

Article

Towards Sustainable Product Carbon Footprint Accounting Through Green Electricity and Green Certificate Mechanisms

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Abstract

Against the global transition toward sustainable energy systems and the rapid development of green electricity trading and green certificate systems, traditional regional average electricity emission factors are no longer sufficient to accurately reflect the carbon emission responsibilities associated with enterprises' actual electricity consumption. This may lead to the double counting of renewable electricity attributes and the overestimation of emission reduction effects. To address this issue, this study focuses on electrical equipment products. Building upon the existing life-cycle accounting framework, a method for constructing provincial residual electricity emission factors coupled with green electricity and green certificate attribute verification mechanisms is proposed. By excluding non-fossil electricity volumes whose environmental attributes have already been claimed through market-based mechanisms, an accounting factor capable of characterizing the actual emission intensity of "residual electricity" is established, together with an accounting model for indirect electricity emissions during the production stage. Furthermore, eleven typical categories of electrical equipment, including transformers, electricity meters, conductors, and power cables, are selected to conduct an empirical cradle-to-gate carbon footprint analysis and evaluate their carbon reduction potential under a 50% green electricity substitution scenario. The results indicate that provincial residual electricity emission factors incorporating renewable electricity attributes can improve the accuracy and transparency of product carbon footprint accounting. This approach provides methodological support for sustainable manufacturing, green procurement, low-carbon supply chain management, and the development of product carbon footprint standards.

Keywords: electrical equipment; product carbon footprint; green electricity; green electricity certificate; sustainable manufacturing; low-carbon supply chain

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1. Introduction

Against the global transition toward low-carbon energy systems and the increasing adoption of product carbon footprint (PCF) standards, accurately quantifying indirect electricity-related emissions has become a critical challenge in industrial carbon accounting [1,2]. Product carbon footprints are increasingly used to support corporate decarbonization strategies, green procurement, supply-chain management, environmental product declarations, and compliance with emerging carbon-related trade regulations [3,4]. In

most existing accounting frameworks, indirect electricity emissions are calculated using regional or national average grid emission factors. However, the accuracy of these calculations can be strongly affected by the spatial heterogeneity and temporal variability in electricity generation mixes and grid emission factors [5,6]. More importantly, the rapid expansion of renewable electricity markets is fundamentally changing the allocation of environmental attributes within electricity systems, creating new challenges for conventional carbon accounting approaches.

As renewable electricity deployment accelerates worldwide, traditional average-grid accounting approaches face growing challenges. These approaches implicitly assume that the environmental attributes of renewable electricity are shared proportionally among all electricity consumers connected to the grid. However, this assumption becomes increasingly problematic as renewable electricity attributes are separately traded and claimed through market-based instruments, such as Guarantees of Origin (GOs) in the European Union, Renewable Energy Certificates (RECs) in the United States, and Green Electricity Certificates (GECs) in China [7,8]. Under these mechanisms, renewable electricity attributes can be exclusively claimed by specific entities, meaning that continued use of conventional average grid emission factors may lead to double counting of renewable attributes and inaccurate estimation of indirect electricity emissions [9,10]. Consequently, accurately distinguishing certified renewable electricity from residual grid electricity has become an increasingly important issue in Scope 2 accounting, product carbon footprint assessment, and corporate greenhouse gas reporting [11]. China provides a representative case for addressing this challenge because it combines rapid renewable electricity expansion, active certificate-based attribute trading, and substantial regional heterogeneity in electricity generation structures. As a result, provincial electricity emission factors vary considerably across regions, and traditional average emission factors may no longer accurately reflect the actual carbon emission responsibilities associated with enterprise electricity consumption, particularly when green electricity and GEC transactions are involved.

Previous studies have made substantial progress in product carbon footprint accounting and electricity-related emission assessment. Existing product carbon footprint methodologies generally quantify indirect electricity emissions using regional or national average electricity emission factors, providing a practical basis for lifecycle carbon accounting across industrial sectors. In parallel, researchers have increasingly explored market-based Scope 2 accounting, electricity attribute allocation, residual-mix methodologies, and renewable electricity certificate mechanisms to improve the accuracy of electricity-related emission reporting. To address the potential double counting of renewable electricity attributes, several countries and regions have introduced residual-mix or residual-blend accounting approaches. These methods calculate the average emission intensity of the remaining electricity supply after deducting renewable electricity whose environmental attributes have already been claimed through certificate systems, thereby improving the consistency of electricity-related emission reporting. However, important limitations remain. Most existing studies focus on electricity-sector accounting, carbon market mechanisms, electricity trading simulations, or system-level emission assessments, while applications at the product level remain relatively limited. In particular, few studies have explored how renewable electricity attribute verification mechanisms can be directly integrated into product carbon footprint accounting frameworks for manufacturing products. As renewable electricity trading and certificate systems continue to expand, this limitation may lead to inconsistencies in indirect electricity emission accounting and reduce the comparability of product carbon footprint results across different accounting approaches. Therefore, a methodological framework is needed to bridge residual-mix accounting and product-level life-cycle carbon footprint assessment.

To address these challenges, this study focuses on the carbon footprint accounting of electrical equipment products. Building upon the existing life-cycle assessment framework, we develop a provincial residual electricity emission factor framework that integrates electricity generation structures, interprovincial electricity exchanges, and green electricity certificate transactions into product-level carbon footprint accounting. The proposed framework separates renewable electricity whose environmental attributes have been claimed through market-based mechanisms and allocates emissions only to residual electricity consumption. Although the empirical analysis is conducted within the Chinese provincial electricity system, the methodology is broadly transferable because it only requires information on electricity generation structures, interregional electricity exchanges, and renewable electricity attribute-tracking systems, such as GECs, RECs, or GOs. Unlike conventional residual-mix approaches that are mainly designed for electricity-sector disclosure or corporate Scope 2 reporting, this study embeds certificate-based residual electricity emission factors into cradle-to-gate product carbon footprint accounting. The methodological advance lies not in redefining residual-mix principles themselves, but in linking electricity attribute allocation with product-level manufacturing inventories, including bills of materials, production electricity consumption, transportation activities, and stage-specific carbon footprint results. This integration establishes a reproducible product-level accounting workflow that bridges market-based electricity attribute allocation and cradle-to-gate life-cycle assessment. As a result, renewable electricity attributes can be consistently propagated from electricity procurement through manufacturing-stage electricity use to final product carbon footprints, thereby extending residual-mix accounting from electricity-sector reporting to product carbon footprint assessment.

2. Methods

2.1. Framework for Calculating the Carbon Footprint of Electrical Equipment Products

In this study, a cradle-to-gate system boundary was adopted for product carbon footprint accounting. “Cradle-to-gate” refers to all life-cycle processes from raw material extraction to the point at which the finished electrical equipment product leaves the manufacturing facility. Accordingly, the system boundary includes raw material acquisition and processing, transportation of raw materials and intermediate products, and manufacturing activities associated with electrical equipment production. Downstream life-cycle stages, including product distribution, installation, use, maintenance, recycling, and end-of-life treatment, are excluded from the present study. This boundary definition is widely adopted in product carbon footprint studies because it enables consistent comparison of manufacturing-related emissions while minimizing uncertainties associated with product operation and disposal pathways.

The carbon footprint accounting objects in this study are typical electrical equipment products. The investigated product categories were identified through surveys and consultations with the material management departments of power grid companies and selected based on their procurement importance, deployment scale, and representativeness within power transmission and distribution systems. Common electrical equipment, including 10 kV transformers (amorphous alloy, dry-type, and oil-immersed transformers), single-phase smart electricity meters, conductors, low-voltage switchgear, power cables, electricity metering cabinets, ring main units, insulators, and tapered concrete poles, were selected as representative products. These products cover major equipment categories widely used in power grid construction, operation, and maintenance and represent a broad range of material compositions, manufacturing processes, and electricity consumption characteristics [12,13].

The life-cycle inventory (LCI) was developed using supplier-specific bills of materials (BOMs), production records, electricity consumption data, and transportation

information collected through enterprise surveys. The inventory includes detailed information on raw material inputs, manufacturing energy consumption, production outputs, and transportation activities. Major raw materials include steel, copper, aluminum, insulating materials, porcelain clay, and cement, while manufacturing data include electricity consumption, fuel consumption, and key production process information. Carbon emission factors for raw materials, fuels, transportation, and electricity were obtained from national standards, government publications, and authoritative databases.

To ensure the representativeness and reliability of the inventory, the investigated samples cover multiple suppliers and product types. For most equipment categories, data were obtained from three or more suppliers, while some categories, such as insulators, include a substantially larger number of suppliers. This multi-supplier inventory design enables the framework to capture supplier-level variability as well as differences in material composition, manufacturing processes, and energy consumption characteristics across product categories. Detailed information on the investigated products is provided in Table 1. Consequently, the inventory provides a representative and diversified sample basis for full-process carbon footprint accounting, validation of green electricity and green certificate offset rules, and assessment of emission reduction effects.

Table 1. Information on typical electrical equipment.

Product Category	Supplier	Production
10 kV amorphous alloy transformer	A	10 kV transformer, 200 kVA, standard, silicon steel laminations, amorphous alloy
	B	10 kV transformer, 200 kVA, standard, silicon steel laminations, amorphous alloy
10 kV dry-type transformer	A	10 kV transformer, 200 kVA, standard, silicon steel laminations, dry-type
	B	10 kV transformer, 200 kVA, standard, silicon steel laminations, dry-type
	C	10 kV transformer, 200 kVA, standard, silicon steel laminations, dry-type
10 kV oil-filled transformer	A	10 kV transformer, 200 kVA, standard, silicon steel laminations, oil-immersed
	B	10 kV transformer, 200 kVA, standard, silicon steel laminations, oil-immersed
	C	10 kV transformer, 200 kVA, standard, silicon steel laminations, oil-immersed
	D	10 kV transformer, 200 kVA, standard, silicon steel laminations, oil-immersed
Single-phase smart electricity meter	A	Single-phase smart electricity meter with usage-based billing
	B	Single-phase smart electricity meter with usage-based billing
Conductors, ground wires	A	Overhead insulated conductors
	B	Overhead insulated conductors
	C	Overhead insulated conductors
Low-voltage switchgear	A	Low-voltage switchgear
	B	Low-voltage switchgear
Power Cables	A	Environmentally Friendly Fire-Resistant Power Cables
	B	Extruded-sheathed low-voltage power cables
	C	Overhead insulated cable
	D	Extruded-sheathed low-voltage power cables
Electricity Metering Cabinet	A	Electricity Metering Cabinet
	B	Electricity Metering Cabinet
	C	Single-phase electricity meter box
	D	Three-phase electricity meter box
Ring Main Unit	A	Enclosed, Fixed, Pneumatic Metal-Enclosed Ring Main Switchgear
	B	Enclosed, Fixed, Pneumatic Metal-Enclosed Ring Main Switchgear
	C	Fully Insulated, Fully Sealed, Metal-Enclosed Ring Main Switchgear
Insulator	A	Other porcelain insulators
	B	Other porcelain insulators
	C	Butterfly porcelain insulator
	D	Other porcelain insulators
	E	Other porcelain insulators

	F	Other porcelain insulators
	G	Other porcelain insulators
	H	Other porcelain insulators
	I	Other porcelain insulators
	J	Other porcelain insulators
	K	Other porcelain insulators
	L	Other porcelain insulators
	A	Tapered concrete pole
Tapered concrete pole	B	Tapered concrete pole
	C	Tapered concrete pole

Note: Supplier letters indicate anonymized supplier codes.

Within this unified boundary, subsequent sections focus on optimizing the calculation methods for indirect electricity-related emissions in the production phase, while other phases continue to use existing, well-established methods. Under the aforementioned system boundary, the carbon footprint of a single electrical equipment product can be expressed as the sum of carbon emissions across all phases, and its overall calculation framework can be represented as:

$$C_{\text{total}} = C_{\text{raw}} + C_{\text{prod}} + C_{\text{trans}} \quad (1)$$

where C_{total} represents the carbon footprint of the raw material stage, t; C_{raw} denotes the carbon footprint of raw material acquisition, t; C_{prod} denotes the carbon footprint of the production stage, t; and C_{trans} denotes the carbon footprint of the transportation stage, t. The calculation methods for carbon emissions from the raw material acquisition and transportation stages have been relatively well established in relevant industry standards and previous studies, and their emission factor systems are relatively stable [14]. Moreover, these stages are not directly affected by market-based mechanisms such as green electricity trading.

Carbon footprint of the raw material acquisition stage:

$$C_{\text{raw}} = \sum_{j=1}^k (AD_{\text{raw},j} \times EF_{\text{raw},j}) \quad (2)$$

where $AD_{\text{raw},j}$ represents the activity data of the j -th type of raw material, kg; and $EF_{\text{raw},j}$ represents the carbon footprint factor of the j -th type of raw material, kg/kg.

Carbon emissions from the production stage, from “component processing” to “finished product inspection and qualification”, were calculated as follows:

$$C_{\text{prod}} = \sum_{j=1}^k (AD_{\text{prod},j} \times EF_{\text{prod},j}) \quad (3)$$

where $AD_{\text{prod},j}$ represents the activity data of energy consumption in the production stage, kg or kWh; and $EF_{\text{prod},j}$ represents the carbon footprint factor of the corresponding energy source, kg/kg or kg/kWh.

Carbon emissions from the inbound transportation of raw materials were calculated as follows:

$$C_{\text{trans}} = \sum_{j=1}^k (AD_{\text{trans},j} \times M_{\text{trans},j} \times EF_{\text{trans},j} / 1000) \quad (4)$$

where $AD_{\text{trans},j}$ represents the transportation distance of the j -th type of raw material, km; $M_{\text{trans},j}$ represents the transported mass of the j -th type of raw material, kg; and $EF_{\text{trans},j}$ represents the carbon footprint factor of the corresponding transportation mode for the j -th type of raw material, kg/(t·km).

The emission factors used in this study were compiled from the national default carbon footprint factor database provided by participating enterprises and supplemented by the provincial residual electricity emission factors developed in this study. To ensure

comprehensive coverage of the cradle-to-gate system boundary, the database was organized into three categories: (i) raw material carbon footprint factors (Table S1), covering major materials and auxiliary inputs used in electrical equipment manufacturing; (ii) transportation carbon emission factors (Table S2), covering common freight transportation modes and vehicle types used for material delivery; and (iii) energy carbon emission factors (Table S3), covering primary and secondary energy sources consumed during manufacturing processes. Together, these factor databases provide a consistent and comprehensive basis for quantifying emissions associated with material acquisition, transportation, and manufacturing activities in the product carbon footprint assessment.

2.2. Construction of Provincial-Level Residual Electricity Emission Factors Based on Green Certificate-Based Attribute Verification

With the gradual improvement in green electricity trading and green certificate-based attribute verification mechanisms, conventional accounting approaches using regional average electricity emission factors can no longer accurately reflect the actual carbon emission intensity of electricity consumption. To address this limitation, this study proposes the concept of provincial-level residual electricity emission factors to represent the average carbon emission intensity of “residual electricity” in provincial power grids after excluding non-fossil electricity whose environmental attributes have been verified through market-based mechanisms. The proposed factor is constructed based on the principles of consistency in data sources, uniqueness of environmental attributes, and emission conservation. This ensures that the environmental attributes of non-fossil electricity verified through green certificates are exclusively claimed by designated entities and are not repeatedly allocated in regional emission factor accounting. The calculation model for the provincial-level residual electricity emission factor is expressed as follows:

$$EF_{\text{province}} = \frac{E_{\text{CO}_2, \text{local}} + E_{\text{CO}_2, \text{import}} - E_{\text{CO}_2, \text{export}}}{E_{\text{total, local}} + E_{\text{net, import}} - E_{\text{net, export}} - E_{\text{market, non-fossil}}} \quad (5)$$

$$E_{\text{CO}_2, \text{import}} = \sum_{i=0}^n E_{\text{net, import}, i} \times E_{\text{export, avg}, i} \quad (6)$$

$$E_{\text{CO}_2, \text{export}} = E_{\text{net, export}} \times E_{\text{export, avg}} \quad (7)$$

where EF_{province} represents the residual CO₂ emission factor of electricity in a given province, kg/kWh; $E_{\text{CO}_2, \text{local}}$ represents the direct CO₂ emissions generated from electricity production within the administrative region of the province, kg; $E_{\text{CO}_2, \text{import}}$ represents the CO₂ emissions corresponding to electricity imported from other provinces, kg; and $E_{\text{CO}_2, \text{export}}$ represents the CO₂ emissions corresponding to electricity exported from the province to other provinces, kg. The input and output data used in the calculation of provincial residual electricity emission factors are provided in Table S4 of the Supplementary Information. $E_{\text{total, local}}$ represents the total annual electricity generation within the administrative region of the province, including thermal power, hydropower, wind power, nuclear power, solar power, etc., kWh; $E_{\text{net, import}}$ represents the net electricity imported by the province from other provinces, kWh; and $E_{\text{net, export}}$ represents the net electricity exported by the province to other provinces, kWh. $E_{\text{market, non-fossil}}$ represents the non-fossil electricity that has been verified through green electricity trading or green certificate trading during the accounting period, including green electricity traded with certificates, as well as the equivalent electricity corresponding to certificates separated from electricity. This electricity has already been allocated to specific electricity-consuming entities and is therefore no longer included in the allocation of the provincial residual electricity volume, kWh. $E_{\text{net, import}, i}$ represents the net electricity imported by the province from province i , kWh; $E_{\text{export, avg}, i}$

represents the average electricity emission factor of exporting province i , kg/kWh; and $E_{\text{export,avg}}$ represents the average electricity emission factor of the province, kg/kWh.

In the practical accounting process, this study clearly distinguishes between the emission factor construction stage and the enterprise-level accounting stage to avoid circular definition. At the enterprise level, only the portion of electricity consumption that has been locked in through green certificates is identified and deducted from the production electricity consumption. The remaining electricity consumption is then multiplied by the determined provincial-level residual electricity emission factor to obtain the indirect electricity-related emissions in the production stage. This technical pathway, characterized by “local correction and overall compatibility”, enables targeted correction of key sources of error in product carbon footprint accounting without disrupting the existing accounting framework.

2.3. An Accounting Model for Electricity-Related Emissions in the Production Stage Under Green Certificate-Based Attribute Verification

On the basis of determining product output, this study adopts an accounting approach in which green electricity is deducted from the total purchased electricity for calculating indirect electricity-related emissions in the production stage. Under this approach, the carbon emission factor of green electricity whose environmental attributes have been verified through green certificates is adjusted to 0 kg/kWh, thereby enabling a more accurate assessment of the enterprise’s actual contribution to carbon reduction. The calculation formula for indirect electricity-related emissions in the production stage is as follows:

$$E_e = (AC_{\text{total}} - AC_{\text{gre}}) \times EF_{\text{province}} \quad (8)$$

where E_e represents the indirect CO₂ emissions associated with electricity consumption in the production stage, kg; AC_{total} represents the total amount of purchased electricity consumed during the enterprise’s production process, kWh; and AC_{gre} represents the amount of green electricity whose environmental attributes have been verified through purchased green certificates, kWh.

To verify the optimization effect of the provincial-level residual electricity emission factor (EF_{province}) proposed in this study, the nationally published 2023 average CO₂ emission factor for electricity in China, which excludes non-fossil electricity traded through market-based mechanisms, and the provincial grid average emission factors were introduced as benchmark reference groups. Based on the empirical carbon footprint accounting of 11 categories of electrical equipment, this study evaluates the impact of changes in electricity emission factors after considering green electricity and green certificates on carbon footprint accounting results.

2.4. Representativeness of the Inventory Dataset

To ensure the representativeness and reproducibility of the inventory dataset, this study integrated supplier-specific bills of materials, production records, electricity and fuel consumption data, transportation activity data, and product output information collected through enterprise surveys. Because detailed product carbon footprint inventories for electrical equipment are generally not publicly available, suppliers were selected using a purposive stratified sampling approach based on procurement relevance, data completeness, geographic coverage, and supplier type.

The sampled manufacturers are distributed across major electrical equipment manufacturing bases in China, including eastern coastal provinces and inland industrial regions. They include major suppliers of transmission and distribution equipment for China’s power grid and collectively account for approximately 70% of the national

production or procurement volume of the investigated product categories. The dataset covers transformers, power cables, conductors and ground wires, switchgear, metering devices, ring main units, insulators, and tapered concrete poles. Both large-scale integrated manufacturers and medium-sized specialized suppliers are included. Detailed inventory coverage and supplier sampling information are provided in Tables S5 and S6 of the Supplementary Information.

To improve data transparency and reduce potential sampling bias, inventory quality was assessed in terms of technological, geographical, and temporal representativeness, completeness, reliability, and bias control. Specifically, product type, rated capacity, material composition, and manufacturing processes were compared across suppliers; recent production and procurement records from comparable accounting periods were prioritized; and each inventory was checked for the inclusion of bills of materials, production energy consumption, transportation activities, and product output. Primary supplier records were used wherever available, while background emission factors were obtained from national standards, government publications, and authoritative databases. Although the dataset does not include every manufacturer in China's electrical equipment industry, its multi-product, multi-supplier, and multi-region structure provides a representative basis for product-level carbon footprint assessment.

2.5. LCA Assumptions

The life cycle assessment (LCA) in this study was conducted under several assumptions to ensure methodological consistency and comparability. A cradle-to-gate system boundary was adopted, including raw material extraction, material processing, inbound transportation, and manufacturing, while downstream stages (distribution, use, maintenance, recycling, and end-of-life treatment) were excluded. Supplier-specific activity data, including bills of materials, production records, electricity and fuel consumption, transportation activity data, and product output information collected through enterprise surveys, were assumed to represent typical manufacturing conditions for the investigated products. Annual-average emission factors were applied for raw materials, fuels, transportation, and electricity, and temporal variations in electricity generation were not explicitly considered. Green electricity and Green Electricity Certificates were assumed to represent exclusive renewable electricity attributes; accordingly, certified renewable electricity was excluded when constructing provincial residual electricity emission factors and calculating indirect electricity emissions. Where allocation was required for shared production processes, emissions were allocated using physical relationships (e.g., mass, energy consumption, or production output), while minor auxiliary inputs with negligible contributions were excluded when reliable activity data were unavailable. The investigated suppliers were selected using a purposive stratified sampling strategy based on procurement relevance, production scale, geographic coverage, supplier type, and data completeness, collectively accounting for approximately 70% of the national production or procurement volume of the investigated product categories.

3. Results

3.1. Cradle-to-Gate Carbon Footprint Accounting for Eleven Categories of Electrical Equipment

Based on the bills of materials and production data provided by suppliers, cradle-to-gate carbon footprint accounting was conducted for 11 categories of typical electrical equipment. The results are shown in Figure 1. Overall, the carbon footprints of different types of electrical equipment exhibit the characteristics of "substantial differences in scale but relatively stable structural composition". Specifically, the raw material stage generally dominates the total carbon footprint, whereas the contributions of the production and

transportation stages are relatively limited. These differences primarily reflect variations in product functions, technical specifications, equipment capacities, material requirements, and manufacturing processes rather than random variability within a homogeneous product population.

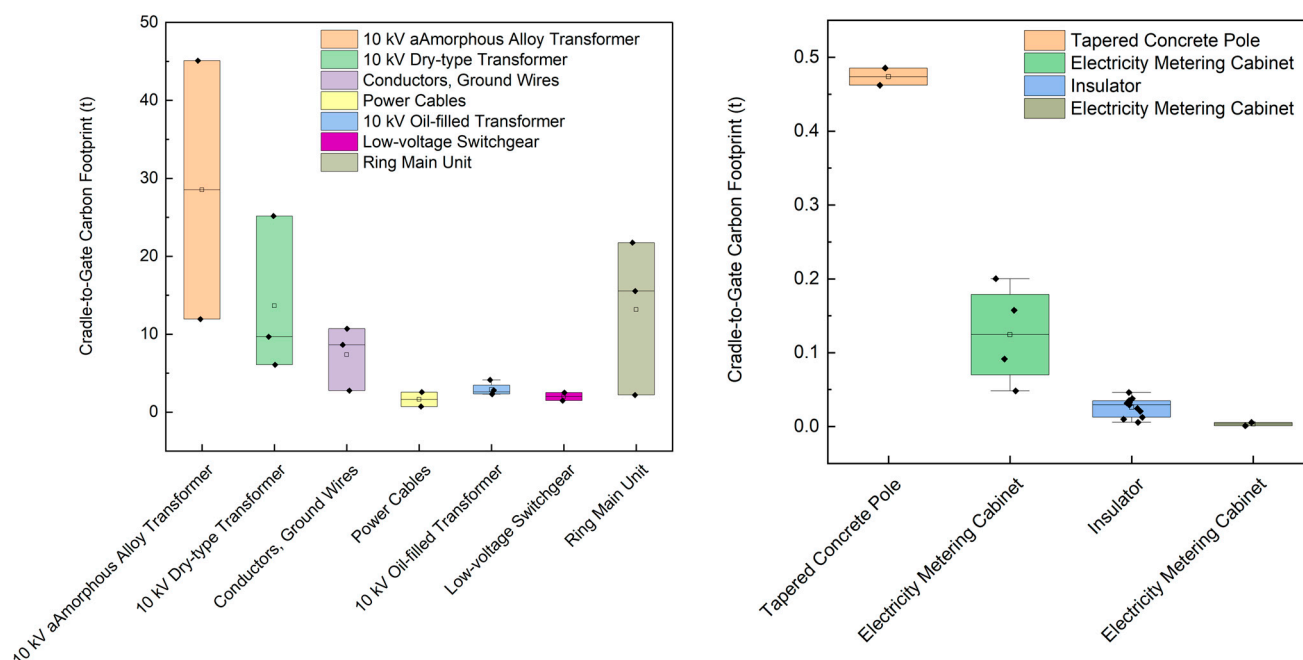


Figure 1. Carbon footprints of eleven types of electrical equipment from cradle to gate.

For transformer products, the carbon footprint of 10 kV amorphous alloy transformers ranges from approximately 1.2×10^4 kg/unit to 4.5×10^4 kg/unit, with the raw material stage accounting for more than 94% of the total. Owing to differences in raw material consumption among suppliers, the carbon footprint levels vary considerably. The carbon footprint of 10 kV dry-type transformers ranges from 6.1×10^3 kg/unit to 2.5×10^4 kg/unit. Notably, the production-stage carbon emissions of a large-capacity model produced by one supplier reach 8.3×10^3 kg/unit, accounting for 32.8% of its total carbon footprint, which is significantly higher than those of other products in the same category. This reflects substantial differences in production energy consumption among products with different capacities and energy efficiency grades. The carbon footprint of 10 kV oil-immersed transformers is relatively concentrated, ranging from 2.3×10^3 kg/unit to 4.1×10^3 kg/unit across suppliers. The raw material stage generally accounts for more than 95% of the total, while the contributions of the transportation and production stages are relatively small.

For cable products, the carbon footprint of overhead insulated conductors varies widely, ranging from 2.8×10^3 kg/km to 1.1×10^4 kg/km. For one supplier, carbon emissions from the production stage reached 1.3×10^3 kg/km, accounting for 46.9% of the total carbon footprint, whereas the production emissions of the same type of product from another supplier were less than 0.5 kg/km. This substantial difference is mainly attributed to variations in product specifications, conductor cross-sectional area, and production processes, which further affect the contribution of production energy consumption to the total carbon footprint and amplify the emission differences among enterprises at this stage. The carbon footprint of power cable products ranges from 7.2×10^2 kg/unit to 2.6×10^3 kg/km, with the raw material stage contributing approximately 90%.

For complete equipment products, the carbon footprint of low-voltage switchgear ranges from 1.5×10^3 kg/unit to 2.5×10^3 kg/unit, with the contribution of raw materials

exceeding 90% in all cases. The carbon footprint of ring main unit products shows a much greater variation. The carbon footprint of one supplier's product is only 2.1×10^3 kg/unit, whereas the product with the highest carbon footprint reaches 2.2×10^4 kg/unit. For the latter, the carbon footprint is mainly derived from the raw material stage, reaching 2.1×10^4 kg/unit and accounting for 97.8% of the total carbon footprint. This indicates substantial differences in equipment capacity, structural complexity, and material consumption between the two products.

For metering and auxiliary products, the carbon footprint of single-phase smart electricity meters is relatively low, ranging from only 1.0 kg/unit to 5.5 kg/unit, while the transportation stage accounts for a relatively high proportion. This is consistent with the characteristics of these products, including small size, light weight, and relatively long transportation distances. The carbon footprint of electricity metering boxes ranges from 48 kg/unit to 200 kg/unit, with a relatively balanced distribution across different life-cycle stages. For insulator products, except for one supplier whose production emissions are abnormally high due to special production processes (1.4×10^4 kg/unit), the carbon footprints of products from other suppliers are mostly within the range of 10 kg/unit to 50 kg/unit, with raw materials remaining the dominant contributor. The carbon footprint of tapered cement poles ranges from 4.6×10^2 kg/unit to 4.9×10^2 kg/unit, with the raw material stage contributing more than 99%, indicating that they are typical material-intensive products.

The life-cycle carbon footprints of distribution equipment are shown in Figure 2, revealing significant stage-specific differences. The raw material acquisition stage is the dominant source of carbon emissions for power equipment, accounting for more than 90% of the total carbon footprint in most products. This is mainly due to the high carbon emission intensity associated with the smelting and primary processing of steel, copper, aluminum, and insulating materials, indicating a strong resource-intensive characteristic. Overall, the carbon footprint of electrical equipment follows a stage distribution pattern characterized by "raw material dominance, with relatively minor contributions from the production and transportation stages", reflecting the typical features of resource-intensive products. Therefore, low-carbon strategies should focus more on green procurement, improving raw material utilization efficiency, and introducing low-carbon alternative materials, rather than merely optimizing logistics routes.

The substantial differences observed among product categories and suppliers further demonstrate the ability of the inventory dataset to capture variations in material composition, manufacturing processes, equipment configurations, and energy consumption characteristics. These differences are consistent with the engineering and functional characteristics of the investigated products. For example, transformers, conductors, and ring main units require substantially different quantities of steel, copper, aluminum, and insulating materials, leading to inherently different carbon footprint levels. Similarly, variations among suppliers are largely associated with differences in product specifications, production technologies, and energy consumption patterns. This indicates that the collected inventory data possess sufficient detail and representativeness for product-level carbon footprint accounting and can effectively reflect real-world variations across products and manufacturers.

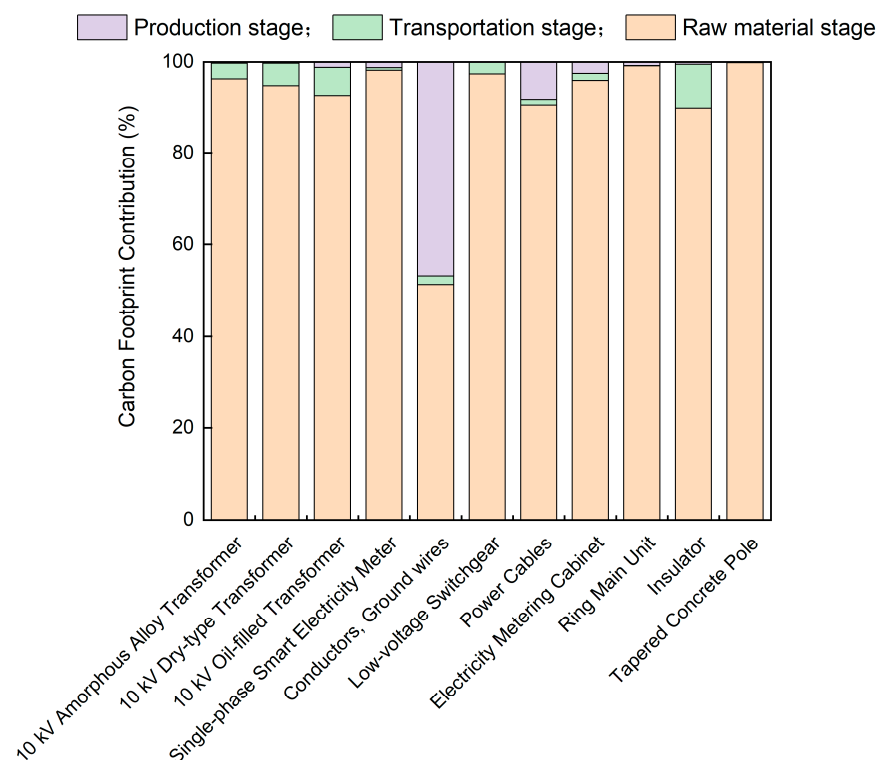


Figure 2. Stage-specific carbon footprint proportions of eleven types of electrical equipment.

3.2. Contribution of Raw Materials to the Carbon Footprint of Electrical Equipment

To identify the main sources of the carbon footprint of electrical equipment, core materials with a cumulative contribution of more than 95% in the raw material stage were selected for analysis. The results are shown in Figure 3. The carbon footprint of raw materials for transformer products mainly comes from metallic materials such as steel and copper, which account for 80–90% of the total raw material carbon footprint. For other products, the main contributing materials vary due to differences in function and structure; however, they all show the common feature of one or two key materials dominating the carbon emissions. For example, aluminum and PC materials in conductors and ground wires account for 79% of the total raw material carbon footprint, red copper and galvanized sheets in low-voltage switchgear account for 81%, and porcelain clay and wood in insulator products contribute as much as 98%. These results indicate a common pattern in which the carbon footprint is highly concentrated in a few high-carbon materials, rather than being evenly distributed among multiple materials.

The high concentration of emissions in a limited number of materials implies that targeted material-focused mitigation strategies may achieve disproportionately large carbon reduction benefits. For example, increasing the use of recycled copper and aluminum, adopting low-carbon steel production technologies, and promoting green material procurement could significantly reduce the embodied carbon of electrical equipment. These findings suggest that material supply-chain management should become a priority in future product carbon footprint reduction strategies.

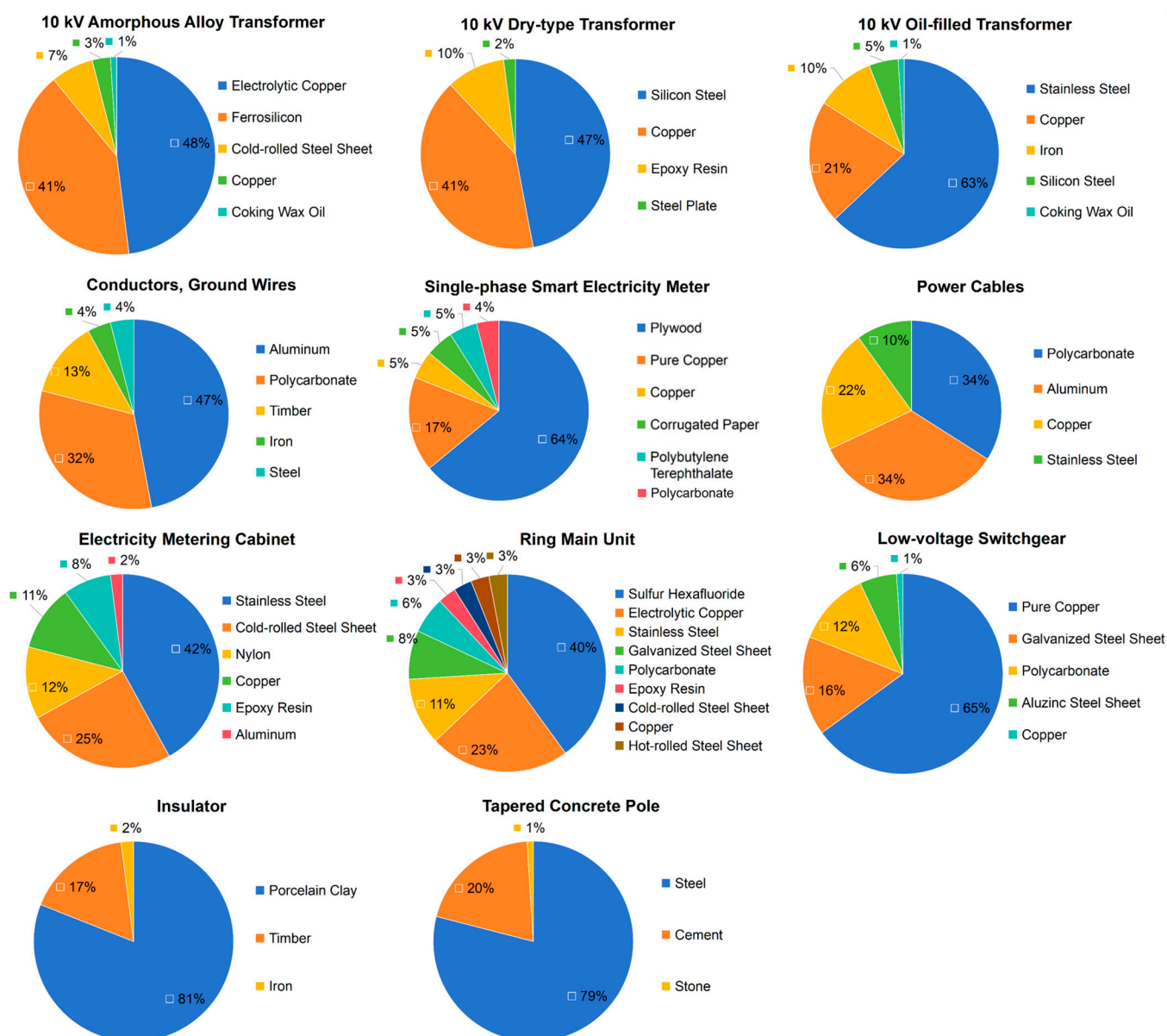


Figure 3. Contributions of major raw materials to the carbon footprints of eleven types of electrical equipment.

3.3. Optimization Analysis of Electricity Emission Accounting in the Production Stage Under the Green Electricity and Green Certificate Mechanism

In addition to raw materials, the production stage contributes substantially to the carbon footprints of certain product categories, such as conductors and ground wires, due to their specific manufacturing processes. For some products, production-stage emissions account for nearly 50% of the total carbon footprint, as shown in Figure 2. During manufacturing, differences in production equipment, processes, and electricity intensity can lead to variations of more than 1.5 times in production energy consumption and carbon emissions for the same type of product. Therefore, accurately accounting for indirect electricity emissions during the production stage is essential for improving the precision of product carbon footprint assessment. As shown in Figure 4, provincial emission factors can more accurately reflect differences in the actual electricity mix among provinces than the national average emission factor. The residual emission factors of Beijing and Tianjin are 40.1% and 29.7% higher than the national average emission factor, respectively, whereas those of Qinghai, Sichuan, and Yunnan are 60.6%, 71.4%, and 74.4% lower,

respectively. This fully demonstrates the limitations of the national average emission factor: although it initially excludes market-based electricity trading volumes, it lacks spatial resolution and therefore cannot reflect the regional differences in China's electricity structure, characterized by higher emission intensities in the eastern region and lower emission intensities in the central and western regions.

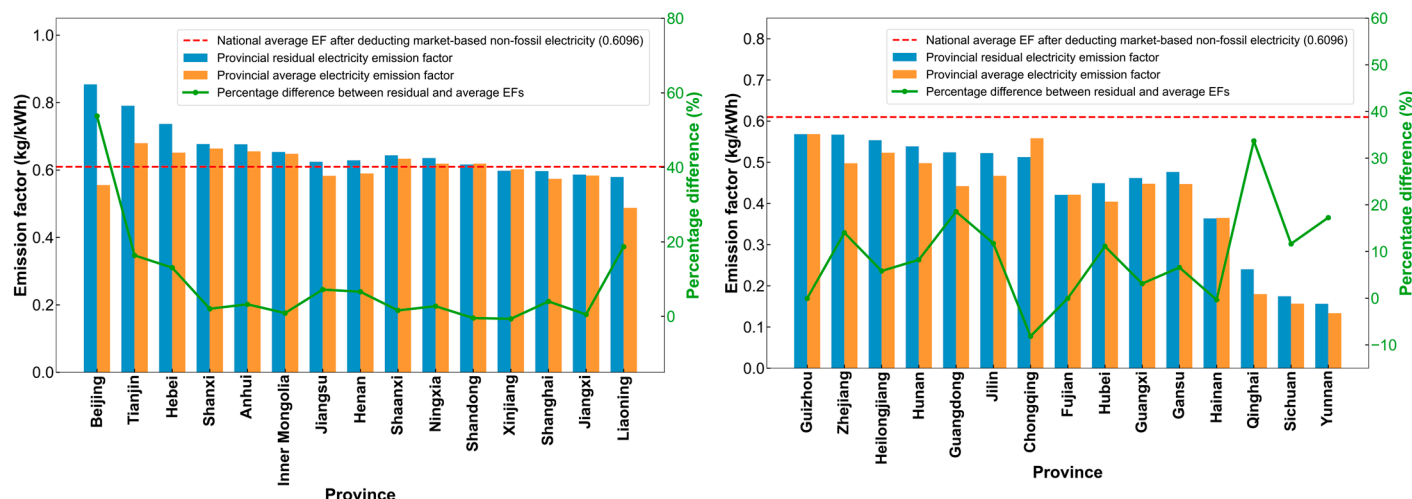


Figure 4. Comparison of electricity emission factors.

Except for a few provinces such as Chongqing and Shandong, where the residual emission factors after considering green electricity and green certificates are slightly lower than the provincial average emission factors, the verified emission factors of most provinces are higher than the original provincial average emission factors, with increases ranging from 0.5% to 53.8%. Among them, Beijing shows the most significant increase, from 0.55 kg/kWh to 0.85 kg/kWh. This indicates that Beijing has a relatively high level of market-based green electricity trading. The original provincial average calculation method based on total electricity consumption allocates the environmental value of green electricity, whose environmental attributes have already been separated, to all electricity consumers, resulting in a serious underestimation of the actual carbon emissions of non-green electricity consumers. In contrast, in provinces with a relatively low share of renewable energy, such as Jiangxi, Guizhou, and Hainan, the electricity emission factors remain almost unchanged. These results indicate that the optimized provincial residual emission factors not only retain provincial-level spatial resolution but also further exclude market-based certified green electricity, thereby achieving coordinated improvement in both spatial accuracy and ownership attribution.

From a policy perspective, the results demonstrate that renewable electricity attribute allocation is becoming increasingly important for carbon accounting systems operating under certificate-based electricity markets. As green electricity trading expands, conventional average-grid emission factors may no longer accurately represent the carbon responsibility associated with electricity consumption. Residual electricity emission factors therefore provide a more robust basis for product carbon footprint accounting and environmental disclosure.

3.4. Scenario Analysis Under Different Green Electricity Substitution Levels

Green electricity procurement may occur at different levels depending on enterprise procurement strategies, certificate availability, regional electricity market development, and low-carbon supply-chain requirements. Therefore, this study evaluates product electricity-related carbon footprints under five certified green electricity substitution levels

(10%, 25%, 50%, 75%, and 100%), representing different degrees of renewable electricity procurement and certificate-based electricity attribute allocation. Detailed electricity-related carbon footprint results under the five certified green electricity substitution scenarios are provided in Table S7 of the Supplementary Information.

The results show that electricity-related carbon footprints decrease almost linearly with increasing certified green electricity substitution levels. Under the proposed accounting framework, electricity-related emissions are determined by product electricity consumption, the applicable electricity emission factor, and the share of electricity not covered by certified green electricity. Consequently, increasing the proportion of certified green electricity directly reduces production-stage indirect electricity emissions, indicating that enterprises with higher renewable electricity procurement can achieve greater carbon footprint reductions.

The 50% substitution scenario is retained as a representative medium-to-high participation case for detailed comparison among national-average, provincial-average, and provincial residual electricity emission factors. Under this scenario, shown in Figure 5, differences among electricity emission factors become more evident in provinces with active green electricity trading. As illustrated by Zhejiang and Jiangsu, provincial residual electricity emission factors provide a more realistic representation of the emission responsibility associated with residual electricity consumption than either national-average or conventional provincial-average emission factors. The complete comparative results for all substitution scenarios are presented in the Supplementary Information.

Overall, the multi-scenario analysis demonstrates that the absolute reduction in electricity-related carbon footprints increases with higher certified green electricity substitution levels, whereas the relative differences among electricity emission factors are primarily governed by regional electricity generation structures and renewable electricity certificate allocation. These results confirm the robustness and practical applicability of the proposed framework under different renewable electricity procurement strategies.

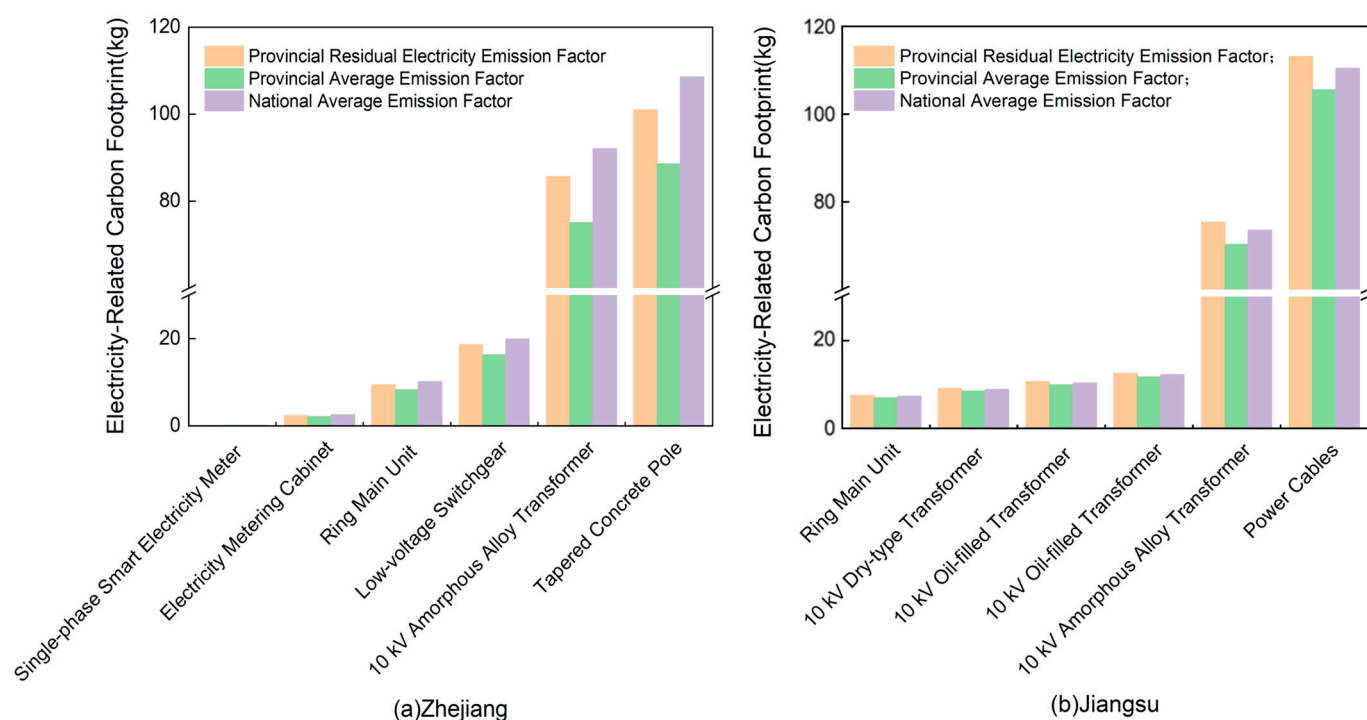


Figure 5. Comparison of electricity-related carbon footprints under different electricity emission factors.

3.5. Uncertainty Analysis

To evaluate the robustness of the proposed accounting framework and quantify the influence of key input parameters, descriptive statistical analyses and a one-at-a-time local sensitivity analysis were conducted based on the valid product samples. Detailed statistical results are provided in Tables S8–S13 of the Supplementary Information. The results show substantial heterogeneity in product carbon footprints across product categories and suppliers. The coefficient of variation at the product-category level ranged from 3.5% to 148.2%, with relatively high variability observed for power cables, amorphous alloy transformers, ring main units, and dry-type transformers. These differences indicate that product specifications, material composition, and production processes can substantially affect product carbon footprint results. In terms of stage contribution, the raw material stage accounted for more than 90% of the total carbon footprint in 26 out of 37 valid samples and more than 95% in 19 samples, further confirming the material-dominant pattern of electrical equipment products.

Provincial residual electricity emission factors also exhibited substantial spatial heterogeneity. Across 30 provincial samples, the residual electricity emission factors ranged from 0.156 to 0.854 kg CO₂/kWh, with a coefficient of variation of 29.1%. Compared with the national average electricity emission factor, the deviations ranged from −74.4% to 40.1%. Compared with conventional provincial average electricity emission factors, the deviations ranged from −8.2% to 53.8%. These results indicate that national average factors or conventional provincial average factors may mask province-level differences in electricity-related emission responsibilities under green electricity and green certificate mechanisms.

A one-at-a-time local sensitivity analysis was further conducted to evaluate the influence of key parameter variations on the carbon footprint results. Following common local sensitivity analysis practice in LCA studies, key input parameters were individually perturbed while keeping other parameters constant. In this study, raw material emission factors, production-stage energy-related emissions, and provincial residual electricity emission factors were varied by $\pm 10\%$, while transportation-related emissions were varied by $\pm 20\%$ to reflect the relatively higher uncertainty associated with transport distances, vehicle types, and loading rates. The results show that different parameters have distinct effects on the total carbon footprint results. Variations in raw material emission factors exerted the largest influence, with an average change of $\pm 8.5\%$ and a maximum change close to $\pm 10.0\%$. In comparison, the average effects of transportation-related parameters, production-stage energy-related emissions, and provincial residual electricity emission factors were $\pm 1.3\%$, $\pm 0.8\%$, and $\pm 0.8\%$, respectively. Overall, the results indicate that the proposed framework is most sensitive to variations in raw material emission factors, whereas uncertainties associated with transportation, production-stage electricity consumption, and provincial residual electricity emission factors have comparatively smaller effects on the overall product carbon footprint. These findings demonstrate the robustness of the proposed methodology while highlighting the importance of obtaining high-quality upstream material inventory data.

4. Discussion

The results of this study are consistent with existing product carbon footprint and life cycle assessment studies of electrical equipment, which have widely identified upstream material production as the dominant source of embodied carbon emissions. Energy-intensive materials such as steel, copper, aluminum, electrical steel, and insulation materials are repeatedly reported as key contributors due to their high upstream energy demand and carbon-intensive production processes [3,15–17]. For example, transformer-related LCA studies have shown that metallic materials such as steel and copper dominate

production-stage emissions [15,17], while cable-related studies indicate that conductor material selection significantly affects life-cycle impacts [18]. These findings are consistent with the results of this study, where raw material production contributes more than 90% of cradle-to-gate emissions across most product categories. Compared with improvements in transportation efficiency or manufacturing energy management, the results indicate that substantially greater emission reductions can be achieved through low-carbon material production, increased use of recycled materials, green procurement, and improved material utilization efficiency. Therefore, decarbonizing upstream material supply chains should remain the primary strategy for reducing the carbon footprint of electrical equipment and promoting sustainable manufacturing.

In addition to material production, electricity consumption during manufacturing also contributes to product carbon footprints. However, conventional life cycle assessment studies typically rely on national or regional average grid emission factors, which do not fully capture the increasing role of renewable electricity trading and certificate-based attribute allocation. Previous studies in regions with mature market-based systems, such as the European Union and the United States, have shown that residual-mix accounting is necessary to avoid inconsistencies between renewable electricity claims and emission allocation. In these systems, Guarantees of Origin (GOs) and Renewable Energy Certificates (RECs) are used to track renewable electricity attributes, ensuring consistency between market transactions and carbon accounting. Similar mechanisms are emerging in China through Green Electricity Certificate (GEC) systems. The results of this study demonstrate that residual electricity emission factors provide a more accurate representation of electricity-related emission responsibility under such market-based conditions. The observed differences between conventional electricity emission factors and provincial residual electricity emission factors indicate that renewable electricity attribute ownership can substantially influence product-level indirect electricity emissions, particularly in regions with active renewable electricity trading. As renewable electricity markets continue to expand, incorporating market-based electricity attribute allocation into product carbon footprint accounting will become increasingly important for improving the transparency, credibility, and comparability of environmental product declarations, green procurement, and corporate greenhouse gas reporting.

From a methodological perspective, the proposed framework should be regarded as a product-level operationalization of established residual-mix accounting principles rather than a fundamentally new electricity accounting methodology. Existing residual-mix approaches have primarily been developed for electricity disclosure, Scope 2 reporting, and electricity-sector carbon accounting [19]. In contrast, this study establishes a reproducible accounting workflow that integrates provincial residual electricity emission factors with supplier-specific life-cycle inventories, production-stage electricity consumption, and product-level carbon footprint assessment. This enables renewable electricity attributes to be consistently propagated from electricity procurement to manufacturing-stage electricity emissions and ultimately to product carbon footprints. Although publicly available benchmark datasets for certified product carbon footprints incorporating renewable electricity attribute allocation remain unavailable, the proposed framework was evaluated through comparisons with published life-cycle assessment studies and established residual-mix accounting principles. The agreement in material contribution patterns and electricity accounting behaviour provides indirect evidence supporting the applicability and internal consistency of the proposed methodology. Future studies should further validate the framework using certified product carbon footprint databases and corporate disclosure datasets as such information becomes available.

The applicability of the proposed framework varies depending on electricity market structure and the maturity of renewable electricity certificate systems. In regions with

well-developed market-based mechanisms, such as Guarantees of Origin (GOs) in the European Union and Renewable Energy Certificates (RECs) in the United States, the framework can be directly applied with minor adaptation [20–23]. Unlike China, where the green electricity certificate system and electricity carbon emission factor accounting guidelines have been increasingly formalized [24,25], emerging or transitional systems such as India and parts of Southeast Asia still require partial modifications due to incomplete certificate coverage and limited data transparency [26–28]. In regions without formal certificate systems, such as many Sub-Saharan African countries, simplified grid-average emission factors remain the primary approach, limiting the applicability of attribute-based allocation methods [29,30]. A detailed comparison of regional applicability is provided in Table S14 of the Supplementary Materials. From a sustainability perspective, the proposed framework provides methodological support for green procurement, environmental product declarations, low-carbon supply-chain management, and emerging carbon-related trade mechanisms such as the Carbon Border Adjustment Mechanism (CBAM). However, successful implementation depends on the availability of transparent electricity generation statistics, electricity exchange data, and renewable electricity certificate tracking systems. As renewable electricity certificate mechanisms become increasingly integrated into international carbon accounting standards, methodologies capable of consistently distinguishing certified renewable electricity from residual grid electricity will become increasingly important for improving the transparency, consistency, and comparability of product carbon footprint assessments.

Several limitations should be acknowledged. First, the proposed framework relies on the availability, completeness, and reliability of regional electricity generation statistics, electricity exchange information, and renewable electricity certificate transaction data, which may not yet be available in all countries. Second, the framework assumes that renewable electricity certificates represent exclusive renewable electricity attributes once verified through market-based mechanisms. Differences in certificate issuance, retirement, and tracking rules may therefore influence the allocation of electricity-related emissions across jurisdictions. Third, annual-average electricity emission factors were adopted in this study and therefore cannot fully capture temporal variations in electricity generation mixes and renewable electricity availability. Finally, although sensitivity analyses were conducted, publicly available benchmark datasets for certified product carbon footprints remain limited, preventing comprehensive external validation of the proposed methodology. Future research should incorporate time-resolved electricity emission factors, probabilistic uncertainty analysis, cross-regional certificate transactions, and independent benchmark datasets to further improve the robustness and applicability of the proposed framework.

5. Conclusions

This study developed a cradle-to-gate product carbon footprint accounting framework for electrical equipment by integrating provincial residual electricity emission factors with green electricity and Green Electricity Certificate (GEC) mechanisms. The proposed framework explicitly accounts for renewable electricity attribute allocation under market-based electricity systems.

The results show that upstream material production dominates the carbon footprint of electrical equipment, accounting for more than 90% of cradle-to-gate emissions for most products. Steel, copper, aluminum, electrical steel, insulation materials, porcelain clay, and cement were identified as the principal emission sources. In addition, electricity-related emissions during manufacturing are highly sensitive to the selection of electricity emission factors, and provincial residual electricity emission factors provide a more

accurate representation of electricity-related emission responsibility by avoiding double counting of renewable electricity attributes.

The proposed framework extends residual-mix accounting from electricity-sector carbon accounting to product-level life-cycle assessment, improving the transparency, consistency, and comparability of product carbon footprint accounting. As renewable electricity markets continue to expand, the framework provides practical methodological support for sustainable manufacturing, green procurement, environmental product declarations, and low-carbon supply-chain management.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18147353/s1>, Table S1: Residual raw material carbon footprint factor database; Table S2: Transportation carbon emission factor database; Table S3: Energy carbon emission factor database; Table S4: Input and output data used to calculate provincial residual electricity emission factors; Table S5: Inventory coverage and supplier sampling summary; Table S6: Inventory data quality assessment matrix; Table S7: Electricity-related carbon footprint results under different certified green electricity substitution levels; Table S8: Product samples and stage-specific carbon footprints; Table S9: Descriptive statistics of product-level carbon footprints; Table S10: Stage contribution statistics of product carbon footprints; Table S11: Provincial electricity emission factors and residual electricity emission factors; Table S12: Parameter settings for local sensitivity analysis; Table S13: Sensitivity analysis results; Table S14: International applicability of the proposed framework under different electricity market and certificate systems.

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