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Time-varying interactions between geopolitical risks and renewable energy consumption

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ADB Working Paper Series

**TIME-VARYING INTERACTIONS
BETWEEN GEOPOLITICAL RISKS
AND RENEWABLE ENERGY
CONSUMPTION**

Yifei Cai and Yanrui Wu

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Abstract

This study utilizes a time-varying parameter Bayesian vector autoregressive model to investigate the dynamic interactions between geopolitical risk (GPR) and renewable energy consumption growth (RECG). The identification strategy is flexible to accommodate cases both with and without sign restrictions. It is shown that GPR shocks have positive impacts on RECG over time. In contrast, RECG shocks decrease GPR in the whole sample period. These results show that renewable energy is a useful tool to reduce geopolitical risks. Meanwhile, the increasing geopolitical risks tend to augment renewable energy consumption. We also provide the responses at different time horizons and during particular geopolitical events. The estimating results are robust when industrial production growth is used as a control variable. Lastly, several implications for economic policy making are discussed.

Keywords: renewable energy consumption, geopolitical risk, time-varying parameter VAR model, robustness checks

JEL Classification: Q20, D80, C11

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1. INTRODUCTION

In recent decades, oil-rich regions such as the Persian Gulf have become the most geopolitically sensitive area. Major geopolitical events such as the Gulf War, Kuwait invasion, and Iraq invasion all occurred in this area. Meanwhile, the gas crisis between the Russian Federation and Ukraine poses a geopolitical challenge to the world in terms of energy security. Moreover, other geopolitical events such as the 9/11 terrorist attack, Madrid bombing, London bombing, Iranian nuclear tensions, ISIS escalation, and the Democratic People's Republic of Korea's nuclear issue all pose a threat to economic stability and could drive the next round of energy transition. Some resource-rich countries even utilize oil and gas supplies as geopolitical weapons to achieve their political goals. Although oil and gas play key roles in supporting growth, the rapid growth of renewable energy is gaining greater attention.

Renewable energy is a potential substitute for fossil fuels and is viewed as the main support for cleaner growth. Since 2018, the share of renewable energy consumption in the US has doubled, as coal's share declined in the same period from 48% to 30%. Although President Donald Trump signals a desire to cut funding for renewable energy and energy efficiency programs, renewable energy consumption is still surging due to the market forces. Besides, 18% of all electricity in the US was produced by renewable sources in 2017. According to a comprehensive study by NREL (2020), renewable energy will generate most of the electricity in the United States (US) by 2050. The driving forces are the development of technology and decreasing cost.

Unlike oil and gas, renewable energy is less dependent on rare earth elements. The key rare elements for renewable energy include neodymium, praseodymium, and dysprosium. Overland (2019) shows that these materials only account for less than 2% of wind turbines which use permanent magnets in the US. Other earth elements for renewable energy include lithium, cobalt (lithium ion battery technology), and copper (electric turbines), but these materials are not rare in the earth's crust. For instance, lithium is widely spread in countries including Australia, the People's Republic of China, the Russian Federation, and the US. The common materials required for renewable energy determine that it is less likely to be a source used as a geopolitical weapon. To some extent, renewable energy, as a substitute for oil and gas, can be a useful tool to alleviate the world's current geopolitical stress.

Overland (2019) argues that the nexus between geopolitical risk and renewable energy represents a new research direction. He suggests that the interaction between the two factors should be modeled as a changing process, because both geopolitical risk and renewable energy have changed dramatically in recent decades. However, existing studies are mainly qualitative rather than quantitative. In this paper, we first provide quantitative evidence in this field by considering a concise model to investigate the dynamics between geopolitical risk and renewable energy consumption. The model belongs to the time-varying parameter Bayesian vector autoregressive (TVP-BVAR) family. The identification is flexible and plausible by combining cognoscibilism (sign restrictions) and agnosticism (no restrictions). The reasons for choosing the TVP-BVAR model can be summarized as follows. Geopolitical risk (GPR) is a time-varying process which has extreme values. From 1985 onwards, the GPR index measured by Caldara and Iacoviello (2018) peaked during the US bombing of Libya (1986), the Kuwait invasion (1990), the Gulf War (1991), the Iraq disarmament crisis (1996), the 9/11 terrorist attack (2001), the Iraq invasion (2003), tensions over Iran's nuclear treaty (2006), the Syrian and Libyan Civil War (2011), the Democratic People's Republic of Korea satellite explosion (2012), and ISIS escalation (2015). Although previous studies like that by

Caldara and Iacoviello (2018) present negative impacts of GPR shock on aggregate economic activity, time-varied responses of economic indicators for GPR shocks are preferred so that one can explore whether there are significant changes during geopolitically sensitive periods.

This study contributes to the literature in several ways. First, changes in geopolitical risk and renewable energy consumption are demonstrated in the TVP-BVAR model, which is complicated enough to reveal time-varied interactions. Second, the identification of the model accommodates both no restriction and sign restrictions. Specifically, GPR shock is identified as a constraint of GDP growth. Moreover, we impose no restrictions on the responses of renewable energy consumption growth (RECG) and real crude oil price returns (RCOR). However, RECG shock is identified as a booster of GDP growth. Sign restrictions are imposed based on existing knowledge that GPR shock tends to slow down aggregate economic growth (Caldara and Iacoviello 2018) and that RECG and economic growth are mutually promoting (Sadorsky 2009; Apergis and Payne 2012; Inglesi-Lotz 2016). Since there are no related studies focusing on the responses of RECG and RCOR to a GPR shock and the responses of GPR and RCOR to a RECG shock, it is reasonable to use the identification strategy of no restriction. Third, we find time-varying impacts of GPR shocks on RECG over time, and that GPR shocks have increasingly positive impacts on RECG. In contrast, an increase in RECG reduces geopolitical risk over time. Specifically, we witness a significant drop in the response of GPR after the 9/11 terrorist attack. Thus, renewable energy consumption is a useful tool to reduce geopolitical risks, providing quantitative support for Overland's (2019) argument. Fourth, the estimations are robust when industrial production growth is used to describe the aggregate economic performance. Fifth, we discuss economic implications for the energy sector.

The rest of the paper is organized as follows. Section 2 reviews previous studies. Section 3 discusses the dataset. Section 4 introduces the econometric model. Section 5 shows the empirical results. Section 6 checks the robustness. The last section concludes the paper.

2. LITERATURE REVIEW

The study of geopolitics was first introduced by Tuathail (1998), who explained the causal relationship between geography and international affairs by focusing on the permanent rivalry, territorial expansion, and military strategies of imperial powers. During World War I, Winston Churchill transformed the energy consumption strategy of the British Navy from coal to oil. Furthermore, oil demand has surged significantly with the industrialization of more emerging economies such as the People's Republic of China, India, Brazil, and so on in recent decades. With growing car ownership, the demand for oil has increased sharply to an unprecedented level. These changes have transformed oil security from a military issue to a core factor of economic growth, and eventually to an important part of household living. Oil production areas such as the Persian Gulf are subject to the influence of geopolitics. As a result, seeking an alternative energy source to replace the leading position of oil in the energy mix is gaining great attention. Renewable energy attracts public attention not only due to its lower CO₂ emissions, but because of its wider availability (Overland 2019).

Existing studies about the nexus between geopolitics and renewable energy are rare for the following reasons. First, there was no representative index to measure geopolitical risk before the seminal work of Caldara and Iacoviello (2018). Second, renewable energy is still in the development stage and is not the main component in the energy mix, though it is growing rapidly. Third, the nexus between geopolitics and renewable energy should be modeled as a time-varying process, since both indicators have changed dramatically over time (Overland 2019). Although there is a paucity of related literature, existing studies put more focus on renewable energy consumption and economic activities.

Generally, increasing economic activity will increase renewable energy consumption, and vice versa (Sadorsky 2009; Apergis and Payne 2012; Inglesi-Lotz 2016). As economic growth slows down, energy consumption also decreases. Sadorsky (2009) uses a panel cointegration test to examine the long-run nexus between renewable energy consumption and income in emerging economies. The results support the statistically significant impact of income on renewable energy consumption in emerging economies: in the long-run perspective, a 1% increase in real income per capita will increase renewable energy consumption by about 3.5%. Apergis and Payne (2012) examine bi-directional causality between renewable energy consumption and growth. The authors argue that renewable energy is commonly viewed as the impetus for energy modernization to achieve sustainable development. High economic growth ensures sufficient investment in research and development to support the development of renewable energy. Inglesi-Lotz (2016) also shows statistically positive impacts of renewable energy consumption on growth. Thus, developing renewable energy can benefit not only the environment, but also growth.

Although no previous studies offer the reactions of renewable energy consumption to policy uncertainties, Kang and Ratti (2013a, 2013b, 2015) and Antonakakis, Chatziantoniou, and Filis (2014) investigate the nexus between policy uncertainty and crude oil. Specifically, Kang and Ratti (2013a, 2013b) implement a structural vector autoregressive (VAR) model to examine the impacts of economic policy uncertainty on real oil price. Their empirical findings show that policy uncertainty shock reduces the real price of oil. Furthermore, policy uncertainty shock slows economic activity. These findings are consistent with Baker, Bloom, and Davis (2016) and Creal and Wu (2017). Antonakakis, Chatziantoniou, and Filis (2014) focus on the relationship between oil price and economic policy uncertainty by building a structural VAR model. Their empirical results illustrate that policy shock can reduce crude oil price changes. With regard to the relationship between GPR and crude oil, Caldara and Iacoviello (2018) present that GPR shock negatively affects crude oil price. This finding is supported by Antonakakis et al. (2017); Cunado et al. (2019); and Plakandaras, Gupta, and Wong (2019).

There are emerging studies on the measurement of policy uncertainty, such as those by Baker, Bloom, and Davis (2016); Creal and Wu (2017); Azzimonti (2018); and Caldara and Iacoviello (2018). Baker, Bloom, and Davis (2016) construct a new economic policy uncertainty index based on newspaper coverage frequency. Within the framework of a VAR model, they find a 90-point increase in economic policy uncertainty foreshadows a significant drop of about 1% in industrial production. Caldara and Iacoviello (2018) propose a GPR index which describes potential risks in geopolitics. Different from the economic policy uncertainty index of Baker, Bloom, and Davis (2016), the GPR index excludes economic events such as financial collapse and economic crisis. Similar to Baker, Bloom, and Davis (2016), Caldara and Iacoviello (2018) find that a geopolitical shock will cut industrial production, employment, gross trade, and real oil

price. The empirical results indicate an adverse impact of GPR on economic activity.¹ Azzimonti (2018) develops a partisan conflict index based on a semantic search approach and then investigates its relationship with investment. The empirical results show that an increase in the partisan conflict index leads to a decrease in aggregate investment in the US. Moreover, Azzimonti (2018) suggests that an increase in the benchmark partisan conflict index will reduce investment rates at firm level.

3. DATA AND ECONOMETRIC MODELS

3.1 Data

Our benchmark model is a reduced-form VAR model including renewable energy consumption growth ($RECG_t$), returns on real crude oil price ($RCOR_t$), GDP growth ($GDPG_t$), and geopolitical risks (GPR_t). The renewable energy consumption (REC_t) data is drawn from the US Energy Information Administration (2019) online database. $GDPG_t$ is the percentage change of GDP over last year $t - 1$, which is obtained from the Federal Reserve Bank of St. Louis. The imported real crude oil price is available from the Energy Information Administration (2019). The geopolitical risk index (GPR_t) is provided by Caldara and Iacoviello (2018).² The GPR is standardized. As a robustness check, we consider the growth of the industrial production index provided by the Federal Reserve Bank of St. Louis.³ The data are quarterly and cover the period from 1985Q1 to 2018Q2. The plots of variables are shown in the appendix.

3.2 Models

The TVP-BVAR model is built as:

$$y_t = c_t + B_{1,t}y_{t-1} + \dots + B_{k,t}y_{t-k} + \mu_t, t = 1, \dots, T \quad (1)$$

where y_t is an $n \times 1$ vector of observed variables which are endogenous; c_t is an $n \times 1$ vector of time-varying trend; $B_{i,t}$ ($i = 1, \dots, k$) is an $n \times n$ vector representing time-varying coefficients in the VAR system; and μ_t represents unobservable shocks with the variance and covariance matrix Ω_t . Unlike Cogley and Sargent (2005), the TVP-BVAR relaxes constant volatility consumption. Thus, the variance-covariance matrix can be defined as:

$$A_t \Omega_t A_t' = \Sigma_t \Sigma_t' \quad (2)$$

where A_t is a lower triangular matrix:

¹ Studies like those by Antonakakis et al. (2017) and Balcilar et al. (2018) investigate the stock market reaction given a geopolitical risk shock. Balcilar et al. (2018) show that geopolitical risk shock can generate more profound impacts on volatility than on returns. Antonakakis et al. (2017) further present that geopolitical risk triggers major negative impacts on oil returns and volatility, but less so on the covariance between crude oil and stock markets.

² The data is available at <https://www2.bc.edu/matteo-iacoviello/gpr.htm>.

³ We utilize augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests to examine the stationarity of $RECG_t$, $RCOR_t$, $GDPG_t$, GPR_t , and IPG_t . The results are available upon request.

$$A_t = \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ a_{n1,t} & \cdots & 1 \end{bmatrix} \quad (3)$$

and Σ_t is the diagonal matrix:

$$\Sigma_t = \begin{bmatrix} \sigma_{1,t} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_{n,t} \end{bmatrix} \quad (4)$$

Given that, equation (1) can be expressed as

$$y_t = c_t + B_{1,t}y_{t-1} + \cdots + B_{k,t}y_{t-k} + A_t^{-1}\Sigma_t\varepsilon_t, t = 1, \dots, T \quad (5)$$

where ε_t represents the independently and identically distributed errors with $\text{var}(\varepsilon_t) = I_n$. By stacking the coefficients in a vector, equation (1) can be rewritten as

$$y_t = X_t' B_t + A_t^{-1}\Sigma_t\varepsilon_t \quad (6)$$

where $X_t' = I_n \otimes [1, y_{t-1}', \dots, y_{t-k}']$. The \otimes denotes the Kronecker product.

To model the coefficient processes in equation (6), the coefficients B_t and the elements of A_t are assumed to be a random walk. In addition, assuming A_t is time-variant is important in the time-varying VAR model. A constant A_t implies that a shock to the i^{th} variable has a time-invariant impact on the j^{th} variable in the system. For the standard deviation of shocks Σ_t , we use a stochastic volatility framework and assume that the elements of this framework follow a geometric random walk. Therefore, the time-varying parameters with dynamics can be specified as follows:

$$B_t = B_{t-1} + v_t \quad (7)$$

$$a_t = a_{t-1} + \zeta_t \quad (8)$$

$$\log \sigma_t = \log \sigma_{t-1} + \eta_t \quad (9)$$

where the distributional assumptions of the above error terms ($\varepsilon_t, v_t, \zeta_t, \eta_t$) are stated as follows. The standard deviations σ_t are assumed as geometric random walks. The other innovations in the model are assumed to be jointly normally distributed. Thus, the variance-covariance matrix of ($\varepsilon_t, v_t, \zeta_t, \eta_t$) can be defined as:

$$\text{Var} \left(\begin{bmatrix} \varepsilon_t \\ v_t \\ \zeta_t \\ \eta_t \end{bmatrix} \right) = \begin{bmatrix} I_n & 0 & 0 & 0 \\ 0 & Q & 0 & 0 \\ 0 & 0 & S & 0 \\ 0 & 0 & 0 & W \end{bmatrix} \quad (10)$$

where I_n is an n – dimensional identity matrix and $Q, S,$ and W are positive definite matrices.

3.2.1 Priors

To determine the prior distributions of the time-varying parameters in the model, the mean of B_0 is defined by the ordinary least square (OLS) estimate of the time-invariant VAR model. The variance of B_0 is four times the variance of the OLS point estimate of the time-invariant model. Thus, the distribution of B_0 is expressed as follows:

$$B_0 \sim N(\widehat{B}_{OLS}, 4 \cdot \text{var}(\widehat{B}_{OLS})) \quad (11)$$

The prior distribution for A_0 is determined by the same method as B_0 :

$$A_0 \sim N(\widehat{A}_{OLS}, 4 \cdot \text{var}(\widehat{A}_{OLS})) \quad (12)$$

The prior distribution for $\log \sigma_0$ specifies that the mean is established as the logarithm of the OLS estimate of the standard errors from time-invariant VAR model. The variance-covariance matrix is four times the identity matrix:

$$\log \sigma_0 \sim N(\log \sigma_{OLS}, 4I_n) \quad (12)$$

Lastly, the prior distributions of the hyperparameters Q , S , and W are specified as,

$$Q \sim IW(k_Q^2 \cdot \tau \cdot \text{var}(\widehat{B}_{OLS}), \tau) \quad (13)$$

$$W \sim IG(k_W^2 \cdot (1 + \dim(W)) \cdot I_n, (1 + \dim(W))) \quad (14)$$

$$S_l \sim IW(k_S^2 \cdot (1 + \dim(S_l)) \cdot \text{var}(\widehat{A}_{l,OLS}), (1 + \dim(S_l))) \quad (15)$$

where τ is the size of the training sample; S_l is the l^{th} block of S ; $\widehat{A}_{l,OLS}$ is the corresponding l^{th} block of \widehat{A}_{OLS} ; and IW and IG are the inverse gamma and inverse Wishart distribution, respectively. The values of k_Q , k_W , and k_S are discussed below. The degree of freedom of the scale matrices of the inverse-gamma prior distribution is equal to one plus the dimension of each matrix. The scale matrices are here constant fractions of the products obtained by multiplying the variances of the matching OLS estimates of the training sample by the degrees of freedom of the appropriate scale matrix.

3.2.2 Identification

We include renewable energy consumption growth, GDP growth, returns on real imported crude oil price, and geopolitical risks in the TVP-BVAR model. The identification of the model allows for both no restrictions and sign restrictions. For a GPR shock, we impose no restrictions on the responses of $RECG_t$ and $RCOR_t$. Furthermore, we assume a GPR shock is associated with a decrease in $GDPG_t$ and an immediate increase in GPR_t , which is shown in Caldara and Iacoviello (2018). When $RECG$ shock is considered, the response of $GDPG_t$ is restricted to be positive. However, no restrictions are imposed on GPR_t and $RCOR_t$. The options of restrictions are summarized in Table 1.

In line with the method proposed by Fry and Pagan (2011), the identification of sign restrictions of a given shock is carried out by Givens rotations. The sign restrictions are examined to determine the applicability of a set of possible transformations of structural residuals into reduced-form residuals. Given an orthonormal matrix D , the following is established:

$$A_t^{-1} \Sigma_t \epsilon_t = A_t^{-1} \Sigma_t D' D \epsilon_t \quad (16)$$

where $D \epsilon_t$ denotes another vector of uncorrelated structural residuals with unit variance. Givens rotations are presented as follows:

$$D = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos(\theta) & -\sin(\theta) \\ 0 & 0 & \sin(\theta) & \cos(\theta) \end{bmatrix} \quad (17)$$

where the parameter θ is drawn from a uniform distribution over the interval $(0, \pi)$. Obviously, we assume that structural shocks to the third and fourth variables do not contemporaneously affect the first two variables. Moreover, the sign restrictions in Table 1 are imposed only in the first two quarters.

Table 1: Sign Restrictions

Shocks\Responses	RECG _t	RCOR _t	GDPG _t	GPR _t
GPR shock	?	?	-	+
RECG shock	+	?	+	?

Note: ? = no restrictions; + and – represent appreciation and depreciation, respectively. Specifically, we assume that a GPR shock is associated with decreasing GDPG_t and increasing GPR_t. Moreover, a RECG shock is associated with increasing GDPG_t and RECG_t.

4. RESULTS

4.1 Results of Standard VAR Model

We first implement the standard VAR model to investigate the impacts of GPR shocks on RECG, RCOR, and GDP growth (GDPG). The lag is determined to be two. The response of RECG to a GPR shock will increase in the first three months with a maximum magnitude of 1.3% (Figure 1). After that, the response gradually decreases to zero. Such a trend indicates GPR shocks make RECG move upward. In contrast, GPR shocks decrease the crude oil returns, since the response remains negative in the first two horizons with a magnitude of –2.5%. After that, the response turns positive and gradually approaches zero after five months. With regard to the response of GDPG, we find that GPR shocks have negative impacts on GDPG in the first two quarters. However, Overland (2019) suggests that the changing geopolitics will dynamically influence other indicators and implies that estimations based on a standard VAR model are less persuasive. Thus, using a time-varying method can provide more insights by combining sign restrictions with no restrictions.

As suggested by Overland (2019), renewable energy is viewed as a powerful tool to reduce GPR. Thus, we investigate the responses of GPR, RCOR, and GDP given a RECG shock by two lags. The results are shown in Figure 2. In panel (a) of Figure 2, we find RECG shock can reduce GPR, with the maximum impacts in the third quarter. In the following periods, the response of RECG approaches zero. These results are consistent with the findings of Overland (2019). The response of RCOR remains positive in the first three quarters and reverts to zero afterward. For the reaction of GDPG, we find RECG shock can increase GDPG in the first three quarters, which is consistent with the finding of a promoting nexus between renewable energy consumption and economic growth. In fact, renewable energy serves a more important role in the US energy mix.

Figure 1: Impulse Responses of Standard VAR Model Given GPR Shock

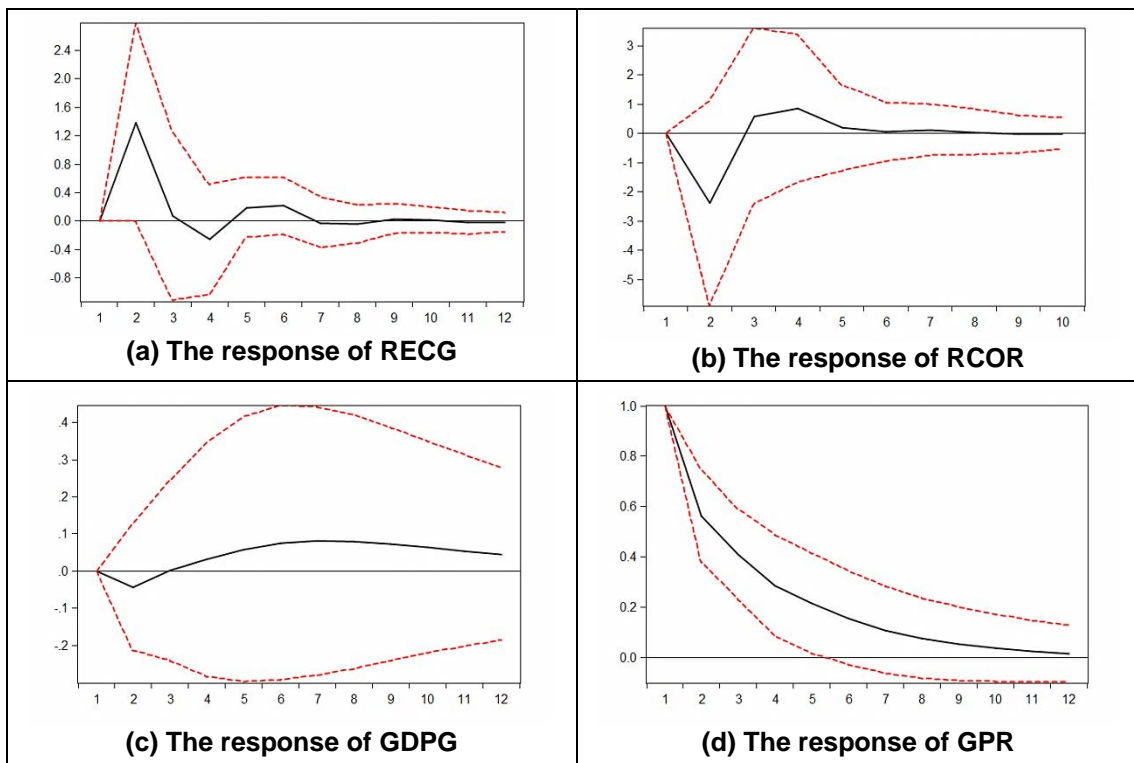
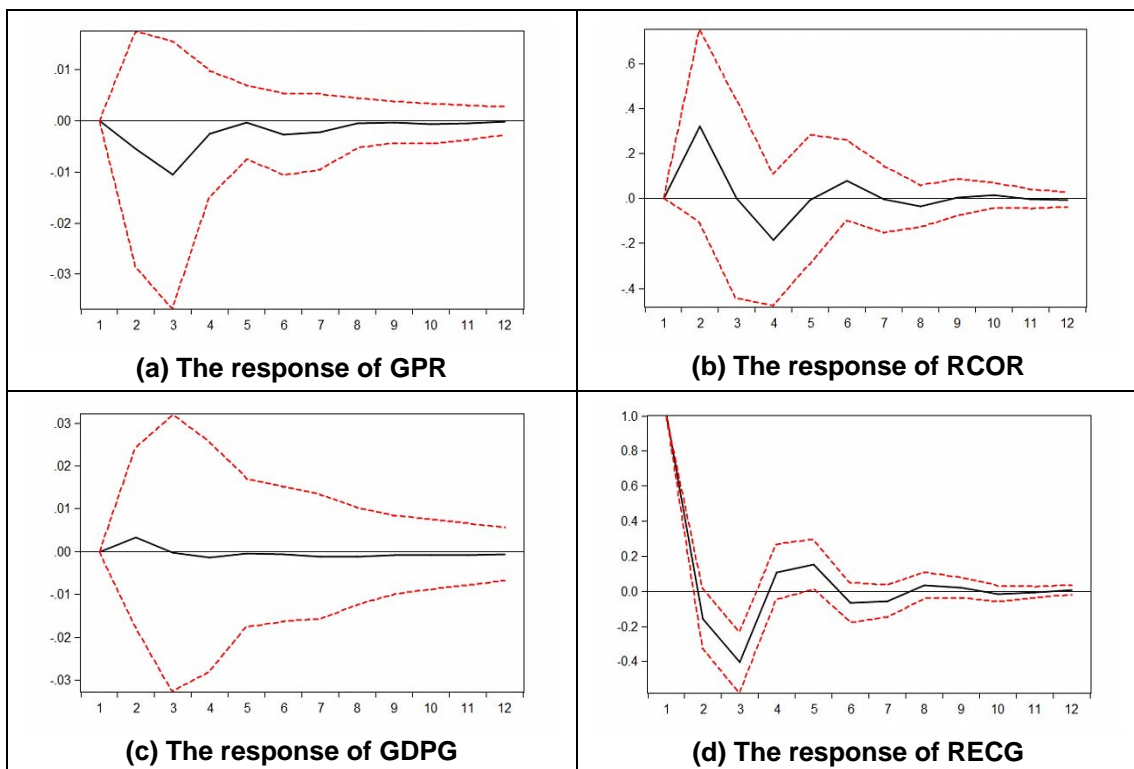


Figure 2: Impulse Responses of Standard VAR Model Given RECG Shock



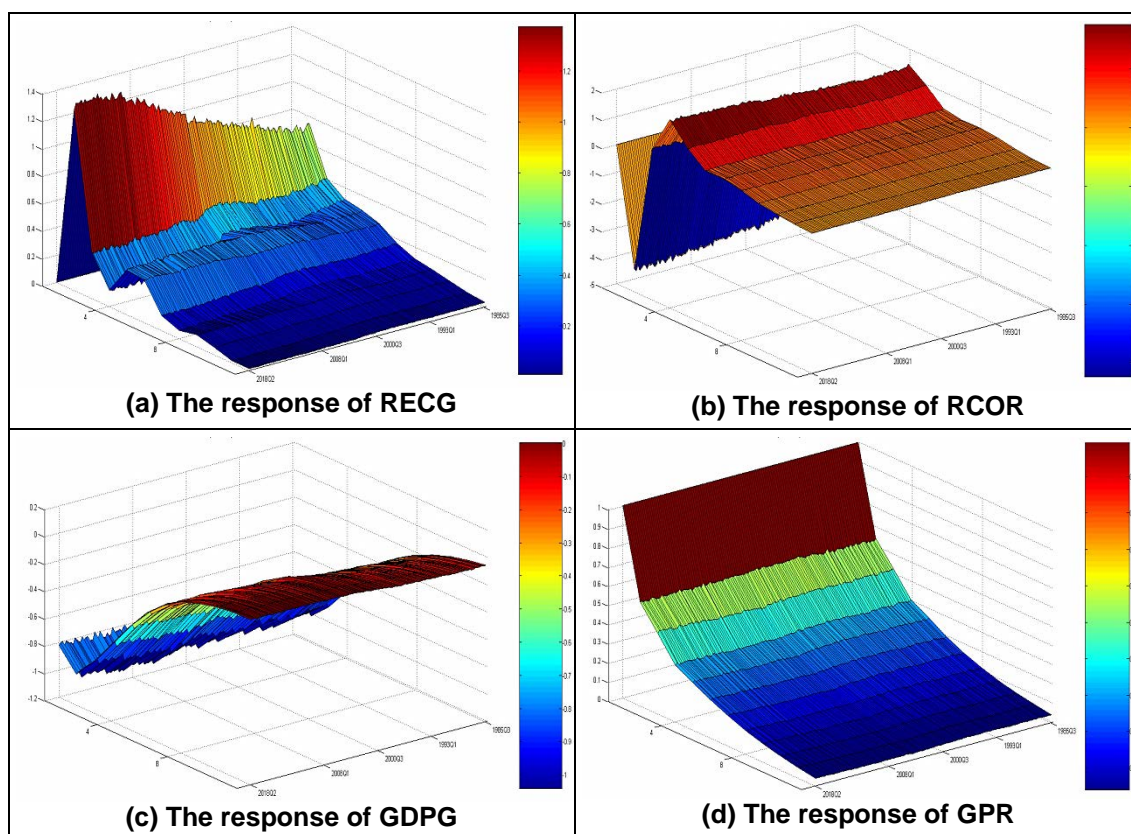
4.2 Results of TVP-BVAR Model with Sign Restrictions

To examine the dynamic interactions, we use two lags for estimation, as used in Primiceri (2005), Franta, Horváth, and Rusnak (2014), and Cai and Menegaki (2019). We use the entire sample period from 1985Q1 to 2018Q2 to derive the priors of the model (Canova, Gambetti, and Pappa 2007).⁴ By considering the priors for the time variation of the coefficients, the choices in existing studies are varied. Especially, the values of k_Q , k_S , and k_W can affect the posterior inference. Better choices can improve the fit of the model (Primiceri 2005). Following Kirchner, Cimadomo, and Hauptmeier (2010), we set $k_Q = 0.01$, indicating the prior attributes only 0.01 of the uncertainty surrounding the OLS estimates to time variation.⁵ In addition, we determine $k_W = 0.01$ and $k_S = 0.1$, which are also consistent with Cogley and Sargent (2005) and Primiceri (2005). To obtain the estimated results, the simulations are calculated with 20,000 iterations of the Gibbs sampler and convergence is established after the first 15,000 iterations.

The estimated median responses to GPR shocks are shown in Figure 3 with the sign restrictions in Table 1 imposed. Specifically, we impose no restrictions on $RECG_t$ and $RCOR_t$. However, we restrict the response of $GDPG_t$ to be negative. Given these conditions, the response of $RECG_t$ to a GPR shock is positive. The largest magnitude occurs in the second quarter. From 1985Q3 to 2019Q1, the magnitude of the response increased from 0.75% to 1.4%. These results indicate that geopolitical risk shocks make increasing impacts on RECG. After four months, there is a slight increase in the fifth month, when the response approaches zero. In terms of the reaction of $RCOR_t$, GPR shocks make the largest impacts in the second quarter with a magnitude of around -4%. After that, the responses become positive and approach zero. In terms of the response of $GDPG_t$, the responses remain negative over the whole sample period. The largest impact occurs in the second quarter with the magnitude of the response being -1%. After that, the reactions gradually approach zero. Overall, the time-varying responses of $RCOR_t$ and $GDPG_t$ are consistent with the results obtained from the standard VAR model in Figure 1. The only exception is $RECG_t$, which responds positively to GPR shocks.

⁴ As Canova et al. (2007) suggest, eliciting the priors over the whole sample is reasonable if a training sample is not available. Franta, Horváth, and Rusnak (2014) also use such a method to generate the priors as Czech Republic data cannot be reached pre-1996. The GPR index is freshly constructed and is used in few studies. Thus, the priors in this study are actually the estimations of a fixed-coefficient VAR model on the full sample from 1985Q1 to 2018Q2 covering a total of 134 observations. There are few studies focusing on the reactions of renewable energy consumption growth given a geopolitical risk shock. Thus, we utilize the full-sample data to elicit the priors.

⁵ Primiceri (2005) presents three reasons behind the choice of time variation of the coefficients. In short, the model misbehaves by choosing a higher k_Q , especially in forecasting (Stock and Watson 1996). Furthermore, Kirchner, Cimadomo, and Hauptmeier (2010) use a Monte Carlo simulation to check the fits with different situations.

Figure 3: Impulse Response of GPR Shocks Over Time

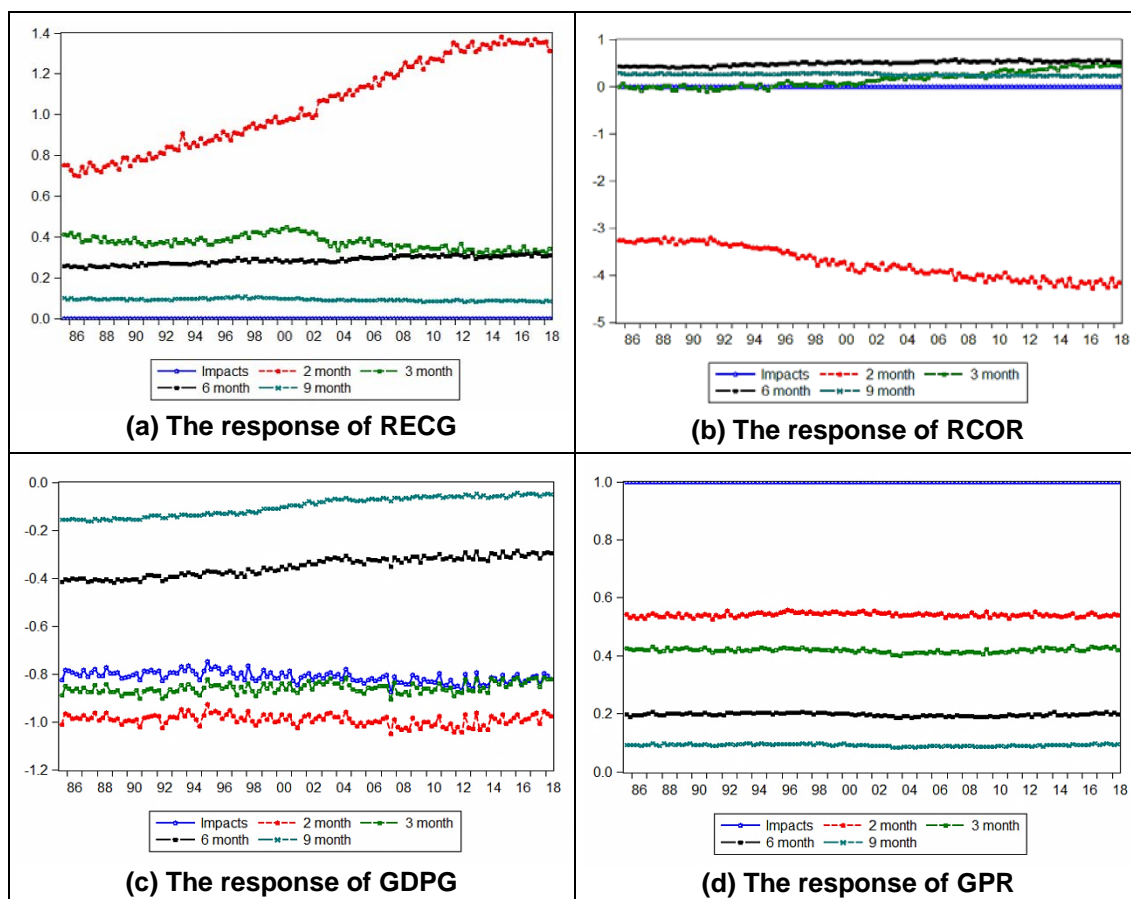
In more detail, this section compares responses over different time horizons. We focus on the responses during the immediate period, and over two, three, six, and nine months. In 1985 Q3, one percentage shock of GPR increases around 0.75% of $RECG_t$. After that, this impact steadily increases to around 1.4% in 2018Q2. The results imply that GPR shocks tend to have an increasing impact on $RECG_t$. However, the estimated results of the standard VAR model cannot provide the time-varying evidence. In recent decades, polarized geopolitics in the Middle East have threatened the world's oil security. The US has been involved in the Gulf War (August 1990–February 1991) and the Iraq invasion (March 2003–May 2003). Although there is no direct evidence that confirms the two wars are related to the manipulation of oil price, the outcomes of these two wars are quite different. According to the EIA (2019), the US imported crude oil price remained at around \$20 per barrel after the Gulf War. However, after the Iraq invasion in 2003, the imported crude oil price increased from \$30 per barrel to \$130 per barrel in 2008. Although there was a significant drop during the financial crisis, the price rebounded to \$100 per barrel from 2011 to 2013. After a period of fierce fluctuation, the price has steadied at around \$60 per barrel in recent years. There are also other geopolitical risks associated with the 9/11 terrorist attack, the Kuwait invasion, tensions over Iran and the nuclear treaty, and the US bombing of Libya in recent decades. These risks threaten the world oil trade, and renewable energy seems to be the most popular energy to substitute crude oil.

Based on panel (a) of Figure 4, GPR shock triggers more renewable energy consumption growth over time. The soaring oil price and dropping renewable energy cost, including the costs of solar and wind power, are the driving factors. As Overland (2019) shows, renewable energy is less dependent upon rare earth elements, which are considered to be the main determinant of fossil fuel costs. The critical components of renewable energy

include dysprosium, neodymium, terbium, europium, and yttrium. However, these critical materials are widely spread in Australia, Brazil, the People's Republic of China, Malaysia, the Russian Federation, Thailand, and the US. The price of these materials is not easily manipulated. Furthermore, Overland (2019) holds that there will be more technological improvement in the near future, able to significantly reduce the cost of renewable energy. Moreover, renewable energy plays an increasingly significant role in electricity production, which is viewed as a good method of decarbonization. To sum up, GPR shocks tend to have an increasing impact on $RECG_t$ over time.

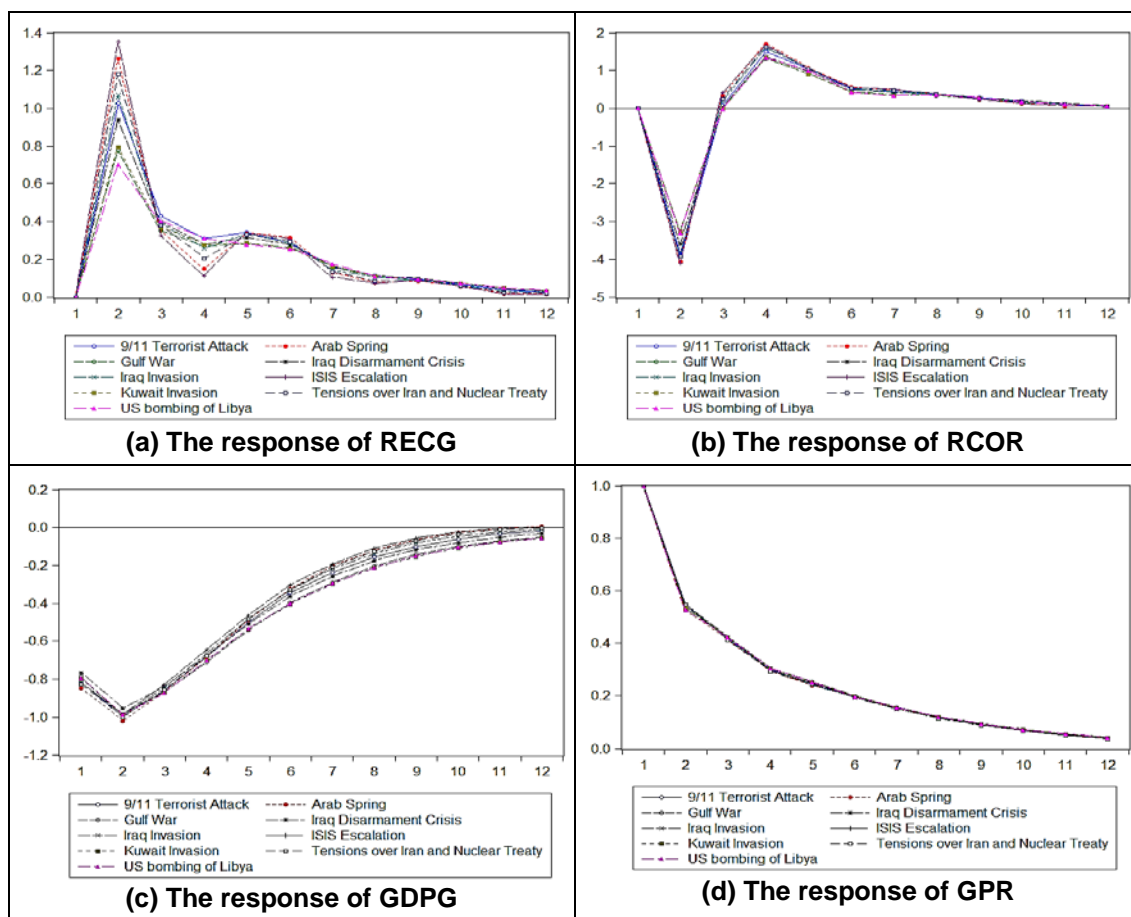
With regard to the response of crude oil returns, the largest impact occurs in the second month after the shock. Based on panel (b) of Figure 4, there is a decreasing trend, with a small slope in the response of $RCOR_t$ in the second horizon. These results imply that GPR shocks tend to decrease crude oil returns. After two months, the responses become positive and approach zero. In terms of the response of GDPG, the impacts bottom out in the second quarter after the shock. The impact of GPR shock on GDPG is comparatively stable over time. The results further indicate that the macroeconomy of the US is not likely to be changed by sudden geopolitical events, although GPR does indeed negatively affect the growth of GDP.

Figure 4: Impulse Response of GPR Shock with Different Time Horizons



To consider the responses of GPR shocks to particular events, we focus on the 9/11 terrorist attack, the Gulf War, the Iraq disarmament crisis, the Iraq invasion, ISIS escalation, the Kuwait invasion, Arab Spring, tensions over Iran and the nuclear treaty, and the US bombing of Libya, respectively.⁶ In terms of the $RECG_t$ response, the shape is considerably stable over 12 horizons (Figure 5). However, the magnitude of the impact is quite different when different geopolitical events are considered. The largest impact is associated with the ISIS escalation, and the smallest is linked with the US bombing of Libya. Arab Spring and tensions over Iran and the nuclear treaty also had an observable impact on $RECG_t$. After the 9/11 terrorist attack, the mean of the GPR index significantly changed, indicating the US experience of a geopolitically sensitive period. In terms of the response of $RCOR_t$, the impacts are homogeneous without significant changes over different horizons. Furthermore, the response of $RGDP_t$ tends to show similar patterns for different geopolitical events. When comparing the results with the standard VAR model, we find that the estimated results are quite similar, with the exception of the response of $RECG_t$, which shows significant time-varying heterogeneity over time.

Figure 5: Impulse Response of GPR Shock to Particular Events

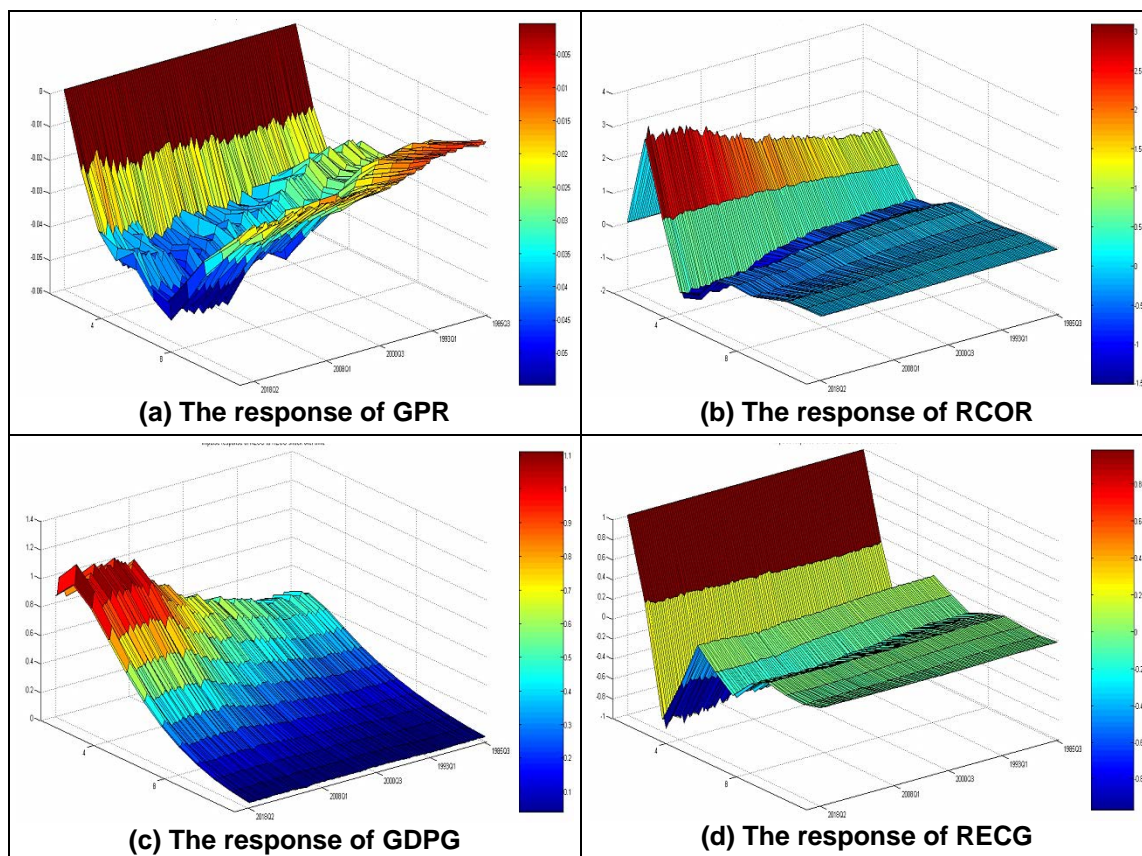


⁶ The dates of these geopolitical events can be found at <https://www2.bc.edu/matteiacoviello/gpr.htm>.

4.3 Results of TVP-BVAR Model with Sign Restrictions Given RECG Shock

The strategy for identifying RECG shock is different from the method for GPR shock. Specifically, we impose sign restrictions on the response of GDPG, that is, a RECG shock will lead to an increase in GDPG, based on existing studies like Sadorsky (2009), Apergis and Payne (2012), and Inglesi-Lotz (2016). However, no restrictions are imposed on the responses of GPR and RCOR. In panel (a) of Figure 6, the response of GPR to a RECG shock tends to be negative over time. The response surface in the 3-D chart (panel a of Figure 6) bottoms in the eighth quarter after the shock. Especially after the 9/11 terrorist attack, the impact dramatically falls. As panel (b) of Figure 6 shows, the response of $RCOR_t$ remains positive in the first three quarters. After that, the response becomes negative and finally reverts to zero. Panel (c) of Figure 6 shows the response of $GDPG_t$, and a RECG shock tends to have a larger impact after the 9/11 terrorist attack. This result indicates that renewable energy consumption has contributed more to economic growth since the 9/11 terrorist attack.

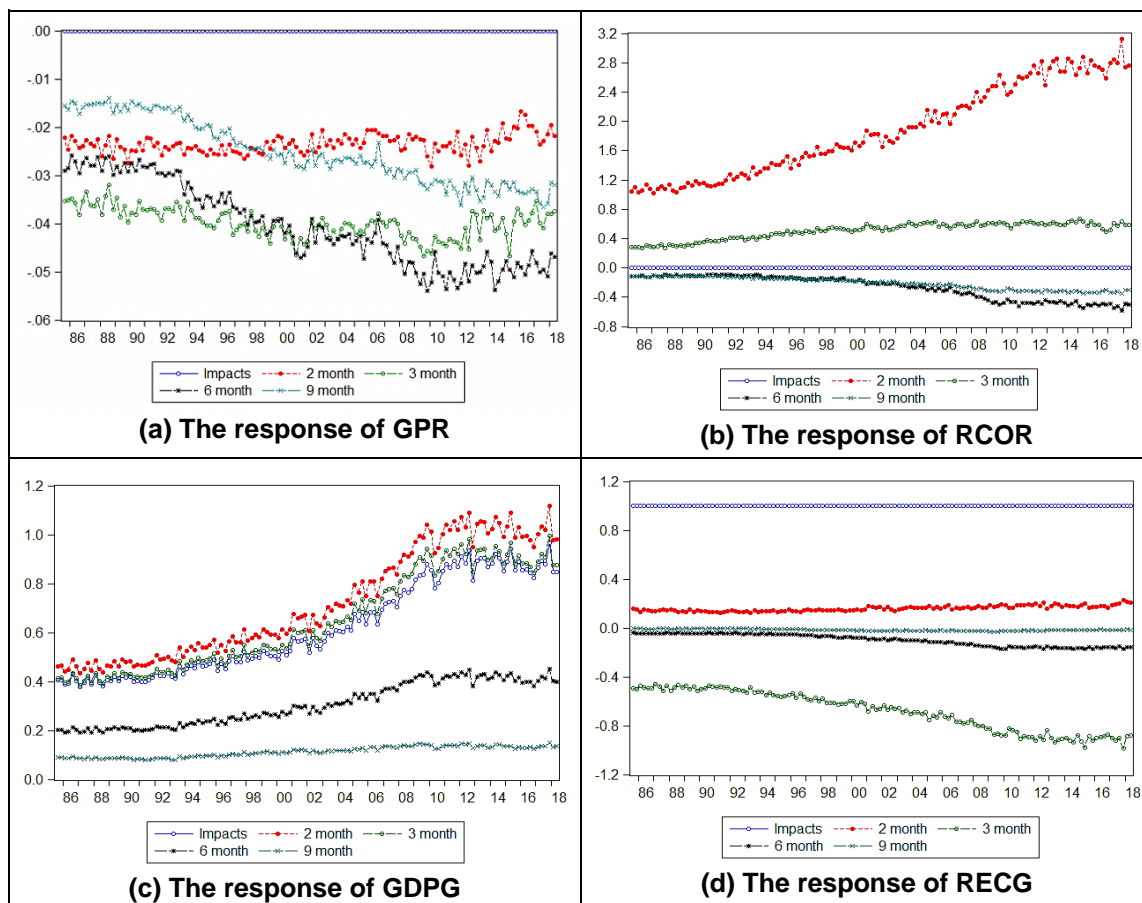
Figure 6: Impulse Response of RECG Shock Over Time



We also report the responses of GPR_t , $RCOR_t$, and $GDPG_t$ to RECG shocks over different time horizons in Figure 7. In panel (a), the response after three quarters tends to decrease across the whole sample period. Thus, the transmission of RECG shocks to GPR_t is not stable. After the 9/11 terrorist attack, the maximum impact occurs in the ninth month. These results imply that RECG shocks tend to have a long-lasting impact on GPR, which further verifies that renewable energy can reduce geopolitical risks.

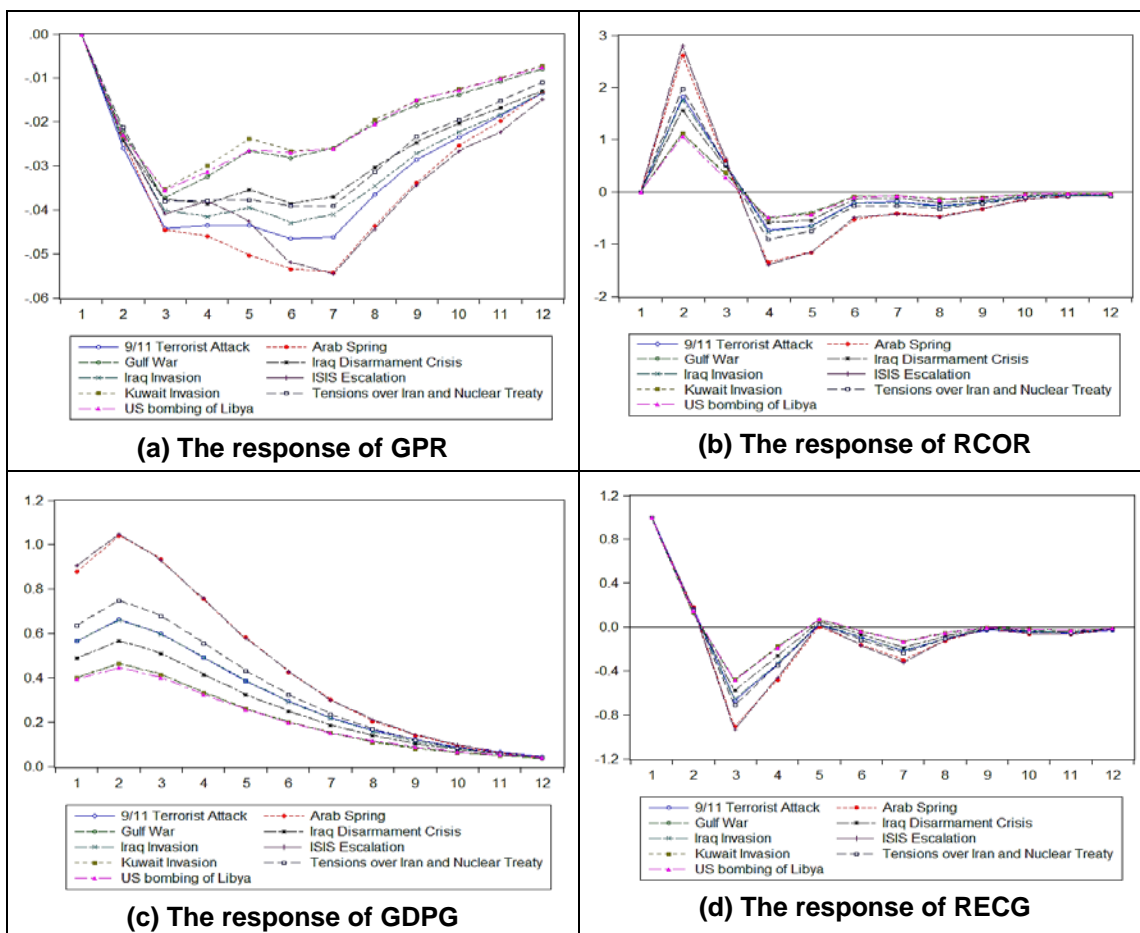
In terms of the responses of $RCOR_t$, we find RECG shocks tend to have an increasingly positive impact during the first three quarters. The response of $GDPG_t$ to an RECG shock is positive over the whole sample period. This increasing trend implies that renewable energy is playing a more important role in economic growth.

Figure 7: Impulse Response of RECG Shock to Particular Events



We also consider the responses of GPR_t , $RCOR_t$, and $GDPG_t$ to an RECG shock during different geopolitical events, such as the 9/11 terrorist attack, the Gulf War, the Iraq disarmament crisis, the Iraq invasion, ISIS escalation, the Kuwait invasion, Arab Spring, tensions over Iran and the nuclear treaty, and the US bombing of Libya. In panel (a) of Figure 8, we find RECG shocks have heterogeneous impacts on GPR over time. In comparison with the results of the standard VAR model, we find the transmission of RECG shocks to GPR is time-varied and shows heterogeneous patterns during different geopolitical events. Specifically, the RECG shocks tend to affect GPR modestly during the Kuwait invasion, the Gulf War and the US bombing of Libya. However, these impacts are greater for Arab Spring, ISIS escalation, and the 9/11 terrorist attack. The difference may be due to the long-lasting nature of these events. These findings confirm the conclusions of Overland (2019) on the key position of renewable energy in cutting geopolitical risks. As for the responses of $RCOR_t$, RECG shocks have impacts with different magnitudes, though the response patterns are similar. In terms of the responses of $GDPG_t$, RECG shocks also affect growth rate differently during different geopolitical events.

Figure 8: Impulse Response of RECG Shock to Particular Events



5. ROBUSTNESS CHECKS

This section checks the robustness of the findings discussed above by using industrial production growth (IPG) and the economic policy uncertainty index to replace GDP growth and GPR, respectively. The results are shown in Figures 9 and 10. We find similar results, in that GPR shocks increase $RECG_t$ over time (Figure 9). Furthermore, GPR shocks tend to affect $RECG_t$ increasingly. In terms of the response of $RCOR_t$, GPR shocks have the largest impact in the second horizon and the effects revert to zero afterward. Finally, the response of IPG remains stable over time. Based on the empirical findings, we can conclude the estimating results are robust.

In panel (a) of Figure 10, we find that RECG shocks decrease the GPR after the first quarter. Furthermore, the responses of RCOR remain positive in the first three quarters and become negative afterward. In terms of the responses of industrial production in panel (c), RECG shocks have increasingly positive impacts on IPG. Overall, the estimations are robust when RECG shocks are considered.

Figure 9: Robustness Check for GPR Shock

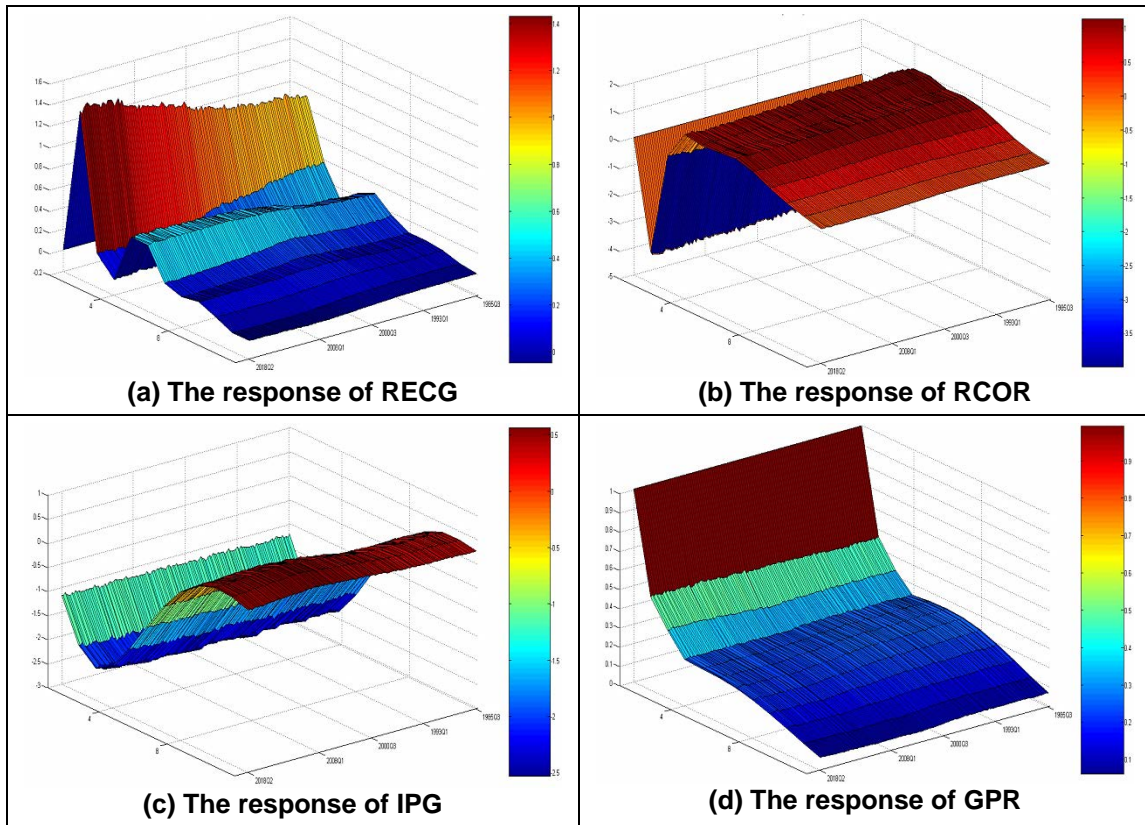
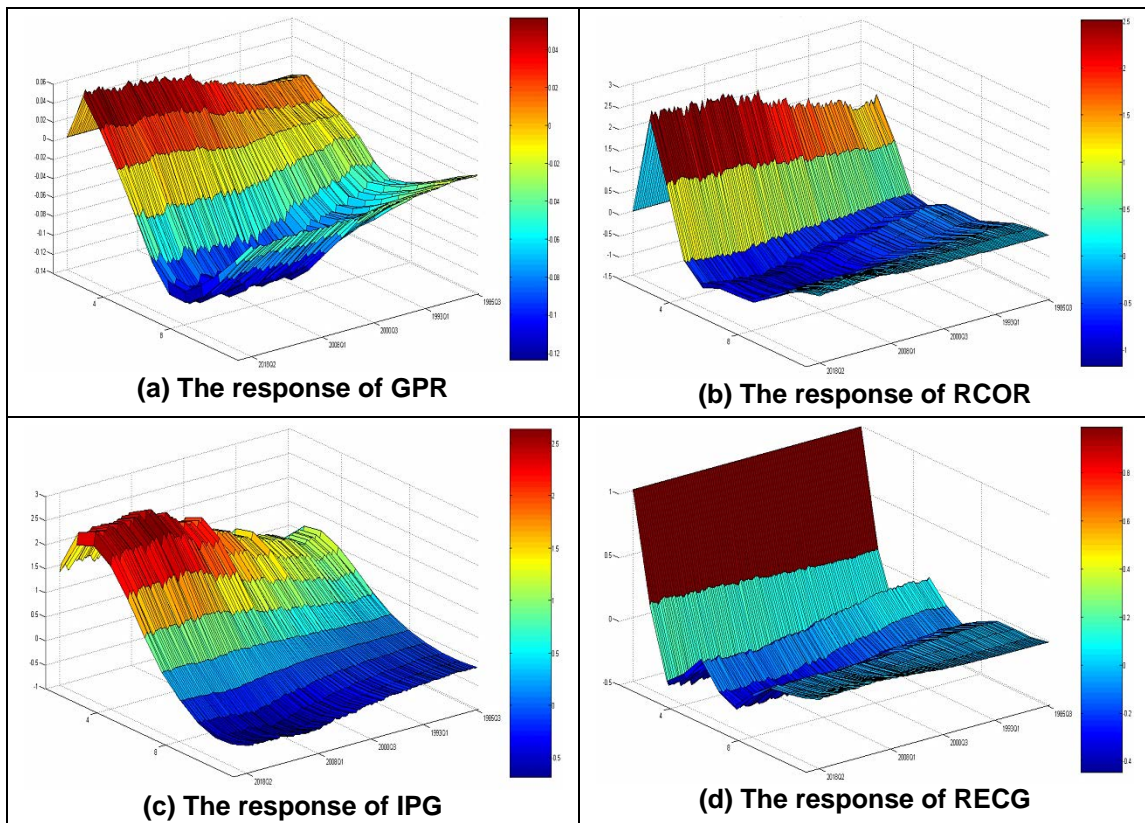


Figure 10: Robustness Check for RECG Shock



6. CONCLUSIONS

Renewable energy accounts for around 11% of total energy consumption (EIA 2019). Although this share is not large, former President Barack Obama called the development of renewable energy “a new era of energy exploration” in the US.⁷ Since 2000, renewable energy consumption has increased by 67%. This study utilizes a time-varying parameter Bayesian VAR model to investigate the impacts of geopolitical shocks on renewable energy consumption growth, by including control variables such as crude oil returns and GDP growth. The identification is a combination of cognoscibilism and agnosticism. We impose sign restrictions on GDP growth and GPR, and free the responses of RECG and RCOR. The maximum impact occurs in the second quarter after the shock. Specifically, one percentage point of GPR shock increases RECG by 0.75% in 1985Q3. However, this figure gradually increases to 1.4% in 2018Q2. Moreover, we find that GPR shocks tend to reduce RCOR in the first two quarters, with a maximum impact of around -4% given one percentage of increase of GPR. After that, the responses slowly revert to zero. The reaction of GDPG given GPR shocks remains steady over the whole sample period. For further analysis, we examine particular geopolitical events such as the 9/11 terrorist attack, the Gulf War, the Iraq disarmament crisis, the Iraq invasion, ISIS escalation, the Kuwait invasion, Arab Spring, tensions over Iran and the nuclear treaty, and the US bombing of Libya. The results show heterogeneities in the responses of RECG when different geopolitical events occur. However, the reactions of RCOR and GDPG are insensitive to different geopolitical events. In terms of the RECG shock, we find an increase in RECG can lead to a decrease in GPR over the whole sample period. Furthermore, the magnitude of this negative impact has increased in recent periods. This implies that renewable energy is becoming a more efficient tool to reduce geopolitical risks. Our study is the first to provide quantitative evidence of the interaction between geopolitical risks and renewable energy consumption. We also employ a standard VAR model, the results of which are similar to the TVP-BVAR model. As robustness checks, we consider industrial production growth and the economic policy uncertainty index. The empirical results are not significantly changed, and thus our empirical findings are robust.

Given the background of polarized geopolitics in the world, especially after the 9/11 terrorist attack, the oil price has fiercely fluctuated in recent decades. Renewable energy seems to be the best substitute for fossil fuels, which are notorious for dirty emissions and reliance upon rare earth materials. In the past 40 years, the US super power has been involved in the Gulf War and the Iraq invasion in 1991 and 2003, respectively. Although there was no official announcement that these two wars mattered to crude oil supply, the military actions of the US mainly took place in the Persian Gulf, where crude oil is abundant. Overland (2019) views renewable energy as a potential tool to alleviate the stress of geopolitics. In this study, we find geopolitical risk shocks tend to have increasingly positive impacts on renewable energy consumption growth in the US. Meanwhile, renewable energy was able to reduce the geopolitical risks over the whole sample span. These results indicate that geopolitical risks play an important role in the increasing consumption of renewable energy. Conversely, renewable energy is a useful tool to reduce geopolitical risks. Unlike fossil fuels, which are not uniformly distributed across the world, the elements required to exploit renewable energy are widely spread. Moreover, wind and solar energy are available everywhere. Thus, developing renewable energy is the best option for energy-poor countries.

⁷ This quote refers to Barack Obama's speech at Trinity Structural Towers wind energy plant in Newton, Iowa on Earth Day, 23 April 2009. <https://www.theguardian.com/world/2009/apr/22/barack-obama-earth-day-wind-power>.

Renewable energy can be used as an efficient tool to buffer against the potential geopolitical risks from countries which use disruptions of oil and gas as geopolitical weapons. In the future, whoever can first master a technology and own the intellectual property rights will win in the energy competition. In addition, renewable energy can help solve the climate change problem because of limited carbon emissions. Developed and developing countries should strength their collaboration in the field of renewable energy exploration. Lastly, governments should encourage the development of electric cars, buses, and public transport to increase the demand for electricity and stimulate demand for renewable energy. As long as the gap between supply and demand of renewable energy emerges, market power will drive the investment flow to renewable energy firms that can use the capital to advance the development of renewable energy.

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APPENDIX

