the application of quantile regression technique, which can address these two issues efficiently.

Since the data and the residual terms are not normally distributed, the estimation results obtained from the Powell (2022)'s panel quantile regression method are more statistically vigorous and informative in terms of policy implication. The obtained results in relation to Eq. (2) and Eq. (3) are presented in Table 7 and 8, respectively. To picture a comprehensive description of explanatory variables' influence on carbon emissions, we report the coefficients at nine different quantiles (from 10 to 90th) of carbon emissions. Looking for different determinants of carbon emissions notices that their effects are clearly heterogeneous across carbon emissions distribution.

The estimation results display that the coefficients of PPPIE are statistically significant and negative in most quantiles, except for the 10th quantile. Specifically, at the 10th quantile, PPPIE has a positive and insignificant impact on carbon emissions, indicating that hypothesis H_1 is not likely to hold for the relatively less air-polluted countries in E7, e.g. Brazil. However, the effect becomes significant and its magnitude increases through the lower to middle quantiles, reaching the highest level at the 70th quantile (0.027), before falling by nearly a half at the 80th (0.017) and 90th (0.015). Therefore, hypothesis H_1 for the favorable effect of PPPIE on environmental quality is confirmed in most E7 countries. This result confirms the findings of Anwar et al., (2021a, 2021b), Buso and Stenger (2018), and Gao et al. (2022) that PPPIE represents a policy tool to tackle environmental degradation while contradicting the conclusions of Cheng et al. (2021), Kirikkaleli and Adebayo (2021), Raza et al. (2021), Shahbaz et al. (2020), and Yang et al. (2022). The benefits of PPPIE on environmental quality become more considerable in relatively intensive carbon emitters, e.g. China, India, and Russia. This may be because the outcomes of PPPIE only are limited to the development and execution of green energy projects while the literature documents many other causes of environmental degradation such as environmental policy contingency (Wang & Wei, 2020; Zhou and Li, 2020), income inequality (Chu & Hoang, 2021), the existing productive capabilities (Alvarado et al., 2021), and the share of the shadow economy (Chu & Hoang, 2022; Ortiz et al., 2022). In countries which are suffering high environmental degradation, there may be still room for significant contributions of green innovation to be witnessed. Nevertheless, in less polluting nations that either consume fewer fossil fuels or have taken the most advantage of green

Table 6 Normality test

Variable	Pr(skewness)	Pr(Kurtosis)	adj. $\chi^2(2)$	prob > χ^2
residual	0.065	0.000	20.91	0.000

Table 7 Panel quantile regression (without interaction variable)

	Qu10	Qu20	Qu30	Qu40	Qu50	Qu60	Qu70	Qu80	Qu90
<i>P</i>	0.005 (0.009)	-0.005*** (0.001)	-0.006* (0.003)	-0.009** (0.004)	-0.019*** (0.004)	-0.015*** (0.004)	-0.027*** (0.003)	-0.017*** (0.003)	-0.015*** (0.002)
<i>G</i>	0.303*** (0.099)	0.596*** (0.010)	0.463*** (0.039)	0.573*** (0.035)	0.413*** (0.034)	0.597*** (0.052)	0.518*** (0.087)	0.787*** (0.011)	0.575*** (0.020)
<i>Y</i>	0.230 (0.262)	1.653*** (0.085)	2.174*** (0.361)	2.373*** (0.150)	2.467*** (0.108)	2.944*** (0.169)	3.050*** (0.131)	3.336*** (0.116)	2.068*** (0.235)
<i>Y</i> ²	-0.024 (0.024)	-0.117*** (0.005)	-0.143*** (0.022)	-0.154*** (0.008)	-0.169*** (0.007)	-0.197*** (0.012)	-0.204*** (0.009)	-0.230*** (0.007)	-0.150*** (0.015)
<i>R</i>	-0.555*** (0.046)	-0.400*** (0.014)	-0.462*** (0.041)	-0.373*** (0.015)	-0.500*** (0.012)	-0.484*** (0.014)	-0.519*** (0.020)	-0.539*** (0.005)	-0.568*** (0.008)
<i>U</i>	-1.238*** (0.344)	-0.947*** (0.041)	-1.293*** (0.087)	-1.248*** (0.059)	-1.042*** (0.120)	-1.058*** (0.089)	-1.090*** (0.116)	-0.778*** (0.031)	-0.837*** (0.033)
<i>T</i>	-0.169 (0.111)	-0.020** (0.009)	-0.063 (0.042)	-0.056*** (0.010)	-0.180*** (0.012)	-0.180*** (0.018)	-0.255*** (0.021)	-0.341*** (0.012)	-0.258*** (0.017)
Constant	6.362*** (2.370)	-1.163*** (0.239)	-1.899** (0.889)	-3.282*** (0.529)	-2.900*** (0.394)	-4.904*** (0.756)	-4.739*** (0.443)	-6.136*** (0.409)	-1.087 (0.942)
No. Obs	152	152	152	152	152	152	152	152	152

Qu is the quantile distribution of dependent variable

***, **, * show statistical significance at 1%, 5%, and 10%, respectively.

Table 8 Panel quantile regression (with interaction variable)

	Qu10	Qu20	Qu30	Qu40	Qu50	Qu60	Qu70	Qu80	Qu90
<i>P</i>	0.006*** (0.001)	− 0.018*** (0.002)	− 0.007*** (0.002)	− 0.006*** (0.002)	− 0.025*** (0.005)	− 0.033*** (0.004)	− 0.029*** (0.007)	− 0.039*** (0.004)	− 0.041*** (0.003)
<i>G</i>	0.612*** (0.034)	0.724*** (0.017)	0.626*** (0.028)	0.617*** (0.045)	0.566*** (0.022)	0.752*** (0.051)	0.819*** (0.092)	0.822*** (0.053)	0.591*** (0.041)
<i>P</i> × <i>G</i>	0.037*** (0.006)	0.036*** (0.003)	0.021*** (0.004)	0.012*** (0.003)	0.038*** (0.010)	0.052*** (0.009)	0.052*** (0.022)	0.061*** (0.008)	0.051*** (0.005)
<i>Y</i>	1.428*** (0.091)	1.652*** (0.060)	2.333*** (0.054)	2.832*** (0.066)	2.639*** (0.055)	3.141*** (0.137)	3.496*** (0.175)	3.583*** (0.091)	2.939*** (0.062)
<i>Y</i> ²	− 0.105*** (0.005)	− 0.118*** (0.003)	− 0.156*** (0.003)	− 0.186*** (0.004)	− 0.174*** (0.004)	− 0.211*** (0.009)	− 0.235*** (0.011)	− 0.245*** (0.005)	− 0.205*** (0.004)
<i>R</i>	− 0.532*** (0.009)	− 0.387*** (0.004)	− 0.422*** (0.009)	− 0.433*** (0.019)	− 0.465*** (0.004)	− 0.481*** (0.011)	− 0.519*** (0.019)	− 0.557*** (0.012)	− 0.603*** (0.010)
<i>U</i>	− 1.056*** (0.032)	− 0.872*** (0.022)	− 1.070*** (0.052)	− 1.159*** (0.035)	− 1.203*** (0.075)	− 0.948*** (0.067)	− 0.955*** (0.041)	− 0.805*** (0.037)	− 0.796*** (0.023)
<i>T</i>	− 0.136*** (0.011)	− 0.060*** (0.007)	− 0.084*** (0.014)	− 0.124*** (0.021)	− 0.176*** (0.012)	− 0.197*** (0.015)	− 0.263*** (0.020)	− 0.361*** (0.018)	− 0.359*** (0.012)
Constant	1.123*** (0.379)	− 1.296*** (0.186)	− 3.229*** (0.211)	− 4.780*** (0.438)	− 3.462*** (0.335)	− 5.952*** (0.620)	− 6.843*** (0.822)	− 6.959*** (0.341)	− 4.188*** (0.250)
No. Obs	152	152	152	152	152	152	152	152	152

Qu is the quantile distribution of dependent variable

***, **, * show statistical significance at 1%, 5%, and 10%, respectively.

technologies in their energy transition, the contribution of PPPIE in reducing carbon dioxide emissions is blurred by the prevalence of other causes. The sudden reduction in the beneficial impacts of PPPIE from the 70th quantile could be clarified by the stronger “rebound effects” that resulted from the development and application of PPPIE’s outcomes in highly polluting countries at the 80th and 90th quantile, including India and Russia. The lower rankings for either the information and communication technology index or economic complexity index of these countries as compared to other E7 economies imply their lower productive capabilities. Therefore, it may require more brown inputs and energy use for the development and application of green innovation in these countries (Rosenbaum, 2019; Vu, 2020). This, in turn, dampens the beneficial impacts of PPPIE on the environment and results in a weaker contribution of PPPIE to the decline of carbon dioxide emission as found in this study.

On the contrary, the estimation results reveal that increasing geopolitical tensions dampen environmental quality across all quantiles of carbon emissions. All estimated coefficients of geopolitical risk are statistically positive at 1% level. Hypothesis H_2 on the negative impact on environmental sustainability is confirmed. This empirical finding supports the “escalating effect” over the “mitigating effect” and is identical to the arguments of Adams et al. (2020) and Anser et al. (2021). In addition, the carbon emissions stimulating effect of geopolitical risk increases as the level of carbon emissions goes up. While the lowest impact of GPR is observed at the 10th quantile (0.303), it obtains the highest impact on the environmental quality at the 80th quantile (0.787). The impact is cut off by one-third at the 90th quantile (0.575) although its degree is still equivalent to the average level. This finding indicates that the recently alarming geopolitical tensions in E7 countries, e.g. China, India, Indonesia, and Russia, inflict adverse consequences on the already low level of environmental quality. The fluctuation in the impact of geographical tension on carbon dioxide emission may be because geographical risk is a comprehensive concept which covers a variety of political and economic risks (Wu et al., 2022). The extent of the “escalating effect” and the potential “mitigating effect” of geographical tension on environmental quality, hence, may depend on the type of risks being suffered and dominated in each country.

The quantile regression analysis reveals that the estimated coefficients of income and its squared are positive and negative, respectively. However, those obtained at the 10th quantile are not statistically significant at any conventional level, thus, indicating the invalidation of the EKC hypothesis in relatively less air-polluted economies. In contrast, the EKC hypothesis holds for countries with higher air pollution, e.g., those from the 20th to 90th quantiles. After developing the economy over a certain threshold, most E7 countries have opportunities to reduce pressures on environmental quality while achieving high economic growth rates to catch the economic prosperity of advanced countries. This outcome aligns with the findings of past studies (Anwar et al., 2021a, 2021b; Chu and Tung, 2022; Yang et al., 2022).

Increasing the share of cleaner energy serves as a solution for controlling air pollution in E7 countries. The estimated coefficient of renewable energy is statistically negative at all quantiles although its magnitude varies. The deployment of renewable energy mostly favors E7 nations that are the least (10th) and highly air polluted (70th to 90th). While the former can pursue economic targets through the development of renewable energy because of its low carbon emissions, the latter which is suffering from severe environmental degradation must reduce dependence on fossil fuels and replace them with cleaner energy sources. Nevertheless, for the moderately polluted E7 nations, the effectiveness of energy transition towards renewables is not highly appraised (compared to other peers). This could occur because these countries may be in a dilemma between maintaining high economic growth and ensuring environmental sustainability. Only when the environment becomes

worse, e.g. severe air pollution, they may switch their economic growth model to a more environmentally friendly one. This important role of green energy in scaling down carbon emissions has been mentioned in previous studies by Danish and Ulucak (2020), Khan et al. (2019), and Pata (2021).

In addition to this, urbanization is disclosed to have a negative and significant influence on carbon emissions across all quantiles. This finding suggests that the relocation of people and resources from rural to urban zones in E7 countries leads to higher energy efficiency and upgraded environmental technologies, which dominate the detrimental effects of greater energy demand on the environment. It proves the pollution-mitigating role of urbanization, allowing these countries to achieve environmental sustainability while expanding urban areas. This finding is in line with Zhu et al. (2018), who find that not only does urbanization reduce carbon emissions but its influence also varies significantly across the distribution of carbon emissions. In particular, we find that the urbanization effect is more substantial at the 10th to 70th quantiles and weaker at the extremely high levels of carbon emissions, 80th and 90th quantiles. In more environmentally ruined countries, heavy investment in infrastructure and congested transportation based on extensive consumption of fossil fuels may reduce the promising effects of urbanization.

International trade may restrict carbon emissions in E7 countries, as the estimated coefficient of trade openness is negative in all quantiles. Empirically, our finding conforms with several studies (Li et al., 2015; Shahbaz et al., 2017; Sohag et al., 2017) and implies that the favorable effect associated with technology transfer and structural change channels dominates the damaging effect combined with the scaling effect (Chu & Hoang, 2022). However, the significance of trade openness is only reported at the 20th and 40th to 90th quantiles. Additionally, the carbon emissions mitigating effect intensifies as the environment degrades. The relatively less polluted E7 countries must redesign their policies regulating international trade practices so that the exporters and importers shift their productions towards environmentally friendly goods. In contrast, the relatively more polluted E7 countries should support the globalization process to secure environmental well-being.

As shown in Table 8, the interaction between PPPIE and GPR is positive and statistically significant through the distribution of carbon emissions. In the presence of severe geopolitical tension, the favorable influence of PPPIE on carbon emissions reduction is restrained. This moderating effect follows a U-shaped pattern with the damaging effects becoming reinforced at less- (10th and 20th) and more polluted E7 nations (50th to 90th). In addition, the harmful effect is bigger in the latter case as illustrated in Fig. 2. This finding implies that countries that have already suffered from ruined air quality will receive fewer environmental benefits from PPPIE when geopolitical instability increases. Hypothesis H_3 on the depressing effect of GPR on the environmental impact of PPPIE on carbon emissions is supported by the situation of the E7 bloc. Given the long-term nature and inherent complexity of PPPIE projects (Mota & Moreira, 2015), the effectiveness of the partnership between the government and private sector is susceptible to the instability of economic and political stances. The heterogeneity in the moderating effect of geographical risk in the PPPIE-environmental quality linkage could be explained by the variety of channels through which geopolitical tension may dampen the beneficial impacts of PPPIE on the environment. In this study, we propose at least 4 channels of moderation, including (1) triggering rent-seeking behaviors that distort the environmental purposes of PPPIE (Angelopoulos & Economides, 2008; Drezner, 2011; Lektzian, 2007), (2) limiting the diffusion and spillover effects of PPPIE's outcomes across countries by hindering the motivations and capacities to adopt green innovation (Anser et al., 2021; Luzzini et al., 2015), (3) exaggregating the

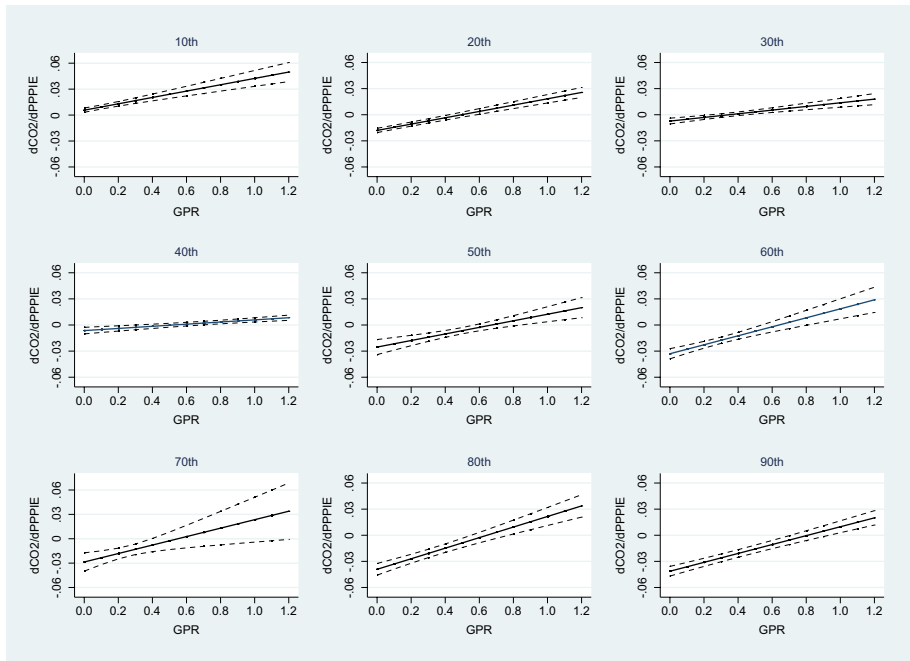


Fig. 2 Marginal impact of PPPIE on carbon emissions conditional on the level of geopolitical risk by quantiles. (Note: Solid line presents the marginal effect. Short—dash lines represent the 90% confidence level)

“rebound effects” of PPPIE (Font Vivanco et al., 2014; Jenkins et al., 2011), and (4) limiting green consumption behaviors by shrinking income and employment rate (Le & Hoang, 2022). Depending on the specific types of geopolitical risks being suffered (Wu et al., 2022), the existing economic, social and institutional conditions and the resilience capacities of each country, the magnitude of such a moderating effect may vary. This alerts policymakers, especially those with high levels of environmental pollution to concentrate on the management of PPPIE when facing geopolitical stiffness to keep the projects in the right direction toward environmental sustainability. Otherwise, the beneficial impacts of PPPIE on environmental quality can be reverted to extract harmful effects on air pollution.

The policy recommendations derived from empirical research depend heavily on the causal relationships. The Dumitrescu and Hurlin (2012) test is used in this work to investigate the direction of causality between the variables of interest. There is a bidirectional relationship between PPPIE and carbon emissions, as shown in Table 9. Similarly, GPR and carbon emissions are the source of two-way causality, and vice versa. The causality result, however, indicates a one-way relationship between GPR and PPPIE. This result corroborates the regression results that show the moderating effect of GPR on PPPIE’s environmental benefits in the E7 nations. Not only does controlling geopolitical stiffness tackle environmental degradation but it also contributes to environmental sustainability by magnifying the effectiveness of PPPIE.

Finally, the current study provides several alternative approaches to test the robustness of the findings. First, we employ carbon emissions measured in metric tons per

Table 9 Dumitrescu-Hurlin causality test

Null hypothesis	$\bar{Z}$ statistics	Null hypothesis	$\bar{Z}$ statistics	Causality flow
$P \rightarrow C$	2.170**	$C \rightarrow P$	4.103***	$P \leftrightarrow C$
$G \rightarrow C$	1.800*	$C \rightarrow G$	2.247**	$G \leftrightarrow C$
$G \rightarrow P$	6.189***	$P \rightarrow G$	-0.215	$G \rightarrow P$

***, **, * show statistical significance at 1%, 5%, and 10%, respectively

capita (instead of kg per 2015 US\$ of GDP) as a dependent variable. Second, we adopt the geopolitical risk historical index, which has a longer time series data but with a smaller newspaper coverage (Caldara and Iacoviello, 2022) to replace the geopolitical risk recent index. Third, we alter Eq. (2) and (3) to keep only PPPIE, GPR, income, and its square. The estimation results of three modifications are presented consecutively in Table 10 where we choose to report the coefficients related to PPPIE, GPR and their interaction to save space. Full estimation outcomes are available upon request. The results suggest that while PPPIE reduces carbon emissions, only does GPR contribute to environmental degradation, but it also dampens the favorable effect of carbon emissions.

5 Concluding remarks and policy implications

The persistent environmental degradation due to high carbon emissions has created a troubling situation worldwide. Despite continuous and enormous efforts taken by various stakeholders to contain carbon emissions to preserve environmental sustainability, the rise in geopolitical tensions across the world, in particular in several E7 nations, has put those efforts at risk. Ineffective international coordination and incredible green subsidies could slow down the process of de-carbonization. Delaying the implication of low-carbon policies would make achieving the emissions reduction targets more difficult, costly, and unsustainable. This research represents a pioneering study which analyses how GPR affects the efficiency of PPPIE in limiting carbon emissions in the E7 bloc. Our findings provides crucial policy implications for governments in tackling environmental degradation through the partnership with the private sector while considering the rise in levels of geopolitical risks.

On the policy front, PPPIE is an effective tool to curb the high level of air pollution in E7 countries. The policymakers should devise policies to encourage strong and effective cooperation between private and public sectors in renewable energy and energy efficiency projects. The tax exemption policies on PPPI in renewable energy projects may also expand the production and consumption of clean energy. Likewise, subsidized loans should be given to private investors in green power plants, e.g. wind and solar. Not only such actions can promote economic growth but they also effectively safeguard the ecological reserves and mitigate environmental contamination. Nevertheless, PPPIE is, indeed, an investment and its outcomes may vary due to how well it is managed against external uncertainties. Specifically, geopolitical tensions are found to not only aggravate carbon dioxide emissions in E7 countries but also limit the beneficial impacts of PPPIE on environmental quality. Thus, designing public–private partnership policies to meet countries' low-carbon commitments while carefully balancing the economic growth rate and dealing with geopolitical instability will be critical for

Table 10 Robustness tests

	Qu10	Qu20	Qu30	Qu40	Qu50	Qu60	Qu70	Qu80	Qu90
Panel A. Carbon emissions (metric tons per capita)									
<i>P</i>	−0.001 (0.003)	−0.010*** (0.003)	−0.003* (0.002)	−0.005*** (0.001)	−0.005*** (0.001)	−0.016*** (0.003)	−0.026*** (0.003)	−0.017*** (0.003)	−0.016*** (0.002)
<i>G</i>	0.663*** (0.041)	0.558*** (0.049)	0.523*** (0.016)	0.418*** (0.017)	0.399*** (0.013)	0.557*** (0.044)	0.508*** (0.054)	0.787*** (0.011)	0.577*** (0.022)
No. Obs	152	152	152	152	152	152	152	152	152
<i>P</i>	−0.015*** (0.004)	−0.021*** (0.004)	−0.011*** (0.003)	−0.021*** (0.004)	−0.026*** (0.003)	−0.026*** (0.006)	−0.030*** (0.001)	−0.035*** (0.005)	−0.037*** (0.002)
<i>G</i>	0.631*** (0.024)	0.932*** (0.067)	0.628*** (0.026)	0.525*** (0.039)	0.591*** (0.046)	0.581*** (0.086)	0.813*** (0.021)	0.869*** (0.020)	0.642*** (0.024)
<i>P x G</i>	0.064*** (0.008)	0.096*** (0.020)	0.023*** (0.007)	−0.014 (0.012)	0.039*** (0.006)	0.025 (0.017)	0.055*** (0.003)	0.060*** (0.015)	0.051*** (0.005)
No. Obs	152	152	152	152	152	152	152	152	152
Panel B. Geopolitical risk historical index									
<i>P</i>	−0.008*** (0.003)	−0.004** (0.002)	−0.014*** (0.002)	−0.013*** (0.004)	−0.011*** (0.002)	−0.016*** (0.004)	−0.017*** (0.004)	−0.014*** (0.005)	−0.016*** (0.006)
<i>G</i>	0.373*** (0.013)	0.307*** (0.089)	0.495*** (0.052)	0.587*** (0.033)	0.558*** (0.075)	0.498*** (0.038)	0.633*** (0.053)	0.781*** (0.040)	0.568*** (0.027)
No. Obs	152	152	152	152	152	152	152	152	152
<i>P</i>	−0.007 (0.006)	−0.012** (0.005)	−0.012*** (0.003)	−0.023*** (0.004)	−0.014*** (0.004)	−0.021*** (0.005)	−0.025*** (0.003)	−0.037*** (0.007)	−0.040*** (0.001)
<i>G</i>	0.478*** (0.049)	0.599*** (0.073)	0.503*** (0.037)	0.611*** (0.050)	0.546*** (0.020)	0.597*** (0.049)	0.720*** (0.047)	0.785*** (0.038)	0.636*** (0.005)
<i>P x G</i>	0.062*** (0.013)	0.039*** (0.007)	−0.006 (0.009)	0.022** (0.009)	0.013*** (0.002)	0.002 (0.016)	0.015 (0.015)	0.046*** (0.014)	0.061*** (0.002)

Table 10 (continued)

	Qu10	Qu20	Qu30	Qu40	Qu50	Qu60	Qu70	Qu80	Qu90
No. Obs	152	152	152	152	152	152	152	152	152
Panel C. Reduced control variables									
<i>P</i>	0.019*** (0.007)	-0.050*** (0.013)	-0.059*** (0.020)	-0.052*** (0.010)	-0.058*** (0.015)	-0.050*** (0.015)	-0.048*** (0.017)	-0.049*** (0.015)	-0.039*** (0.013)
<i>G</i>	1.596*** (0.093)	1.511*** (0.131)	1.591*** (0.170)	1.734*** (0.169)	1.660*** (0.124)	1.687*** (0.155)	1.611*** (0.124)	1.836*** (0.137)	2.071*** (0.102)
No. Obs	152	152	152	152	152	152	152	152	152
<i>P</i>	-0.074*** (0.011)	-0.112*** (0.010)	-0.110*** (0.012)	-0.110*** (0.009)	-0.120*** (0.018)	-0.118*** (0.020)	-0.121*** (0.017)	-0.110*** (0.019)	-0.101*** (0.009)
<i>G</i>	2.493*** (0.171)	2.443*** (0.096)	2.361*** (0.162)	2.379*** (0.133)	2.577*** (0.493)	2.404*** (0.215)	2.196*** (0.089)	2.174*** (0.154)	2.457*** (0.097)
<i>P x G</i>	0.226*** (0.048)	0.262*** (0.025)	0.243*** (0.037)	0.253*** (0.029)	0.300*** (0.088)	0.268*** (0.054)	0.219*** (0.046)	0.173** (0.068)	0.174*** (0.047)
No. Obs	152	152	152	152	152	152	152	152	152

Qu is the quantile distribution of dependent variable.

***, **, * show statistical significance at 1%, 5%, and 10%, respectively.

policymakers. The first and foremost policy initiative to be taken should involve easing the level of geopolitical insecurity. Reducing geopolitical risk will encourage cleaner energy production and diminish the detrimental impacts of fossil fuels on the environment while allowing governments to achieve higher economic growth rates in a sustainable manner. However, some geopolitical risks are unavoidable and unpredictable. In such cases, the extent to which geopolitical risks cause environmental consequences either directly or indirectly through their dampening impacts on the effectiveness of PPPIE depends largely on how well a country responds to the geopolitical tension and manages its PPPIE.

Based on the four potential channels through which geographical risk may interfere with the PPPIE–environmental quality linkage as proposed in this study, we suggest four strategies to ensure the effectiveness of PPPIE in achieving environmental sustainability goals when a country suffers a high level of geopolitical risks. First, during the geopolitical uncertainty periods, governments should adopt stringent environmental regulations and restructure the public–private partnership models in a way that increases PPPIE’s transparency in terms of the choice of technology, materials, project management, and risk sharing. This would prevent the rent-seeking behaviors among both authorities and economic actors that distort the decision-making of PPPIE. Second, despite that new urgent issues may arise when a country faces uncertainty caused by geopolitical risks, environmental controls should be always kept among top priorities. In fact, the deployment of renewable energy is found to be more efficient for economic growth than non-renewables (Doğan et al., 2020). This implies a possible win–win solution for the environment–growth nexus. Accordingly, governments could encourage and leverage the diffusion of PPPIE outcomes through supply chains as one of their economic resilience strategies. This may create significant positive externalities to the economy, society, and environment at the same time. Third, the adoption of more stringent environmental regulations and reducing costs of adopting environmental-related technologies through subsidies may negate the “rebound effects” of green innovation (which tends to increase during geopolitical uncertainty periods. Fourth, stabilizing the economy to quickly recover from the economic hardships caused by high geopolitical tension such as decreased income, rising unemployment, and dim economic outlooks is also a crucial strategy. This would help enhance energy efficiency and achieve sustainable development targets by accelerating the adoption of PPPIE outcomes in consumption and production activities.

This research has some drawbacks that leave room for forthcoming research. First, the study gives a primary focus on the long-run impacts of PPPIE and GPR on air pollution, measured by carbon emissions in E7 nations. Future research could expand the discussion about these relationships by exploring and comparing both the long- and short-run environmental influences of these two determinants. In additions, further examination about either the effects of various types of public–private partnership investment on air pollution or other proxies of environmental quality, e.g. ecological footprint could also provide more insightful results and implications. Limited sample of analyzed countries is another limitation of this research. This opens up a new research direction which revisit the hypothesized relationships for other country groups, such as G20, OECD, and Belt and Road Initiative countries. Such region- or group-focused research will provide helpful insights into the interrelationships among the concerned factors that support policymakers to better tailor their environmentally-related strategies.

Appendix 1

See Fig. 3.

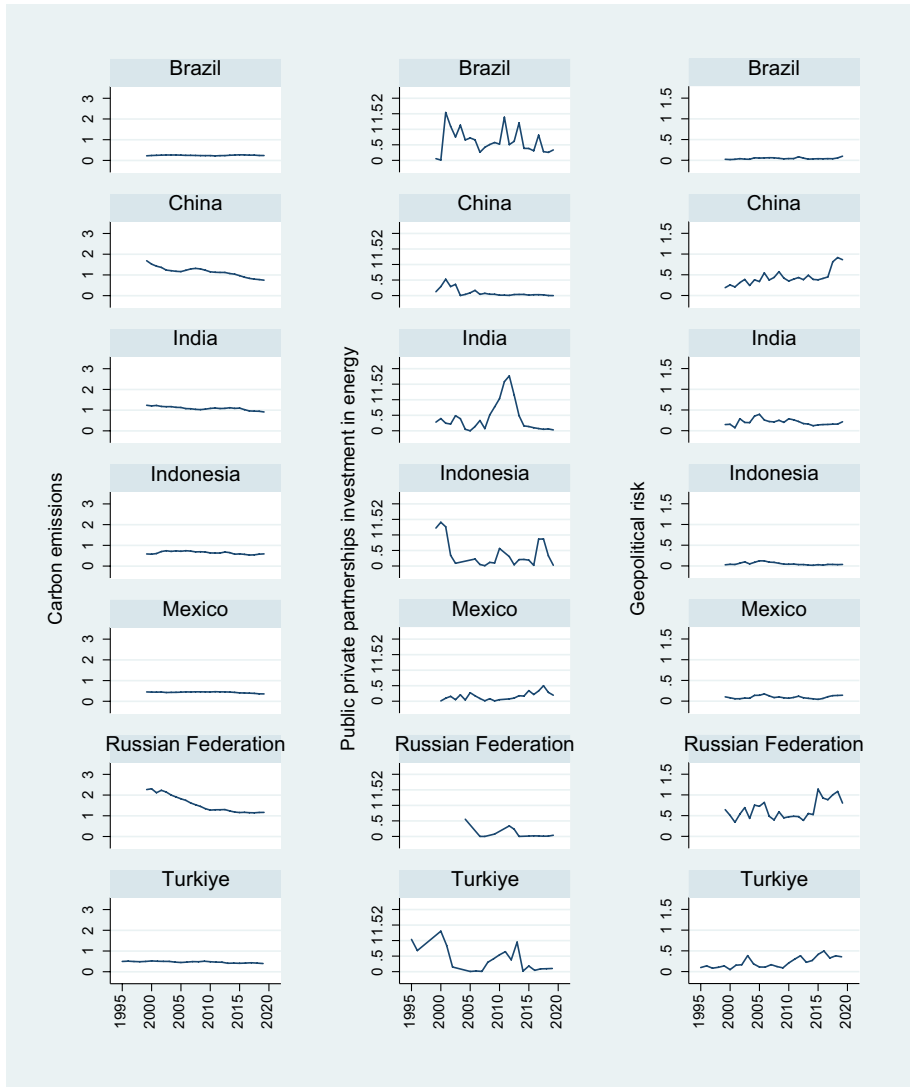


Fig. 3 Carbon emissions, Public–private partnership investment in energy, Geopolitical risk in E7 countries (1995–2019).

Appendix 2

See Fig. 4.

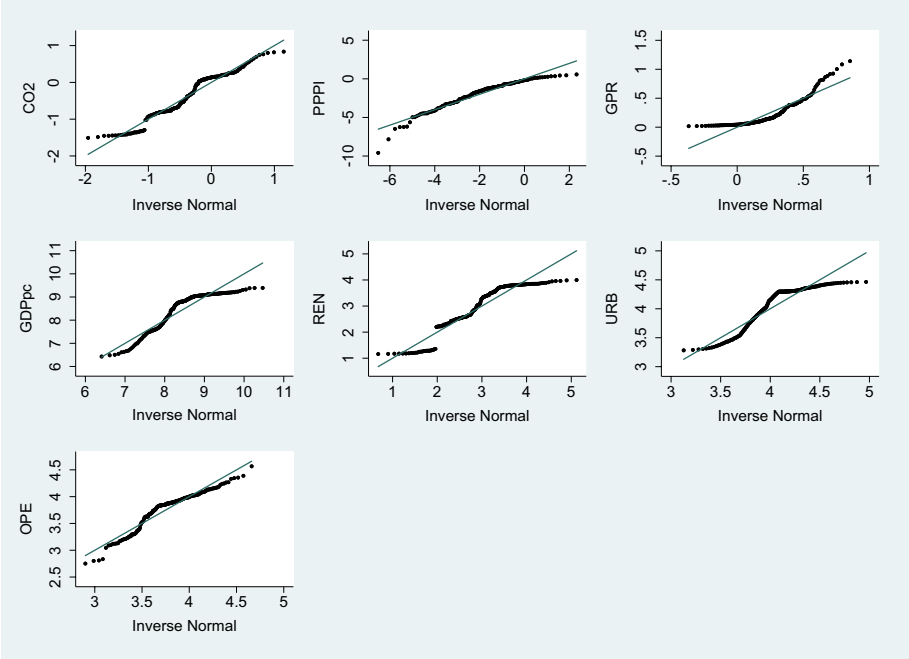


Fig. 4 The normal Q-Q plot.

Appendix 3

See Fig. 5.

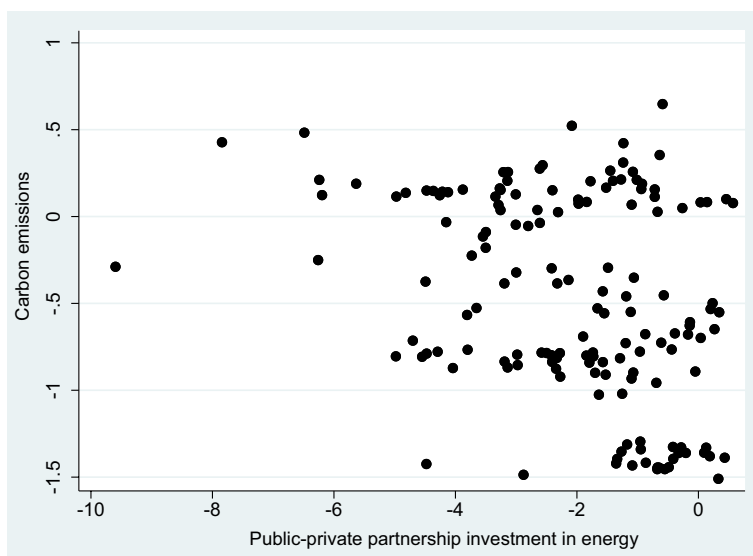


Fig. 5 The scatter relationship between carbon emissions and PPPIE.

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Data availability All data analyzed during this study are freely gathered from public sources.

Declarations

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