Environmental Science & Technology

Multidimensional Analyses Reveal Unequal Resource, Economic, and Environmental Gains and Losses among the Global Aluminum Trade Leaders

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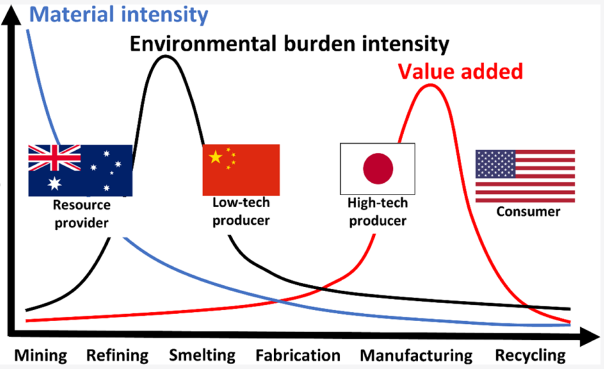
Cite This: *Environ. Sci. Technol.* 2021, 55, 7102−7112

ABSTRACT: Disputes around trade inequality have been growing over the last 2 decades, with different countries claiming inequality in different terms including monetary deficits, resource appropriation and degradation, and environmental emission transfer. Despite prior input−output-based studies analyzing multidimensional trade consequences at the sector level, there is a lack of bottom-up studies that uncover the complexity of trade imbalances at the product level. This paper quantifies four types of flows, monetary, resource, embodied energy use, and embodied greenhouse gas (GHG) emissions, resulting from aluminum trade for the four economies with the highest aluminum trade, that is, the United States, China, Japan, and Australia. Results show that the United States has a negative balance in monetary flows but a positive balance in resource flows, embodied energy use, and GHG emissions. China has a positive balance in monetary and resource flows but a negative balance in embodied energy use and GHG emissions. Japan has a positive balance in all flows, while Australia has a negative balance in all flows. These heterogeneous gains and losses along the global leaders of aluminum trade arise largely from their different trade structures and the heterogeneities of price, energy use, and GHG emission intensities of aluminum products; for example, Japan mainly imports unwrought aluminum, and its quantity is 3 times that of the exported semis and finished aluminum-containing products that have similar energy and GHG emission intensities but 20 times higher prices, while Australia mainly exports bauxite and alumina that have the lowest prices, the quantity of which is 25 times that of imported semis and finished products. This study suggests that resource-related trade inequalities are not uniform across economic and environmental impacts and that trade policies must be carefully considered from various dimensions.



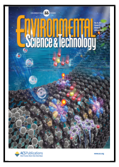
KEYWORDS: *aluminum, trade inequality, embodied energy, embodied GHG emissions, material flow analysis, industrial ecology*

1. INTRODUCTION

Trade inequality is a major source of geopolitical tension. In recent years, different countries have claimed that they have suffered from trade inequality in various forms, including the following: (1) trade deficits in monetary terms,[1] for example, large and chronic US trade deficits with other countries, such as China; (2) ecological burden,[2] for example, through export-oriented extraction or manufacturing industries and the import of various solid wastes from developed economies, countries such as China have experienced increases in environmental pollution and human health impacts; and (3) resource appropriation and degradation,[3] for example, mines in Australia, Latin America, and Southeast Asia that have the richest reserves have become the focus of global competition.

Provoked and justified by the above partial understanding of trade inequality, there is a tendency for countries to take trade protection policies in the last few years. For example, the US Trump government first imposed additional tariff on steel and aluminum imported from other countries in 2018,[4,5] such as China, European Union, and Russia, and then started a comprehensive trade war against China[6] and many other countries[7] to protect its domestic employment. In 2018, China banned the import of 24 types of wastes, followed by Vietnam, Malaysia, and Thailand,[8,9] to stop the transfer of garbage and associated pollutions from developed economies. Australia

Received: December 31, 2020
Revised: April 19, 2021
Accepted: April 19, 2021
Published: April 29, 2021



https://doi.org/10.1021/acs.est.0c08836

changed its foreign investment framework and implemented critical mineral strategies to promote the country's mineral extraction and downstream processing sectors.[10] These measures seem reasonable under the auspices of protecting themselves from the negative effects of unequal trade. However, they are not effective in many cases and result in other negative effects.

International trade has resulted in the geographic reallocation of traded commodities and the capital, labor, natural resources such as water and land, materials, energy, and environmental emissions embodied in these commodities.[11] For a specific commodity, flows from country A to country B can be classified into direct flows and indirect flows (Figure 1).

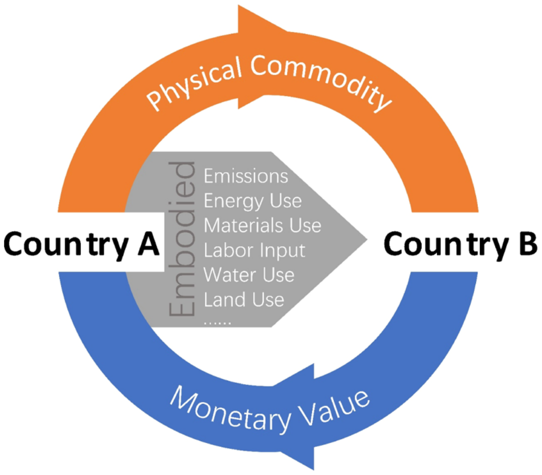


Figure 1. Direct and indirect flows resulting from the trade of a physical commodity. Color flows (physical commodity and monetary value) are direct flows; gray flows (i.e., embodied emissions, energy use, and so on) are indirect flows.

Direct flows include the physical flow and monetary flow, for which the directions are opposite to each other. Indirect flows (also referred to as virtual, hidden, or embodied flows) are linked to the direct physical flows and have the same direction.

When a country experiences unbalanced direct and indirect trade flows, unequal exchange happens. Unequal, however, does not necessarily mean unfair because, in addition to market failures, comparative advantage—the foundation of international trade—can also result in trade imbalances.[12] Unequal exchange theory was first proposed by economists,[13] with a focus on the inequality of monetary flows usually measured in USD.[14] It was then introduced into the research field of resource and environmental system analysis at the end of 1980s.[15,16] Since then, direct physical flows measured by the mass of materials traded among countries have often been analyzed,[17−19] as well as virtual flows of water,[20−22] land use,[23,24] energy use,[25,26] and environmental emissions[27−29] embodied in international trade. Particularly, there is a growing body of literature on greenhouse gas (GHG) emissions embodied in trade due to the concern with and debate on global warming responsibility and "carbon leakage".[30,31]

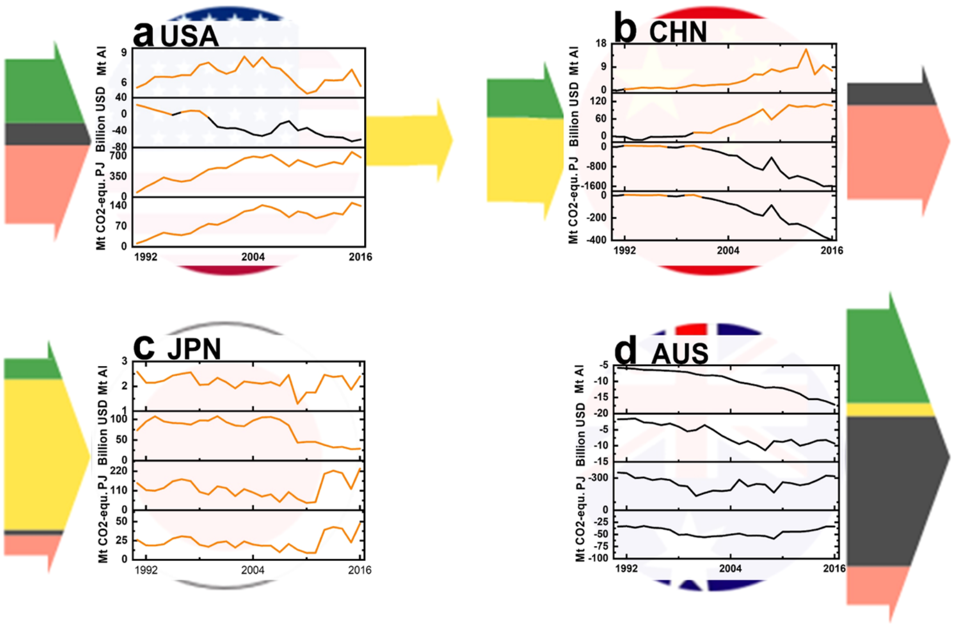
With increasing attention paid to the complexity and multidimensional nature of international trade, recent studies based on IO methods have considered more than one type of impact from the international trade and highlighted the mismatch of countries' benefits and costs.[27,29,32,33] For example, a comprehensive global assessment by Dorninger et al. showed that an ecologically unequal exchange allows high-income countries to gain both resource and monetary surplus from low-income countries through international trade, which enlarges disparities among countries.[33] However, to date, research on multidimensional trade inequality is inadequate. Most of these studies are based on the input−output method which is a top-down approach to analyze trade inequality at the sector level, and typically not at a high enough sectoral resolution to provide sufficient understanding of technology-specific mechanisms and possible solutions.

Here, we report on a product-level study that aims to characterize and explain the broad impacts of international trade of a specific material by applying a bottom-up method and by examining both direct and indirect trade flows and their multiple implications for resource, economic, and environmental inequalities among major trading nations. We take aluminum as a case study because of its technological versatility and application in multiple economic sectors, its essential role in economic development, and its importance as the second highest production volume metal after steel.[34] In addition, the production of alumina and primary aluminum (PA) is highly energy- and GHG emission-intensive. Prior research showed that in 2014 the aluminum industry accounted for 4% of global industrial final energy demand and 3% of the industry's total direct CO_2 emissions.[35] Trade in aluminum has also been the focus of recent political activity; for example, the United States investigated the effects of aluminum imports on national security and proclaimed a 10% *ad valorem* tariff on aluminum articles in 2018[36] and on derivative aluminum articles in 2020.[37] Then, relevant countries, including China, the European Union, Canada, Mexico, Norway, Russia, and Turkey, opened WTO complaints against the US steel and aluminum tariffs.[38] Australia was exempt from the US global steel and aluminum tariffs but launched antidumping probes into Chinese aluminum products in 2020.[39]

We focus on the global leaders of aluminum trade: the United States, China, Japan, and Australia. The former three countries are the top three importers, while the latter is the top exporter.[40] The United States, China, and Japan are also the three largest economies in the world, together accounting for ~50% of the global gross domestic product. Thus, these four countries are the most representative and influential countries in the global aluminum industry. Specifically, we (i) perform a coupling analysis of direct trade flows (both monetary and physical flows) and indirect trade flows (embodied energy and GHG emissions) for aluminum, (ii) analyze how each country's aluminum trade evolved during 1991−2016, and (iii) explore how and why these four economies have contributed to, suffered from, and benefited from economic and environmental inequalities with the rest of the world in the trade of aluminum.

2. MATERIALS AND METHODS

2.1. Identification of ACPs. The anthropogenic life cycle of aluminum is composed of four principal life stages: production, fabrication and manufacturing, use, and waste management and recycling (Figure S1 in the Supporting Information).[34,41,42] More than 100 aluminum-containing products (ACPs) are identified (Table S1 in the Supporting Information) and are classified into six groups according to their position in the value chain: (1) bauxite, (2) alumina, (3) end-of-life (EOL) products and scrap (EP&S), (4) unwrought



Total Net-import	🟩 Resource t Al	🟨 Economic Value USD	⬛ Embodied Energy Use J	🟥 Embodied GHG Emission t CO_2
USA	176×10^6	-659×10^9	129×10^{17}	236×10^7
CHN	107×10^6	1117×10^9	-130×10^{17}	-283×10^7
JPN	57×10^6	1991×10^9	32×10^{17}	61×10^7
AUS	-259×10^6	-165×10^9	-865×10^{17}	-117×10^7

Figure 2. Cumulative and annual balance of trade in resource, economic, energy, and environmental consequences for (a) the United States, (b) China, (c) Japan, and (d) Australia from 1991 to 2016.

aluminum (UA), (5) semis, and (6) finished products (FPs). The first, second, and third groups can be regarded as raw materials to produce UA, while the fifth and sixth groups consist of semifinished products and FPs, respectively. There are two sources of UA: PA, produced from natural ores and concentrates (e.g., bauxite), and secondary aluminum (SA), produced from EP&S. Only trade of scrap is quantified in the group EP&S because trade of most EOL products such as e-waste, old ships, and cars have been banned[43] or their data are unavailable.[44]

2.2. Calculation of Direct and Indirect Trade Flows. A diagram illustrating the data sources and decision tree used in the calculation of these four trade flows of aluminum contained in each ACP is shown in the Supporting Information (see Figure S2), and all the equations can be seen in Section 3 of the Supporting Information.

Direct trade flows (monetary and physical flows) are collected directly from the UN Comtrade Database[45] in which monetary trade value data are available for all ACPs in 1991−2016, while physical trade value data may be unavailable for some ACPs in the group of FPs for a few years. Adjusted by the US consumer price index,[46] monetary trade value is converted into 2000 USD. ACP's monetary trade value is then allocated to aluminum contained in it by mass. The physical trade value of aluminum contained in a specific traded ACP is determined by multiplying the ACP's physical trade value by its physical aluminum content (Table S1 in the Supporting Information). For those FPs for which physical trade data do not exist, physical trade values are estimated by dividing monetary trade value in constant 2000 USD by prices (in constant 2000 USD), which are deduced by historical prices and the method of linear interpolation.

Indirect flows, including energy use and GHG emissions embodied in aluminum for ACPs, are calculated by multiplying the "cradle-to-product" (CTP) energy use and GHG emission intensities of aluminum contained in ACPs (indicated by EI_{Al}^{CTP} and GI_{Al}^{CTP}) by their physical aluminum content. EI_{Al}^{CTP} and GI_{Al}^{CTP} are the accumulation of the process incremental energy use and GHG emission intensities of aluminum in an ACP (indicated by EI_{Al}^{Inc} and GI_{Al}^{Inc}) from the bauxite mining process (the starting point of aluminum's life cycle) to the process that the ACP is generated in.

EI_{Al}^{Inc} and GI_{Al}^{Inc} are calculated by life cycle inventory (LCI) data from the aluminum industry (International Aluminum Institute[47−51] and European Aluminum Association[52−54]), which provide LCI data sets[55] by the production process (process-based LCA) for multiple years that are periodically updated. Both direct and indirect energy use and GHG emissions are calculated (Figure S1 in the Supporting Information). The energy use and GHG emissions from the international transportation process are not considered because they are commodity-specific and have been shown to be relatively insignificant.[56] PA production and SA through EP&S management (including EP&S collection, sorting, separation, and recycling) are considered as two independent systems. This means the CTP energy use and GHG emission intensities of EP&S are calculated, starting from collection instead of mining.

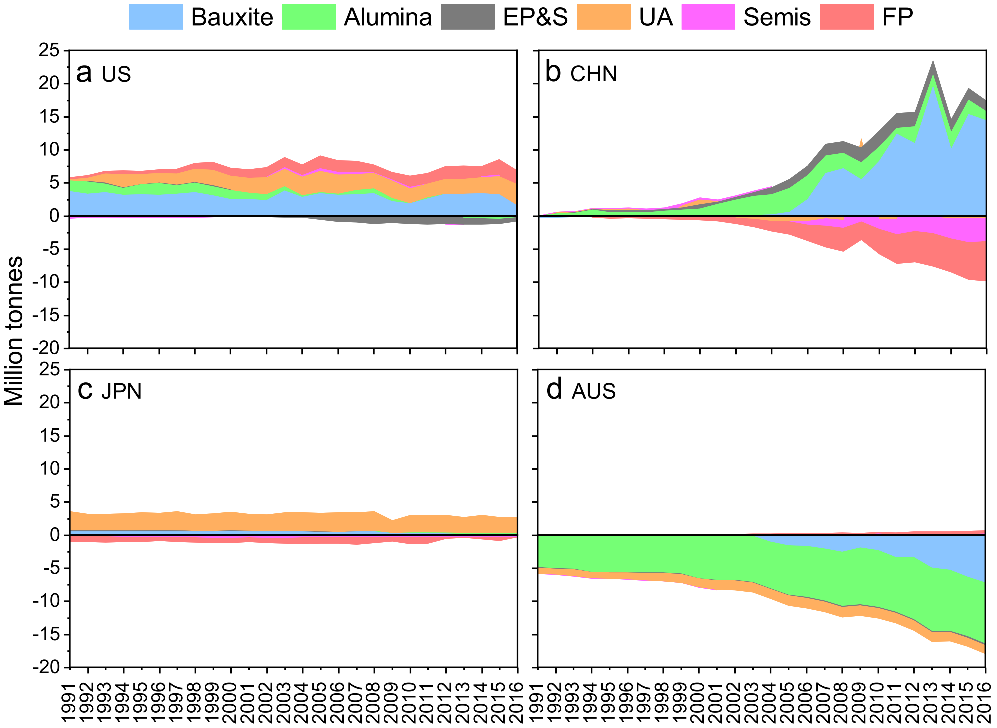


Figure 3. Net import of aluminum embedded in different product groups measured by mass for (a) the United States, (b) China, (c) Japan, and (d) Australia from 1991 to 2016. EP&S = EOL products and scrap, UA = unwrought aluminum, semis, FP = finished products, Mt = million tonnes.

The input−output LCA method is used to estimate the energy use and GHG emission intensities for the manufacturing process of each finished ACP because LCI data for each individual manufacturing process are unavailable. Burdens are calculated using the aggregate energy use and GHG emission intensities for the industry sector to which each finished ACP belongs (Table S1 in the Supporting Information). To avoid double counting, only direct energy use and GHG emissions for the manufacturing process are calculated.

For each ACP, a country's trade flows consist of aluminum imports and exports with the rest of the world. Balances of trade in each of the four flows are measured. A positive physical trade balance or monetary trade balance means countries gain resources and economic benefits from international trade. A positive embodied energy use balance and an embodied GHG emission balance mean that countries derive ecological benefits from trade as energy use and emissions occur elsewhere. In contrast, negative physical, monetary, or ecological trade balances imply that a country suffers from trade as energy use and emissions occur domestically but products are consumed elsewhere.

3. RESULTS

3.1. Gains and Contributions of These Four Countries. The contributions and gains of each targeted country are shown in Figures 2 and S5. Overall, the four countries resulted in unequal trade in these four flows for years 1991−2016. More precisely, the United States has a negative balance in monetary value and a positive balance in resources, energy, and GHG emissions. China has a negative balance in energy and GHG emissions and a positive balance in physical and monetary values, a feature consistent with China's status as a developing and manufacturing nation. Japan, as a manufacturing powerhouse with few domestic reserves, has a positive balance in all flows and keeps getting not only resources and economic benefits but also energy and environmental benefits in the aluminum international trade. Australia, as the largest exporter of aluminum resources (bauxite accounted for 55% of Australia's total export in 2016), has a negative balance in all flows.

The gain and contribution of these four countries changed during the past quarter century. China has experienced the most dramatic changes in trade balances for each of the four flows, as it hugely expanded its production, manufacturing capacity, and final demand for aluminum. China became the net importer in physical flow in 2000 and, since then, its trade balances in all flows expanded very fast and more intensively than those in the other countries in 2016 (see Figure S5). The United States had a positive balance in all flows before 1999. Then, with the decrease of the domestic aluminum-containing product output,[34] the negative balance of monetary value has enlarged and got more and more energy and environmental benefits from international trade. Australia has increased negative balance in all flows during the time span investigated, especially for physical trade. Japan showed the least change. It kept a positive balance in all flows in the time span under scrutiny. However, this positive balance in monetary value has been declined in the last decade.

3.2. Resource Consequences. None of the countries showed a neutral balance in physical flows from 1991 to 2016 (see Figures 3 and S6). The United States was the net importer over the entire study period. Except for EP&S, the United States imported all groups of ACPs, especially bauxite, UA, and FPs. The quantity of imported ACPs is 6 times that of the exported ACPs. China's aluminum imports have grown very fast and overtook those of Japan in the year 2002 and of the United States in the year 2009 as the biggest net aluminum

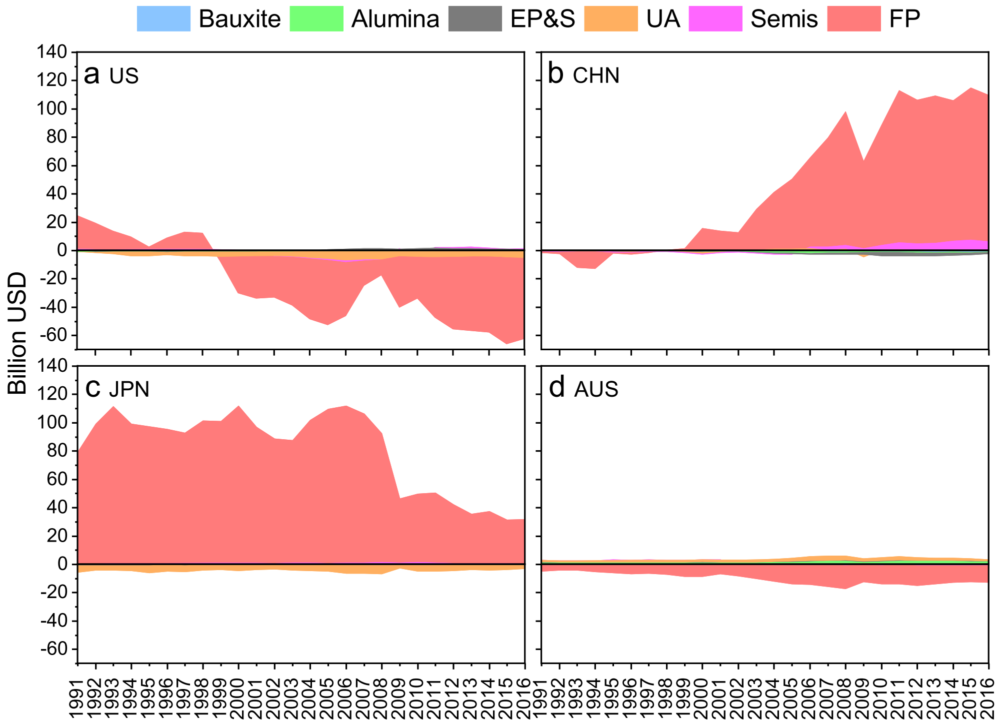


Figure 4. Money net-earned by trade of different ACP groups for (a) the United States, (b) China, (c) Japan, and (d) Australia from 1991 to 2016. EP&S = EOL products and scrap, UA = unwrought aluminum, semis, FP = finished products.

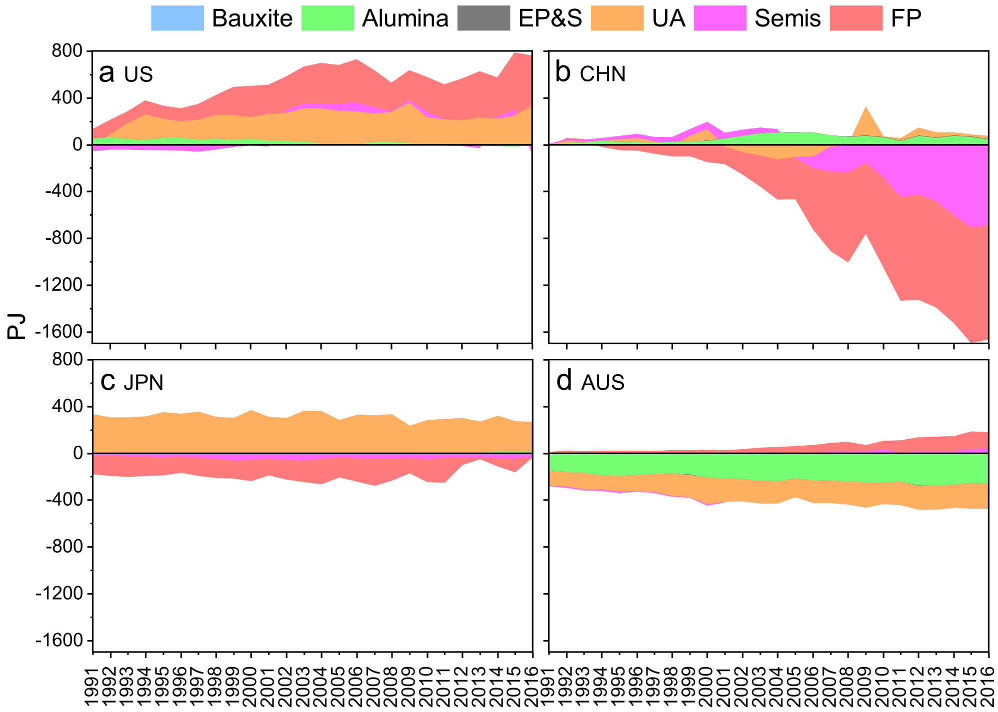


Figure 5. Net import of embodied energy in aluminum trade for (a) the United States, (b) China, (c) Japan, and (d) Australia from 1991 to 2016. EP&S = EOL products and scrap, UA = unwrought aluminum, semis, FP = finished products, PJ = Petajoule = 10^{15} J.

importer. As the major manufacturer, China mainly imported commodities like bauxite, alumina, and EP&S, which are all raw materials (bauxite accounted for more than 80% of imported aluminum raw materials), and exported finished goods and semis, such as building and construction products and consumer durables. For UA, China maintained an almost stationary balance between imports and exports. In 2016, Japan was the third largest aluminum importer. Japan mainly imported UA and exported semis and FPs, mainly transportation equipment. The quantity of UA is 3 times that of exported semis and FPs. Australia, as it is rich in aluminum resources, is the only net exporter in physical flow among these four countries. It mainly exported bauxite, alumina, and UA, while imported FPs and semis to meet the domestic demand.

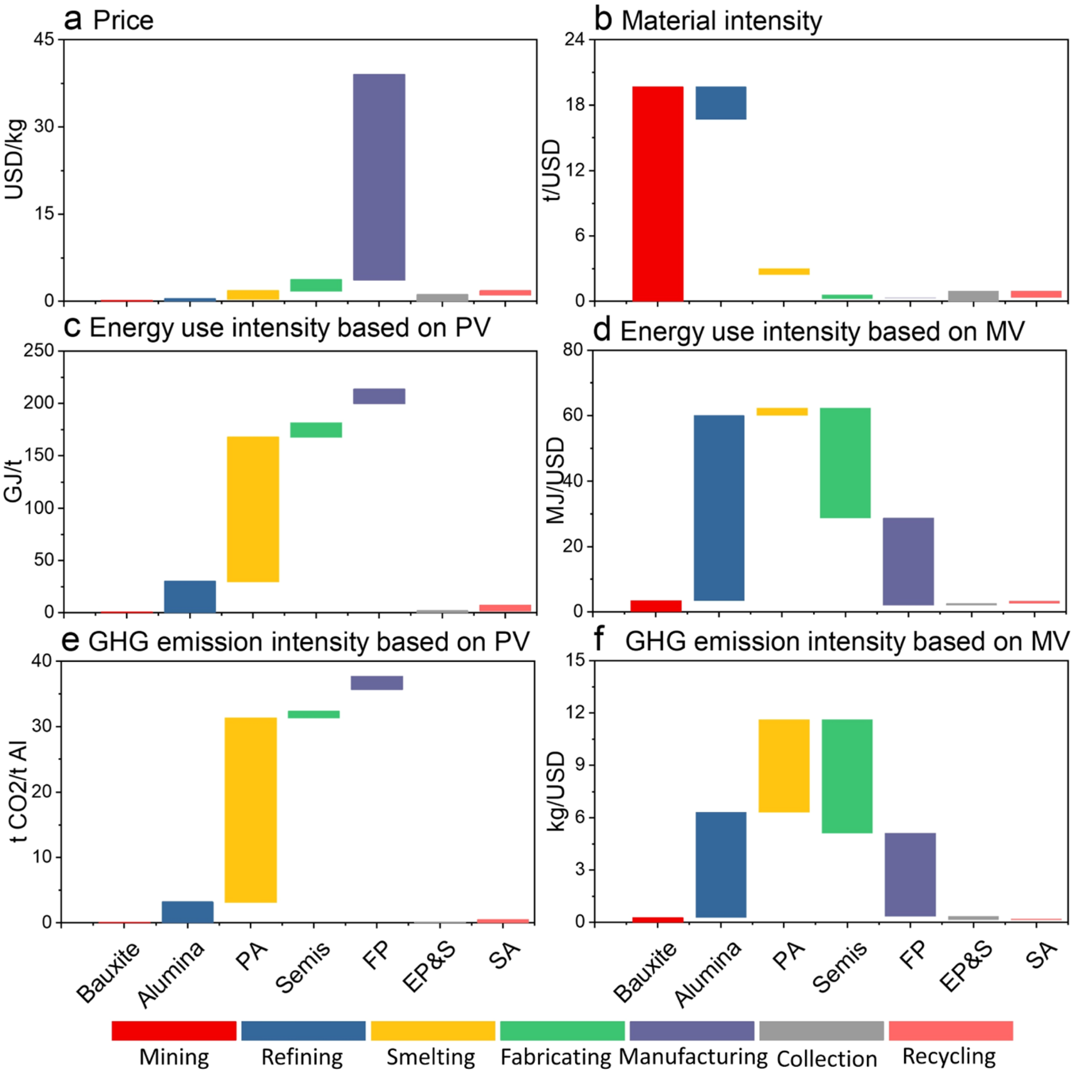


Figure 6. (a) Price, (b) material intensity, (c) embodied energy use intensity based on physical value, (d) embodied GHG emission intensity based on physical value, (e) embodied energy use intensity based on monetary value, and (f) embodied GHG emission intensity based on monetary value of different ACP groups. Price is the average of these four countries' export and import prices. PV = physical value, MV = monetary value; price = monetary value per *t* Al; material intensity = *t* Al per USD; energy use intensity based on monetary value = CTP energy use per *t* USD; GHG emission intensity based on monetary value = CTP GHG emissions per USD; energy use intensity based on physical value = CTP energy use per *t* Al; GHG emission intensity based on physical value = CTP GHG emissions per *t* Al.

The quantity of exported aluminum products is 25 times that of imported semis and FPs.

3.3. Economic Consequences. All four countries have monetary trade imbalances during 1991–2016. Except for Japan, trade imbalances in China, the United States, and Australia have continued to widen (see Figures 4 and S7). With the rapid increase of FP export, China's aluminum monetary trade has undergone a sharp increase. China became a country with monetary surplus in 2000 and overtook Japan as the country with the highest aluminum trade gains in 2008. The United States turned into a net importer of FPs in 1999, resulting in monetary trade deficits since then that have widened with the rapid increase of FP import. Australia, although a main country that exports aluminum ore and concentrates in the global aluminum cycle, suffered from negative monetary imbalances because of the import of finished products, which have generally higher prices than aluminum ores and concentrates. Australia's trade deficit is lower and is growing more slowly than that of the United States. Japan has always been a surplus country in monetary flow from 1991 to 2016. With the decline of net exports of FPs in the last decade, Japan's trade surplus meets a similar synchronized decline. Overall, these four countries' aluminum trade in monetary value is dominated by FPs because FPs have much higher prices than other ACPs (see Figure 4).

3.4. Energy and Environmental Consequences. The trade balance of embodied energy and GHG emissions in each country is demonstrated together because energy use and GHG emissions are linked and provide similar insights. Aluminum international trade has led to a reallocation of energy use and GHG emissions for the four target countries over the study period (see Figures 5, S8, and S9). China, as the largest manufacturer of semis and FPs in the world, carries a large net burden in domestic energy use and GHG emissions, totaling 13.0 EJ and 2.8 $\mathrm{Gt_{CO2eq}}$ during the whole research period. Australia, as a main resource provider, bears 8.65 EJ energy and 1.2 $\mathrm{Gt_{CO2eq}}$ environmental costs from 1991 to 2016, especially in UA and alumina trade. The United States is

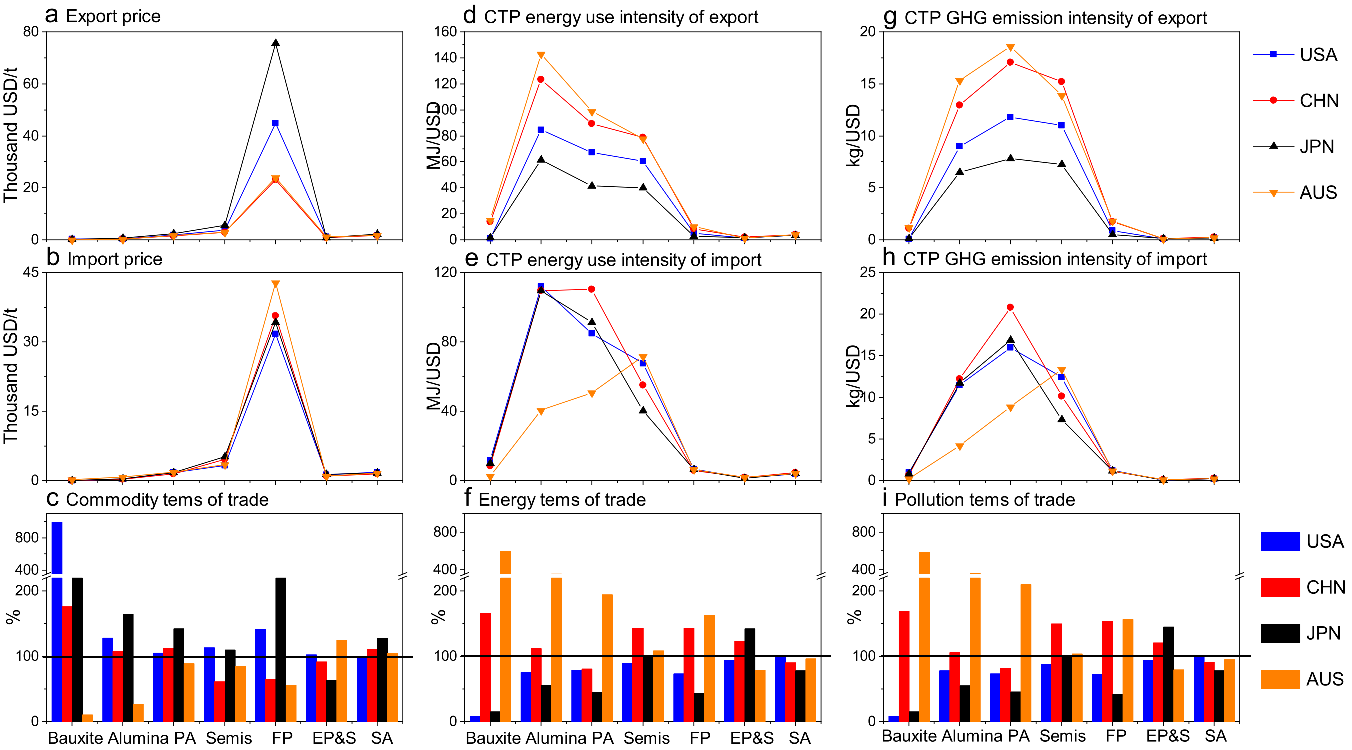


Figure 7. Seven ACP groups' (a) export price, (b) import price, (c) CTOT, (d) CTP energy use intensity of export, (e) CTP energy use intensity of import, (f) ETOT, (g) CTP GHG emission intensity of export, (h) CTP GHG emission intensity of import, and (i) PTOT of these four countries during 1991 to 2016. CTOT = export price/import price. ETOT = CTP energy use intensity of export/CTP energy use intensity of import. PTOT = CTP GHG emission intensity of export/CTP GHG emission intensity of import.

a net exporter of embodied energy and GHG emissions. Due to the import of nearly all types of ACPs, the United States has outsourced 12.9 EJ energy and 2.4 $\mathrm{Gt_{CO2eq}}$ GHG emissions in the whole research period. Like China, Japan exported mainly semis and FPs. However, Japan is also a net exporter of energy and GHG emissions. This is because UA, semis, and FPs have the highest energy and GHG emission intensities (about 31–38 $t\mathrm{CO_2}/t$ Al). Japan mainly net-imported UA at quantities 3 times that of semis and FPs it exported, offsetting the energy and environmental burden from exported ACPs. China, on the other hand, has a balance in UA trade, which cannot compensate the energy and environmental burdens from exported FPs and semis.

3.5. Reasons for Unequal Exchange. Based on previous studies,[57−59] the reasons for these heterogeneous gains and losses in aluminum trade among the four countries include the following: (1) different structures of aluminum trade; (2) the heterogeneity among different ACPs and ACP groups; and (3) the heterogeneity of the same ACP or ACP group produced in different countries. We analyze on these reasons below.

3.5.1. Different Structures of Aluminum Trade. Our multidimensional analyses show that these four countries play totally different roles in the global aluminum trade system, with Australia being mainly as a resource provider, China as a low-tech producer, Japan as a high-tech manufacturer, and the United States mainly as a consumer. As shown in Figure 3, the United States imported all ACPs except scrap. The amount of scrap the United States exported was very small, so the monetary value and the embodied energy and GHG emissions were far from compensating those of other imported ACPs. Australia was the only country that exported bauxite, alumina, and UA, and its physical trade was dominated by the export of these three with low value-added products. The profits Australia earned from these products were not enough to offset the costs this country had to pay for the import of high value-added FPs, and it suffered from substantial burdens of energy use and GHG emissions for the exported alumina and UA. Both China and Japan imported low value-added products but in different forms. China mainly imported bauxite, alumina, and scrap for smelting aluminum, which is very energy- and emission-intensive, while Japan mainly imported UA and , hence, outsourced almost all resources, energy- and emission-intensive industrial processes, such as refining and smelting (see Figure 6). Both China and Japan exported FPs, but the former country also exported many semis, which have higher value than UA but lower than most FPs.

3.5.2. Heterogeneity among Different ACPs. ACPs are heterogeneous because the same kilogram of aluminum contained in different ACPs can have different prices and different embodied CTP environmental burdens (see Figure 6). Generally, an ACP with higher manufacturing degrees will have higher prices and higher embodied CTP energy use and GHG emissions because each additional industrial process requires additional inputs of labor, raw materials, and energy and generates more emissions. However, as illustrated in Figure 6, the two processes with the highest energy use and GHG emissions are PA smelting and alumina refining, while the processes with the highest value addition are FP manufacturing and semis fabrication. In particular, the high energy and emission intensities of PA smelting results in a dramatic difference of embodied CTP environmental burdens among the group of bauxite, alumina, and scrap and the group of UA and manufactured products. Conversely, the high value-added FP manufacturing results in a considerable difference in monetary prices between the finished products and all other ACPs. Therefore, countries, like Japan, that import UA and export manufactured products can transfer energy and environment burdens to the trade partners, while those countries, like Japan and China, that export FPs can earn profits from the international trade.

3.5.3. Heterogeneity of ACPs Produced in Different Countries. The same ACP or ACP groups produced in different countries can have different CTP-embodied energy use, GHG emissions, and value additions. This is because different countries have different industrial technologies, energy mixes and efficiencies, GHG emission intensities per energy use, labor productivities, and intellectual levels. This heterogeneity can be explained by the so-called "terms of trade"[60] and relevant extensions. Commodity terms of trade (CTOT), energy terms of trade (ETOT), and pollution terms of trade (PTOT) are used to estimate the countries' ability to obtain money, energy, and environmental benefits from international trade.[61] The higher the CTOT, the better ability that countries have to obtain money benefit; while the lower the ETOT and PTOT, the better ability that countries have to obtain energy and environmental benefits (see section 5 of the Supporting Information). As shown in Figure 7, an item produced and exported from Japan and the United States generally has higher value addition and lower CTP-embodied energy use and GHG emissions than in other countries. In contrast, an item produced in China and Australia generally has lower value addition and higher CTP-embodied energy use and GHG emissions than in other countries. This means that, when exporting the same product, China and Australia earn less profits but bear higher environmental burdens than Japan and the United States. Fortunately, the CTOT, ETOT, and PTOT of China and Australia have been improved during the past 26 years, especially in their main exported ACPs (see Figure S10−S12).

4. DISCUSSION

This study provides an attempt to couple different dimensions of trade analyses to explore both the direct and indirect impacts of aluminum trade in the United States, China, Japan, and Australia—four main actors in the global aluminum industry but with different profiles in the aluminum supply chain. These four countries have different gains and contributions in the aluminum international trade, which mainly result from the different and changing structures of aluminum trade and the heterogeneity of ACPs in different countries, and these two factors reflect the different comparative advantages of these four countries.

With very rich natural resource and energy endowment, Australia plays an irreplaceable role of providing minerals (including bauxite) and raw products to the world; however, its manufacturing industries are relatively weak compared to those of the other countries. The United States used to have the strongest manufacturing capacity during 1940s to early 1970s, and they were a net exporter of aluminum semis and FPs in most of the 1970s.[62] Then, the United States gradually moved part of its energy- and emission-intensive industries, such as the aluminum smelting industry, to other countries: this production shift has determined a reduction of alumina import and also an increase of FP import after 2000. However, it is worth noting that the United States still has the capability of alumina refining, aluminum smelting, and especially semis manufacturing. Theoretically, the United States could rely entirely on the domestic capacity to meet the internal demand for aluminum semis, and it is the only country out of the four that generates such a large amount of old scrap that can be exported.[4] As a country lacking in natural mineral resources, Japan must import aluminum. However, its high energy prices and strict environmental regulation restricted the development of alumina refining and aluminum smelting industries in Japan;[63] thus, it imports UA ingot rather than bauxite or alumina. In addition, Japan became one of the global manufacturing countries since 1970s[62] and has been very competitive in the manufacturing of aluminum semis and FPs. China achieved a rapid growth of manufacturing capacity after it entered the World Trade Organization in 2001[41] and subsequently experienced sharp increases in the import of bauxite, alumina, and scrap and in the export of semis and FPs. However, this also resulted in the corresponding high energy use and environmental emissions/pollutions in China.[64]

Our results suggest that complete equality in the international trade seems extremely difficult to achieve. Some processes are not cost-effective, such as mining which has high resource cost or refining and smelting which have high energy and environmental cost (see Figure 6b,d,f). Countries that have capacity for mining, refining, or smelting processes will pay more for the same profits than other countries. Outsourcing these processes is a good strategy for competitive countries and has happened in the past decades. Four of the five bauxite mines in Australia are controlled by two multinational corporations that are headquartered outside of the country. With significant shifts of refining and smelting capacity from the United States and Japan to China over the past decades, the latter has become the center of PA production.[47] For China, outsourcing mining, refining, or smelting processes and exporting high-value semis and FPs is the best development strategy, while Australia needs to continue to extend the production chain and produce more semis and FPs. Once Australia and China upgrade their aluminum industries and produce higher technology products, relocation of these low cost-effective processes from these two countries can be expected.

However, strategies that are beneficial at a country level may simply transfer the resource and environmental burden to other countries, perpetuating trade inequality on a global level. Countries do not always have clear motivations to reduce their own gains and help other counties achieve trade balances. On the contrary, they tend to enlarge their comparative advantage and gain benefits from the international trade. Hence, actions to reduce trade inequality and lessen the overall energy and environmental burdens of industrial manufacturing need to be considered within a global framework.

Aluminum scrap is another source of aluminum besides bauxite. SA, as the downstream product of aluminum scrap, can supplement primary or virgin aluminum inputs but generally at far lower energy and environmental costs. Hence, further developing the global aluminum recycling system is a way to help reduce trade inequalities. To make full use of the available aluminum scrap, improvements in domestic collection, classification, and pretreatment capability are necessary to prevent aluminum from quality degradation during recycling,[65] even if this scrap is exported and recycled by other countries.[66]

However, the current amount of aluminum scrap is far from being sufficient to substantially reduce the reliance on bauxite extraction and PA production.[67] If countries that produce PA have less efficient technologies with high energy and GHG emission intensities in their aluminum industries, then the relocation of production to these countries may increase the total resource use and emissions on a global level. To address these challenges, one strategy is to incentivize the adoption of advanced production techniques and green technologies along with the relocation of these industries. International organizations such as the WTO, FDI, and the International Aluminum Association can further promote countries to reduce green technology trade restrictions.[68]

By coupling multiple dimensions and analyzing the direct and indirect flows of a widely applied metal such as aluminum, this study provides new insights into the global trade inequality issue. We recommend that physical, monetary, and embodied trade flows be considered simultaneously and call for a more careful and comprehensive research for trade policy-making at the commodity level. Besides the four dimensions that are analyzed in this study, there are other factors that could be included in future studies to gain a comprehensive understanding of different countries' comparative advantages as well as real gains and losses in the trade of aluminum as well as of other materials. These factors include, but are not limited to, water use, labor input, land use, toxic emissions, impacts on human health, and the ecosystem. To further strengthen the findings or reveal additional insights, integration of the method developed in this study with complementary quantitative information achievable by means of MFA/SFA techniques or extended input−output methods is highly recommended.

4.1. Uncertainty Analysis. All flows need to be calculated based on the aluminum content data, which may have a high variability. We collected the highest and the lowest content levels reported from former studies[41,56] and used the full ranges to evaluate the robustness of the results. We find that aluminum contents only affect the scales of these four flows but not the trends and directions, suggesting that the conclusions in this study are relatively robust (Supporting Information section 6 and Figure S4).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c08836.

> Detailed information about monetary value, physical value, embodied energy use, GHG emissions, calculation methods, and results (PDF)

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Notes

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■ ACKNOWLEDGMENTS

This study was sponsored by the National Natural Science Foundation of China under the project 71961147003 and Key Research Project of Frontier Science of Chinese Academy of Sciences (no. QYZDB-SSW-DQC012).

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