



RESEARCH REPORT · AUGUST 2026

China's Transformer Industry in the Energy Transition:

Industrial Decarbonisation, Material Innovation, and Global Market Signals



ABOUT EARTH & LIFE SYMBIO

Earth & Life Symbio (E&L) is a Singapore-headquartered organisation working across Asia and partnering globally to advance low-carbon industrial growth, energy transition and nature-positive development. Our mission is to catalyse the transition towards a thriving, climate-resilient world where low-carbon industrial growth, energy transition and nature-positive development advance together. E&L brings together and activates the ecosystem across Asia's manufacturing economies and energy sectors - aligning policy, capital, industry, science and civil society to turn climate and nature ambitions into coordinated action and scalable real-economy impact. Our work spans corporate engagement, investor dialogue, policy-aligned research, and on-the-ground study tours, with a strong emphasis on hard-to-abate industries, biodiversity risk, and nature-positive finance.

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Foreword

The global energy transition is entering a more infrastructure-intensive phase. Clean-energy technologies attract much of the attention, while the industries that make electrification possible receive much less. Transformers, cables, switchgear and power electronics form the backbone of modern electricity systems. Their availability, performance and supply chains will influence both the pace of electrification and the evolution of global industrial competitiveness.

Earth & Life Symbio (E&L) launched the Energy & Hard-to-abate Industry Transition research series to examine how power-sector decarbonisation is reshaping strategic manufacturing industries. The series treats climate policy and manufacturing competitiveness as interconnected questions, with particular attention to the interaction between technology, materials, industrial policy, trade and corporate transition.

This inaugural report focuses on China's transformer industry. It examines how rising global demand, the growing importance of low-carbon materials, product-carbon-footprint requirements, and evolving international market expectations are creating both challenges and opportunities for Chinese manufacturers. While the report focuses on transformers, its analytical framework is intended to inform future research on a broader range of energy-equipment manufacturing sectors.

We hope this report contributes to constructive dialogue among policymakers, manufacturers, investors, and other stakeholders working to accelerate industrial competitiveness while advancing the global energy transition.



Executive Summary

The global energy transition is becoming increasingly infrastructure-intensive. Renewable-energy deployment, electrification, the replacement and expansion of ageing grids, and the rapid growth in data-centre electricity demand are increasing the need for the equipment that connects power generation to end users. Transformers are central to this shift. As the world's largest transformer producer, China will play an important role in determining how this growing demand is met.

The industry is being reshaped by three reinforcing changes. First, structural demand growth is creating a prolonged transformer investment cycle. Second, manufacturing is becoming more sensitive to material choices, as electrical steel and other inputs affect both product performance and embedded emissions. Third, market expectations are broadening. Cost, quality, delivery and reliability remain fundamental, but in selected markets, verified carbon information, supply-chain transparency and customer confidence in environmental claims are becoming increasingly relevant.

This report finds that steel is the largest source of production-stage emissions in a transformer, with grain-oriented electrical steel (GOES) representing the most important initial opportunity for action. China's large and diversified manufacturing base, together with its growing export capacities, provides a strong industrial foundation. However, more consistent material-level emissions data and stronger product-carbon-footprint capabilities will be needed if this manufacturing strength is to translate into a credible supply of lower-carbon equipment.

These changes are already visible in both China's domestic policy environment and international markets. Chinese central state-owned enterprises (SOEs) are being encouraged to strengthen green supply-chain management. They have issued guidelines to promote Life Cycle Assessment (LCA) and prioritize the procurement of low-carbon materials. Internationally, European utility procurement practices, Scope 3 emissions management and emerging product-carbon-footprint requirements are creating additional demand for credible supply-chain data.

The European Commission's proposed expansion of the Carbon Border Adjustment Mechanism (CBAM) to selected downstream products is one tangible signal within this broader shift. If adopted, the proposal would increase the value of verified material-emissions data for certain categories of distribution-transformer exports to the European Union. Its direct coverage of the transformer market would remain limited. CBAM is one driver of improved carbon-data readiness within a broader sector transition.

The priority is therefore to link lower-carbon materials, credible emissions data, product innovation and supportive policy. Manufacturers can begin with high-impact and relatively concentrated supply chains such as GOES. Material suppliers and transformer manufacturers can jointly validate both technical performance and carbon claims. Large buyers can use procurement to create demand for verified lower-carbon products, while public policy can support common accounting approaches, demonstration projects and early market development.

The objective is to build a transformer manufacturing base that can meet rapidly growing electrification demand while becoming progressively lower-carbon, more resilient and globally competitive.

A framework for understanding the energy equipment manufacturing transition

The report examines the transition through five connected dimensions, which also provide the logic for its chapter structure:

Dimension	Question for the analysis	Focus in this report
Energy-transition demand	What is expanding the need for energy equipment?	Grid investment, renewable integration, electrification and data-centre growth (Chapter 1)
Industrial capability	What enables reliable and scalable supply?	Production capacity, technology, supply chains, delivery and export capability (Chapter 1)
Materials and carbon footprint	Where do performance and emissions converge?	Electrical steel, alternative core materials, efficiency and embedded carbon (Chapter 2)
Policy and market signals	What is changing the direction of the market?	Domestic procurement, customer expectations, carbon data and trade rules (Chapters 3-4)
Transition pathways	How can the transition be advanced in practice?	Sequenced action by customers, manufacturers, suppliers and policymakers (Chapters 4-5)

CHAPTER 1

Demand growth is creating a transformer supercycle

The global energy transition is reshaping electricity systems at an unprecedented pace. Renewable-energy deployment, the electrification of transport and industry, the replacement and expansion of ageing grids, and the growth of digital infrastructure are all increasing demand for network equipment. Transformers are therefore becoming an increasingly strategic component of the physical infrastructure through which electrification is delivered.

This demand is structural and is likely to extend beyond a conventional equipment cycle. It is expanding the transformer market while increasing the value of manufacturing capabilities that can deliver reliable equipment with high efficiency, transparent supply chains and progressively lower material emissions.

China's transformer industry is well positioned to contribute to this transition because of its scale, broad product range and established manufacturing base. The challenge is to strengthen these capabilities so that reliable and cost-competitive supply progresses alongside higher efficiency, material decarbonisation and changing international market expectations.

1.1 Transformers are indispensable to electrification

Among major categories of power equipment, the transformer is relatively inconspicuous. It lacks the clear public visibility associated with solar panels, wind turbines, batteries and electric vehicles. Its function is nevertheless fundamental: voltage must be transformed repeatedly as electricity moves from generation through transmission and distribution networks to end users.

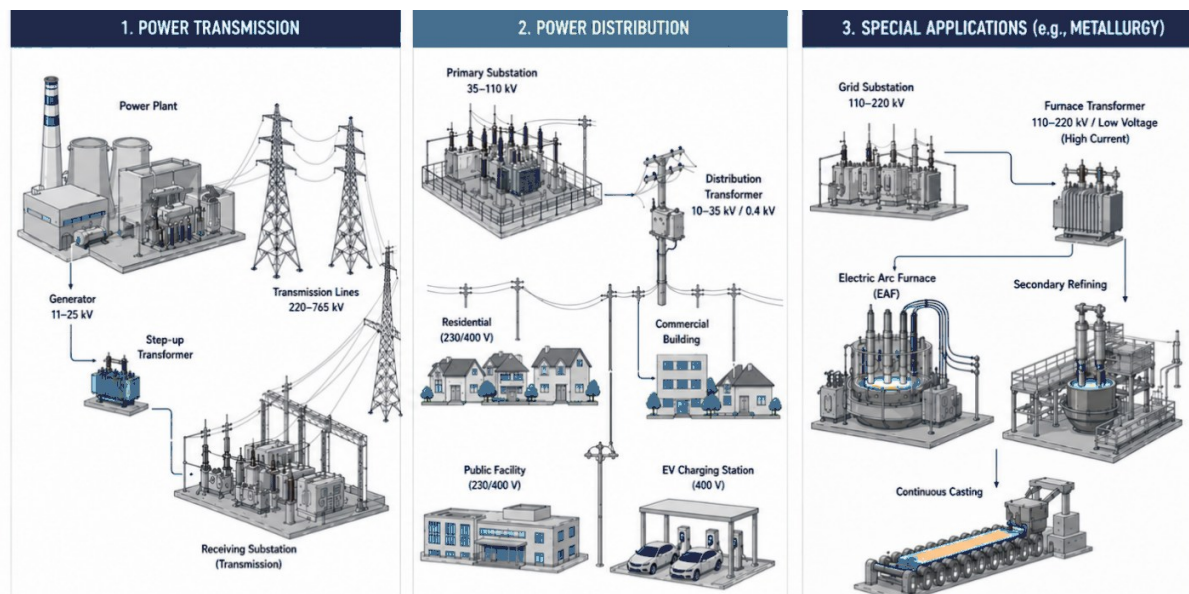
A transformer uses electromagnetic induction to raise or lower voltage, enabling efficient long-distance transmission and safe end use. Its climate relevance has two distinct dimensions. First, energy losses accumulate throughout an operating life that commonly extends for 30–40 years. Second, the production of electrical steel, copper or aluminium, insulation materials and other components creates an embedded carbon footprint before the transformer is energised.

Transformers can be grouped into three broad categories according to function and voltage class:

Category	Voltage Range	Typical Application	Installation Location
Power transformers	110 kV and above	Step-up and step-down transformation in high-voltage transmission networks	Large substations
Distribution transformers	35 kV and below	Conversion of higher network voltage to levels usable by end users	Residential areas, streets, industrial parks
Special / industrial transformers	Application-dependent	Metallurgy, chemicals, rail traction and other specialized applications	Industrial sites

The scale of these products varies considerably. A large power transformer serving a data centre can weigh several hundred tonnes, cost tens of millions of RMB and take two to three years to move from order to commissioning. A distribution transformer serving a residential neighbourhood may weigh less than a tonne and can be shipped within weeks. Both depend heavily on steel, copper or aluminium and insulation materials, and both can remain in service for 30 to 40 years. Material and efficiency choices made today can therefore influence power-system emissions well into the future.

Figure 1. Applications of Power Transformers



Source: Image created by ChatGPT; Earth & Life Symbio analysis.

1.2 The global transformer “supercycle”

The global transformer market is experiencing an unusually strong and prolonged period of demand growth. Several drivers are operating simultaneously: replacement of ageing equipment, expansion of electricity networks, renewable-energy interconnection, tighter efficiency requirements and rapidly growing electricity demand from data centres.

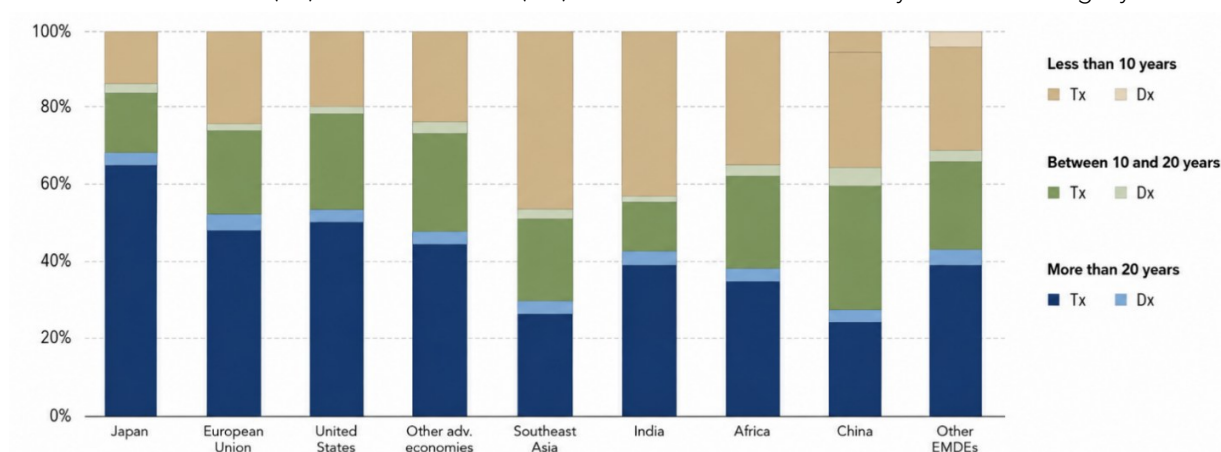
Replacement of ageing grid infrastructure

Ageing grid infrastructure is creating significant replacement demand, particularly in advanced economies. The average age of transformers in service worldwide is often estimated at around 40 years.¹ Large parts of the electricity networks in Europe and North America were built during the 1960s and 1970s, leaving substantial portions of the installed equipment base at or approaching the later stages of their design lives.

Modelling by the U.S. National Renewable Energy Laboratory (NREL) estimates that the U.S. has approximately 60–80 million distribution transformers, with roughly 55% having been in service for more than 33 years.² Additionally, about 70% of transmission lines and power transformers are 25 years or older.³ Ageing insulation and other components can increase the risk of electrical faults, short circuits, fires, and equipment failure. Replacement of this ageing stock is therefore expected to remain an important source of transformer demand.

Figure 2. Typical Economic Life of Power Grid Investment by Region

Share of transmission (Tx) and distribution (Dx) infrastructure investment by asset life category

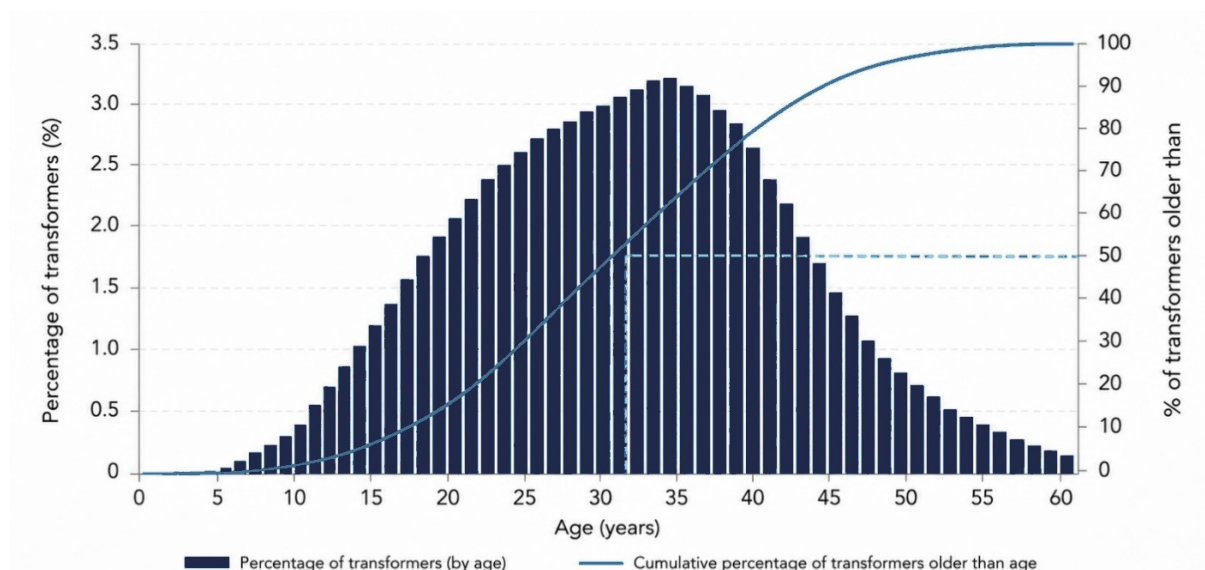


Source: IEA, October 2023; Earth & Life Symbio analysis.

Note: Transmission infrastructure (Tx); distribution infrastructure (Dx).

Figure 3. Age Distribution of Power Transformers in the United States

Distribution of transformer population by age and cumulative percentage of transformers older than a given age



Source: National Renewable Energy Laboratory; Earth & Life Symbio analysis.

Note: Transformer age is calculated as of the year of data collection.

China's installed fleet is generally younger. Efficiency standards are nevertheless accelerating the upgrade cycle. In 2025, the fourth revision of the mandatory national standard *Minimum Allowable Values of Energy Efficiency and Energy Efficiency Grades for Power Transformers (GB 20052-2024)* officially came into force. The standard establishes S13 (Grade 3) as the minimum market entry threshold, mandates the phase-out of low-efficiency products rated S11 and below, and promotes the widespread adoption of high-efficiency energy-saving transformers, including S20 (Grade 2) and S22 (Grade 1).⁴ *The Implementation Plan for the High-Quality Development of Energy-Saving Equipment (2026-2028)*, issued by four ministries in 2026, further calls for more than 75% of new transformer capacity meeting energy-saving standards by 2028. These requirements will bring forward the replacement of less-efficient units.⁵

Grid investment

Grid investment remains the largest underlying source of transformer demand in China and globally. In China, continued investment by State Grid and China Southern Power Grid is supporting the extension of ultra-high-voltage backbone networks, reinforcement of provincial grids, upgrading of urban distribution networks, and rural grid modernization.

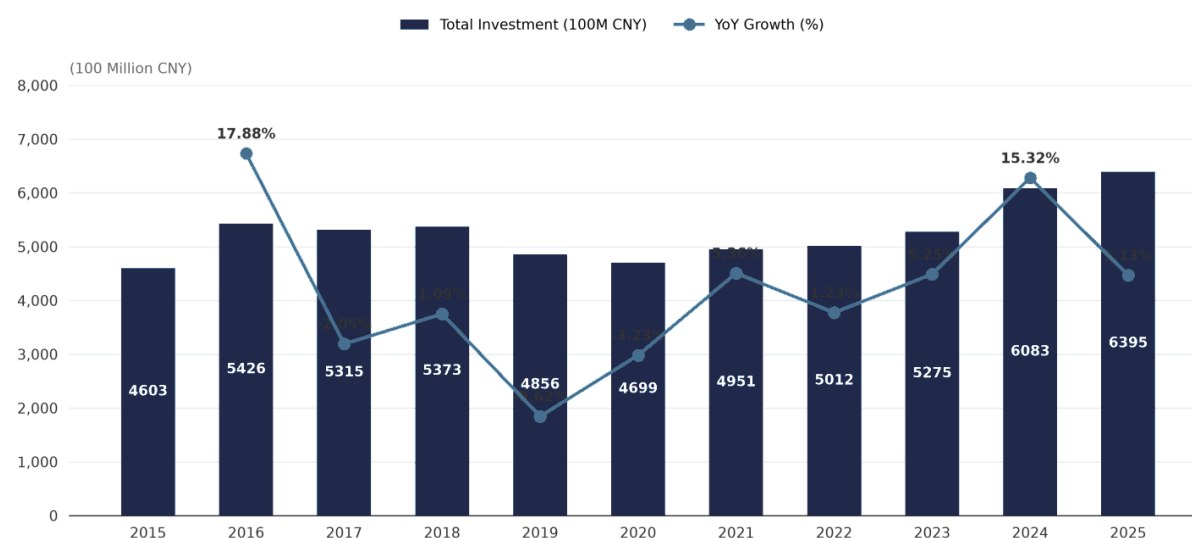
State Grid Corporation of China (SGCC) plans to allocate approximately RMB 4 trillion (around USD 560 billion) to fixed-asset investments during the 15th Five-Year Plan period (2026-2030), representing a 40% surge compared to its total investment

during the 14th Five-Year Plan period.⁶ Continued development of ultra-high-voltage networks and distribution infrastructure is expected to sustain procurement across multiple transformer voltage classes.

Internationally, grid investment is also rising as electricity systems adapt to renewable-energy deployment, network digitalization, electrification and increasing power demand. These investment requirements are strengthening demand for transformers alongside other network equipment.

Figure 4. China Power Grid Investment and Year-on-Year Growth (2015-2025)

Bars: total investment (left axis); line: year-on-year growth rate (right axis)



Source: National Energy Administration; Earth & Life Symbio.

Renewable energy interconnection

Renewable-energy deployment adds another major source of transformer demand. Solar and wind projects require step-up transformers for grid connection because their native output voltages are considerably lower than those of transmission networks and most distribution systems. Utility-scale solar inverters typically produce AC output in the range of 480-800 V, while modern wind turbines predominantly generate at 1,140 V. Grid interconnection points are mainly at the 35 kV level.

The IEA projects that global renewable capacity will grow by approximately 4,600 GW by 2030. Applying an indicative ratio of 1.2 to 1.5 units of step-up transformer capacity for each unit of generation capacity suggests a requirement on the order of 5,500-6,900 GVA.^{7,8}

Data centre

Rapid growth in data-centres electricity demand is adding another source of

transformer demand. Global data-centre electricity consumption increased by around 17% in 2025, considerably faster than overall global average electricity-demand growth of 3%.

The United States is currently the largest source of AI-related data-centre expansion. New facilities are increasingly moving beyond the tens-of-megawatts scale associated with conventional data centres towards hundreds of megawatts and, in some announced developments, gigawatt-scale campuses. Larger facilities can also require connection at higher voltage levels, increasing demand for substation equipment and large transformers.

China is similarly integrating computing-power development into its infrastructure planning. Continued expansion of the domestic data-centre base is therefore likely to add to transformer and associated power-equipment demand.^{9,10}

Large technology companies can also influence supply-chain decarbonisation. Several major data-centre buyers already quantify construction-related Scope 3 emissions and procure lower-carbon steel, concrete and other materials. Framework procurement for substations and power-distribution equipment could provide a practical route for extending embodied-carbon requirements to electrical equipment. Transformer cores have yet to become a standard category in these programmes.

1.3 China: the world's largest transformer producer and exporter

China is the centre of gravity of global transformer manufacturing. In 2025, the industry's output value exceeded RMB 300 billion, while available industry estimates suggest that China accounted for more than half of global transformer production. One widely cited estimate places the cumulative capacity of transformers connected to China's electricity system at approximately 16 billion kVA.¹¹

China has developed R&D and manufacturing capabilities across a broad range of equipment, from 10 kV distribution transformers to 1,000 kV ultra-high-voltage (UHV) AC transformers and $\pm 1,100$ kV UHV DC converter transformers. Its domestic grid-development programme has provided manufacturers with opportunities to develop and deploy equipment at very large scale.

China's transformer manufacturers compete across different product segments and market positions. Table 1 summarises the major companies identified in the underlying research and indicates their representative customers and technical strengths.

Table 1. Indicative competitive landscape of major transformer manufacturers

Company	Country	Representative customers	Market position and capabilities
China Electrical Equipment Group (CEE)	China	State Grid; China Southern Power Grid; Saudi Electricity Company; Vattenfall	Major UHV transformer producer and core supplier for China's UHV projects.
Hitachi Energy	Japan	State Grid; China Southern Power Grid; American Electric Power; RWE; Saudi Electricity Company	Strong in UHV, flexible DC and offshore-wind transformers; advanced nuclear and HVDC transformer technology.
Siemens Energy	Germany	EU grid companies; PG&E; State Grid; India's power utilities	Major supplier of 500 kV-plus transformers with a strong position in European and Middle Eastern high-end markets.
TBEA	China	State Grid; China Southern Power Grid; Saudi Electricity Company; Tenaga Nasional; Brazilian utilities	Global UHV and converter-transformer supplier with a strong cost position and rapidly growing orders in Asia and Africa.
Toshiba Energy	Japan	Tokyo Electric Power; Kansai Electric; Shinkansen railway; Korea Electric Power; Duke Energy	Strong in high-efficiency and superconducting-transformer R&D; a major supplier to Japan's high-speed rail system.
GE Vernova	United States	U.S. utilities; Canadian utilities; Mexico's power sector; European wind developers	Core North American grid-modernisation supplier with experience in renewable interconnection.
Jiangsu Huapeng Transformer	China	State Grid; China Southern Power Grid; major Chinese power groups; North American utilities	Full-range transformer exporter; North America accounts for roughly 30% of its business.
Mitsubishi Electric	Japan	Japanese utilities; Southeast Asian grids; data-centre operators such as NTT; defence-equipment manufacturers	Strong in compact smart transformers for rail, data centres and other critical infrastructure.

Company	Country	Representative customers	Market position and capabilities
Wujiang Transformer	China	State Grid; China Southern Power Grid; major Chinese power groups; utilities in the United States and UAE	Strong in UHV reactors and converter-transformer technology, including high-capacity converter transformers and low-noise UHV reactors.
Schneider Electric	France	Commercial real estate; industrial companies; data-centre operators including Amazon and Google; European distribution utilities	Leading supplier of low-voltage and environmentally oriented distribution transformers, supported by digital and IoT capabilities.
Hyosung Heavy Industries	South Korea	Korea Electric Power; Vietnam Electricity; U.S. utilities; Middle Eastern renewable-energy developers	Fast-growing HVDC transformer business with strong offshore-wind applications.
Taikai Group	China	State Grid; China Southern Power Grid; major Chinese power groups; European utilities	Supplies transformers for industrial 220 kV substations and energy-storage systems.
Eaton	United States	North American distribution utilities; Microsoft and Google data centres; industrial manufacturers; defence customers	Strong dry-type transformer supplier; a major North American distribution-transformer provider with growing data-centre demand.

Source: Company annual reports, public disclosures and Earth & Life Symbio analysis.

The global transformer market comprises several segments without a single hierarchy. Chinese manufacturers have built particularly strong positions in UHV and converter-transformer projects, supported by the scale of China's domestic grid and their experience delivering large infrastructure programmes.

Established European, Japanese, South Korean and US suppliers continue to hold important positions in specialised and high-value segments, including HVDC, offshore wind, nuclear applications and dry-type transformers, as well as in mature utility markets in Europe and North America.

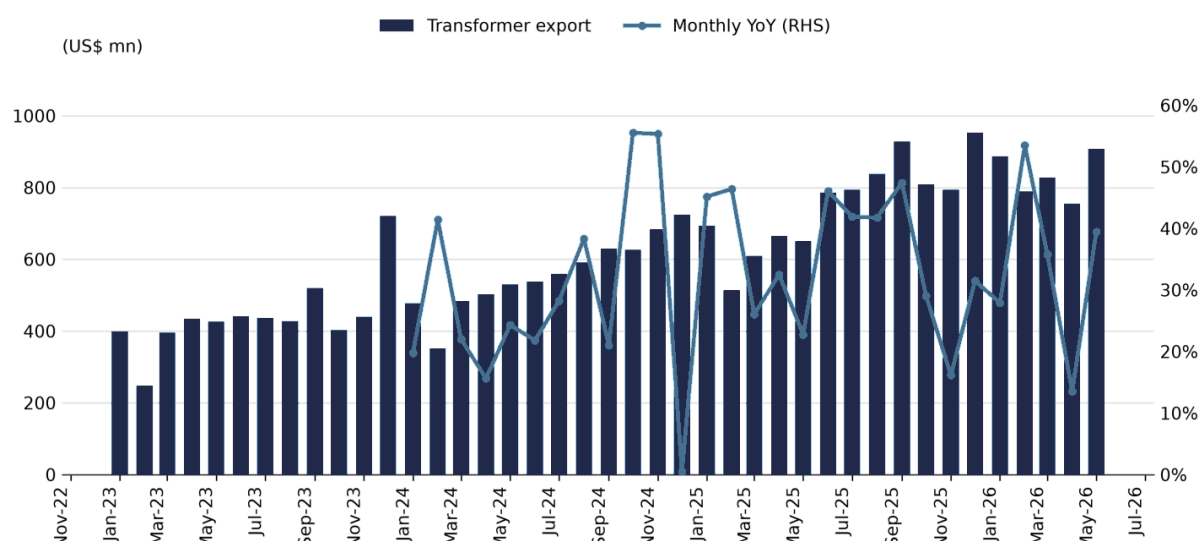
The competitive shift is a gradual redistribution of market positions: Chinese manufacturers are moving from domestic scale and large infrastructure projects towards broader international participation, while established suppliers continue to defend technology-intensive applications and long-standing utility relationships.

China's domestic market remains the bedrock of its transformer industry, even as exports expand at a faster rate. Export revenue surged by approximately 36% year-on-year in 2025, led by rapid growth in power transformers. This momentum sustained into 2026, with cumulative exports reaching RMB 42.63 billion (\$6.0 billion) from January to July, up 26% year-on-year.^{12,13} Export prices also increased, pointing to growth in value as well as volume.

This export surge is directly driven by a global supply-demand imbalance. Currently, the global supply deficit stands at approximately 30% for power transformers and roughly 10% for distribution transformers.¹⁴ According to industry tracking data, the average lead time for standard power transformers has stretched to around 128 weeks (approx. 2.5 years), while lead times for step-up transformers serving large data centers have exceeded 160 weeks, with specialized orders taking four to five years; in the U.S., delivery times have similarly surged from 50 weeks to 127 weeks.¹⁵ In contrast, Chinese manufacturers offer delivery lead times of just 10 to 12 months¹⁶. This decisive turnaround-time advantage has underpinned the rapid expansion of China's transformer exports.

Figure 5. Transformer Export Value Grew 39% Year on Year in May 2026

Transformer exports (USD million) and monthly year-on-year growth



Source: China Customs; Earth & Life Symbio.

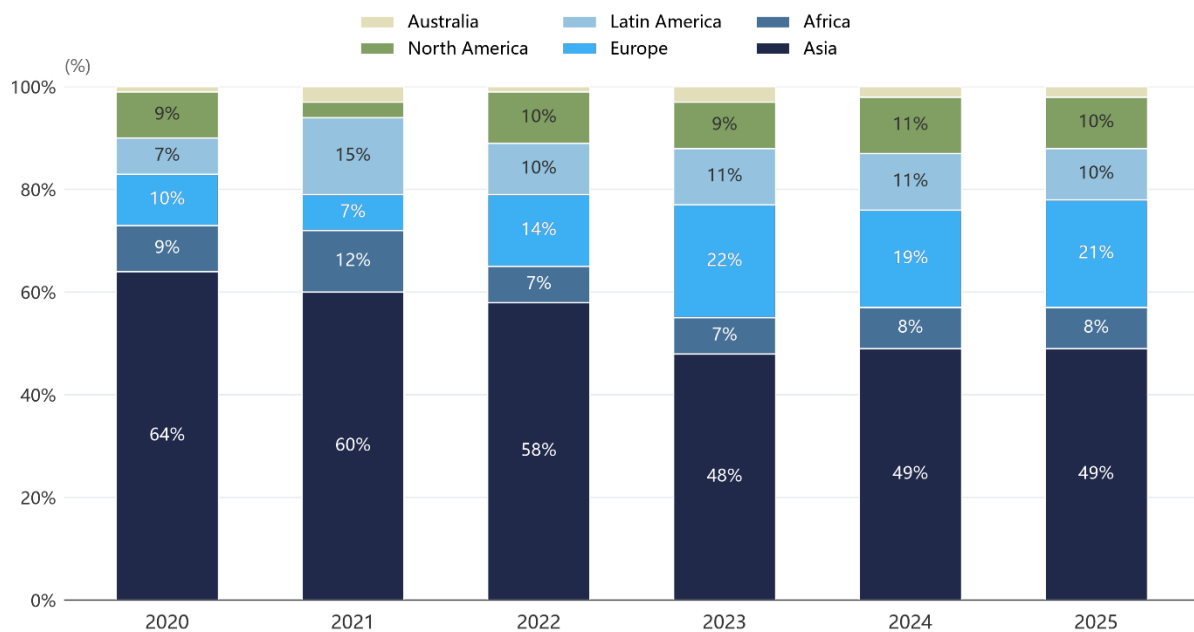
Export-market conditions differ considerably by region. Asia continues to account for roughly half of China's transformer export volume, with Vietnam and India among important destination markets. Africa offers longer-term growth potential as electricity-access expansion increases demand for standard distribution equipment.

Europe is also becoming more important. China's transformer exports to the region increased by 42.2% year on year in 2025, supported in part by replacement and expansion of grid infrastructure.

North America presents a different market structure. Transformer shortages and long lead times create underlying demand, but utility qualification requirements, security restrictions and domestic-content expectations constrain direct access for Chinese suppliers, particularly in higher-voltage applications. Privately financed data-centre projects may offer an entry route for selected products, although access remains dependent on project-specific technical, security and supplier-qualification requirements.

Figure 6. Market Share by Region (2020-2025)

Regional distribution of transformer market share



Source: Bank of America Research; Earth & Life Symbio analysis.

CHAPTER 2

Material choices shape both carbon footprints and manufacturing innovation

Transformers are material-intensive products, and raw materials account for most of their production-stage carbon footprint. Their cores, windings, tanks, radiators, bushings and insulation systems rely on electrical steel, structural steel, copper, aluminium, insulating fluids and other specialised materials. The emissions associated with transformer manufacturing therefore extend upstream into the steel, non-ferrous-metal, chemical and forestry supply chains.

Material choices also affect transformer performance. Core materials influence no-load losses; conductor materials affect load losses; and insulation systems shape thermal performance, safety and equipment life. Decarbonising transformer manufacturing requires coordinated attention to material emissions, electrical performance, reliability and lifetime efficiency.

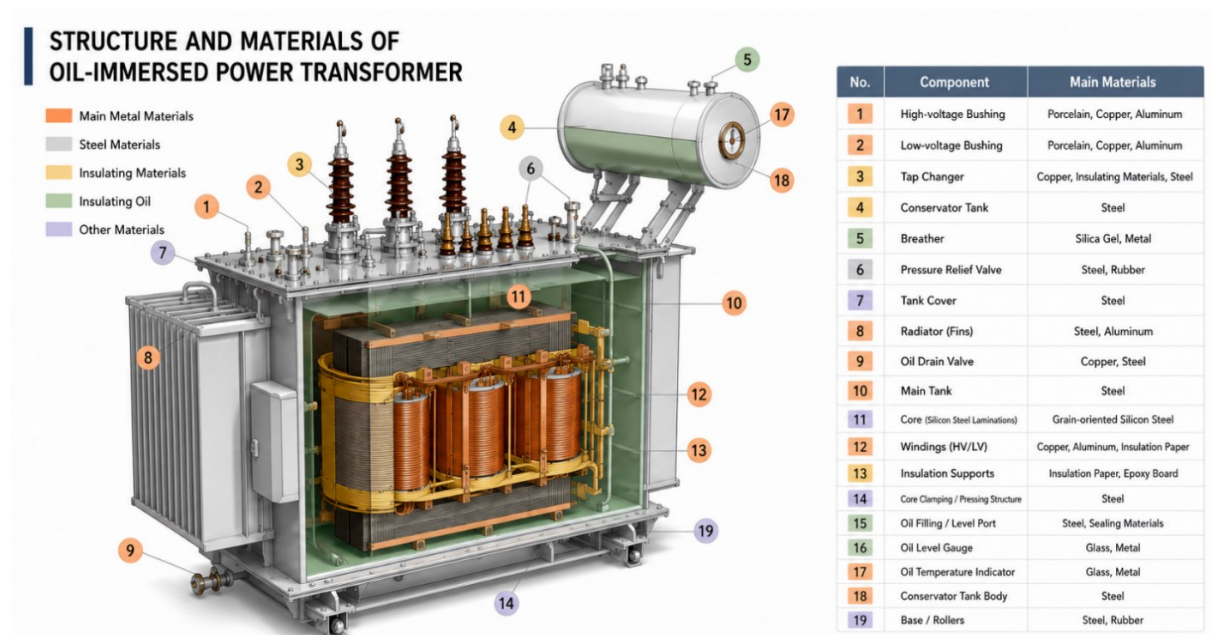
Two major transformer designs illustrate these differences. Oil-immersed and dry-type transformers perform the same fundamental function—transferring electricity between voltage levels—but use different approaches to insulation and heat management.

Feature	Oil-Immersed Transformer	Dry-Type Transformer
Insulating medium	Mineral oil or natural ester oil	Epoxy resin, other solid insulation or air
Cooling method	Oil circulation	Natural or forced-air cooling
Typical application	Transmission and distribution networks, outdoor substations, renewable interconnection (hundreds of kVA to hundreds of MVA)	Buildings, industrial facilities, metro systems, data centres and other indoor applications (typically up to 35 kV / 20 MVA)
Fire and leakage considerations	Requires management of insulating fluid and fire and leakage risks	Avoids liquid-oil leakage and is often preferred where fire-safety requirements are high
Principle material differences	Greater use of insulating fluid, steel tanks and cooling equipment	Greater importance of resin and solid insulation systems

Oil-immersed transformers place the magnetic core and windings inside a steel tank containing insulating fluid. The fluid provides electrical insulation and transfers heat from the active components to radiators or cooling surfaces. The principal material groups include GOES in the core, copper or aluminium in the windings, cellulose-based insulation paper, mineral or ester insulating fluid, and structural steel in the tank, radiators and supports.

Oil-immersed designs are widely used in outdoor substations, transmission and distribution networks, renewable-energy connections and other applications that require high capacity and strong thermal performance. Their liquid cooling system allows large amounts of heat to be removed from a relatively compact active part. The trade-offs are the need to manage oil quality, leakage, fire risk and end-of-life recovery. The oil, the steel tank and the electrical steel core therefore all need to be considered when assessing the material footprint of the unit.

Figure 7. Structure and Materials of an Oil-Immersed Power Transformer



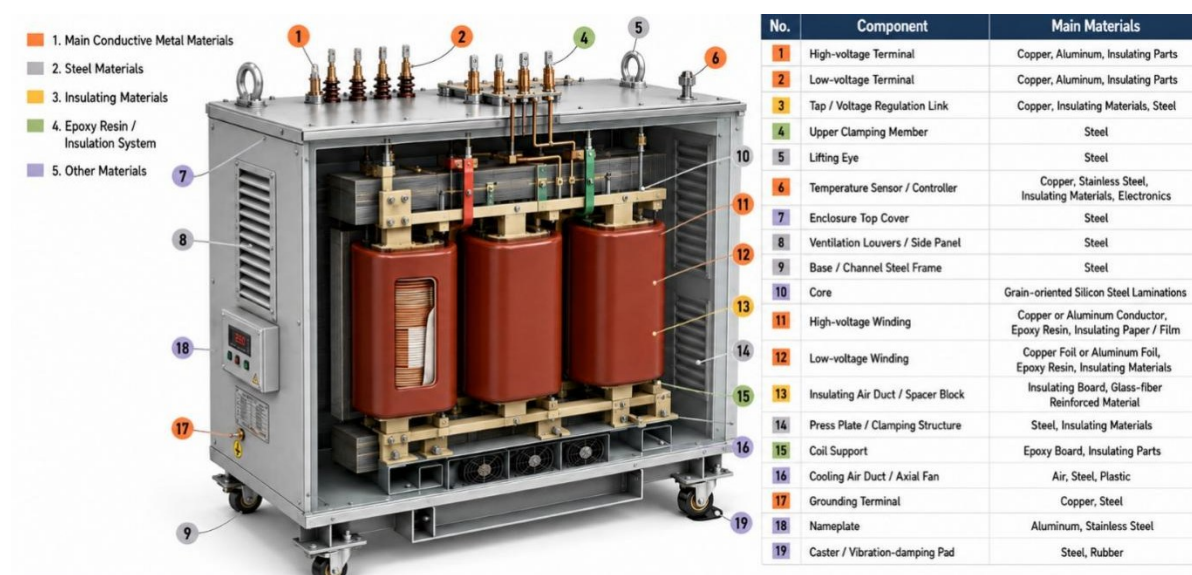
Source: Image created by ChatGPT; Earth & Life Symbio analysis.

Dry-type transformers use air and solid insulation instead of a liquid-filled tank. Their cores still rely primarily on electrical steel, while windings commonly use copper or aluminium. Resin, air, cellulose, aramid and other solid insulation materials become more important, while the oil-management and cooling systems associated with oil-immersed designs are removed or simplified.

Dry-type transformers are often selected for buildings, factories, hospitals, underground facilities, commercial premises and data centres, especially where fire safety, indoor installation, limited maintenance and the avoidance of oil leakage are important. They are generally more suitable for low- and medium-voltage distribution applications, although dry-type designs are also available for larger and more specialised installations. Their material priorities therefore differ from those of oil-immersed units: resin and solid insulation become more important, while the oil tank, radiators, conservator and breather are removed or simplified.

These differences change the relative importance of individual material supply chains. Electrical steel and conductors remain central in both designs, while material choices affect production-stage emissions and electrical performance over decades of operation.

Figure 8. Structure and Materials of a Dry-Type Distribution Transformer



Source: Image created by ChatGPT; Earth & Life Symbio analysis.

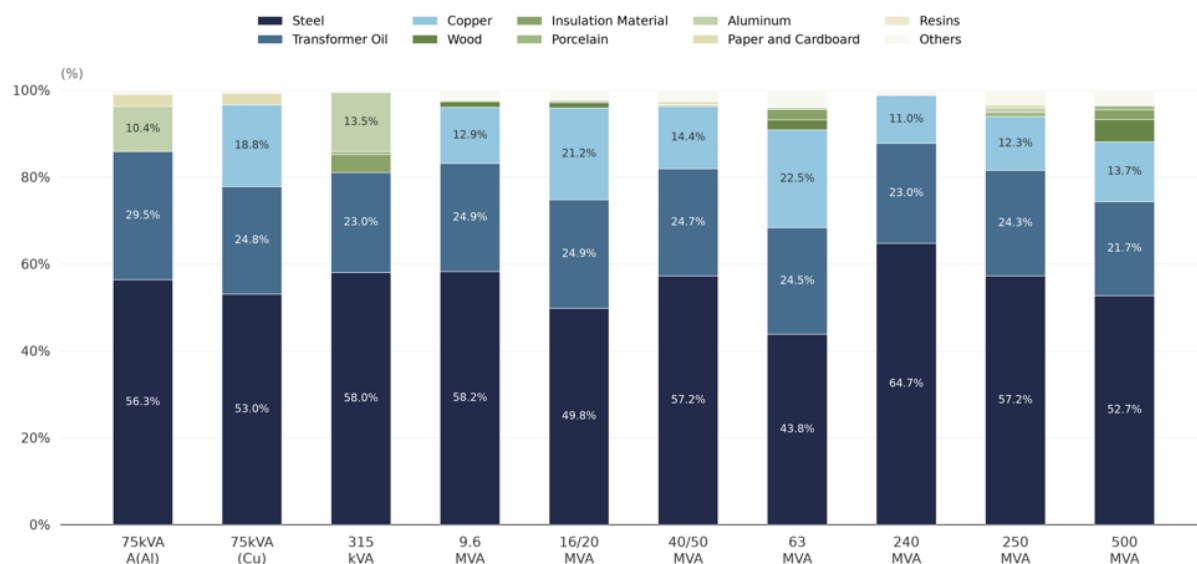
2.1 Steel is central to the transformer material base

A 2025 study by the China Electric Power Research Institute, Harvard University and other institutions (Liu et al., 2025) conducted a life-cycle carbon analysis of ten transformers spanning distribution, large distribution and transmission classes, from a 75 kVA distribution unit to a 500 MVA transmission unit. Metals dominate the material mix, averaging roughly 70% of total mass and ranging from 66% to 76% across the sample. Steel accounts for around half of raw-material weight; transformer oil ranks second at roughly 24%; and copper, used in eight of the ten units, averages about 12.7%. Aluminium appears mainly in the windings of smaller distribution units. Epoxy resin is used in dry-type transformers, with porcelain bushings, insulating paper and wood making up smaller shares.¹⁷

The sample demonstrates the material intensity of transformer manufacturing and provides a useful indication of where production-stage emissions are concentrated.

Figure 9. Material Composition Breakdown of Various Transformers

100% stacked relative mass comparison across different capacity tiers.



Source: Life-cycle CO₂ emissions of various transformers under different scenarios with multiple functional units; Earth & Life Symbio analysis.

2.2 Steel is the largest production-stage carbon hotspot

A transformer's production-stage carbon footprint depends on material emissions intensities, production route, energy source, recycled content, geography and accounting boundary.

Indicative emission factors used in the underlying analysis illustrate these differences:

Material	Carbon Emission Factor (kgCO ₂ e/kg)
Silicon steel sheet	~6
Cold-rolled steel	~2.2
Copper	~5.4
Aluminium	~6.9
Transformer oil	~4.8
Other auxiliary materials	0.5 - 5.0

Combining material quantities with emissions factors indicates a consistent hierarchy across the transformer models examined. Steel typically contributes approximately 50-68% of production-stage embedded carbon emissions. Transformer oil can contribute a further 20-30%, while copper and aluminium also

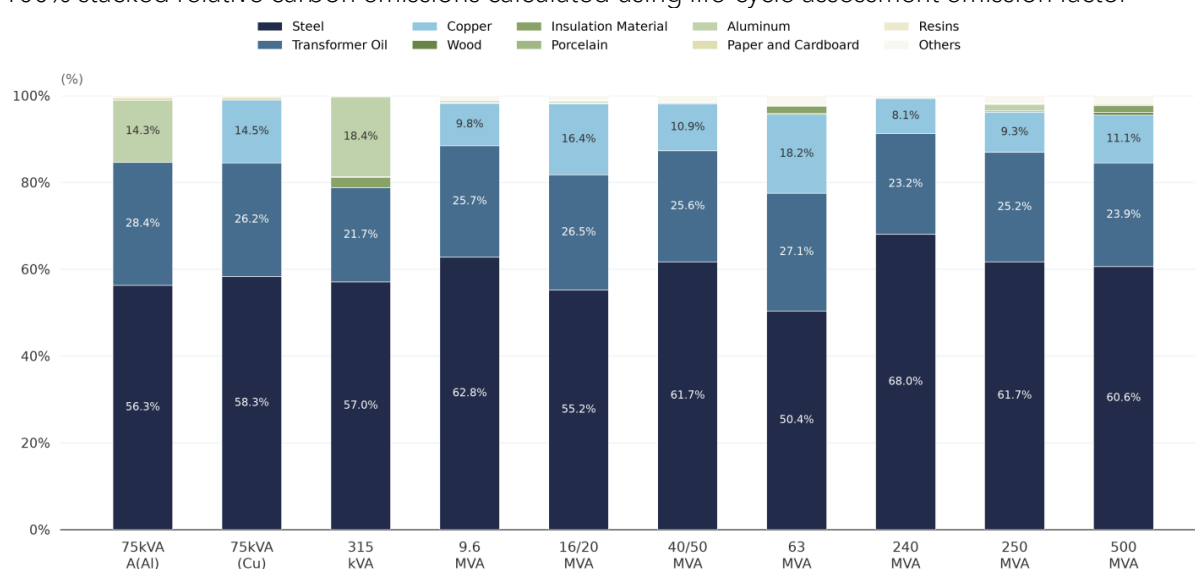
make material contributes depending on transformer capacity and design.

This concentration suggests a clear prioritization strategy. Decarbonisation efforts should begin with the materials that combine a large physical share, high emissions intensity and feasible opportunities for intervention.

Steel is the first priority, but different steel components require different approaches. GOES in the magnetic core has demanding electrical and metallurgical requirements and therefore needs a product-specific decarbonisation pathway. Structural steel used in tanks and other components can draw on a wider range of lower-carbon production routes. Copper, aluminium and insulating fluids require their own technical specifications and verified carbon-footprint data.

Figure 10. Embodied Carbon Footprint Breakdown of Various Transformers

100% stacked relative carbon emissions calculated using life-cycle assessment emission factor



Source: Life-cycle CO₂ emissions of various transformers under different scenarios with multiple functional units; Earth & Life Symbio analysis.

2.3 Operating efficiency and embedded carbon are distinct but increasingly connected priorities

The analysis above concerns production-stage emissions: the embedded carbon generated during raw-material extraction and manufacturing. A full life-cycle assessment also includes emissions associated with electricity lost during transformer operation.

Over an operating life of 30–40 years, the indirect emissions generated by a transformer's operating losses are typically several times, and sometimes tens of times, larger than its production-phase footprint. Multiple studies find that for large transmission transformers, operating-phase emissions can account for more than 90% of total life-cycle emissions.

Transformer losses have two principal components. **No-load losses** occur whenever a transformer is energised and are strongly influenced by the magnetic performance of the core material. **Load losses** vary with utilisation and are influenced primarily by conductor resistance in copper or aluminium windings.

This distinction matters because efficiency and embedded carbon are not interchangeable metrics. A higher-performance core material may reduce no-load losses over decades of operation, while the carbon footprint of producing that material depends on steelmaking route, energy consumption and other upstream factors. Material choices should be assessed against both production-stage emissions and operating losses.

Procurement needs to evaluate both dimensions. Magnetic performance and transformer-loss data establish the operating-efficiency case, while verified product carbon footprints establish the production-stage emissions case.

China's total-owning-cost approach (DL/T 985-2022) already provides a useful foundation. The method incorporates initial purchase cost, no-load losses and load losses into an economic assessment over the asset life. Carbon metrics can be added to this framework.

The relative importance of embedded emissions is also likely to increase as electricity systems decarbonise. As the emissions intensity of grid electricity declines, the carbon associated with a given quantity of operating losses also declines. Production-stage emissions consequently represent a larger share of the remaining life-cycle footprint.

China has established quantitative targets and evaluation frameworks to accelerate the deployment of higher-efficiency transformers, but procurement rarely places an explicit value on material emissions. The policy gap is the limited integration of embedded carbon into procurement alongside established efficiency and reliability criteria.

2.4 Material-specific pathways can reduce embedded carbon

Given the wide range of materials used in transformers, manufacturers should prioritise materials that combine high emissions impact with a technically credible decarbonisation pathway. Substitution should meet electrical, thermal, safety and long-term reliability criteria.

Component	Principal materials	Conventional upstream pathway	Low-carbon material-management focus
Magnetic core	Grain-oriented electrical steel (GOES)	Ironmaking and crude steel are commonly produced through the blast-furnace/basic-oxygen-furnace (BF-BOF) route, followed by rolling, silicon-alloy processing and energy-intensive annealing.	Request product-specific carbon-footprint data; distinguish verified lower-carbon GOES from generic steel claims; validate magnetic performance and no-load-loss outcomes.
Windings	Copper or aluminium conductors	Primary copper and aluminium are generally produced from mined ore through smelting, refining and rod/wire processing; secondary metal enters through recycling and refining routes.	Develop specifications for low-carbon and recycled copper or aluminium, while retaining requirements for conductivity, purity, mechanical performance and traceability.
Tank, radiators and fittings	Structural steel; in some products, aluminium	Structural components are commonly fabricated from BF-BOF, then rolled, welded, coated and assembled.	Identify recycled-content, EAF and renewable-electricity pathways; verify compatibility with corrosion, welding and reliability requirements.
Liquid insulation system	Mineral oil, natural esters or synthetic esters; cellulose paper and pressboard	Mineral oil is refinery-derived; ester and fibre-based systems depend on agricultural, chemical and forestry supply chains.	Assess product carbon footprint together with feedstock origin, land-use and deforestation risk, forest-fibre traceability, safety, low-temperature performance and end-of-life treatment.
Dry-type insulation system	Epoxy resin, air, cellulose or aramid-based insulation	Resins are generally derived from petrochemical value chains and are formulated for specific thermal and dielectric requirements.	Request supplier PCFs and formulation-level environmental data; validate fire safety, durability and electrical performance before substitution.

Grain-oriented electrical steel is the priority material

GOES is one of the most consequential transformer inputs and one of the most technically challenging steel products to decarbonise.

Conventional GOES production normally combines primary iron- and steelmaking with tightly controlled refining, casting, rolling, decarburising and high-temperature annealing. Primary steelmaking and repeated thermal processing are important sources of emissions. Increasing the use of high-quality scrap can reduce reliance on carbon-intensive primary ironmaking. However, transformer-grade GOES imposes stringent requirements on chemistry, residual elements, texture and validated magnetic performance. Residual copper contamination can constrain high-quality steel recycling, while nitrogen control and other metallurgical factors create additional challenges for electric-arc-furnace production. GOES decarbonisation requires coordinated control of feedstock quality, steelmaking, process energy and final magnetic performance.¹⁸

In the near term, reductions can come from renewable electricity, more efficient furnaces and annealing, heat recovery, improved material yield and carefully controlled use of production scrap. Higher-scrap routes may offer further reductions where chemistry and magnetic performance can be validated and the electricity supply is sufficiently low-carbon. Higher-performance and thinner GOES can simultaneously reduce transformer no-load losses. That operating benefit should be assessed alongside, but separately from, the embodied carbon of producing the steel.

Commercial examples demonstrate technical feasibility

Several commercial examples indicate that lower-carbon GOES can be produced and used in transformers.

- **Thyssenkrupp Electrical Steel** reports that its bluemint® powercore® GOES has 50% lower CO₂ intensity than its conventional product and has been supplied for transformer applications.¹⁹
- **Baosteel** announced in 2024 that its BeyondECO oriented and non-oriented electrical-steel grades could reduce manufacturing emissions by more than 30% relative to the company's conventional production route and had received third-party certification. A 220 kV transformer using GOES from the Qingshan production base subsequently passed testing.²⁰
- **Shanxi Taigang Stainless Steel** (TISCO) reports that it has developed high-grade GOES using a full-scrap, short-process production route after addressing metallurgical challenges including nitrogen control and micro-titanium inhibitors. The company reports a 76% reduction in emissions per tonne and application in high-efficiency transformers.²¹

Insulation requires a broader sustainability assessment

Sustainable insulation is a supply-chain management issue. Insulating oil is critical because virtually all large power transformers are oil-immersed, and oil-immersed units account for more than 97% of distribution transformers.²²

Insulation systems create a distinct set of environmental and supply-chain considerations.

Mineral insulating oil is fossil-derived. Natural-ester fluids produced from vegetable oils can offer advantages including higher fire points and biodegradability and may, under appropriate conditions, have lower life-cycle greenhouse-gas emissions than conventional mineral oil.²³

However, carbon performance depends on feedstock and production route. Agricultural feedstocks can create emissions and land-use impacts, while fibre-based insulation introduces forestry and traceability considerations.²⁴

A credible sustainable-insulation strategy should combine product-level carbon-footprint information with safeguards covering feedstock sourcing, land-use and deforestation risk, forest-fibre traceability, technical performance under relevant climatic conditions, and end-of-life recovery or disposal.

Insulating paper requires particular attention to fibre sourcing. Manufacturers can strengthen traceability by requiring suppliers to demonstrate that wood and wood-based materials originate from legally and responsibly managed sources, supported where appropriate by recognised certification schemes such as FSC®, PEFC or SFI®.

Waste-derived feedstocks, including waste cooking oil for insulating fluids, may offer additional opportunities and warrant further technical and life-cycle assessment.

Copper and aluminium should form the next material priority

Copper and aluminium are important contributors to both transformer cost and production-stage emissions. Their strategic importance is also increasing as electrification expands demand from power networks, data centres, vehicles and other sectors.

Greater use of recycled copper or aluminium can reduce reliance on primary production. Manufacturers need product-level carbon data, traceability of recycled content and evidence that conductors meet requirements for conductivity, purity, thermal performance, mechanical properties and long-term reliability.

CHAPTER 3

Policy, trade rules and downstream demand are creating a market for lower-carbon materials

Creating a market for lower-carbon transformers requires clear demand signals that justify investment in new production routes, carbon-data systems and product validation.

Three sources of demand are beginning to emerge. First, Chinese industrial and state-owned-enterprise policies are introducing product carbon footprints, green procurement and supply-chain carbon management into the policy framework. Second, international trade rules are increasing the value of traceable emissions data for selected export products. Third, utilities and large corporate buyers are beginning to incorporate Scope 3 emissions and embodied carbon into procurement decisions.

These signals differ substantially in scale and maturity. In China, procurement by grid companies and other large state-owned enterprises has the greatest potential to create demand at scale. Embedded carbon is not yet a consistent factor in transformer tender evaluation. Internationally, CBAM provides a more immediate compliance signal for selected products, while utility and data-centre procurement demonstrates how carbon performance can gradually become a commercial differentiator.

3.1 China has established a policy direction, but procurement demand remains limited

China's policy framework increasingly addresses both transformer efficiency and the sustainability of manufacturing inputs. Under the broader carbon-peaking and carbon-neutrality ("dual carbon") agenda, green design, recyclable materials and product carbon footprints are appearing in industrial-policy and supply-chain-management requirements.

The Ministry of Industry and Information Technology, jointly with other ministries, issued the *Implementation Plan for the High-Quality Development of Energy-Saving Equipment* (2026-2028), which explicitly calls for the promotion of green and low-carbon design across the equipment life cycle. It also encourages greater use of recyclable and lower-carbon materials and reduced reliance on virgin materials.

For transformers specifically, the plan identifies several areas of technological development and material upgrading:

Policy area	Core Content
Key Technologies and Materials for Energy-Saving Equipment	Development and deployment of high-magnetic-induction, ultra-low-loss and low-noise GOES; low-loss amorphous alloys; nanocrystalline materials; advanced insulation; high-performance winding wire; and other critical components
Green Manufacturing Processes	Greater automation and process optimisation in core stacking, winding, welding and drying; improved core utilisation; and greater use of environmentally preferable insulating oils, gases, resins and coatings

The policy focuses on transformer efficiency and equipment performance. Its emphasis on green design, recyclable inputs and environmentally preferable materials provides a foundation for explicit embedded-carbon requirements.

China is also beginning to develop the methodological infrastructure needed for product-level carbon accounting. The China Electricity Council (CEC) has issued an initial group of product carbon-footprint quantification standards covering transformers, power cables, smart meters and other electrical products. These standards begin to address a previous methodological gap. As their use expands, greater alignment with internationally recognised life-cycle-assessment (LCA) principles would improve comparability between products and suppliers.²⁵

Energy-efficiency regulation is considerably more mature. National standards continue to tighten transformer-loss requirements, increasing demand for thinner and lower-loss GOES and, where technically appropriate, amorphous core materials. Efficiency standards and production-stage carbon performance address different dimensions. Product-level emissions data remain necessary.

A second important development is the *Guidelines for Green and Low-Carbon Supply Chain Development of Central State-Owned Enterprises (Trial)*. The guidelines incorporate life-cycle assessment, green procurement, supplier carbon management and resource circularity into central SOE supply-chain management.

Several provisions have direct implications for transformer manufacturing and procurement:

Article	Core Requirement	Potential Relevance to Transformers
Art. 8 green and low-carbon Design	Life-cycle assessment, product carbon footprints, lower-carbon materials and greater use of recycled inputs	Incorporate carbon performance into transformer eco-design and evaluate lower-carbon GOES and recycled metals where technically suitable
Art. 9 Green Procurement	Prioritize energy-,water- and material-efficient products; increase procurement of recycled and remanufactured products	Develop lower-carbon procurement specifications for GOES, conductors, insulating fluids and insulation components
Art. 10 Supplier Management	Tiered & classified dynamic management; incentive & constraint mechanisms	Introduce carbon-performance criteria into management of steel, conductor and insulation suppliers
Art. 12 Procurement Coordination	Information sharing among central SOEs; acceptance of third-party certifications (green electricity consumption certification, etc.)	Enable utilities and manufacturers to recognise verified supplier environmental information
Art. 13 Green Manufacturing	Clean energy substitution; increase renewable energy & green electricity consumption ratio; high-efficiency equipment; replacement of outdated equipment	Use rooftop PV, procure green power and, where feasible, establish direct renewable-electricity connections; improve the efficiency of vacuum-drying and annealing furnaces to reduce emissions from transformer manufacturing operations.
Art. 14 Green Logistics	Green packaging, recyclable tote boxes, rooftop PV storage, new-energy transport vehicles, rail-water-road multimodal transport	Large transformer transport: green/recyclable packaging, multimodal transport coordination
Art. 15 Resource Circularity	Extended producer responsibility; recycling of scrap steel, non-ferrous metals, rare earths, new energy equipment	Improve recovery of copper, electrical steel, insulating oil and other materials from retired transformers
Art. 17 Technology development	Support low-carbon & zero-carbon industrial-process innovation	Encourage low-carbon transformer manufacturing and material-processing technologies (e.g., annealing process optimization)

These policies establish a supportive framework, but their effect on purchasing decisions remains limited. The SOE supply-chain guidelines are still at the trial stage, while product-carbon-footprint standards are in an early phase of implementation. Based on the procurement practices reviewed for this report, transformer tenders by major Chinese grid buyers currently apply no consistent and binding weighting to embedded carbon or verified lower-carbon materials.

Operating efficiency is supported by mandatory standards and established total-owning-cost methodologies. Embedded carbon is increasingly recognised in policy but is not yet consistently valued in procurement.

The next step is to translate existing policy objectives into measurable procurement criteria. Verified product carbon footprints, material-level emissions data or an appropriately designed carbon value could be introduced alongside existing requirements for cost, efficiency, quality and reliability. If implemented carefully, procurement could create a demand signal for lower-carbon steel, recycled non-ferrous metals and lower-carbon insulation materials without weakening technical performance requirements.

3.2 CBAM provides a targeted signal, but its direct coverage remains limited

The EU Carbon Border Adjustment Mechanism (CBAM) entered its definitive regime in 2026. Finished transformers are not currently covered under the existing scope of CBAM, although several important transformer inputs—including steel and aluminium—fall within covered material sectors.

The regulatory direction may nevertheless be moving further downstream. In December 2025, the European Commission proposed extending CBAM from 2028 to approximately 180 additional steel- and aluminium-intensive downstream products.

The proposed list includes two transformer categories:

- CN 8504 31 80 – certain non-liquid dielectric transformers with a power-handling capacity not exceeding 1 kVA; and
- CN 8504 33 00 – certain non-liquid dielectric transformers with a power-handling capacity above 16 kVA but not exceeding 500 kVA.

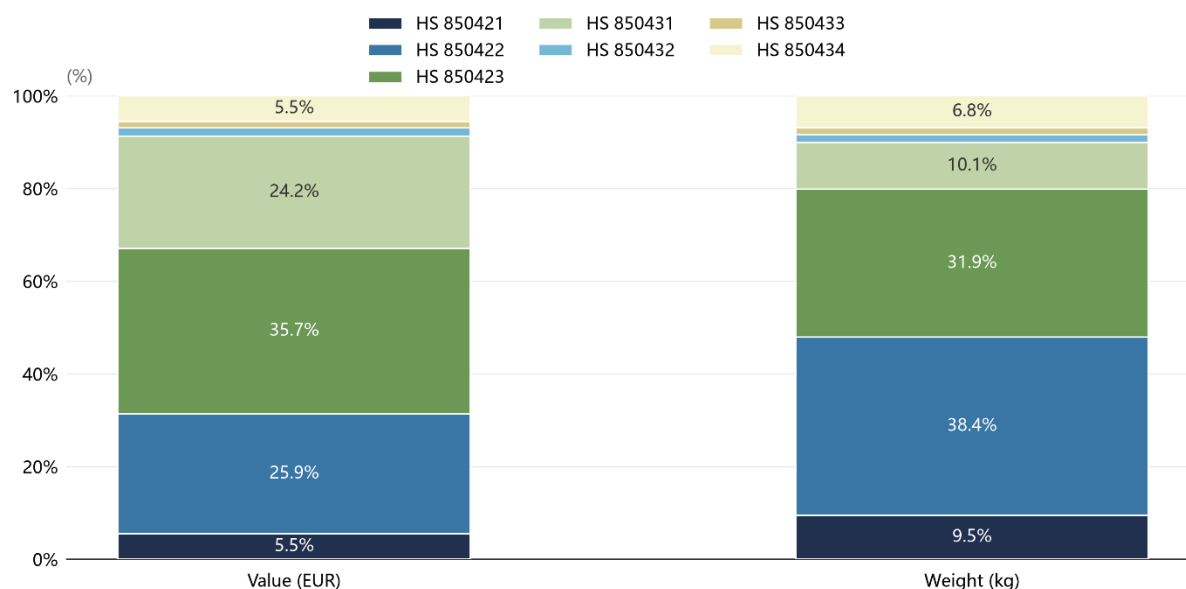
The proposal remains subject to the EU legislative process. Its final product scope, implementation timetable and detailed verification requirements should therefore not be treated as settled.²⁶

Analysis of EU import data undertaken for this report indicates that the transformer categories included in the proposal represented approximately **21.7% of the value** and **9.9% of the weight** of China's transformer exports to the EU. The largest categories of Chinese liquid-dielectric transformer exports—CN 8504 21, CN 8504 22 and CN 8504 23—are not included in the proposed extension.

The proposed expansion could create meaningful compliance and data requirements for affected exporters. Most Chinese transformer exports to the EU by weight would remain outside the proposed scope, making CBAM a targeted regulatory signal for the sector.

Figure 11. EU27 Transformer Imports from China: Value and Weight Share

Seven transformer categories, 2025; 100% stacked share



Source: Access2Markets; Earth & Life Symbio.

Under the proposed downstream methodology described in the materials reviewed for this report, embedded emissions would reflect covered precursor materials such as steel and aluminium. Verified supplier data would allow manufacturers and importers to demonstrate actual emissions and reduce reliance on regulatory default values where permitted.

The default values relevant to several transformer materials also warrant attention. The values reviewed for this report place China relatively high among major producing countries for GOES, aluminium wire and structural steel components. Benchmarked against other major steel-producing nations, China sits in the high range across all three materials most relevant to transformers: grain-oriented silicon steel at 8.09 tCO₂/t (behind only Indonesia, India, and Türkiye), aluminium wire at 4.88 tCO₂/t (the highest in the sample), and structural steel components at 6.04 tCO₂/t (significantly above most major steel producers).²⁷

For manufacturers, the strategic implication is therefore primarily about **data readiness**. A traceable emissions-data chain from steelmaking through GOES production and component fabrication can improve the accuracy of a finished product's carbon footprint and reduce reliance on conservative default assumptions.

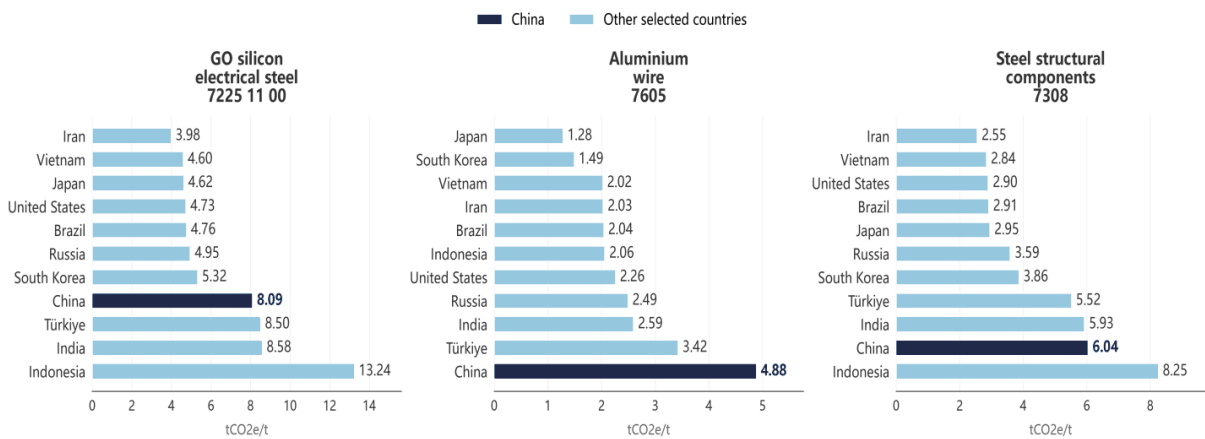
This is particularly relevant for GOES. The material accounts for a substantial share of transformer production-stage emissions and is supplied by a relatively

concentrated group of producers. China produced approximately 3.36 million tonnes of GOES in 2025, representing around 70% of estimated global output, according to the industry sources reviewed for this report. A relatively concentrated supplier base makes targeted engagement on verified product-level emissions data more practicable than for highly fragmented material categories.^{28,29}

An early example already exists. In 2022, Baosteel and Hitachi Energy jointly assessed the life-cycle carbon footprint of transformers using different GOES grades. Baosteel developed life-cycle carbon-footprint information for its electrical-steel products, while Hitachi Energy modelled the implications across transformer configurations. The collaboration illustrates how material suppliers and equipment manufacturers can connect upstream carbon information with product-level assessment.

Figure 12. CBAM Default Values for Key Transformer Materials

Selected major steel-producing countries; China highlighted. Values are sorted from low to high within each material



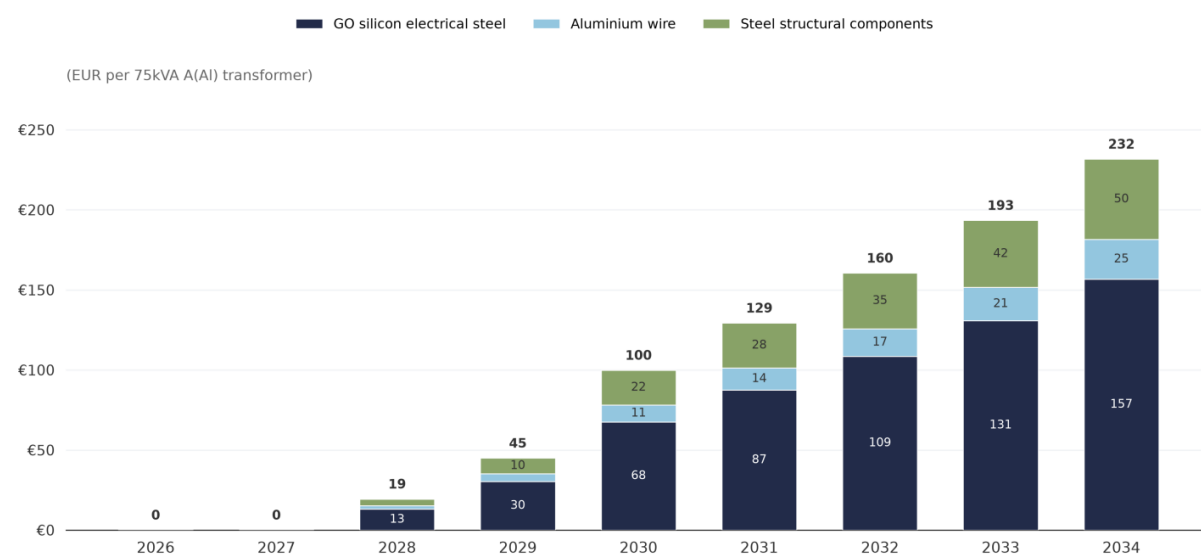
Source: European Commission CBAM corrected default-values workbook (Version 2, 6 August 2026; Regulation (EU) 2026/1740); Earth & Life Symbio analysis.

The report also models the potential CBAM exposure of a 75 kVA aluminium-wound transformer under a set of assumed future policy parameters. Under those assumptions, the material-related cost rises from approximately €19 in 2028 to €232 in 2034 as the assumed payment share increases from 10% to 100%.

The more durable conclusion is that companies able to produce auditable material-emissions data will be better prepared for evolving trade and customer requirements regardless of the eventual level of CBAM-related cost.

Figure 13. Estimated CBAM Cost for Key Transformer Materials

75 kVA A(Al) transformer; China default values. Assumes EUR 75.36/tCO₂ in 2026, growing at 3% annually



Source: European Commission CBAM default-values workbook; material-breakdown table; Earth & Life Symbio analysis.

Case Baosteel and Hitachi Energy: Joint Life-Cycle Carbon Footprint Calculation for Grain-Oriented Silicon Steel Transformers

In 2022, Baosteel and Hitachi Energy jointly published life-cycle carbon footprint results for grain-oriented silicon steel transformers. Baosteel built a life-cycle carbon footprint calculation model for its silicon steel products in line with relevant LCA standards and specifications. Hitachi Energy then calculated full life-cycle transformer emissions across multiple combinations of silicon steel grades and transformer models.³⁰

Case China's First Batch of Carbon-Neutral Certified Export Transformers

In August 2026, supported by the State Grid Liyang Power Supply Company, Jiangsu Huapeng Transformer Co., Ltd. secured carbon-neutral certification from the British Standards Institution (BSI) for 15 units of 35kV/6000kVA box-type transformers. Marking China's first batch of carbon-neutral certified export transformers, these units are bound for Europe to support local computing and data center projects.

The certification covers the complete cradle-to-gate emissions, adhering to ISO 14068-1:2023 standards across a bill of materials (BOM) exceeding 100 itemized components—including steel, copper, aluminum, and transformer oil—as well as manufacturing energy consumption. Net emissions of 1,242 tCO₂e were offset using 1,250 tons of verified carbon credits.

Rather than relying on low-carbon materials, the core value of this certification lies in establishing a traceable carbon accounting system. This milestone signals that product-level carbon data disclosure and supply chain carbon management are becoming essential gatekeepers for power equipment entering premium global markets.³¹

3.3 Utilities and data centres can create commercial demand

Large downstream buyers are beginning to use Scope 3 targets, procurement criteria, internal carbon prices and material-specific pilots to influence infrastructure supply chains.

European transmission-system operators provide some of the clearest examples.

TenneT operates extensive transmission networks in the Netherlands and Germany. The company estimates that the production, transport and installation of major assets—including cables, overhead lines, towers, offshore platforms, transformers and substations—account for more than 74% of its Scope 3 emissions.

Against a 2019 baseline, TenneT has set targets to reduce Scope 1 and 2 emissions by 95% and selected Scope 3 emissions by 30% by 2030. Its supply-chain decarbonisation work has included pilots involving lower-carbon steel and concrete, lower-carbon aluminium conductors and alternative fuels. TenneT Germany has tested lower-carbon steel in lattice towers and substations, while TenneT Netherlands has introduced sustainability criteria in steel-plate procurement.

These initiatives are bringing material emissions into infrastructure procurement through early pilots.³²

Elia Group provides a more explicit example of carbon being incorporated into procurement economics. Through Elia in Belgium and 50Hertz in northern and eastern Germany, the group serves around 30 million end users. It applies an internal carbon price of EUR 200/tCO₂e in procurement for new assets, including electrical equipment and major infrastructure.

Under its procurement approach, certified supplier carbon-footprint estimates can be monetised as an additional evaluation factor. More advanced applications can incorporate carbon-footprint values at tender stage and reconcile them against project data later, creating the possibility of financial rewards or deductions. The approach demonstrates how carbon information can influence commercial decisions while technical qualification requirements remain in place.³³

Portugal's transmission-system operator REN provides a different set of examples focused on material and circularity. Its activities include transformer-oil regeneration, testing of plant-based alternatives to mineral insulating oil, and hydrotreated vegetable oil as a substitute for fossil diesel.

Case TenneT and Hitachi Energy provide an early transformer-specific example

A framework agreement between Hitachi Energy and TenneT Germany provides one of the clearest transformer-specific examples identified in this research.

The companies agreed to use lower-carbon copper conductors in transformers. Hitachi Energy reports that the first 380 MVA transformer delivered under the programme in 2026 achieved an 18% reduction in raw-material embedded carbon. Once all units covered by the programme are operational, the company estimates cumulative avoided emissions of approximately 9,500 tonnes of CO₂e.

The significance of this case lies less in the specific percentage reduction than in the procurement mechanism. A large infrastructure buyer translated a Scope 3 objective into a multi-year material requirement, giving the equipment manufacturer and its upstream suppliers a clearer demand signal.

The example demonstrates how verified material requirements, long-term procurement and supplier collaboration can begin to create a commercial market for lower-carbon transformer inputs.

Data centres could become another source of demand

Large technology companies represent a second potential source of downstream demand because of the rapid expansion of data-centre infrastructure and corporate Scope 3 commitments.

Google has set a target to reduce its combined absolute Scope 1, 2 (market-based) and Scope 3 greenhouse-gas emissions by 50% by 2030 from a 2019 baseline. It has joined the Sustainable Steel Buyers Platform to work with peers on the development and procurement of lower-carbon steel.

For redesigned U.S. data-centre specifications, Google asks general contractors to report the greenhouse-gas footprint information for selected construction materials through the EC3 platform and encourages the use of lower-carbon alternatives.³⁴

The combination of rapidly expanding electrical-equipment demand and increasingly sophisticated Scope 3 management creates a plausible pathway through which embodied-carbon requirements could eventually extend to transformers and substations.

CHAPTER 4

Turning early pilots into a scalable market for low-carbon transformers

Early applications of lower-carbon GOES and other materials show that reducing the production-stage carbon footprint of transformers is technically feasible. The next challenge is market formation: moving from individual demonstration projects to repeatable procurement across different manufacturers, transformer classes and applications.

This transition requires coordinated action across the value chain. Product claims need common accounting and verification rules. Buyers need mechanisms that recognise verified carbon performance without compromising efficiency, reliability or affordability. Manufacturers and suppliers need opportunities to validate new materials at commercial scale. Successful pilots then need to be converted into longer-term procurement commitments that provide sufficient demand visibility for upstream investment.

Public policy can support this process by reducing coordination costs and some of the risks faced by early movers. Its role is to create conditions under which verified lower-carbon products can compete on technical, economic and environmental performance while allowing multiple technology pathways.

4.1 Establish common carbon-performance rules and recognise them in procurement

The first priority is to establish a credible and comparable basis for defining a lower-carbon transformer.

Industry associations, utilities, manufacturers and material suppliers should work towards consistent approaches covering system boundaries, emissions accounting, treatment of recycled materials, supplier-specific data and third-party verification. Production-stage material emissions should be reported separately from operating losses so that improvements in embedded carbon can be assessed without weakening established requirements for transformer efficiency and reliability.

A common methodology would also help distinguish product-specific improvements from generic environmental claims. Where lower-carbon materials are used, manufacturers should be able to demonstrate both the emissions characteristics of those inputs and their effect on final transformer performance.

Procurement is then the most direct mechanism for giving verified carbon performance commercial value.

In China, State Grid and China Southern Power Grid could explore incorporating verified product-carbon-footprint information into existing procurement and total-owning-cost evaluation frameworks. Technical performance, efficiency, safety and reliability would remain the basic entry conditions. Among products meeting those requirements, an appropriately designed carbon criterion—such as a transparent evaluation weighting or internal carbon value—could allow transformers with demonstrably lower production-stage emissions to receive additional recognition.

GOES is a logical starting point because it represents a significant share of production-stage emissions, has a relatively concentrated supplier base, and directly affects transformer efficiency. Procurement criteria should evaluate carbon intensity together with magnetic performance and transformer losses.

Early lower-carbon products may carry additional costs associated with material production, verification, testing or smaller production volumes. Time-limited support mechanisms—including demonstration funding, technical-assessment support or preferential green and transition finance—could help address these initial barriers.

Such support should be linked to measurable product performance and should decline as technologies mature and procurement volumes increase. It should also remain accessible to smaller manufacturers and avoid concentrating support among incumbent suppliers.

The objective is to reduce the initial cost and coordination barriers that prevent technically credible lower-carbon products from reaching sufficient scale to compete through normal procurement.

4.2 Expand pilots across products, voltage classes and applications

Baosteel's lower-carbon GOES in a 220 kV transformer provides an early demonstration. The next stage should test lower-carbon materials across a broader range of transformer types, manufacturers and operating environments. Relevant applications include distribution transformers, renewable-energy step-up transformers and large power transformers.

Distribution transformers may be particularly suitable for early scaling because their designs are relatively standardised and procurement volumes are large. They can therefore provide opportunities to test repeatable specifications, supplier-data requirements and procurement mechanisms across larger product volumes.

Large power transformers remain equally important for technical validation because of their high material intensity, long operating lives and demanding reliability requirements. Demonstrations across different voltage classes can help establish

where lower-carbon materials are commercially and technically ready and where further development is required.

Material innovation should also extend beyond GOES. Structural steel, copper and aluminium conductors, insulating fluids and solid insulation systems all contribute to the production-stage footprint. Pilots should follow the material hierarchy identified in Chapter 2 and phase material improvements in sequence.

Each pilot should generate a consistent set of evidence. At minimum, this should include:

- product carbon footprint and accounting boundary;
- proportion of the footprint based on supplier-specific verified data rather than generic factors;
- no-load and load losses;
- relevant reliability and safety test results;
- incremental cost relative to an appropriate conventional benchmark; and
- expected or measured life-cycle performance.

Comparable reporting would allow buyers and policymakers to distinguish genuine improvements from claims based on different accounting assumptions.

Where pilots demonstrate acceptable performance, the next step should be to move beyond one-off procurement. Multi-year framework agreements, indicative purchasing commitments or progressively increasing lower-carbon procurement requirements can provide upstream suppliers with clearer demand expectations.

This is particularly important for steel and other material producers considering investment in lower-carbon production routes. A technically successful demonstration creates evidence; a credible procurement commitment creates a market.

4.3 Build value-chain commitments around measurable demand and credible data

A transformer's carbon footprint is the cumulative result of decisions made across the supply chain. Steelmakers, copper and aluminium suppliers, insulation producers, transformer manufacturers and final buyers each control different parts of the emissions profile. Credible market development therefore needs both data from each stage and accountability across these relationships.

Material suppliers should progressively provide verified product-level carbon-footprint information and increase the availability of lower-carbon product grades

where technically feasible. Transformer manufacturers should develop product roadmaps, strengthen supplier-data coverage and disclose the extent to which their product carbon footprints rely on measured data and estimates.

Large utilities and other major buyers can provide the strongest demand signal. Where consistent with their broader climate strategies, they can establish time-bound Scope 3 objectives, indicate expected demand for lower-carbon materials or equipment, and communicate the procurement criteria that suppliers will be expected to meet.

The value of these commitments depends on specificity. General net-zero or green-supply-chain statements provide limited investment certainty to suppliers. More useful signals include indicative purchasing volumes, carbon-performance thresholds, recognised verification methodologies, implementation timelines and transparent tender-evaluation rules.

At the same time, procurement commitments should retain flexibility as technologies and accounting methodologies evolve. Common reporting templates and third-party verification can reduce duplicated data requests and improve comparability across buyers. Appropriate confidentiality arrangements will also be necessary because supplier-level emissions and production data can be commercially sensitive.

Aggregated or anonymised results from demonstration projects can provide substantial public value. Information on cost premiums, technical performance, verified emissions reductions and data availability can help buyers, policymakers and manufacturers understand which approaches are ready for wider deployment.

4.4 From demonstration to market formation

The evidence reviewed in this report suggests that no single intervention will create a lower-carbon transformer market.

Standards provide a common language. Carbon-footprint data make performance measurable. Procurement gives that performance economic value. Demonstration projects reduce technical uncertainty. Longer-term purchasing commitments provide suppliers with confidence to invest. These mechanisms are mutually reinforcing.

A practical market-development sequence could therefore proceed in stages:

a. Establish a baseline. Develop

comparable product-carbon-footprint methodologies and improve supplier-specific data, beginning with high-impact materials such as GOES.

b. Validate performance. Test

lower-carbon materials across representative transformer types while maintaining efficiency, safety and reliability requirements.

c. Create early demand. Introduce

carbon criteria into selected utility and corporate procurement programmes and use targeted, time-limited support where early costs remain a barrier.

d. Convert successful pilots into repeat procurement. Use

framework agreements, procurement targets or other demand commitments to provide manufacturers and material suppliers with greater market visibility.

e. Scale and improve. Expand

successful approaches across additional voltage classes, manufacturers and materials, while publishing comparable evidence on cost, performance and emissions outcomes.

The purpose of this sequence is to integrate verified carbon performance into mainstream equipment procurement.

If successful, lower-carbon materials would become one of several normal dimensions of transformer competitiveness—alongside efficiency, reliability, delivery capability and cost.

CHAPTER 5

Lessons for the wider energy-equipment industry

The transformer case illustrates a broader challenge across the energy transition. Expanding renewable energy, electricity networks, storage and electrification requires large quantities of manufactured equipment; producing that equipment, in turn, requires steel, aluminium, copper, chemicals and other materials from industries that are themselves difficult to decarbonise. Energy transition and industrial decarbonisation are therefore increasingly interconnected. The framework developed in this report can be applied to other energy-equipment products by identifying material hotspots, distinguishing binding regulation from customer signals, testing credible lower-carbon alternatives and assessing which actors have sufficient purchasing power to change the market.

5.1 The analytical framework can be applied beyond transformers

Wind towers and offshore wind foundations provide a clear example. Both are highly steel-intensive and are beginning to face requirements relating to embedded carbon, supplier emissions data and supply-chain traceability. Dajin Heavy Industry and Tianshun Wind Energy show how export-oriented equipment suppliers are responding through greenhouse-gas inventories, green procurement and lower-carbon steel initiatives. In practice, product quality, localisation, delivery and cost remain fundamental, with carbon performance emerging as an additional differentiator in selected markets.^{35,36}

Beyond transformers and wind towers, motors, pumps, compressors, switchgear and GIS assemblies are also intensive users of steel and aluminium. Different equipment categories will face different combinations of trade exposure, material-emissions hotspots, technical constraints and buyer pressure. A single definition or policy instrument is therefore unlikely to work across all sectors; interventions should be designed around the specific product, market and purchasing structure.

5.2 From clean-energy deployment to cleaner industrial supply chains

The transformer supercycle puts manufacturing capacity at the centre of electrification. Equipment supply must expand while its material footprint declines. This creates a dual challenge: scale up supply while reducing its footprint. China's role in transformer and wider energy-equipment production gives it an opportunity to combine industrial scale and reliable delivery with higher efficiency, lower-carbon manufacturing and stronger supply-chain transparency.

Efficiency standards, utility procurement, product carbon footprint expectations,

supply-chain disclosure and evolving trade rules are broadening the definition of product performance. Their legal status and reach vary, but together they increasingly connect lifetime efficiency, material emissions and the quality of underlying data. Carbon performance is most likely to become durable when it is integrated into established dimensions of industrial competitiveness rather than treated as a separate environmental requirement.

Manufacturers can begin by identifying material hotspots, working with suppliers on credible data and validating lower-carbon inputs while maintaining performance, reliability and cost competitiveness. Large buyers can convert technical feasibility into commercial demand through procurement, while material suppliers can provide product-specific verified emissions information. Policymakers can support the transition through common accounting methodologies, demonstration programmes, green public and SOE procurement, appropriate financing mechanisms and international cooperation.

5.3 Building an equipment manufacturing base for global electrification

The global energy transition will require substantially more electricity infrastructure. Transformer and other power-equipment manufacturing capacity must therefore expand at the same time that the carbon intensity of manufacturing declines. This creates a dual challenge: **scale up supply while reducing its footprint.**

These objectives can advance together. Material innovation can reduce production-stage emissions; improved electrical steel and transformer design can lower operating losses; stronger carbon-data systems can increase supply-chain transparency; and procurement can reward verified improvements without compromising technical performance.

The transition will nevertheless be gradual. Cost, reliability, supply availability and technical qualification will continue to determine whether new materials can move from demonstration to mainstream use. Carbon performance is most durable when integrated into these existing dimensions of industrial competitiveness.

For manufacturers, the opportunity is to develop products that combine high efficiency, lower embedded carbon, reliable performance, resilient supply chains and competitive cost.

For policymakers and large buyers, the task is to create the conditions under which those attributes are recognised and rewarded by the market.

The framework developed in this report can now be extended to other strategic

equipment categories—including wind-power equipment, high-voltage cables, switchgear, storage systems and other infrastructure essential to electrification. Each will require its own assessment of material hotspots, technical constraints, market signals and procurement opportunities.

The broader objective is a manufacturing system capable of supporting the scale of global electrification while progressively reducing the carbon footprint of the infrastructure on which that transition depends. The immediate opportunity is to turn the lessons from early transformer and material pilots into **repeatable procurement practices, credible product data and scalable industrial solutions.**



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