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Energy-food nexus scarcity risk and the synergic impact of climate policy: A global production network perspective

Yan Xia [a,b], Bingqian Yan [c,*]

[a] Institutes of Science and Development, Chinese Academy of Sciences, Beijing 100190, China
[b] School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing 100049, China
[c] National Academy of Economic Strategy, Chinese Academy of Social Sciences, Beijing 100028, China

A R T I C L E I N F O

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A B S T R A C T

Carbon neutrality has been a global consensus to navigate away from catastrophic climate change. In particular, such climate changes also generate inevitable influences on economic securities, such as energy security and food security, through energy structure transformation etc. Energy and food are essential elements for human beings, and they are naturally linked to sustainable development. Usually, emergency events, such as the COVID-19 pandemic, may threaten energy security or food security in a region, the risk of which would be amplified due to the energy-food nexus effect. This is no doubt also a challenge and an opportunity for countries to achieve carbon neutrality. To realize the stable pathways to carbon neutrality, it is important to analyze the energy scarcity risk and food scarcity risk of each industry and country as well as the nexus effect between energy and food. In this paper, we combine multi-regional input-output (MRIO) analysis with network control analysis (NCA) to investigate the dependence degree of each country and region on energy and food resources as well as the risk transmission network of the energy-food scarcity nexus. Base on this, the impact of climate policy on energy-food nexus scarcity risk is analyzed. We found some interesting conclusions. First, regarding the risk transmission network of the energy-food scarcity nexus, China, Germany and the US are the main generators, and the main receptors are Taiwan, Mexico and the Netherlands. These results imply that international trade transfers energy/food scarcity to geographically distant regions via the international supply chain. Second, as for the scarcity risk per unit of output, small economies that rely heavily on imported energy or food (such as Cyprus and Luxemburg) have the highest scarcity risk and are among the top receptors of transmitted risks. We suggest collaborative conservation and management of energy and food resources. Third, the analyses that assess the emission intensity and scarcity risk find that implementation of emission control policies could significantly decrease initial energy scarcity risk and energy-food nexus scarcity risk. This implies that besides emission reduction achievement, climate policies bring co-benefits of energy-food nexus security. Moreover, the co-benefit of energy and food nexus security for low income economies associated with climate policy is much higher than that for high income economies.

1. Introduction

Climate change generates severe impacts on the global economy and society. To curb the increasing greenhouse gas emissions, many countries have announced target dates for achieving carbon neutrality, many aiming for 2050 (e.g., Japan, Germany and Canada). Meanwhile, we also note that such climate policies also generate inevitable influences on economic securities, such as energy security and food security, through energy structure transformation etc (McCollum et al., 2011). Therefore, it is of importance to analyze the effect of climate policy on energy and food security to provide supports for effective policy formation and the basis of that is the accurate estimation of energy and food nexus scarcity risk and their transmission network.

Energy and food are essential elements for human beings, and they are naturally linked to sustainable development (Wang et al., 2021). On one hand, energy is used in the whole production chain of final products, such as machine operation and transportation. An energy shortage could limit production capacity and ultimately exert a negative impact on economic growth. On the other hand, as another international commodity, food is increasingly interconnected with energy. In line with the

* Correspondence to: 816 Keyan Building, Dongchang Hutong, Dongcheng District, Beijing, China.
E-mail address: yanbingqian2018@126.com (B. Yan).

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ongoing socio-economic development trends, food productions are being increasingly determined by energy use, industrial activities and waste management (Lee et al., 2020; Crppa et al., 2021). One example is that a proportion of clean energy comes from biomass. In these cases, there is a trade-off between energy and food. In other cases, especially in resource shortages, a synergy can be found between energy and food. For instance, emergency events, such as the COVID-19 pandemic, may threaten energy security or food security in a region, the risk of which would be amplified due to the energy-food nexus effect. The pandemic continues to expose weaknesses in our food systems, which threaten the lives and livelihoods of people around the world, particularly the most vulnerable and those living in fragile contexts. The extreme weather triggered by global climate change has severely hit crop yields and pushed up food prices (Lee et al., 2020; Wang et al., 2021). In the last ten years, the frequency and intensity of conflict, climate variability and extremes, and economic slowdowns and downturns have increased and are undermining food security and nutrition around the world. Of particular concern are low- and middle-income countries, because the negative impacts on food security and nutrition are greatest in these countries: they carry the biggest burden of the world's population who are undernourished (13%) and children who are stunted (24%) (FAO, 2021). To maintain the healthy and stable growth of an economy, it is important to analyze the energy scarcity risk and food scarcity risk of each industry and country as well as the nexus effect between energy and food.

Particularly, in the influence of climate change, energy and food scarcity risk become more complicated: climate change may worsen the spatial imbalance of energy supply and demand and decrease food production, which would cause energy and food market to fluctuate more extensively and frequently and thus increase the energy-food nexus scarcity risk of an economy. Meanwhile, given the increasingly stringent situation of global warming, many countries have announced to take strict measures to achieve carbon neutrality before certain time schedule. For instance, on September 22, 2020, Chinese government promised the world to strive to reach the peak of CO2 emissions by 2030 and achieve carbon neutrality by 2060 (Mallapaty, 2020). As a result, it is also interesting to investigate the potential impact climate policy on energy-food nexus scarcity risk.

Previous studies on the nexus between energy and food can be roughly classified into two strands: one strand investigates energy consumption during the food production process, such as Islam et al. (2021). The other strand evaluates biomass energy in the agriculture industry. The first strand focuses on the macro, one-directional relationship between energy and food, which cannot reveal the true nexus relationship between energy and food resources. The second strand focuses on the micro and local relationship, which cannot reflect the systematic risk at the national level. Recently, more studies have quantified the nexus between energy and food within regions or river basins (e.g., Li et al., 2021). However, these studies concentrate on comparing the synergy of energy consumption and food supply within different cropping systems or farming systems, while the quantification of energy-food nexus scarcity risk is lacking in the literature.

Moreover, with production advances and trade interconnections, countries and regions are increasingly interconnected. A country faces not only local energy scarcity risk but also other countries' energy scarcity risks transferred via trade across borders. The analysis of energy scarcity risk should be conducted from a systematic perspective. This brings us to the research questions of this paper: What is the energy scarcity risk of each industry and each country? How do we characterize the nexus between energy and food? What do the risk transmission networks of energy scarcity risk, food scarcity risk and the energy-food scarcity nexus look like? What is the potential impact of climate policies on energy-food nexus scarcity risk? To answer these questions, we combine multi-regional input-output (MRIO) analysis with network control analysis (NCA) to track the scarcity transmission network. To be more specific, this study can be distinguished from the previous literature by the following four aspects: First, the initial energy scarcity risk and food scarcity risk of each industry and country are estimated by quantifying potential output losses when local energy and food are in shortage. Second, the risk transmission king into account the transmission mechanism and indirect effect of energy and food scarcity risk via the trade network. Third, the nexus between food and energy is also addressed to reveal the interconnections and trade-offs. Finally, the potential impact of climate policy on energy-food nexus scarcity risk is analyzed by assessing the relationship between emission intensity reduction and scarcity risks.

The rest of the paper is organized as follows. Section 2 reviews the related literature. Section 3 introduces MRIO analysis and NCA to construct the energy risk transmission network. Section 4 describes the empirical results for each industry and each country using the world input-output table. Section 5 analyzes the potential impact of climate policy on energy-food nexus scarcity risks. Section 6 concludes the paper.

2. Literature review

The nexus concept can be traced back to many scientific domains, such as the nexus of socialism and political traditions (Wittfogel, 1955; Lele et al., 2013). The interaction between the three essential resources for human society (food, energy and water) have been emphasized since the oil crisis in the 1970 s. The relevant researches increased dramatically after the Bonn conference titled "the Water, Energy, and Food Security Nexus – Solutions for the Green Economy", which was held in 2011. These researches involve discussions on nexus of energy-agriculture, energy-food, food-water, energy-food-water, and energy-food-water-land, in particular (Endo et al., 2017; Zhang et al., 2019). As the food-energy-water nexus has become a vibrant research pursuit, different kinds of reviews are conducted to understand the methodology, method and tools of the nexus analysis (Fan et al., 2019; Zhang et al., 2019; Endo et al., 2020). Endo et al. (2020) further provided a review on these review articles.

Despite that the centrality of nexus analysis varies and diverse methods and tools have been used in different contexts, those methods and tools were borrowed from conventional disciplines and can be roughly categorized into three types. They are: resource-environmental footprint quantification, assessment and systematic simulation, and optimal management methods (Zhang et al., 2019). Among them, the first category aims at quantifying the resources and economic efficiency associated with the food-energy-water system. The bottom-up life cycle assessment (LCA) and top-down input-output analysis (IOA) are the mainly used methods (Roy et al., 2009; Owen et al., 2018; White et al., 2018). The second category engages in assessing and modeling the performance of food-energy-water systems (Feng et al., 2013; Daher and Mohtar, 2015; Chen and Chen, 2016; Li et al., 2021). Three types of methods and tools, indicator systems (IS), system dynamic (SD) models and network analysis (NA) have been used in this domain. The third category studies the optimization of the whole food-energy-water systems, and the relevant researches are still rare but emerging. Since this paper focuses on assessing the interdependence network of the nexus system, the methods of input-output analysis (IOA) and network analysis (NA) are of the most relevant, which are reviewed thoroughly next.

The first strand of literature links the food-energy-water nexus system with economic activities by using IOA, to describe the resource flows in different economic systems (Chen and Chen, 2016; Owen et al., 2018; White et al., 2018; Yang et al., 2018). For instance, White et al. (2018) utilized the inter-regional input-output approach to assess the water-energy-food nexus embodied in the intra-regional and transnational inter-regional trade in East Asia. Results showed that China is a net virtual exporter of nexus resources to Japan and South Korea. Owen et al. (2018) investigated the interaction between the energy, water and food impacts of products at different points along their supply chains in the UK through a global multi-regional input-output model.

Similar to the virtual flow of energy-food-water resources, the resource scarcity risk could also transfer across geographical borders. In this respect, Feng et al. (2014) incorporated water scarcity into MRIO analysis to assess virtual water flows among 30 provinces in China. They found that consumption in highly developed provinces depends on water resources in water-scarce inland provinces. Qu et al. (2018) quantified local water scarcity risk as potential output loss due to local water scarcity and examined the impacts of local water scarcity risk on the global trade system from 1995 to 2009. They showed that local water scarcity risk can be transmitted to downstream economies through the global supply chain.

The second strand of literature, which is related with this paper, uses Network Control Analysis (NCA) to investigate the dominant control and dependence relationships of resource flows among industries and countries. Different from embodiment analysis, which is based on the Leontief inverse matrix, NCA is based on the network control matrix, which evaluates the relative size of resource flows from industry A to industry B and vice versa per unit of production. Resource flows from industry A in one region to industry B in another region along a global supply chain do not necessarily mean that industry B bears the risk from industry A, since industry B might supply more embodied resources to industry A along other global supply chains. It is the net size of resource flow between the two industries that matters for examining resource risk transmission and thus quantifying the total resource scarcity risk in each industry. For example, Chen and Chen (2015) conducted NCA to analyze the extent to which the energy consumption of each industry is controlled by other industries.

Furthermore, literature which studies the relationship between climate policy and energy security is also relevant to this paper. Climate change has made the issue of energy and food security more complicated: climate change could cause the conventional energy and food market to fluctuate more frequently and extensively, heavily increasing the economic risks (Farrell et al., 2006; Jewell et al., 2016). Consequently, relationship between climate policy and energy security have gained lots of attentions from academia. Based on integrated assessment models (IAMs), Bollen et al. (2009) found that climate policies can reduce global energy trades and energy imports of leading countries, as well as increase the diversity of energy systems. Additionally, climate policies can also help to decrease the cost competitiveness of fossil fuel energy and accelerate the diffusion of non-fossil technology (McCollum et al., 2013; Cherp et al., 2016; Schumacher, 2017).

However, few researches take the energy scarcity transmission network into account, when analyzing the impact of climate policies. Meanwhile, the impact of climate policy on energy-food nexus scarcity risk is also seldom studied. To fill part of the literature gap, this paper specifically evaluates energy scarcity risk, food scarcity risk and energy-food scarcity nexus risk and their corresponding risk transmission networks, through combining MRIO analysis and NCA. By doing so, we aim to show how a holistic assessment of the energy-food nexus can promote sustainable planning in different countries. At the same time, we also aim to investigate the potential impact of climate policies on the overall energy scarcity risk, food scarcity risk, as well as energy-food nexus scarcity risk at both industrial and country level, which include all the scarcity risks that are transmitted to other trading partners. The main dataset we use is obtained from WIOD, covering from 2000 to 2014. Policy implications are consequently drawn from the results.

3. Methodology

3.1. Multi-regional input output analysis

Without loss of generality, let us consider an MRIO model with n economies and m industries. We use superscript (r and s) to indicate economies and subscript (i and j) to indicate industries. The $N \times N$ matrix $\mathbf{Z}^{rs}$ will be classified as the intermediate input flows that are produced in economy r and used in economy s; the $N \times 1$ vector $\mathbf{y}^{rs}$ as the final goods produced by economy r and required by economy s; the $N \times 1$ vector $\mathbf{x}^{s}$ as the outputs produced in economy s; the $N \times 1$ vector $\mathbf{v}^{rs}$ as the value added in economy s. Based on the above defined variables, the direct input coefficient matrix can be defined as $\mathbf{A} = \mathbf{Z}\widehat{\mathbf{x}}^{-1}$, where ^ denotes the diagonal matrix. The row balance condition or gross output production of the MRIO model can be written as:

$$\mathbf{Ax} + \mathbf{y} = \mathbf{x} \tag{1}$$

Solving the above equation, we get the classical Leontief equation:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{Ly} \tag{2}$$

where $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix, whose element l_{ij}^{rs} indicates the total products produced in industry i that are required for the production of one unit of final products in industry j. When dividing the intermediate inputs z_{ij}^{rs} by the total production of industry i, we arrive at the allocation coefficients $\mathbf{H} = \widehat{\mathbf{x}}^{-1}\mathbf{Z}$ proposed by Ghosh. The column balance condition or the gross output production of the MRIO model can be written as:

$$\mathbf{x}'\mathbf{H} + \mathbf{v}' = \mathbf{x}' \tag{3}$$

Solving the above equation, we get the classical Ghosh equation:

$$\mathbf{x} = \mathbf{v}'(\mathbf{I} - \mathbf{H})^{-1} = \mathbf{v}'\mathbf{G} \tag{4}$$

where $\mathbf{G} = (\mathbf{I} - \mathbf{H})^{-1}$ is the Ghosh inverse matrix, whose element g_{ij}^{rs} indicates the changes in gross outputs in industry j for exogenously specified changes in inputs of primary factors in industry i. Ghosh's model is known as a "supply-driven" input-output model, which is an alternative for Leontief's traditional "demand-driven" input-output model.

3.2. Network control analysis

Input-output analysis is applied to environmental analysis, yielding ecological network analysis (Hannon, 1973). The ecosystem is considered a network of elements interacting with each other through the flow of energy or materials. For instance, pre-multiplying the Leontief element l_{ij}^{rs} with the energy intensity e_i^r in industry i, we reach the energy use in industry i in economy r induced by one unit of final product in industry j in economy s. This is also called the embodied energy flow from industry i in economy r to industry j in economy s. Each element in the ecological network analysis acts as both a generator of outputs to other network elements and a receiver of inputs from other elements. Based on this static flow analysis, Patten (1978) developed network control analysis (NCA) to measure the control relationship in an ecosystem (the dominance of one element over another). In this paper, we applied this concept to investigate how much energy is controlled by a sector or a country. For sectors (or countries), controlled energy indicates the energy flows that come into other sectors and economies through the process of consumption and are controlled by the sector (or economies). In fact, network control analysis is closely related to input-output analysis. The two main matrices that are used to construct the network control matrix correspond to the Leontief and Ghosh matrix.

The control relationship can be measured from the controller's perspective using a control allocation matrix:

$$\mathbf{CA} = \left[ca_{ij}\right] = \begin{Bmatrix} l_{ij} - g_{ij} > 0, \quad ca_{ij} = \dfrac{l_{ij} - g_{ij}}{\sum_{i=1}^{m} l_{ij} - g_{ij}} \\ l_{ij} - g_{ij} \leq 0, \quad ca_{ij} = 0 \end{Bmatrix} \tag{5}$$

CA indicates the extent to which industries on the production side control other industries on the consumption side. On the other hand, the control relationship can also be formulated from the observer's perspective using a dependence allocation matrix:

$$\mathbf{DA} = [da_{ij}] = \begin{Bmatrix} l_{ij} - g_{ij} > 0, & da_{ij} = \dfrac{l_{ij} - g_{ij}}{\sum_{j=1}^{m} l_{ij} - g_{ij}} \\ l_{ij} - g_{ij} \le 0, & da_{ij} = 0 \end{Bmatrix} \tag{6}$$

DA shows the extent to which the industries on the consumption side are dependent on other industries on the production side. The degree of dependence of each country's final demand on other countries' resources can then be obtained by

$$\mathbf{D} = \begin{bmatrix} \boldsymbol{d}^{11} & \cdots & \boldsymbol{d}^{1n} \\ \vdots & \ddots & \vdots \\ \boldsymbol{d}^{n1} & \cdots & \boldsymbol{d}^{nn} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\rho}^{1} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{\rho}^{n} \end{bmatrix} \begin{bmatrix} \boldsymbol{da}^{11} & \cdots & \boldsymbol{da}^{1n} \\ \vdots & \ddots & \vdots \\ \boldsymbol{da}^{n1} & \cdots & \boldsymbol{da}^{nn} \end{bmatrix} \begin{bmatrix} \boldsymbol{y}^{11} & \cdots & \boldsymbol{y}^{1n} \\ \vdots & \ddots & \vdots \\ \boldsymbol{y}^{n1} & \cdots & \boldsymbol{y}^{nn} \end{bmatrix} \tag{7}$$

where $\boldsymbol{\rho}^r$ represents the resource intensity of all industries in economy $\boldsymbol{r}$. The dependence degree of economy s's final demand on economy r's resources is $\boldsymbol{d}^{rs} = \sum_{t=1}^{n} \boldsymbol{\rho}^r \boldsymbol{da}^{rt} \boldsymbol{y}^{ts}$. Denote $\boldsymbol{\rho}^r_{(e)}$ as the energy intensity vector of economy $\boldsymbol{r}$, whose element $\rho^r_{(e)j}$ indicates the energy use per unit of output produced by industry $\boldsymbol{j}$ in economy $\boldsymbol{r}$. Similarly, $\boldsymbol{\rho}^r_{(f)}$ denote the food input intensity vector of economy $\boldsymbol{r}$, whose element can be obtained by summing the direct input coefficient from the industry of *crop and animal products, hunting and related service activities* over all economies, i.e., $\rho^r_{(f)j} = \sum_{s=1}^{n} a^{sr}_{(f)j}$.

3.3. Risk transmission network

Denoting the initial energy scarcity of industry $\boldsymbol{i}$ in economy $\boldsymbol{r}$ as es^r_i, the risk transmission network of resource scarcity (such as energy scarcity es and food scarcity fs) can be formulated by combining the resource scarcity and the control relationship among industries:

$$\mathbf{R}_{(e)} = \left[r^{rs}_{(e)ij} \right] = es^r_i ca^{rs}_{ij} \tag{8}$$

$$\mathbf{R}_{(f)} = \left[r^{rs}_{(f)ij} \right] = fs^r_i ca^{rs}_{ij} \tag{9}$$

Correspondingly, the risk transmission of resource scarcity from economy $\boldsymbol{i}$ to economy $\boldsymbol{j}$ can be calculated as $\sum_i \sum_j es^r_i ca^{rs}_{ij}$.

3.3.1. Initial energy scarcity risk

As for the initial energy scarcity risk, it represents the risk of sectors running out of not being supplied with enough energy to meet the production requirement. It is calculated as the potential loss of output that would occur if that risk happens, which can be estimated by combining the occurrence probability of energy scarcity in economy $\boldsymbol{r}$ (EP^r), sectoral vulnerability of energy scarcity of each sector (EV^r_i), as well as the total output of each sector (Liu and Chen, 2020).

$$es^r_i = EP^r \times EV^r_i \times x^r_i \tag{10}$$

The occurrence probability indicates the share of potentially reduced energy use due to energy scarcity, estimated by the energy stress index (ESI). Similar as in Liu and Chen (2020), we define ESI as the ratio of energy imports to the total amount of energy consumption:

$$ESI^r = IE^r / CE^r \tag{11}$$

where ESI^r, IE^r and CE^r represent energy stress index, imported energy and energy consumption in economy $\boldsymbol{r}$, respectively. It is obvious that ESI^r ranges from 0 to 1, with 0 meaning that energy consumption is self-sufficient and 1 indicating a high probability of energy scarcity. Without further information, we assume that the distribution of ESI^r is lognormal as in Qu et al.(2017), with the median value as the imports-to-consumption ratio at the country level ($\mu_{er} = logESI^r$) and standard deviation ($\sigma_e = 1$):

$$e^{er} \sim (\mu_{er}, \sigma_e^2) \tag{12}$$

Based on this, the occurrence probability of energy scarcity can be estimated as the expectation of ESI^r:

$$EP^r \sim e^{\mu_{er} + \frac{\sigma_e^2}{2}} \tag{13}$$

Particularly, for $ESI^r = 0$, the $EP^r = 0$. It is clear that the occurrence probability of scarcity of each economy is constructed from a probabilistic perspective and is positively related with the economy's energy stress. Economies with high energy stress (i.e. high import-to-consumption ratio) generally face high occurrence probability of energy scarcity.

The second component of estimation initial scarcity risk, sectoral vulnerability of energy scarcity, is measured via energy consumption intensity and quantifies the percentage of sectoral output loss due to one percent of energy shortage. Similar as in Liu and Chen (2020), the vulnerability (distributed from one to one) is defined by converting the sectoral energy intensity (distributed from 0 to $+\infty$):

$$EV^r_i \sim \frac{\rho^r_{(e)i}}{\rho^r_{(e)i} + 2\varepsilon_e} \tag{14}$$

where the parameter ε_e is set as 0.5. The logic behind the calculation of sectoral vulnerability of scarcity is that for sectors with higher energy consumption intensity, one percent of energy shortage will lead to higher percentage of sectoral output loss. In contrast, for sectors with lower energy consumption intensity, the energy shortage has relatively smaller influence on sectoral output loss.

With the occurrence probability of energy scarcity (EP^r) and sectoral output loss due to one percent of energy scarcity (EV^r_i) (i.e. sectoral vulnerability of scarcity), the sectoral initial energy scarcity can be obtained by combining these two components with total output of each sector (x^r_i).

3.3.2. Initial food scarcity risk

Similarly, the initial food scarcity risk represents the risk of sectors running out of not being supplied with enough food to meet the production requirement. It is calculated as the potential loss of output that would occur if that risk happens, which can be estimated by combining the occurrence probability of food scarcity in economy $\boldsymbol{r}$ (FP^r), sectoral vulnerability of food scarcity of each sector (FV^r_i), as well as the total output of each sector.

$$fs^r_i = FP^r \times FV^r_i \times x^r_i \tag{15}$$

where the occurrence probability of food scarcity in economy $\boldsymbol{r}$ is $FP^r \sim e^{\mu_{fr} + \frac{\sigma_f^2}{2}}$, with a median value $\mu_{fr} = logFSI^r$ and standard deviation $\sigma_f = 1$. Note that the food stress index (FEI) is the ratio of food imports to the total amount of food consumption: $FSI^r = IF^r / CF^r$, where FSI^r, IF^r and CF^r represent food stress index, imported food and food consumption in economy $\boldsymbol{r}$, respectively. Similar to the sectoral vulnerability of energy scarcity, we define the sectoral vulnerability of food scarcity as $FV^r_i \sim \frac{\rho^r_{(f)i}}{\rho^r_{(f)i} + 2\varepsilon_f}$, where $\rho^r_{(f)i}$ is the food input coefficient of industry $\boldsymbol{i}$, which can be obtained by summing industry i's input coefficients from agriculture industry over all economies: $\rho^r_{(f)i} = \sum_{s=1}^{n} a^{sr}_{(f)i}$. The parameter ε_f is set as 0.5.

3.3.3. Energy-food scarcity nexus risk

To investigate the nexus effect and identify the trade-offs and synergies between energy and food scarcity, the nexus risk of energy-food scarcity is calculated on the basis of the initial risk of energy and food scarcity and an intensity-based weighting scheme:

$$sn_i^r = w_{(e)i}^r \times es_i^r + w_{(f)i}^r \times fs_i^r \quad (16)$$

where $w_{(e)i}^r = E_i^r / \sum_i E_i^r$ and $w_{(f)i}^r = F_i^r / \sum_i F_i^r$ are the weights of energy and food scarcity risk of industry i in economy r, with E_i^r and F_i^r as the energy and food consumption of industry i in economy r. Consequently, $\sum_i E_i^r$ and $\sum_i E_i^r$ indicate the total energy and food consumption during production in economy r. Then, similar to Eqs. (8) and (9), the risk transmission network of the energy-food nexus scarcity can be formulated by combining the nexus scarcity and the control relationship among industries: $\mathbf{R}_{(e-f)} = \left[r_{(e-f)ij}^{rs}\right] = sn_i^r ca_{ij}^{rs}$. Then the total transmitted scarcity risk (which includes all the scarcity risks transmitted to other trading partners) can be obtained as the row sum of $\mathbf{R}_{(e-f)}$: $\sum_j sn_i^r ca_{ij}^{rs}$).

4. Empirical results

4.1. Overall results of dependence degree

The data we use for empirical analysis is obtained from the 2016 release of World Input Output Database (WIOD, Dietzenbacher et al., 2013; Timmer et al., 2015). The world input output tables cover 28 EU countries and 15 other major countries in the world for the period from 2000 to 2014. Together, the countries cover more than 85 per cent of world GDP (at current exchange rates) (Timmer et al., 2016). Moreover, the satellite account of WIOD provides the detailed energy use by industry and country, which fit well for the data requirement of this research.

By using the data from WIOD, we calculated the dependence network of each economy's final demand on other economies' energy supply from 2000 to 2014. Fig. 1 shows the average degree of energy dependence by year. In general, the average energy dependence decreased from 0.06 in 2000 to 0.01 in 2014, even though the overall decrease trend was slightly reversed during 2008–2009 and 2011–2012. Since the element of the dependence allocation matrix is non-zero only if the corresponding element in the Leontief matrix is larger than that in the Ghosh matrix, the decreasing trend of average dependence degree implies increasing interdependence among economies and industries.

By estimating the total dependence of each economy's one unit final demand on other economies' energy supply and food supply, we find that the economies with the highest dependence degrees are generally small ones (Supporting Information A). This is mainly because that small economies rely heavily on importing inputs from other economies, while the opposite holds true for big countries.

4.2. Initial scarcity risk

The initial energy scarcity risks for different economies are presented in Fig. 2, in which only the top 10 sufferers of energy scarcity are presented. Japan and China had the largest economic losses of more than 300 billion euros. For Japan, its high import-to-consumption ratio of energy (94%) leads to an overall high risk of energy scarcity. A different story holds for China. China's energy stress is low (the import-to-consumption ratio is only 15%), but its total economic outputs are the largest, and overall energy intensity is relatively large (5.13TJ/M.euro, ranked 11th among all countries and regions). This means that China is heavily dependent on energy. Thus, if energy scarcity occurs in China, it will suffer more economic losses. In addition, China's economic losses are primarily contributed by *Electricity, gas, steam and air conditioning supply (24), Manufacture of coke and refined petroleum products (10), Manufacture of basic metals (15), Manufacture of chemicals and Chemical products (11) and Manufacture of other non-metallic mineral products* (14) (over 75% of the total initial economic losses). Interestingly, although Korea and India are not in the top five output production economies, they are the 3rd and 4th economies with the largest initial risk of energy scarcity. This is mainly caused by the high energy intensity in India (10.18TJ/M.euro, which is second highest) and high import-to-consumption-ratio of energy in Korea (82%). Similarly, due to their large total economic outputs, Germany and the US are also more likely to suffer from energy scarcity than other economies. As for industries, *Electricity, gas, stream and air conditioning supply* (24), *Manufacture of coke and refined petroleum products* (10) and *Manufacture of chemicals and chemical products* (11) are essentially the major contributors to initial risk for each economy due to their relatively high energy intensity.

Fig. 3 shows the five main industries in the top economies and regions whose initial food scarcity risks are the highest. Among them, *Crop and animal production, hunting and related service activities* (1), *Manufacture of food products, beverages and tobacco products* (5), and *Accommodation and food service activities* (36) are the top three contributors and account for more than 70% of the economic losses if food scarcity occurred. The economic loss of China is the largest, at more than 60 billion euros, because China is the largest production country. Consequently, China would suffer a large amount of economic loss if food scarcity occurred in this area. The rest of the world (RoW), the US, Germany and Japan are the secondary sufferers of food scarcity, and their economic losses are over 20 billion euros, since these are also major economies with large product outputs. Due to its high dependence on food imports, Belgium also suffers a large amount of economic loss if food scarcity occurs. Compared with the initial risk results of energy scarcity, great differences are found in the main economies and industries that suffer economic losses. Some economies and industries suffer mainly from energy scarcity or food scarcity, while some suffer from both kinds of scarcity. Therefore, it is necessary and useful to evaluate the trade-offs and synergies between energy and food resources, that is, the energy-food nexus.

By combining the previous results of energy scarcity risk and food scarcity risk, we get the nexus impact of energy and food scarcity. Fig. 4 shows the initial risk of energy-food nexus scarcity for the top ten economies. The nexus risk of each economy is not only influenced by its characteristics of economic development but is also related to energy and food consumption preference. For instance, Spain is not among the top six economies with the highest energy and food scarcity risk, but it is ranked 6th highest according to the initial risk of the energy-food scarcity nexus. Korea, India and France are not among the top 10 economies with the highest food scarcity risk, and the Netherlands is not among the top 10 economies with the highest energy scarcity risk; however, these three countries are ranked as the third, eighth, ninth and tenth economies, respectively, according to the initial risk of the energy-food scarcity nexus. This indicates the amplified effect of the energy and food nexus and has crucial implications for the coordinated management of energy and food resources. Meanwhile, the results show that the main industries that suffer from the economic losses of energy-food scarcity are much more concentrated, including *Electricity, gas, steam and air conditioning supply* (24), *Manufacture of food products, beverages and tobacco products* (5), *Manufacture of coke and refined petroleum products* (10) and *Manufacture of chemicals and chemical products* (11). The top five industries that suffer the most from energy-food scarcity account for more than 90% for all economies. Such results demonstrate the synergic effect of energy and food resources.

4.3. Risk transmission network

The transmission of energy-food scarcity nexus risk in the international trade system is shown in Fig. 5.[1] China, Germany and the US are the main exporters of energy-food scarcity nexus risk. This is related with these three country position in the global value chain and their high export volume in the global trade market. According to world input-output table, China, Germany and the US are the top three exporters

[1] For the detailed description of risk transmission network of energy scarcity risk and food scarcity risk, please refer to Supporting Information B.

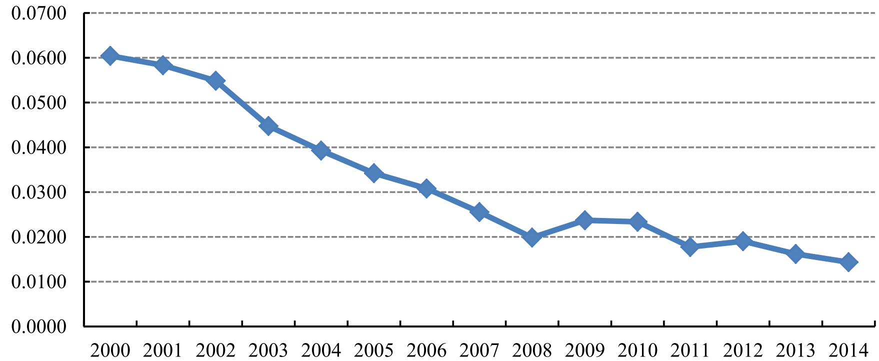

Fig. 1. The global average of dependence degree.

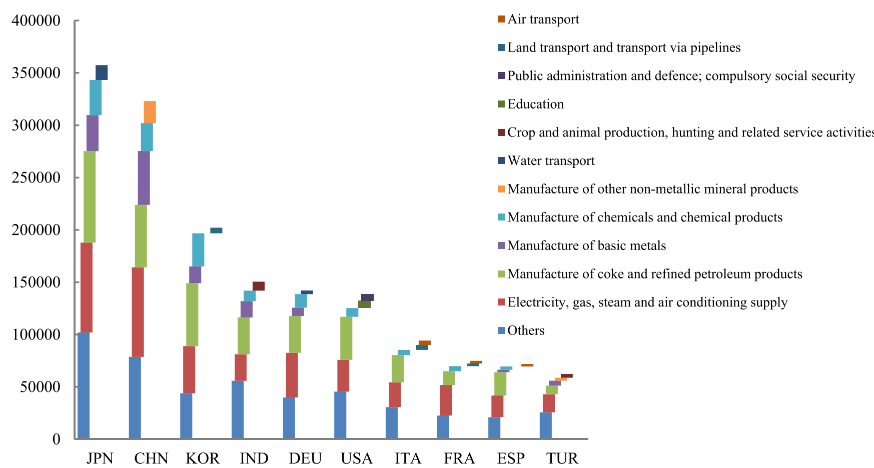

Fig. 2. Initial risk of energy scarcity (unit: M.euro), Note: Five main industries in top ten economies suffered energy scarcity risks are displayed.

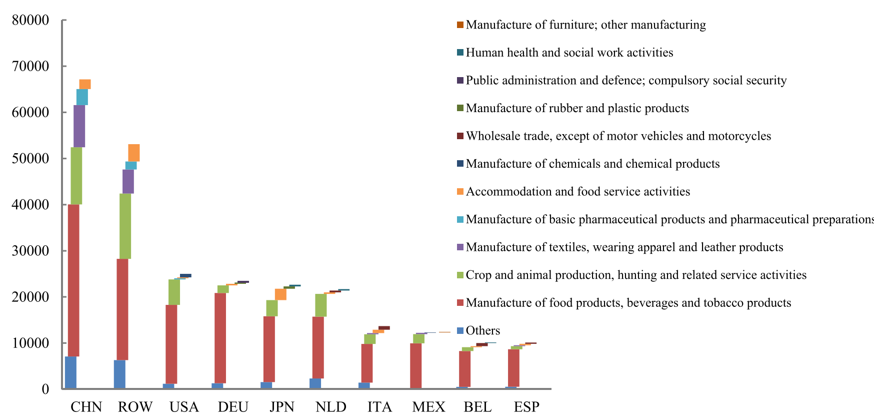

Fig. 3. Initial risk of food scarcity (unit: M.euro), Note: Five main industries in top ten economies suffered food scarcity risks are displayed.

in 2014, whose exports account for 36% of the global exports. Moreover, China propagates a large amount of economic losses to Korea and Taiwan, while the US mainly transfers economic losses to Mexico and Canada. This is consistent with the intuition that the closest trading partner would receive higher risk scarcity. This result indicates that once energy and food scarcity occur simultaneously in these countries, it would not only lead to economic losses in their own region but also impact other regions via the international trade chain. Except for the previously mentioned exporters, Korea also transmitted their risks, which contributed to 21% of the potential total economic losses of Taiwan. On the other hand, Taiwan, Mexico and Canada are the major receptors of energy-food scarcity, which implies that these regions would suffer great economic losses once energy-food scarcity occurred in their control regions.

The risk transmission network is obtained by combining the initial scarcity risk and the control allocation matrix. The top five generators of initial energy-food nexus scarcity are basically the top five generators in the risk transmission network, except Japan. This implies that besides transmitting economic losses to other countries, Japan also depends on other regions' energy and food resources and thus is not an absolute generator in the initial risk transmission network.

Note that the estimation of scarcity risk includes scale effect, which implies that larger economies tend to have larger scarcity risks. On the other side of the coin, scarcity risk per unit of output, which get rid of the

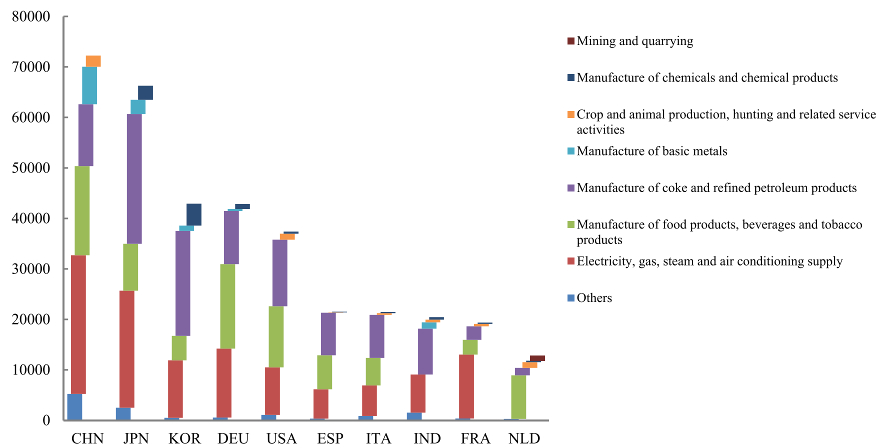

Fig. 4. Initial risk of energy-food scarcity nexus, Note: Five main industries in top ten economies suffered energy-food nexus scarcity risks are displayed.

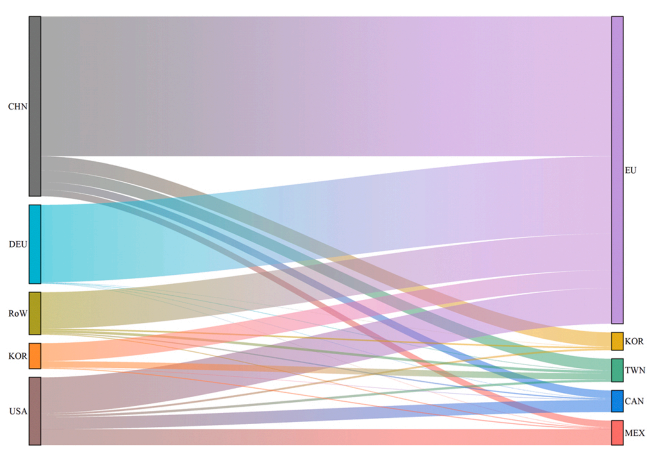

Fig. 5. Initial risk transmission network of energy-food scarcity nexus (unit: M. euro), Note: the top five exporters/importers of economic losses caused by energy-food nexus scarcity risks are listed. The economies listed on the left are the generators of energy-food nexus scarcity risks, while economies on the right are the receptors of energy-food nexus scarcity risk.

scale effect, also contains important information of the extent an economy depends on other economies for production. Therefore, it is also meaningful to investigate the scarcity risk per unit of output as well as its transmission network. Table 1 shows the top economies whose initial energy-food nexus scarcity risk per unit of output is the highest and bottom ten economies whose initial energy-food nexus scarcity risk per unit of output is the lowest. It is interesting to find that the top ten economies are basically small countries that are heavily rely on imported energy or food, such as Malta, Luxemburg and Japan, while bottom economies are generally countries with relatively abundant resources.

As for the transmission network of energy-food nexus scarcity risk per unit of output, we also find that small economies are the top receptors of transmitted scarcity risk (supporting information B). Again, the main participants in global production chain, such as China, Germany, Spain, France, Italy, Japan and Korea, are the major risk source economies. Among the top receptors, Hungary, Portugal and Slovenia have regulated or promised to reach carbon neutrality at certain time, which could help to reduce their dependence on fossil fuel energies and thus reduce their own scarcity risk. However, the risk transmission network should also be taken into account, in order to decrease the total scarcity risk. In this aspect, it might be beneficial to set carbon neutrality goals for a group of economies.

Table 1
Initial energy-food nexus scarcity risk per unit of output in each economy (2014).

No	Country	Scarcity risk per unit of output	No	Country	Scarcity risk per unit of output
31	MLT	1.457	14	EST	0.100
28	LUX	1.398	42	TWN	0.080
25	JPN	1.385	30	MEX	0.055
9	CYP	1.313	12	DNK	0.052
26	KOR	1.268	21	IDN	0.031
3	BEL	1.223	33	NOR	0.028
27	LTU	1.179	6	CAN	0.016
35	PRT	1.137	44	ROW	0.015
23	IRL	1.106	37	RUS	0.009
41	TUR	1.100	1	AUS	0.004

Note: Economies are ranked according to their energy-food nexus scarcity risk per unit of output from high to low. Only the top ten and bottom ten economies are displayed in the table.

5. The potential impact of climate policy on energy-food nexus scarcity risk

The focus of this section is to explore the potential impact of climate policy on energy-food nexus scarcity risk. One obvious indication of climate policy is the reduction of emission intensity, defined as emission per unit of output of each industry-economy combination. Therefore, we investigate the potential impact of climate policy on energy and food scarcity risk from the perspective of analyzing the effect of emission intensity change on scarcity risk. To this end, we calculated the emission intensity of each industry-economy combination by using the data from 2000 to 2014 included in the environmental account of WIOD. Together with the initial energy scarcity risk, food scarcity risk and energy-food nexus scarcity risk at industry and economy level, we get the panel data set from 2000 to 2014. Then the following regression model (with industry fixed effect and economy-year fixed effect) is employed for the analysis:

$$scarcityrisk_{i,k,t} = \beta_0 + \beta_1 ei_{i,k,t} + \lambda_i + \gamma_{k,t} + \mu_{i,k,t} \tag{17}$$

where $scarcityrisk_{i,k,t}$ is initial or total transmitted energy scarcity risk, food scarcity risk or energy-food nexus scarcity risk of industry i and economy k in year t, $ei_{i,k,t}$ indicates the emission intensity of industry i and economy k in year t, λ_i and $\gamma_{k,t}$ are industry fixed effect and economy-year fixed effect, respectively, $\mu_{i,k,t}$ is the error term.

Table 2 summarizes the regression results of emission intensity on initial scarcity risk. Results in column (1) and (3) in Table 2 show that emission intensity change is positively related with initial energy scarcity risk and energy-food nexus scarcity risk. This demonstrates that

Table 2
Impact of emission intensity reduction on initial scarcity risks.

	(1) Energy scarcity risks	(2) Food scarcity risks	(3) Energy-food nexus scarcity risks
Emission intensity	324.953***	-6.461***	190.073***
	(5.470)	(−6.918)	(6.145)
Constant	10371.596***	97.350***	435.272***
	(554.041)	(330.220)	(44.653)
Fixed_Effect	'Yes'	'Yes'	'Yes'
Robust	'Yes'	'Yes'	'Yes'
N	36904	36960	36904
dfres	658	659	658

Note: (1) * , * *, and * ** represent the estimation is statistically significant under the confidence interval of 90%,95% and 99%. (2) the robust standard error is used in all the regression model and the values in the brackets are the t-value of the corresponding estimated coefficient.

when emission intensity decrease by 1 unit (ton per euro), energy scarcity risk and energy-food nexus scarcity risk would decrease by 0.325 million euros and 0.190 million euros, respectively. The results reveal that emission intensity reduction could largely reduce initial energy scarcity and energy-food nexus scarcity, i.e., the implementation of climate policy brings co-benefits of energy and food security, which is also supported in McCollum et al. (2011). This co-benefit provides another supportive evidence for implementing climate policies, such as carbon neutrality. Researchers found that the cumulative policy costs would reduce by 100–600 billion US dollars in 2030 (i.e., 0.1%−0.7% of the GDP), when the co-benefits of climate policies are considered (McCollum, 2013).

Another interesting finding from Table 2 is that emission intensity is negatively related with initial food scarcity risk. As shown in Tables 2, 1 unit decrease of emission intensity would increase food scarcity risk by 0.006 million euros. This may be caused by the fact that some fossil energy is replaced by renewable energy generated from food, which leads to the slightly increases the food scarcity risk. For instance, Sarkodie et al. (2019) found that biomass energy, obtained from biomass resources such as forest and agricultural residues, municipal waste and energy crops, can partly replace the demand for fossil fuel energy and thus support the economy decarburization and reducing GHG emissions. However, the positive effect of emission intensity reduction on energy scarcity risk is larger than that on food scarcity risk, therefore, the overall effect on energy-food nexus scarcity risk is still positive.

The regression results of emission intensity on total transmitted scarcity risk also show that emission intensity reduction can significantly reduce total transmitted energy scarcity and energy-food nexus scarcity risk, while increase total transmitted food scarcity risk (Supporting Information C). However, the magnitude of climate policy impact is around two times higher for the total transmitted scarcity risk than that for initial scarcity risk. The result reveals that emission intensity reduction in upstream economies can significantly decrease the total transmitted energy scarcity and energy-food nexus scarcity risk, from which the economies in the downstream benefit. Therefore, countries should collaborate together to cope with climate change and help to reduce emission intensity.

In this paper, we also evaluate the heterogeneous effect of emission intensity change on energy and food scarcity risk for different economies at different development stage. To this end, we collect GDP per capita data at constant price from the World Bank Database and rerun the above regressions for different economy groups. Specifically, we take the GDP per capita of Upper Middle Income countries as the division line and classify the economies into two groups. As shown in Table 3 and Table 4, no matter for initial scarcity risk or total transmitted scarcity risk, the effect of emission intensity reduction is always higher for lower income economies than that for higher income economies (except that the effect on total transmitted energy scarcity risk for higher income economies is not significant). These results imply that the co-benefit of energy and food nexus security for lower economies associated with climate policy is much higher than that for high income economies. That is, the cost of implementing climate policy for lower economies would be much lower, when considering the co-benefit of energy and food nexus security. This provides supports for low income countries to participate in emission reduction actions.

6. Conclusion and policy implications

By combining multi-regional input-output analysis and network control analysis, this paper investigated the dependence degree of each country and region on energy and food resources as well as the risk transmission network of the energy-food scarcity nexus. The initial risk of energy and food scarcity of each industry in each region was estimated on the basis of ESI, FSI and energy and food intensity per unit of output in each industry. Based on the initial risk of energy and food scarcity and an intensity-based weighting scheme, the initial risk of the energy-food scarcity nexus was calculated. Furthermore, by combining the initial risk of energy scarcity, food scarcity, the energy-food scarcity nexus and the control allocation matrix, the energy scarcity risk transmission network, food scarcity risk transmission network and risk transmission network of the energy-food scarcity nexus were evaluated. Compared to previous studies, this paper tracks the transmission network and nexus impact of energy and food resources. The results provide insight into integral resource management. In the end, the potential impact of climate policy (as indicated by emission intensity reduction) on scarcity risks is analyzed.

Due to the control allocation relationship, there are large differences between main risk sufferers and main generators in the risk transmission network. For energy scarcity, Japan, China and Korea are the top three economies that would have the largest economic losses if energy scarcity

Table 3
Heterogeneous impact of emission intensity reduction on initial scarcity risks.

	Energy scarcity risks		Food scarcity risks		Nexus scarcity risks	
	Lower income	Higher income	Lower income	Higher income	Lower income	Higher income
emico	1638.464***	223.455***	-16.075***	-5.694***	585.045***	159.553***
	(3.514)	(5.202)	(−3.864)	(−6.544)	(4.107)	(5.654)
constant	13000.087***	10166.699***	198.205***	90.096***	467.766***	427.883***
	(55.214)	(784.905)	(93.739)	(343.377)	(6.504)	(50.285)
Fixed_Effect	'Yes'	'Yes'	'Yes'	'Yes'	'Yes'	'Yes'
Robust	'Yes'	'Yes'	'Yes'	'Yes'	'Yes'	'Yes'
N	2464	34440	2520	34440	2464	34440
dfres	43	614	44	614	43	614

Note: (1) * , * *, and * ** represent the estimation is statistically significant under the confidence interval of 90%,95% and 99%. (2) The robust standard error is used in all the regression model and the values in the brackets are the t-value of the corresponding estimated coefficient. (3) The GDP per capita of Upper Middle Income countries (14771 constant 2011 international $) is used to divide the economies into two groups: lower income group and higher income group. Lower income group includes three economies: India, Indonesia and China, while higher income group includes the rest 41 economies in WIOD.

Table 4
Heterogeneous impact of emission intensity reduction on total transmitted scarcity risks.

	Total transmitted energy scarcity risks		Total transmitted food scarcity risks		Total transmitted nexus scarcity risks	
	Lower income	Higher income	Lower income	Higher income	Lower income	Higher income
emico	11929.175***	-219.056	-71.602***	-16.419***	3470.321***	412.707***
	(2.740)	(−0.930)	(−2.826)	(−4.895)	(2.948)	(5.214)
constant	69482.391***	34556.190***	1024.514***	226.647***	4345.062***	1614.489***
	(31.608)	(486.382)	(79.547)	(224.054)	(7.309)	(67.639)
Fixed_Effect	'Yes'	'Yes'	'Yes'	'Yes'	'Yes'	'Yes'
Robust	'Yes'	'Yes'	'Yes'	'Yes'	'Yes'	'Yes'
N	2464	34440	2520	34440	2464	34440
dfres	43	614	44	614	43	614

Note: (1) * , * *, and * ** represent the estimation is statistically significant under the confidence interval of 90%,95% and 99%. (2) the robust standard error is used in all the regression model and the values in the brackets are the t-value of the corresponding estimated coefficient. (3) The GDP per capita of Upper Middle Income countries (14771 constant 2011 international $) is used to divide the economies into two groups: lower income group and higher income group. Lower income group includes three economies: India, Indonesia and China, while higher income group includes the rest 41 economies in WIOD.

occurs. In contrast, in the transmission network, economic losses caused by energy scarcity are mainly found in China, the US and Germany and are mainly propagated to Korea, Mexico and the Netherlands. Regarding the risk transmission network of the energy-food scarcity nexus, China, Germany and the US are the main generators, and the main receptors are Taiwan, Mexico and the Netherlands. These results imply that international trade transfers energy/food scarcity to geographically distant regions via the international supply chain.

The nexus impact of energy-food scarcity can be analyzed by combining energy scarcity risk and food scarcity risk, which are influenced by the economic development and energy and food consumption preferences of each country and region. Economies that are among the top generators of both the energy and food risk transmission networks are also the main generators of the energy-food nexus risk transmission network. For example, China, Germany and the US are among the top five generators in the energy, food and energy-food nexus risk transmission networks. In particular, although Korea and Japan are not among the top ten generators of the food risk transmission network, they are among the 5th and 6th generators of the energy-food nexus risk transmission network. These results indicate the amplified effect of the energy-food nexus and suggest collaborative conservation and management of energy and food resources. Moreover, countries and regions close to the main risk generators, such as Mexico, Canada, the Netherlands and Korea, should pay more attention to scarcity risk, since they are the main victims of the energy-food scarcity nexus.

The analyses that assess the emission intensity and scarcity risk find that implementation of emission control policies could significantly decrease initial energy scarcity risk and energy-food nexus scarcity risk. Although emission intensity change is negatively related with initial food scarcity risk, the positive effect of emission intensity on energy scarcity risk is much larger, therefore, the overall effect on energy-food nexus scarcity risk is still positive. This implies that besides emission reduction achievement, climate policies bring co-benefits of energy-food nexus security. That is, when the co-benefits energy-food nexus security is taken into account, the economies of climate policy would be higher. Moreover, the positive effect of emission intensity change on total transmitted scarcity risk is two to three times of that on initial scarcity risk, which indicate emission intensity reduction in upstream economies could also help decrease scarcity risks in downstream economies. Therefore, collaborative conservation and management of energy and food resources should be suggested. In the meantime, the co-benefit of energy and food nexus security for low income economies associated with climate policy is much higher than that for high income economies. This provides supports for low income countries to participate in emission reduction actions.

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CRediT authorship contribution statement

Yan Xia provided Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision and Funding acquisition. **Bingqian Yan** contributed to Conceptualization, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft and Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Statement of exclusive submission

This paper has not been submitted elsewhere in identical or similar form, nor will it be during the first three months after its submission to the Publisher.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.04.008.

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