Carbon-economic inequality in global ICT trade

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Highlights
Carbon losses and economic gains of ICT trade are unevenly distributed among regions

Emerging regions bear 82% of emissions while developed regions gain 58% of value-added
Carbon-economic inequality arises from fragmented international ICT production
Closing national carbon efficiency and export structure gaps drive global CEI decrease
Carbon-economic inequality in global ICT trade

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SUMMARY

The expansion of information and communications technology (ICT) trade has contributed to rising trade imbalances and international tensions. A detailed assessment of the potential carbon and economic impacts of ICT trade is pertinent. We assess to what extent and how the carbon costs and economic benefits embodied in ICT trade were unevenly distributed among global regions in the period 2000–2018 using multiregional input-output models. We show that in 2018, emerging economies received 82% of the CO2 emissions while developed economies gained 42% of the value-added in ICT exports. This carbon-economic inequality (CEI) decreased (i.e., improved) by 16% from 2000 to 2018, arising from global production fragmentation, with developed economies retaining downstream high value-added ICT marketing but outsourcing upper- and middle-stream carbon-intensive material extraction and manufacturing to emerging economies. This study provides insights for enhancing negotiations and cooperation among global regions to light a path toward sustainable ICT trade.

INTRODUCTION

Information and communication technology (ICT) lays the vital infrastructure for today’s digital and interconnected world. From the ubiquitous sensors in smart devices and the rise of 5G and satellite networks to the booming video meetings and education during the COVID-19 pandemic, the rapid development of ICT has been delivering a variety of economic, societal, and environmental benefits. Among them are improved industrial productivity, global connectivity, and environmental management capability.1 Because of this, the 2030 Agenda for Sustainable Development, which calls for cross-national common actions to combat poverty, inequality, and climate change, has identified ICT as a catalyst to resolve global sustainability challenges.1 However, a good wish does not promise a smooth ride into the future. One potential obstacle is the huge disparities in national access and use of ICT. In 2021, 90% of individuals in developed regions used the Internet, but the proportion was only 27% in developing regions.1 This inequality between people and regions, also known as the “digital divide”, can undermine the role of ICT in realizing global sustainable development goals. Addressing ICT-related inequality is urgent, considering recent increased attention to the relationship between digital transformation and sustainable development.6–8

ICT goods and services are produced and distributed through a globally dispersed and complex network that includes licensing of patents, contract manufacturing, end-product assembly, and extensive intermediate goods trade. For example, 5G chips designed in the United States and manufactured in Taiwan and South Korea are exported to Chinese manufacturers that use the chips for the baseband of smartphones destined for the European markets. Production globalization enables countries to benefit economically by leveraging their comparative advantages in producing and trading ICT in international markets. Following the adoption of the Information Technology Agreement in 1997, the volume of global ICT trade has expanded rapidly and in 2018 exceeded 2,000 billion US dollars (USD bn) or 13% of the total international trade in the year.7 However, with trade imbalances between regions, the gains from international ICT trade were not evenly distributed to trading countries.8–10 For example, ICT/electronics goods accounted for 32% of the US trade deficit (111 USD bn) with China (mainland) in 2019.11 This large imbalance has enflamed the trade conflict between China and the United States and aggravated controversies about the inequality in global ICT trade.

Many studies have shown that international trade could reallocate economic, social, and environmental impacts among trading countries or regions. The impacts include those related to value-added, employment, greenhouse gas emissions, air pollution, and health burdens.12–15 When production is fragmented across national borders, trade-related outcomes can be transferred and displaced along global supply

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chains. However, limited existing research has examined the uneven distribution of carbon costs and economic benefits arising from trade within regions. In particular, ICT trade stands at the center of current high-tech trade friction and has drawn rare attention when modeling the interaction between international trade and climate change. Therefore, a detailed assessment of the carbon-economic inequality (CEI) in ICT trade between countries and regions is required to address the rising bilateral trade disputes and tensions surrounding current global ICT trade.

This study aims to assess to what extent and how both the carbon costs and economic benefits arising from ICT trade are unevenly distributed among the world’s major economies or regions. It helps to advance the understanding of the status, sources, and drivers of the inequality in ICT trade and provides information for international negotiation strategies regarding trade and climate change. We first estimate the domestic CO₂ emissions and value-added embodied in the ICT exports of the world’s 44 major regions between 2000 and 2018 using multiregional input-output (MRIO) analysis. We then trace how the ICT trade-related emissions and value-added are unevenly transferred along the global production chain using structural path analysis (SPA). Based on these results, CEI indices are proposed to quantify the extent to which carbon and economic impacts are mismatched in global, regional, and bilateral ICT trade. Thus, quantitative information can be presented to policymakers to timely incorporate measures to reduce ICT trade barriers and imbalances between different countries. Finally, we identify the major socio-economic factors driving the CEI changes using structural decomposition analysis (SDA).

The results reveal that ICT trade has resulted in significantly uneven distributions of carbon costs and economic benefits among global regions. Unevenly higher shares of CO₂ emissions were generated in emerging regions while the bulk of value-added was enjoyed by developed regions. International production fragmentation allows developed regions to retain downstream high value-added ICT marketing activities and to outsource upper- and middle-stream carbon-intensive raw materials extraction and intermediate inputs manufacturing to emerging regions. The global CEI declined by 16% from 2000 to 2018, contributed mainly by the reductions (by up to 80% and down to 19%) in mutual CEIs between major emerging economies (i.e., China, India, and Russia) and developed economies (i.e., the USA, the EU-28, and Japan). But in general, emerging regions suffered from inequalities in the carbon-economic exchange in ICT trade. The faster improvements in carbon efficiency and ICT export structure in emerging economies contributed to the decreases in CEIs. However, the widening value-added rate gap between emerging and developed regions offsets some of the decreases. These findings provide a complete picture of how ICT trade unevenly reallocates carbon and economic impacts among global regions and highlight the significance of international negotiation strategies aiming at carbon-economic balances in bilateral ICT trade.

RESULTS

ICT trade-related emissions and value-added

We first estimated the emissions and value-added embodied in global ICT trade using Equations 2 and 3, and found that they both increased significantly during 2000–2018 (see Figure 1). Overall, the growth rate of value-added was higher than that of emissions. Specifically, from 2000 to 2018, emissions embodied in ICT goods and services traded internationally grew by 34%, from 377 to 506 megatons (Mt) of CO₂ (Figure 1A). Over the same period, the economic wealth created by ICT exports increased by 154%, from 547 to 1,391 USD bn (Figure 1B). In both cases, declines were recorded in three special years: in 2001 due to the “Internet Bubble” crash, in 2009 as a result of the global financial crisis, and in 2015–2016 due to the so-called de-globalization period.

While the overall trends are similar, the geographical composition of emissions and value-added induced by ICT trade changed significantly. China surpassed the rest of the world (RoW) as the largest contributor (37%) to ICT trade-related emissions (Figure 1C), and meanwhile, it also largely increased its share in value-added from 5% to 21% (Figure 1D). This is mainly because China had expanded its ICT exports by 15 times since it acceded to the World Trade Organization (WTO) in 2001. Rising shares in emissions and value-added were also observed for India and the RoW. In contrast, declining shares were observed for developed economies, in particular the USA, Japan, and the EU-28. In 2018, five developed regions accounted for 42% of the total value-added created by ICT trade, whereas the rest ten emerging regions received 82% of the total emissions. The unmatched shares show that carbon and economic outcomes of ICT trade were unevenly distributed between emerging and developed regions, which raises questions about how such inequality arises.
Unequal transfers of emissions and value-added

We further explore the transfers of trade-related emissions and value-added between global regions to track how the carbon and economic impacts were unequally distributed along ICT production chains. The largest net transfers of emissions and value-added mainly occurred in bilateral ICT trade between China and other regions. In 2018, China gained 56, 23, and 19 USD bn of trade surplus via trading ICT goods and services with the USA, the EU-28, and the RoW, respectively (see Figure S1). Correspondingly, China net-absorbed 46, 25, and 16 Mt CO$_2$ associated with trade with these regions, respectively. A situation of so-called “double imbalance” happened between Japan and China and between the EU-28 and the RoW. For instance, Japan had a net gain of 27 USD bn in ICT trade with China in 2018 while net-outsourced 17 Mt CO$_2$ to the latter. The reverse transfers show that some developed economies possessed comparative advantages in both value-added creation and emission generation.

From the perspectives of exports and imports, deficits and surpluses in emissions and value-added in ICT trade varied significantly between developed and emerging regions. Comparisons can be made between the USA and China, the world’s largest importer and exporter in ICT trade, respectively. In 2018, the USA recorded deficits of 83 USD bn and 87 Mt CO$_2$, while China recorded surpluses of 103 USD bn and 116 Mt CO$_2$ (see Figure S2). Since 2000, many economies have become net importers, causing more emissions and value-added abroad than domestically. Among them, Russia and the RoW had become net emission exporters but net value-added importers. In contrast, Japan was an exporter of value-added but an importer of CO$_2$ emissions during 2000–2012. Major ICT exporters such as China, Taiwan, South Korea, and India were the net exporters of value-added and emissions throughout the study period.
The net transfers of emissions and value-added have intensified over time and across space. In 2000, South Korea, Russia, China, Taiwan, and the RoW had net surpluses in ICT value-added and emission trade. Since 2006, China has emerged as the world’s major surplus country and dominated the largest outflows of both emissions and value-added. A difference between the trend of carbon flows and that of economic flows can be observed, with emission transfers peaking in 2005 while value-added transfers continued growing. Overall, the carbon-economic exchange via ICT trade between regions over time has become more balanced. In 2006, China generated 2.36 kg of CO₂ per US dollar of ICT goods exported to the USA, but the ratio decreased to 0.64 kg of CO₂ per US dollar in 2018. The overall global picture shows that the advanced economies were able to obtain higher shares of economic benefits than domestic carbon emissions through ICT trade.

Figure 2 shows the transfer flows of emissions and value-added along global ICT production chains calculated using Equations 4 and 5. The final production process (e.g., end-product assembly and marketing) generated less than 2% of total emissions, whereas the primary production process (e.g., raw materials
extraction) generated 35%. This is quite different for value-added: downstream equipment integration and marketing accounted for 54% of the total value-added created by ICT trade, with another 29% from midstream intermediate inputs, and the remaining 17% from upstream raw materials.

The contributions of various production stages to emissions and value-added were generally uneven. Upstream sectors that provide carbon-intensive energy and raw material inputs generated a large proportion (80%) of emissions in ICT production chains, while downstream sectors that manufacture ICT final products retained a high share (45%) of value-added (see Figure S3). Further breakdown of the production chain impacts in Sino-US ICT trade to sectors reveals that the bulk of emissions were related to electricity, metals and non-metals, chemicals, and mining products, while a high proportion of value-added was attributed to ICT and services products (see Figure S4). Contributions to the emissions and the value-added generated in different production stages differed vastly between emerging regions and developed regions. China contributed substantially to upstream emissions and value-added, while the EU-28 and the USA contributed mainly to downstream stages. China’s shares of total emissions from the primary and final production stages were respectively 44% and 17%, while the shares for the EU-28 in these stages were respectively 7% and 18% (see Figure S5). Emerging economies mainly supplied carbon-intensive raw materials or intermediate inputs, while developed economies manufactured high-profit ICT products in global production networks.

Carbon-economic inequality and its drivers
We calculated the global CEI in ICT trade using Equation 6 during 2000–2018 and identified its components (see Figure 3). The global CEI increased rapidly from 2001 to 2005, followed by decreases from 2005 to 2014, and marginal increases after 2015. CEI decreased in the earlier years because China had gradually overtaken Japan as the world’s largest ICT exporter, as China possessed much less unfair superiority (versus Japan) when exporting ICT goods to other emerging regions. The moderate rebound of CEI during 2015–2018 was due to the transfer of ICT trade from China to the RoW, which suffered more from unfair inferiority compared with developed regions. The Belt and Road Initiative embarked in 2013 enhanced the trade links between China and many RoW economies, which facilitated the transfer. Since 2014, the RoW has substantially increased its ICT exports and imports. The main global CEI determinants include the EU-28 and the USA which
performed at levels well above the global average and China and the RoW which performed at below-average levels. The regional composition of global CEI shows the unequal carbon-economic exchanges between economies. Developed regions generally created more value-added, while emerging regions produced higher shares of emissions.

We further calculated the CEIs experienced by individual regions using Equations 7 and 8, by comparing their received emissions and value-added from ICT exports and imports. As depicted by the rightmost column in each heatmap in Figure 4, emerging regions are generally faced with inequalities in carbon-economic exchange in ICT trade with other regions. The developed regions generally benefited from these inequalities. Overall, the USA, the EU-28, and Japan ranked in the top three of the carbon-economic exchange benefit lists, while Russia and China suffered from the greatest inequalities (see Figure S6).

Mutual CEI in bilateral ICT trade reveals more details on the inequalities. Large mutual CEI indices (greater than 5) mainly existed between a major emerging economy (i.e., China, Russia, or India) and a developed economy (i.e., the USA, the EU-28, or Japan) (see Figure 5). Emerging regions generally showed disadvantaged CEIs when trading with developed regions. In particular, Russia suffered from the largest mutual CEIs with all other economies. In contrast, the USA benefited from bilateral ICT trade with almost every other region. For example, Russia released 11.67 kg of CO₂ per USD of ICT goods exported to the USA in 2000, while the latter released only 0.39 kg of CO₂ per USD for its exports to the former. Other emerging economies, e.g., Brazil, Indonesia, Australia, and Turkey, also suffered the same inequality when trading with the USA, the EU-28, and Japan, but they benefited from trading with China, Russia, and India. They took up the middle range in the global carbon-economic exchange driven by ICT trade.

The mutual CEIs between emerging and developed regions generally decreased from 2000 to 2018. The CEIs decreased significantly in the largest unequal trading pairs, i.e., between China, Russia, and India and the USA, the EU-28, and Japan, with falls of 19%–80%. The main contributor was the large carbon efficiency improvements achieved in emerging regions. Since 2000, Russia has substantially narrowed its carbon efficiency gap with Japan, the EU-28, and the USA. China has also managed to catch up with Japan and the USA after 2005. However, the carbon efficiency gap between India and the EU-28 has widened. Hence the decline of India’s CEI with developed regions was smaller than that of China or Russia with the developed regions.

The sectoral value-added rate gaps between emerging and developed regions widened over time which in turn enlarged the mutual CEIs. An example is the value-added rate disparity between China and Japan which contributed to an increase of 47% in mutual CEI. The increase outweighed the reduction effect resulting from carbon efficiency improvements. The sectoral value-added rate of India improved slightly faster than those of the USA and the EU-28. India mainly exported ICT services which have higher value-added than ICT goods. In addition, structural adjustments in final ICT exports contributed to reductions in the CEIs between developing and developed regions. In contrast, the effect of structural improvements in intermediate ICT production was diverse among different pairs of trade partners. For example, the effect was negative for the CEI (reduction) between Russia and developed regions but positive for the CEIs between China/India and the USA/Japan.

It is noteworthy that the CEIs between Mexico and the USA, Taiwan and the USA, and Turkey and the USA even increased by 241%, 185%, and 147%, respectively, from 2000 to 2018. The reasons are similar: the USA had largely widened its lead in value-added level and production structure related to ICT goods compared with these emerging economies. This indicates that these emerging economies need to improve the sectoral value-added level and production structures, e.g., retaining high value-added ICT marketing or outsourcing carbon-intensive ICT components and parts, as a means to reduce the inequalities with developed economies.

The drivers of inequalities reveal the comparative advantages of each region in carbon-economic exchanges in ICT trade. Russia and China achieved the largest improvements in sectoral carbon efficiency, which in turn enabled them to generate lower emissions in exchange for each unit of domestic value-added via ICT exports. In contrast, India must shorten its carbon efficiency gap with the EU-28 and Japan. Meanwhile, the USA, the EU-28, and Japan benefited most from the larger improvements in sectoral value-added rate, especially when trading ICT with China. This helped them to generate more value-added for the same amount of emissions. Regarding ICT production and export structure,
comparative advantages were not that comparable among different pairs of regions. However, emerging regions generally benefited from their larger structural improvements in ICT export structure, while developed regions performed better in domestic ICT production structure.

Figure 4. Mutual CEIs faced by global regions during 2000–2018
The horizontal axis shows the CEI indices of the focal region relative to other regions; the vertical axis shows the CEI indices of other regions to the focal region. Our results show that all CEI indices range between 0.24 and 40.9 during 2000–2018, with higher values indicating more serious inequality. When a pair of regions has a CEI index value of less than 1 (in blue), the region at the vertical axis receives more value-added relative to emissions from ICT trade with the region at the horizontal axis. When the value is larger than 1 (in red), the region suffers the absorption of more emissions relative to the value-added from bilateral trade. Darker colors signify higher levels of inequality.
DISCUSSION

Global ICT trade has expanded rapidly since the 2000s, but rising international trade tensions and the global supply chain disruptions caused by the coronavirus pandemic point to a volatile future. Of interest is who will emerge as winners and losers. Quantifying to what extent and how the carbon costs and economic benefits of ICT trade could be unevenly distributed among global regions serves as useful pointers. Our findings show that ICT trade has triggered huge inequalities between developed and emerging economies through carbon and economic exchange. Our analyses indicate that in the context of deglobalization, sustainable ICT trade may necessarily entail a wider and deeper range of synergistic strategies, i.e., balancing carbon and economic concerns, to yield mutual benefits among global regions.

It is often assumed that ICT goods and services are high value-added and low carbon-intensive. Emerging economies, such as China and India, had leveraged ICT exports for economic development and sustainable transformation. This study shows that such a pursuit comes with a significant carbon burden. Although previous studies had portrayed the immense potential of ICT application in reducing industrial emissions via enabling intelligence and dematerialization,23 substantial emissions could be generated in processing raw materials and intermediate inputs for manufacturing ICT products themselves. Technological progress and increased functionality have also turned ICT devices and services into carbon-intensive items.24 While the total or net carbon impacts of ICT remain controversial, ICT production or exports appear to be not instrumental in mitigating national carbon emissions. These findings have implications for national policies on the trade-off relationship between ICT trade and climate change. The results also advance a new vision for international organizations, e.g., WTO and the International Telecommunication Union, which prioritize ICT trade or promote ICT as a means to achieve sustainable development.25,26

Figure 5. Drivers of changing mutual CEIs in bilateral ICT trade between major emerging and developed regions during 2000–2018

The dotted black lines show the cumulative changes of mutual CEIs, with a value of less than 1 indicating a decrease in CEI, and vice versa for values of greater than 1. The solid lines in different colors show the contributions of individual effects to the total changes of mutual CEIs obtained using Equation 9. (A–I) show the drivers of changing mutual CEI in bilateral ICT trade between specific emerging region (China, India and Russia) and specific developed region (USA, EU-28 and Japan).
During the study period, the carbon emissions and value-added associated with ICT trade are unevenly distributed among global regions. China gains substantial and rising surpluses in ICT trade, but its share of total value-added is lower than that of total CO₂ emissions. The converse has been observed in the EU-28, the USA, and Japan. The international inequalities are a reflection of regional comparative advantages in global ICT production and value chains, with advanced economies dominating the R&D, design, and marketing activities of core ICT parts while emerging economies specialize in raw materials extraction, intermediate processing, and assembly operations. Increasingly fragmented international ICT production has facilitated the retention of high value-added design and marketing in the USA and the EU-28 but outsourcing of carbon-intensive ICT manufacturing to China and other emerging countries.

The COVID-19 pandemic has struck at the very core of the global ICT/electronic production network regions, e.g., China and other East Asian regions like Taiwan, Japan, and Korea. ICT intermediate imports from China dropped dramatically between January and April 2020. The escalating trade disputes, especially between China and the USA, would have also increased the volatility of ICT trade. Recent reshoring trends, particularly in advanced economies’ manufacturing, could also exert significant effects on the layout and resilience of the global production chain. All of these shocks may weaken global production chain link and collaboration and thus drive a rebound in the global inequality in ICT trade. For instance, supply chain shortage and higher production costs would raise the prices of key ICT products, thus enabling developed countries to gain more shares of value-added; or the transfers of manufacturing plants to less efficient Southeast Asia and RoW countries may result in more carbon emissions, thus exacerbating global inequality. Facing these challenges requires enhanced bilateral and multilateral mechanisms for trade negotiations and cooperation, which could provide avenues that foster future sustainable ICT trade and supply chains.

While global CEI in ICT trade dropped slightly between 2000 and 2018, mutual CEIs between emerging economies and developed economies fell substantially. The decreases were largely driven by the narrowing gaps in sectoral carbon efficiencies between the two regions. Universal climate mitigation actions can help to reduce inter-regional inequalities. Structural adjustments in intermediate ICT production and final ICT exports will reduce CEIs as emerging regions have been making progress in improving their involvement and contribution to the global ICT production chain, e.g., switching from high-volume to high-revenue marketing, and expanding local investment and consumption to decouple export-related value-added from local emissions. For example, between 1978 and 2018, China’s investment in ICT equipment increased by 21.8% annually. In addition, Chinese ICT giant Huawei has continuously made breakthroughs in overseas markets, which greatly increased its global sales until the USA tighten the restriction on Huawei’s access to chips. As emerging economies accelerate their investment in domestic ICT infrastructure such as 5G and data centers, the CEIs that they have been experiencing could be further mitigated. For developed economies, disseminating low-carbon technologies to emerging economies and imposing carbon taxes on ICT imports may help sustain their comparative advantages while still retaining carbon-economic benefits. Uncovering the determinants of changes in inequality provides implications for regions that are dedicated to reducing their inequalities with other regions by fulfilling the competitiveness of carbon-economic exchange in ICT trade.

Noticing the trade-related inequality among countries, the United Nations has proposed to promote an equitable multilateral trading system and implemented a special and differential treatment principle for less-developed economies under WTO agreements. The implementation of border carbon taxes, suggested as an internationally transferred mitigation outcome suggested in the Paris Agreement, may incent the transition to more efficient emerging countries. However, ICT trade that triggers significant carbon-economic inequality has been receiving scant attention in such international initiatives. This study verifies that the inequality in global ICT trade remains significant despite the large reductions achieved in the past two decades. Global efforts to ensure digital transformation and sustainable development should build on incorporating ICT trade into these international trade agreements, climate change negotiations, and cooperation on supply chain and carbon technology.

**Limitations of the study**

This study calculated the ICT trade-related emissions, value-added, and inequality using an MRIO model that incorporates the assumption of a stable linear economic structure and homogeneous product industries. Uncertainty in the results might arise when many regions and sectors over a long period need to be
accounted for in the context of global trade modeling. In addition, this study only investigated the 2000–2018 period due to data limitations. The results may not cover the most recent situation of global ICT trade, in particular, the decoupling of the United States and China in high-tech trade during 2019–2022. To provide timely policy implications, there is a need to update the dataset of global MRIO tables and emission inventory, considering ICT trade has been evolving continually.

**STAR METHODS**

Detailed methods are provided in the online version of this paper and include the following:

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**SUPPLEMENTAL INFORMATION**

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.105604.

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**AUTHOR CONTRIBUTIONS**

X.Z., Q.-W.W., and B.S. designed the study and prepared the manuscript. X.Z., Y.H., and B.S. collected data and performed calculations. All authors (X.Z., Y.H., D.-Q.Z., B.-W.A., Q.-W.W., B.S., and P.Z.) participated in performing the analysis and contributed to writing the manuscript. Q.-W.W. and B.S. coordinated and supervised the project.

**DECLARATION OF INTERESTS**

The authors declare no competing interests.

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STAR METHODS

KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---------------------|--------|------------|
| Deposited data      |        |            |
| Global MRIO tables for 2000–2018 of 67 regions and 45 sectors | OECD Inter-Country Input-Output (OECD-ICIOT) Database | http://oe.cd/icio |
| Country-specific sectoral emission inventory of 44 regions and 56 sectors for 2000–2016 | World Input-Output Database Environmental Accounts | https://ec.europa.eu/jrc/en/research-topic/economic-environmental-and-social-effects-of-globalisation |
| Price deflators     | World Input-Output Database (WIOD) United Nations Statistical Division (UNSD) | https://www.rug.nl/ggdc/valuechain/wiod/wiod-2016-release http://unstats.un.org/snaama/Introduction.asp |
| Country-specific sectoral emission inventory of 44 regions and 56 sectors updates to 2017 | This paper | https://data.mendeley.com/datasets/r9gvn38y5n/1 |
| Country-specific sectoral emission inventory of 44 regions and 56 sectors updates to 2018 | This paper | https://data.mendeley.com/datasets/dshkw23dk9/1 |
| Software and algorithms | MathWorks | https://www.mathworks.com |

RESOURCE AVAILABILITY

Lead contact
Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Bin Su (subin@nus.edu.sg).

Materials availability
This study did not generate new unique materials.

Data and code availability
- This paper analyzes existing, publicly available data which are listed in the key resources table. The results data generated during the analysis can be found in Supplemental Data S1, S2, S3, S4, S5, S6, S7, S8, S9, S10 and S11.
- Code for the analysis is written in MATLAB and is available from the lead contact upon reasonable request.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon reasonable request.

METHOD DETAILS

Data sources
Three sets of data are used in this study: (1) time-series global MRIO tables; (2) the corresponding country-specific sectoral emission inventory; (3) country-specific sectoral price deflators.

The global MRIO tables data are obtained from the 2021 edition of OECD Inter-Country Input-Output Tables (OECD-ICIOT), which covers 67 regions and 45 sectors for 1995–2018. In comparison to other Global MRIO databases, OECD-ICIOT provides the most recent 1995–2018 time series data and uses a sector classification that closely matches the United Nations’ definition of the ICT sector. The country-specific sectoral emission inventory of 44 regions and 56 sectors for 2000–2016 is publicly available by
the Joint Research Centre of the European Commission. The emission inventory has been updated to 2018 using the IEA and OECD’s emission database and harmonized with the OECD-ICIOT database for 44 regions (including 43 major countries/regions and the RoW) and 42 sectors. Price deflators by country/region and sector were compiled from various sources, including the World Input-Output Database (WIOD) and national statistics. We then use the data treatment approaches to aggregate sectors and regions, harmonize sector classification in MRIO tables with that in emission inventory, and compile MRIO tables in constant price.

The results and discussion are presented at an aggregate level for 15 major countries/regions: China mainland, Taiwan, Japan, South Korea, the EU-28, the USA, Canada, Mexico, Brazil, Russia, India, Indonesia, Australia, Turkey, and the RoW. Data at the detailed level of 42 sectors for each region are used in the calculations. For ease of understanding, the results are aggregated into 12 major sectors according to the International Standard Industrial Classification Rev. 4. Following the definitions by the United Nations Conference on Trade and Development, ICT goods and services refer to sector C26 (i.e., computer, electronic and optical products), and sector J61-63 (i.e., telecommunications, computer and information services) in OECD-ICIOT, respectively. Detailed regional and sectoral aggregations are given in Tables S1 and S2.

Multi-regional input-output analysis

The environmentally extended MRIO model is used to account for the inter-regional carbon-economic exchanges driven by ICT trade. The model describes the direct and indirect environmental and economic linkages among different sectors in different regions. The basic MRIO model can be expressed as follows:

\[
X = (I - A)^{-1}Y 
\]

(Equation 1)

where \(X\) is the economic output matrix that shows the total output in sector \(i\) triggered by exports from region \(r\) to region \(s\), \(A = (A_{ij}^r)\) is the technical coefficients matrix reflecting the monetary flows from sector \(i\) in region \(r\) to sector \(j\) in region \(s\), \(I\) is the identity matrix, \((I - A)^{-1}\) is the Leontief inverse matrix, and \(Y\) is the final demand matrix that can be divided into domestic final consumption (\(Y^r\)) and exports (\(Y^rs\)).

The domestic emissions and value-added induced by international trade can be further calculated from Equation 1 as follows:

\[
E = \bar{e}(I - A)^{-1}Y 
\]

(Equation 2)

\[
V = \bar{v}(I - A)^{-1}Y 
\]

(Equation 3)

where \(E = (E^r)\) and \(V = (V^r)\) represent the total emissions and value-added, respectively, generated in region \(r\) to produce the goods and services exported to region \(s\). Also, \(\bar{e}\) and \(\bar{v}\) respectively refer to the vectors containing sectoral emissions intensities (\(\bar{e} = f'(\bar{x}')^{-1}\)) and value-added coefficients (\(\bar{v} = d'(\bar{x}')^{-1}\)), where \(f', d', \text{ and } \bar{x}'\) are the vectors of sectoral emissions, value-added, and total outputs of region \(r\), respectively. The export- and import-related emissions and value-added of each region are simple row and column sums, respectively, in matrices \(E\) and \(V\), without the entry on the diagonal, which represents domestic production for domestic consumption, i.e., internal trade within the region.

Structural path analysis

The SPA approach is used to study how the carbon costs and economic benefits of ICT trade are unevenly distributed among regions. The technique quantifies transmissions in the upstream process and identifies important paths by tracing back the intricate production chains. It provides an exhaustive attribution of carbon and economic impacts to specific regions and sectors. The emissions and value-added embodied in inter-regional trade flow in Equations 2 and 3 can be rewritten as a summand of different production layers:

\[
E = \bar{e}Y + \bar{e}A_{P2}^rY + \bar{e}A_{P1}^rA_{P2}^rY + \bar{e}A_{P1}^rA_{P2}^rA_{P3}^rY + \cdots 
\]

(Equation 4)
\[ V = \sum_{PL^0} v_I + \sum_{PL^1} v_{AY} + \sum_{PL^2} v_{A^2Y} + \sum_{PL^3} v_{A^3Y} + \cdots \]  
(Equation 5)

where \( PL^k \) represents the emissions and value-added generated by the \( k \)th production layer for international traded commodities. Taking the emissions generated in the production process of 5G networks as an example, \( Y \) can be deemed to be the telecom operators’ demand for 5G base stations, and \( \varepsilon_IY \) represents the direct emissions generated in the deployment phase (\( PL^0 \)). To provide a base station, infrastructure equipment companies (e.g., Ericsson, Huawei, and Nokia) need to purchase parts and accessories (e.g., antennas, chips, and filters) from their upstream suppliers. Emissions given by \( \varepsilon_{AY} \) are released by these suppliers in manufacturing the required parts or accessories (\( PL^1 \)). In turn, the suppliers also need to purchase raw materials (e.g., glasses, metals, and chemicals). Thus, \( \varepsilon_{A^2Y} \) emissions are released to produce the materials (\( PL^2 \)) and so forth. The process continues similarly for all production tiers. Within each sector in each region and at each layer, the processing of products entails the release of emissions into the atmosphere.

**CARBON-ECONOMIC INEQUALITY ESTIMATION**

The CEI in ICT trade is measured by the Theil index. This index is widely used to determine the level of disparities in the distribution of environmental and economic impacts between regions. The global level of CEI can be calculated by:

\[ CEI_{\text{total}} = \sum_r p'_r \ln \frac{E_{m/r}}{C_{0/r}} \]  
(Equation 6)

where \( CEI_{\text{total}} \) is the carbon-economic inequality in global trade, \( p'_r \) is the domestic value-added share obtained by region \( r \) in global trade, \( E_{m/r} = E_m/E' \) and \( V_{m/r} = V_m/V' \) denote the emission and value-added level of region \( r \) compared with the global average, respectively. The lower boundary of CEI is zero and a larger value indicates higher inequality. The CEI component relative to region \( r \) is \( p'_r \ln \frac{E_{m/r}}{V_{m/r}} \), showing the contributions of each region to global CEI. A negative value for the component indicates that the region has received a higher ratio of emissions than value-added and thus the region has suffered from CEI in trade, and vice versa.

A mutual CEI index, defined as the ratio of the received emissions divided by the ratio of gained value-added in bilateral trade, is further constructed to measure the disproportionality of carbon costs and economic benefits between trade pairs. The mutual CEI can be calculated by:

\[ CEI_{rs} = \frac{E_{rs}}{V_{rs}} = \frac{E_{sr}}{V_{sr}} \]  
(Equation 7)

where \( CEI_{rs} \) is the mutual carbon-economic inequality in bilateral trade between regions \( r \) and \( s \), thereby reflecting the mismatch between the exchange rate of emissions and value-added in bilateral trade. When the value of \( CEI_{rs} \) is one, the mutual carbon-economic exchange is equal. The smaller the ratio implies the more carbon-economic benefits region \( r \) experiences (fewer emissions, higher value-added), and vice versa for region \( s \).

Similarly, the CEI experienced by individual regions can be calculated by:

\[ CEI' = \frac{\sum E_s}{\sum V_s} \]  
(Equation 8)

where \( CEI' \) is the overall carbon-economic inequality experienced by region \( r \) when trading with all other regions, measured as the ratio of export-related emissions to import-related emissions, divided by the ratio relative to value-added.

**Structural decomposition analysis**

The SDA approach is used to decompose ICT trade-related emissions and value-added into changes in a range of production and consumption factors. The technique is widely used to determine the underlying drivers of a dependent variable, such as \( CO_2 \) emissions or value-added. Here, the CEI in bilateral
ICT trade can be decomposed into changes in four factors, i.e., disparity in domestic carbon efficiency, disparity in domestic value-added ratio, disparity in inter-regional production structure, and disparity in inter-regional ICT export structure. The evolution of mutual CEI in Equation 7 from time 0 to time T can be formulated as:

\[
D(\text{CEI}^T) = D(\text{CEI}^0) + D_E(\text{CEI}^T) = D_E(\text{CEI}^0) + D_E(\text{CEI}^T)
\]

where \(D(\text{CEI}^T)\) denotes the total change in the mutual CEI between regions \(r\) and \(s\), \(D_E(\text{CEI}^T)\) is the carbon efficiency effect which gives the contribution of changes in sectoral emission intensity disparity between regions \(r\) and \(s\), \(D_E(\text{CEI}^T)\) is the value-added effect which gives the contribution of changes in sectoral value-added ratio disparity, \(D_L(\text{CEI}^T)\) is the production structure effect which gives the contribution of changes in production structure disparity, and \(D_Y(\text{CEI}^T)\) is the export structure effect which gives the contribution of changes in export structure disparity. If \(D > 1\), a larger value of \(D\) indicates a greater increasing effect on CEI. If \(D < 1\), a smaller value of \(D\) indicates a greater decreasing effect on CEI. These sub-effects are derived using the multiplicative D&L method and attribution analysis. Similar SDA can be applied to the evolution of the CEI experienced by individual region in Equation 8.