Tracing metal footprints via global renewable power value chains

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Abstract: The globally booming renewable power industry has stimulated an unprecedented interest in metals as key infrastructure components. Many economies with different endowments and levels of technology participate in various production stages and cultivate value in global renewable power industry production networks, known as global renewable power value chains (RPVCs), complicating the identification of metal supply for the subsequent low-carbon power generation and demand. Here, we use a multi-regional input-output model (MRIO) with a value chain decomposition model to trace the metal footprints (MFs) and value-added of major global economies' renewable power sectors. We find that the MFs of the global renewable power demand increased by 97% during 2005—2015. Developed economies occupy the high-end segments of RPVCs while allocating metal-intensive (but low value-added) production activities to developing economies. The fast-growing demand for renewable power in developed economies or developing economies with upper middle income, particularly China, is a major contributor to the embodied metal transfer increment within RPVCs, which is partly offset by the declining metal intensities in developing economies. Therefore, it is urgent to establish a metal-efficient and green supply chain for upstream suppliers as well as downstream renewable power installers for just transition in the power sector across the globe.

Introduction

Renewable power plays crucial roles in achieving a sustainable, low-carbon energy future and meeting ambitious global climate targets, such as carbon neutrality [1,2,3]. However, renewable power infrastructure (solar modules, wind turbines, etc.) relies heavily on many metals, such as iron, copper, aluminum, and precious metals[4,5,6]. Different economies with great variations in metal endowments, technological levels participate in different stages in renewable power industry production network to create value, that is, renewable power value chains (RPVCs) [7,8 9,10]. For example, solar PV value chains use metal ore (copper, aluminum, etc.) from China[11] and Africa[12,13], and modules (silver, copper, etc.) from Europe[14], the United States[15] and China[16,17], which are then assembled in Asian economies (excluding Japan, e.g., China) and finally sold globally[18]. With the rapid expansion of renewable power and the increasing complexity of RPVCs, it is extremely challenging and difficult to know who supplies metal products for whose renewable power generation[19,20]. To clearly trace the metals in RPVCs helps the stakeholders and policy makers understand the place and magnitude of metal-related negative side effects, thus, enable them to formulate trade policies and foster sustainable and responsible RPVCs.

The key to solving the difficulties in understanding who supplies metal equipment for whose renewable power generation lies in revealing the linkages between RPVCs and metal demand. Currently, there are some researchers focusing on estimating renewable power sectors' metal demand and constraints. For example, Wang et al. found that the cumulative amount of critical metals required for the production of China's solar power from 2015 to 2050 will exceed the present national reserve by 1.4 to 123 folds[11]. Similar studies have been carried out for wind power-related[10,21], hydroelectricity-related[22,23], and nuclear power-related[24,25] metal demand. Most of the previous estimates focus on direct metal intensity used in construction or operation of typical plants compiled from a variety of literature sources. While a more comprehensive and harmonized accounting for indirect metal uses related to supply chains activities (e.g., transportation, service), including that embodied in cross-border trade, are scarce.

In the context of a more internationally fragmented renewable power production network, more economies and industries are involved and connected. Although previous studies have estimated the regional-specific metal demands for renewable power sectors, they are far from sufficient to draw a detailed and comprehensive picture of the interactions between RPVCs and metal use.[26,27,28]. It is because these previous studies did not tell the differences between metal use in renewable power related intermediate and final products, nor did they capture the metal uses of renewable power fully and consistently. Hence, it is difficult to precisely trace the true upstream metal costs induced by per unit output of renewable power sectors, or identify the roles of different economies in global RPVCs. Therefore, it is in urgent need to conduct a more detailed accounting for metal use and value-added of different production stages along RPVCs and extend the coverage of metal uses in all life cycle stages, given that the crucial information such as the metal costs induced by renewable energy and the position of each economy along RPVCs for reasonably allocating metal use responsibility remains poorly understood. Moreover, both the scales of renewable power sectors and the renewable power products trade have witnessed massive growth in the last two decades (e.g., the solar photovoltaic modules import of USA increased by ~70 times in recent 15 years)[29,30], which inevitably changes the profiles of metals consumption as well as metal embodied in international trade[31,32]. In this context, it is also vital to unveil the evolution trajectory of metal demand induced by renewable power and the driving forces behind, which is essential to promote cross-boundary joint actions for supply-chain efficient metal use in RPVCs.

To address these problems, we develop a quantitative framework to gauge metal footprints (MFs, the total metal ores embodied in RPVCs) in global RPVCs by combining a multiregional input-output model (MRIO) with a value chain decomposition model. The metal use obtained from the global MRIO database, EXIOBASE 3, with high sectoral resolution (163 sectors), covers not only direct metal uses, but also indirect uses associated with mining, manufacturing and other supply chain activities. The metal uses embodied in intermediate inputs that cross border multiple times in renewable power value chains are portend meanwhile. Specifically, we consider a full set of metal ores used by 7 renewable power sectors (including bioenergy, geothermal power, hydropower, wind power, solar PV, ocean power, and solar thermal) in this model. We focused on the extensively studied metals that are crucial ingredients of renewable power infrastructure components, consisting of majority of the weight or crucial to the proper functioning. We divided the metals into four groups, bulk metals such as aluminum, copper, iron, lead, zinc; precious metals such as silver and platinum-group metals; scarce metals such as nickel, tin and rare earth elements; and other non-ferrous metals group with antimony, cadmium, chromium, cobalt, germanium, magnesium, manganese, mercury, strontium, titanium, tungsten, and further others included. We, for the first time, trace the spatial-temporal changes of renewable power sectors' MFs and value-added in 49 economies during 2005-2015. Furthermore, the value chain status of each economy is presented by comparing domestic metal ore export with the corresponding domestic value-added (see methods). As a result, we provide a more holistic view of the growing imbalances in economic benefits and metal costs within RPVCs, which highlight the urgent need to formulate appropriate responsible strategies. In addition, the structural decomposition analysis (SDA) model is applied to investigate the differentiated contribution of each domestic and foreign driving factor to the embodied metal changes in trade. By doing so, we reveal the driving mechanism of growing MFs inequality, enabling to inform decision-makers and practitioners to formulate targeted measures and policies for mitigating potential growing metal inequities and efficient metal use in the RPVCs.

Methods

Metal footprints of renewable power demand

The input-output models used to estimate the MFs are all derived from the classical Leontief equation[90]. This method can identify the input-output relationships between different economies and sectors, as well as the quantity and type of intermediate product inputs required by each economy and sector to produce one unit of output. Using this method, the production process of the final products (e.g., electricity) can be traced.

In a multi-regional input-output (MRIO) model, different economies and sectors are connected through international trade. The technical coefficient matrix $\mathbf{A}$, in which the element $a^{sr}_{nele,\ ele}$, demonstrates the intermediate inputs of non-electricity (*nele*) sectors in economy *s* required to produce a unit output of electricity (*ele*) sector in economy *r*. $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$ denotes the Leontief inverse matrix, which captures both direct and indirect inputs to satisfy per unit of electricity demand. The demand matrix $\mathbf{Y}$, with elements y^{sr}_{ele}, indicates the renewable electricity demand in economy *r* is from economy *s*. To calculate the supply chain metal use embodied in goods and services for renewable power production, we extend MRIO analysis with the metal use as an environmental indicator. $\mathbf{m}$ is a vector of the direct intensity of metal consumption (the volume of domestic metal ores extracted per unit of total output from each sector) for all sectors, for example, m^{s}_{nele} indicates the direct metal intensity of non-electricity sector in economy *s*. Then the total (including both direct and indirect) metal use embodied in all goods and services for renewable electricity demand via supply chain can be mathematically expressed as follows:

$$\widehat{\mathbf{m}}\mathbf{B}\mathbf{Y}_{ele} = \begin{bmatrix} m^{s}_{nele} & 0 & 0 & 0 \\ 0 & m^{s}_{ele} & 0 & 0 \\ 0 & 0 & m^{r}_{nele} & 0 \\ 0 & 0 & 0 & m^{r}_{ele} \end{bmatrix} \times$$

$$\begin{bmatrix} b^{ss}_{nele,nele} & b^{ss}_{nele,ele} & b^{sr}_{nele,nele} & b^{sr}_{nele,ele} \\ b^{ss}_{ele,nele} & b^{ss}_{ele,ele} & b^{sr}_{ele,nele} & b^{sr}_{ele,ele} \\ b^{rs}_{nele,nele} & b^{rs}_{nele,ele} & b^{rr}_{nele,nele} & b^{rr}_{nele,ele} \\ b^{rs}_{ele,nele} & b^{rs}_{ele,ele} & b^{rr}_{ele,nele} & b^{rr}_{ele,ele} \end{bmatrix} \times \begin{bmatrix} 0 & 0 \\ y^{ss}_{ele} & y^{sr}_{ele} \\ 0 & 0 \\ y^{rs}_{ele} & y^{rr}_{ele} \end{bmatrix} \quad (1)$$

where, $\widehat{\mathbf{m}}$ is a matrix with the direct metal intensity for all sectors on the diagonal. We change the demand matrix $\mathbf{Y}$ with zeros for all sectors other than renewable power sectors, namely, production of electricity by hydro, wind, biomass and waste, solar photovoltaic, solar thermal, tide, wave, ocean, and geothermal. The total renewable electricity demand covers that for both economic production and final demand, such as by households, government, investment, and the coverage applies for the whole analysis.

The metal footprints of renewable power demand of economy *s* can also be expressed as follows:

$$\mathbf{MF}_{ele}^{s} = \sum_{r \neq s}^{N} (\widehat{\mathbf{m}}_{c}^{s}\mathbf{B}^{ss}\mathbf{y}^{ss} + \widehat{\mathbf{m}}_{c}^{r}\mathbf{B}^{rs}\mathbf{y}^{ss} + \widehat{\mathbf{m}}_{c}^{r}\mathbf{B}^{rr}\mathbf{y}^{rs} + \widehat{\mathbf{m}}_{c}^{s}\mathbf{B}^{sr}\mathbf{y}^{rs}) \qquad (2)$$

where, the subscript *c* represents ten types of metals.

Metals embodied in trade

Metal embodied in exports (MEE) is expressed as follows according to Xu and Dietzenbacher[91]:

$$\mathbf{MEE}^{r} = \underbrace{\sum_{s \neq r}^{N} (\widehat{\mathbf{m}}^{r}\mathbf{B}^{rr}\mathbf{y}^{rs})}_{1} + \underbrace{\sum_{s,k \neq r}^{N} (\widehat{\mathbf{m}}^{r}\mathbf{B}^{rs}\mathbf{y}^{sk})}_{2} \qquad (3)$$

where, the metal embodied in exports can be divided into two parts. The first part represents the metal embodied in economy *r*'s renewable power export that is consumed in another economy. The second part represents the metal embodied in the economy *r*'s intermediate products, which are exported and then used to produce renewable power for consumption for all other economies.

Similarly, metal embodied in import (MEI) is expressed as:

$$\mathbf{MEI}^{r} = \underbrace{\sum_{s,k \neq r}^{N} (\widehat{\mathbf{m}}^{k}\mathbf{B}^{ks}\mathbf{y}^{sr})}_{3} + \underbrace{\sum_{s \neq r}^{N} (\widehat{\mathbf{m}}^{s}\mathbf{B}^{sr}\,\mathbf{y}^{rr})}_{4} \qquad (4)$$

where, the third part represents the global metals embodied in the goods and services imports by economy *s* to produce renewable power and finally consumed in economy *r*. The fourth part provides the metals in other economies that are embodied in the intermediate products imported by producers in economy *r* to generate renewable power for consumption.

Tracing metal use or value-added embodied in global RPVCs

Based on the input-output model, the total bilateral trade of metal use or value-added (export from *s* to *r* as example) can be written as:

$$\mathbf{MEEVC}^{sr} = \underbrace{(\widehat{\mathbf{m}}^{s}\mathbf{B}^{ss})^{T}\#\mathbf{y}^{sr}}_{1} + \underbrace{(\widehat{\mathbf{m}}^{s}\mathbf{L}^{ss})^{T}\#(\mathbf{A}^{sr}\mathbf{B}^{rr}\mathbf{y}^{rr})}_{2}$$

$$
\begin{aligned}
&+ \underbrace{(\widehat{\mathbf{m}^s}\mathbf{L}^{ss})^T \# \left[\mathbf{A}^{sr}\mathbf{B}^{rr}\sum_{t\neq s,r}^{G}\mathbf{y}^{rt} + \mathbf{A}^{sr}\sum_{t\neq s,r}^{G}\mathbf{B}^{rt}\mathbf{y}^{tt} + \mathbf{A}^{sr}\sum_{r\neq s,r}^{G}\mathbf{B}^{rt}\sum_{u\neq s,t}^{G}\mathbf{y}^{tu}\right]}_{3} \\
&+ \underbrace{(\widehat{\mathbf{m}^s}\mathbf{L}^{ss})^T \# \left[\mathbf{A}^{sr}\mathbf{B}^{rr}\mathbf{y}^{rs} + \mathbf{A}^{sr}\sum_{t\neq s,r}^{G}\mathbf{B}^{rt}\mathbf{y}^{ts} + \mathbf{A}^{sr}\mathbf{B}^{rs}\mathbf{y}^{ss}\right]}_{4} \\
&+ \underbrace{\left[(\widehat{\mathbf{m}^s}\mathbf{L}^{ss})^T \# (\mathbf{A}^{sr}\mathbf{B}^{rs}\sum_{t\neq s}^{G}\mathbf{y}^{st}) + \left(\widehat{\mathbf{m}^s}\mathbf{L}^{ss}\sum_{t\neq s}^{G}\mathbf{A}^{st}\mathbf{B}^{ts}\right)^T \# (\mathbf{A}^{sr}\mathbf{x}^{r})\right]}_{5} \qquad (5) \\
&+ \underbrace{(\widehat{\mathbf{m}^r}\mathbf{B}^{rs})^T \# \mathbf{y}^{sr} + \left(\sum_{t\neq s,r}^{G}\widehat{\mathbf{m}^t}\mathbf{B}^{ts}\right)^T \# \mathbf{y}^{sr}}_{6} \\
&+ \underbrace{\left[(\widehat{\mathbf{m}^r}\mathbf{B}^{rs})^T \# (\mathbf{A}^{sr}\mathbf{L}^{rr}\mathbf{y}^{rr}) + \left(\sum_{t\neq s,r}^{G}\widehat{\mathbf{m}^t}\mathbf{B}^{ts}\right)^T \# (\mathbf{A}^{sr}\mathbf{L}^{rr}\mathbf{y}^{rr})\right]}_{7} \\
&+ \underbrace{\left[(\widehat{\mathbf{m}^r}\mathbf{B}^{rs})^T \# (\mathbf{A}^{sr}\mathbf{L}^{rr}\mathbf{e}^{r*}) + \left(\sum_{t\neq s,r}^{G}\widehat{\mathbf{m}^t}\mathbf{B}^{ts}\right)^T \# (\mathbf{A}^{sr}\mathbf{L}^{rr}\mathbf{e}^{r*})\right]}_{8}
\end{aligned}
$$

Defining "#" as an elementwise matrix multiplication operation, we obtain the total bilateral exports of economy *s* by summing across the *G* economies and *N* sectors, as can be found in Wang and Koopman[92,93]. To clarify the meaning of the eight terms on the right-hand side of the formula, we take metals as an example and provide the following explanations: The first term is the domestic metals of economy *s* embodied in the final product exports of economy *s*. The second term represents the domestic metals of economy *s* embodied in intermediate goods exports to *r*, which are used by *r* to produce final goods that are consumed in *r*. The third term represents the domestic metals embodied in economy *s*' intermediate exports and used by the direct importing economy *r* to produce intermediate products that are exported to a third economy *t* for the production of final consumption goods. The fourth term represents the domestic metals embodied in economy *s*' exports of intermediate goods used by other economies for their production of final goods that are returned to economy *s*. The fifth term represents a double calculation, that is, the double counting of domestic metals owing to the repeated intermediate goods trade necessary to produce final exports for economy *s*. The sixth term captures the foreign metals used in the final exports of economy *s*. The seventh term indicates the foreign metals used by economy *s* to produce intermediate goods exports, which are then used by other economies to produce their domestic final goods. The last term represents the foreign metals embodied in intermediate goods exports and used by economy *r* to produce its intermediate and final goods exports to the world, which are included in the double count of *s'* exports that originate in foreign economies. Because the double calculation part does not belong to any economy, it is disregarded[19]. To trace the total value-added embodied in global renewable power value chains ($\mathbf{VEEVC}^{sr}$), the **m** vector can be replaced with **v** vector, which represents the direct value-added coefficients of all sectors.

To obtain the percentage of an economy's domestic metal costs or economic gains in total metal use or value-added embodied in exports for satisfying foreign renewable power demand, two indicators, DMUR and DVAR, were defined and derived as follows:

$$\mathrm{DMUR}^{s} = \sum_{i=1,2,3} \mathbf{MEEVC}_{i}^{s} \Big/ \sum_{i=1,2,3,6,7} \mathbf{MEEVC}_{i}^{s} \tag{6}$$

$$\mathrm{DVAR}^{s} = \sum_{i=1,2,3} \mathbf{VEEVC}_{i}^{s} \Big/ \sum_{i=1,2,3,6,7} \mathbf{VEEVC}_{i}^{s} \tag{7}$$

where, $\mathbf{MEEVC}_{i}^{s}$ or $\mathbf{VEEVC}_{i}^{s} (i = 1,2,3)$ indicate the domestic parts of total metal use or value-added embodied in exports in equation (5), and $\mathbf{MEEVC}_{i}^{s}$ or $\mathbf{VEEVC}_{i}^{s}$ $(i = 6,7)$ denote the foreign parts.

Structural decomposition analysis

Structural decomposition analysis (SDA) is widely used to explore the driving force behind changes in resource use or emissions embodied in trade, such as materials resources[94], carbon emissions[95] and mercury emissions[96]. According to equations (12) and (13), MEE (metals embodied in exports) and MEI (metals embodied in imports) depend on the direct sectoral metal intensity vector **m**, input matrix **A**, and demand matrix **Y**[91]. We then decompose the input matrix **A** into production technology (**H**) and intermediate product input trade structure (**T**). Similarly, the levels of demand (**y**) and final product trade structure (**D**) are used to reflect the demand matrix **Y**. Because of the form of bilateral trade, we divide the five factors into domestic (r) and foreign (-r). The resulting expression for the SDA is as follows:

$$\mathbf{MEE}^{r} = h^{r}\left(\mathbf{m}^{(\mathrm{r})}, \mathbf{m}^{(-\mathrm{r})}, \mathbf{T}^{(\mathrm{r})}, \mathbf{T}^{(-\mathrm{r})}, \mathbf{H}^{(\mathrm{r})}, \mathbf{H}^{(-\mathrm{r})}, \mathbf{D}^{(\mathrm{r})}, \mathbf{D}^{(-\mathrm{r})}, \mathbf{y}^{(\mathrm{r})}, \mathbf{y}^{(-\mathrm{r})}\right) \quad (8)$$

$$\mathbf{MEI}^{r} = g^{r}\left(\mathbf{m}^{(\mathrm{r})}, \mathbf{m}^{(-\mathrm{r})}, \mathbf{T}^{(\mathrm{r})}, \mathbf{T}^{(-\mathrm{r})}, \mathbf{H}^{(\mathrm{r})}, \mathbf{H}^{(-\mathrm{r})}, \mathbf{D}^{(\mathrm{r})}, \mathbf{D}^{(-\mathrm{r})}, \mathbf{y}^{(\mathrm{r})}, \mathbf{y}^{(-\mathrm{r})}\right) \quad (9)$$

The first polar is calculated by changing each variable in turn; for example, first changing the first variable, then the second variable, followed by changing the third variable, etc. The second polar is calculated in opposite; we change the last variable first, then the last variable, etc. The changes in MEE and MEI between year t-1 and t are decomposed by h_{polar1}^{r} and h_{polar2}^{r}, or g_{polar1}^{r} and g_{polar2}^{r}, and the geometric average is determined.

$$\Delta\mathbf{MEE}_{t-1,t}^{r} = \frac{\mathbf{MEE}_{t}^{r}}{\mathbf{MEE}_{t-1}^{r}} = \sqrt{\mathrm{h}_{polar1}^{r} \times \mathrm{h}_{polar2}^{r}} \quad (10)$$

$$\Delta\mathbf{MEI}_{t-1,t}^{r} = \frac{\mathbf{MEI}_{t}^{r}}{\mathbf{MEI}_{t-1}^{r}} = \sqrt{\mathrm{g}_{polar1}^{r} \times \mathrm{g}_{polar2}^{r}} \quad (11)$$

The decomposition of the MEE and MEI changes over a period of years was calculated by multiplying the number of consecutive years. The total change in years 0 to t can be expressed as:

$$\Delta\mathbf{MEE}_{0-t}^{r} = \frac{\mathbf{MEE}_{t}^{r}}{\mathbf{MEE}_{0}^{r}} = \frac{\mathbf{MEE}_{1}^{r}}{\mathbf{MEE}_{0}^{r}} \times \frac{\mathbf{MEE}_{2}^{r}}{\mathbf{MEE}_{1}^{r}} \times \cdots \times \frac{\mathbf{MEE}_{t}^{r}}{\mathbf{MEE}_{t-1}^{r}}$$

$$= \Delta\mathbf{MEE}_{0,t}^{r} \times \Delta\mathbf{MEE}_{1,2}^{r} \times \cdots \times \Delta\mathbf{MEE}_{t-1,t}^{r} \quad (12)$$

$$\Delta\mathbf{MEI}_{0-t}^{r} = \frac{\mathbf{MEI}_{t}^{r}}{\mathbf{MEI}_{0}^{r}} = \frac{\mathbf{MEI}_{1}^{r}}{\mathbf{MEI}_{0}^{r}} \times \frac{\mathbf{MEI}_{2}^{r}}{\mathbf{MEI}_{1}^{r}} \times \cdots \times \frac{\mathbf{MEI}_{t}^{r}}{\mathbf{MEI}_{t-1}^{r}}$$

$$= \Delta\mathbf{MEI}_{0,t}^{r} \times \Delta\mathbf{MEI}_{1,2}^{r} \times \cdots \times \Delta\mathbf{MEI}_{t-1,t}^{r} \quad (13)$$

Data sources

There are currently several widely used global multi-regional input-output tables, including EXIOBASE, the World Input-Output Database (WIOD), the Global Trade Analysis Project (GTAP), and Eora, which differ in sectoral and regional resolution[97-100]. We chose the time series EXIOBASE mainly because of its high sectoral resolution (163 sectors), including seven renewable power sectors, such as wind power and solar PV[101]. The table covers 44 economies, including 31 European Union member economies and 13 other major ones. The remaining uncovered parts of the world were divided into 5 regions. The currency flows in the multi-regional input-output table are expressed in million EUR. The high-resolution EXIOBASE describes complicated global sectoral linkages between each renewable power sector and all other sectors, allowing us to track direct and indirect metal use or value added along the global RPVCs. Moreover, EXIOBASE facilitates a detailed account of the metal use or value-added of different production stages along RPVCs, thereby revealing the relationships between metal costs and the economic gains of each economy. EXIOBASE is a popular database for revealing the material and other impacts (e.g., emissions) embedded in the global trade of renewable power sectors[35,102,103].

A set of environmental satellite accounts were provided by each sector-region combination and year, which contained metal ores. The selected metals were grouped into four categories, as suggested in the reports of the United Nations Environment Programme (UNEP) and Word Bank[46,47], including bulk metal ores, precious metal ores, scarce metal ores, and others. Bulk metal ores include bauxite, copper, iron, lead, and zinc ores; precious metal ores include silver and platinum-group metal ores; scarce metal ores include nickel and tin ores; and others include other non-ferrous metal ores. To capture the latest evolution in metals embodied in trade, we use data spanning 2005, 2010, and 2015; all values in 2010 and 2015 were adjusted to the 2005 constant prices. Furthermore, higher levels of disaggregation of metal types and corresponding sectors in EXIOBASE are urgently required, which is crucial for comprehensively understanding how renewable power value chains affect diversified metal consumption worldwide.

Results

The MFs of global and regional renewable power sectors

The evolutionary trends in the MFs of the global renewable power sectors are shown in **Fig.1**. Along with the rapid expansion of renewable power infrastructure across the world, the MFs of the global renewable power sectors increased by 50% (347 kt) from 2005 to 2015. Comparatively, the renewable power installed capacity is growing faster, which increased by 125% (1101 GW) during 10 years. Both MFs and installed capacity in wind power and solar PV sectors had the largest increase rate (6-46 times of installed capacity and 2-5 times of MFs for renewable power). All the results show that the installed capacity and electricity generation is growing much faster than MFs of the renewable power sectors, which is mainly due to the technical improvement and material substitution. Technical improvement such as size enlargement, optimization or upgrading of steel are crucial contributors. For instance, wind power technology has witnessed remarkable improvement towards larger turbines, with the global average turbine capacity shifting from 1 MW in 2000 to 2.6 MW in 2018 and metal intensity reduced by approximate 10%[33]. Besides, the materials substitution technology is useful to mitigate the metal footprint. For instance, compared to steel towers, a concrete-steel hybrid modular tower of wind turbine could reduce 16% of the steel demand, which is increasing the market share particular in China[34].

Significant discrepancies exist in the MFs of different economies due to their vast differences in the scale of their renewable power industries and in their metal use efficiency. For example, China is the global leader for renewable power with 67.7 GW of newly-added installed capacity (43% of the global total, 1381TWh, account for 21% of the global electricity generation), accounted for 19.6% of the total MFs of global renewable power sectors. In comparison, the United States, the second-largest economy added 17.3 GW of renewable power capacity in 2015 (11% of the global total, 568TWh, account for 8.7% of the global electricity generation), accounted for only 1.2% of global renewable power sectors' MFs. One complicating factor is that the intensity of metal use in the renewable sector of the United States is one-third that of China. In addition, less developed economies, such as Latin America, Other Asia, Africa, and the Middle East held half (35%) of the global MFs of renewable power sectors with only 10% of the global renewable power installations in 2015. It is mainly due to the high metal use intensity for renewable power generation in these less developed economies. For example, the metal use intensity in European is about two thirds that of the Latin America value.

There are also striking differences in the types of metals consumed by the various renewable power sectors. **Fig. 1** shows that there are huge differences across countries regarding the composition of metals contributing to the total MFs for each renewable power sector. For example, for wind power, China uses more than 50% iron ore inputs, whereas copper dominates in Poland and the United Kingdom. One of the important causes is that the materials preference differs between countries due to the material availability, cost, and other factors. In the Chinese tower market, the ratio of steel tower and mixed tower is approximate 7:1. On the contrary, because of the high price of steel, the mixed tower is preferred in Europe. In addition, if the metals needed for renewable power depend on foreign imports, the composition of MFs may also differ which is related to the metal intensity of the importing country. Moreover, the MFs varies greatly for different renewable power sectors. Iron and copper were found to be the dominant metals in the production of global renewable power, accounting for 42% and 31% of the total MFs of the global renewable power sector, respectively. Followed by bauxite and other non-ferrous (accounting for 6.1% and 5.5%). Rare earth footprint accounts for less than 0.1%.

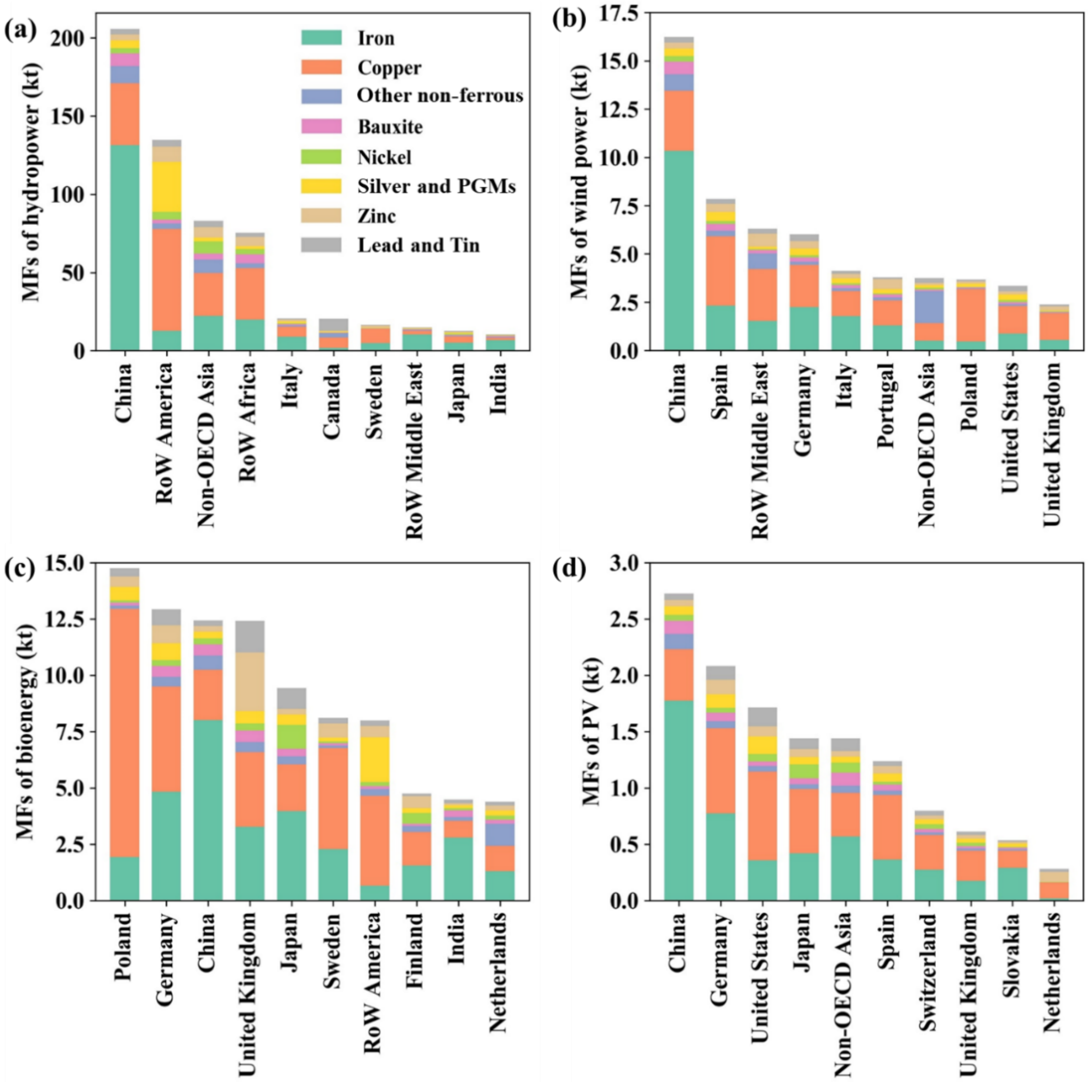


Fig. 1 Metal footprints of the renewable power sectors by metal types in 2015.
(a) top ten economies in hydropower sector's MFs, **(b)** top ten economies in wind power sector's MFs, **(c)** top ten economies in bioenergy sector's MFs, **(d)** top ten economies in solar PV sector's MFs. We focus specifically on these 4 main renewable power sectors, given that their MFs are more than 90% of the total. Moreover, the metal footprint of top ten economies together accounts for more than two thirds of the global footprint in each of the four renewable power sectors, which are representative for the results analysis.

Outsourced MFs in RPVCs

Outsourcing of metals indicates that a country increases metal ore extraction outside its borders for domestic consumption of renewables power technologies.

During 2005-2015, the outsourced metals increased by 38% or 175.51 kt, mainly driven by developed economies (**Fig. 2**). In RPCVs, developed economies outsourced large and growing amounts of metal consumption for renewable power sectors to less developed economies, which leads to an increase in metal mining and production in less developed economies[35]. Here, we aggregated the results to 10 regions (i.e. Europe, Africa, the Middle East, North America, Latin America, Other Asia, China, India, Russia, Australia) to clarify the outsourced MFs flow patterns.

Europe maintained the largest importer of metals with over 51% of global total import volume during the period concerned (**Fig. 2a and 2b)**. One reason is that the majority of European countries depend chiefly on metal and mineral products imports from other continents with a small fraction of domestic supply. For example, Europe mines only 1.7% of the world's iron, 1.9% of its gold and 2.8% of its nickel. Meanwhile, according to Eurostat, the European Union imported 8 billion euros worth of solar panel products in 2020, 75% of which came from China. Thus, Europe's renewable power industry is heavily dependent on international markets to secure the raw materials it requires, with 85% of its iron ore, and 77% of its raw materials imported from outside. In 2015, Europe imported 267 kt, mostly from Latin America (37 kt), Other Asia (35.1 kt), and China (30 kt). It is noteworthy that China became the second largest importer quickly (49.5 kt in 2005 and 140 kt in 2015), the imported metals were mainly from Australia (40.9 kt), Latin America (32.9 kt), and Other Asia (33 kt). Comparatively, the United States was increasingly relying on metals abroad, with the ratios of embodied metals imports to its MFs increasing from 88% in 2005 to 98% in 2015 (**Fig. S3)**, although it has rich indigenous mineral resources. The reason is that the United States shifted its manufacturing base overseas to seek greater economic and environmental benefits from trade and the integration of supply chains. The United States imported 8.5 kt and 18.7 kt of metals from Latin America in 2005 and 2015. Unlike the developed economy, over 62% of metal consumed by China's renewable power sectors was satisfied by domestic supplies, China still relied on some metals (e.g., nickel) from outside sources. It can be explained by the scarce domestic metal reserves and supply, for instance, according to the China Geological Survey report, the external dependence of nickel is more than 70%.

From the export perspective, more than half of the metal ores or primary processed metals embodied in trade originated from less developed economies, such as those in Latin America, Africa, and the Other Asia (**Fig. 2a and 2b**). The embodied metal exports from these regions accounted for 39%-44% of global exports in the renewable power sector from 2005 to 2015. Latin America was the largest exporter of primary products among the three. Latin America exported large amounts of metals, accounting for 16%-21% of the traded metals during 2005-2015. What's more, Russia and Australia (14% of the total metal transfer in 2015) are also important metal exporters in supporting global renewable power development. The outsourcing pattern of metals reflects a large number of metal leakages, for metal almost flows from areas with high metal intensity to regions with low intensity.

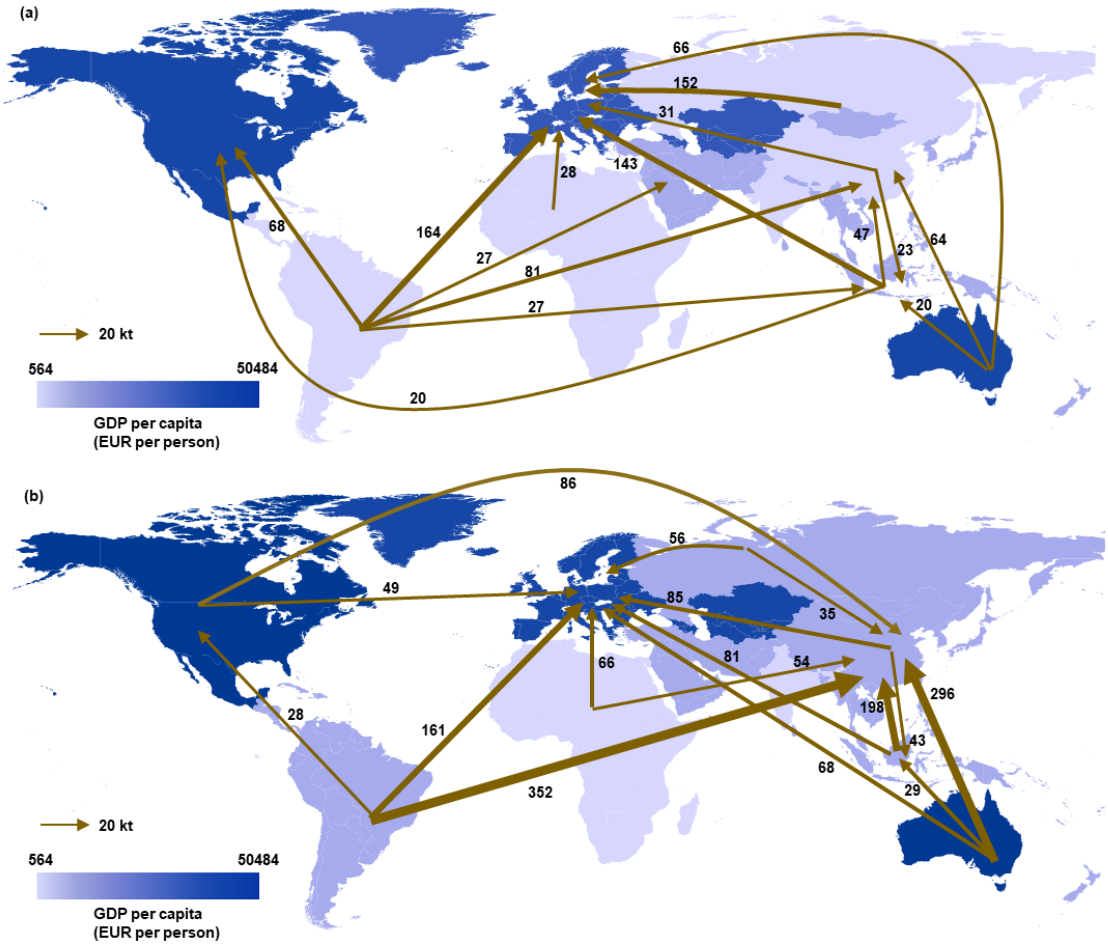
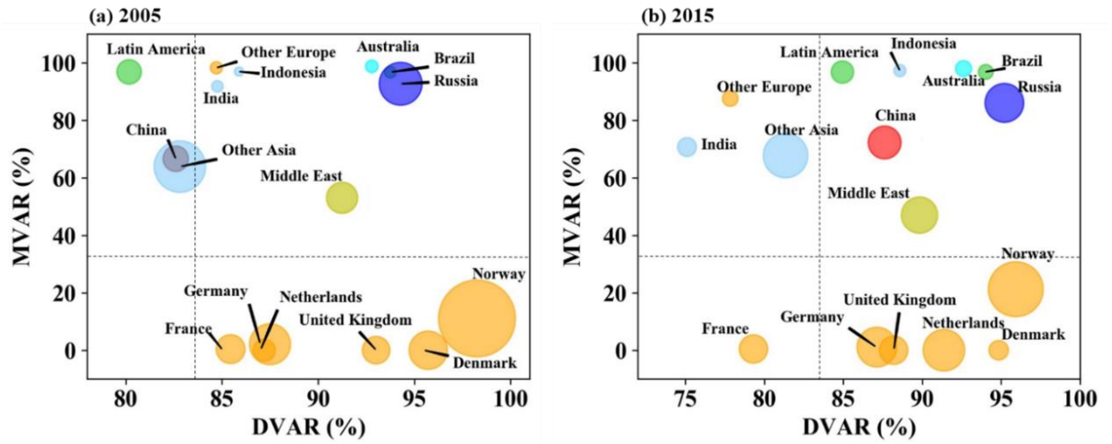


Figure 2 Major international flows of metals (>20 kt) embodied in renewable power value chains (RPVCs) among ten groups of economies. (a) 2005, (b) 2015, the

economies are shaded according to value of Gross Domestic Product (GDP) per capita. The arrows indicate the direction and magnitude of foreign metal ores embodied in renewable power consumed by destination economy. Nearly 80% of global total flows are shown.

The positions of economies in the RPVCs

Each economy participates in the RPVCs at different production stages and generates distinct economic gains with varied metal costs. To assess the difference between the metal costs and the gains of each economy and demonstrate their position in the RPVCs (**Fig.3**), we apply two indicators, the share of territorial economic gains in an economy's total gains induced by renewable power exports (DVAR) and the share of domestic metal extraction in an economy's total metal exports induced by renewable power export (MVAR). DVAR and MVAR are affected by both domestic and foreign sectoral metal intensity, direct value-added coefficient, export structure and so on. The absolute share of domestic value added in each economy (size of the bubble in **Fig. 3**) is determined by DVAR and gross renewable power exports of each economy, indicating the true economic benefits in the RPVCs.



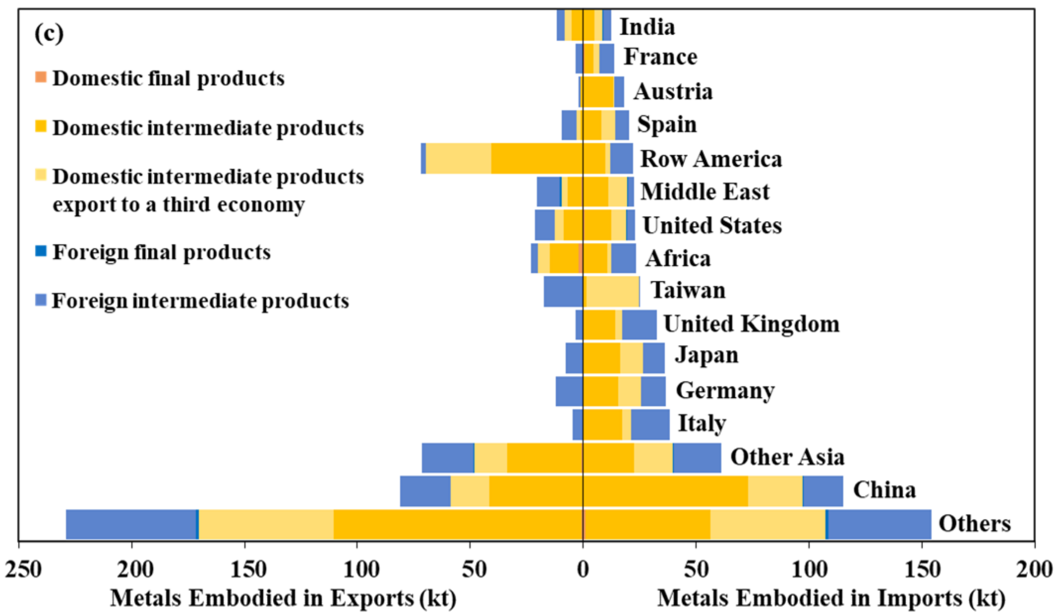


Fig. 3 Shares of domestic metal extractions in total exports induced by renewable power (MVAR), domestic value-added in total economic gains from renewable power exports (DVAR), and the decomposition of metals embodied in RPVCs for economies. MVAR and DVAR for different economies in 2005 **(a)** and 2015 **(b)**. The colors of the bubble represent distinct regions. The horizontal and vertical lines indicate the global average MVAR and DVAR, respectively. The economies with less than 1% of the global total value-added are not shown. **(c)** the metals embodied in exports and imports for economies in 2015, in an order of metals embodied in imports for the top 15 economies. The remaining economies belong to Others, which share for less than 24.5% of global metals embodied in import.

Generally, developed economies occupied high-end segments in the RPVC. Developed economies, such as European countries (at the bottom of **Fig. 3a and 3b**), who exported high-tech and high value-added intermediate products, consumed the least territorial metals (**Fig. 3c**). The reason is that developed economies tend to have high-tech sectors and add a large amount of value through high-end manufacturing or in design stages that consume low levels of metal. As shown in **Fig. 3a and 3b,** Norway, Germany, and the Netherlands contributed a large share (DVAR more than 85% in 2015) of its value-added while consuming far below average (the horizontal dotted line) of the metal extracted locally. With low domestic metal consumption–high value-added, these countries occupy the top location in the RPVC. In comparison, the less developed economies tended to export low-end, low value-added products, such as ore and steel plates. The less developed economies (i.e., Latin America, Other Asia) contributed a large portion (MVAR about 70% in 2015, **Fig. 3b**) of the metals mined domestically (**Fig. 3c**), but got the least value-added (2%-7% economic gains of the world's total, the size of bubble) in the renewable power sectors. Because they have the lowest production costs and the loosest environmental regulations in the world, less developed economies have become the destination for manufacturing processes outsourced from developed economies [35]. It is interesting to see that, China, as the world top renewable power installer, holds the value added share of 0.87% in global, similar to France (0.79%), mainly due to the similar scale of renewable power export and the position in production stages, i.e. exporting intermediate products for processing and consumed by trade partners.

During 2005-2015, the positions of major developed or developing economies within global RPVCs were likely to sustain, with an increasing gap of metal costs and economic gains between developed and developing economies. Developed economies participate upstream (design) and downstream (service) industries and gain more value-added with much less domestic metal consumption. Taking Germany as an example, the value-added increased by 140 million EUR (5.8% of the global total increase) during the period concerned, with the metal embodied in Germany's exports increasing by only 4.6 kt (2.2% of the global total increase). Conversely, the less developed economies participate industries in the middle of the global RPVCs have a higher increase rate of domestic metal products export than that of value-added gains. For example, the metal embodied in Latin America's export increased by 14.6 t (3% of the global total increase, **Fig. 3a and 3b**), with a slight increase in value-added (1.5% of the global total increase). Differently, China moved up towards upstream position within the global RPVCs, by shifting exports of primary products in the metal extraction stage to manufactured products in the intermediate stage (**Fig. 3c**). To be specific, the share of the intermediate goods export in total export of China increased by 5.6%, from 66% to 72% between 2005 and 2015. The Chinese export-related gains share in global value-added increased by 2%, with its proportion in the domestic metals embodied in exports remaining unchanged.

The growing MFs inequality and its driving forces

The metal footprints (MFs) inequality rises with developed economies' continuous outsourcing of metals demand for renewable power sector to less developed economies, which can be observed in three aspects. First, the MFs of renewable power per capita in developed European economies were higher than less developed economies generally. For instance, the MFs in Sweden were ~20 times of that in African economies in 2005 and grew to 31 times in 2015. Second, the gap between metals embodied in export (MEE) and in import (MEI) along global renewable power value chain continued to expand for economies. The net export (MEE minus MEI) in less developed economies increased by as high as 300% during 2005-2015. Third, the inequality grown from the perspective of territorial metal consumption for per unit of export-induced value-added along RPVCs. The value of less developed economies (e.g. Africa) was as high as 3 times of that in developed economies (e.g. Europe) in 2005, which increased to 4.5 times in 2015.

We examined the driving forces of the metals embodied in trade to uncover the drivers of growing MFs inequality along the global RPVCs, see **Fig. 4**. The final demand was the major force of the inequality growth. Motivated by the renewable power ambition, the domestic final demands (Q) boosted the MEI growth by 113%~438% in developed economies such as the United States and European economies in 2005-2015. Meanwhile, half of the final demands (Q) from developed economies (e.g., USA and European economies) induced a massive growth (178%~211%) of MEE for the less developed economies, such as those in Latin American, Africa, and Other Asia. Comparatively, the changes in production technology (H) and trade structure (T, D) contributed to a moderate growth of metal inequality (see **Fig. S10** for further explanation). Production technology (H) shifts caused the MEI increase in developed economies (except USA, Spain) by a wide range of 10%~210%, and MEE growth in less developed economies by 1%~12%.

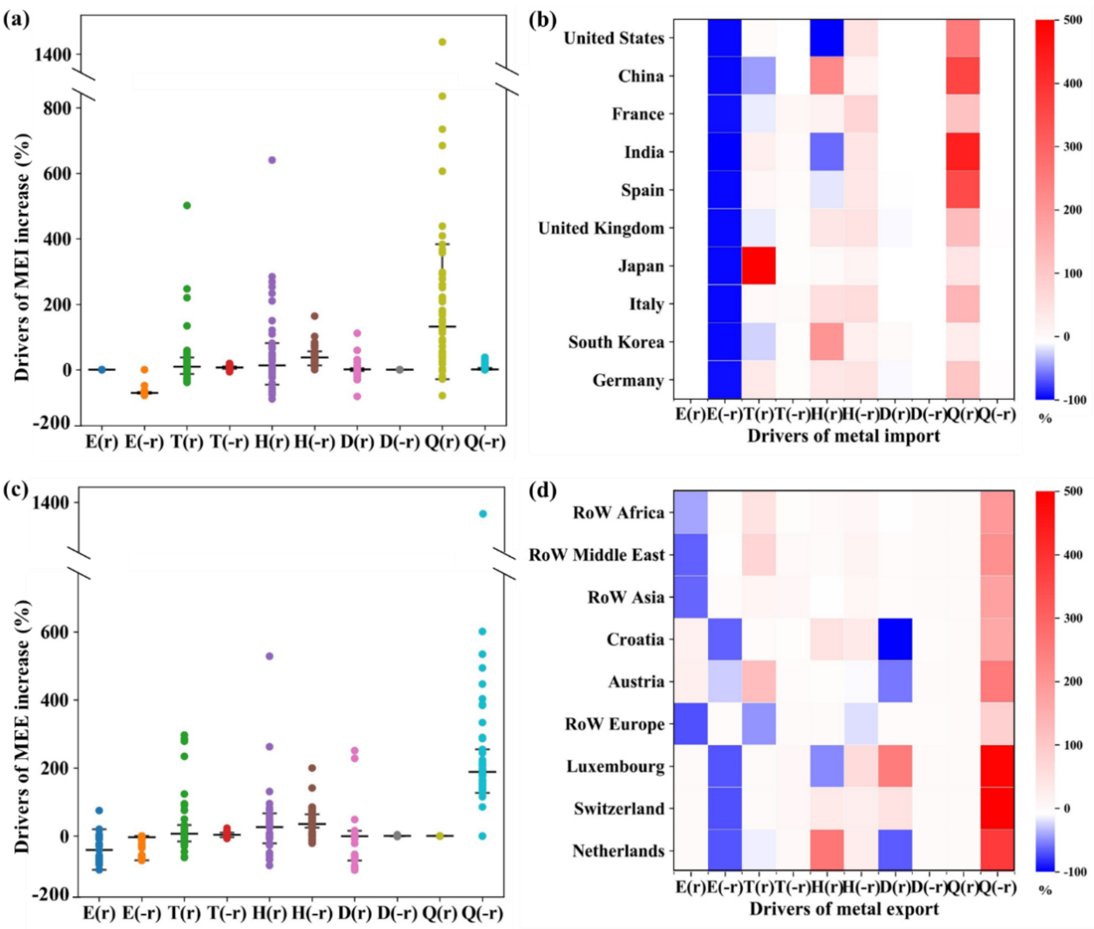


Fig. 4 Drivers of the changes in metal embodied in export and import for global average (left) and major economies (right) during 2005-2015.

a and c the average contribution of driving forces to the metal embodied in import (MEI) and export (MEE) at global level. **b and d** the contribution of each factor to the MEI of top nine importers and MEE of top nine exporters. The performance of each driver for remaining economies are shown in Fig.S10. E represents the metal intensity vector, T indicates intermediate product inputs trade structure, H indicates production technology, D indicates final product trade structure and Q indicates final demand. E(r) indicates the domestic metal intensity and E(-r) indicates the abroad metal intensity.

On the contrary, the declining metal intensity (E) was a major force to dampen the metal inequality. The intensity declines in less developed economies offset the MEI growth of developed economies by 71%~74%, and MEE growth of less developed economies by 41%~64% under the rapid technology progress, higher than the global average, 36%. The metal intensity reduction mainly occurred in the upstream metal mining and production sectors, such as mining of iron ores, copper ores as well as precious metal ores, with the decrease rate of 27%~100% in countries of Latin American, Africa, and Other Asia from 2005 to 2015. Notably, the metal inequality growth driven by the vigorous final demands and other drivers could not be offset by the reduction from efficiency gains, indicating the growing imbalanced metal effects among economies to support the global renewable power market.

Discussions

We investigate, for the first time, the metal footprints (MFs) and value-added of global and major economies' renewable power sectors to understand who supplies metal products for whose renewable power generation. We reveal the imbalances in global RPVCs in which less developed economies supported the renewable power generation of developed economies by mining and processing metal products with low economic value. In addition, the results provide valuable information for the reasonable and scientific management of metal resources and RPVCs.

The growing MFs inequality along global RPVCs may hinder the just net-zero transition and climate goals achievement. Our results show that the fast clean and low-carbon power transition in developed economies is built on the ever-growing imports of metal-intensive but low value-added products from less developed economies. A recent study reports that the future renewable energy will lead to $PM_{2.5}$ emissions from metal production regionally concentrated in regions such as India and China. Similarly, the displacement of metal mining and production also leads to greenhouse gas (GHG) emissions shift to less developed countries. For instance, Democratic Republic of Congo produces ~0.4Mt copper for global clean energy technologies, which generates ~1Mt CO_2 emissions, equivalent to 40% of national total anthropogenic emission in 2020[36,37,38,39]. Our research and previous literature both pointed that these less developed economies tend to rely on carbon-intensive metal extraction and mining production technologies under weak environmental regulations and limited climate finance. An example is that the CO_2 emission intensity of solar PV manufacturing in South Africa (400 $kgCO_2/kW$) is nearly three times of that in Germany (150 $kgCO_2/kW$). **If no further actions taken, more carbon emissions may be shifted to the primary metal suppliers, thus, impeding the just and timely net-zero transition.** In this regard, it is crucial to trace the supply-chain environmental performance in the RPVCs and incorporate the environmental standards into trade policy to promote carbon-efficient production in less developed economies[30]. The developed economies could share the responsibility of carbon emission reduction in the minerals filed through diverse means, such as low-carbon technology transfer, international climate financial aids expansion, and market-based mechanisms cooperation (e.g. Clean Development Mechanism) to stimulate the just net-zero transition[40].

Furthermore, the just net-zero transition and climate goals may be also challenged by the potential metal supply risk. Existing evidence shows that the global metal demand driven by the ambitious renewable power expansion could not be achieved without significant production increase, such as a two-fold increase of nickel from 2010s to 2040[10,30]. From a distinct view, our results potentially indicated that many other issues such as trade conflicts or geopolitical tensions affects the metal prices and further metal supply resilience through the complicated RPVCs. As the fierce competition aggravates the metal scarcity, the net-zero transitions of developing economies, such as China, India, Africa and the Middle East, would be more uncertain, due to metal affordability and availability issues.

The economic benefits and metal costs of joining global RPVCs are extremely imbalanced. Our results highlight an imbalance in the economic benefits and metal product supply in global RPVCs. The acquisition of clean energy and economic benefits in developed economies usually occurs at the expense of the environment and metal resource reserves in less developed economies. For example, in 2015, the United States imported 98% (21.54 kt) of its renewable power components, which led to a flow of 5.78 kt of metals from Latin America to the United States. Given that the global power system will transition quickly from fossil fuel-based generation to renewable resource-based generation, this imbalance may have some key implications for both energy and metal systems. For example, as metal production involves high levels of pollution and environmental emissions, large-scale development of renewable energy systems will cause serious environmental problems in the upstream of the industrial chain, potentially leading to overall detrimental effects globally.

To alleviate this imbalance in global RPVCs and its significant impact on the metal supply, strategies aimed at increasing the sustainability of the supply chain in both the production and consumption sides should be implemented in parallel. First, technological progress on the production side can improve the efficiency of metal production, reduce its environmental impact, and mitigate the metal inequality among economies[41]. For further metal efficiency improvement, technology innovation for reducing metal intensity and encouraging material substitution in renewable power will play major roles. Developed economies, such as USA and EU have introduced critical material strategies to support R&D on material efficiency[30]. Considering the mismatch between technology innovation and implementation, technology transfer to accelerate the penetration of metal efficient technologies in less developed countries are needed[42].

In addition to traditional measures, financial tools[43] such as new taxes[44] and MFs label certificates[9] meant to make transparent the true cost of embodied metal products could be adopted for metal mining and producing economies (e.g., South Africa, Congo, China, and Chile). That is, the environmental costs and health costs of the water, atmosphere, and soil pollution and climate change caused by the extraction, smelting, and transportation of metal should be taken into account in the prices of metal products. Tax measures would increase the monetary cost of the product and would be shared by economies throughout the supply chain. On the one hand, market behavior can directly encourage producers to reduce production costs[31]; on the other hand, the final consumption side (the European and American renewable power sectors) can be guided toward metal products with lower environmental costs. Moreover, market selection can help to reduce or even phase out metal products with high production costs or that are nonenvironmentally friendly.

Notably, there has been some initial activity toward sustainable supply chain management using market tools. For example, the United States and European trade policies emphasize that companies that export photovoltaic modules need to issue supply chain traceability certificates[45,46]. In China, a supply chain traceability system for important products is also considered an effective measure for supervising the supply chain[47]. In 2019, Changzhou Customs of China applied for 7 certificates of origin for solar modules that it exported to Chile, which facilitated $4 million in solar PV sales[48]. Under a bilateral agreement, these goods are expected to enjoy more than $200,000 in tariff concessions at customs in the importing country[49]. In the future, it is possible that an increasing number of costs and taxes[50] could be incorporated into trade policies based on the consumption of specific metals in the upstream supply chain to help sustainably manage the renewable power supply chain.

Changes in the pattern of metal demand may bring new risks to the supply of renewable power, adding uncertainties of energy security. The production of coal, oil, and natural gas needed for traditional power generation is mainly concentrated in the Middle East and the United States[51,52]. Our results show that the metals needed for renewable power are mainly extracted in Latin American, Africa, and Other Asia. The dependence of renewable power development on raw materials from these regions has reshaped the pattern of resource demand in the global power sector.

These changes may create new risks of metal supply in renewable power development, as indicated in existing studies. For example, as shown in **Fig. 3b**, nearly 50% of the metals used in renewable power come from Latin America, Africa, and the other Asia. However, some of these major metal suppliers are faced with uncertain supply policies and geopolitical tensions situations, which may disrupt the metal supply chain, thereby affecting the stability and resilience of the renewable power market. In 2018, The DRC's president signed a new mining law that increased the mining tax on copper from 2% to 10%, leading to the suspension of operations at Mutanda, the country's largest copper mine[53]. Price volatility followed and led to a 20% drop in worldwide copper and cobalt production[54]. Another example is that, the base metal price, such as Nickel and aluminum, continued to rise in 2022 because of supply chain disruptions, in part due to Russia's invasion of Ukraine. As a result, the decline in costs of renewable technologies due to technological innovation and economies of scale largely reversed. For example, prices for wind turbines and solar photovoltaic modules rose 9% and 16%, respectively. Thus, in turn, the renewable power development in those economies under rapid expansion, such as United States, are threatened. Thus, import-dependent economies need to reduce their dependence on external suppliers and diversify their metal supply to improve the metal supply self-reliance. The United States government has set a good example. In 2010, the United States government formed an interdepartmental working group on strategic mineral supplies for critical metals to improve policies, plans, and procedures for addressing supply chain risks related to metal minerals used for renewable power generation, with the goal of diversifying their supply and reducing their heavy reliance on a single economy for metal components used in renewable power generation[55].

In addition, our result indicated that the trade structure could be modified to mitigate the metal supply risk and consumption inequality along RPVCs among economies. The import-dependent developed economies can adjust the distribution of traded goods towards metal-efficient sources. For both producers and consumers, the trade policies can incorporate resource (e.g. metal) efficiency standards to select export/import sources rather than simply transferring metal consumption to downstream countries[56]. An example is that, China issued guidelines for high-quality trade in 2021 with strict control on the carbon- or energy-intensive products export[57]. Besides, it is vital to establish a high-level joint governance framework for standardizing metal efficiency performance to promote metal efficiency of whole supply-chain to ensure reliable metal supply in RPVCs.

In the future, developing countries may be confronted with the challenge of meeting the metal demand for renewable power technologies. Global economies are deploying renewable power with great ambition. According to the IEA, the demand for metal minerals for clean power technologies is projected to quadruple by 2040 under sustainable development[30], and 60% of the growth is expected to be driven by developing economies (China, India, Brazil, etc.)[1,58]. However, our results show that less developed economies were more inefficient in the utilization of metal resources than developed economies. Therefore, improving the efficiency of metal utilization by reducing metal loss in primary production and throughout the whole life cycle is crucial for less developed economies. **Previous studies** have found that less developed economies could save 1,041 tons of rare earth metals by 2050 if they increased the efficiency of their metal use in the renewable power sector to its potential level as determined by the average efficiency level under a net zero emissions scenario[59].

In the long term, effective recycling and reuse can significantly reduce the explosive demand for materials and its environmental consequences in less developed economies. Currently, there are two approaches to recycling, namely, end-of-life (EOL) recycling and co-metals. EOL recycling is the most common method at present. 90% of the base metal materials in the renewable power sector can be recycled through decommission, such as by dismantling and disposing of turbine steel, copper, aluminum, and other metals[60,61]. However, the recycling rate is still subject to many factors, such as the depreciation rate of renewable power infrastructure, and recycling techniques[10]. For instance, a wind turbine has a lifespan of 20 years[62], indicating that recently installed wind turbines cannot be potentially direct recycled until 2040. In addition, recycling during mining and refinery is also considered as a promising measure to alleviate metal shortage. Scientific evidence has shown that waste tailings may become increasingly important in the future[63]. For example, more than 10 kt of gallium is expected to be recycled from bauxite ore, and more than 15 kt of indium is available from indium tailings annually[64,65]. However, these techniques are still faced with pronounced challenges, such as the high cost of tailings and waste collection, metal loss during the remitting process[66,67]. It suggests that encouraging a centralized collection of tailings would be one of the most efficient ways to mitigate the waste of metal resources in the production process, in addition to improving recycling techniques[68].

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