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Multi-Dimensional Analyses Reveal Heterogenous Gains and Losses among the Global Aluminum Trade leaders

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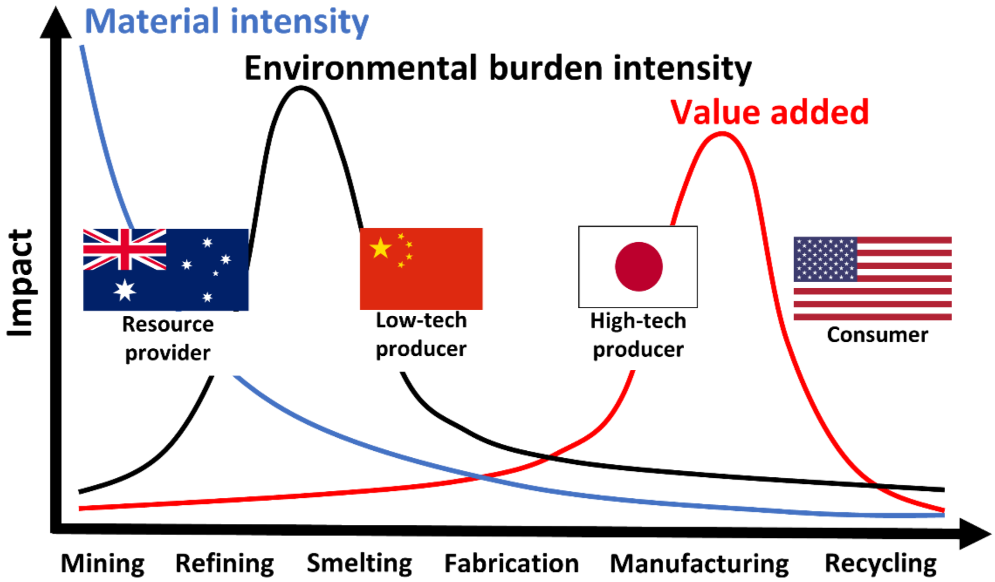
ABSTRACT: Disputes around trade inequality have been growing over the last two decades, with different countries claiming inequality in different terms including monetary deficits, resource appropriation and degradation, and environmental emissions transfer. Some studies have noted and analyzed the complexity of trade imbalances and their various consequences, but lacked industrial perspective and not provided enough insights about the formation mechanism and solutions. This paper quantifies (1) the direct monetary flows, (2) direct resource flows, and (3) indirect energy use and GHG emissions embodied in aluminum trade for the four economies with the highest aluminum trade flows, *i.e.*, US, China, Japan, and Australia. Results show that resource-related trade inequalities indeed not uniform across economic and environmental impacts. The US has a negative balance in monetary flows but positive balances in resource flows, embodied energy use and GHG emissions. China has a positive balance in monetary and resource flows but negative balances in embodied energy use and GHG emissions. Japan has a positive balance 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. In country level, outsourcing mining process which has the highest material intensity and refining and smelting processes which have the highest environmental burden intensity, and keeping domestic manufacturing which has the highest value added and exporting finished products is a good developing strategy. To reduce trade inequality in world level, global aluminum recycling system should be developed and the production and green technologies transfer between countries should be promoted.

KEYWORDS: aluminum; trade inequality; embodied energy; embodied GHG emissions; material flow analysis; sustainable resources management



Material intensity
Environmental burden intensity
Value added
Impact
Resource provider
Low-tech producer
High-tech producer
Consumer
Mining
Refining
Smelting
Fabrication
Manufacturing
Recycling

TOC art

1. INTRODUCTION

Disputes around trade inequality have been growing in the last two decades. Different countries have claimed they have suffered from trade inequality in various terms, which can be characterized by: (1) Trade deficits in monetary terms,[1] *e.g.*, large and chronic US trade deficits with other countries, such as China, have resulted in US unemployment and economic slowdown; (2) Ecological burden,[2] *e.g.*, through export-oriented extraction or manufacturing industries and the import of various solid wastes from developed economies, countries like China have experienced increases in environmental pollution and human health impacts; and (3) Resource appropriation and degradation,[3] *e.g.*, mines in Australia, Latin America, and Southeast Asia that have the richest reserves have become the focus of global competition. Because of that, since 2018, international trade tensions have increased markedly, particularly between the US and other countries including China, Canada, Mexico, and several European Union countries.[4–6] In the same year, China banned the import of 24 types of waste, followed by Vietnam, Malaysia, and Thailand.[7,8] Recognizing the growing significance of critical minerals for high-tech industries, Australia has implemented the critical minerals strategy to promote the country's minerals extraction and downstream processing sectors.[9] These and other measures are justified under the auspices of protecting themselves from the negative effects of unequal trade.

International trade results in the geographic reallocation of traded commodities and the capital, labor, natural resources such as water and land, materials, and energy, and environmental emissions embodied in these flows.[10] For a specific commodity, flows from country A to country B can be classified into direct flows and indirect flows (Figure 1). Direct flows include physical flow and monetary flows, 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 directions.

When a country experiences unbalanced direct and indirect trade flows, unequal exchange happens. Unequal, however, does not necessarily mean unfair[11] 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,[11] with a focus on the inequality of monetary flows usually measured by US dollar.[13] It was then introduced into the research field of resource and environmental systems analysis in the end of 1980s.[14,15] Since then, the direct physical flow measured by the mass of materials traded among countries is often analyzed,[16,17,17,18] as well as virtual flows of water[19–21], land use[22,23], energy use[24,25] and environmental emissions[26–28] embodied in international trade. Particularly, there is a rapidly 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'.[29,30] With the complexity and multi-dimensional nature of international trade has been paid attention recently, some studies considered more than one impact from the international trade and highlight the mismatch of countries' benefits and costs in international trade. [26,28,31,32] Despite the important insights discovered in previous studies, there is a lack of the analysis on industry level, and most of studies didn't provide ample understanding of the formation mechanism and solutions.

Here, we report on an industry study that aims to understand the broad impacts of international trade and explore the reasons, by examining both the direct and indirect trade flows and multiple consequences from physical flows and monetary flows to indirect energy use and GHG emissions.

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.[33] In addition, the production of alumina and primary aluminum is highly energy and GHG emissions intensive. Prior research showed that in 2014 the aluminum industry accounted for 4% of global industrial final energy demand and 3% of industry's total direct CO_2 emissions.[34] Trade in aluminum has also been the focus of recent political activity; for example, the US investigated the effects of aluminum imports on the national security and proclaimed a 10% *ad valorem* tariff on aluminum articles in March 2018.[35]

We focus on the global leaders of aluminum trade: the US, China, Japan, and Australia. The former three countries are the top three importers, while the latter is the top exporter.[36] US, China, and Japan are also the three largest economies in the world, together accounting for ~50% of global gross domestic product (GDP). 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

Identification of aluminum-containing products (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 (SI)).[33,37,38] More than one hundred ACPs are identified (Table S1 in the SI) and are classified into six groups according to their position in the value chain: (1) bauxite, (2) alumina, (3) end of life (EOL) products & scrap (EP&S), (4) unwrought aluminum (UA), (5) semis, and (6) finished products (FP). The first, second and third groups can be regarded as raw materials to produce unwrought aluminum, while the fifth and sixth groups consist of semi-finished products and finished products, respectively. There are two sources of unwrought aluminum: primary aluminum (PA), produced from natural ores and concentrates (*e.g.*, bauxite), and secondary aluminum (SA), produced from EOL products & scrap (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[39] or their data are unavailable[40].

Calculation of direct and indirect trade flows. A diagram illustrating data sources and decision tree used in the calculating of these four trade flows of aluminum contained in each ACP is shown in SI (see Figure S2) and all the equations can be seen in section 3 of the SI.

Direct trade flows (monetary and physical flows) are collected directly from the UN Comtrade Database[41] 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 finished products for a few years. Adjusted by US consumer price index,[42] monetary trade value is converted into 2000 US dollars. ACP's monetary trade value is then allocated to the 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 SI). For those FP which physical trade data do not exist, physical trade values are estimated by dividing monetary trade value in constant 2000 US dollars by prices (in constant 2000 US) 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 emissions intensity 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 emissions intensity of aluminum in a ACP (indicated by EI_{Al}^{Inc} and GI_{Al}^{Inc}) from 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[43–47] and European Aluminum Association[48–50]), which provide a LCI data sets[51] by production process (process-based LCA) for multiple years that is periodically updated. Both direct and indirect energy use and GHG emissions are calculated (Figure S1 in the SI). Energy use and GHG emissions from transportation process are not considered because they are commodity-specific and have been shown to be relatively insignificant. Primary aluminum production and secondary aluminum through EP&S management (including EP&S collection, sorting, separation, and recycling) are considered as two independent systems. That means CTP energy use and GHG emissions intensities of EP&S are calculated starting from collection instead of mining.

Input-Output LCA (IOLCA) method is used to estimate energy use and GHG emissions intensity for manufacturing process of each finished ACP, because LCI data for each individual manufacturing process are unavailable. Burdens are calculated using aggregate energy use and GHG emissions intensities for the industry sector to which each finished ACP belongs (Table S1 in the SI). To avoid double counting, only direct energy use and GHG emissions for 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 (PTB) or monetary trade balance (MTB) means countries gain resources and economic benefits from international trade. A positive embodied energy use balance (EUB) and embodied GHG emission balance (EEB) means 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.

Uncertainty analysis. As all of flows need to be calculated based on aluminum content data which may have high uncertainty, we collected the highest and lowest contents from former studies[37,52] and compared all the results. Results show that aluminum contents only have effect on the scale of these four flows instead of the trends and directions, which show that the conclusions in this study are relatively robust.

3. RESULTS

3.1 Gains and contribution of these four countries

Contributions and gains of each targeted country are shown in Figure 2 and Figure S4. Overall, the four countries resulted in unequal trade in these four flows for years 1991-2016. More precisely, the US has negative balance in monetary value and positive balance in resources, energy, and GHG emissions. China has negative balance in energy and GHG emissions and 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 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 is accounted 55% of Australia's total export in 2016), has a negative balance in all flows.

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 is hugely expanded its production, manufacturing capacity, and final demand for aluminum. China became 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 S4). The US had positive balance in all flows before 1999. Then, with the decrease of domestic aluminum-containing products output,[33] 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 Resources consequences

None of the countries showed a neutral balance in physical flows from 1991 to 2016 (see Figure 3). The US was a net-importer over the entire study period. Except for EP&S, the US imported all groups of ACPs, especially bauxite, unwrought aluminum, and finished products. China's aluminum imports have grown very fast and overtook those of Japan in the year 2002 and of the US in the year 2009 as the biggest net aluminum importer. As the major manufacturer, China mainly imported commodities like bauxite, alumina, and EP&S, and exported finished goods and semis, such as building & construction products and consumer durables. For unwrought aluminum, China maintained an almost stationary the balance between imports and exports. At 2016, Japan was the third largest aluminum importer. Japan mainly imported unwrought aluminum and exported finished products mainly transportation equipment. 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, unwrought aluminum, while imported finished products and semis to meet the domestic demand.

3.3 Economic consequences

All four countries have monetary trade imbalances during 1991-2016. Except for Japan, trade imbalances in China, US, and Australia have continued to widen (see Figure 4 and Figure S6). With the rapid increase of finished products 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 US turned into a net-importer of finished products in 1999, resulting in monetary trade deficits since then that have widened with the rapid increase of finished products import. Australia, although it is a main country exporter aluminum ore and concentrates in the global aluminum cycle, it suffered from negative monetary unbalances because of the import of finished products, which have generally higher prices than aluminum ores and concentrates. Australia's trade deficit is lower and it is growing more slowly than that of the US. Japan has always been a surplus country in monetary flow from 1991 to 2016. With the decline of net-exports of finished products in the last decade, Japan's trade surplus meets a similar synchronized decline. Overall, these four countries' aluminum trade in monetary value are dominated by finished products, because finished products have much higher prices than other ACPs (see Figure 4).

3.4 Energy and environmental consequences

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 Figure 5, Figure S7, and Figure S8). China, as the largest manufacturer of semis and finished products to the world, carries a large net burden in domestic energy use and GHG emissions that sum amounts are 130×10^{17} J and 283×10^{7} t_{CO2eq} during the whole research period. Australia, as a main resources provider, bear 865×10^{17} J energy and 117×10^{7} t_{CO2eq} environmental costs from 1991 to 2016, especially in unwrought aluminum and alumina trade. The US are a net-exporter of embodied energy and GHG emissions. Due to importing nearly all types of ACPs, the US have outsourced 129×10^{17} J energy and 236×10^{7} t_{CO2eq} GHG emissions in the whole research period. Like China, Japan exported mainly semis and finished products. However, Japan is also a net-exporter of energy and GHG emissions. That is because unwrought aluminum, semis and finished products have the highest and similar energy and GHG emissions which are about 31-38 tCO2/t Al. Japan imported three times of unwrought aluminum than exported finished products and semis, offsetting the energy and environmental burden from exported ACPs. While, China meets a balance in unwrought aluminum trade which can't compensate the energy and environmental burden from exported finished products and semis.

3.5 Reasons for unequal exchange

Based on previous studies[53–55], reasons for these heterogenous 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:

- **Different structures of aluminum trade.** Our multi-dimensional analyses show that these four countries play totally different roles in the global aluminum trade system, with Australia mainly as a resource provider, China a low-tech producer, Japan as high-tech manufacturer, and the United States mainly as a consumer. As shown in Figure 3, the US imported all ACPs except scrap. The amount of scrap the US 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 unwrought aluminum, 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 added finished products and it suffered from substantial burdens of energy use and GHG emissions for the exported alumina and unwrought aluminum. 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 emissions intensive, while Japan mainly imported unwrought aluminum, hence, can outsourced almost all resources, energy, and emissions-intensive industrial processes, such as refining and smelting (see Figure 6). Both China and Japan exported finished products, but the former country also exported many semis, which have higher value than unwrought aluminum but lower than most finished products.

- **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 emission, 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 primary aluminum smelting and alumina refining, while the processes with the highest value-added are finished product manufacturing and semis fabrication. In particular, the high energy- and emissions-intensity of primary aluminum smelting results in a dramatic difference of embodied CTP environmental burdens among the group of bauxite, alumina, scrap, and the group of unwrought aluminum and manufactured products. Conversely, the high value added of finished products manufacturing results in a considerable difference of monetary prices between finished products and all other ACPs. Therefore, those countries, like Japan, that import unwrought aluminum and export its manufactured products can transfer energy and environment burdens to trade partners, while those countries, like Japan and China that export finished products can earn profits from the international trade.

- **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 added. 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 "term of trade"[56] and relevant extensions. Commodity terms of trade (CTOT), energy terms of trade (ETOT) and pollution terms of trade (PTOT) are used to estimate countries' ability to obtain money, energy and environmental benefits from international trade.[57] The higher the CTOT, the better; while the lower the ETOT and PTOT, the better (see section 5 of the SI). As shown in Figure 7, an item produced and exported from Japan and the US generally has higher value-added 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-added 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 US. Fortunately, China and Australia's CTOT, ETOT, and PTOT have been improved during the past 26 years, especially in their main exported ACPs (see figure S9-11).

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 US, 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 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 US used to have the strongest manufacturing capacity during 1940s-early 1990s and they were a net exporter of aluminum semis and finished products in most 1990s.[58] Then, the US gradually moved part of its energy and emissions intensive industries, such as the aluminum smelting industry, to other countries: this production shift has determined a reduction of alumina import but also an increase of finished products import after 2000. However, it is worth noting that the US still have capability in alumina refining, aluminum smelting, and especially semis manufacturing. Theoretically, the US 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;[59] thus, it import unwrought aluminum ingot rather than bauxite or alumina. In addition, Japan became one of the global manufacturing countries since 1970s[58] and has been very competitive in the manufacturing of aluminum semis and finished products. China had a rapid growth of manufacturing capacity after it entered the World Trade Organization in 2001[37] and subsequently experiences sharp increases in the import of bauxite, alumina, and scrap and in the export of semis and finished products. However, it also resulted in the corresponding high energy use and environmental emissions/pollutions in China.[60]

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 who have 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 it is happening 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 US and Japan to China over the past decades, the latter has become the center of primary aluminum production.[43] 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, this good strategy in country level can only transfer resource and environmental burden among countries. It cannot reduce trade inequality in world level. In fact, countries do not have motivations to reduce their own gains and help other counties achieve trade balance. On the contrary, they tend to enlarge their comparative advantage and gain benefits in more aspects from the international trade. So, reducing trade inequality need to be done in world level.

Aluminum scrap is another source of aluminum besides bauxite. Secondary aluminum, as the down-stream product of aluminum scrap, supplements primary aluminum inputs but generally at lower energy and environmental costs. Hence, developing a global aluminum recycling system is a chance to help balance trade inequalities. To make full use of every aluminum scrap, countries have responsibility to have a well domestic collection, classification, and pretreatment capability to prevent from being degraded using, even if these scraps are exported and recycled by other countries. However, the current amount of aluminum scrap is far from being enough to reduce reliance on bauxite extraction and further processing, making the demand for and production of primary aluminum unavoidable. If countries that produce primary aluminum have backward technologies and high energy and GHG emissions intensities in their aluminum industries, relocation of these processes to these countries may increase the total resource use and emissions in global level. To address these challenges, one strategy is to transfer advanced production technologies and green technologies along with the relocation of these industries. International organizations, such as WTO and international aluminum association, should promote to reduce production and green technology restrictions in aluminum international trade and clean energy.

By coupling multiple dimensions and analyzing the direct and indirect flows of a widely applied metal 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 more careful and comprehensive research for trade policy making. 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.

ASSOCIATED CONTENT

Supporting Information. Detailed information about monetary value, physical value, embodied energy use and GHG emissions calculation method and results (PDF).

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Notes

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FIGURES

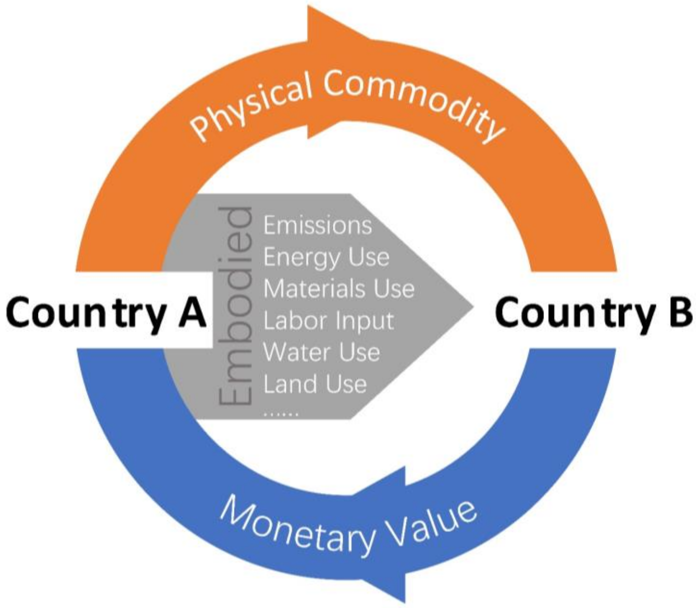
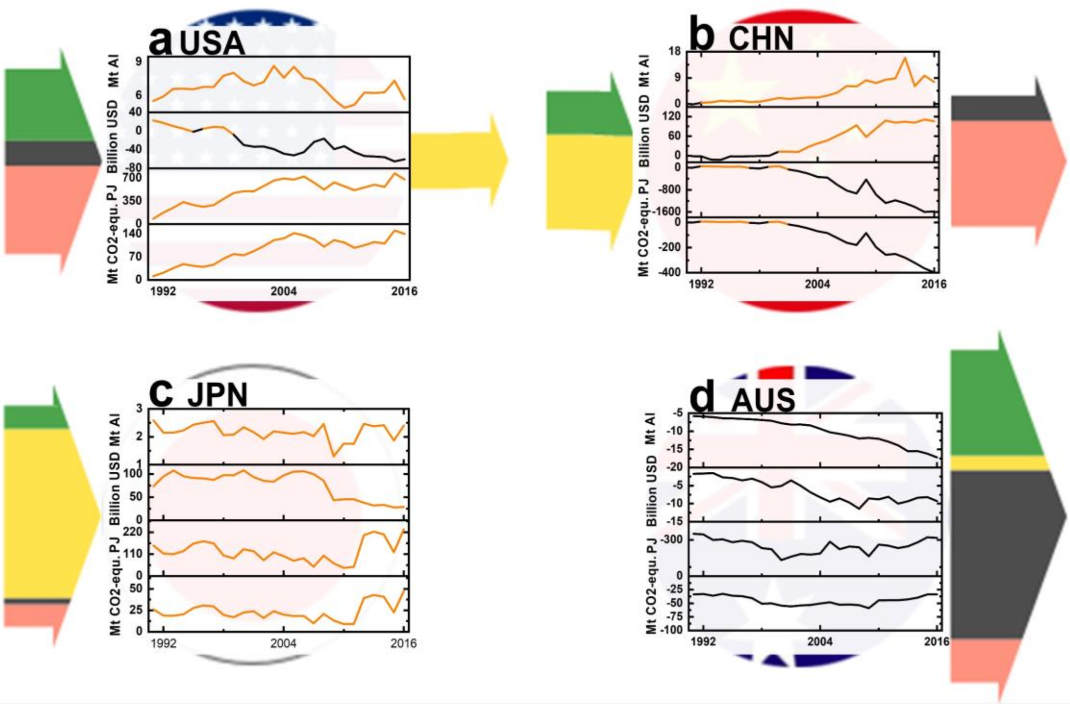


Figure 1. Direct and indirect flows resulting from the trade of a physical commodity. Color flows (physical commodity and monetary value) are direct flows; Grey flows (i.e. embodied emissions, energy use, and so on) are indirect flows.



Total Net-import	Resource	Economic Value	Embodied Energy Use	Embodied GHG Emission
	t Al	USD	J	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) US, (b) CHN, (c) JPN, (d) AUS from 1991 to 2016.

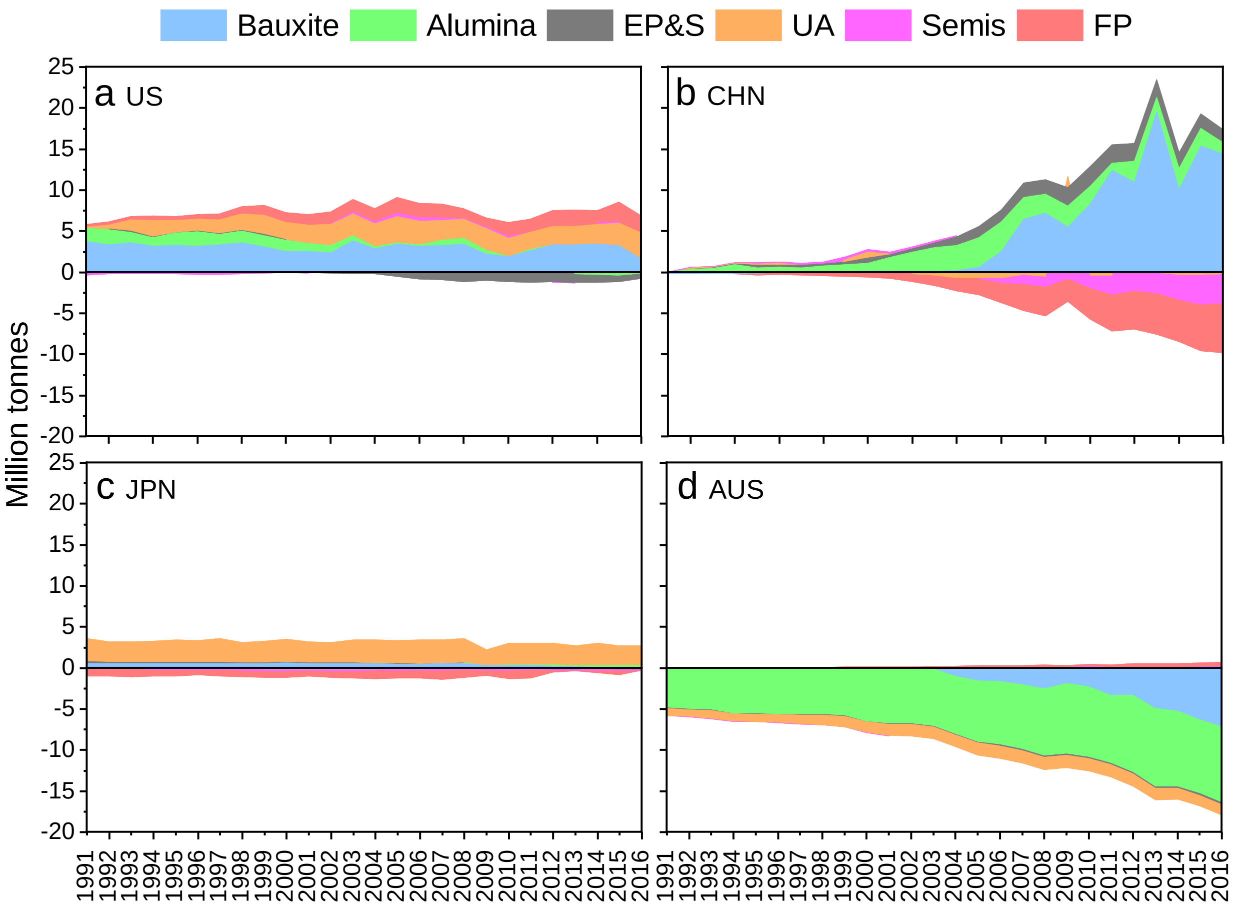


Figure 3. Net import of aluminum embedded in different product groups measured by mass for (a) the US, (b) China, (c) Japan, and (d) Australia from 1991 to 2016. EP&S = EOL Products & Scrap, UA = Unwrought Aluminum, Semis, FP = Finished Products, Mt = Million tonnes.

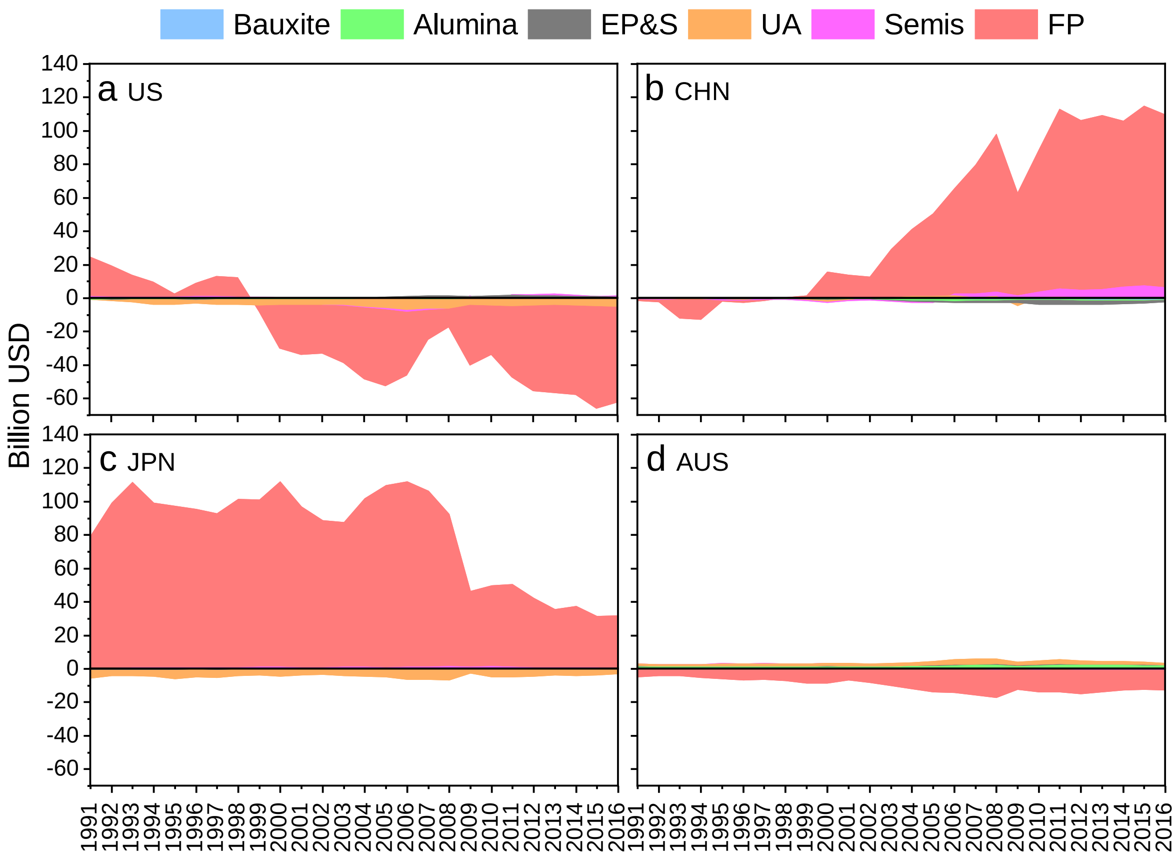


Figure 4. Money net-earned by trade of different ACP groups for (a) the US, (b) China, (c) Japan, and (d) Australia from 1991 to 2016. EP&S = EOL Products & Scrap, UA = Unwrought Aluminum, Semis, FP = Finished Products.

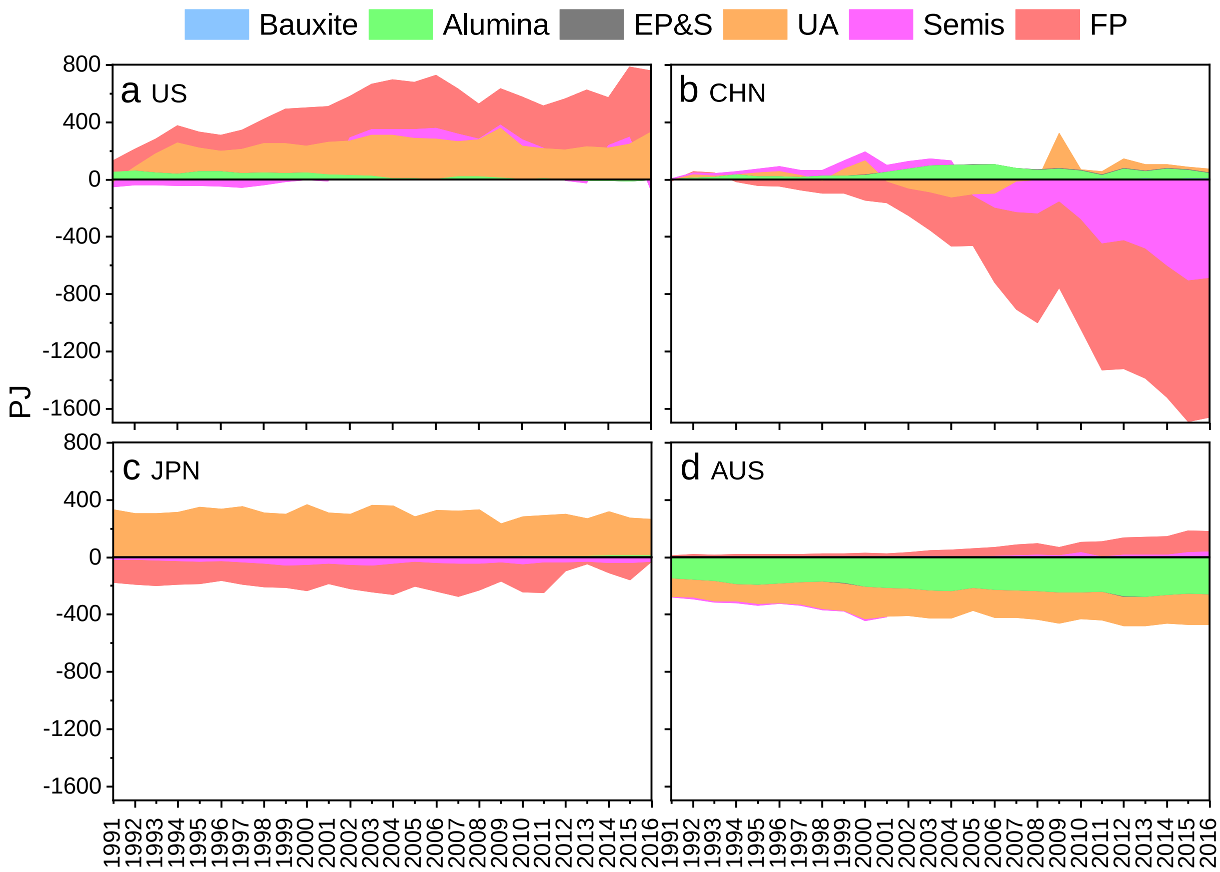


Figure 5. Net import of embodied energy in aluminum trade for (a) the US, (b) China, (c) Japan, and (d) Australia from 1991 to 2016. EP&S = EOL Products & Scrap, UA = Unwrought Aluminum, Semis, FP = Finished Products, PJ = Petajoule = 10^{15} J.

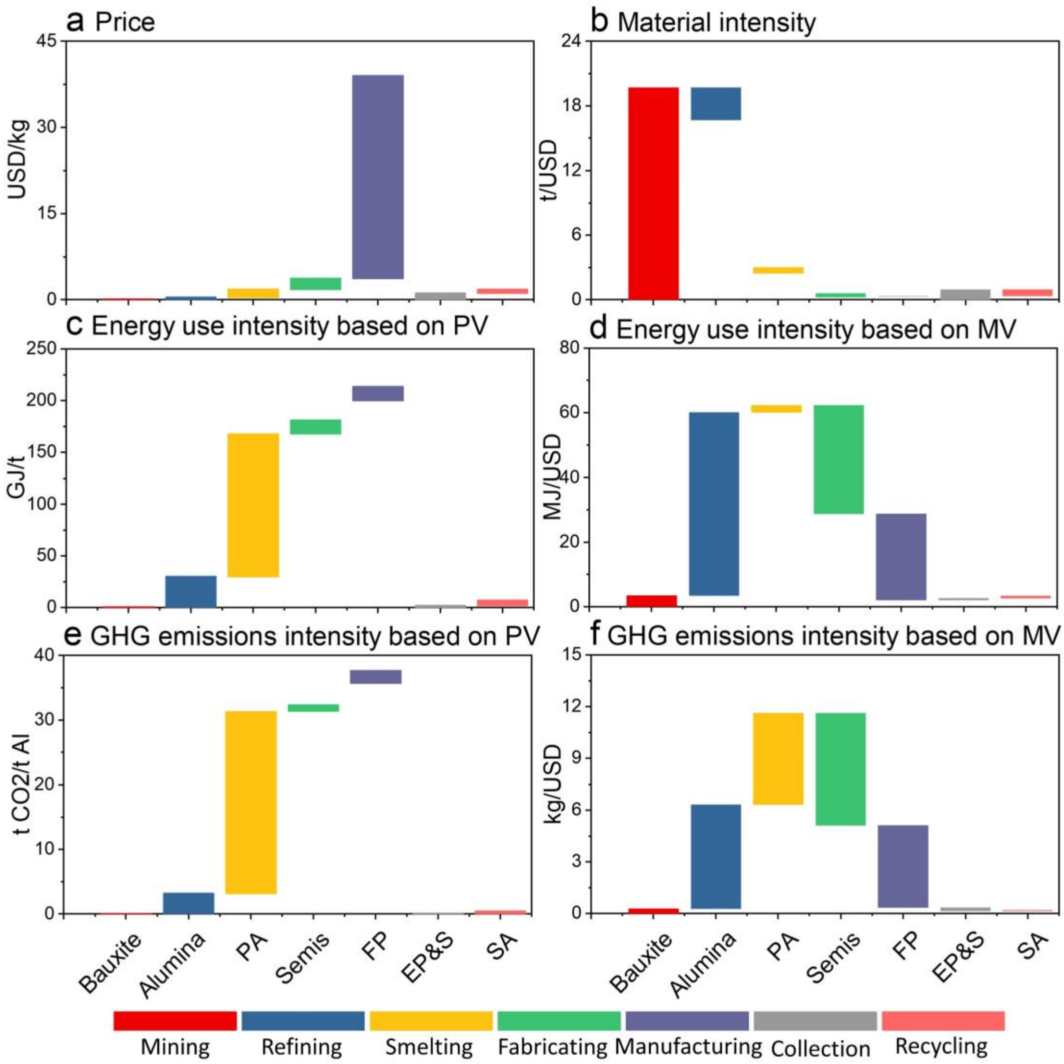


Figure 6. (a) Price, (b) Material intensity, (c) Embodied energy use intensity based on physical value, (d) Embodied GHG emissions intensity based on physical value, (e) Embodied energy use intensity based on monetary value, and (f) Embodied GHG emissions intensity based on monetary value of different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

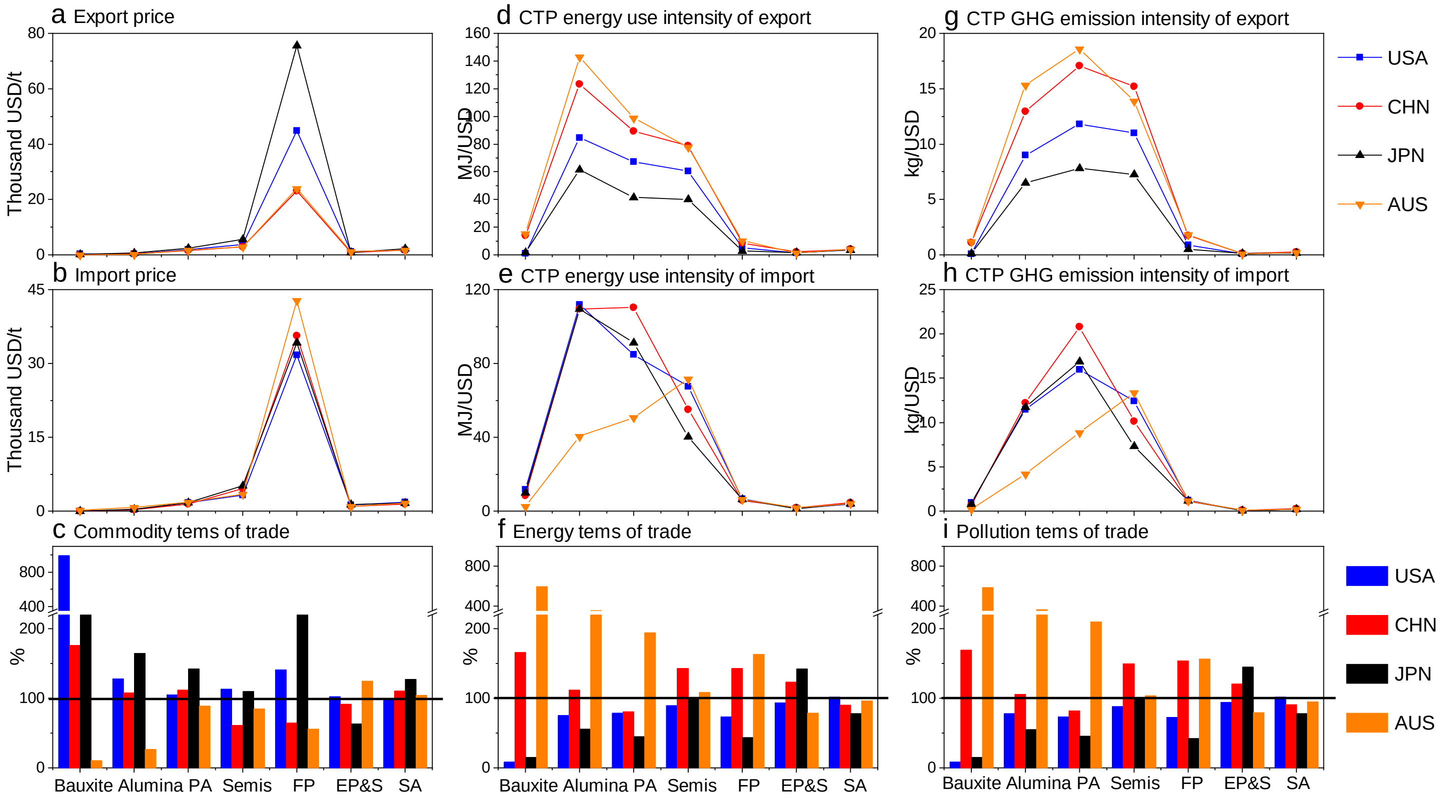


Figure 7. The seven ACP groups' (a) Export price, (b) Import price, (c) Commodity terms of trade, (d) CTP energy use intensity of export, (e) CTP energy use intensity of import, (f) Energy terms of trade, (g) CTP GHG emissions intensity of export, (h) CTP GHG emissions intensity of import, and (i) Pollution terms of trade of these four countries during 1991 to 2016. Commodity terms of trade = Export price / Import price. Energy terms of trade = CTP energy use intensity of export / CTP energy use intensity of import. Pollution terms of trade = CTP GHG emissions intensity of export / CTP GHG emissions intensity of import.

Supporting Information for:

Multi-Dimensional Analyses Reveal Heterogenous Gains and Losses among the Global Aluminum Trade leaders

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Content

6. Life Cycle of Aluminum in the Anthroposphere and Its Life Cycle Analysis Boundary

The life cycle of aluminum in the anthroposphere can be seen in Figure S1, which is composed of eight life stages: Mining, Refining, Smelting, Fabrication, Manufacturing, Use, Collection & Pre-treating, and Recycling. Except Use stage, each of these life stages can produce aluminum-containing products (ACPs) to be traded between countries. These APCs can be seen in table S1. More detailed information about life cycle of aluminum can be seen in the former research[1].

Different from life cycle of aluminum, the boundary of aluminum LCA study also contains Paste/Anode production process and Energy generation process. Energy use and GHG emissions from Mining, Refining, Paste/Anode production, Smelting, Fabrication, Manufacturing, Collection & Pre-treating, and recycling compose the direct energy use and GHG emissions. Indirect energy use and GHG emissions are from energy (both electricity and fuel) generation processes. GHG emissions not only contain carbon dioxide emissions but also perfluorocarbons (PFCs) emissions from smelting process.

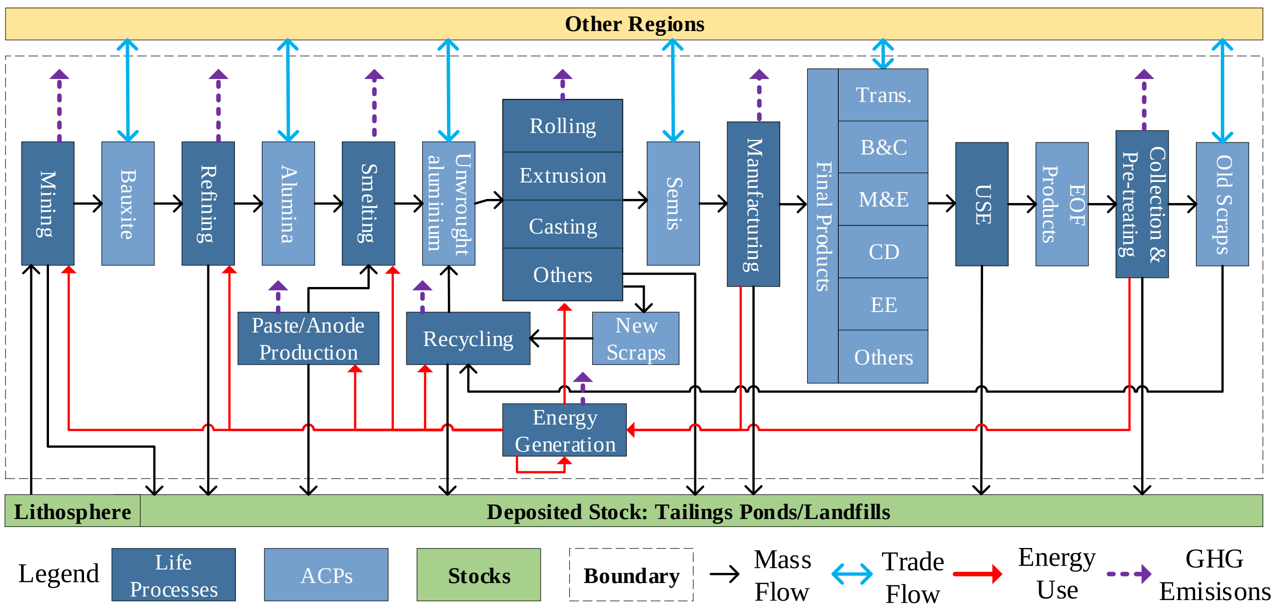

Figure S1: Schematic diagram for the anthropogenic aluminum life cycle and its LCA boundary.

7. The List of Aluminum-Containing Products and Their Aluminum Content

There are 143 items of APCs had been accounted. All the APCs have been divided into six group according to the life stages which can be seen in Table S1. They are Bauxite (2 items), Alumina (1 item), EOL products & Scrap (1 item), Unwrought aluminum (1 item), Semis (6 items), Finished products (132 items). For the finished APCs, based on their applications, we divide them into Transportation (29 items), Building & Construction (6 items), Machinery & Equipment (33 items), Consumer Durables (48 items), Electrical Engineering (7 items), and others (9 items). Codes of ACPs are SITC 1 codes, which is the first version of Standard International Trade Classification. The aluminum concentration for ACPs are also shown in Table SI, and data sources can be found in former research[2,3].

Table S1: The list of aluminum-containing products (ACPs) in the international trade and their aluminum concentration data.

Life Stage	Categories of ACPs	SITC1	Commodity Name	Al Content (%)		
				Average	Bottom	Top
Mining	Bauxite	2833	Bauxite and concentrates of aluminum	27.8	23.8	31.8
		28401[a]	Ash and residues bearing nonferrous metals	50	40	60
Refining	Alumina	51365	Aluminum oxide and hydroxide	43.2	34.3	52.1
Collection & Pre-	EOL products & Scrap	28404	Aluminum waste and scrap	84	80	88

treating						
Smelting & Recycling	Unwrought Aluminum	6841	Aluminum and aluminum alloys, unwrought	95.8	92	99.5
Fabrication	Semis: Sheets & Plates	68422	Plates,sheets and strip of aluminum	95	91	99
	Semis: Foil	68423	Aluminum foil	74	49	99
	Semis: Extrusions	68421	Bars,rods,angles,shapes and wire of aluminum	97	95	99
		68425	Tubes,pipes & blanks,hollow bars of aluminum	98	97	99
		68426	Tube and pipe fittings of aluminum	97	97	97
	Castings	-	-	-	-	-
	Semis: Others	68424	Aluminum powders and flakes	99	99	99
Manufacturing	Transportation, Air	7114	Aircraft incl jet propulsion engines	75	75	75
		7341	Aircraft, heavier than air	67.5	60	75
		7349	Parts of aircraft, balloons airships	67.5	60	75
		89999	Catapults and sim. aircraft launching gear, etc.	75	75	75
	Transportation, Marine	7351	Warships of all kinds	2	1	3
		7353	Ships and boats, other than warships	2	1	3
		7359	Special purpose ships and boats	2	1	3
	Transportation, Rail	71966	Railway & tramway track fixtures & fittings	3	3	3
		7311	Railway locomotives steam and tenders	3	3	3
		7312	Electric railway locomotives, not self generat.	3	3	3
		7313	Railway locomotives, not steam or electric	3	3	3
		7314	Mechanically propelled railway and tramway	3	3	3

			cars			
		7315	Rail & tram passenger cars not mech propelled	3	3	3
		7316	Rail.&tram.freight cars,not mechanically propd.	3	3	3
		7317	Parts of railway locomotives & rolling stock	3	3	3
	Transportation, Road	7321	Passenger motor cars, other than buses	vary in time and region		
		7322	Buses, including trolleybuses	vary in time and region		
		7323	Lorries and trucks, including ambulances, etc.	5.9	5.9	5.9
		7324	Special purpose lorries, trucks and vans	5.9	5.9	5.9
		7325	Road tractors for tractor trailer combinations	3.7	3.6	3.8
		7326	Chassis with engs. Mntd. For vehicles of 732.1	vary in time and region		
		7327	Other chassis with engines mounted	vary in time and region		
		7328	Bodies & parts motor vehicles ex motorcycles	vary in time and region		
		7329	Motorcycles, motorized cycles and their parts	21	12	30
		7331	Bicycles & other cycles, not motorized, & parts	20	20	20
		7333	Trailers & oth vehicles not motorized, & parts	7.55	7.5	7.6
		7334	Invalid carriages	20	20	20
	Transportation, application parts	7113	Steam engines and steam turbines	2	2	2
		7115	Internal combustion engines, not for aircraft	vary in time and region		
	Building & Construction (B&C)	6324	Builders woodwork & prefab. Buildings of wood	10	10	10
		6912	Fin.structural parts & structures of aluminium	99	99	99
		6913	Wire,cables,ropes etc.not insulated,aluminium	99	99	99

		69882	Flexible tubing and piping of base metal	30	30	30
		69884	Bells (non electric),of base metal	30	30	30
		69886	Name plates,sign plates,etc.of base metal	30	30	30
	Machinery & Equipment (M&E)	7111	Steam generating boilers	0.5	0.5	0.5
		7112	Boiler house plant	0.5	0.5	0.5
		7121	Agricultural machinery for cultivating the soil	1	1	1
		7122	Agricultural machinery for harvesting,threshing	1	1	1
		7123	Milking machines,cream separators,dairy farm eq	1	1	1
		7125	Tractors, other than road tractors	3.7	3.6	3.8
		7129	Agricultural machinery and appliances, nes	1	1	1
		7151	Machine tools for working metals	2	2	2
		7152	Other metalworking machinery	2	2	2
		7171	Textile machinery	2	2	2
		7172	Machinery ex.sewing mach. For working hides etc	2	2	2
		7173	Sewing machines	2	2	2
		7181	Paper mill and pulp mill machinery, etc.	2	2	2
		7182	Printing and bookbinding machinery	2	2	2
		7183	Food processing machines, excluding domestic	2	2	2
		7184	Construction and mining machinery, nes	0.5	0.5	0.5
		7185	Mineral crushing etc. & glass working machinery	2	2	2

		7191	Heating and cooling equipment	2	2	2
		7192	Pumps and centrifuges	3	3	3
		7193	Mechanical handling equipment	0.5	0.5	0.5
		7195	Powered tools, nes	2	2	2
		71961	Calendering mach.& similar rolling machines	2	2	2
		71963	Weighing machinery and weights therefor	3	3	3
		71964	Spraying machinery	2	2	2
		71965	Automatic vending machines	2	2	2
		7197	Ball, roller or needle roller bearings	2	2	2
		7198	Machinery and mechanical appliances, nes	1.25	0.5	2
		7199	Parts and accessories of machinery, nes	2.5	2	3
		7295	Electrical measuring & controlling instruments	3	3	3
		8613	Binoculars, microscopes & other optical instrum	3	3	3
		8617	Medical instruments, nes	3	3	3
		8618	Meters and counters,non electric	3	3	3
		8619	Measuring,controlling & scientific instruments	3	3	3
	Consumer Durables (CD)	69723	Domestic utensils of aluminium	97	97	97
		69792	Imdoor ornaments of base metals,n.e.s.	10	10	10
		6981	Locksmiths wares	5	5	5
		6982	Safes,strong rooms,strong room fittings etc.	5	5	5
		7141	Typewriters and cheque writing machines	5	5	5

		7142	Calculating & accounting machines etc	5	5	5
		7143	Statistical machines cards or tapes	5	5	5
		7149	Office machines, nes	5	5	5
		71941	Domestic food processing appliances,non elect.	3	3	3
		71942	Domestic refrigerators, non electrical	2.25	1.5	3
		71943	Domestic water heaters,non electrical	3	3	3
		71962	Mach.for cleaning or filling containers	1.4	1.4	1.4
		7241	Television broadcast receivers	3	3	3
		7242	Radio broadcast receivers	2	2	2
		7249	Telecommunications equipment nes	1	1	1
		72501	Domestic refrigerators, electrical	2.25	1.5	3
		72502	Domestic washing machines whether or not elec.	1.95	1.95	1.95
		72503	Electro mechanical domestic appliances nes	3	3	3
		72504	Electric shavers & hair clippers	3	3	3
		72505	Electric space heating equipment etc.	3	3	3
		7261	Electro medical apparatus	3	3	3
		7262	X ray apparatus	3	3	3
		7291	Batteries and accumulators	5	5	5
		7292	Electric lamps	5	5	5
		7293	Thermionic valves and tubes, transistors, etc.	3	3	3
		7294	Automotive electrical equipment	5	5	5

		7296	Electro mechanical hand tools	5	5	5
		7297	Electron and proton accelerators	5	5	5
		7299	Electrical machinery and apparatus, nes	5	5	5
		8124	Lighting fixtures and fittings and parts	2	2	2
		8210	Furniture	3	3	3
		8413	Apparel and clothing accessories of leather	3	3	3
		8612	Spectacles and spectacle frames	25	25	25
		8614	Photographic cameras and flashlight apparatus	5	5	5
		8615	Cine. Cameras, projectors, sound recorders etc.	5	5	5
		8616	Photographic & cinematographic equipment nes	5	5	5
		8641	Watches, watch movements and cases	10	10	10
		8642	Clocks, clock movements and parts	10	10	10
		8911	Phonographs, tape & other sound recorders etc.	1	1	1
		8914	Pianos and other string musical instruments	10	10	10
		8918	Musical instruments, nes	10	10	10
		8919	Parts and accessories of musical instruments	10	10	10
		8941	Baby and invalid carriages not motorized	1	1	1
		8942	Childrens toys, indoor games, etc.	1	1	1
		8944	Other sporting goods	1	1	1
		8945	Fair ground amusements, etc.	1	1	1
		8951	Office and stationery supplies of base metals	10	10	10

	Electrical Engineering (EE)	7116	Gas turbines,other than for aircraft	2	2	2
		7117	Nuclear reactors	2	2	2
		7118	Engines, nes	2	2	2
		7221	Electric power machinery	3	3	3
		7222	Apparatus for electrical circuits	3	3	3
		7231	Insulated wire and cable	3	3	3
		7232	Electrical insulating equipment	3	3	3
	Others	5714	Hunting and sporting ammunition	3	3	3
		69213	Tanks,etc.for storage or manuf.use of aluminium	98	98	98
		69222	Casks,drums,etc.used for transport of aluminium	98	98	98
		69232	Compressed gas cylinders of aluminium	98	98	98
		69885	Stoppers,crown corks,bottle caps,of base metal	40	40	40
		69887	Soldering & welding rods,etc,of base metal	40	40	40
		69894	Articles of aluminium,n.e.s.	95	95	95
		6943	Non military arms	3	3	3
		9510	Firearms of war & ammunition thereof	3	3	3

a. This data is adjusted by H0-281820 and H0-281830. Because SITC1-28401 includes ash and residues containing other non-ferrous metal except aluminum.

8. Calculation Process of Direct and Indirect Trade Flows

Data gathered through literature review for quantifying direct and indirect trade flows of aluminum contained in each ACP can be grouped into four categories: (1) data on monetary trade volume (MTV) of the ACP measured by US dollars; (2) data on physical trade volume (PTV) of the ACP measured by net weight; (3) data on physical content of aluminum in the ACP; and (4) data on energy use and GHG emissions intensities of aluminum for each process. The detailed calculation processes of PTV, MTV, and embodied energy use and GHG emissions of aluminum in an ACP are as follows.

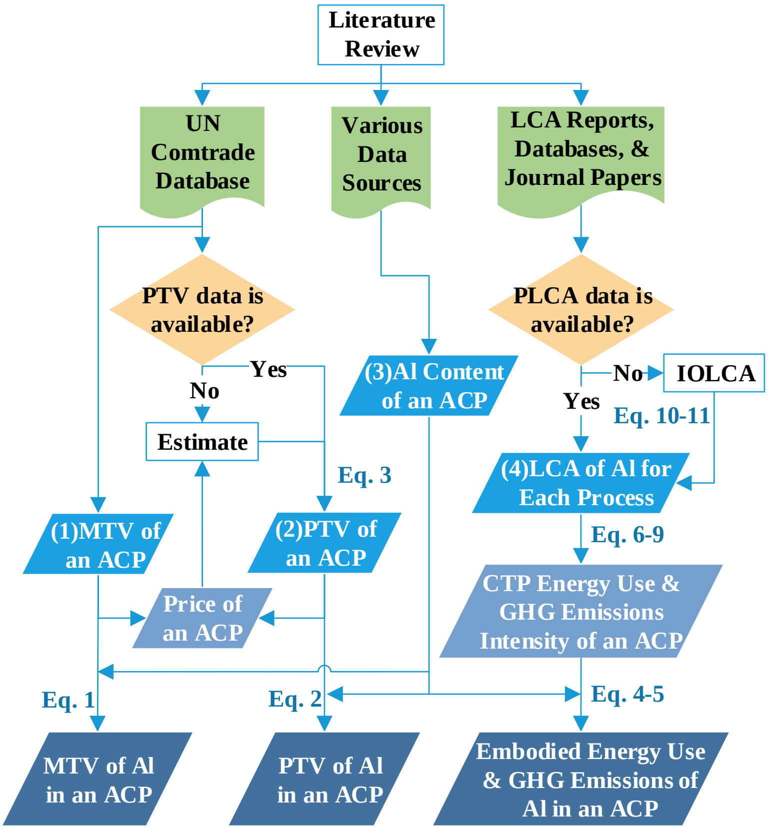

Figure S2. Data sources and process for calculating the monetary trade volume (MTV), physical trade volume (PTV), and energy use and GHG emissions embodied in the trade of aluminum contained in a specific aluminum-containing product (ACP).

8.1 Calculation of direct trade flows

To calculate monetary flow and physical flow of aluminum trade, data in the first, second, and third groups are used. Sources of data on physical aluminum contents in ACPs have been described in detail in our former studies[1,2,4] and are also available in Table S1. For each ACP, aluminum trade flows measured by monetary value ($MF_{Al,i,j}$) and physical value ($PF_{Al,i,j}$) are calculated by equations (1), (2), and (3),

$$MF_{Al,i,j} = MF_{P,i,j} \times C_{Al,i} \quad (1)$$

PTV data available $$PF_{Al,i,j} = PF_{P,i,j} \times C_{Al,i} \quad (2)$$

PTV data unavailable $$PF_{Al,i,j} = MF_{P,i,j}/P_{P,i,j} \times C_{Al,i} \quad (3)$$

where $PF_{P,i,j}$ and $MF_{P,i,j}$ indicate physical and monetary value of ACP_i in year j, respectively, $C_{Al,i}$ denotes the average aluminum content of ACP_i, and $P_{P,i,j}$ is the price of ACP_i in year j.

8.2 Calculation of indirect trade flows

Two indirect flows that are energy use ($EF_{Al,i,j}$) and GHG emissions ($GF_{Al,i,j}$) embodied in aluminum for ACP_i in year j are calculated by equations (4) and (5), based on data in the first and second groups,

$$EF_{Al,i,j} = PF_{Al,i,j} \times EI_{Al,i,j}^{CTP} \quad (4)$$

$$GF_{Al,i,j} = PF_{Al,i,j} \times GI_{Al,i,j}^{CTP} \quad (5)$$

where $EI_{Al,i,j}^{CTP}$ and $GI_{Al,i,j}^{CTP}$ indicate cradle to product (CTP) energy use and GHG emissions intensity of aluminum contained in ACP_i in year j.

Based on the framework in figure S1, $EI_{Al,i,j}^{CTP}$ and $GI_{Al,i,j}^{CTP}$ are calculated as the accumulation of the process incremental energy use and GHG emissions intensity (indicated by $EI_{Al,i,j}^{Inc}$ and $GI_{Al,i,j}^{Inc}$) of aluminum from bauxite mining process (the start point of aluminum's life cycle) to the process k (the process that the ACP is generated in), as shown in equation (6) and (7). However, $EI_{Al,i,j}^{Inc}$ and

$GI_{Al,i,j}^{Inc}$ couldn't obtained directly. Energy use and GHG emissions per ACP output in each process (indicated by EI_P^{Inc} and GI_P^{Inc}) is used as supplementary. $EI_{Al,i,j}^{Inc}$ and $GI_{Al,i,j}^{Inc}$ are equal to $EI_{P,i,j}^{Inc}$ and $GI_{P,i,j}^{Inc}$ divided by the average aluminum content of ACP_i, which can be seen in equation (8) and (9),

$$EI_{Al,i,j}^{CTP} = \sum_{i=1}^{k} EI_{Al,i,j}^{Inc} \quad (6)$$

$$GI_{Al,i,j}^{CTP} = \sum_{i=1}^{k} EI_{Al,i,j}^{Inc} \quad (7)$$

$$EI_{Al,i,j}^{CTP} = \sum_{i=1}^{k} EI_{P,i,j}^{Inc}/C_{Al,i} \quad (8)$$

$$GI_{Al,i,j}^{CTP} = \sum_{i=1}^{k} GI_{P,i,j}^{Inc}/C_{Al,i} \quad (9)$$

The key to calculate indirect flows is to obtain reliable data on EI_P^{Inc} and GI_P^{Inc}. Various LCA reports, databases, and papers about energy use and GHG emission for each ACP production process have been searched. Data in the US,[5,6] Japan,[7] China,[8] Australia, Europe,[9–11] and the world average[12–16] are collected, some of which have time specific data, some not. Those data vary across areas and over time. In comparison, world average data are much complete and accurate. And there is an obvious decline trend over time because of technology improvement, especially in electrolysis process which has the highest energy use and GHG emissions among all the production processes. We use life cycle inventory (LCI) data from aluminum industries (International Aluminum Institute and European Aluminum Association) which collected by process based LCA (PLCA) and build a time series LCI data set to avoid the uncertainties due to improvements in energy efficiency across the industry. Both direct and indirect energy use and GHG emissions are calculated. Energy use and GHG emissions from transportation process are ignored. Life cycle of primary aluminum production and life cycle of EP&S recycling are seen as two independent systems. Secondary aluminum production process begins with EP&S collection & pre-treating rather than bauxite mining.

Incremental PLCA data in manufacturing process are unavailable. Input-Output Life Cycle Assessment (IOLCA) method is used to explore energy use and GHG emissions intensity in manufacturing process for finished ACPs (indicated by $EI_{Finished\ ACP}^{Inc}$ and $GI_{Finished\ ACP}^{Inc}$), which is calculated by energy use and GHG emissions intensity for industry which finished ACP belongs to. To avoid double counting, only direct energy use and GHG emission for manufacturing process are calculated. Equation (10) and (11) show the calculation processes. $EI_{Finished\ ACP_{i,j}}^{Inc}$ and $GI_{Finished\ ACP_{i,j}}^{Inc}$ indicates the incremental energy use and GHG emissions intensity of finished ACP *i* in the year *j*; $EI_{Industry_{m,j}}^{dir}$ and $GI_{Industry_{m,j}}^{dir}$ are direct energy use and GHG emissions intensity of industry *m* in the year *j*; finished ACP *i* is belongs to industry *m*; $P_{P,i,j}$ indexes the price of the ACP *i* in the year *j*. More details about calculated process can be seen in SI 3.2.

$$EI_{Finished\ ACP_{i,j}}^{Inc} = EI_{Industry_{m,j}}^{dir} \times P_{P,i,j} \tag{10}$$

$$GI_{Finished\ ACP_{i,j}}^{Inc} = GI_{Industry_{m,j}}^{dir} \times P_{P,i,j} \tag{11}$$

8.3 Calculation of trade balance

Because the direction of the monetary trade flow is the opposite of that of the physical trade flow and the embodied energy use and GHG emission flows (Figure 1), the balance of the MTV of aluminum (MTB) is accounted as the difference between the export flow and the import flow, while the balance of the PTV of aluminum (PTB), of the embodied energy use (EUB), and of the embodied GHG emissions (EEB), is accounted as the difference between the respective import flow and export flow. After determining the volumes and balances of the four trade flows of the aluminum contained in each ACP, total trade volumes and balances of each of the four trade flows can be summed up for each of the six ACPs groups and all ACPs. Equations are as follows,

$$MTB_{Al,i,j} = MF_{Al,i,j}^{Export} - MF_{Al,i,j}^{Import} \tag{12}$$

$$PTB_{Al,i,j} = PF_{Al,i,j}^{Import} - PF_{Al,i,j}^{Export} \tag{13}$$

$$EUB_{Al,i,j}^{Import} = EF_{Al,i,j}^{Import} - EF_{Al,i,j}^{Export} \tag{14}$$

$$GEB_{Al,i,j}^{Import} = GF_{Al,i,j}^{Import} - GF_{Al,i,j}^{Export} \tag{15}$$

9. Coefficients of Energy Use and GHG Emissions for Aluminum

9.1 Coefficients of Energy Use and GHG Emissions for Raw Material and Semis Products

9.1.1 Energy use

Direct energy use coefficients are from International Aluminum Institute (IAI) and European Aluminum (EAA). We prefer to use data from IAI, because these data are world average which can more accurately reflect the energy use and GHG emissions of these four countries' aluminum industries than that from EAA which only show European average. LCI data collected by EAA are acted as complement.

IAI had collected global aluminum industry data for use in LCAs since 1998. These LCI data have been published in years 2000[12], 2003[13], 2007[14], 2013[15], and 2017[16], which report worldwide aluminum production in years 1995-1998, 2000, 2005, 2010, and 2015. IAI also reports energy intensity and energy consumption of smelting and refining from the year 1980 to 2017[17] and perfluorocarbon emissions in the period 1990-2017. However, IAI LCAs only include five processes: Mining, Refining, Paste/Anode production, Electrolysis, and Ingot casting. For semi-production and secondary aluminum production processes, data from EAA's ecological profile reports are used. EAA has been collected LCA data from European producers and manufacturers since 1992 and a series of reports had been published. Early reports, which published in years 1996, 2000, and 2005[10], are not available. Fortunately, some data in these early reports had been published in the 2008 version, which can cover data in years 1998, 2002, and 2005. And in 2013 and 2018, EAA reported LCA data in 2010 and 2015[9,11].

Data from IAI and EAA are not always in the same study period. In order to combine data from IAI and EAA into a timeseries database, some adjusts are needed. The data source of energy use coefficients for each production process are detailed in Table S2-S3.

Indirect energy use intensity is energy input per output in petrol coke and pitch production and energy production. Coefficients for petrol coke and pitch production and coefficients for fuel production can be seen in table S4-S5. IAI provides historical aluminum industry global power mix data on the website, which are used to estimate secondary energy use for electricity. The calculation process has been shown in Table S6.

Table S2: Data source of direct energy use coefficients. Year in this table is the time that data be collected.

Life Stage	1991~1995	1996~2000	2001~2005	2006~2010	2011~2016
Mining	IAI (1995-1998)[a]	IAI (2000)	IAI (2005)	IAI (2010)	IAI (2015)

Refining	IAI (1991-2016)				
Paste/Anode Production	IAI (1995-1998)[a]	IAI (2000)	IAI (2005)	IAI (2010)	IAI (2015)
Electrolysis	IAI (1991-2016)				
Ingot Casting	IAI (1995-1998)[a]	IAI (2000)	IAI (2005)	IAI (2010)	IAI (2015)
Rolling	EAA (1998)	EAA (1998, 2002)[b]	EAA (2005)	EAA (2010)	EAA (2015)
Extrusion	EAA (1998)	EAA (1998, 2002)[b]	EAA (2005)	EAA (2010)	EAA (2015)
Foil	EAA (1998)	EAA (1998, 2002)[b]	EAA (2005)	EAA (2010)	EAA (2015)
Powder & Flake[d]	EAA (1998)	EAA (1998, 2002)[b]	EAA (2005)	EAA (2010)	EAA (2015)
Collection & Pre-treating	EAA (1998)	EAA (1998, 2002)[b]	EAA (2005)	EAA (2005)[c]	EAA (2005)[c]
Recycling	EAA (1998)[a]	EAA (1998, 2002)[b]	EAA (2005)	EAA (2010)	EAA (2015)

a. In IAI's 1998 report, data in different production processes are collected during 1995-1998.

b. Coefficients from 1996 to 2000 are the average value of data collected in the year 1998 and 2002.

c. There are no date collected by EAA after 2005.

d. Assumed to have the same energy use coefficients of extrusion.

Table S3: Calorific values for types of fuel[18].

Fuel	Heavy Oil	Diesel & LFO	Gasoline	Natural Gas	Propane	Coal
Calorific value (TJ/Gg)	40.4[a]	43	44.3	48	47.3[b]	26.7[c]

a. Calorific value of residual fuel oil

b. Calorific value of liquefied petroleum gases

c. Calorific value of anthracite

Table S4: Coefficients of energy input in petrol coke and pitch production[19].

Process	Petrol coke	Pitch
Energy use coefficient (MJ/kg)	4.165	0.421

Table S5: Indirect energy input for fuel production[3].

Fuel	Heavy Oil	Diesel & LFO	Gasoline	Natural Gas	Propane	Coal
Energy use coefficient (MJ/MJ delivered)	0.0305	0.0385	0.0969	0.0292	0.0292[a]	0.0058

a. Assumed to be the same coefficient of natural gas.

Table S6: Secondary energy use for electricity[20].

Electricity source	Hydro	Coal	Oil	Natural Gas	Nuclear	Secondary Energy production (MJ/MJ delivered)	Transmission energy loss (MJ/MJ delivered)	Total secondary energy (MJ/MJ delivered)
1991	57%	33 %	1%	4%	5%	0.96	0.0950	1.0542
1992	57%	32 %	1%	5%	5%	0.95	0.0950	1.0452
1993	57%	30	1%	6%	5%	0.94	0.0950	1.0320

		%						
1994	58%	28 %	1%	6%	6%	0.89	0.0950	0.9885
1995	53%	35 %	2%	6%	5%	1.06	0.0950	1.1565
1996	51%	37 %	1%	6%	5%	1.10	0.0950	1.1905
1997	51%	37 %	0%	7%	5%	1.12	0.0950	1.2197
1998	48%	39 %	0%	8%	5%	1.17	0.0950	1.2687
1999	48%	39 %	1%	7%	6%	1.17	0.0950	1.2628
2000	46%	40 %	1%	8%	5%	1.21	0.0950	1.3061
2001	43%	44 %	1%	8%	4%	1.33	0.0950	1.4210
2002	42%	46 %	0%	7%	4%	1.37	0.0950	1.4616
2003	40%	49 %	0%	7%	4%	1.43	0.0950	1.5265
2004	41%	48 %	1%	7%	4%	1.41	0.0950	1.5011
2005	45%	44 %	1%	7%	4%	1.29	0.0950	1.3802
2006	42%	48 %	1%	6%	3%	1.38	0.0950	1.4789
2007	42%	49 %	0%	6%	3%	1.41	0.0950	1.5093

2008	40%	50 %	0%	7%	3%	1.46	0.0950	1.5534
2009	38%	51 %	0%	8%	2%	1.50	0.0950	1.5958
2010	41%	51 %	0%	5%	2%	1.45	0.0950	1.5418
2011	39%	53 %	0%	7%	1%	1.53	0.0950	1.6288
2012	38%	53 %	0%	8%	2%	1.54	0.0950	1.6390
2013	36%	54 %	0%	8%	1%	1.59	0.0950	1.6800
2014	31%	58 %	0%	10%	1%	1.72	0.0950	1.8110
2015	30%	59 %	0%	9%	2%	1.72	0.0950	1.8182
2016	28%	61 %	0%	10%	1%	1.80	0.0950	1.8930

9.1.2 GHG emissions

Both IAI and EAA don't report GHG emissions data. Direct GHG emissions coefficients are calculated by direct energy use coefficients. IAI have provided technical guidance[21] and tools[22] to support aluminum producers and researchers quantifying GHG emissions. We use them to estimate GHG emissions. Some estimated parameter and source can be seen in Table S7-S10.

Indirect GHG emissions coefficients from electricity production in the period 1991-2016 are estimated by IAI global power mix data. These data are shown in Table S11. Global perfluorocarbon emissions intensity during 1991 to 2016 have been reported by IAI, which are used immediately.

Table S7: Direct GHG emissions intensity data[23].

Fuel	Heavy Oil	Diesel & LFO	Gasoline	Natural Gas	Propane	Coal
Carbon emissions coefficient (kg CO_2e/kg)	3	3	2	2.79	3	2.5

Table S8: Emission factors for calculating process CO_2 emissions from petrol coke and pitch production[a].

Process	Petrol coke production	Pitch production
Emission factor (kg CO_2/kg)	0.2472	0.0258

a. These data are calculated by fuel use in production. Emission coefficients of fuels are from IPCC (2006).

Table S9: Emission factors for calculating process CO_2 emissions from Paste/Anode consumption[22].

Process	Søderberg (Paste consumption)	Prebake (Anode consumption)
Emission factor (kg CO_2/t Al)	1700	1600

Table S10: Indirect emissions from fuel production[3].

Fuel	Heavy Oil	Diesel & LFO	Gasoline	Natural Gas	Propane	Coal
Emission coefficient (kg CO_2/MJ delivered)	0.009	0.015	0.015	0.014	0.014[a]	0.005

a. Assumed to be the same coefficient of natural gas.

Table S11: GHG emissions coefficients for electricity production.

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Coefficient	0.3546	0.3502	0.3435	0.3286	0.3845	0.3945	0.4022	0.4162	0.4159	0.4286	0.4655	0.4793	0.5010
Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Coefficient	0.4932	0.4546	0.4876	0.4975	0.5097	0.5204	0.5103	0.5335	0.5360	0.5481	0.5878	0.5904	0.6145

9.1.3 Converting process incremental data into CTP data

Section 4.2 and 4.3 illustrate the process incremental energy use (or GHG emissions) intensity of raw materials and semis. We should convert these data into CTP data. Factors we use are shown in Table S12.

Table S12: Factors to convert process incremental data into CTP data[12–16].

Conversion factor (Input/Output)	1991~1995	1996~2000	2001~2005	2006~2010	2011~2016
Bauxite/Ingot-unalloyed	5.0880	5.1680	5.2680	5.5710	5.5000
Alumina/Ingot-unalloyed	1.9280	1.9250	1.9230	1.9340	2.0000
Anode/Ingot-unalloyed	0.3862	0.3844	0.3130	0.3916	0.4399
Paste/Ingot-unalloyed	0.0568	0.0566	0.1220	0.0484	0.0232
Electrolysis/Ingot-unalloyed	1.0000	1.0000	1.0000	1.0000	1.0000
Aluminum waste & scrap/Secondary aluminum	1.0140	1.0140	1.0090	1.0410	1.0190

Ingot-unalloyed/Extrusion	0.8850	1.0130	1.0080	1.0000	1.0030
Secondary aluminum/Extrusion	0.5590	0.3240	0.3240	0.3230	0.2910
Ingot-unalloyed/Rolling	1.0200	1.0120	1.0040	1.0040	1.0040
Secondary aluminum/Rolling	0.3830	0.3830	0.3830	0.4060	0.3470
Ingot-unalloyed/Foil	1.0320	1.0320	1.0070	1.0100	1.0070
Secondary aluminum/Foil	0.5950	0.5950	0.5950	0.3900	0.1550
Ingot-unalloyed/Powder and flake	0.8850	1.0130	1.0080	1.0410	1.0030
Secondary aluminum/Powder and flake	0.5590	0.3240	0.3240	0.3230	0.2910

9.2 Estimating Method of Incremental Energy Use and GHG Emissions for Manufacturing Process

Input-Output Life Cycle Assessment (IO-LCA) is used to calculating incremental energy use (GHG emissions) intensity (indicated by $EI_{Finished\ ACP}^{Inc}$ and $GI_{Finished\ ACP}^{Inc}$) intensity for manufacturing process of each finished ACP, which is calculated by direct energy use and GHG emissions intensity (indicated by $EI_{Industry}^{dir}$ and $GI_{Industry}^{dir}$) for industries which finished ACP belongs to. So, the key is to estimate direct energy use and GHG emissions intensity of industries which ACPs belongs to.

Direct energy use (GHG emissions) intensity of industry is calculated by IO tables and their satellite. Figure S3 shows the structure of an input-output table. According to the environmental input-output analysis developed by Leontief[24], direct energy use and GHG emissions intensity for industry *m* in the year *j* can be obtained as follows:

$$EI_{Industry_{m,j}}^{dir} = TE_{m,j}/X_j \tag{15}$$

$$GI^{dir}_{Industry_{m,j}} = TG_{m,j}/X_j \quad (16)$$

where A is the technical coefficients matrix in the year j, $TE_{m,j}$ and $TG_{m,j}$ are the total energy use and GHG emissions for industry m in the year j; total output is denoted by X which contains domestic consumption and export.

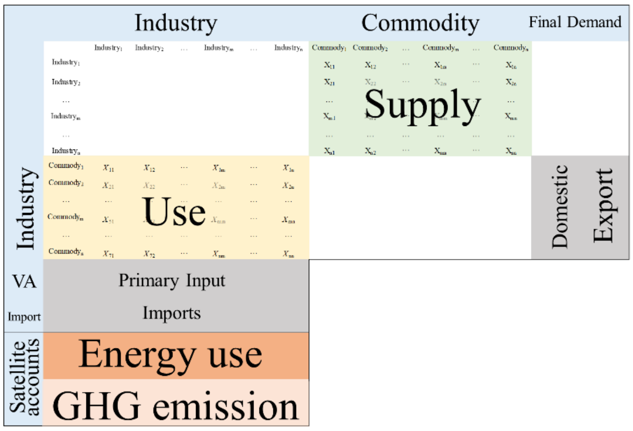

Figure S3: Basic structure of an economic input-output table.

There are four countries involved in this study, US, China, Japan, and Australia, which publish IO tables every few years. And based on these official IO tables, Eora database has developed timeseries of environmentally extended IO tables for the four countries from 1990 to 2015. Except China, other three countries' IO table have very detailed sector category (more than 300 sectors). So, we use these three countries' environmentally extended IO tables in Eora database to calculate incremental energy use (GHG emissions) intensity in each finished ACP' manufacturing process. Eora database didn't publish IO table for the year 2016, so we use the IO tables in 2015 to replace.

The first step is locating finished ACPs into different sectors of the three countries' IO table. According to some convert files provided by these three countries[25–28], the relationship between finished ACPs and IO table sectors can be seen in table S13. And then, based on IO tables in Eora database and equation 15 and 16, each industry's direct energy use (GHG emissions) intensity for the three countries can be calculated.

Incremental energy use (GHG emissions) intensity for finished ACPs' manufacturing processes are calculated by each country's export price and industry's direct energy use (GHG emissions) intensity (Equation 10 and 11). However, due to US, Japan and Australia have very different economic structure and technical condition, environmental coefficients about some finished ACPs in the three countries are quite different. Hence, we adopt the average value.

Table S13: The conversion table between finished ACPs and IO sectors of US, Japan, and Australia.

SITC1	Short Description	US IOT	Japan IOT	Australia IOT
7114	Aircraft incl jet propulsion engines	Aircraft engine and engine parts manufacturing	Aircrafts	Aircraft
7341	Aircraft, heavier than air	Aircraft manufacturing	Aircrafts	Aircraft
7349	Parts of aircraft,balloons airships	Other aircraft parts and auxiliary equipment manufacturing	Aircraft	Aircraft
89999	Catapults and sim.aircraft launching gear,etc.	Guided missile and space vehicle manufacturing	Aircrafts	Aircraft
7351	Warships of all kinds	Ship building and repairing	Ships (except steel ships)	Ships and boats
7353	Ships and boats, other than warships	Boat building	Ships (except steel ships)	Ships and boats
7359	Special purpose ships and boats	Ship building and repairing	Ships (except steel ships)	Ships and boats
71966	Railway & tramway track fixtures & fittings	Railroad rolling stock manufacturing	Rolling stock	Railway equipment
7311	Railway locomotives steam and tenders	Railroad rolling stock manufacturing	Rolling stock	Railway equipment
7312	Electric railway locomotives, not self generat.	Railroad rolling stock manufacturing	Rolling stock	Railway equipment
7313	Railway locomotives, not steam or electric	Railroad rolling stock manufacturing	Rolling stock	Railway equipment
7314	Mechanically propelled railway and tramway cars	Railroad rolling stock manufacturing	Rolling stock	Railway equipment
7315	Rail & tram passenger cars not mech propelled	Railroad rolling stock manufacturing	Rolling stock	Railway equipment
7316	Rail.&tram.freight cars,not mechanically propd.	Railroad rolling stock manufacturing	Rolling stock	Railway equipment

7317	Parts of railway locomotives & rolling stock	Railroad rolling stock manufacturing	Rolling stock	Railway equipment
7321	Passenger motor cars, other than buses	Automobile manufacturing	Passenger motor cars	Finished cars
7322	Buses, including trolleybuses	Heavy duty truck manufacturing	Passenger motor cars	Finished cars
7323	Lorries and trucks, including ambulances, etc.	Heavy duty truck manufacturing	Passenger motor cars	Trucks
7324	Special purpose lorries, trucks and vans	Heavy duty truck manufacturing	Passenger motor cars	Trucks
7325	Road tractors for tractor trailer combinations	Heavy duty truck manufacturing	Passenger motor cars	Trucks
7326	Chassis with engs. Mntd. For vehicles of 732.1	Motor Vehicle Body Manufacturing	Motor vehicle bodies	Motor vehicle parts
7327	Other chassis with engines mounted	Motor Vehicle Body Manufacturing	Motor vehicle bodies	Motor vehicle parts
7328	Bodies & parts motor vehicles ex motorcycles	Motor vehicle parts manufacturing	Motor vehicle parts and accessories	Motor vehicle parts
7329	Motorcycles, motorized cycles and their parts	Motorcycle, bicycle, and parts manufacturing	Two-wheel motor vehicles	Motor vehicle parts
7331	Bicycles & other cycles, not motorized, & parts	Motorcycle, bicycle, and parts manufacturing	Bicycles	Finished cars
7333	Trailers & oth vehicles not motorized, & parts	Truck trailer manufacturing	Other transport equipment	Motor vehicle parts
7334	Invalid carriages	Motorcycle, bicycle, and parts manufacturing	Bicycles	Finished cars
7113	Steam engines and steam turbines	Turbine and turbine generator set units manufacturing	Pumps and compressors	Pumps
7115	Internal combustion engines, not for aircraft	Motor vehicle parts manufacturing	Internal combustion engines for vessels	Industrial machinery and equipment
6324	Builders woodwork & prefab. Buildings of wood	Wood windows and doors and millwork	Wooden fixtures	Prefabricated buildings

6912	Fin.structural parts & structures of aluminium	Plate work and fabricated structural product manufacturing	Aluminum (inc. regenerated aluminum)	Fabricated metal products
69313	Wire,cables,ropes etc.not insulated,aluminium	Spring and wire product manufacturing	Electric wires and cables	Fabricated metal products
69882	Flexible tubing and piping of base metal	Fabricated Pipe and Pipe Fitting Manufacturing	Plumber's supplies, powder metallurgy products and tools	Fabricated metal products
69884	Bells (non electric),of base metal	All other miscellaneous manufacturing	Other metal products	Fabricated metal products
69886	Name plates,sign plates,etc.of base metal	Sign manufacturing	Other metal products	Fabricated metal products
7111	Steam generating boilers	Power boiler and heat exchanger manufacturing	Boilers	Industrial machinery and equipment
7112	Boiler house plant	Power boiler and heat exchanger manufacturing	Boilers	Industrial machinery and equipment
7121	Agricultural machinery for cultivating the soil	Farm machinery and equipment manufacturing	Machinery for agricultural use	Tillage, seeding, planting and fertilising equipment
7122	Agricultural machinery for harvesting,threshing	Farm machinery and equipment manufacturing	Machinery for agricultural use	Harvesting, haymaking and silage making equipment
7123	Milking machines,cream separators,dairy farm eq	Farm machinery and equipment manufacturing	Food processing machinery	Industrial machinery and equipment
7125	Tractors, other than road tractors	Farm machinery and equipment manufacturing	Machinery for agricultural use	Agricultural tractors

7129	Agricultural machinery and appliances, nes	Farm machinery and equipment manufacturing	Food processing machinery	Industrial machinery and equipment
7151	Machine tools for working metals	Metal cutting and forming machine tool manufacturing	Metal processing machinery	Industrial machinery and equipment
7152	Other metalworking machinery	Other industrial machinery manufacturing	Metal processing machinery	Industrial machinery and equipment
7171	Textile machinery	Other industrial machinery manufacturing	Textile machinery	Industrial machinery and equipment
7172	Machinery ex.sewing mach. For working hides etc	Other general purpose machinery manufacturing	Textile machinery	Industrial machinery and equipment
7173	Sewing machines	Other general purpose machinery manufacturing	Textile machinery	Industrial machinery and equipment
7181	Paper mill and pulp mill machinery, etc.	Other industrial machinery manufacturing	Other special machinery for industrial use	Industrial machinery and equipment
7182	Printing and bookbinding machinery	Other industrial machinery manufacturing	Other special machinery for industrial use	Industrial machinery and equipment
7183	Food processing machines, excluding domestic	Other industrial machinery manufacturing	Food processing machinery	Industrial machinery and equipment
7184	Construction and mining machinery, nes	Construction machinery manufacturing	Machinery and equipment for construction and mining	Construction machinery
7185	Mineral crushing etc. & glass working machinery	Mining and Oil and Gas Field Machinery Manufacturing	Machinery and equipment for construction and mining	Machinery for crushing, grinding, mixing
7191	Heating and cooling equipment	Air conditioning, refrigeration, and warm air heating equipment manufacturing	Refrigerators and air conditioning apparatus	Air conditioning

7192	Pumps and centrifuges	Pump and pumping equipment manufacturing	Pumps and compressors	Pumps
7193	Mechanical handling equipment	Material handling equipment manufacturing	Conveyors	Hoists, cranes, lifting and loading machinery
7195	Powered tools, nes	Power-driven handtool manufacturing	Metal machine tools	Industrial machinery and equipment
71961	Calendering mach & similar rolling machines	Rolling mill and other metalworking machinery manufacturing	Other general industrial machinery and equipment	Industrial machinery and equipment
71963	Weighing machinery and weights therefor	Other general purpose machinery manufacturing	Other general industrial machinery and equipment	Industrial machinery and equipment
71964	Spraying machinery	Other general purpose machinery manufacturing	Other general industrial machinery and equipment	Industrial machinery and equipment
71965	Automatic vending machines	Other general purpose machinery manufacturing	Other general industrial machinery and equipment	Industrial machinery and equipment
7197	Ball, roller or needle roller bearings	Ball and roller bearing manufacturing	Bearings	Industrial machinery and equipment
7198	Machinery and mechanical appliances, nes	Other Industrial Machinery Manufacturing	Other special machinery for industrial use	Industrial machinery and equipment
7199	Parts and accessories of machinery, nes	Other Industrial Machinery Manufacturing	Other general machines and parts	Industrial machinery and equipment
7295	Electrical measuring & controlling instruments	Industrial process variable instruments manufacturing	Analytical instruments, testing machine, measuring instruments	Surgical and medical
8613	Binoculars, microscopes & other optical instrum	Optical instrument and lens manufacturing	Other photographic and optical instruments	Photographic and scientific equipment

8617	Medical instruments, nes	Surgical and medical instrument manufacturing	Medical instruments	Surgical and medical
8618	Meters and counters,non electric	Watch, clock, and other measuring and controlling device manufacturing	Analytical instruments, testing machine, measuring instruments	Photographic and scientific equipment
8619	Measuring,controlling & scientific instruments	Analytical laboratory instrument manufacturing	Professional and scientific instruments	Photographic and scientific equipment
69723	Domestic utensils of aluminium	Cutlery, utensil, pot, and pan manufacturing	Other metal products	Fabricated metal products
69792	Imdoor ornaments of base metals,n.e.s	Ornamental and architectural metal products manufacturing	Other metal products	Fabricated metal products
6981	Locksmiths wares	Hardware manufacturing	Other metal products	Fabricated metal products
6982	Safes,strong rooms,strong room fittings etc.	Hardware manufacturing	Other metal products	Fabricated metal products
7141	Typewriters and cheque writing machines	Vending, commercial, industrial, and office machinery manufacturing	Copy machine	Electronic equipment
7142	Calculating & accounting machines etc	Vending, commercial, industrial, and office machinery manufacturing	Electronic computing equipment (except personal computers)	Electronic equipment
7143	Statistical machines cards or tapes	Vending, commercial, industrial, and office machinery manufacturing	Electronic computing equipment (accessory equipment)	Electronic equipment
7149	Office machines, nes	Vending, commercial, industrial, and office machinery manufacturing	Other office machines	Electronic equipment
71941	Domestic food processing appliances,non elect	Other fabricated metal manufacturing	Other metal products	Fabricated metal products

71942	Domestic refrigerators, non electrical	Other fabricated metal manufacturing	Other metal products	Air conditioning
71943	Domestic water heaters,non electrical	Heating equipment (except warm air furnaces) manufacturing	Gas and oil appliances and heating and cooking apparatus	Water heater, non-electric
71962	Mach.for cleaning or filling containers	Packaging machinery manufacturing	Other electrical devices and parts	Electrical equipment
7241	Television broadcast receivers	Broadcast and wireless communications equipment	Radio and television sets	Electrical equipment
7242	Radio broadcast receivers	Broadcast and wireless communications equipment	Radio and television sets	Electrical equipment
7249	Telecommunications equipment nes	Telephone Apparatus Manufacturing	Cellular phones	Electronic equipment
72501	Domestic refrigerators, electrical	Household refrigerator and home freezer manufacturing	Household electric appliances (except air-conditioners)	Domestic refrigerators
72502	Domestic washing machines whether or not elec.	Household laundry equipment manufacturing	Household electric appliances (except air-conditioners)	Clothes washing machines
72503	Electro mechanical domestic appliances nes	Small electrical appliance manufacturing	Household electric appliances (except air-conditioners)	Household appliances
72504	Electric shavers & hair clippers	Small electrical appliance manufacturing	Household electric appliances (except air-conditioners)	Household appliances
72505	Electric space heating equipment etc.	Household Cooking Appliance Manufacturing	Household electric appliances (except air-conditioners)	Space heaters, electric
7261	Electro medical apparatus	Electromedical and electrotherapeutic apparatus manufacturing	Medical instruments	Surgical and medical

7262	X ray apparatus	Irradiation apparatus manufacturing	Medical instruments	Surgical and medical
7291	Batteries and accumulators	Storage battery manufacturing	Batteries	Electrical equipment
7292	Electric lamps	Electric lamp bulb and part manufacturing	Electric lighting fixtures and apparatus	Electrical equipment
7293	Thermionic valves and tubes, transistors, etc.	Electron tube manufacturing	Electron tubes	Electronic equipment
7294	Automotive electrical equipment	Motor vehicle parts manufacturing	Electrical equipment for internal combustion engines	Electrical equipment
7296	Electro mechanical hand tools	Power-Driven Handtool Manufacturing	Metal machine tools	Industrial machinery and equipment
7297	Electron and proton accelerators	All other miscellaneous electrical equipment and component manufacturing	Other electrical devices and parts	Electrical equipment
7299	Electrical machinery and apparatus, nes	Other general purpose machinery manufacturing	Other electronic components	Electronic equipment
8124	Lighting fixtures and fittings and parts	Lighting fixture manufacturing	Electric lighting fixtures and apparatus	Electrical equipment
8210	Furniture	Metal and other household furniture (except wood) manufacturing1	Metallic furniture and fixture	Furniture
8413	Apparel and clothing accessories of leather	Leather and hide tanning and finishing	Woven fabric apparel	Clothing
8612	Spectacles and spectacle frames	Ophthalmic goods manufacturing	Other photographic and optical instruments	Spectacles and sunglasses
8614	Photographic cameras and flashlight apparatus	Photographic and photocopying equipment manufacturing	Camera	Photographic and scientific equipment

8615	Cine. Cameras, projectors, sound recorders etc.	Audio and video equipment manufacturing	Video recording and playback equipment	Electronic equipment
8616	Photographic & cinematographic equipment nes	Photographic and photocopying equipment manufacturing	Other photographic and optical instruments	Electronic equipment
8641	Watches, watch movements and cases	Watch, clock, and other measuring and controlling device manufacturing	Watches and clocks	Photographic and scientific equipment
8642	Clocks, clock movements and parts	Watch, clock, and other measuring and controlling device manufacturing	Watches and clocks	Photographic and scientific equipment
8911	Phonographs, tape & other sound recorders etc.	Audio and Video Equipment Manufacturing	Magnetic tapes and discs	Electronic equipment
8914	Pianos and other string musical instruments	Musical instrument manufacturing	Musical instruments	Miscellaneous manufacturing
8918	Musical instruments, nes	Musical instrument manufacturing	Musical instruments	Miscellaneous manufacturing
8919	Parts and accessories of musical instruments	Musical instrument manufacturing	Musical instruments	Miscellaneous manufacturing
8941	Baby and invalid carriages not motorized	All Other Transportation Equipment Manufacturing	Bicycles	Miscellaneous manufacturing
8942	Childrens toys, indoor games, etc.	Doll, toy, and game manufacturing	Toys and games	Miscellaneous manufacturing
8944	Other sporting goods	Sporting and athletic goods manufacturing	Sporting and athletic goods	Miscellaneous manufacturing
8945	Fairground amusements, etc.	Sporting and athletic goods manufacturing	Miscellaneous manufacturing products	Miscellaneous manufacturing

8951	Office and stationery supplies of base metals	Office supplies (except paper) manufacturing	Other metal products	Fabricated metal products
7116	Gas turbines,other than for aircraft	Turbine and turbine generator set units manufacturing	Turbines	Industrial machinery and equipment
7117	Nuclear reactors	Power Boiler and Heat Exchanger Manufacturing	Boilers	Industrial machinery and equipment
7118	Engines, nes	Other industrial machinery manufacturing	Engines	Industrial machinery and equipment
7221	Electric power machinery	Motor and Generator Manufacturing	Other industrial heavy electrical equipment	Electrical equipment
7222	Apparatus for electrical circuits	Printed circuit assembly (electronic assembly) manufacturing	Integrated circuits	Electronic equipment
7231	Insulated wire and cable	Communication and energy wire and cable manufacturing	Electric wires and cables	Electrical equipment
7232	Electrical insulating equipment	Communication and energy wire and cable manufacturing	Other electrical devices and parts	Electrical equipment
5714	Hunting and sporting ammunition	Ammunition manufacturing	Ordnance	Firearms
69213	Tanks,etc.for storage or manuf.use of aluminium	Metal tank (heavy gauge) manufacturing	Metal containers, fabricated plate and sheet metal	Sheet metal products
69222	Casks,drums,etc.used for transport of aluminium	Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing	Metal containers, fabricated plate and sheet metal	Sheet metal products
69232	Compressed gas cylinders of aluminium	Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing	Metal containers, fabricated plate and sheet metal	Sheet metal products
69885	Stoppers,crown corks,bottle caps,of base metal	Crown and closure manufacturing and metal stamping	Bolts, nuts, rivets and springs	Fabricated metal products

69887	Soldering & welding rods,etc,of base metal	Other general purpose machinery manufacturing	Other metal products	Fabricated metal products
69894	Articles of aluminium,n.e.s.	Other fabricated metal manufacturing	Other metal products	Fabricated metal products
8943	Non military arms	Arms, ordnance, and accessories manufacturing	Ordnance	Firearms
9510	Firearms of war & ammunition thereof	Arms, ordnance, and accessories manufacturing	Ordnance	Firearms

10. Definition of Terms of Trade

Terms of trade (TOT) is commonly used to represent the competitiveness of countries in international trade. In this paper, we use the main three variants of TOT to calculate the ability of these four countries to get monetary, energy and environmental benefits in aluminum international trade.

Commodity terms of trade (CTOT) is used to analyze the profitability of countries which is defined as the ratio between a country's commodity export price and its import price. When the export price is larger than import price, CTOT is higher than 100%. That means the country can get monetary value from a same product or product group's international trade.

Energy terms of trade (ETOT) and pollution terms of trade (PTOT) are used to measures the energy and environmental gains and losses that a country get from international trade.[29] They are estimated by the ratio between a product or product group's CTP energy use and GHG emissions intensity of export and its CTP energy and GHG emissions intensity of import. When ETOT and PTOT are smaller than 100%, the energy and environmental burden embodied in the export goods are lower than that in imported goods. The country can get energy and environmental benefits from other countries by international trade.

The higher TOT, the better a country's profitability. On the contrary, the lower ETOT and PTOT, the better a country's ability to get energy and environmental benefits from other countries.

11. Uncertainty analysis

The results are mainly sensitive to the aluminum content of ACPs. We calculate the resource, monetary value, energy, and environmental burden in these four countries' aluminum trade under different aluminum contents (Figure S4). Results show that aluminum content has great impact on the absolute value of four flows. But it won't change the trends and directions of the four flows, which means it do not change the conclusions of this study.

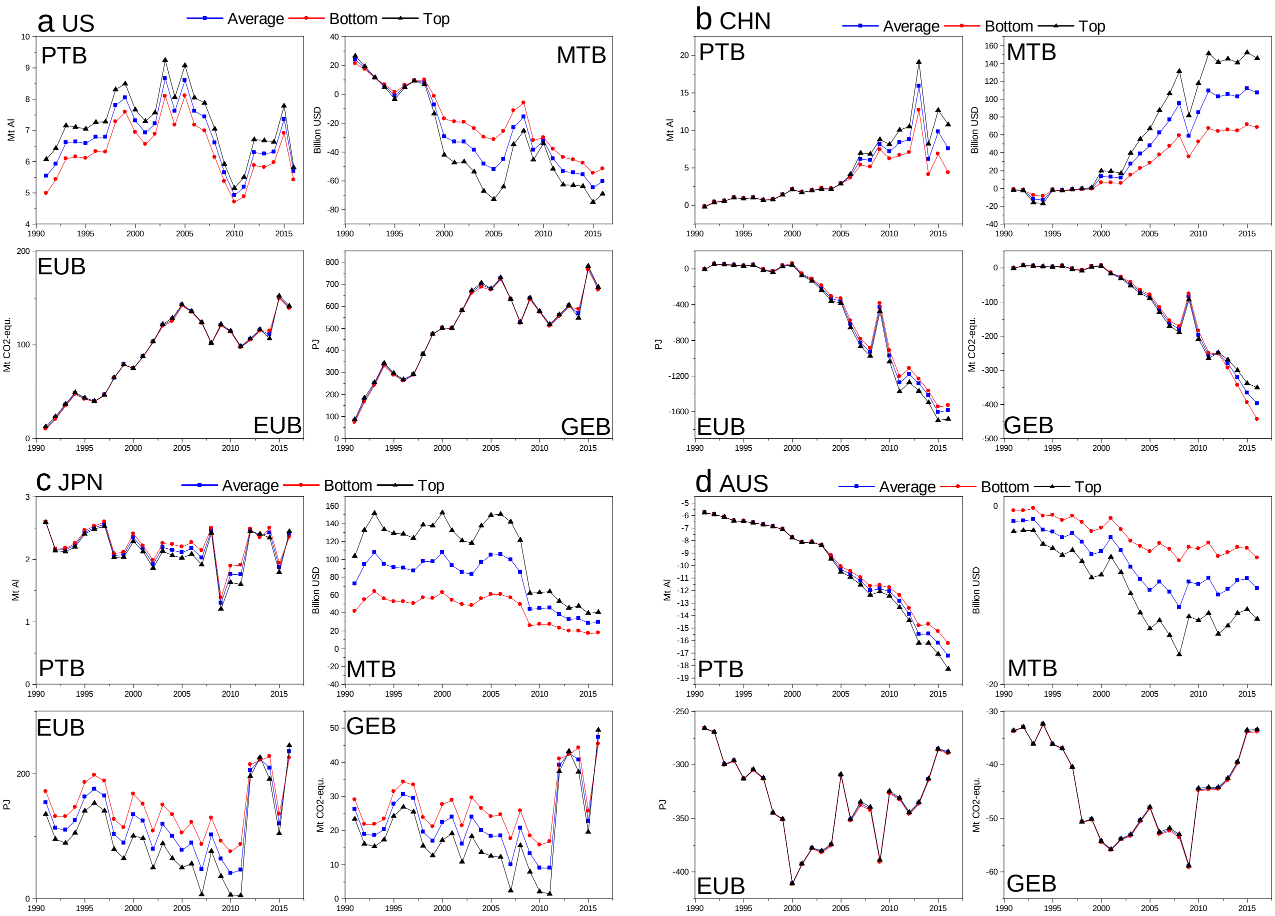

Figure S4 The average, bottom, and top value of PTB, MTB, EUB, and GEB for (b) China, (c) Japan, and (d) Australia from 1991 to 2016.

12. Results

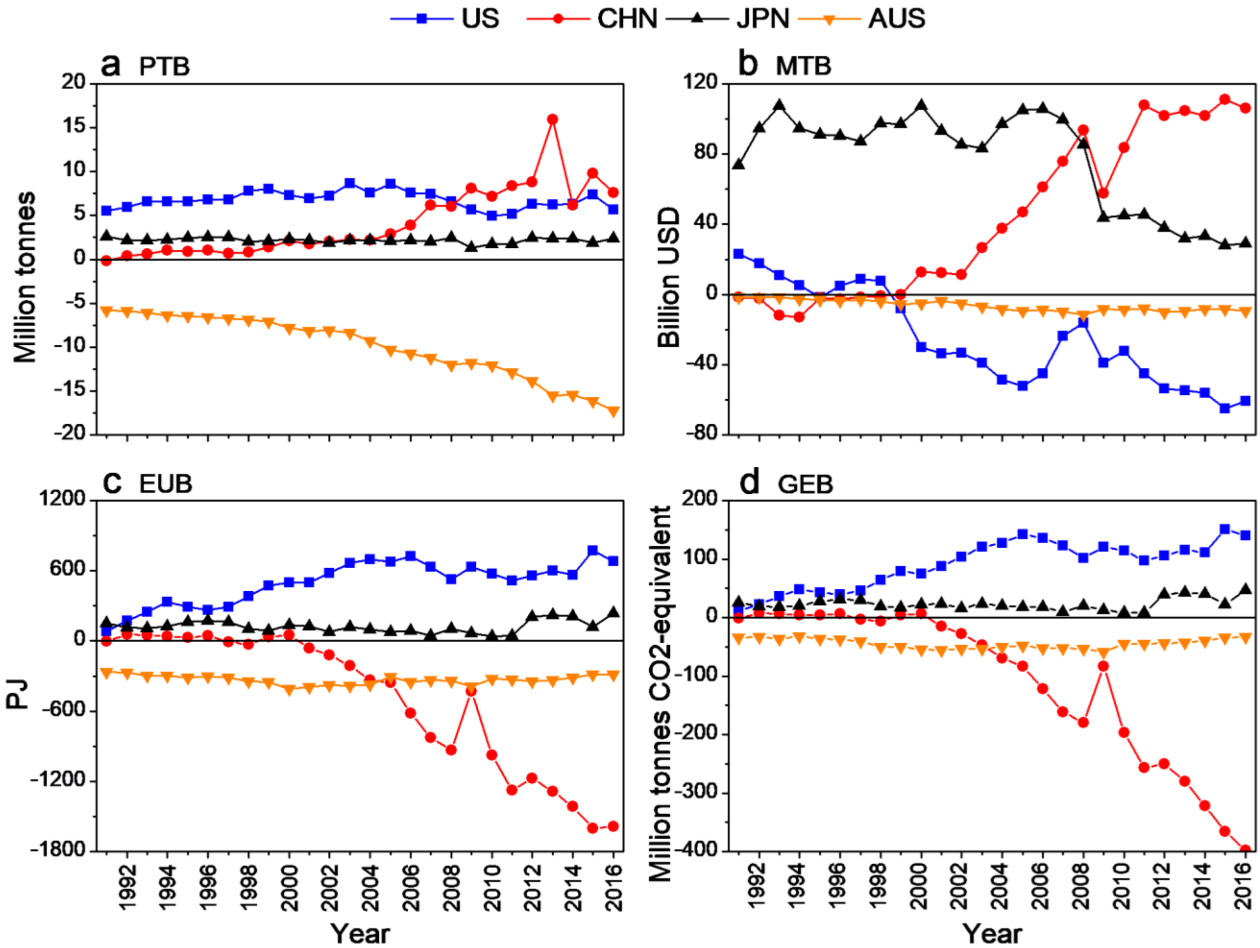

Figure S5 Aluminum trade balance in resource, economic, energy and environmental consequences for these four countries.

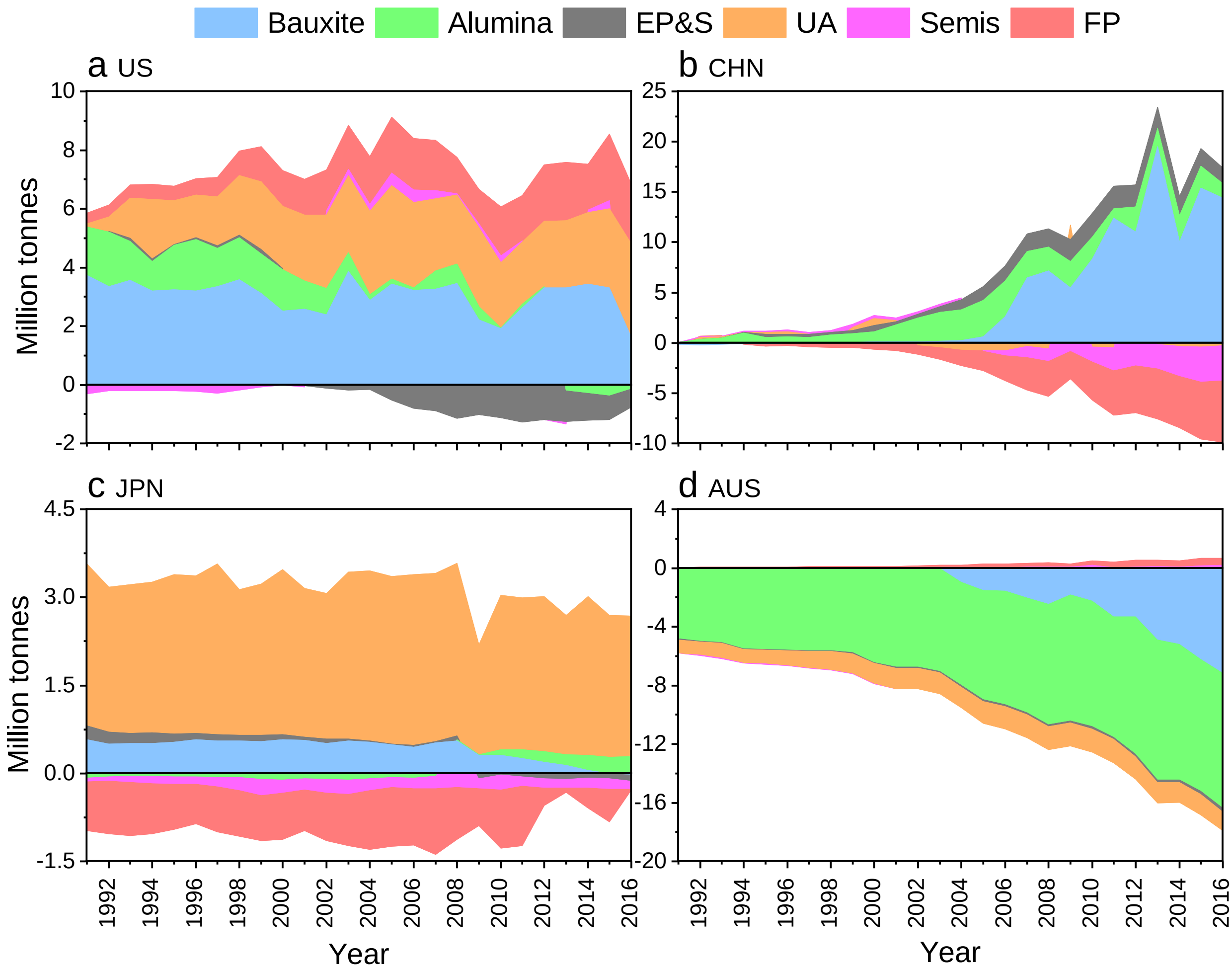

Figure S6 Net import of aluminum embedded in different product groups measured by mass for (a) the US, (b) China, (c) Japan, and (d) Australia from 1991 to 2016. EP&S = EOL Products & Scrap, UA = Unwrought Aluminum, Semis, FP = Finished Products. Mt = Million tonnes.

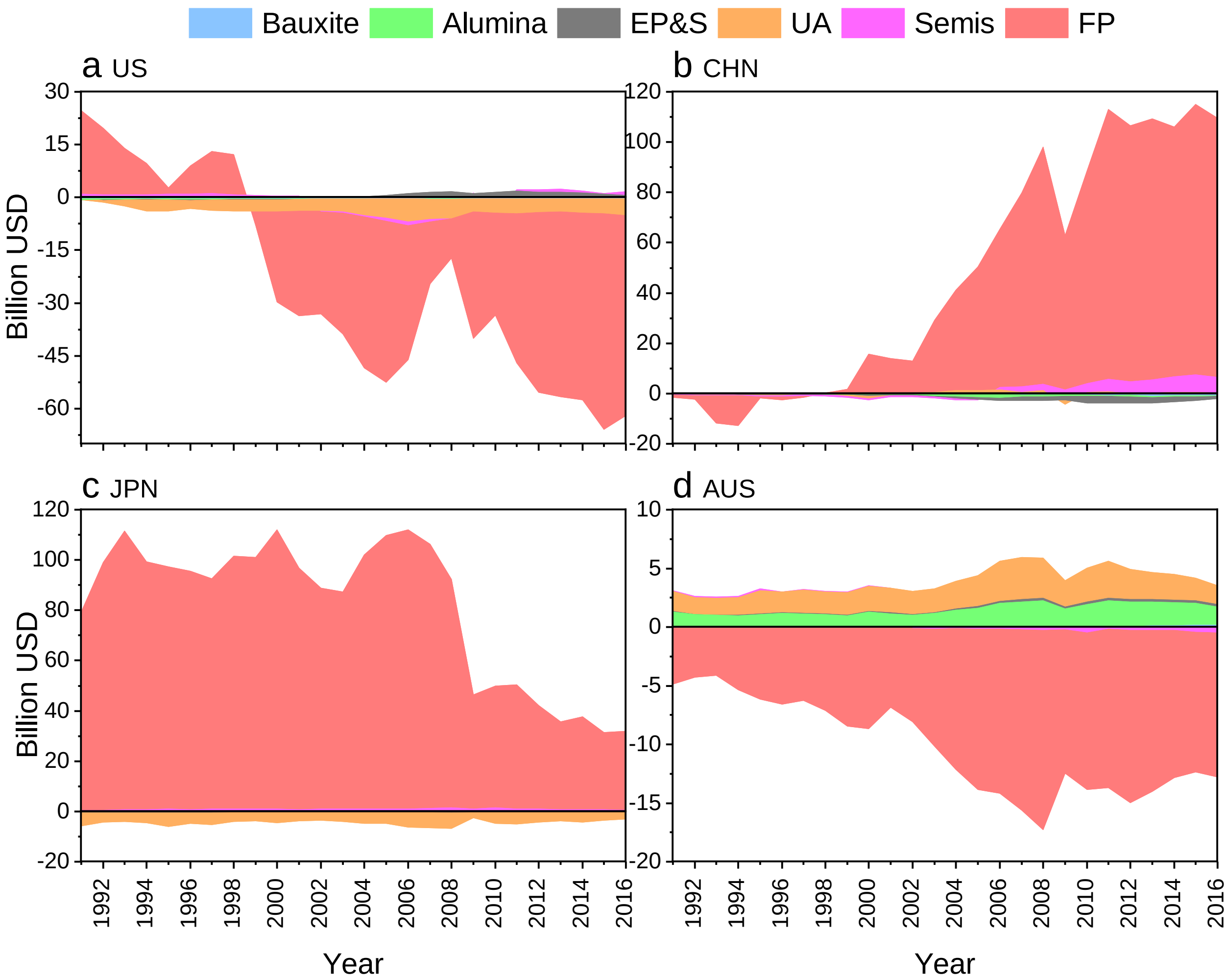

Figure S7 Money earned by trade of different ACP groups for (a) US, (b) China, (c) Japan, and (d) Australia from 1991 to 2016. EP&S = EOL Products & Scrap, UA = Unwrought Aluminum, Semis, FP = Finished Products.

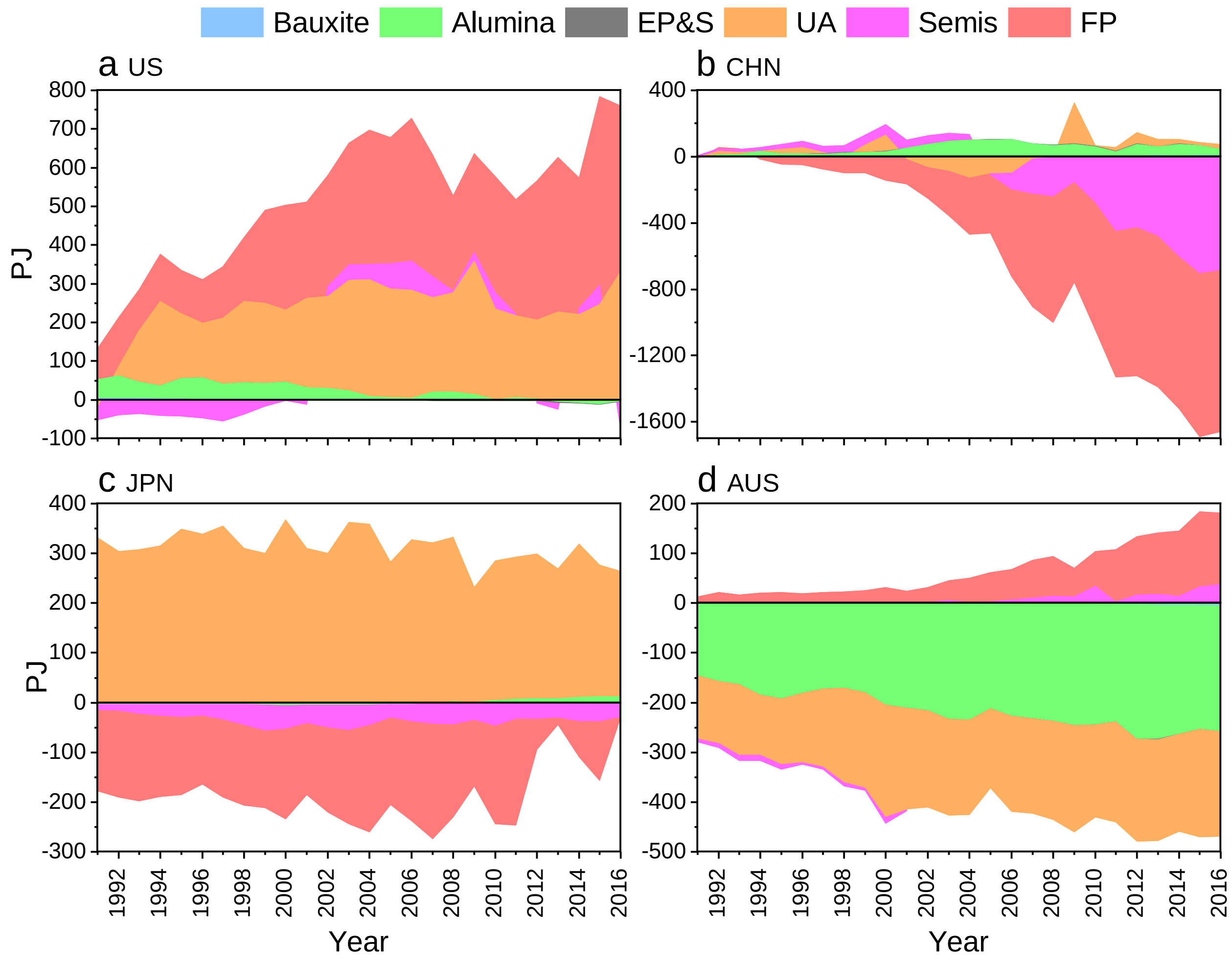

Figure S8 Net import of embodied energy in aluminum trade for (a) US, (b) China, (c) Japan, and (d) Australia from 1991 to 2016. EP&S = EOL Products & Scrap, UA = Unwrought Aluminum, Semis, FP = Finished Products. PJ = Petajoule = 10^{15} J.

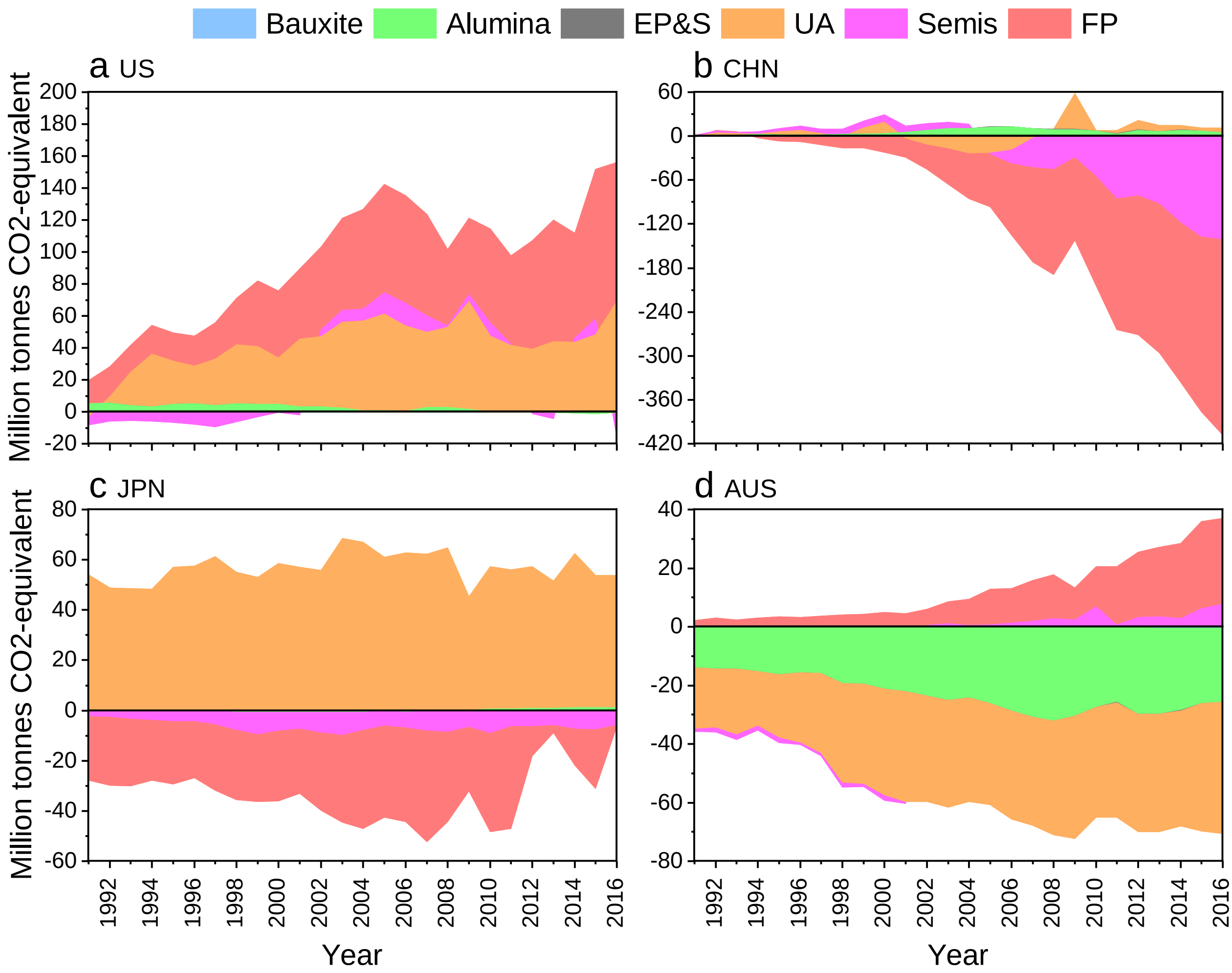

Figure S9. Net import of embodied GHG emissions in aluminum trade for (a) US, (b) China, (c) Japan, and (d) Australia from 1991 to 2016. EP&S = EOL Products & Scrap, UA = Unwrought Aluminum, Semis, FP = Finished Products.

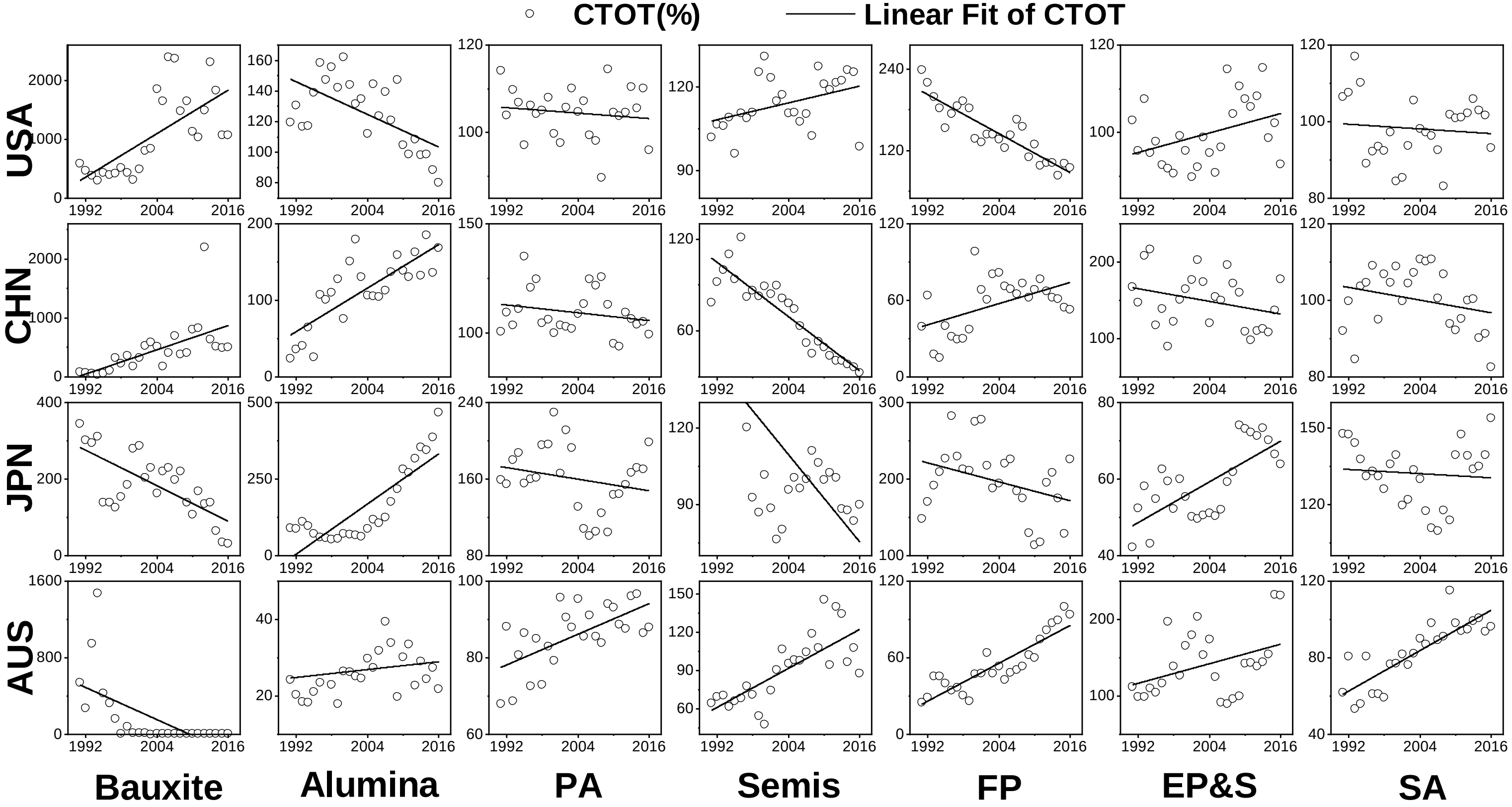

Figure S10 The seven ACP groups' commodity terms of trade of these four countries. CTOT = Commodity terms of trade; Linear fit of CTOT shows the trend of each of ACP's CTOT.

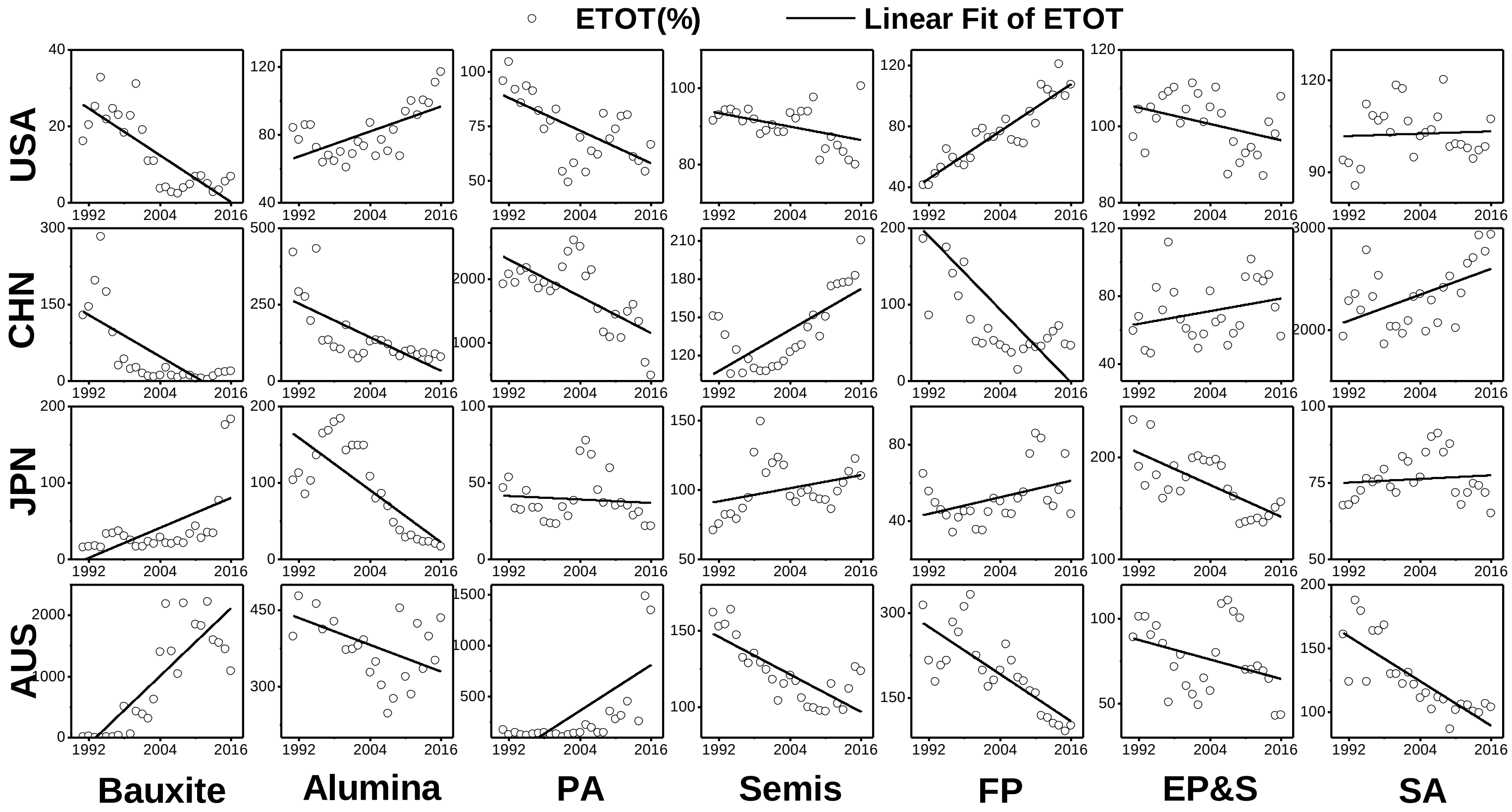

Figure S11 The seven ACP groups' energy terms of trade of these four countries. ETOT = Energy terms of trade; Linear fit of ETOT shows the trend of each of ACP's ETOT.

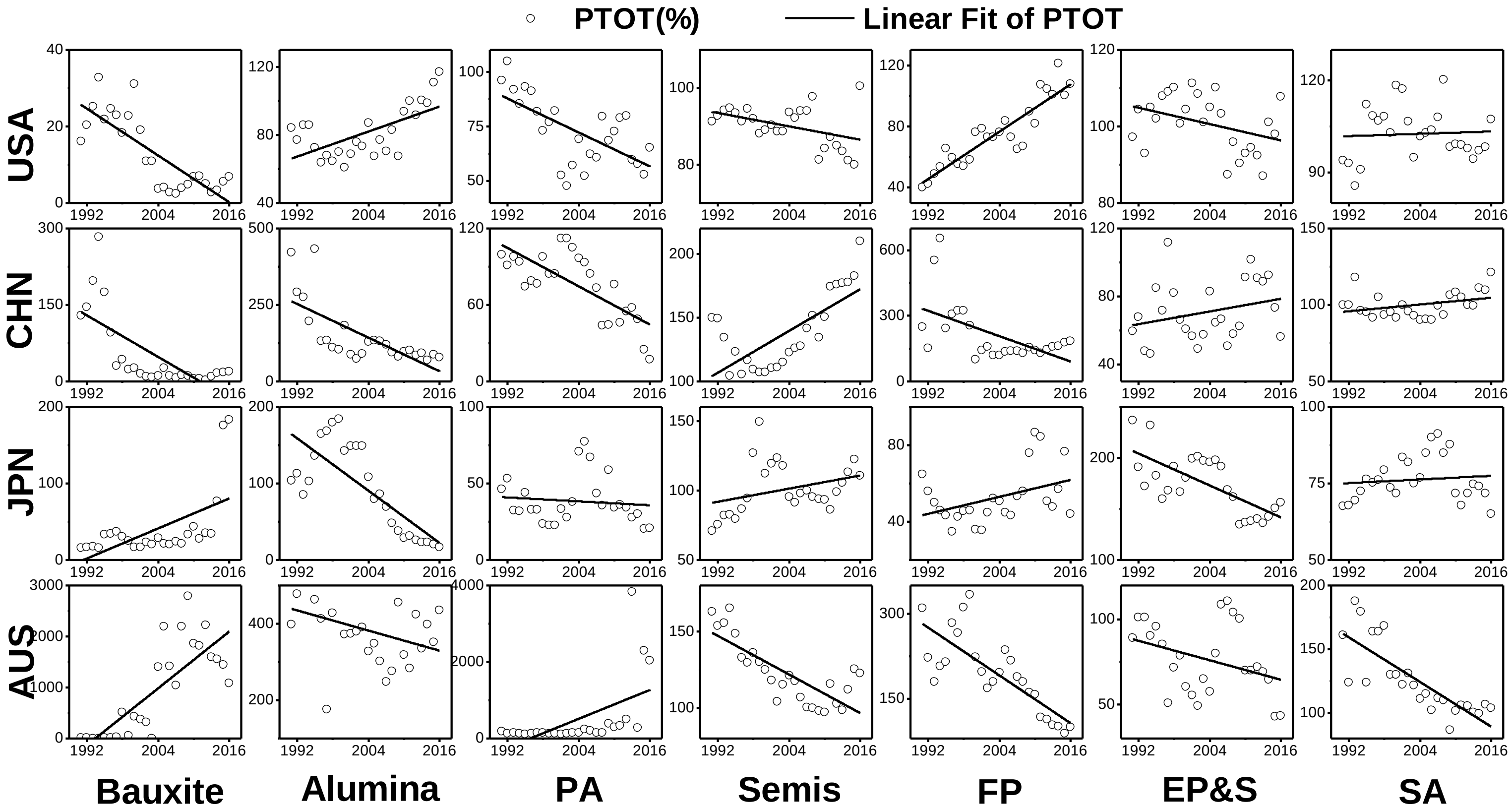

Figure S12 The seven ACP groups' pollution terms of trade of these four countries. PTOT = Pollution terms of trade; Linear fit of PTOT shows the trend of each of ACP's PTOT.

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