(This is a preliminary version of the paper and will be updated in future revisions.)

Analysing the potential of secondary aluminium in achieving decarbonisation of the global aluminium industry

Zijie Ma[1], Alvaro Calzadilla[1], Matthew Winning[1]

1 Institute for Sustainable Resources, University College London, 14 Upper Woburn Place, London WC1H 0NN, United Kingdom

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Abstract

Achieving the climate change goals of the Paris Agreement requires all industries contribute to the achievement of carbon emission reduction targets. However, climate change mitigation in the material sector faces the dual challenge: satisfying rapidly rising global demand for materials while achieving the decarbonisation of the whole industry supply chain. As a traditionally high energy consumption, emissions, and pollution industry, the global Aluminium (Al) industry is facing increasing necessity to achieve such decarbonisation. Notably, the production of secondary Al can reduce by more than 90% the energy costs and CO2 emissions. The significance of secondary Al as a key method in achieving the decarbonisation of global Al industry is still underexplored.

This study explores the potential of secondary Al industry in achieving the decarbonisation of the global Al industry. First, we quantified the global Al stocks and flows from 1970 to 2017 for 10 regions by building the regional Material flow analysis (MFA) models. Then, by splitting the bauxite, primary Al production, secondary Al production and Al recycling sectors on the basis of the GTAP 11 database, we further updated the Environmental Global Applied General Equilibrium (ENGAGE) model incorporating the detailed Al sectors. Finally, by building the integrated modelling framework that hard-links regional MFAs with the global ENGAGE model, the environmental, resource and economic impacts of secondary Al in achieving decarbonisation of Al industry are further assessed. We use the integrated modelling framework to conduct different circular economy policies and decarbonisation interventions across the regional Al supply chain and further assess the decarbonisation potential under the future scenarios from 2018 to 2050.

Our findings indicate that implementing circular economy strategies holds substantial potential for decarbonisation. We found that: 1) implementing a production tax significantly reduced primary Al production, driving a shift toward secondary Al production. Moreover, while the cost of primary Al production increased, the secondary Al industry gained competitive advantages in the market; 2) extending product lifetimes played a critical role in reducing overall Al demand. Specifically, gradually increasing lifetimes from 10% to 100% across regions by 2050 could achieve a 68% decrease in primary Al production, further leading to a 71% reduction in CO2 emissions by 2050; 3) gradually increasing the recycling rate to reach the theoretical maximum in each region by 2050 could help reduce bauxite inputs by 40% compared to 2017 and is expected to achieve a 72% reduction in CO2 emissions by 2050.

The outcome of this research helps clarify the economic and environmental significance of secondary Al in achieving the decarbonisation of the global Al industry and further provides valuable references and policy recommendations for the circular economy development of both regional and global Al industries.

Introduction

Climate change is a global emergency that goes beyond national borders. To achieve the key goals from Paris Agreement (United Nations, 2015), that is, stabilizing global average temperature at 2 ◦C above pre-industrial levels by 2050, requires all industries must contribute to the achievement of carbon emission reduction targets in proportion. This includes those sectors which have traditionally been considered hard to decarbonise. Currently, the metal production and usage accounts for more than 10% of global greenhouse gas (GHG) emissions, however, a clear vision of a future metal use system in line with long-term climate goals is lacking (Watari et al. 2020). The circular economy agenda for metals is a long-term agenda, and the actions must be taken soon (Voet, Van der et al. 2019).

Aluminium (Al) is the second most used metal in our modern society, as a result of the combination of various excellent properties such as light weight, high strength, good corrosion resistance and high conductivity (Ciacci et al. 2013), Al has been widely used in transportation, packaging, building and construction sectors (Pedneault et al. 2021). The global Al demand is estimated to triple at least by 2050, however, the production of primary Al uses 3.5% of global electricity and causes 2% of global CO_2 emissions (Mission Possible Partnership, 2022), according to the Paris Agreement (United Nations, 2015), meeting a 50% cut in emissions by 2050 in Al industry against growing demand would require at least a 75% reduction in CO_2 emissions per ton of Al produced a challenging prospect. Therefore, there is an urgent need to explore decarbonisation pathways for global Al industry, which requires efforts from both the supply side and the demand side (Chen *et al.*, 2014). From the perspective of the supply-side, a detail material flow map can identify opportunities to improve material efficiency, promote circular economy and further contribute to the decarbonisation (Yang *et al.*, 2023). From the perspective of the demand-side, the various modelling methods can be used to examine circular supply chains and analyse the environmental, economic, and social impacts of different decarbonisation strategies for moving the linear economy toward to the circular economy (Hanes et al. 2021).

The current Al industry decarbonisation pathways mainly focus on three areas: electricity decarbonisation (Kalt et al. 2022), direct emissions reduction (such as the development of the inert anode technologies or the implementation of Carbon Capture and Storage technology) (European Aluminium & CRU Group 2019), and recycling and resource efficiency (IAI 2021). However, the decarbonisation of electricity grids and the development of the direct emissions reduction technologies will require significant technology innovation and investment and may not make remarkable contribution to carbon emission reduction targets in the short-term (ibid.). Therefore, here, this dissertation focuses on exploring the decarbonisation potential of the Al industry in terms of recycling and improving resource efficiency. As an important part of the circular economy, promoting the long-term use of secondary Al is a key factor in reducing GHG emissions (Li et al. 2020). The IEA estimated that secondary Al production from end-of-life (EoL) scrap can reduce energy intensity by more than 90%, the GHG emissions and energy can be decreased up to 95.8% and 95.1% respectively, under correct conditions of secondary Al production (Eheliyagoda et al. 2022). Therefore, production of secondary Al can markedly reduce energy costs and CO_2 emissions. The increasing growth of global demand for Al, has led to the importance of sustainable management for secondary Al.

As the world's leading primary producer and consumer of Al, over 80% of global increased utilization of primary Al was attributed to China (Zhang et al. 2015). Because China has maintained a strong production and consumption trend of Al over recent decades, the Al products in China are still in their early stage of use. However, the scenario analysis of China's future Al cycle has revealed that the China's old Al scrap generation will increase dramatically in the next few decades (Dai et al. 2019). If the domestic Al can be effectively recycled, the carbon emissions of China's Al industry will be largely alleviated. However, there is no single intervention that will encourage more domestic recycling of domestically produced scrap Al, and a range of circular economy interventions will need to be pursued. China's efforts on promoting low-carbon transition of its Al industry will arguably contribute the process of the future development of circular economy in the global Al industry, which is of great significance.

This study will first provide a detailed modelling and long-term projections of the Al dynamics cycle from both physical and economic perspective through the construction of an integrated modelling framework comprising a Material flow analysis (MFA) model and a Computable General Equilibrium (CGE) model. This integrated modelling framework will hard link the MFA and CGE models to assess the environmental, resource and economic impacts of secondary Al in achieving decarbonisation of Al industry, by conducting the different circular economy policies and decarbonisation interventions across the China's Al supply chain. The outcome of this study will help clarify the significance of secondary Al in achieving the decarbonisation of global Al industry and further provide the valuable reference and policy recommendations for the circular economy development of the regional and global Al industry.

Methods

Dynamic Material Flow Analysis model

MFA is an effective analytical method to trace the fate of material along its whole life cycle in a defined system, and it can further provide new perspectives and reference for resources and environmental issues (Laner & Rechberger 2016). The detailed life cycle framework of Al is shown in Figure 1 for the example of China. The material flow analysis model traces the whole life cycle of Al, which from its primary products to its end-of-life scrap. Mining is the first stage where the bauxite is mined from the ore, and the bauxite is transferred into alumina through Bayer process, Sintering process or other process in refining stage (Pedneault et al. 2021). Then, in the production stage, the alumina is first converted into primary Al liquid through electrolysis, and then casted into Al ingot. The Al ingots are fabricated into different semis products through different processes (rolling, extrusion, wire drawing and others treatment) in fabrication stage, including the Al strip, Al sheet, Al plate and so on. After this, the semis products are further produced into different Al-contained final products which are used in car, building, packaging, and other products in manufacturing stage, and then enter the in-use stage. Since Al is widely used in several products, the Al-contained products are divided into seven end-use sectors (Chen & Shi 2012) with different quantification parameters like product lifetimes, consumption structure and stock per capita curves (Dai et al. 2019). The seven end-use sectors are Transportation (Trans), Building and Construction (B&C), Container & Packaging (C&P), Electricity Engineering (EE), Machinery and Equipment (M&E), Consumer Durables (ConDur), and Others (Others).

Besides the transformation flow, the international trade of different life cycle Al-containing products (ACPs) is also included in regional or national level of MFA, which including the bauxite, alumina, Al ingot, semis products, final products, and Al scrap. Compared with other metals, Al has the considerable recoverability and recycling rate (Chen 2013), the recycling flow of Al including the pre-consumer scrap from fabrication and manufacturing stage and the post-consumer scrap from in-use stock.

Finally, the material losses from different stages are also collected and calculated. All flows and stocks are balanced in metal (Al) content.

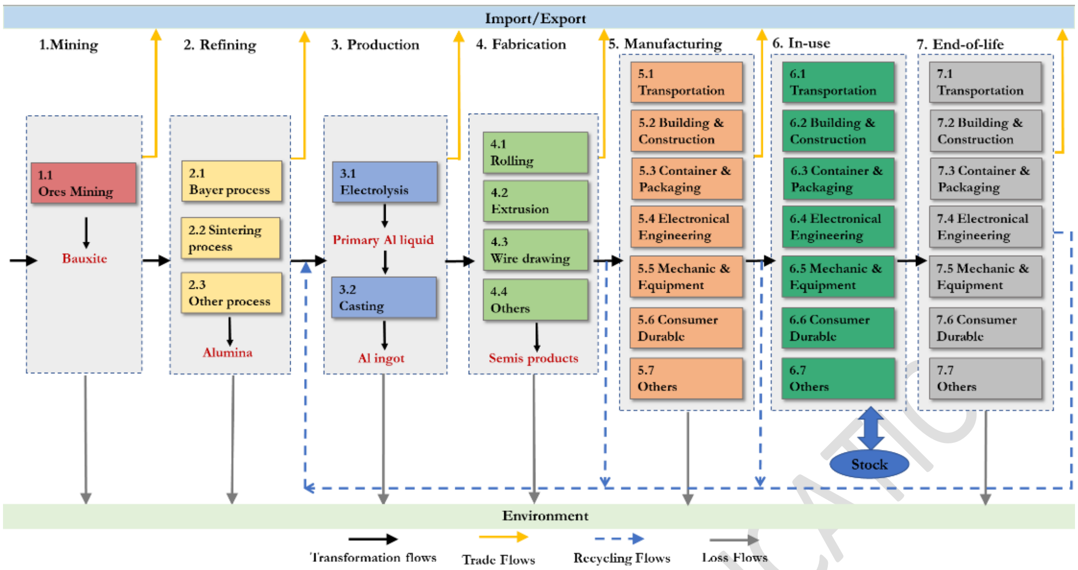

Figure 1 Life cycle framework of Aluminium in mainland China.

Introducing aluminium into the GTAP database

CGE models are one of the most common tools based on a top-down modelling framework, used to analyse the long-term economic implications of climate change policy (Wang & Chen 2006). CGE models capture trade and sectoral interlinkages through general price effects stemming from policy-induced technological changes. Winning *et al.* (2017) developed a global CGE model (ENGAGE-material) that comprises an advanced level of detail related to steel industry and enables global analysis of changes in materials throughout the supply chain to allow for the assessment of the macro-economic impacts of a variety of future fiscal and environmental steel policies and technological developments. The development of a global CGE model for the Al industry (based on Winning *et al.*, 2017) will not only provide a greater understanding of the regional technologies and global Al markets, it will also consider the resource efficiency and circular economy impacts of different policy, political and technology futures at the global scale (Nechifor et al. 2020). The model will be used to assess the economy impacts of different decarbonisation interventions of the global Al industry with a particular focus on China.

Similar to the ENGAGE-material model, the global Al CGE model is a special version of the UCL ENGAGE model which is a standard multi-sectoral, multi-region, dynamic CGE model. ENGAGE model is based upon standard general equilibrium assumptions such a market clearance, zero profits, and utility maximisation/cost minimisation of representative agents (Winning et al. 2017). The global Al CGE model will enable the consideration of demand and supply interactions across all factors of production (capital, labour, land) and commodity markets through price and quantity changes induced by different policy interventions (Nechifor et al. 2020), and will comprise the detail of both sectoral level (bauxite mining, primary and secondary Al production, downstream industries sectors) and macro-economic level (GDP, terms of trade, exports) across all regions considered.

Specifically, since the ENGAGE-materials model is built upon the GTAP 11 database (GTAP, 2023), while the Al sector is incorporated within the broader non-ferrous metals (nfm) sector in the original GTAP11 database rather than being classified as a separate sector. The splitting of the Al sector is based on the production data generated by the MFA model, combined with the national input-output tables and trade data from UN COMTRADE database (United Nations 2022), and employs the SplitCom program developed by Horridge (2005) to integrate four Al sectors (bauxite from Other Extraction (oxt), alumina, primary Al, secondary Al and recycling Al from Metals nec (nfm)) into the GTAP 11 database.

Hard linking between MFA and CGE models

MFA models take historic patterns and future dynamics of in-use stocks as cornerstones to explore the life-cycle resources and environmental impacts along with the development of in-use stocks (Cao et al. 2019). However, considerations of the economic costs and benefits are missing in these MFA models. CGE models represent the interactions of different economic sectors (e.g., firms, households and government) based on a consistent microeconomic behavioural framework (Andersen et al. 2019), while they do not account for the physical flow or the in-use stocks of materials. These in-use stocks represent the physical basis for service and production activities, and their dynamic development will set boundary conditions for future resources demand, availability of scrap, and consequent resource and emission impacts, which will further influence the future sectoral demand (Cao et al. 2019). Therefore, the proposed integrated framework that aims to link global Al industry MFA and CGE models together can comprehensively assess large-scale and long-term socioeconomic material metabolism from both the physical and economic perspectives.

Figure 2 illustrates the detailed framework of hard linking between the MFA and CGE models. The stock-driven model (which is a part of the MFA model) can be used for future projection of consumption demand and scrap availability, for which the in-use stock of metals contained in products is considered as the driving force behind the metal cycle (Pauliuk *et al.*, 2013a; Pauliuk *et al.*, 2013b). Because the in-use stock represents the physical service provided directly by metals and provides a more accurate and explicit estimation of demand (Dai et al. 2019), this approach becomes more recognized and widely used (Hatayama *et al.*, 2010, 2012; Pauliuk *et al.*, 2012; Dong *et al.*, 2019). CGE models include a production module, a final demand module (government and households), and a trade module. The circular economy policies and decarbonisation interventions will be implemented in the upstream, midstream, and downstream of China's Al supply chain. The resource-level impact will be captured by the output from the MFA model, and the economic-level impact will be captured by the output from the CGE model. Notably, the MFA model can provide the carbon emission equivalents for the entire Al life cycle, while CGE model can provide sector-level carbon emission equivalents, thus, the environmental-level impact will be co-represented by the carbon output from both models.

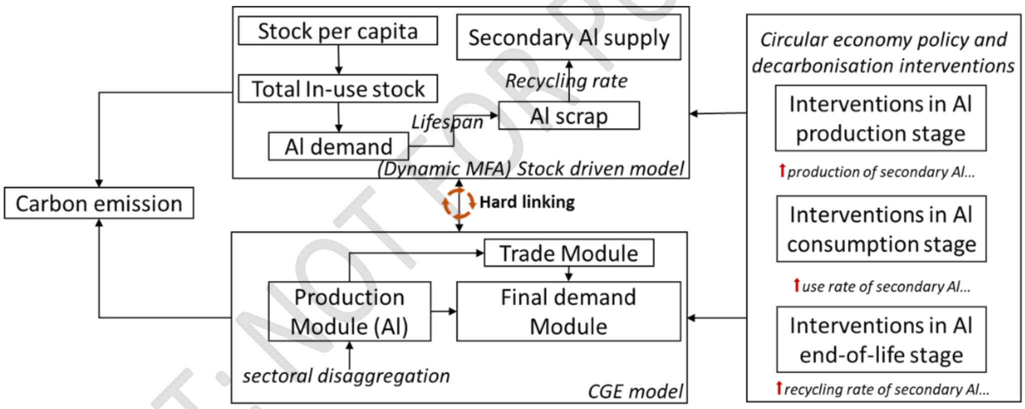

Figure 2 Framework of hard linking between MFA and CGE models

Results and Discussion

Rapid growth in secondary aluminium production presents decarbonisation potential

Figure 3 illustrates the global production of Al-containing products (ACPs) in different life cycle stages across 10 regions. The production of all ACPs has shown a growth trend, with the global cumulative production of bauxite reaching approximately 1,400 million tons (Mt) over the past 50 years. Among the regions, Other Producer is the largest bauxite producers, followed by China; together, these two regions produced ~830 Mt of bauxite, accounting for 60% of the global total. Bauxite undergoes refining to produce alumina, with Other Producer and China remaining the primary global centres for alumina production. Notably, China's share of alumina production (27%) exceeds its share of global bauxite production (15%), while other producer's alumina production (29%) is lower than its bauxite share (44%). This indicates that China is a net importer of alumina, and Other Producer is a net exporter. Additionally, while Other Asia contributes significantly to global bauxite production, its alumina production represents only 2% of the global output, implying that Other Asia mainly exports bauxite.

Al ingots are categorized into primary and secondary ingots based on the raw material. Over the past 50 years, the cumulative global production of primary Al ingots (~1,250 Mt) has been doubled that of secondary Al ingots (~535 Mt). China, Europe, and Other Producer lead in primary Al ingots production, whereas Europe, North America, and China are the main producers of secondary Al ingots. Secondary Al production consumes only 30% of the energy required for primary production (Allwood, 2014), suggesting that China and Other Producer should consider expanding their domestic capacity for secondary Al ingot production while aiming to reduce primary production. The global accumulation of Al scrap has reached approximately 600 Mt, with Europe, North America, and China collectively contributing 62% of total. The recycling rate of global Al scrap is about 89%, the rising scrap generation alongside high recycling rates presents a promising opportunity to transition the Al industry from primary to secondary production pathways.

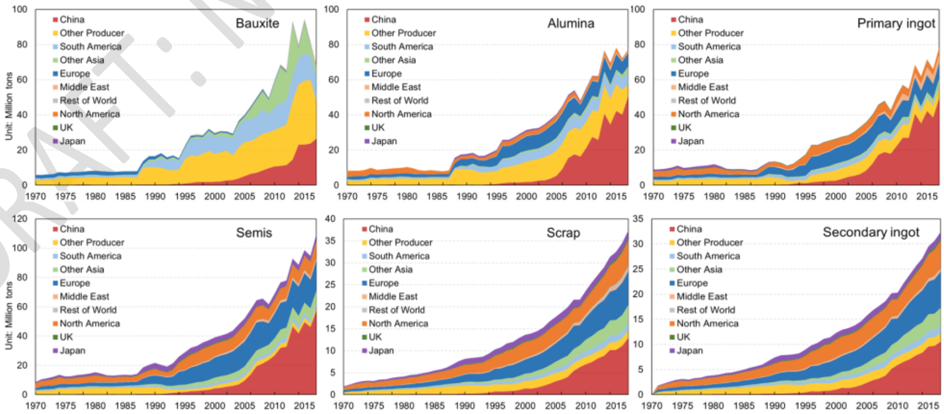

Figure 3 Al production by life cycle stage in 10 regions (1970-2017)

Circular economy strategies alone are insufficient to achieve the aluminium industry's 1.5°C emission target

Figure 4 illustrates the future CO_2 emission for the global Al industry under different scenarios for 2018 to 2050. The results indicate a downward trend in CO_2 emissions across all scenarios over the next 30 years, even in the BAU scenario where no additional measures are implemented. This trend is attributed to a fixed future Al consumption demand, where, as more in-use Al stock reaches end-of-life stage, the increasing input of recycled Al reduces the need for raw material inputs across all scenarios over time. The global Al industry relied exclusively on raw materials for production in 1970. Over time, both raw and recycled material input have increased, with raw materials initially growing at a faster rate. However, after peaking at 90 Mt in 2020, raw materials input began a continuous decline (Figure 5). This shift is largely driven by significant amounts of Al products that China input in at the beginning of the 21st century gradually reaching end-of-life stage, leading to a marked increase in recycled material use (Dai et al. 2019).

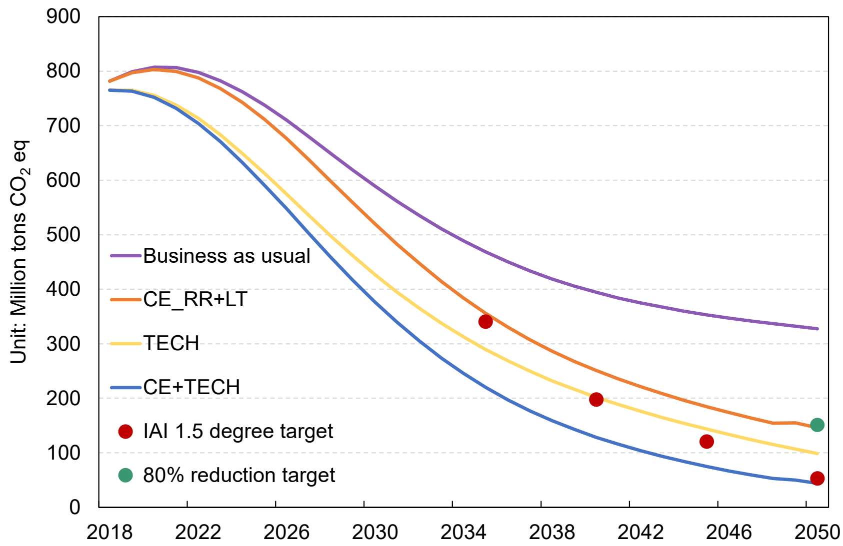

Figure 4 Future CO_2 emissions of the global Al industry (2018-2050)

Specifically, under the BAU scenarios, a 57% reduction is expected by 2050. The CE_RR+LT scenarios (increased recycling rates and lifetime extension) could achieve the IAI's target of an 80% reduction in CO_2 emissions by 2050 (IAI 2022). However, this scenario still falls short by 93 Mt CO_2-eq in meeting the IAI's ambitious 1.5°C reduction target (IAI 2021). The TECH scenario performs slightly better than the CE_RR+LT scenario but remains 45 Mt short of the 1.5°C reduction target. This indicates that the IAI initiative's 1.5°C emission reduction target cannot be achieved in the global Al industry through circular economy strategies or technology innovation alone. However, with an ambitious CE+TECH scenario, the global Al industry could potentially reduce emissions to only 44 Mt CO_2-eq by 2050, achieving a 94% reduction from 2017 levels and exceeding the IAI's 1.5°C target (53 Mt CO_2-eq).

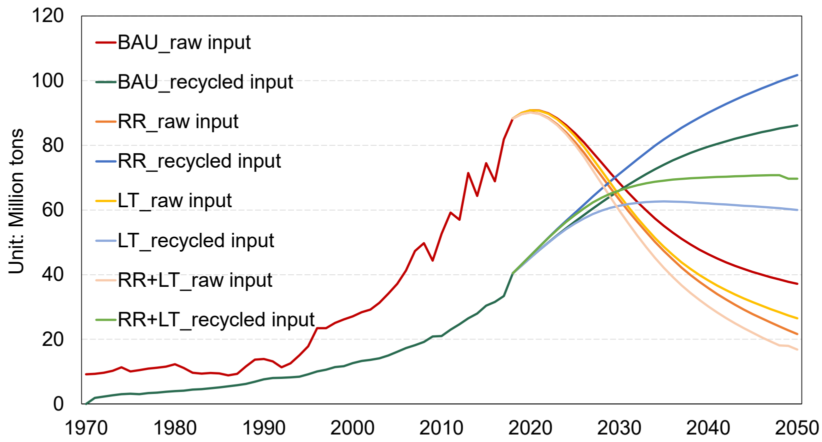

Figure 5 Comparison of the proportions of raw and recycled inputs in Global Al production under the different scenarios

Our results indicate that enhancing the energy mix and power generation efficiency in the global Al industry through technology innovation presents the most effective decarbonisation strategy. According to the IEA (IEA, 2024), the emissions intensity of the total power mix under the Net Zero Emissions (NZE) scenario is expected to decline by approximately 60% from today's levels by 2030. The Al industry should aim to reduce its power supply emissions intensity by at least this margin, including by reducing its reliance on unabated coal-generated power. To achieve the NZE target, the Al industry must adopt additional decarbonisation measures, such as accelerating the transition to renewable energy sources and implementing breakthrough low-carbon technologies. Overall, this analysis highlights the importance of promoting collaboration across different countries within the Al supply chain. It suggests that any strategy for decarbonising the global Al industry should consider regional disparities and inequalities, ensuring a more balanced and equitable approach to environmental stewardship and economic development.

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