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Investigating the Effects of the United States' Economic Slowdown Related to the COVID-19 Pandemic on Energy Consumption in Other Countries—A Global Vector Autoregressive Model

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Abstract: The COVID-19 pandemic has caused a drop-in economic activity and energy consumption of the United States. This work aims to investigate the spillover effects of the United States' COVID-19 economic recession on economic growth and energy consumption in other nations using a global vector autoregressive (GVAR) approach and quarterly data between 1990 and 2013 from 41 major countries/regions. On the one hand, the simulation results indicate that the US COVID-19 recession has a negative impact on other countries' economic growth through trade ties, reducing the economic growth of other countries, especially for countries which have a close trade relationship with the US. In addition, the spillover effects of the US economic recession have different impacts on other countries' energy consumption. Countries with the closest trade ties to the US are most affected, such as Japan and China. In addition, the impact of the US' economic shock on energy consumption in developing countries is significant in the short term, while its impact on developed countries is significant in the long term. On the other hand, the simulation results of energy spillover effects indicate a reduction in US energy consumption slightly reduces economic growth in other nations. In addition, a reduction in energy consumption in the US does not have a significant negative impact on energy consumption in other developed countries. Furthermore, the spillover effect of declining energy consumption in the US on energy consumption in developing countries is significant in the short term. However, the spillover effects of falling energy consumption in the US on developing countries are different. The spillover effect of the decline in energy consumption in the US causes a slight decline in energy consumption in China and Brazil, whereas the spillover effect of the decline in energy consumption in the US does not cause a decline in energy consumption in India and Brazil.

Keywords: COVID-19; spillover effects; US economic growth; energy consumption; GVAR

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Citation: Hu, S.; Li, R. Investigating the Effects of the United States' Economic Slowdown Related to the COVID-19 Pandemic on Energy Consumption in Other Countries—A Global Vector Autoregressive Model. *Energies* **2021**, *14*, 2984. https://doi.org/10.3390/en14112984

Academic Editor: Akhtar Kalam

Received: 9 April 2021
Accepted: 17 May 2021
Published: 21 May 2021

1. Introduction

The COVID-19 pandemic not only has created huge challenges for the global public health system [1,2], but has also had a huge impact on energy [3], economic [4] and environmental [5] systems. As of now, at the end of April 2021, the number of confirmed cases in the United States has reached more than 32 million, and the number of deaths has exceeded 570,000. The US has become the hardest hit area of the global pandemic [6]. According to the statistics released by the Bureau of Economic Analysis (BEA) on 30 July 2020, the initial annualized quarterly growth rate of GDP in the second quarter of 2020 in the United States was −32.9%, the largest decline since the 1940s. The COVID-19 pandemic has not only had a huge impact on the US economy, but energy consumption has also been deeply affected. According to the estimations of EIA, liquid fuel consumption in the US averaged 16.2 million b/d in the second quarter of 2020, 4.1 million b/d (20%) less than the same period in the second quarter of 2019. The decrease reflects the restrictions on travel and the reduction in economic activity related to the mitigation efforts taken during the COVID-19 pandemic. EIA forecasts that the electricity consumption of 2020 in the US will be 3.6% down from that of 2019. At the same time, total natural gas consumption will average 82.4 billion cubic feet per day (Bcf/d) in 2020, which is 3.0% down from that in 2019. It is also estimated that coal consumption in the US will decrease by 26% in 2020 [7]. Until now, the world has not got rid of the COVID-19 pandemic, and most of the countries in the world suffered from it. The economic shock of the most affected and the most influential country, the United States, has given rise to economic and energy problems in other countries [8,9]. This has renewed attention on the causality between economic growth and energy consumption.

1.1. Conclusions of the Causality between Energy Consumption and Economic Growth

For decades, scholars have performed a lot of empirical research and testing in this area. People use econometric technology and regional data to construct many econometric models to test the link between energy consumption and economic growth. Abundant research has been carried out on the determinants and causality between energy consumption and economic growth. However, the evidence on causality is still unclear, and there is no consistent conclusion [10,11]. In a study, the results of Granger-causality discovered the presence of a causality between energy consumption and economic growth, both in the long run and in the short run, which supports the hypothesis of growth [12]. Similarly, an empirical study of Granger causality between GDP and energy consumption in other countries has been carried out in relevant research [13–16]. However, many studies have confirmed that there exists a two-way causality between economic growth and energy consumption. In Belloumi's study, the Johansen cointegration method was applied to test the causality between energy consumption per capita and GDP per capita in Tunisia from 1971 to 2004. Using a vector error correction model, the two variables were correlated with a cointegration vector, and the study drew the conclusion that there exists a long-term bidirectional causality between the two sequences and a short-term one-way causality between energy and GDP [17]. Chen et al. employed a panel co-integration, as well as vector error correction models, to explore the dynamic economic–energy–environment relationship of 188 countries from 1993 to 2010. The study concluded that energy consumption gives rise to a negative impact on GDP of the entire world and developing countries, but has no impact on developed countries [18]. A recent study examined the long-run energy–economic relationship in 25 OECD countries, using data from 1981 to 2007, and the results of the causality tests indicate that there is a bi-directional causality between energy consumption and economic growth [19]. There are similar cases that indicate bidirectional energy-growth causality [19–24]. Using a panel analysis, a study investigated the causal nexus between energy consumption and GDP, and indicated a unidirectional panel causal relationship between the two [25,26]. There are also other studies that drew similar conclusions, that there is a unidirectional causal link between the two [27]. Judging from the research conclusions drawn from previous studies, there are many findings that note the existence of bi-directional causality in energy–economic relationship [28,29].

1.2. Methods in Studying the Causality between Economic Growth and Energy Consumption

From the research methods of previous studies, linear and nonlinear econometric models are widely used in relevant study on the causality between economic growth and energy consumption [30]. Some people think that the consumption of energy and income in developed countries increase linearly, while the relationship between the two in developing countries demonstrates an exponential increase. Therefore, it is necessary to capture the non-linear relationship in the estimation. However, the differences in most results of different studies can be attributed to various model specifications, econometric techniques used, data types, selected countries, energy measures, sample sizes and national resource endowments [31,32]. In terms of econometric techniques, the most widely used techniques in previous studies were Granger/Sims causality tests, Engle-Granger/Johansen-Juselius cointegration and errorcorrection models [33–36]. Traditional Granger causality tests have been criticized for the reason that the tests are limited to some process and can only be used for time-related processes. This test is not suitable for processes that rely on time invariants [37,38]. Traditional unit root tests and cointegration tests are also criticized for limitations in low power and size characteristics for small samples. More and more people adopt the autoregressive distributed lag (ARDL) model proposed by Pesaran. These tests do not need to pre-check the unit roots of cointegration and causal relationships. The tests can be used regardless of the same or different unit roots of the variables. Recently, Carmona et al. [28] tested the causal energy-growth relationship by decomposing two sequences into non-stationary natural and stationary (transient) cyclical components. The findings of the study are consistent with most of the research conclusions mentioned earlier, namely that the presence of the two-way causal relationship between energy consumption and economic growth has been verified. With the advent of panel technology, some researchers have used panel data to explore the causal relationship between the two variables. Since the panel combines cross-sectional data and time series data, the estimation results are significantly reliable. The application of panel data has observably increased the degree of freedom and has allowed some advanced econometric methods using panel data, such as the FMOLS method and DOLS method [39–42]. At the same time, the deviations in traditional OLS estimation methods due to the endogeneity and serial correlation of the regressors are also corrected [43–46].

One disadvantage of the existing research is that it only focuses on analyzing the energy-growth causality in a single country or a certain region, without considering the potential spillover effects between them. The analysis focused on a certain country or region is easily restricted by its factor endowments, sample data, variable selection and other factors, and it is easy to ignore the interaction and dynamic connections among countries around the world, meaning the conclusions often have certain limitations. In the highly globalized world economy, it is surprising that spillover effects are not considered. In fact, the economic growth or energy consumption shock in a country may also have an impact on that of other countries. This kind of international transmission effect may be particularly relevant to shocks generated by large countries or countries with close trade and financial ties.

The economic shock of a superpower not only has a strong impact on the economy and energy consumption of itself but also threatens other countries in the era of open trade. This kind of effect arouses public curiosity, so this article analyzes the spillover effects of the shock of US economic and energy consumption caused by the pandemic and carries out an empirical analysis on the data between 1990 and 2013 from 41 counties and regions, both from long-run and short-run perspectives. To this end, we adopted the global vector autoregressive (GVAR) model proposed by Pesaran. The GVAR model enhances the VAR or vector error correction (VECM) model of a single country through corresponding foreign variables. Then, through a connection matrix, each country model is connected into a whole, and the interdependence of countries can be analyzed through impulse response analysis. Although the GVAR method is best used to study the transmission of international shocks, it has not been used to explore the relationship between economic growth and energy consumption. A complex macroeconomic modeling interaction is required. Using the macroeconometric GVAR model, the complex interdependence between various economic entities can be described. Some scholars have explored the influence of the potential economic deceleration of BRICs on the economic development of the US and the European Union 17 (EU17) through the GVAR model [47–49]. Obviously, the GVAR model can be easily used to analyze some propagation mechanisms, conduction effects and shock effects in various environments [50,51].

Data have been collected from 1990 to 2013 in 41 major countries around the world. Under the framework of economic cooperation and trade links between countries, the dynamic interaction and two-way spillover effects of economic growth and energy consumption between the US and other developed or developing countries are analyzed quantitatively. The contribution of this article is mainly the following three points. The first is to explore whether the US economic downturn caused by the pandemic slows down the economic growth of other countries in the world. In the short or long term, will the economic shock and energy consumption shock from the United States have an influence on economic growth and energy consumption in various regions of the world? Secondly, what is the specific negative impact on the economy and energy consumption of the United States caused by the pandemic of COVID-19 on developed and developing countries? What is the difference in the performance of this spillover effect in different countries? We empirically analyze the performance of this spillover effect from a quantitative perspective so that people can better understand the specific impact of the US pandemic on the economy and energy consumption of other countries. The third is to creatively apply the macro-econometric model of GVAR to study the impact of the pandemic on the economy and society, making the research on the impact of the pandemic on the economy and society more comprehensive and multidimensional and, at the same time, expanding the scope of the GVAR model's empirical application.

The remainder of this study is structured as follows. The second part gives an overview of the GVAR model and introduces the construction of the model, as well as the sources of the data we used in this study. The third part conducts an empirical results analysis on dynamic interactions and the spillover effects between the US and other counties, which includes the negative shock of US economic growth and energy consumption. The fourth part represents the conclusions based on the results of GIRF analysis, and points out the limitations of this study.

2. Materials and Methods

2.1. Methodology

In the context of globalization, frequent and close trade exchanges make the economic and social development levels of various countries affect each other. The GVAR methodology provides quantitative analysis of the relative importance of different shocks and channels of transmission mechanisms, with a general but practical global modeling framework, which makes it suitable for conducting policy analysis. The associated GVAR model is a global model combining individual country vector error correcting models, in which domestic variables are related to foreign variables of specific countries in the same way. The latter are constructed on the basis of the domestic variables so as to match the international trade, financial or other desired patterns of the country that are taken into consideration, and to substitute the common unobserved factors. This compact model of the world economy relies exclusively on observable factors that include macroeconomic aggregates and financial variables.

The GVAR model is established on the basis of a global system composed of the VARX* models of various countries. By considering the internal connections between countries, it is convenient to analyze the spillover of individual effects and the shock results of global variables. The GVAR model is flexible and expandable. In addition, it has the characteristics of compact model structure, easy maintenance and strong operability. The model considers three ways of interconnection between countries. They are independent and internally interconnected. They are domestic variables that depend on the present and lag values of foreign variables, and the variables of each country are affected by global exogenous variables; the i-th country is affected by the present shock of the j-th country, and dependence can be reflected in the error covariance matrix. In view of the advantages of the GVAR model, we use the following steps to construct the GVAR model to better understand the two-way spillover effects of economic growth and energy consumption between the US and other countries.

The model assumes that a country's variables are relevant to exogenous variables such as foreign weighted variables, trend items and oil prices. Referring to the method of Zhang [52], suppose Xi represents the domestic variable vector of the i-th country, Xi^*

represents the foreign variable vector of the *i*-th country and *Xi* and *Xi** are vectors of order *ki* and *ki**, respectively.

Set the VARX* model of the *i*-th country in the following form (assuming that the lag order is 1),

$$X_{it} = a_{i0} + a_{i1}t + \Phi_i X_{i,t-1} + \Lambda_{i0} X_{it}^{*} + \Lambda_{i1} X_{i,\ t-1}^{*} + \epsilon_{it} t = 1,2,\cdots,\ T_i = 0,1,2\cdots,\ N. \quad (1)$$

Here Φ_i is a $k_i \times k_i$ coefficient matrix, Λ_{i0} and Λ_{i0}^{*} are the coefficient matrices of $k_i k_i^{*}$ respectively, and ε_{it} is the vector of $k_i \times 1$ of the independent impact of each country. It is assumed that the autonomous impacts of countries are non-sequentially related, and the average value is 0. Foreign variables such as foreign economic output y_i^{*} are constructed as follows, $y_{it}^{*} = {}_{j=0}^{N} w_{ij}^{y} y_{jt}$. Among them, the weight w_{ij}^{y} is obtained from the WIOD multi-regional input-output table and the energy consumption data of each country, and represents the element in the *i*-th row and the *j*-th column. Other foreign variables for the models in each country are also constructed in a similar way.

Combine domestic variables with foreign variables to form a $\left(k_i + k_i^{*}\right) 1sz$ vector Zi: $z_{it} = \begin{pmatrix} x_{it} \\ x_{it}^{*} \end{pmatrix}$. Further, Formula (1) can be expressed as follows

$$A_i Z_{it} = a_{i0} + a_{i1}t + B_i Z_{i,t-1} + \varepsilon_{it}. \quad (2)$$

Here, $A_i = (I_{ki}, -\Lambda_{i0}),\ B_i = (\Phi_i,\ \Lambda_{i1})$. A_i and B_i $\left(k_i + k_i^{*}\right)$-order matrices, and A_i is a full-rank matrix, that is, $rank(A_i) = k_i$. Combine the models of all countries to obtain a $k \times 1$ vector, where $k = \sum_{i=0}^{N} k_i$ represents the number of endogenous variables in the model and the variables of each country can be represented by X_i, namely

$$Z_{it} = W_i X_t\ i = 0,1,2,N. \quad (3)$$

w_i is a $\left(k_i, +, k_i^{*}\right) \times k_i$ matrix, the elements of which are known. This matrix connects the VARX* models of various countries into a global vector autoregressive model. Therefore, (2) and (3) can be combined into

$$A_i W_i X_t = a_{i0} + a_{i1}t + B_i W_i X_{t-1} + \varepsilon_{it}.$$

Here $A_i W_i$ and $B_i W_i$ are $k_i \times k$ matrices. Write these equations in the form of superimposition on top and bottom, $GX_t = a_{i0} + a_{i1}t + HX_{t-1} + \varepsilon_t$ among them,

$$a_0 = \begin{pmatrix} a_{00} \\ a_{10} \\ \vdots \\ a_{N0} \end{pmatrix} a_1 = \begin{pmatrix} a_{01} \\ a_{11} \\ \vdots \\ a_{N1} \end{pmatrix} \varepsilon_t = \begin{pmatrix} \varepsilon_{0t} \\ \varepsilon_{1t} \\ \vdots \\ \varepsilon_{Nt} \end{pmatrix} G = \begin{pmatrix} A_0 W_0 \\ A_1 W_1 \\ \vdots \\ A_N W_N \end{pmatrix} H = \begin{pmatrix} B_0 W_0 \\ B_1 W_1 \\ \vdots \\ B_N W_N \end{pmatrix}$$

G is a $k \times k$ full-rank matrix. Therefore, the GVAR model can be expressed in the following form,

$$X_t = G^{-1} a_0 + G^{-1} H X_{t-1} + G^{-1} \varepsilon_t.$$

By estimating the VARX* model of a single equation, combined with the connection matrix we calculated above, a new matrix G can be constructed without the need for parameter estimation in GVAR. This action greatly reduces the workload of estimating coefficients under the premise of ensuring the degree of freedom of the model, so that an analysis similar to the VAR model can also be performed in the GVAR model.

The above formula is further expressed as an error correction form similar to VECM,

$$G \Delta X_t = a_0 + a_1 t + (G - H) X_{t-1} + \varepsilon_t$$

$$G - H = \begin{bmatrix} (A_0 - B_0)W_0 \\ (A_1 - B_1)W_1 \\ \vdots \\ (A_N - B_N)W_N \end{bmatrix} = \begin{bmatrix} \alpha_0\beta_0' W_0 \\ (A_1 - B_1)W_1 \\ \vdots \\ (A_N - B_N)W_N \end{bmatrix}.$$

It can also be written in the following form,

$$G - H = \widetilde{\alpha}\widetilde{\beta}'$$

among them, $\widetilde{\alpha}$ is the $k \times r$ block diagonal matrix, which represents the global short-term adjustment coefficient, $\widetilde{\beta}$ is the $k \times r$ cointegration space matrix,

$$\beta = \left(W_0'\beta_0, W_1'\beta_1, \ldots W_N'\beta_N\right), r = \sum_{i=0}^{N} r_i,\ k = \sum_{i=0}^{N} k_i$$

adding global common variables to the model makes the GVAR model generalized,

$$X_{it} = a_{i0} + a_{i1}t + \Phi_i X_{i,t-1} + \Lambda_{i0}X_{it}^* + \Lambda_{i1}X_{i,t-1}^* + \varphi_{i0}d_t + \varphi_{i1}d_{t-1}$$
$$T = 1, 2, \cdots, T;\ i = 0, 1, 2, \cdots, N$$

among them, d_t is a $s \times 1$ vector, which represents a global common variable. It is assumed that it is a weak exogenous variable for the global economy. Therefore, the extended GVAR model is

$$GX_t = a_{i0} + a_{i1}t + HX_{t-1} + \varphi_0 d_t + \varphi_1 d_{t-1} + \varepsilon_t$$

among them, the definitions of $a_0, a_1, G, H, \varepsilon_t$ have been given in the preceding text, and φ_0, φ_1 are $\varphi_0 = \begin{bmatrix} \varphi_{00} \\ \varphi_{10} \\ \vdots \\ \varphi_{N0} \end{bmatrix}, \varphi_1 = \begin{bmatrix} \varphi_{00} \\ \varphi_{11} \\ \vdots \\ \varphi_{N1} \end{bmatrix}$.

This formula can be used to predict the endogenous variables in the system based on the original state of the system and exogenous global variables. The ingenious aspect is that the coefficients in the VARX* model of the countries are estimated, respectively, in the model of each country, avoiding the estimation of the GVAR model. Research shows that the number of countries in the GVAR model is large enough and some assumptions are satisfied [53]. This method of indirectly estimating the GVAR model through the estimation subsystem is reasonable. The GVAR model can reflect both the long-run and short-run relationship between the variables. On this basis, it can be used for variable prediction, generalized impulse response function analysis and variance decomposition, and can be used to explore the dynamic interaction and shock effect among the economies within the economic system. From model construction to impulse response function analysis, we can use GVAR Toolbox 2.0 (2014).

2.2. Data Sources

The GVAR model constructed in this paper covers 41 countries in WIOD, including Australia, Austria, Belgium, Bulgaria, Brazil, Canada, Switzerland, China, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Croatia, Hungary, Indonesia, India, Ireland, Italy, Japan, South Korea, Lithuania, Luxembourg, Latvia, Mexico, Netherlands, Norway, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Sweden, Turkey and the United States. Among them, the EU regions include Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Sweden—a total of 26 countries. When building the GVAR model, we selected 41 countries for modeling. The annual economic aggregate and energy consumption of these countries take a large proportion of more than 70% of the world economy and energy consumption, respectively, so they reflect the characteristics of the world economy and energy consumption to a certain extent. Considering the availability of data, the length of the sample selection is 1990–2013. The model is estimated based on data on energy consumption and real GDP and 3 additional macroeconomic variables (energy efficiency, the proportion of total imports and exports in GDP and the proportion of industrial added value in GDP). Actual GDP represents the economic development level, energy consumption represents the energy consumption level, the proportion of total import and export to GDP represents the degree of openness to trade and the ratio of the added value in industry to GDP represents the industrial structure. These indicators are selected to describe the actual situation of each region and reflect regional development. The heterogeneity between these variables may act as an energy-growth transmission mechanism.

Real GDP is measured in USD millions, and total energy consumption is measured in millions of tons of oil equivalent. Energy efficiency, the proportion that total import and export account for in GDP, and the proportion of industrial added value in GDP are based on percentages. All the data we collected comes from the World Development Indicators database of the World Bank Website, International Monetary Fund (IMF) database and BP Statistical Review of World. In order to obtain a more accurate estimate, we use the quarterly value of each variable series. In addition, the global variable was the oil price index, and the average value of all trading days of the Brent crude oil price in the quarter was used as the quarterly value. The definitions and sources of the data are demonstrated in Table A1.

2.3. Model Settings

After obtaining the time series data of the corresponding variables in each country, we needed to construct a weight matrix to calculate foreign variables and solve GVAR. The most commonly used is a trade or financial matrix. But these matrices are often used to analyze financial or economic policy fields. To express the close growth-energy relationship among countries in the world, with reference to the research of Montresor and Marzetti [54], we constructed an "international trade-energy consumption" matrix between countries based on data from the database of the input–output of the world and energy consumption data of various countries.

In addition, country-specific weights were computed by dividing the PPP-GDP figure of each country by the sum across countries, so that the weights could be added up to one across the countries. These were used for the computation of global shocks (i.e., shocks to a variable across all countries) in impulse response analysis. The country-specific weights are shown in Table A3.

Before constructing an econometric model, testing the stability of data was first necessary. To this end, we used both the ADF test and the weighted symmetric Dickey Fuller (WS) test, which makes use of the reversibility of time of the smooth autoregressive process to improve its power performance, which was originally proposed by Park and Fuller (1995) [55]. The lag order was selected according to the AIC criterion. The unit root test was performed on both domestic and foreign variables, including intercept and time trend. Part of results is shown in Table A4. The unit root test results obtained for the time series of various variables in different countries were different. Most of the original series were non-stationary time series, but there was no unit root process in the first difference form of each series. With this in mind, Johansen's cointegration test was performed to determine the area where the number of each cointegration relationship allowed a deterministic trend in the cointegration space. On the basis of tracking statistics, we discovered that the number of cointegration relations in France, Mexico, Sweden and Turkey was 1, the number of cointegration relations in Slovakia was 2, and there was no cointegration relationship in other countries' individual VARX* models.

Next, we carry out an estimation of the individual VARX* models. We included all five macro variables in the model for each country, including domestic variables and the corresponding foreign variables. Although the GVAR model can freely set the variables included in any individual VARX model, it is very flexible in this regard. The reason why we included these five macro variables in each individual model was to ensure that the estimation results were comparable. Next, we determined the selection of lag order in each VARX* models. The lag orders of the domestic and foreign variables, respectively, could be selected using the Akaike information criterion (AIC) or the Schwarz Bayesian criterion (SBC). We chose the AIC criteria.

The main assumption underlying the estimated results of the individual country VARX* models is the weak exogeneity of x_{it} in regard to the long-term parameters of the conditional model that are defined by the above part. This assumption is compatible with a certain degree of weak dependence across u_{it} [56]. Following Johansenm [57] and Granger and Lin [58], in the context of cointegrating models, the weak exogenous hypothesis implies no long-run feedback from x_{it} to x^{*}_{it}, without necessarily ruling out the lagged short-run feedback between the two groups of variables. Under this circumstance, x^{*}_{it} is regarded as the "long run forcing" for x_{it}, which indicates that the error correction terms in the VECMX* models of individual country will not enter in the marginal model of x^{*}_{it}. As suggested by Johansen (1992) [57], weak exogeneity can be determined by the joint significant tests of the estimated error correction term in the auxiliary equation of the extrinsic variable x_{it} of specific regions. There is a demand of the GVAR model that the foreign variables in the model with cointegration relationship meet the condition of weak exogeneity. Therefore, the models of France, Mexico, Sweden, Turkey and Slovakia needed to be tested for weak exogeneity. The results of weak exogeneity test are shown in Table A5.

Next, we performed the average pairwise cross-section correlations test. A simple diagnostic of the extent to which the country-specific foreign variables were promotional in cutting down the cross-section correlation of the variables in the GVAR model was provided by the average pairwise cross-section correlations for the levels and first differences of the endogenous variables, as well as those of the associated residuals over the selected estimation period. The part of results of average pairwise cross-section correlations of residuals are shown in the Table A6. Finally, we conducted a structural stability test of the GVAR model, indicating that all its eigenvalues were on or inside the unit circle.

3. Empirical Results and Analysis

After the statistical test and GVAR model estimation were completed, the dynamic interaction and two-way spillover effects of economic growth and energy consumption between the US and developed or developing countries were analyzed with the help of the generalized function of the impulse response, which can measure the impact of a standard deviation of the random error term and can give rise to the present and future values of other variables, as well as intuitively reflect the dynamic reciprocal action between the variables in the model and the individual spillover effect.

Impulse responses refer to the time profile of the effects of shocks of the specific variables or identified shocks on the future states of a dynamical system and on all the variables in the model. The impulse responses of shocks to specific variables considered for the GVAR model are the generalized impulse response functions (GIRFs), introduced in Koop, Pesaran and Potter [59] (1996), and adapted to VAR models in Pesaran and Shin [60] (1998). Compared with the standard impulse response analysis of traditional VAR literature, GIRF integrates the impact of shock waves into a single variable based on the observed residual covariance matrix, with no need for orthogonal process. This is an ideal function for the GVAR setting. The fact that the error term is not orthogonalized means that GIRFs may be related to each other, causing problems in structural interpretation. Evidence from Table A6 that the residual correlation is weak shows that each GIRF is not greatly influenced by other shocks in this system.

When conducting GIRF analysis, we aggregated 26 EU countries based on data for constructing the aggregation weights above. The remaining countries are analyzed as separate economies. The horizontal axis in the image represents the number of periods during which the fluctuations continue, and we have selected 40 quarters. The vertical axis represents the fluctuation caused by the unit shock. The solid line indicates the response function curve, and the dashed line represents the confident interval of 90% under Bootstrap simulation, which is calculated based on 100 repetitions of GIRF. We will select the European Union, Japan, South Korea, Australia, Canada and the United Kingdom as representatives of advanced economies, and China, Brazil, Indonesia, India, Mexico and Turkey as representatives of emerging economies.

3.1. The Spillover Effect of the Negative Shock of US Economic Growth

Figure 1 shows the dynamic response process of economic growth in representative developed economies under the negative economic shock from the United States. In general, we can see from the figure that the dynamic response of the GDP of these developed countries is negative, and the degree of response changes over time. It fluctuates in the short-term (within five years) and will stabilize to a certain extent in the long-term (within five years). The following is a detailed description. Among these representative developed economies, Canada, Japan and the United Kingdom have the closest trade ties with the United States. The European Union, South Korea and Australia followed. Under the shock of a negative standard deviation of US economic growth, the dynamic response process of economic growth in developed countries shows a negative U-shaped characteristic. In the first twelve periods, the GDP curves of all countries showed a downward trend, but it was not significant. In terms of response speed, the response speeds of these countries are roughly the same. However, in terms of response level, among these countries, Japan had the largest decline. By the 12th period, Japan had the largest negative response value of -0.54%, while Australia had the smallest decline, and the minimum is -0.1%. This again confirms the fact that, among these countries, Japan and the United States have the closest trade ties, and Australia and the United States have the smallest trade ties. After the 12th period, the GDP curves of various countries began to show an upward trend, but the increase was significantly smaller than the decrease. Eventually, it converges to a fixed negative value around the 24th period, and this feature is significant in all countries. Among them, Japan has the largest long-term negative response value, which fluctuates around -0.4%, while the response value of other countries is about half of it, and the response value of other countries is between -0.1% and -0.2%. Judging from the results of the GIRF chart, it is undeniable that the US economic shock has brought a negative spillover effect to the economic growth of developed nations, indicating that the US economic downturn caused by the pandemic will inevitably bring pressure to developed countries' economic development. In the short run, the economic growth of these countries has been impacted to varying degrees. Among them, Japan is the most impacted, followed by the United Kingdom and the European Union, and Australia has endured the least impact. In the long run, the economic downturn in the United States has reduced the economic growth of representative developed countries.

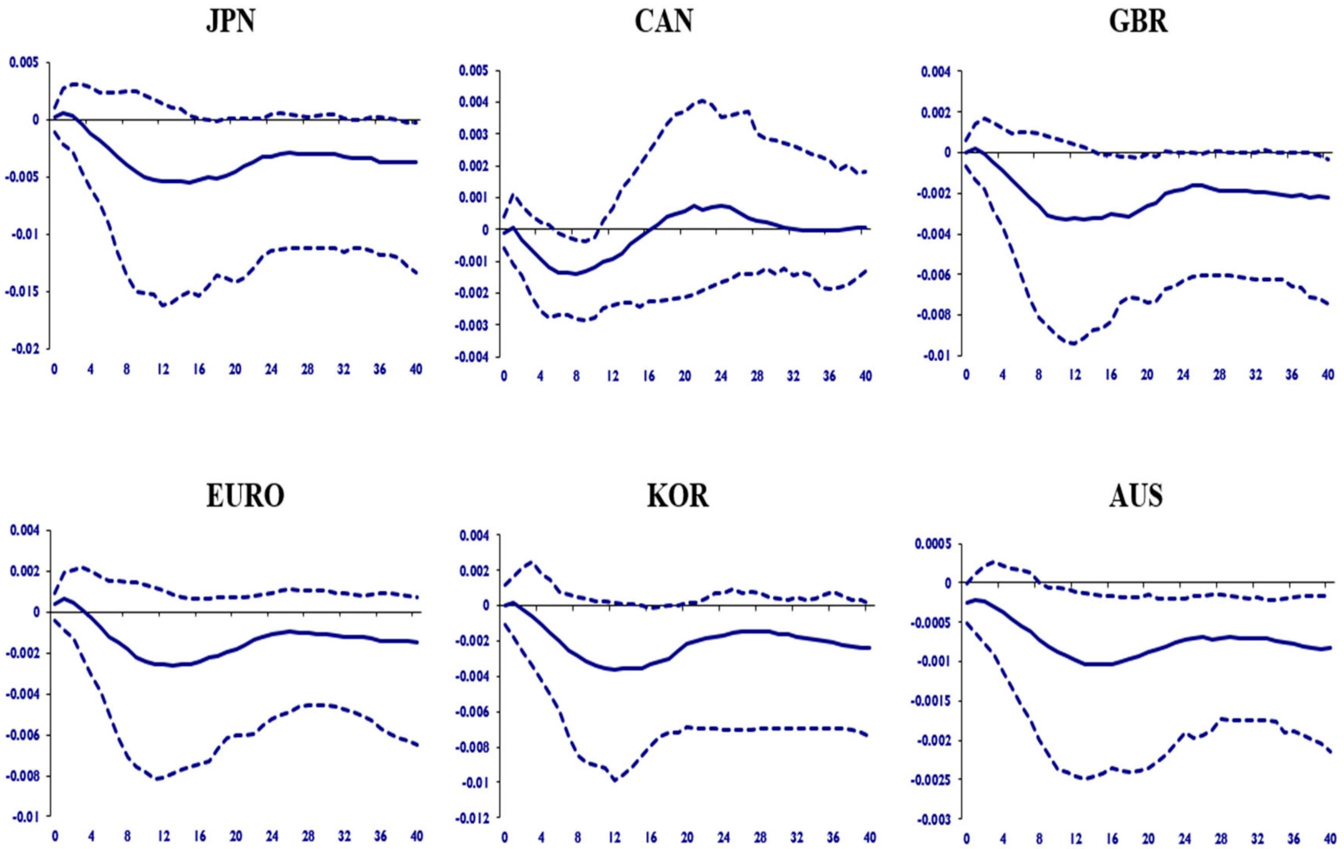

Figure 1. The GIRF curve of economic growth in developed countries under the negative shock of one standard deviation of US economic growth.

Figure 2 demonstrates the dynamic response process of economic growth of representative developing countries under the negative influence of one standard deviation of US economic growth. Generally, it can be seen from the graph that the dynamic response of GDP of these developing countries is negative, and the response degree changes with time. It fluctuates in the short run (within five years) and will approach zero in the long run (within five years). The following is a detailed description. Among these representative developing countries, China and Mexico have the closest trade relations with the United States. Followed by India and Brazil and, finally, Indonesia and Turkey. Under the negative shock of the US economy, the performance of developing countries varies. It can be roughly divided into two situations. One is composed of China, Mexico and India, and the other is composed of Brazil, Indonesia and Turkey. On the one hand, the GIRF curves of China, Mexico, and India fluctuate significantly and show similar trends. The immediate response values of these three countries in the 0th period (which is the first quarter after the shock) were all negative and, in the first eight periods, the degree of negative response continued to deepen and fell after the eighth period (which is the fourth quarter of the second year after the shock). In general, in the short term, the spillover effect of the negative economic shock in the United States on the economic growth of these three countries is very significant, although the degree of response of these countries to the shock is different in value. After the twelfth period (that is, the fourth quarter of the third year after the shock), the GIRF curves of these three countries have all approached zero and stabilized. This shows that the economic growth of China, Mexico and India will be negatively influenced by the US economic shock in the short term, and the impact will be very rapid. However, after about two years, this effect gradually disappears. That is to say that the spillover effect of the US economic shock on the economic growth of China, Mexico and India was short-term and significant. In the long run, the impact of this economic shock will fade, but it is not significant. On the other hand, regardless of the bilateral trade volume in statistics or the direction of foreign trade, Brazil, Indonesia and Turkey do not have close trade with the United States. The GIRF graphs of these countries are roughly similar, showing a negative dynamic response process; the response value gradually increases in the previous period and then stabilizes at a fixed value but, unfortunately, this result is not significant.

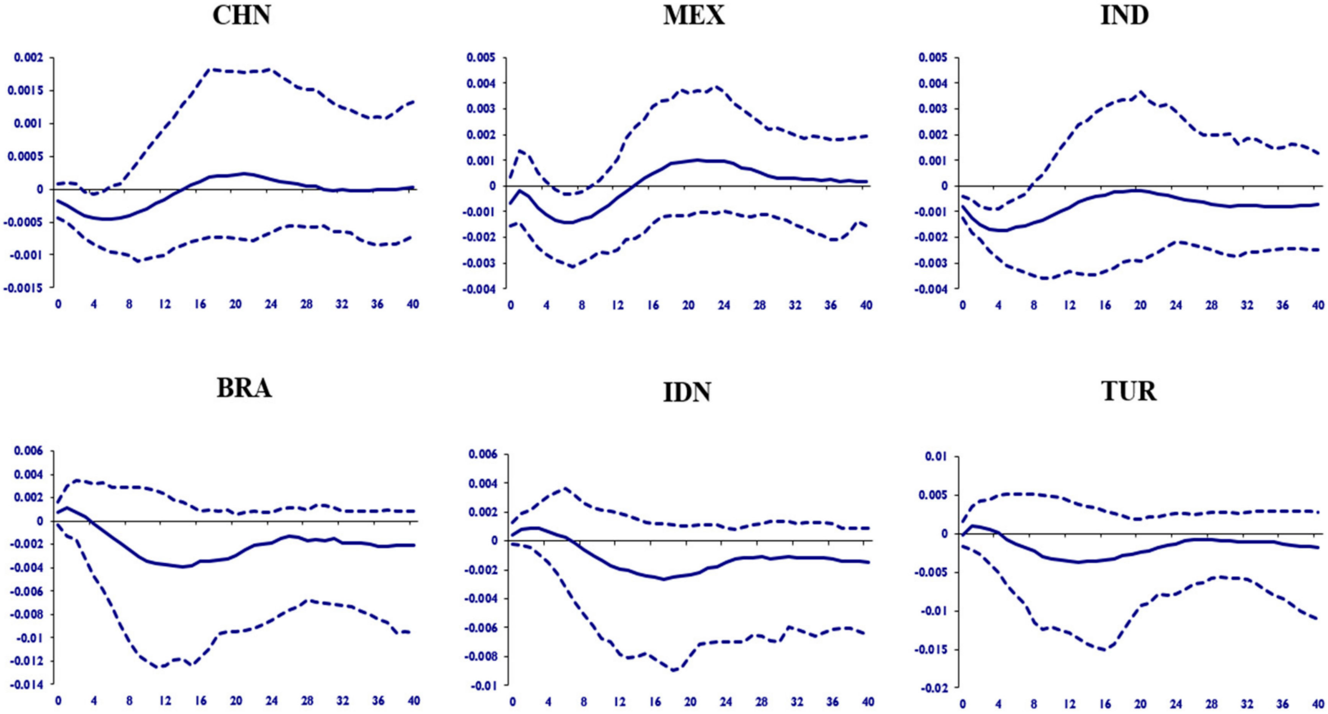

Figure 2. The GIRF curve of economic growth in developing countries under the negative shock of one standard deviation of US economic growth.

Whether it is from the analysis of developed countries or from the analysis of developing countries, there is no doubt that the pandemic not only caused losses to the US economy but that this shock will also spread to other countries around the world, along with trade ties. The first to bear the brunt is the trading partner countries with the closest trade ties with the United States, such as Japan, China and Mexico, and the impact of this kind of shock on developed countries is far more profound than on developing countries. Under the shock of the US economy, the dynamic response process of the economic growth of countries such as Australia, Indonesia and Turkey, which are not close to the US trade ties, is also negative, but not significant. A possible reason for this difference is the heterogeneity of trade associations.

Figure 3 shows the spillover of the US economic shock on the energy consumption of representative developed economies. In general, the negative economic shock in the United States reduced energy consumption in developed countries. With the exception of Canada and Australia, the GIRF charts of the other developed economies show similar trends, and the response process is always negative. In the 0th period, the immediate response values were all close to 0, but then the curve showed a downward trend. Around the 12th period (around the third year after the shock), the response level stabilized near a certain fixed value, and then stabilized; this performance in the later period was highly significant. When the response value of each country reaches the maximum, it can be concluded, by comparison, that the peak value of Korea is the smallest among these countries, which is about half of other countries. In the long term (within ten years), the response values of Japan, the United Kingdom and the European Union will be maintained at around −0.9%, while South Korea and Australia will be around −0.2% and −0.1%, respectively. The response speed of countries is roughly the same. This shows that the economic shock caused by the pandemic in the United States will gradually reduce the consumption of energy in these countries. In the long run, however, this spillover effect is obvious. That said, the degree of influence on different countries is different; similar to the response to economic growth, Japan's influence is deeper.

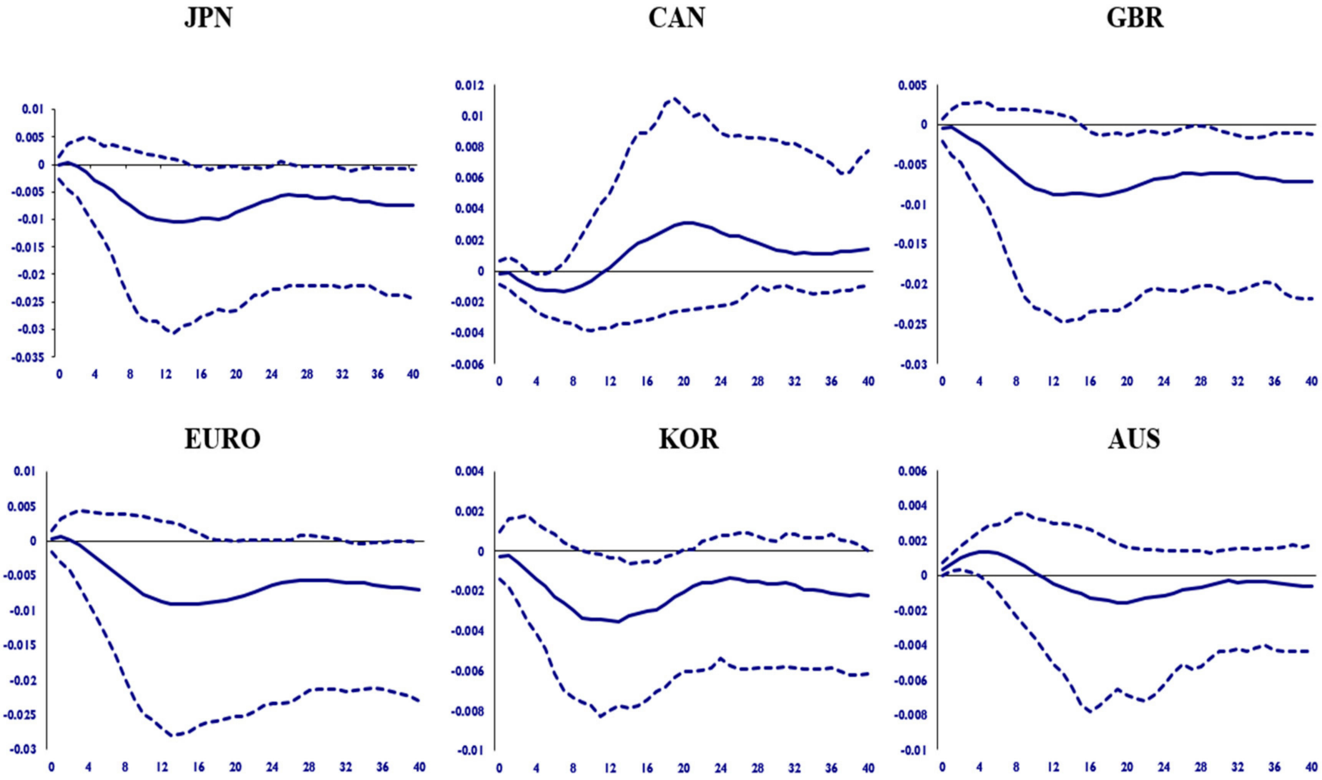

Figure 3. The GIRF curve of energy consumption in developed countries under the negative shock of one standard deviation of US economic growth.

Figure 4 presents the spillover of the US economic shock on the energy consumption of representative developing economies. On the whole, it can be roughly divided into two situations, one is composed of Mexico, India and Indonesia, and the other is composed of China, Brazil and Turkey. The GIRF curve trends of China, Brazil and Turkey are roughly the same, and they all fluctuate below the horizontal axis. At first, the immediate response values in the 0th period were all less than 0. In the following four quarters (within the first year after the shock), the curve began to decline. When the curve in China fell to about −0.15%, the decline stopped, and the corresponding value in the other two countries was −0.5%. Judging from the negative performance in the early stage of the curve, China's performance is the most significant, while the performance of the other two countries is not significant. After the fourth quarter, the response levels of these three countries were relatively stable, and the response values gradually tended to zero. This shows that the negative economic shock of the United States can gradually reduce the energy consumption of China in the short run, and the spillover effect of this economic shock is gradually deepening. However, in the long run, this effect will disappear over time. What differs from the response process of these countries is the performance of Mexico, India and Indonesia. Their GIRF curves are all located above the horizontal axis, and their immediate response values in period 0 are all 0. In the first four quarters (within the first year after the shock), Mexico and India's response levels will be very weak, and the response values will be significantly close to zero. In the later period, the curves of these two countries also remained on the positive side, but this positive response is not very significant in the long run (within ten years). This reflects the fact that the negative shock of the US economy will not affect the energy consumption of Mexico and India, and the spillover effects caused by the US economic downturn will not affect the energy consumption of these two countries.

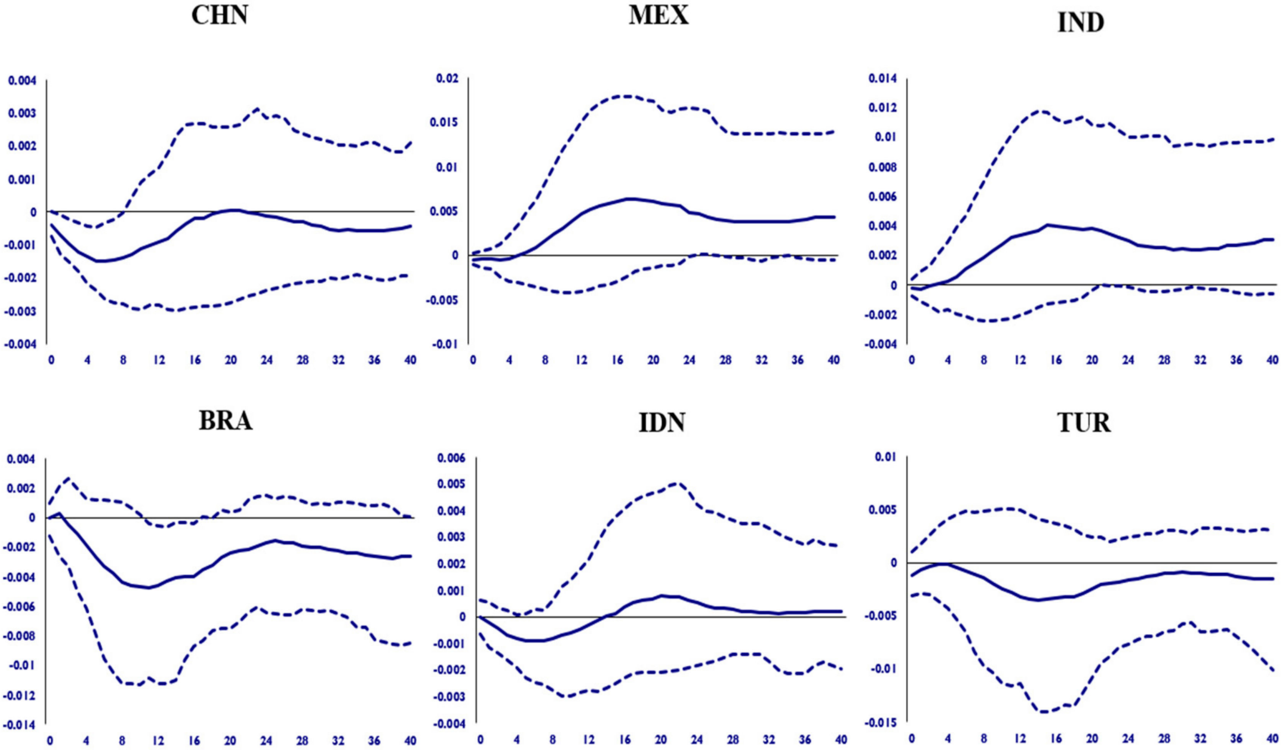

Figure 4. The GIRF curve of energy consumption in developing countries under the negative shock of one standard deviation of US economic growth.

Whether from the perspective of developed or developing countries, in general, the spillover effect of the negative shock of the US economy on other countries' energy consumption is to reduce the energy consumption of these nations to varying degrees. Countries with the closest trade ties to the United States, such as Japan and China, have suffered the most from this impact. However, the difference is that the impact of the US economic shock on developing countries' energy consumption is significant in the short term, while the impact on developed countries is significant in the long term (within ten years).

3.2. The Spillover Effect of the Negative Shock of US Energy Consumption

Figures 5 and 6 show the spillover of the negative shock of US energy consumption on the economic growth of other nations. Figure 5 shows the situation of representative developed countries, and Figure 6 shows the situation of representative developing countries.

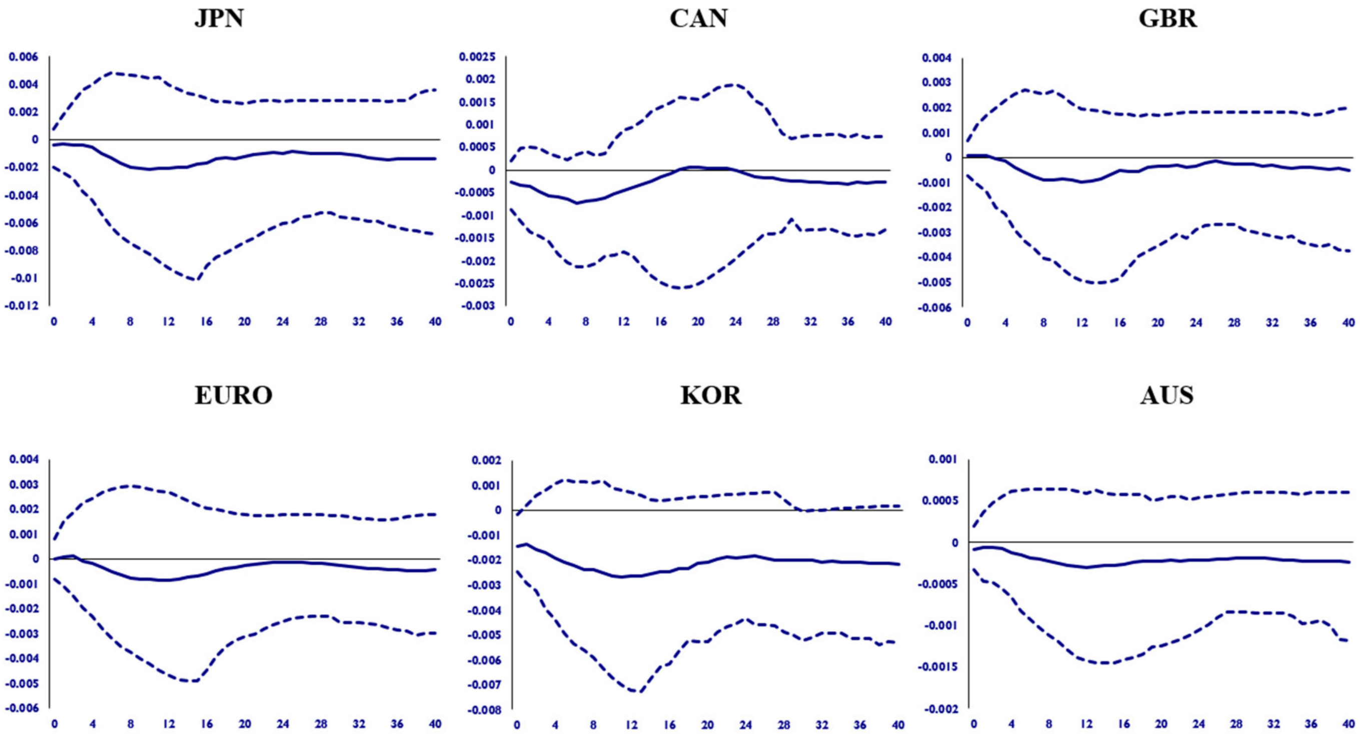

Figure 5. The GIRF curve of economic growth in developed countries under the negative shock of one standard deviation of US energy consumption.

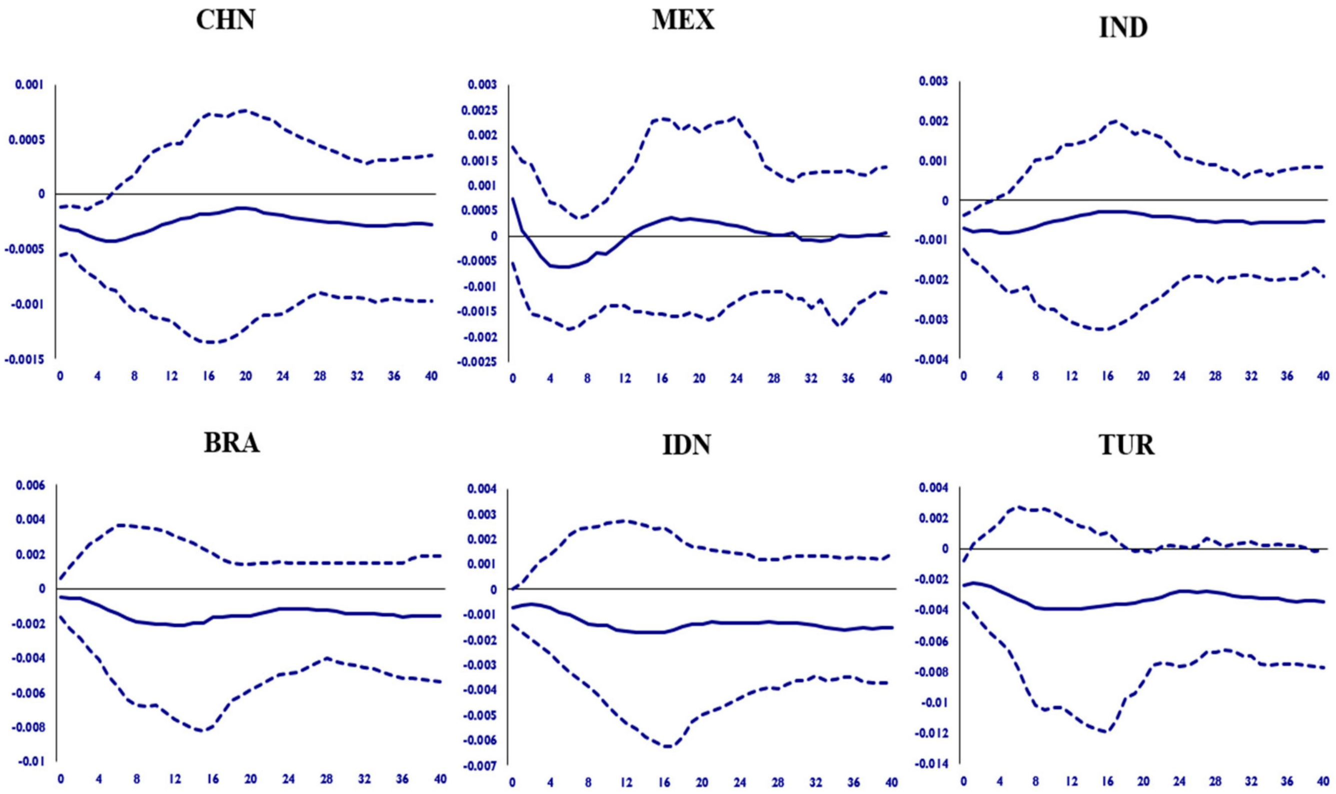

Figure 6. The GIRF curve of economic growth in developing nations under the negative shock of one standard deviation of US energy consumption.

Under the shock of a negative standard deviation of energy consumption in the US, the dynamic response process of economic growth in both developed and developing nations showed negative characteristics. In the first twelve periods (within the first three years after the shock), the GDP curves of countries fluctuated slightly below the horizontal axis, and the fluctuations were very small. In terms of response speed, the response speeds of these countries are roughly the same. Excluding Canada and South Korea, the immediate response values of developed countries are all close to 0, and the absolute value of immediate response values of developing countries is slightly larger than that of developed countries. In the first eight quarters, the GIRF chart showed a slight downward trend. After the 12th period (the third year after the shock), the curves all showed a stable trend, but the performance was not significant. The GIRF curves of Japan, Canada, the United Kingdom and the European Union have stabilized near the horizontal axis, but the long-term response values of developing nations such as Brazil, China and India are larger than those of the developed countries mentioned above. This shows that the shock of the pandemic on energy consumption in the United States has spillover effects. Specifically, the negative shock of energy consumption has spread to other countries along the international trade chain, and has a negative effect on other nations, namely the reduction in energy consumption of the United States will slightly reduce the economic growth of other countries.

Figures 7 and 8 show the spillover of the negative shock of US energy consumption on that in other countries. Figure 7 shows the spillover situation of representative developed economies. Figure 8 shows the spillover situation in representative developing countries.

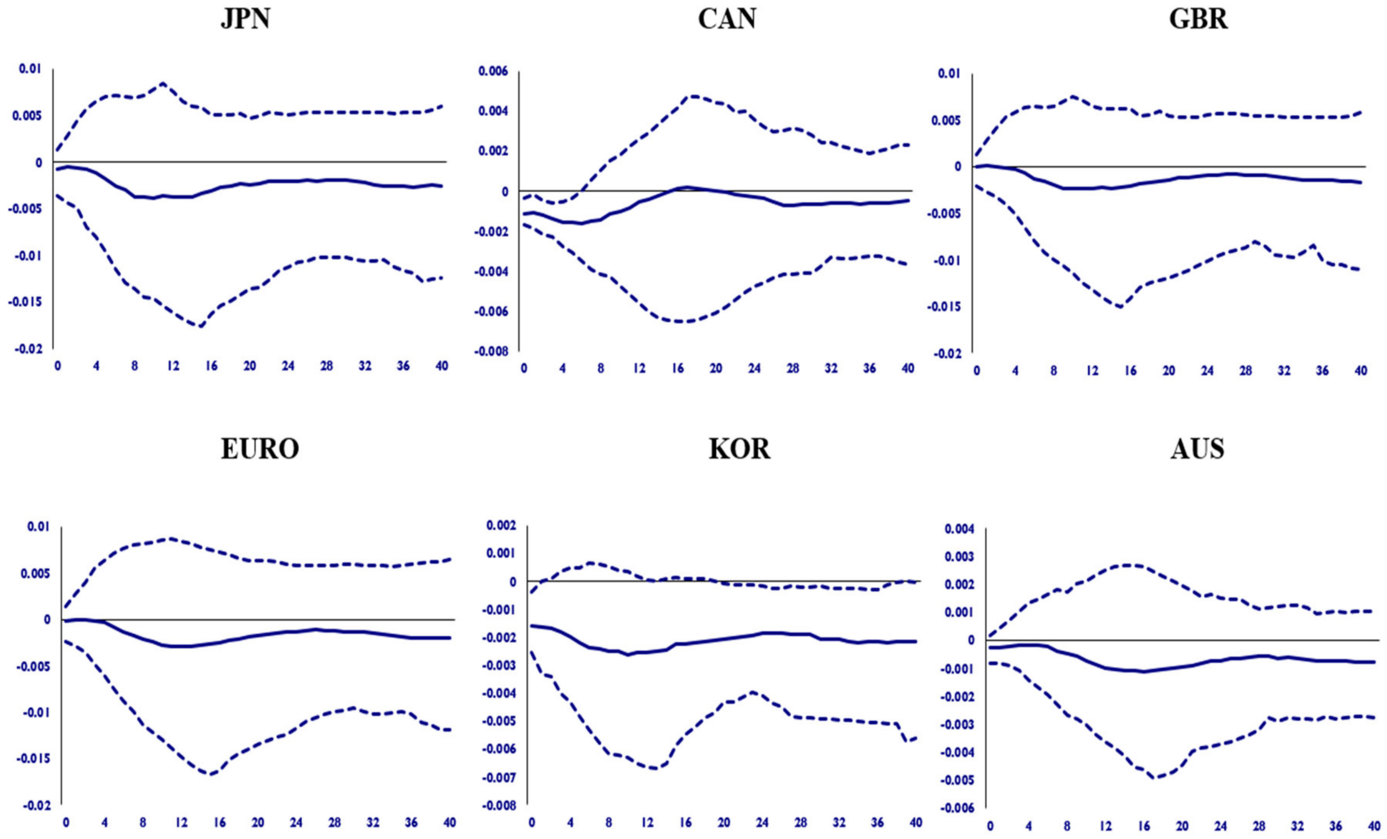

Figure 7. The GIRF curve of energy consumption in developed countries under the negative shock of one standard deviation of American energy consumption.

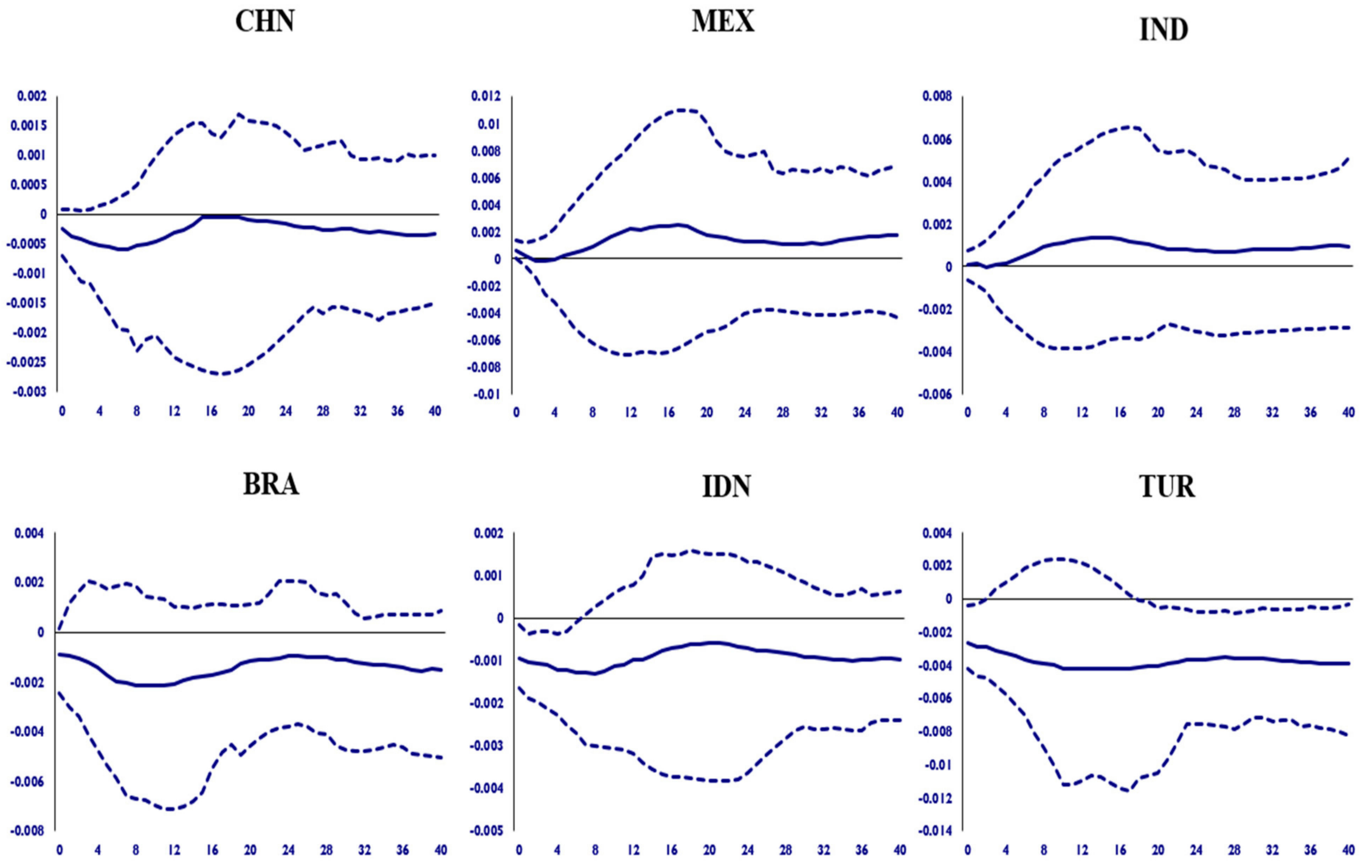

Figure 8. The GIRF curve of energy consumption in developing countries under the negative shock of one standard deviation of American energy consumption.

According to Figure 7, in the case of the energy consumption shock from the US, the energy consumption of other developed countries has shown a negative response characteristic. The GIRF curves are all located below the horizontal axis. The immediate response values of Canada and South Korea are between −0.1% and −0.2%, and this performance is significant. The immediate response values of Japan, the United Kingdom, the European Union and Australia are all around 0, but they are not significant from the results. In the following twelve periods, the GIRF curves of these developed countries all showed a slight downward trend. After the twelfth period (the third year after the shock), the GIRF curves fluctuated around a fixed value, and the deviation from this fixed value was small. Among them, Japan has the largest negative response, and the absolute value of the response is about twice that of other countries. This indicates that the reduction in energy consumption of the US has not had a significant negative influence on energy consumption in other developed countries. This spillover effect is not very significant.

According to Figure 8, in the case of the energy consumption shock from the United States, the energy consumption of most developing countries showed negative response characteristics, but Mexico and India showed positive response characteristics. In terms of immediate response values, the response values of China, Brazil, Indonesia, and Turkey are all negative, all around −0.2%, but China has the greatest degree of negative response. The immediate response values of Mexico and Turkey are both close to zero. In the first four quarters (within the first year after the shock), this performance was remarkable. In the long run, the response level of each country remains at a relatively stable level. However, long-term performance is not significant, which indicates that the reduction in energy consumption in the US spilled over to these developing countries in the short term, and the influence was a slight reduction in energy consumption of countries such as China and

Brazil. The energy consumption of Mexico and India will not be affected by the energy consumption of the United States.

4. Conclusions

The COVID-19 pandemic has heralded a severe economic shock to the United States, where the pandemic is the worst. A series of closure measures and economic recession have led to a reduction in the country's energy consumption. Existing studies have shown that there is a two-way causality between economic growth and energy consumption. Today, countries in the world are more closely connected through trade ties. Then, will the economic shock and energy consumption in the United States affect the two elements in other countries around the world to a certain extent? This article uses quarterly data from 41 major countries and regions between the second quarter of 1990 and the fourth quarter of 2013, and uses the GVAR model to conduct an analysis on the two-way spillover effects of the US' economic downturn and reduced energy consumption. The model is estimated based on data of the energy consumption and economic growth and three other macroeconomic variables (the potential transmission mechanism between energy consumption and economic growth). The GVAR model we constructed is based on a global system composed of 41 countries' VARX* models. By considering the relationship between internal trade and energy consumption between countries, it is easy to analyze the spillover of individual effects from the United States. The results of our GVAR model passed the stability test.

The conclusions regarding the US economic shock are as follows. On the one hand, we discussed the effects of the US economic shock on other countries' economic growth. Through GIRF analysis, we found that no matter from which perspective, whether developed countries or developing countries, there is no doubt that the pandemic not only caused losses to the US economy but that this impact on the US economy will also spread to the world along trade ties. In other countries, the US economic shock has reduced the level of economic growth. The first to bear the brunt is the trading partner countries with the closest trade ties to the United States, such as Japan, China and Mexico, and the influence of such shocks on the economic growth of developed countries is far more profound than that of developing countries. Under the shock of the US economy, the dynamic response process of the economic growth of countries such as Australia, Indonesia and Turkey, which are not very close to the US trade ties, is also negative, but not significant. A possible reason for this difference is the heterogeneity of trade associations. On the other hand, we discussed the influence of the US economic shock on other countries' energy consumption. Despite being in a developed country or a developing country, in general, the spillover effect of the negative economic shock of the United States on the energy consumption of other countries is to reduce that of these countries to varying degrees. The countries with the closest trade ties to the United States, such as Japan and China, have suffered the most from this impact. But the difference is that the impact of the US economic shock on developing countries' energy consumption is significant in the short term, while the impact on developed countries is long-term.

The conclusions regarding the impact of US energy consumption are as follows. On the one hand, we discussed the impact of the US energy consumption shock on other countries' economic growth, finding that the impact of the pandemic on US energy consumption has spillover effects. Specifically, the negative impact of energy consumption has spread to other countries along the international trade chain, and has a negative effect on other countries. In other words, the reduction in US energy consumption will slightly reduce the economic growth of other countries. On the other hand, we discussed the influence of US energy consumption on that in other nations, discovering that the reduction in energy consumption in the US has not had a significant negative effect on energy consumption in other developed countries. This spillover effect is not very significant. The reduction in energy consumption in the United States spilled over to developing countries in the short term, and the impact was to slightly reduce the energy consumption of these countries such as China and Brazil. The energy consumption of Mexico and India will not be affected by the energy consumption of the United States.

In short, on one hand, the simulation results of economic spillover effects indicate that the spillover effects of the US COVID-19 recession have a negative impact on economic growth in other countries through trade ties, reducing the economic growth of other countries, especially for countries that have close trade relationships with the US. Similarly, the spillover effects of the US economic recession have different impacts on energy consumption in other countries. The countries with the closest trade ties to the United States, such as Japan and China, have suffered the most from this impact. However, the difference is that the impact of the US economic shock on developing countries' energy consumption is significant in the short term, while the impact on developed countries is long-term. On the other hand, the simulation results of energy spillover effects indicate the reduction in US energy consumption slightly reduces the economic growth of other countries. In addition, the reduction in energy consumption in the United States has not had a significant negative impact on energy consumption in other developed countries. Furthermore, the reduction in energy consumption in the United States spilled over to developing countries in the short term, and the impact was to slightly reduce the energy consumption of countries such as China and Brazil. The energy consumption of Mexico and India will not be affected by the energy consumption of the United States.

Therefore, we call on the international community to strengthen communication and cooperation to jointly and actively respond to this human challenge. Finally, there are two limitations to our study. First of all, the data update regarding the degree of different variables and different countries is inconsistent, so the data should be updated in the future. Secondly, we only studied the spillover effects of the shock of the US pandemic on the economy and energy consumption of certain countries, and further research can be carried out for other countries.

This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.

Author Contributions: Conceptualization, R.L.; methodology, R.L. and S.H.; software, R.L.; validation, R.L. and S.H.; formal analysis, S.H.; investigation, S.H.; resources, S.H.; data curation, S.H.; writing—original draft preparation, R.L. and S.H.; writing—review and editing, S.H.; visualization, R.L.; supervision, R.L.; project administration, R.L.; funding acquisition, R.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Natural Science Foundation of Shandong Province, China, grant number ZR2018MG016 and the High-end Technology Innovation Think Tank Youth Project of China Association for Science and Technology under (Grant No. 20200608CG080611).

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Not Applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The definitions and sources of the variables.

Symbol	Definition	Source	The Unit of Measurement of Each Variable
y	GDP in purchasing power parity terms	International Monetary Fund (IMF) database	USD 100,000,000
ee	energy efficiency	World Development Indicators (WDI) database	MJ/USD 2011 PPP GDP
tro	proportion of total import and export to GDP	World Development Indicators (WDI) database	%
enc	primary energy consumption	BP Statistical Review of World	Million tons
ins	the proportion of industrial added value to GDP	World Development Indicators (WDI) database	%
poil	nominal price of Brent crude oil price in USD	BP Statistical Review of World	USD

Table A2. Abbreviations of the countries.

Country	Abbreviation	Country	Abbreviation
Australia	AU	India	IN
Austria	AT	Ireland	IE
Belgium	BE	Italy	IT
Bulgaria	BG	Japan	JP
Brazil	BR	Korea	KR
Canada	CA	Lithuania	LT
Switzerland	CH	Luxembourg	LU
China	CN	Latvia	LV
Cyprus	CY	Mexico	MX
Czech	CS	Netherlands	NL
Germany	DE	Norway	NO
Dennmark	DK	Poland	PL
Spain	ES	Portugal	PT
Estonia	EE	Romania	RO
Finland	FI	Russia	RU
France	FR	Slovak	SK
United Kingdom	GB	Slovenia	SI
Greece	GR	Sweden	SE
Croatia	HR	Turkey	TR
Hungary	HU	United States	US
Indonesia	ID		

Table A3. Country Weights.

Country	y	ee	tro	enc	ins
AU	0.020299	0.020299	0.020299	0.020299	0.020299
AT	0.006733	0.006733	0.006733	0.006733	0.006733
BE	0.008221	0.008221	0.008221	0.008221	0.008221
BG	0.000875	0.000875	0.000875	0.000875	0.000875
BR	0.037761	0.037761	0.037761	0.037761	0.037761
CA	0.028282	0.028282	0.028282	0.028282	0.028282
CH	0.010073	0.010073	0.010073	0.010073	0.010073
CN	0.120369	0.120369	0.120369	0.120369	0.120369
CY	0.000412	0.000412	0.000412	0.000412	0.000412
CS	0.003562	0.003562	0.003562	0.003562	0.003562
DE	0.059028	0.059028	0.059028	0.059028	0.059028
DK	0.005532	0.005532	0.005532	0.005532	0.005532
ES	0.023492	0.023492	0.023492	0.023492	0.023492
EE	0.000363	0.000363	0.000363	0.000363	0.000363
FI	0.004197	0.004197	0.004197	0.004197	0.004197
FR	0.045153	0.045153	0.045153	0.045153	0.045153
GB	0.043161	0.043161	0.043161	0.043161	0.043161
GR	0.004537	0.004537	0.004537	0.004537	0.004537

Table A3. *Cont.*

Country	y	ee	tro	enc	ins
HR	0.001001	0.001001	0.001001	0.001001	0.001001
HU	0.002284	0.002284	0.002284	0.002284	0.002284
ID	0.014191	0.014191	0.014191	0.014191	0.014191
IN	0.031776	0.031776	0.031776	0.031776	0.031776
IE	0.004103	0.004103	0.004103	0.004103	0.004103
IT	0.035051	0.035051	0.035051	0.035051	0.035051
JP	0.096758	0.096758	0.096758	0.096758	0.096758
KR	0.020231	0.020231	0.020231	0.020231	0.020231
LT	0.00069	0.00069	0.00069	0.00069	0.00069
LU	0.000938	0.000938	0.000938	0.000938	0.000938
LV	0.000447	0.000447	0.000447	0.000447	0.000447
MX	0.018848	0.018848	0.018848	0.018848	0.018848
NL	0.014349	0.014349	0.014349	0.014349	0.014349
NO	0.00743	0.00743	0.00743	0.00743	0.00743
PL	0.008502	0.008502	0.008502	0.008502	0.008502
PT	0.003849	0.003849	0.003849	0.003849	0.003849
RO	0.003007	0.003007	0.003007	0.003007	0.003007
RU	0.02689	0.02689	0.02689	0.02689	0.02689
SK	0.00158	0.00158	0.00158	0.00158	0.00158
SI	0.000811	0.000811	0.000811	0.000811	0.000811
SE	0.008578	0.008578	0.008578	0.008578	0.008578
TR	0.015181	0.015181	0.015181	0.015181	0.015181
US	0.261457	0.261457	0.261457	0.261457	0.261457

Table A4. Unit root test result at the 5% significance level (determine the lag order based on AIC criterion).

Domestic Variables	y	y	ee	ee	tro	tro	enc	enc	ins	ins
Statistic	ADF	WS	ADF	WS	ADF	WS	ADF	WS	ADF	WS
critical value	−3.4500	−3.2400	−3.4500	−3.2400	−3.4500	−3.2400	−3.4500	−3.2400	−3.4500	−3.2400
AU	−1.5107	−1.2549	−1.8191	−1.4503	−1.8652	−1.4065	0.3227	−0.4620	−1.9110	−0.3609
AT	−0.6790	−1.0600	−1.7295	−2.0358	−2.4456	−1.7102	0.0396	−0.1766	−2.2476	−2.5066
BE	−0.5584	−1.0556	−2.2086	−0.1377	−2.9678	−2.2798	0.7815	0.5822	−2.1472	−0.3584
BG	−2.7832	0.0926	−1.5204	−1.4940	−1.7196	−2.0380	−2.8109	−1.6896	−2.5888	−0.4095
BR	−1.4980	−1.2991	−1.2848	−1.3895	−1.1762	−1.4221	−1.4780	−1.4302	−1.7711	−1.8554
CA	−1.9924	−1.2416	−3.1290	−0.4694	−2.3659	−0.7494	−2.0241	−1.6002	−2.0290	−2.2784
CH	−2.9200	−0.7042	−2.3883	−1.2700	−2.7827	−1.4777	−2.1946	−1.9150	−1.5794	−0.9791
CN	−3.9271	−3.7522	−2.3625	−0.8450	−1.0111	−1.1470	−2.7419	−2.7256	−2.3189	−0.6442
CY	2.9302	0.1610	−2.7200	−0.8625	−1.8340	−1.9448	1.4477	0.6937	−0.5002	−1.0934
CS	−2.2740	−1.2755	−2.2357	−2.3819	−2.8803	−2.9549	−2.4629	−0.6704	−2.3603	−2.5372
DE	−3.1067	−2.6397	−2.5110	−2.1704	−2.6312	−1.8191	−1.5595	−1.5915	−1.0879	−0.6258
DK	−0.4142	−0.7074	−2.3070	−1.8105	−2.5516	−2.3370	−2.2762	−0.1560	−1.1349	−1.5037
ES	−1.1523	−1.6286	−1.0058	−0.5242	−1.6884	−1.5627	1.5430	0.1102	0.6093	−0.5884
EE	−2.4889	−2.5700	−0.2608	−0.8421	−1.3910	−1.7679	−4.1438	−0.2219	−2.2364	−2.5172
FI	−0.9463	−0.9646	−3.0411	−1.5389	−2.2110	−1.1107	−0.4127	−0.6750	−0.3528	−0.9509
FR	−0.5330	−1.0840	−2.6377	−1.3695	−1.8274	−2.1052	−0.8169	0.4724	−1.6266	−1.6018
GB	−0.8791	−1.3686	−4.5314	0.1218	−1.7522	−1.9722	−0.0444	0.1870	0.3538	−0.4013
GR	−1.9983	−2.2965	−1.1160	−1.4716	−2.2780	−2.3063	3.5434	0.5424	−1.1933	−1.1897
HR	−1.4826	−1.5736	−1.8559	−0.7311	−2.1410	−2.3928	−1.1583	−1.1059	−1.3500	−1.0924
HU	−1.0455	−1.2328	−1.7616	−1.2653	−1.0343	−1.4193	−0.9338	−0.7008	−1.4482	−1.4988
ID	−1.3852	−1.6345	−0.3339	−0.9185	−1.6253	−1.6926	−2.0765	−0.6407	−1.5259	−1.6901
IN	−2.7306	−0.7552	−0.9790	−1.0468	−0.6617	−1.1593	−0.6244	−0.9916	−0.1491	−0.5395
IE	−1.3622	−1.8359	−1.3305	−1.7125	−1.7970	−1.6548	0.7557	−0.1393	−1.0701	−1.1401
IT	0.5635	−0.3343	0.5923	−0.0921	−2.1011	−2.1951	1.8946	0.4884	−2.3519	−2.3596
JP	−1.9979	−1.7672	−0.5206	−0.2074	−2.5774	−1.3275	−0.7908	0.6570	−2.2454	−0.8355
KR	−1.3581	0.2484	−2.8651	−1.7440	−2.2444	−1.7189	−3.6067	0.8546	−1.3299	−1.7148
LT	−2.4062	−2.1506	−2.3731	−1.2898	−1.8517	−1.5263	−3.5694	−2.1988	−2.0392	−2.3381
LU	−0.9294	−1.1663	−1.6369	−1.5073	−1.7563	−1.8219	−1.1643	−1.4375	−1.7561	−0.8821
LV	−2.6529	−2.6445	−1.3718	−1.4774	−1.3322	−1.4020	−4.4942	−0.0499	−1.2926	−1.3745
MX	−1.7574	−1.7809	−1.4577	−1.4584	−3.8556	−4.0204	−1.2858	−1.6183	−2.1445	−0.6492
NL	−0.1737	−0.7973	−2.2244	−2.2661	−1.5443	−1.7469	1.2016	0.3106	−2.2290	−1.7118
NO	−0.9976	−0.5302	−1.5636	−1.7168	−2.3160	−2.4098	−2.3728	−2.5536	−2.1387	−2.2834
PL	−2.6526	−2.5549	−0.9160	−1.3203	−2.5050	−2.6632	−1.7495	−1.0140	−1.1547	−1.5815
PT	0.3293	−0.4775	−0.9826	−0.3869	−2.2121	−1.7105	−0.3215	−0.1253	−2.2423	−0.3883

Table A4. *Cont.*

Domestic Variables	**y**	**y**	**ee**	**ee**	**tro**	**tro**	**enc**	**enc**	**ins**	**ins**
RO	−2.6282	−0.5609	−2.6125	−2.6278	−2.5766	−1.3555	−2.8437	−0.8427	−1.6186	−0.7887
RU	−3.8236	−0.4930	−2.8734	−0.3960	−2.2420	−2.0743	−2.5317	−0.6829	−1.9168	−1.4249
SK	−2.4120	−1.9915	−2.0105	−1.7024	-5.6220	−2.7736	−2.1535	−0.5376	−0.7496	−1.2466
SI	−1.4176	−1.1512	−2.5235	−0.3896	−3.8527	−2.0900	−0.2962	−0.9350	−2.8364	−2.8527
SE	−2.0781	−1.3686	−2.3795	−0.7914	−3.8941	−0.3977	−2.6379	−2.7758	−1.4946	−1.8365
TR	−1.3757	−1.5700	−1.2827	−1.6859	−1.1006	−1.3732	−1.5680	−1.9091	−0.7828	−1.2722
US	−0.7125	−1.2446	−3.8330	−0.7147	−2.3717	−2.0958	−0.7762	−0.5058	−2.3701	−2.1356
Foreign Variables	**ys**	**ys**	**ees**	**ees**	**tros**	**tros**	**encs**	**encs**	**inss**	**inss**
Statistic	ADF	WS	ADF	WS	ADF	WS	ADF	WS	ADF	WS
critical value	−3.4500	−3.2400	−3.4500	−3.2400	−3.4500	−3.2400	−3.4500	−3.2400	−3.4500	−3.2400
AU	−1.1286	−1.4215	−2.4172	−0.9579	−2.0084	−2.2580	0.4851	−0.3152	−1.3644	−1.6893
AT	−1.6499	−0.9647	−2.5396	−0.8259	−3.3835	−2.9153	−1.4586	−0.4339	−2.0881	−1.8194
BE	−1.2938	−1.1017	−2.4188	−1.5074	−2.6472	−2.8705	−0.9140	−0.4500	−2.1493	−1.8234
BG	−1.1811	−1.0741	−2.2474	−0.9773	−2.0902	−2.3748	−0.4321	−0.6213	−0.9368	−1.4088
BR	−0.8934	−1.1683	−2.5914	−0.7793	−2.1840	−2.4570	0.7552	−0.1927	−1.4962	−1.8117
CA	−0.8455	−1.2182	−2.7366	−1.0653	−2.1262	−2.1945	0.2563	−0.5132	−2.1343	−2.2992
CH	−1.3735	−1.3379	−2.2718	−1.2439	−2.6985	−2.9531	−2.2646	−0.4027	−2.3948	−2.6784
CN	−1.1912	−1.2734	−2.8958	−0.1823	−2.2760	−2.5518	0.7630	0.0411	−1.9741	−2.1157
CY	−1.8403	−2.0846	−1.6537	−1.0830	−2.4254	−2.5231	0.5139	−0.0684	−1.0340	−1.4099
CS	−1.7235	−1.0989	−2.7141	−0.8125	−3.3561	−2.5065	−1.2053	−0.2047	−1.9639	−1.6647
DE	−1.3839	−1.1156	−2.6466	−1.0283	−2.6244	−2.7579	−0.6602	−0.3986	−1.9228	−2.1149
DK	−1.1702	−1.1787	−2.3791	−0.9439	−2.7169	−2.6571	−2.1700	−0.4514	−1.3894	−1.7118
ES	−0.7476	−1.0445	−2.4611	−0.6461	−2.3950	−2.6013	0.5814	−0.3095	−2.1517	−2.4537
EE	−2.0703	−1.8765	−2.0689	−1.3748	−1.9839	−2.1225	−4.0179	−0.7990	−1.9266	−2.1140
FI	−2.3123	−2.3425	−0.9950	−1.1449	−2.1544	−1.8571	−4.2349	−0.3107	−2.1359	−2.4312
FR	−1.0310	−1.1701	−2.5806	−0.9675	−2.4440	−2.6958	0.1398	−0.2800	−1.6381	−2.0050
GB	−0.7992	−1.2056	−2.4628	−1.1547	−2.2196	−2.4306	0.6423	−0.1751	−1.2097	−1.6252
GR	−1.0055	−0.5963	−2.4716	−0.3260	−2.4527	−2.6222	0.4824	−0.4051	−1.9343	−0.9858
HR	−1.4265	−1.0225	−2.5602	−0.4685	−4.3366	−2.5359	0.0730	−0.5143	−2.1138	−2.4047
HU	−1.6607	−0.9601	−2.4489	−0.9684	−3.2854	−2.9088	−1.0980	−0.4162	−1.7675	−1.4587
ID	−1.1395	−1.1642	−2.6726	−0.9241	−2.0913	−2.3805	0.2374	−0.4386	−1.7559	−1.9473
IN	−1.2881	−1.3189	−2.6011	−0.5080	−2.1437	−2.4001	0.2880	−0.4316	−1.8876	−2.1559
IE	−0.9959	−1.1781	−2.9698	−0.7296	−2.5216	−2.7633	0.6463	−0.1714	−1.9925	−2.2734
IT	−1.3009	−1.0466	−2.5122	−0.7291	−2.6365	−2.7785	−0.1780	−0.3169	−1.6941	−1.7593
JP	−1.5724	−1.4174	−2.5700	−0.7735	−1.8261	−1.7495	−0.0130	−0.6329	−1.7378	−2.0000
KR	−1.5396	−1.4132	−2.3475	−0.9142	−1.9392	−2.2082	−0.0744	−0.6446	−1.4755	−1.8551
LT	−2.4705	−2.3405	−1.2928	−1.2374	−1.6840	−1.9654	−4.6822	0.0441	−2.2616	−2.5174
LU	−1.0403	−1.1036	−2.7031	−0.5273	−2.5858	−2.8325	0.7876	−0.1292	−2.1800	−2.3632
LV	−2.1742	−1.8904	−1.6890	−1.2008	−1.6091	−1.8505	−4.6283	−1.8803	−1.9801	−2.2770
MX	−0.6151	−1.0923	−2.8535	−0.5511	−2.0936	−1.9263	0.3298	−0.2883	−1.7843	−2.0807
NL	−1.2130	−1.1970	−2.6845	−0.9817	−2.4100	−2.6775	−0.2783	−0.4053	−1.7695	−2.0861
NO	−1.3668	−1.3249	−2.1435	−0.9881	−2.7923	−2.1474	−2.8708	−1.0031	−1.6619	−2.0144
PL	−1.7183	−1.1139	−2.6487	−0.8009	−3.0913	−3.0383	−1.9164	−0.7081	−1.8230	−1.9246
PT	−0.6929	−1.0481	−2.4900	0.1314	−1.9225	−2.0571	1.0393	−0.0900	−0.2092	−0.8971
RO	−1.5394	−0.7822	−2.2989	−0.4663	−2.4657	−2.4499	−0.7221	−0.5890	−2.3537	−1.2358
RU	−0.8727	−1.1022	−2.6669	−0.8004	−2.3434	−2.5826	−1.5581	−0.7874	−1.0874	−1.4988
SK	−1.6478	−0.8348	−2.5356	−1.3525	−2.7639	−2.9886	−1.5749	−0.4967	−2.1972	−2.3656
SI	−1.4783	−1.3974	−2.0867	−0.8077	−2.0615	−2.3533	−0.6029	−0.5035	−1.1925	−1.6086
SE	−1.2354	−1.3436	−1.9159	−1.2750	−2.5776	−2.7894	−2.8704	−0.8282	−1.2265	−1.6422
TR	−1.0435	−1.1636	−2.2112	−0.8677	−2.4822	−2.7407	0.6414	−0.2269	−1.1370	−1.2702
US	−1.2098	−1.3408	−2.6864	−0.9748	−1.5528	−1.7958	0.2022	−0.5340	−1.7983	−1.9286

Table A5. Test for weak exogeneity at the 5% significance level.

Country	**F Test**	**Fcrit_0.05**	**ys**	**ees**	**tros**	**encs**	**inss**	**poil**
FR	F(1.79)	3.961892	0.009678	0.003936	0.231023	0.06085	0.084665	5.753764
MX	F(1.79)	3.961892	0.195472	0.880341	1.078184	0.008847	0.696638	9.806077
SK	F(2.78)	3.113792	0.947624	0.15655	1.225315	0.339064	1.360141	6.579848
SE	F(1.79)	3.961892	1.074382	0.005338	0.724602	0.701016	0.799591	0.981701
TR	F(1.79)	3.961892	0.054658	0.000559	0.223045	0.103181	0.552213	5.263006

Notation: the result of other counties is zero, which indicates no co-integration relationship in the test.

Table A6. Average pairwise cross-section correlations: residuals.

	y			**ee**			**tro**			**enc**			**ins**		
	Levels	**First Differences**	**VECMX* Residuals**	**Levels**	**First Differences**	**VECMX* Residuals**	**Levels**	**First Differences**	**VECMX* Residuals**	**Levels**	**First Differences**	**VECMX* Residuals**	**Levels**	**First Differences**	**VECMX* Residuals**
AU	0.2345	0.1107	−0.0656	0.0196	−0.0198	−0.0002	−0.2307	−0.3558	0.0259	0.0374	−0.0445	0.0054	−0.0973	−0.1075	0.0239
AT	0.5353	0.5852	0.0632	0.2971	0.3162	−0.0095	0.5535	0.6109	0.1499	0.2038	0.2308	−0.0367	0.1568	0.0753	0.0108
BE	0.5223	0.5334	0.0881	0.2385	0.2193	−0.0215	0.5739	0.6235	0.1885	0.3229	0.3528	0.006	0.1977	0.1496	−0.0217
BG	0.1421	0.0746	−0.0478	−0.0155	0.0057	−0.0423	0.1178	0.0931	−0.1470	0.1878	0.196	−0.0550	−0.0765	−0.0758	−0.0124
BR	0.3618	0.4916	−0.0532	0.121	0.1737	−0.0406	0.2011	0.2881	−0.1453	0.2455	0.3302	0.0114	−0.0172	−0.0075	−0.0863
CA	0.5341	0.525	0.0311	0.1636	0.0624	−0.0301	0.4182	0.5632	0.0799	0.1358	0.1292	0.0277	0.1882	0.1519	−0.0039
CH	0.5101	0.5949	−0.0083	0.1437	0.1117	−0.0388	0.4386	0.4685	0.0499	−0.0780	−0.0263	−0.0549	0.0472	0.048	−0.0045
CN	0.1305	0.2736	−0.0310	0.0031	0.1489	0.0188	0.3362	0.4923	0.0516	0.0859	0.0555	−0.0247	0.1128	0.0652	0.0399
CY	0.3219	0.3255	0.0684	0.0205	0.0042	−0.0417	0.2553	0.3115	−0.0247	0.0285	−0.0191	−0.0316	0.0565	−0.0257	−0.0651
CS	0.426	0.4435	−0.0180	0.1685	0.1453	0.0015	0.3823	0.4192	0.0831	0.2573	0.2837	−0.0303	0.1224	0.0666	−0.0065
DE	0.4602	0.5922	0.0714	0.2472	0.2986	−0.0070	0.5231	0.6022	0.154	0.2934	0.3407	−0.0007	0.1441	0.1495	−0.0486
DK	0.5289	0.555	0.0942	0.2581	0.2543	0.0077	0.5244	0.5854	0.1188	0.1593	0.1813	−0.0145	0.2264	0.1829	0.0089
ES	0.5047	0.566	0.0833	−0.0684	−0.1121	−0.0300	0.529	0.5927	0.1346	0.2464	0.2139	−0.0391	0.154	0.0835	0.0523
EE	0.499	0.5099	−0.0027	0.1896	0.1695	0.0012	0.369	0.442	0.0122	0.2208	0.2985	0.0109	0.185	0.1317	0.0562
FI	0.5848	0.6293	0.0456	0.1853	0.1463	−0.0141	0.4893	0.5838	0.0799	0.2348	0.2711	−0.0379	0.2058	0.1556	0.0069
FR	0.5422	0.5733	0.0868	0.2977	0.2962	0.0073	0.564	0.6168	0.18	0.3142	0.3835	0.0558	0.0555	0.095	0.0278
GB	0.5339	0.545	0.0035	0.304	0.2951	−0.0074	0.321	0.3769	−0.0084	0.2976	0.3322	−0.0061	0.0442	0.0347	−0.0778
GR	0.3007	0.2407	0.0216	−0.0383	−0.0805	−0.0436	0.5108	0.5956	0.1372	0.0902	−0.0536	−0.0094	−0.0315	−0.0640	0.0896
HR	0.3664	0.354	−0.1041	0.1266	0.0464	−0.0386	0.3364	0.3656	−0.0048	0.1438	0.178	0.0388	0.0824	0.0689	0.065
HU	0.4757	0.4821	0.0021	0.2475	0.2339	−0.0207	0.3512	0.3729	0.1336	0.2803	0.2702	0.0029	0.1127	0.0959	−0.0184
ID	−0.0074	0.1032	−0.0376	0.07	0.1073	0.0196	0.2636	0.2942	0.0065	0.0044	−0.0238	−0.0114	0.0185	−0.0380	0.0224
IN	0.0202	−0.1224	0.0442	−0.0901	−0.2039	−0.0085	0.368	0.439	0.0197	−0.1363	−0.1823	−0.0348	0.1118	0.09	0.0025
IE	0.4468	0.3889	0.0515	0.1911	0.203	−0.0564	0.117	0.179	0.0527	0.2685	0.3273	−0.0404	−0.0172	−0.0632	0.0413
IT	0.5426	0.5941	0.089	0.177	0.1806	−0.0031	0.5071	0.5566	0.1574	0.3254	0.3453	0.0147	0.223	0.1779	−0.0229
JP	0.4282	0.5282	−0.0094	0.0745	0.026	−0.0211	0.5024	0.5888	−0.0510	0.3362	0.3556	0.0061	0.0855	0.0429	−0.1076
KR	0.2037	0.2443	0.0228	0.079	0.0146	−0.0168	0.3768	0.4563	0.0573	0.0512	0.028	0.012	0.0003	0.0456	0.0325
LT	0.3663	0.4002	−0.0506	0.0328	−0.0456	−0.0422	0.4355	0.5394	0.1026	−0.0253	−0.1052	−0.0487	0.2178	0.1854	0.0699
LU	0.4271	0.465	−0.0267	0.1461	0.1572	−0.0311	0.5098	0.5765	0.0734	0.136	0.182	−0.0287	0.1239	0.0718	−0.0108
LV	0.3747	0.3322	−0.0725	0.2915	0.2696	−0.0072	0.2369	0.25	−0.0070	0.1821	0.2413	−0.0205	0.1397	0.1262	0.0594
MX	0.3309	0.3907	−0.0208	−0.0033	−0.0304	−0.0268	0.1686	0.2061	0.0053	0.085	0.0587	−0.0179	0.1194	0.0869	0.084
NL	0.5183	0.5803	0.0354	0.308	0.292	0.0151	0.1845	0.2231	0.0891	0.2884	0.3117	0.0255	0.1491	0.1188	0.0633
NO	0.3913	0.4293	−0.0118	0.199	0.2622	0	0.5476	0.6009	0.1214	−0.0264	−0.0340	−0.0225	0.1659	0.1451	0.0058
PL	0.2895	0.2458	−0.0376	0.2283	0.2481	0.0147	0.504	0.5416	0.0854	0.2362	0.2785	0.042	−0.0004	0.0117	0.0594
PT	0.4059	0.5067	0.0588	−0.1107	−0.1963	−0.0184	0.2363	0.3047	0.0293	0.1056	0.1191	0.0476	0.0631	−0.0090	−0.0707

Table A6. *Cont.*

	y			**ee**			**tro**			**enc**			**ins**		
	Levels	**First Differences**	**VECMX* Residuals**	**Levels**	**First Differences**	**VECMX* Residuals**	**Levels**	**First Differences**	**VECMX* Residuals**	**Levels**	**First Differences**	**VECMX* Residuals**	**Levels**	**First Differences**	**VECMX* Residuals**
RO	0.255	0.2014	−0.0579	0.0935	0.0665	−0.0335	0.5334	0.6074	0.1474	0.2052	0.2005	−0.0325	0.0231	0.0054	−0.0176
RU	0.2808	0.3345	−0.0145	0.2034	0.1548	−0.0056	0.1359	0.1643	−0.1894	0.1399	0.3109	0.0141	0.1133	0.027	0.0037
SK	0.4761	0.5032	0.0148	0.1557	0.1322	−0.0083	0.0561	0.1098	−0.1054	0.2625	0.3165	0.0267	−0.0793	−0.0118	0.0098
SI	0.5144	0.5333	0.0381	0.2467	0.1897	−0.0034	0.2629	0.3948	−0.1174	0.2401	0.256	−0.0424	0.0676	−0.0187	−0.0252
SE	0.547	0.5925	0.1041	0.2285	0.2025	−0.0199	0.3399	0.374	0.0474	0.1576	0.1838	−0.0216	0.1009	−0.0430	0.0041
TR	0.2285	0.2624	−0.0943	0.0216	0.0181	−0.0356	0.4216	0.5003	0.1504	0.039	−0.0042	−0.0431	0.0735	−0.0294	−0.0174
US	0.4893	0.5392	−0.0464	0.0311	−0.0511	0.019	0.2192	0.2176	−0.0562	0.275	0.29	0.0478	0.1268	−0.0162	−0.0303

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