Title page

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Global value chain participation and trade-induced energy inequality

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Abstract Under economic globalization, developing countries are suffering from international-trade-induced resource and environmental cost based on their ways of participating in global value chain (GVC), hence inequality between trading economies occurred. Existing literature mainly focuses on revealing the fact of ecological exchange inequality behind trades, but rarely delves into the trigger and mechanism towards such inequality, not least any studies on the influence of GVC participation. Moreover, most of the existing studies treat energy, which is a key factor to economic growth and global climate change, as a subset of environmental indicators for ecological unequal exchange analysis, thus lack a whole-picture of trade-induced energy inequality with regard to its modes, driving factors, and the heterogeneous mechanism of its driving factors. This study firstly explores the trade-induced energy use and energy inequality using multi-regional input-output analysis and the production decomposition analysis, then econometric analysis is applied to further explore how different participation in GVC affects a country's trade-induced energy use, which illustrate the mechanism of trade-induced energy inequality. Our results uncover a striking difference in the domestic energy use per value-added of countries engaged in bilateral trade. From year 2000 to 2014, trade induced energy use per value-added in developed countries always remain the lowest around the globe, while that of the developing nations is more than twice higher, indicating that the trade-induced energy inequality was remained during the studied period. The econometric analysis displays that participation in forward-linkage of the GVC can significantly reduce the domestic energy use per value-added while participation in backward-linkage may increase energy use per value-added, indicating that the GVC participation is a key driving factor for trade-induced energy inequality. Our heterogeneity examination results further reveal that: first, the influential mechanisms of GVC participation on energy use per added value cross energy types are similar between coal and new energy, but oil and natural gas have their own influential

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mechanism. Second, the impact of GVC participation on energy use per added value amplifies as the GVC activities become more complex. Third, resource endowment would affect national industrial developing pattern, leading to striking difference among the impacts of GVC participation on nations rich with resource endowment and that on nations poor in resource endowment. Namely, forward-linkage GVC participation shows a greater effect on energy use per added value of resource-deficient nations, whilst backward-linkage GVC participation exerts more substantial impact on energy use per added value of resource-wealthy nations. Our findings imply that optimizing GVC participation is beneficial to domestic resource conservation and environmental protection, especially for developing countries, for which enhancing their rank of GVC is feasible to reduce their trade-induced resources and environmental costs.

Keywords: global value chain participation; trade-induced energy inequality; energy use per value-added; heterogeneity; forward-linkage participation; backward-linkage participation

1.Introduction

Each country produces goods and service according to its own comparative advantages and reaps profits from products exchange. This forms the framework of international trade and promote world economic development. Along with the deepening of international industrial division, global value chain (GVC)——featured by global division and re-integration of producing activities——has progressed by leaps and bounds, taking every economy into its arms through international trading network. The rise of GVC has phenomenally changed the ways of how each nation obtains resources, production layout and trading interactions, positioning itself as a new organizing and administrating power in the game. This progress has offered the developing countries more opportunities to participate in global economic development and to share the fruit of international economic advancement, welfare betterment and poverty reduction(Kano et al., 2020; Lee et al., 2012; Lee et al., 2017; Los et al., 2015; Pietrobelli and Rabellotti, 2011; Timmer et al., 2014).

However, the economic boost also comes with the excessive resource extraction and drastic environmental deterioration, especially in developing countries, where low- value added but high-resources and emission-intensive goods are produced, while developed countries can tend to maintain and ameliorate their own environment owing to long-term capital accumulation. Developing countries, on the other hand, have long sacrificed their environment to gain comparative advantage and economic benefits in trade. Such unbalanced trade-induced inequality between economies at different stages of economic development bears witness to the Unequal Exchange Theory (Emmanuel, 1972), Dependency Theory (Prébisch, 1950) and the World

System Theory (Wallerstein, 1974). Trade-induced inequality is a resurrection of global socioeconomic inequality, and has hindered sustainability by transferring environmental burdens from wealthier to poorer countries(Chen et al., 2021; Gellert et al., 2017; Givens et al., 2019; Pozo et al., 2020; Wiedmann and Lenzen, 2018). High-income nations located at the core of global economic system enjoy cutting-edge industrial technology and well-run infrastructure, also benefiting from the net resource transfer from peripheral low-income countries (Jorgenson and Clark, 2009). Meanwhile, due to the fact that high-income nations play a more principal part both in the global value chain and in the global economy, their income derived from natural resource exportation also ranks considerably higher than that of low-income nations (Piñero et al., 2019; Prell et al., 2014).

Unlike the analytical perspective of traditional trading theory, the unequal exchange theory believes that international trade has given birth to ecological exchange inequality between nations. Core nations can drive its socioeconomic development with resources from peripheral nations and transfer their environmental costs to the latter (Hornborg, 2009; Jorgenson, 2006; Rice, 2007). More specifically, financial investment or high-value goods from core nations would flow into peripheral nations in exchange for under-valued goods produced there via international trade, which allows the core countries to prosper from economic growth whilst transferring their environmental costs of their consumption to peripheral nations. This contributes to the depletion of natural resource stocks, concomitant growth of pollutants and local environmental disruptions in peripheral nations (Jorgenson, 2012; Yu et al., 2014).

Ecologically exchange inequality is supported by a series of evidence. Existing studies provide empirical evidence for the existence of ecological exchange inequality by different accounting frameworks including production-based (Zhang et al., 2020; Zhang et al., 2017), final-demand-based (Hubacek et al., 2015; Prell et al., 2014), income-based (Liang et al., 2017; Marques et al., 2012), household-consumption-based (Chen et al., 2019; Wu et al., 2019a), total-consumption-based (Wiedmann and Lenzen, 2018; Wu et al., 2019b) frameworks and etc. As researches delve deeper progress and become specific, ecological factors such as water (Chen et al., 2021), land (Chen et al., 2021; Kan et al., 2021), carbon dioxide (Prell and Feng, 2016), air pollution (Li and Liu, 2020; Meng et al., 2016), together with energy (Dorninger et al., 2021; Kan et al., 2019; Kan et al., 2020; Li et al., 2020b) are studied to represent the theory of ecologically exchange inequality. Focusing specially on trade-induced energy inequality, a large number of studies have been implemented from the global (Kan et al., 2019; Wu et al., 2019a; Wu et al., 2019b), regional (Dorninger and Eisenmenger, 2016; Li et al., 2020b), national (Zhu et al., 2020), urban (Li et al., 2020a) and sectorial (Liu et al., 2020) level.

However, existing literature mainly focuses on revealing the fact of ecological exchange inequality behind trades, but rarely delves into the trigger and mechanism towards such inequality, not least any studies on the influence of GVC participation. As globalization and global industrial division deepens, alongside comes the modulation of how nations participate in the global value chain and their trade modes, hence a much more complicated impact on their economic development as well as resources and environmental issues. Therefore, investigating into the link between GVC participation and ecological exchange inequality behind trade would strike great policy significance for both economic development and environmental and resource management. Also, current analysis on trade-induced inequality simply views energy as a subset of ecological exchange inequality alongside other elements. To our knowledge, there hasn't been any comprehensive and in-depth discussion specifically aiming at exchange inequality in the field of energy, albeit the fact that energy being a key contributing factor to economic growth can not only affect international trade and economic development, but also concern global environmental pollution and greenhouse gas control. Therefore, we attempt to illustrate a whole-picture of the trade-induced energy inequality, depict of its mode, and explore its drivers and how such driving factors' influence vary with different trading modes and energy types. Conducting such research is critical to portray and better understand the forming mechanism of trade-induced energy inequality and help with relative policy decisions.

In this essay, we aim to explore the influential mechanism of GVC participation on trade-induced energy inequality. Wang et al. (2007) divided trade into three modes: final trade, one-time-cross-border intermediate trade and multi-cross-border intermediate trade, and categorized GVC participation patterns as forward-linkage participation and backward-linkage participation. In this essay we apply the same division of trading modes and GVC participation patterns to evaluate energy inequality behind global trade from year 2000 to 2014, and then reveal the influencing mechanism of GVC participation patterns and trade modes on such energy inequality using econometric models.

To achieve the aim of this study, we first apply a production decomposition model based on the global multi-region input-output tables to calculate domestic energy use driven by per unit added-value in the production of each country's export to each partner country. This will allow us to reveal the degree and mode of trade-induced energy inequality. Then, we construct a panel data by matching the results of energy use per unit of added-value with socioeconomic panel data of each nation, and adopts econometric approach to estimate the impact of different GVC participation patterns (forward- and backward-linkage participation of GVC) on energy use per added-value, and by reference how the difference of GVC participation drives trade-induced energy inequality. Moreover, in order to further investigate the heterogeneity of the impact of GVC participation on energy inequality, we conduct several econometric analyses by decomposing energy use per unit of added value according to energy types and trade modes, and differentiating the sample countries by resource endowment.

Our research shows that energy use per value-added incurred by trade varies notably across countries, indicating a manifest unequal exchange of energy behind global trade. We also find that such inequality mainly exists between the developed and the developing nations, the exchange mode stable with time. Our empirical results show that different participation pattern in the value chain is a driver of great significance to trade-induced energy inequality. Forward-linkage GVC participation can diminish energy use per value-added while backward-linkage GVC participation amplifies it. How it influences on trade-induced energy inequality, however, varies greatly with energy type, trade mode and the nation's resource endowment. These heterogeneities reflect the potential pathways of GVC participation impacts on each nation's energy consumption.

We expand on existing literature in three ways. First, we present the first comprehensive analysis of unequal exchange of energy behind the global trade from the perspective of trade-induced domestic energy use per unit of value-added. Second, we quantify the influencing power of GVC participation to trade-induced energy inequality in this study. In addition, we conduct the heterogeneity analysis of energy type (coal, oil, natural gas, renewable energy), trade mode (final trade, one-time-cross-border intermediate trade and multi-cross-border intermediate trade) and national natural resource endowment. Last, we make an expansion on sample data from 2000 to 2014 in contrast to the previous studies using data prior to 2009 for the analysis of global trade energy use, which can provide useful experience and lessons to current trade and energy policies suggestions.

2.Methodology

The calculation of trade in value-added terms can reflect a nation's real economic benefit from trading, and has been widely applied (Backer et al., 2018; Johnson, 2014). In this paper, we also apply the trade in value-added terms to measure the economic benefits gained by a nation's participation in international trade, which is able to avoid the double-counting in traditional trade computations and can reflect a nation's real benefit more accurately. We also use the multi-regional input-output framework, which has been broadly applied in the analysis of energy and environmental issues of trade and global value chains, to estimate trade and energy use in value-added terms (Al-mulali and Sheau-Ting, 2014; Chen et al., 2018; Hubacek et al., 2017; Ji et al., 2020a; Ji et al., 2020b; Lin and Sun, 2010; Meng et al., 2018; Su and Ang, 2017; Wang et al., 2018; Wang et al., 2020; Wiedmann and Lenzen, 2018; Zhang et al., 2014). Despite of the maturity of this methodology, most existing studies focus solely on estimating the absolute value of either the economic benefit or the environmental cost rather than setting the two into the same picture. In this paper, we combine both estimations to accurately portray the degree of inequality of cross-nation energy exchange.

2.1 Production of decomposition model

In this paper we assimilate the production decomposition model proposed by Wang et al. (2017), which provide a methodology to decompose production activities to different types depending on whether they are for domestic demand without involving trade, traditional international trade (without involving trade in intermediate goods), simple GVC activities, or complex GVC activities. Hence, in this paper a nation's total production is classified into domestic consumption (without trade) and three trade types- final trade (the same as traditional trade), one-time-cross-border intermediate trade (also simple GVC activities) and multi-cross-border intermediate trade (also complex GVC). For the final trade, the exporter produces the final goods and the importer is the direct consumer of the final goods; As for the one-time-cross-border intermediate trade, the exporter produces unfinished product which will be finished and consumed by the importer; and in the multi-cross-border intermediate trade, one example is that the first country exports its unfinished goods, which will be further processed in a second country, and then consumed or further processed in a third country, in short, the exported goods will cross national border more than once. Based on the production decomposition model, we decompose the Leontief inverse matrix to separate the energy use induced by each type.

From the gross output balance, we can derive:

$$\begin{aligned} X &= AX + Y \\ &= A^D X + Y^D + A^F X + Y^F \\ &= A^D X + Y^D + E \end{aligned} \quad (1)$$

Where X represents total production, A, A^D *and* A^F the input coefficient matrix, domestic input coefficient matrix and imported input coefficient matrix, respectively. Y, Y^D *and* Y^F portray respectively final demand, domestic final demand and foreign final demand. E is total export, respectively.

Take region *r that has trade with region s* as the example. According to the equilibrium condition:

$$X^r = A^{rr} X^r + Y^{rr} + \sum_{r \neq s}^{M} EX^{rs} \quad (2)$$

As gross output $X = (I - A)^{-1} Y = BY$, according to Wang et al. (2013), we can derive: $B^{ss} = L^{ss} + L^{ss} \sum_{t \neq s}^{M} A^{st} B^{ts}$. So, region *r*'s total export EX^{rs} is:

$$\begin{aligned} EX^{rs} &= Y^{rs} + A^{rs} L^{ss} Y^{ss} + A^{rs} L^{ss} \sum_{t \neq s}^{M} A^{st} B^{ts} Y^{ss} \\ &+ A^{rs} \sum_{t \neq s}^{M} B^{st} Y^{ts} + A^{rs} \sum_{t}^{M} B^{st} \sum_{u \neq s}^{M} Y^{tu} \\ &= EX^{rs}_{final} + EX^{rs}_{one} + EX^{rs}_{multi} \end{aligned} \quad (3)$$

Where B is the Leontief inverse matrix that represents complete input coefficient matrix; $L^{rr} = (I - A^{rr})^{-1}$ is the domestic consumption coefficient matrix; $EX^{rs}_{final} = Y^{rs}$ depicts the final export from *r* to *s* (that is, the trade between the exporter *r*, also being the final producer, and the importer *s*, also being the final consumer); $EX^{rs}_{one} = A^{rs} L^{ss} Y^{ss}$ shows the traditional one-time-cross-border intermediate trade where *r* is the exporter and *s* is the importer (crossing *r*'s border with *s* only once, that is, the exporter *r* produces unfinished product which will be finished by importer *s* and consumed also by the importer *s*) and, $EX_{multi}^{rs} = A^{rs}L^{ss}\sum_{t \neq s}^{M} A^{st}B^{ts}Y^{ss} + A^{rs}\sum_{t \neq s}^{M} B^{st}Y^{ts} + A^{rs}\sum_{t}^{M} B^{st}\sum_{u \neq s}^{M} Y^{tu}$ represents the trade that happens among *r*, *s*, and other countries (crossing border more than once, namely multi-cross-border intermediate trade, and *s* is the final consumer).

We use E^r to portray energy use coefficient and VA^r value added coefficient. Then we can derive the exporting-trade-induced domestic energy use of region *r* $EREX^{rs}$ and the export-induced domestic added value matrix $VAEX^{rs}$ as follows,

$$\begin{aligned} EREX^{rs} &= E^r L^{rr} EX^{rs} \\ &= E^r L^{rr} EX_{final}^{rs} + E^r L^{rr} EX_{one}^{rs} + E^r L^{rr} EX_{multi}^{rs} \\ &= ER_{final} + ER_{one} + ER_{multi} \end{aligned} \quad (4)$$

$$\begin{aligned} VAEX^{rs} &= VA^r L^{rr} EX^{rs} \\ &= VA^r L^{rr} EX_{final}^{rs} + VA^r L^{rr} EX_{one}^{rs} + VA^r L^{rr} EX_{multi}^{rs} \\ &= VA_{final} + VA_{one} + VA_{multi} \end{aligned} \quad (5)$$

Where ER_{final} reflects trade-induced domestic energy use, ER_{one} is one-time-cross-border intermediate trade-induced domestic energy use, and ER_{multi} is multi-cross-border intermediate trade-induced domestic energy use. Energy use induced by foreign trade depicts the energy consumption that comes along with the economic benefits from international economic activities. Likewise, VA_{final} represents domestic value-added from final exportation, VA_{one} is the value-added of intermediate export gained by the direct importer, VA_{multi} is the value-added absorbed by the original exporter. For nations mainly relied on processing trade, only a minor part of their total exportation can be attributed to domestic value-added. As the traditional calculating method often overestimates the total amount of trade in value-added. Thus, trade in value-added, especially domestic value-added in total exports can reflect the real economic benefits from the participation of global production division.

We define value-added and energy use per unit as $er^r = ER^r / X^r$ and $va^r = VA^r / X^r$. Therefore, the total trade-induced energy efficiency of a nation's production can be further broken down as:

$$\begin{aligned} DEV^r &= \frac{ER^r}{VA^r} \\ &= \frac{ER_d^r + EREX_{export}^r}{VA_d^r + VAEX_{export}^r} \\ &= \frac{VA_d^r}{VA^r} \times \frac{ER_d^r}{VA_d^r} + \frac{VA_{export}^r}{VA^r} \times \frac{ER_{export}^r}{VA_{export}^r} \\ &= \frac{VA_d^r}{VA^r} \times \frac{ER_d^r}{VA_d^r} + \frac{VA_{final}^r}{VA^r} \times \frac{ER_{final}^r}{VA_{final}^r} + \frac{VA_{one}^r}{VA^r} \times \frac{ER_{one}^r}{VA_{one}^r} + \frac{VA_{multi}^r}{VA^r} \times \frac{ER_{multi}^r}{VA_{multi}^r} \\ &= DEV_d^r + DEV_{export}^r \end{aligned} \quad (6)$$

In the following paragraphs we use DEV_{export} to depict the domestic energy use per value-added at different stage along the value chains, hence the energy consumption incurred by trade.

$$DEV^{r}_{export} = \frac{EREX^{r}_{export}}{VAEX^{r}_{export}} \left(export \in \{final, one, multi\}\right) \tag{7}$$

The higher the DEV_{export}, the higher exportation-incurred domestic energy use per value-added, hence higher energy consumption.

2.2 Econometric model

To identify the influence on domestic energy consumption of different stage along the value chain, we compose the following econometric model:

$$DEV_{it} = \alpha + \beta GVC_{it} + \gamma X_{it} + \mu_{i} + \lambda_{t} + \varepsilon_{it} \tag{8}$$

Where i refers to nations, t refers to years, dependent variable DEV is energy use per unit of value-added from domestic consumption or trade. The key independent variable, GVC_{it}, is the proxy for different participating stage along the global value chain. X_{it} is the aggregate of other controlled variables that can affect DEV, including the scale of trade (*trade*), structure of goods (mh_{com}), population (*pop*), GDP per capita (*pcgdp*), energy intensity (*eintensity*), energy consumption structure (*estrc*) and technology level (*rde*). μ_i and λ_t represent respectively the fixed effect of nation and year.

According to Wang et al. (2017), we bracket the participation of global value chain GVC_{it} into two types by the destination of domestic value added and the source of added value of final products, and define a pair of indices named forward-linkage participation of GVC (GVC_f) and backward-linkage participation of GVC (GVC_b), respectively. Then we divide the total value-added by its whereabouts:

$$\begin{aligned} VA' &= \widehat{V}AX \\ &= \widehat{V}L\widehat{Y^{D}} + \widehat{V}L\widehat{Y^{F}} + \widehat{V}LA^{F}B\hat{Y} \\ &= \widehat{V}L\widehat{Y^{D}} + \widehat{V}L\widehat{Y^{F}} + \widehat{V}LA^{F}L\widehat{Y^{D}} + \widehat{V}LA^{F}\left(B\hat{Y} - L\widehat{Y^{D}}\right) \\ &= VA_{domestic} + VA_{final} + VA_{inter} \end{aligned} \tag{9}$$

Or by its origin:

$$\begin{aligned} VA'_{y} &= \widehat{V}AB\hat{Y} \\ &= \widehat{V}L\widehat{Y^{D}} + \widehat{V}L\widehat{Y^{F}} + \widehat{V}LA^{F}B\hat{Y} \\ &= \widehat{V}L\widehat{Y^{D}} + \widehat{V}L\widehat{Y^{F}} + \widehat{V}LA^{F}L\widehat{Y^{D}} + \widehat{V}LA^{F}\left(B\hat{Y} - L\widehat{Y^{D}}\right) \\ &= VA_{y\_domestic} + VA_{y\_final} + VA_{y\_inter} \end{aligned} \tag{10}$$

GVC_f and GVC_b are:

$$GVC_f = \frac{\widehat{V}ALA^F L\widehat{Y^D} + \widehat{V}ALA^F\left(B\hat{Y} - L\widehat{Y^D}\right)}{VA'} = \frac{VA_{inter}}{VA'} \tag{11}$$

$$GVC_b = \frac{\widehat{V}ALA^F L\widehat{Y^D} + \widehat{V}ALA^F\left(B\hat{Y} - L\widehat{Y^D}\right)}{VA'_y} = \frac{VA_{y\_inter}}{VA'_y} \tag{12}$$

Both indexes are the portray of the participation degree in GVCs on the basis of value-added; the only difference lies in how the total value is divided. Forward-linkage participation of GVC means domestic value added generated from GVCs production and trade activities as a share of total value added, and the backward-linkage participation of GVC demonstrates the percentage of a country's final goods production contributed by both domestic and foreign factors that involve cross country production sharing activities. Hence, a country's position in the global production network is indicated by the relative values of these two indices.

According to the concept of the position along GVC proposed by Koopman et al. (2010), a nation's position along the GVC is intimately interlocked with its forward-linkage and backward-linkage participation. If a nation is more deeply involved in forward-linkage-participation, it will be placed relatively at the upstream of the GVC, and vice versa. We then define the position along the GVC index as:

$$GVC_{position} = \ln\left(1 + \frac{IV}{E}\right) - \ln\left(1 + \frac{FV}{E}\right) \tag{13}$$

3.Data

We apply the global multi-regional input-output table (updated to year 2014) from the World Input-Output Database (WIOD) in our estimation of each nation's energy use per added-value based on the production decomposition model. The database divides the world into 44 regions (where ROW is the aggregate for other unmentioned parts of the world, mostly countries in Africa and South America), each of them consists of 56 sectors. The energy use data comes from the World Input-Output Database Environmental Accounts, published by European Commission's Joint Research Centre in July, 2019. The database shares the same nation and sector division with the WIOD database and has detailed statistics about total amount of energy from year 2000 to 2016. Based on the environmental accounts, we divide energy into oil, coal, natural gas and renewable energy. The original unit for total energy use in the environmental accounts is trillion joule (tj); in this paper we convert the unit into ton of standard coal equivalent (tce) and apply the conversion rate of United Nations standard. Content of each energy category are listed in

Table **1**, based on the environmental accounts from the World Input-Output table.

In our econometric analysis of the influence from different participation in the GVC on energy use per value-added, variable *DEV,* GVC_f and GVC_b are calculated by the production decomposition model.

Table 1
Energy category.

Energy type	Definition	Contents
Coal	Coal, coke, crude oil	Hydrogenated coal, Lignite, Coke, crude oil
Oil	Aviation kerosene	Aviation kerosene
	Petrol	Petrol
	Fuel oil	Marine fuel oil, Oil for entering specific ports
	Others	Crude petrol and others
Natural gas	Natural gas	Natural gas
Renewable energy	Renewable energy	Geothermal energy, hydroelectricity, nuclear power, wind power, solar power and other renewable energy

Data source: authors sorted by the WIOD environmental accounts.

As for the controlled variables, the scale of trade (*trade*) is evaluated by the ratio of total amount of imported and exported goods and service to GDP, and structure of goods (mh_{com}) represented by the proportion of medium- and high-tech manufacture in total end-product exportation. Population (*pop*) is the population of the region concerned and economic development (*pcgdp*) represented by the logarithm of GDP per capita. The structure of energy consumption (*estrc*) is represented by the proportion of fossil energy consumption in total energy consumption, energy intensity (*eintensity*) represented by energy consumption per GDP unit and technology level (*rde*) the ratio of research and development expenditure to total GDP. All the controlled variables' data come from world bank database and International Energy Agency (IEA) energy database, and is deflated to 2010 price standard. Descriptive statistics are listed in Table 2.

Table 2
Descriptive statistics.

Variable	Meaning	Obs	Ave	St.d	Min	Max	Note
DEV_{export}	Energy use per unit value-added from different paths	630	6.82	5.90	0.86	55.86	tce/dollar
DEV_{final}		630	5.187	5.57	0.58	62.37	
DEV_{one}		630	7.19	6.25	0.95	54.59	
DEV_{multi}		630	8.03	6.66	1.02	55.83	
GVC_f	Participating at the premier stages in the GVC	630	0.18	0.08	0.04	0.46	
GVC_b	Participating at the latter stages in the GVC	630	0.18	0.08	0.05	0.51	
position	Exact position along the GVC	630	-0.003	0.05	-0.17	0.19	
trade	Openness	630	0.93	0.59	0.20	3.93	Ratio of trade to GDP
mh_{com}	Structure of goods	630	0.53	0.16	0.16	0.85	The proportions of medium- and high-tech manufacture in total end-product exportation
pcgdp	Economic development	630	9.97	.97	6.72	11.63	The logarithm of GDP per capita
eintensity	Energy intensity	630	4.75	0.33	3.98	5.70	the logarithm of energy consumption per GDP unit
estrc	Structure of energy consumption	630	0.76	0.17	0.15	1	Proportion of fossil energy consumption in total energy consumption
research	Research and development expenditure	588	1.49	0.91	0.05	4.29	The ratio of research and development expenditure to GDP
pop	Population	630	10.2	26.56	0.04	136.43	Population (ten million)

4.Results and discussions

4.1 Trade-induced energy inequality

Fig.1 depicts the domestic energy use per value-added of each nation from year 2000 to 2014. In the time dimension, energy use per value-added (DEV) declines significantly all around the globe, and the decline is particularly pronounced in developing countries, indicating energy saving efforts and technology advancement. From the country dimension, energy use per value-added differs strikingly among nations. From year 2000 to 2014, DEV_{export} of developed countries always remain the lowest around the globe, mostly between 3-5tce/dollar. DEV_{export} of the developing nations, on the other hand, are higher, over 10tce/dollar in average. In 2000 the lowest DEV_{export} happens in America, Western Europe and Japan, while the highest in Asian countries, Russia and ROW, and such pattern remains the same till 2014.

Such pattern reflects the inequality of energy use and economic value exchange between developed and developing countries. The latter has to pay more energy in order to gain the same economic value-added, which founds the base of trade-induced energy inequality via trade.

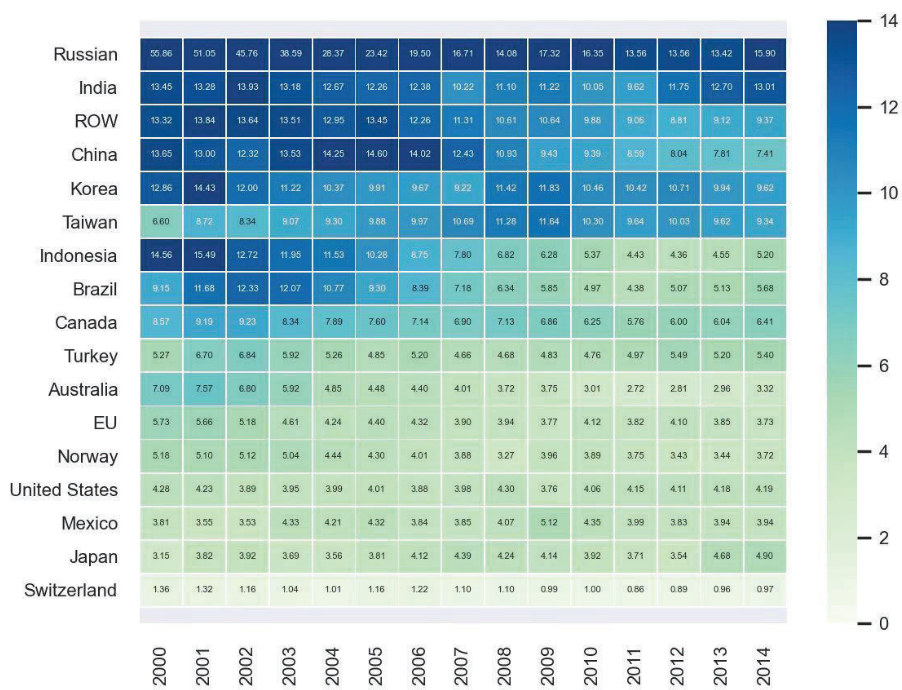


Fig. 1. Trade-incurred energy use per value-added（kg/dollar)

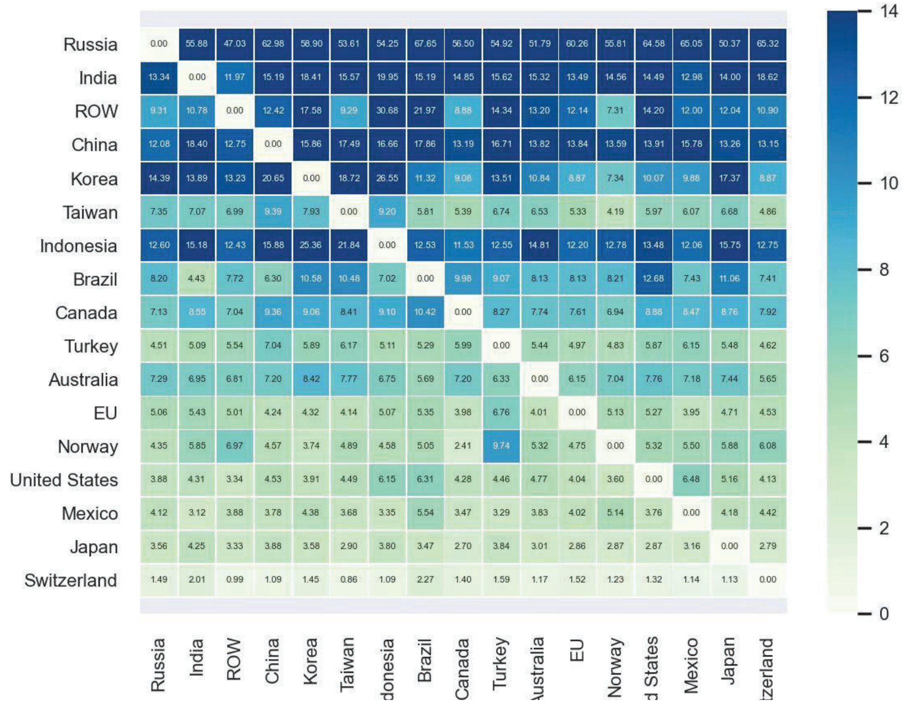
Note: The horizontal axis shows the year and the longitudinal axis the nation. The number in each matrix is the trade-incurred energy use per value-added, and the shade of color is a depiction of the amount of energy use.

Trade-incurred domestic energy use per value-added only lies the bedrock of trade-induced energy inequality; the value-added flow and energy flow behind bilateral trading network is the real reflection of the existence of trade-induced energy inequality. When the export-incurred domestic energy use is higher than the import-incurred energy use of the other party, trade-induced energy inequality exists.

Fig. 2 reveals the energy use per value-added behind the global trading network in year 2000 and 2014. Despite the fact that, compared to 2000, energy use per value-added in 2014 drops dramatically around the globe, the trade-induced energy inequality remains chronic and the pattern barely changes. For example, in 2000 domestic energy use per value-added of India is only lower than that in China and Russia, and in 2014 only Russia bears higher trade-incurred domestic energy use per value-added than India. Both in 2000 and 2014, Russia bears higher domestic energy use per value-added than all of his trading partners. In 2000, only Korea and Russia witness higher domestic energy use per value-added than China. In 2014, the list expands to Korea, India, Russia and ROW. Other developing countries share similar pattern, indicating that developing countries have to pay high energy consumption for low value-added when trading with the developed nations.

Developed countries tell a distinctively different story. In 2000, America bears lower energy uses than most of its trading partners, all except Japan, Switzerland and Mexico. In 2014 the only change in the list is that Australia replaces Japan. The same goes with the European Union (EU). Only Japan, America, Turkey, Switzerland and Norway rates higher than the EU in 2000, and the list shortens to America, Turkey, Switzerland and Norway in 2014, indicating that developed economies only shoulder minimal energy consumption to gain great value-added from international trades.

The results reveal that, considering trade-incurred domestic energy uses, the trade- induced energy inequality exists between developed economies and developing economies, between developed economies, and between developing economies. The greatest degree of energy unequal exchange is observed between developed economies and developing economics. China, India, Russia and ROW regions have to pay more energy to gain the same amount of economic benefits than other countries. On the contrary, compared to the local negative externalities that foreign countries own consumption lead to, countries represented by the EU, Japan, and the US bring more energy induced inequalities to foreign countries due to their own consumption. And these higher negative environmental externalities have a greater negative impact on countries such as China, India, and Russia. Developing countries gain unit trade benefit with much higher energy consumption, bearing a heavier energy burden.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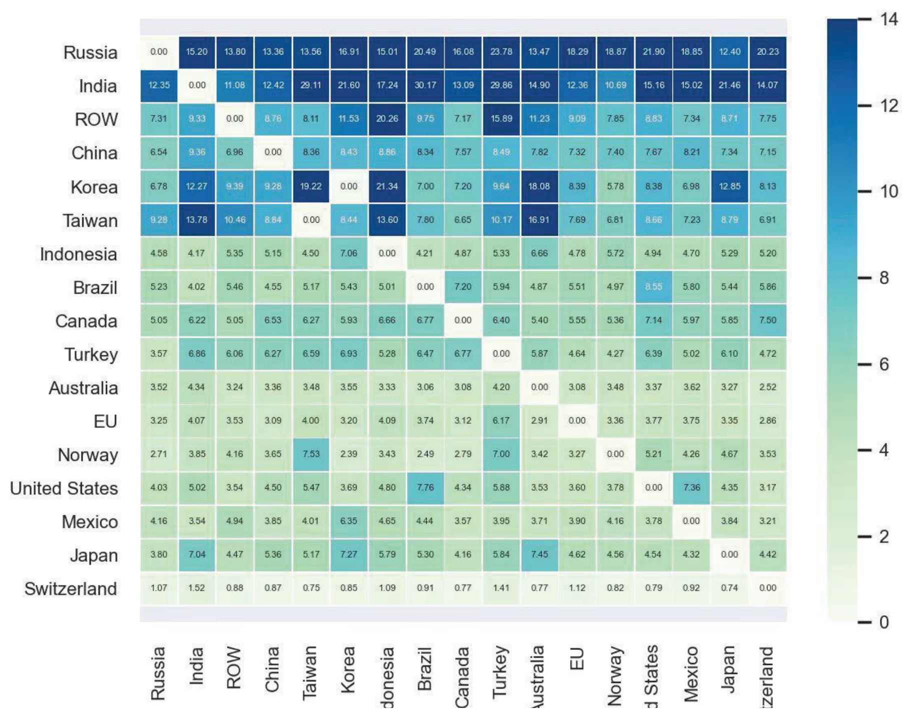
(a)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(b)

Fig. 2. Energy use per value-added behind the global trade（kg/dollar)

Note: (a) and (b) represent respectively the energy use per value-added behind global trade in 2000 and 2014. Each box of the matrix shows the energy use per value-added of the exportation from Y-axis nation to the X-axis nation, and the shade refers to the amount of energy use.

4.2 How different participation in the GVC leads to trade-induced energy inequality

4.2.1 Benchmark results

Our model estimates the influence of different participation patterns, including forward-linkage and backward-linkage, on DEV_{export}.

Table **3** shows fundamental estimation results, where column (1) and (4) illustrate the simple regression results. Column (2), (3), (5) and (6) are the results taking controlled variables into consideration.

Table 3 we can see that different pattern of participation in the global value chain can significantly affect DEV_{export}. While there exists a manifest negative relation between DEV_{export} and forward-linkage participation, there is a discernible positive link between DEV_{export} and backward-linkage participation, the relationship significantly over 10% and 1% respectively. Our result confirms that participation in the GVC is the key drive to trade-induced energy inequality.

Nations participating at forward are located at the upstream of the value chain who exports high-value-added intermediate goods and plays the value-exportation role, in other words high domestic benefits. Meanwhile, the manufacture and material supply for high-value-added products are relatively low-energy-cost, resulting in high energy efficiency and low energy consumption. Nations participating at backward stages, on the other hand, are located at the downstream of the value chain and mainly plays the low-technic role such as assembling and reprocessing. Facing both a lack of core technology and the right to price and a technology blockage from upstream nations, they have no contact to key technology, resulting in low production efficiency and high cost, in other words stuck at the low-value-added, high-energy-use and high-pollution link (Koopman et al., 2010).

Table 3

Basic regression.

Variable	(1) DEV_{export}	(2) DEV_{export}	(3) DEV_{export}	(4) DEV_{export}	(5) DEV_{export}	(6) DEV_{export}
GVC_f	-8.656	-18.06***	-13.78*			
	(-1.40)	(-2.62)	(-2.07)			
GVC_b				33.09***	42.23***	30.68***
				(5.43)	(3.30)	(3.44)
trade		4.574***	4.898***		-1.810	0.315
		(3.97)	(4.06)		(-1.09)	(0.17)
mh_{com}		3.937	5.044		2.797	3.907

		(1.59)	(1.40)		(1.17)	(1.05)
pcgdp		-17.56***	-17.10***		-16.97***	-16.45***
		(-13.31)	(-9.96)		(-12.83)	(-9.81)
estrc		14.83***	10.38**		14.25***	9.002**
		(3.82)	(2.65)		(3.67)	(2.37)
pop			0.576***			0.587***
			(6.27)			(6.22)
eintensity			10.66***			10.95***
			(3.08)			(3.04)
research			3.011***			2.605***
			(5.32)			(4.70)
constant	11.87***	168.1***	104.3***	4.918***	158.8***	95.11***
	(12.03)	(14.52)	(6.38)	(4.80)	(13.52)	(6.68)
Obs	630	630	588	630	630	588
R^2		0.482			0.485	
#Group	42		42	42		42
FE (nations)	YES	YES	YES	YES	YES	YES
FE (years)	YES	YES	YES	YES	YES	YES
F	1.964	27.83	1.947e+06	29.50	28.24	1.025e+06
#Country		42			42	

Note: In all regression models, the dependent variable is energy use per value-added. For the first three columns, the key independent variable is the involvement of premier-stage-participation, and for the latter three columns, the key independent variable is the involvement of latter-stage-participation. We control fixed effect by nations and by years. *, **, *** means significant over 10%, 5% and 1% respectively.

4.2.2 Robustness

There are two potential disturbances to our analyses. First, an economy's participation in the GVC might be determined by its own low resource cost or high technology level. Secondly, there might exist some unobserved factors that affect both energy use per value-added and the way an economy participates in the GVC. Both are threats to the credibility of our results.

We conduct two robustness tests to answer the questions above. Firstly, we replace the participating stage by one-period and two period lags as the instrumental variable and re-estimate the econometric model by generalized method of moments (GMM). Our results show that, after controlling endogeneity bias by GMM, different participation patterns in the GVC still significantly affect DEV_{export} and the trend is the same with the basic regression model (See Table 4, column (1)-(2)). In our first stage regression, coefficients for one-period lag are 0.74 and 0.58 respectively and significant over 1%, concluding strong interdependency between each instrumental variable and the intrinsic variable. The results of Kleibergen-Paap rk Lm test and Kleibergen-Paap Wald rk F test also confirm such interdependency. Hansen J statistics cannot deny the assumption that the instrumental variables are over-identifications, confirming that the instrumental variables are exogenous.

Secondly, we replace the key independent variables by the position along the GVC and the regression results are listed in Table 4, column (3). According to Table 4, one unit increase in the GVC will cause in average a cut of 23.2 units in DEV_{export}, meaning that the upper a nation's positioned, the lower the domestic energy use per exported value-added, in consistence with our basic regression results.

Table 4
Robustness.

Variable	(1) DEV_{export}	(2) DEV_{export}	(3) DEV_{export}
GVC_f	-22.35**		
	(-2.40)		
GVC_b		48.95***	
		(3.00)	
position			-23.15***
			(-4.00)
Controlled variables	YES	YES	YES
FE (nations)	YES	YES	YES
FE (years)	YES	YES	YES
Kleibergen-Paap rk LM statistics	47.49	97.046	
	[0.0000]	[0.0000]	
Kleibergen-Paap Wald rk F	140.207	67.606	
Hansen	[0.4059]	[0.1870]	
Obs	491	491	588
R^2	0.557	0.564	
#Country	39	39	42
Instrumental variables	First order regression	First order regression	
L.GVC_f	0.7374*** (10.77)		
L2.GVC_f	-0.0341 (-0.57)		
L.GVC_b		0.5835*** (11.01)	
L2.GVC_b		-0.1256*** (-3.22)	
F	140.21 [0.0000]	67.61 [0.0000]	

Note: column (1)-(2) are results estimated by GMM, column (3) the results taking the position along the global value chain index as key independent variable. *, **, *** refers to significance over 10%, 5% and 1%, respectively.

4.2.3 Heterogeneity of the impact of GVC participation on energy inequality

4.2.3.1 Energy type

Will the influence of different participation on trade-incurred energy inequality vary with different energy type? To answer this question, we conduct the regressions of GVC participation on trade-incurred coal, oil, natural gas and renewable energy use per domestic value-added respectively (See Table 5).

Table 5 reveals that, despite the consistency among different types of energy, the effect is much higher in coal and renewable energy than oil or natural gas. The results of forward-linkage and backward-linkage participation of GVC on coal consumption are both significant at 0.1 level, so are that on renewable energy. Oil and natural gas, however, are less sensitive. On the other hand, the influential mechanism differs between oil and natural gas. While oil is significantly impacted by forward-linkage participation of GVC yet insensitive to backward-linkage participation of GVC, the results are very different for natural gas, which is significantly impacted by backward-linkage participation of GVC yet insensitive to forward-linkage participation of GVC.

Table 5 reveals the different influential mechanism of GVC participation on different energy types. Coal and renewable energy are mainly employed in electricity generation and coal is also used as industrial fuel, both are tightly integrated in global value chain production and highly relevant to GVC participation. Oil, on the other hand, is majorly applied in transportation, the rest in chemical industry, while natural gas is mostly consumed in architecture, industrial fuel and electricity generation, hence a substantial part already consumed domestically before the rest being spent in GVC production, meaning they will be less affected by GVC participation. What's more, oil, as a chemical industrial material with various uses, differs in the GVC participation from natural gas whose main use is as one kind of fuel. In oil industry, energy is mostly consumed at the upstream and midstream like oil harvesting and refining, while natural gas as a fuel and material for electricity generation is mostly consumed at the midstream and downstream, leading to the result that participating at the forward stage will significantly affect oil use per value-added while participating at the backward stage will significantly affect natural gas use per value-added.

Table 5

Energy type.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Variable	DEV_{coal}	DEV_{coal}	DEV_{oil}	DEV_{oil}	DEV_{gas}	DEV_{gas}	DEV_{new}	DEV_{new}
GVC_f	-7.555***		-4.404**		4.118		-5.182***	
	(-3.46)		(-2.83)		(1.13)		(-4.74)	
GVC_b		9.920*		3.653		8.590**		2.972**
		(2.00)		(1.53)		(2.86)		(2.21)

Controlled variable	YES	YES	YES	YES	YES	YES	YES	YES
Constant	39.76***	36.57***	16.96***	14.67***	22.10***	22.12***	5.038***	2.489*
	(4.07)	(3.67)	(6.72)	(6.43)	(6.13)	(6.58)	(4.03)	(1.87)
Obs	575	575	588	588	560	560	588	588
#Group	41	41	42	42	40	40	42	42
FE (nations)	YES	YES	YES	YES	YES	YES	YES	YES
FE (years)	YES	YES	YES	YES	YES	YES	YES	YES
F	2.830e+06	2.430e+07	1.900e+07	1.200e+07	8.541e+06	6.390e+07	6.840e+07	5.508e+06

Note: dependent variables for column(1)-(2), (3)-(4),(5)-(6),(7)-(8) are coal, oil, natural gas and renewable energy respectively, and key independent variable for column (1), (3), (5), (7) is forward-linkage participation of GVC while key independent variable for column 2,4,6,8 is backward-linkage GVC participation. *, **, *** means significant over 10%, 5% and 1% respectively

4.2.3.2 Trade mode

Will the influence of global value chain participation on domestic energy use per value-added shows heterogeneity in different trade mode? To answer this question, we divide trade-incurred energy use per value-added into energy use incurred by final trade, by one-time-cross-border intermediate trade and by multi-cross-border intermediate trade and conduct a regression model for each (see Table 6)

Table 6 reveals that, firstly, a negative link between forward-linkage participation of GVC with energy use per value-added exists across all types of trade, and a positive link between backward-linkage GVC participation works with every trading type as well, confirming our basic regression results. Secondly, the negative impact of forward-linkage participation of GVC on energy use per value-added incurred by multi-cross-border intermediate trade is greater than that of one-time-cross-border intermediate trade, which is even greater than that of final trade. The positive influence of backward-linkage GVC participation on energy use per value-added incurred by multi-cross-border intermediate trade is also greater than that of one-time-cross-border intermediate trade, which is even greater than that of final trade, indicating a magnifying effect of the influence as the trade mode becomes more complex.

The shift from final trade to one-time-cross-border intermediate trade to multi-cross-border intermediate trade depicts the expansion of production line and the elaboration and specialization of international division, where each nation focuses on a specific link along the value chain based on its own endowments and advantages. Nations with technology advantages specialize in design and research, whilst nations with a labor boon focus on production. In this process, energy use moves downstream and concentrates in the producing and manufacturing countries, and the impact on energy use per value-added will be further magnified as the nation moves along the GVC. Moving up can dramatically cut down domestic energy use per value-added while moving down will significantly increase it.

Table 6
Trade mode.

Variable	(1) DEV_{final}	(2) DEV_{final}	(3) DEV_{one}	(4) DEV_{one}	(5) DEV_{multi}	(6) DEV_{multi}
GVC_f	3.063		-15.76**		-32.22***	
	(0.44)		(-2.21)		(-3.76)	
GVC_b		23.50**		33.00***		37.37***
		(2.32)		(4.16)		(3.72)
Controlled variable	YES	YES	YES	YES	YES	YES
Constant	82.31***	81.14***	114.0***	103.7***	122.5***	104.6***
	(5.35)	(6.11)	(6.79)	(6.83)	(6.35)	(6.17)
Obs	588	588	588	588	588	588
#Group	42	42	42	42	42	42
FE (nations)	YES	YES	YES	YES	YES	YES
FE (years)	YES	YES	YES	YES	YES	YES
F	1.178e+06	94708	3.090e+07	4.913e+06	2.210e+07	386021

Note: *, **, *** means significant over 10%, 5% and 1% respectively.

4.2.3.3 Natural resource endowment

The participation pattern for a nation or region in the GVC affects its trade-incurred energy use per value-added might be influenced by its own natural resource endowment. We bracket our samples into resource-wealthy nations and resource-deficient nations, based on the ratio of its mining output to total output.

Table 7 lists the heterogeneity regression results. We discover that the cut-down of domestic energy use per value-added from forward-linkage participation of GVC mainly takes place in resource-deficient nations, and the rise in energy use per value-added from backward-linkage participation of GVC also mainly takes place in resource-deficient nations, indicating a possible impact of resource endowments on a nation's GVC participation. With abundance in resources, the resource-wealthy nations conduct their economic activities around the exploitation of resources, and despite the possible technology advancement, moving upstream will not affect the center place of resource exploitation, which means energy use will not reduce, but might even increase. Moving downstream, on the other hand, means an expansion of the value chain. Due to the advantage in resource abundance, such expansion usually takes the form of energy-intensive manufacturing, increasing the domestic energy use per value-added dramatically. That's why backward-linkage participation of GVC exerts greater impact than forward-linkage participation of GVC on resource-wealthy nations. Similarly, forward-linkage participation of GVC exerts greater impact than backward-linkage participation of GVC on resource-deficient nations.

Heterogeneity regression results show that resource-wealthy and resource-deficient nations should make different policy decisions, the former aiming to control backward-linkage participation of GVC and energy overuse, the latter focusing on moving up the GVC, which will be essential to cut down the energy consumption. Compared to resource-wealthy nations, it is relatively easier for resource-deficient nations to realize a transformation of production through a change of position along the GVC.

Table 7
Resource endowment.

	(2)	(3)	(5)	(6)
Variable	Resource-wealthy nations	Resource-deficient nations	Resource-wealthy nations	Resource-deficient nations
GVC_f	57.91	-34.06***		
	(1.09)	(-4.84)		
GVC_b			63.67**	11.40
			(2.38)	(1.12)
Controlled variables	YES	YES	YES	YES
Constant	255.8***	28.71	287.0***	26.22
	(7.72)	(1.43)	(5.89)	(1.19)
Obs	116	472	116	472
#Group	9	33	9	33
FE (nations)	YES	YES	YES	YES
FE (years)	YES	YES	YES	YES
F	2238	1.494e+06	34717	256461

Note: *, **, *** means significant over 10%, 5% and 1% respectively.

5.Conclusion and policy implications

In this paper, we apply the production decomposition model to evaluate the trade-induced energy inequality from year 2000 to 2014. We discover a protruding asymmetry of trade-incurred domestic energy use per value-added between bilateral trading parties. Some nations were benefited from low energy use per value-added through participating the GVCs over a long period, while others experienced massive cost of high energy use per value-added, indicating the latter consuming a large amount of their own energy to meet the former party's consumption and only received minimal economic gains from the former party. However, the former party only needs to consume a small amount of domestic energy to meet the latter's consumption demand and acquire great economic benefits from the latter party. Our results show that such asymmetry is most notable between the developed and developing countries. Despite the fact that the overall global energy use per value-added decreases, the asymmetry mode doesn't change significantly between developed and developing countries during our research time-span sample.

Our econometric empirical analysis based on the panel data reveals that forward-linkage GVC participation can diminish domestic energy use per value-added while backward-linkage participation of GVC amplifies it, indicating that GVC participation is an important driver for trade-induced energy inequality. Gradually elaboration of global division positions the developed countries at the upstream of the value chain and the developing countries downstream, resulting in the developed countries holding high-value-added, low-energy-cost links whilst transferring the low-value-added, high-energy-cost production to developing countries, triggering an trade-induced energy inequality in global trade.

Moreover, we discover multiple heterogeneity in the influential mechanism of GVC participation on domestic energy use per value-added. Firstly, trade-incurred coal and renewable energy use will be significantly affected by GVC participation, whilst the influence on the use of oil or natural gas relatively small. Participating at the forward stages will affect oil use while participating at the forward stages will affect natural gas use. Such heterogeneity reflects the specific features of each energy type's production chain and consumption features. Secondly, the more complex the trade mode, the stronger the influence. From cross-border final trade to one-time-cross-border intermediate products transaction to multi-cross-border intermediate trade, trade-incurred energy use per value-added mounts up. Thirdly, nations with wealthy resource endowments will be affected more severely by backward-linkage participation whilst nations with less resource endowment will be affected more severely by forward-linkage participation, indicating a difference in developing pattern between these two types of nations.

Our conclusion systematically confirms the existence of trade-induced energy inequality in trade, also depicting profoundly how GVC participation leads to such asymmetry. Our conclusion has strong policy implications. Our discovery shows that, in order to reduce trade-induced energy inequality, those at the inferior stage should promote their rank along the GVC to gradually cut their external trade's excessive use on their own resources and to reduce environmental pollution. As for specific energy and trading policy, each nation should take its own action in correspondence with its own characteristics. For those with poor resource endowments whose energy use mainly relies on coal, oil and renewable energy and are deeply involved in the GVC, their main focus should be on the promotion of its rank along the chain, which generates a high margin of return. Those with abundant resource endowments whose energy use mainly relies on natural gas and are less involved in the GVC, a promotion in ranks might not cause a profound change, while a declination in ranks can significantly increase energy use. Therefore, these nations should on one hand prevent a decline in rank whilst on the other hand seek for a boost in energy efficiency and better technology advancement.

Declarations of interest

None.

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Abstract Under economic globalization, developing countries are suffering from international-trade-induced resource and environmental cost based on their ways of participating in global value chain (GVC), hence inequality between trading economies occurred. Existing literature mainly focuses on revealing the fact of ecological exchange inequality behind trades, but rarely delves into the trigger and mechanism towards such inequality, not least any studies on the influence of GVC participation. Moreover, most of the existing studies treat energy, which is a key factor to economic growth and global climate change, as a subset of environmental indicators for ecological unequal exchange analysis, thus lack a whole-picture of trade-induced energy inequality with regard to its modes, driving factors, and the heterogeneous mechanism of its driving factors. This study firstly explores the trade-induced energy use and energy inequality using multi-regional input-output analysis and the production decomposition analysis, then econometric analysis is applied to further explore how different participation in GVC affects a country's trade-induced energy use, which illustrate the mechanism of trade-induced energy inequality. Our results uncover a striking difference in the domestic energy use per value-added of countries engaged in bilateral trade. From year 2000 to 2014, trade induced energy use per value-added in developed countries always remain the lowest around the globe, while that of the developing nations is more than twice higher, indicating that the trade-induced energy inequality was remained during the studied period. The econometric analysis displays that participation in forward-linkage of the GVC can significantly reduce the domestic energy use per value-added while participation in backward-linkage may increase energy use per value-added, indicating that the GVC participation is a key driving factor for trade-induced energy inequality. Our heterogeneity examination results further reveal that: first, the influential mechanisms of GVC participation on energy use per added value cross energy types are similar between coal and new energy, but oil and natural gas have their own influential mechanism. Second, the impact of GVC participation on energy use per added value amplifies as the GVC activities become more complex. Third, resource endowment would affect national industrial developing pattern, leading to striking difference among the impacts of GVC participation on nations rich with resource endowment and that on nations poor in resource endowment. Namely, forward-linkage GVC

participation shows a greater effect on energy use per added value of resource-deficient nations, whilst backward-linkage GVC participation exerts more substantial impact on energy use per added value of resource-wealthy nations. Our findings imply that optimizing GVC participation is beneficial to domestic resource conservation and environmental protection, especially for developing countries, for which enhancing their rank of GVC is feasible to reduce their trade-induced resources and environmental costs.

Research Highlights

- Trade-induced energy inequality is explored using multi-regional input-output analysis and the production decomposition analysis
- Econometric analysis is applied to further explore the influential mechanism of such energy inequality
- Trade-induced energy inequality is observed and has not been reduced from year 2000 to 2014
- GVC participation is a key driving factor for trade-induced energy inequality
- Multiple heterogeneity exists in influential mechanisms of GVC participation on trade-induced energy inequality

Dear Editor,

Please find enclosed the original manuscript entitled ***"Global value chain participation and trade-induced energy inequality"*** for possible publication in your journal of ***Energy Economics***.

Under economic globalization, developing countries are suffering from international-trade-induced resource and environmental cost based on their ways of participating in global value chain (GVC), hence inequality between trading economies occurred. To our knowledge, Existing literature mainly focuses on revealing the fact of ecological exchange inequality behind trades, but rarely delves into the trigger and mechanism towards such inequality, not least any studies on the influence of GVC participation. Moreover, most of the existing studies treat energy, which is a key factor to economic growth and global climate change, as a subset of environmental indicators for ecological unequal exchange analysis, thus lack a whole-picture of trade-induced energy inequality with regard to its modes, driving factors, and the heterogeneous mechanism of its driving factors. Therefore, we attempt to illustrate a whole-picture of the trade-induced energy inequality, depict of its mode, and explore its drivers and how such driving factors' influence vary with different trading modes and energy types. And conducting such research is critical to portray and better understand the forming mechanism of trade-induced energy inequality and help with relative policy decisions.

We firstly explores the trade-induced energy use and energy inequality using multi-regional input-output analysis and the production decomposition analysis, then econometric analysis is applied to further explore how different participation in GVC affects a country's trade-induced energy use, which illustrate the mechanism of trade-induced energy inequality. Our results uncover a striking difference in the domestic energy use per value-added of countries engaged in bilateral trade. From year 2000 to 2014, trade induced energy use per value-added in developed countries always remain the lowest around the globe, while that of the developing nations is more than twice higher, indicating that the trade-induced energy inequality was remained during the studied period. The econometric analysis displays that participation in forward-linkage of the GVC can significantly reduce the domestic energy use per value-added while participation in backward-linkage may increase energy consumption per value-added, indicating that the GVC participation is a key driving factor for trade-induced energy inequality. Our heterogeneity examination results further reveal that: first, the influential mechanisms of GVC participation on energy use per added value cross energy types are similar between coal and new energy, but oil and natural gas have their own influential mechanism. Second, the impact of GVC participation on energy use per added value amplifies as the GVC activities become more complex. Third, resource endowment would affect national industrial developing pattern, leading to striking difference among the impacts of GVC participation on nations rich with resource endowment and that on nations poor in resource endowment. Namely, forward-linkage GVC participation shows a greater effect on energy use per added value of resource-deficient nations, whilst backward-linkage GVC participation exerts more substantial impact on energy use per added value of resource-wealthy nations.

Our conclusions have strong policy implications. The findings imply that optimizing GVC participation is beneficial to domestic resource conservation and environmental protection, especially for developing countries, for which enhancing their rank of GVC is feasible to reduce their trade-induced resources and environmental costs.

We confirm that this manuscript has not been published previously, and it is not being considered elsewhere, and we will not submit it to elsewhere before a decision is made by this journal. Your consideration would be highly appreciated.

Best regards,
Sincerely yours,

Xi Ji
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