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High-resolution data unveils overestimation of China's electricity carbon footprint in international LCA databases

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Dear Editor,

The power system serves as a critical nexus between energy production and end-use consumption. It functions as the key conduit through which embodied carbon is allocated to industrial products. It is estimated that in 2024, approximately 14.21 gigatons (Gt) of embodied carbon globally—accounting for 38.9% of the total—and over 5.5 Gt in China alone, representing 48.9%, were distributed via power systems.[1] Since electricity permeates every stage of the product life cycle, the product carbon footprint (PCF) is greatly influenced by the electricity carbon footprint (ECF). The PCF has been a pivotal metric in evaluating a product's environmental impact and its low-carbon profile. Regulatory frameworks such as the European Union's Carbon Border Adjustment Mechanism (CBAM) and Battery Regulation explicitly establish PCFs as prerequisites for market access. Consequently, the magnitude and credibility of the PCF directly affect a product's international competitiveness. According to data on global merchandise trade issued by the World Trade Organization, Chinese exports accounted for 14.2% of the international market share in 2023.[2] Therefore, China's ECF is not only crucial for Chinese products but also a key concern for stakeholders throughout the global industrial supply chain.

However, the data on China's ECF in international life cycle assessment (LCA) databases, such as Ecoinvent and GaBi, exhibit considerable uncertainty. In Ecoinvent 3.11, for example, the synthesized dataset for Chinese electricity is based on a limited sample of power generation units, covering only 100 MW and 500 MW coal-fired units. But by 2022, China's installed coal-fired power units exceeding 600 MW have been above 50% of the total capacity. Furthermore, the inventory data for Chinese coal power in Ecoinvent 3.11 dates back to 2012, whereas the GaBi data dates back to 2018. This means a time lag of over a decade. Additionally, Ecoinvent 3.11 uses data from hydropower plants in Switzerland and Austria from the 20th century to represent hydropower in China, which differs substantially geographically. The accumulation of these multiple uncertainties has severely undermined the credibility of China's ECF data, posing significant challenges to the advancement of global green and low-carbon development as well as the promotion of fair international trade. Using the Web of Science and CNKI with "China's electricity carbon footprint" as the topic yielded only 575 relevant records. Among them, merely 33 articles concentrate on the accounting of the electricity carbon footprint. The current body of work shows several recurrent limitations: (i) Most studies are confined to a single generation technology and lack system-level integrative analysis. (ii) Studies of coal-fired power predominantly rely on outdated datasets, missing the decarbonization effects of recent technological advances, while research on renewable energy largely stays at the component scale. (iii) Merely five studies conduct national-scale accounting, and they exhibit issues of temporal lag and/or incomplete inclusion of generation technologies.[3-5] Consequently, it is imperative to undertake a comprehensive reassessment of China's ECF.

This study employs the LCA methodology, defining the functional unit as the transmission of 1 kWh of electricity through the power grid. The system boundary covers the entire process, from raw material extraction and transportation to power generation and electricity transmission. It also includes the construction of infrastructure for both power plants and transmission networks. The analysis is based on 2022 operational data from over 62,000 power generation units across China, comprising detailed information on fuel consumption, fuel characteristics, and electricity output for coal-fired and gas-fired units. For the coal mining process, empirical data were collected from approximately 90% of the country's coal mines, ensuring maximum temporal, spatial, and technological consistency across unit processes. These data were drawn from the GIS-LCA spatialized background dataset developed by the Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences. Activity data for other power sources were obtained from the literature, while all background data were sourced from the Ecoinvent 3.11 database. Based on uncertainties in parameters such as the actual carbon content, the carbon oxidation rate and renewable energy components, the minimum–maximum interval of results was calculated using the IPCC 2021 assessment method.

This study, based on the GIS-LCA methodological framework and software, performed spatial modeling at the actual geographic locations of generating units and thereby constructed a high-resolution carbon footprint model of China's electricity system (Figure 1A).[6] We introduce a novel power-flow–carbon-flow coupled modeling approach and integrate interprovincial coal and electricity trade data to elucidate how cross-provincial power flows shape consumption-side carbon footprints, thereby markedly enhancing the model's real-world representativeness. The model calculates average ECFs at national, regional, and provincial grid levels. Contribution analysis based on parameter intervals indicates that direct emissions from coal-fired power generation represent the largest share of the ECF, accounting for 80.4% to 81.2% of the national average ECF. Direct emissions from coal mining are the second largest contributor (12.5%–12.9%), followed by direct emissions from gas-fired power generation (2.0%–2.1%). Remaining contributions, arising from other indirect processes, range from 3.8% to 5.1%. Overall, approximately 95% of the carbon footprint is attributable to on-site emissions reported by enterprises, suggesting that the results provide a robust and representative estimate of China's ECF in 2022.

The estimated interval for the average ECF in China is [649.6, 678.4] gCO_2eq/kWh. In comparison, the values reported by GaBi 2022 and Ecoinvent 3.11 are 767.0 gCO_2eq/kWh and 838.9 gCO_2eq/kWh, respectively, exceeding this study's interval by [88.6, 117.4] gCO_2eq/kWh and [160.5, 189.3] gCO_2eq/kWh, as illustrated in Figure 1B. Although Ecoinvent 3.11 has updated its Chinese ECF data in recent versions, it continues to overestimate China's ECF by approximately 23% to 29%. Moreover, comparative analysis shows that Ecoinvent 3.11 significantly overestimates average grid-level ECFs across major Chinese regions. Specifically, the overestimations for the Northeast, North, Central, and Northwest grids all exceed 25%, as shown in Figure 1B.

Between 2012 and 2022, the share of non-fossil fuel-based electricity generation in China increased markedly from 21.3% to 33.5%, while the installed capacity of non-fossil sources reached 48.1% of the total. During this period, installed capacities of wind and solar power grew by factors of 4.9

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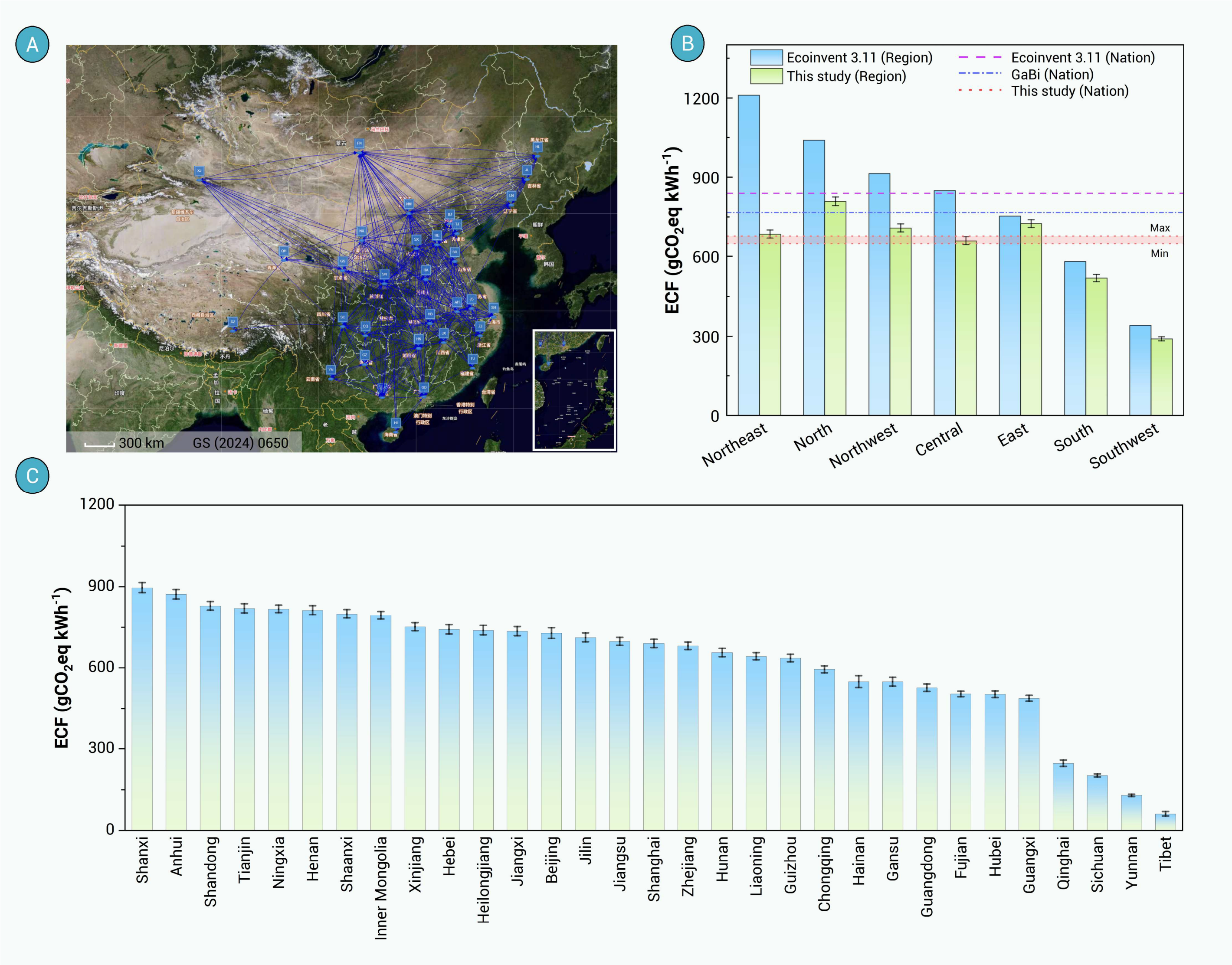

Figure 1. Framework of China's ECF accounting model (A), national and regional ECFs (B), and provincial ECFs (C).

and 114.2, respectively.[3] Simultaneously, coal-fired power units were continuously upgraded to enhance efficiency and reduce emissions, resulting in a 7.4% decrease in average coal consumption per unit of electricity generated. The proportion of high-capacity units (≥600 MW) rose to 56.6%. The widespread adoption of ultra-high-voltage transmission technologies further contributed to a substantial reduction in line losses, from 6.74% to 4.86%.[3] However, these significant advancements in China's power infrastructure and technology are inadequately captured by mainstream international LCA databases. As a result, the carbon footprint of China's electricity is systematically overestimated, failing to accurately reflect the current state of China's power sector. This discrepancy is prevalent across numerous international databases. Consequently, the carbon footprint calculations of Chinese products tend to be overestimated. This overestimation not only undermines the competitiveness of Chinese products in the global green market but also diminishes recognition of China's genuine efforts toward a green and low-carbon transition. Such distortions compromise fairness in both international trade and global climate cooperation.

Further analysis reveals significant regional disparities in ECFs across China's power grids. The ECF interval for the North China Grid is [793.4, 825.9] gCO_2eq/kWh, whereas the Southwest China Grid is [283.0, 297.8] gCO_2eq/kWh—a difference exceeding 2.7 times, demonstrating pronounced regional heterogeneity. At the provincial grid level, the contrast is even more marked: the difference between the highest ECF in Shanxi and the lowest in Tibet surpasses 830 gCO_2eq/kWh, representing over a 14-fold variation, as illustrated in Figure 1C. These disparities primarily result from China's vast territory and uneven distribution of resources. For instance, the North is rich in coal resources and heavily dependent on thermal power, leading to higher ECFs, while the Southwest, endowed with abundant hydropower resources, exhibits substantially lower ECFs.[7] This marked spatial heterogeneity underscores the inadequacy of using a single national average ECF factor to capture regional differences. Applying a uniform national ECF in calculating PCFs may inadvertently penalize enterprises in low-carbon regions, thereby undermining their decarbonization efforts and impeding China's advancement toward green and low-carbon development.

The complexity of grid interconnection and power transmission can substantially alter regional ECFs. Using Beijing as an example, although its production-side ECF is relatively low, large inflows of electricity from higher-ECF provinces—Hebei, Shanxi, and Inner Mongolia—together with losses over long-distance transmission, raise its consumption-side ECF to about 33.8%–40.0% above the local level. This pattern demonstrates the strong cross-regional dependence of ECFs and indicates that relying solely on production-side data cannot faithfully represent the spatial distribution of emission responsibility. Therefore, developing a regionalized ECF model that captures interprovincial electricity flows and carbon transfers provides an essential basis for more scientific, equitable, and effective mitigation policies, and is fundamental to coordinated regional decarbonization and targeted interventions.

China is undergoing a profound green and low-carbon transformation, marked by a rapid expansion in renewable energy development. Between 2022 and 2024, the share of non-fossil fuel electricity generation increased by 3.4%, and the installed capacity of renewable power surpassed 1,889 GW—exceeding coal-fired capacity for the first time in history. Additionally, the standard coal consumption per unit of thermal power generation decreased by 0.4%, reflecting further improvements in China's clean power supply capabilities. China currently leads the world in both installed capacity and electricity generation from renewable sources, and its contribution to global green and low-carbon development should not be underestimated. However, China's unique national circumstances must be duly considered, necessitating a departure from the rigid reliance on existing international carbon footprint management frameworks. Embracing a philosophy of compatibility and transcendence, China must accelerate innovation in carbon footprint accounting methodologies and build high-resolution, localized databases. Developing carbon footprint assessment tools tailored to national circumstances can significantly enhance the scientific rigor, precision, and regional applicability of accounting practices. By establishing a carbon footprint management system that integrates China's realities with global standards, the country can shift from a passive follower to a proactive leader, thereby amplifying its influence in global green trade and offering uniquely Chinese solutions to global climate governance.[8]

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DECLARATION OF INTERESTS

The authors declare no competing interests.