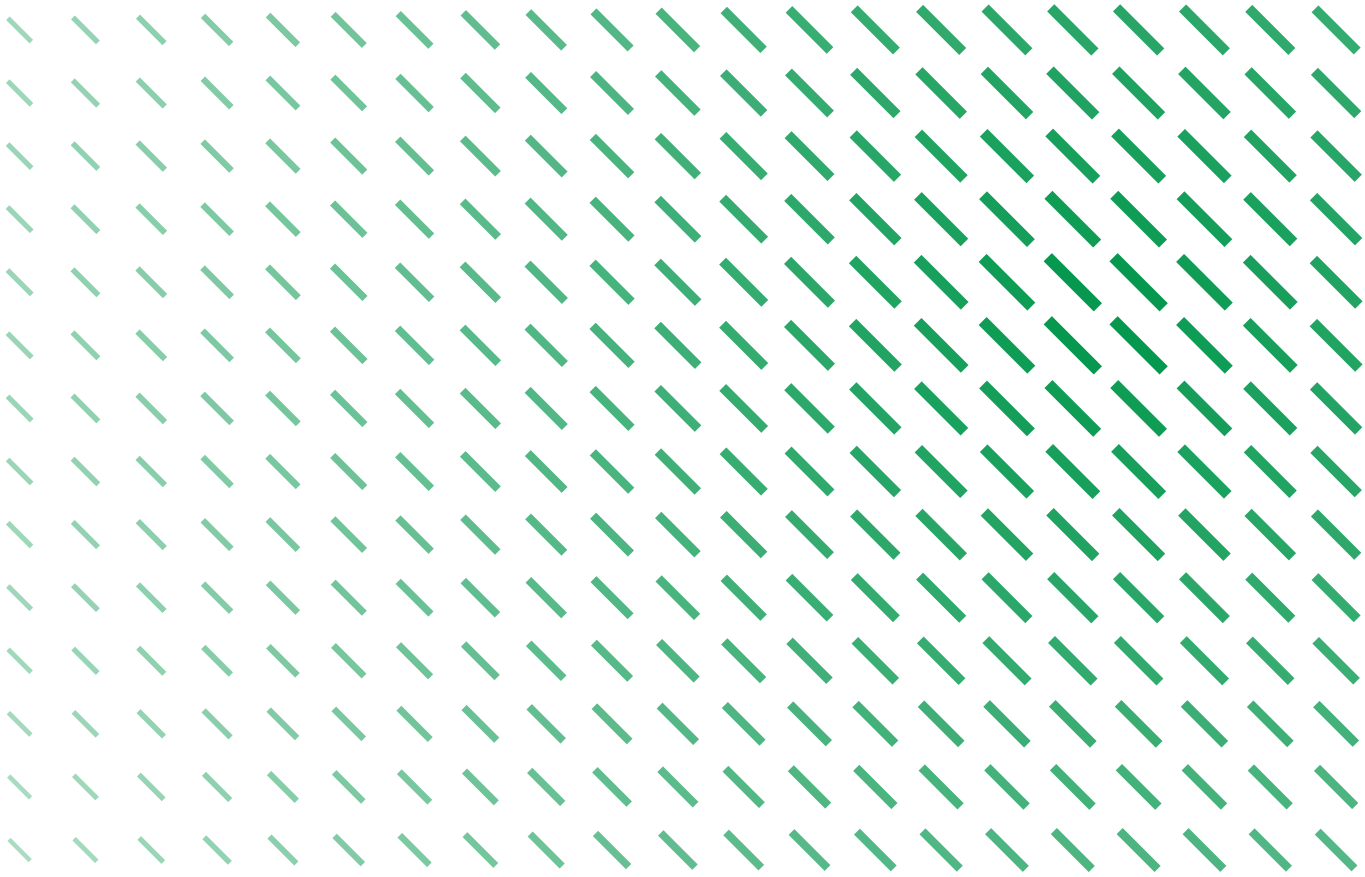
DISCUSSION PAPER

Critical Currents:
Mapping Manufactured Criticality in Transformer Supply Chains

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Key Points

- Power transformers enable voltage conversion and are essential to electricity transmission, distribution, grid expansion, and system resilience.
- Global transformer demand grew by approximately 23% between 2019 and 2024, while nameplate capacity expanded by less than 5%.
- Transformer lead times have tripled, prices have surged, and import dependence has intensified across major economies.
- Energy-system vulnerability increasingly reflects not only fuel and resource supply but also concentrated, specialized manufacturing capacity.
- Grid resilience requires policymakers to look beyond resource availability to manufacturing bottlenecks that can constrain critical equipment supply.

Abstract

Transformers are essential for delivering electricity from generation to consumers, and their production relies on specialized grain-oriented electrical steel (GOES) made from high-purity ferrosilicon. However, their supply chain is struggling to meet accelerating demand. Rystad Energy's analysis of 324 power transformer manufacturing facilities across 51 countries, operated by 196 manufacturers, finds that demand has grown 23% since 2019, while nameplate capacity has increased by less than 5%; average prices for imported units rose 41% from 2020 to the second quarter of 2024. This paper uses qualitative supply-chain chokepoint analysis, drawing on trade statistics, price data, capacity estimates, technical literature, policy documents, and secondary patent literature. It argues that current supply pressures reflect structural features of transformer production that constrain effective supply beyond cyclical disruption. Producer concentration, specialized manufacturing capabilities, qualification barriers, and technological lock-in constrain supply at different points in the chain. Applying the manufactured criticality framework, the paper shows how intermediary, quality, and institutional criticalities interact within a single chain: high-purity ferrosilicon constrains GOES production, stringent GOES specifications narrow usable material, and qualification requirements restrict admissible suppliers. Greater reliance on scrap-based steelmaking may further narrow the feedstock window for premium GOES. These vulnerabilities are compounded by data opacity, with production volumes, capacity utilization, and grade-specific output rarely disclosed. The findings highlight midstream manufacturing as an overlooked dimension of energy security, critical minerals, and grid resilience.

Keywords: transformers; electrical steel; ferrosilicon; supply chains; manufactured criticality; grid resilience; critical minerals; quality criticality

Introduction

01

As countries pursue their commitments under the 2015 Paris Agreement and their broader net zero emissions (NZE) goals, electrification has become a central pillar of energy transition policy (IEA 2026a). Globally, electricity currently accounts for one-fifth of final energy consumption. However, this share could more than double by 2050, with generation rising from about 30,000 TWh in 2024 to over 62,000 TWh by 2050, representing an average annual growth rate of 2.8% (IAEA 2025).

Falling renewable costs, data-center and industrial-automation demand, and the electrification of fossil-fuel-dependent sectors are accelerating this growth, straining grid infrastructure already adapting to greater supply-side variability (Yeboah et al. 2025).

Modern grids must integrate variable renewables, dynamic loads, and weather-induced shocks while relying on geographically dispersed supply chains, making resilience a matter not only of operational continuity, but also of absorbing structural, technological, and demand-side transformation (van der Vleuten et al. 2013; Garwood 2024). Equipment availability is thus central to resilience: when delivery lead times extend to several years, the supply chain becomes a binding constraint on grid recovery, expansion, and adaptation, making procurement timelines a key determinant of resilience.

1.1 Research Question and Scope

Viewing the grid as an interconnection of physical equipment, rather than an abstract network, reveals systemic stresses that might otherwise be overlooked. Transformers, which convert electricity between voltage levels to transmit and distribute power across network nodes, are indispensable to grid functioning (see Appendix A) and increasingly important for renewable integration, electrification, and network expansion. However, their production is constrained by long lead times, slow capacity expansion, and geographically dispersed supply chains (Kivrak 2019b; DOE 2024b).

> “Transformer supply vulnerabilities extend beyond conventional resource scarcity to concentrated industrial capabilities.

Power transformers comprise laminated steel cores wound with copper or aluminum conductors. These cores require grain-oriented electrical steel (GOES),[1] a specialized alloy produced through proprietary metallurgical processes, which depend on high-purity ferrosilicon. Neither GOES nor high-purity ferrosilicon is a commodity input: both are technically exacting, capital-intensive, and produced using proprietary processes by a small number of facilities globally, creating supply vulnerabilities that extend beyond our conventional understanding of resource scarcity to concentrated industrial capabilities.

Rystad Energy's analysis of 324 power transformer manufacturing facilities across 51 countries finds that end-market demand grew 23% from 2019 to 2024, while nameplate capacity increased by less than 5%, and average nominal prices for imported units rose 41% from 2020 to the second quarter of 2024 (Christoffersen 2025). Despite a partial recovery from their 2023-2024 peak (Table 1), lead times remain more than double pre-pandemic baselines, consistent with a structural shift rather than purely cyclical supply volatility.

These pressures are particularly well documented in the United States, where power transformer demand has surged by 116% since 2019, while lead times have increased from 30.6 weeks pre-pandemic to 128 weeks by mid-2025, and average unit prices have risen by 77% (Thomas et al. 2025). Similarly, U.S. generator step-up transformer demand has grown even faster, by 274%, with lead times now exceeding 144 weeks, or nearly three years (Patel 2026).

These structural issues raise a fundamental question: How do manufacturing constraints, material quality risks, technological lock-in, trade policy exposure, and governance opacity across the ferrosilicon-GOES-transformer chain constrain transformer availability and shape the pace and resilience of electricity system expansion?

For Saudi Arabia, this question has direct relevance. Renewable-energy expansion, grid development, and industrial localization depend on timely access to transformers and related equipment (Pasquali 2026). The scale is substantial, with $293 billion in power and renewable-energy spending projected by 2030, coupled with the expansion of the transmission network to 160,000 km (Arab News 2021; ITA n.d.).

Compared with centralized conventional generation, geographically dispersed wind and solar installations require more grid connection points and associated voltage-conversion equipment, increasing the transformer intensity of electricity-system expansion (Hirschberg et al. 2026). Shortages could affect both project delivery and the resilience of local assembly in the face of upstream dependencies on GOES, ferrosilicon, qualified suppliers, and specialized manufacturing know-how.

Table 1. Average annual lead times for large power transformers.

Time period	Average lead times
2018-2019	~30-60 weeks
2021-2022	~105 weeks
2022-2023	~120 weeks
2023-2024	~190 weeks
2024-2025	~128-143 weeks

Note: Average annual lead times for large power transformers in the United States and selected global markets (averages and ranges from cited sources based on market estimates).

Source: Boucher et al. (2025); IEA (2025).

1 GOES is often referred to as silicon steel and cold rolled grain-oriented steel.

1.2 Electrification, Grid Expansion, and the Emerging Constraint

Addressing this question requires shifting attention from short-term procurement challenges to the structure of transformer supply chains. Unlike traditional energy-resilience debates, which emphasized fuel availability, generation diversity, and transmission networks, emerging vulnerabilities arise from concentrated manufacturing capabilities, processing capacity, and specialized industrial inputs whose substitutability is technically constrained.

This paper builds on the manufactured criticality framework, developed by Laing et al. (forthcoming), and applies it to the transformer supply chain. That framework assesses criticality in terms of effective supply, defined as the quantity of an input usable by a specified application within the required time horizon. It identifies three mechanisms that restrict effective supply: intermediary, quality, and institutional criticality.

1.3 Methodology and Paper Structure

The paper uses qualitative supply-chain chokepoint analysis to trace the ferrosilicon-GOES-transformer chain, drawing on trade statistics, price indices, published estimates, technical literature, policy documents, and secondary patent literature. It examines how concentrated, slow-to-replace industrial nodes create electricity-system vulnerability and uses the manufactured criticality framework as a lens to explain how these risks emerge. The analysis distinguishes observed market constraints (lead times and price increases), inferred structural vulnerabilities (such as qualification barriers and effective capacity limits), and prospective transition risks (such as future GOES demand and scrap-related quality degradation). Data opacity is both a limitation of the analysis and a finding in itself.

Section 2 reviews the literature on grid resilience, critical materials, energy transition materials, transformer markets, and policy responses to identify the missing midstream in existing analyses. Section 3 examines the industrial, trade, and governance conditions shaping transformer constraints. Section 4 examines electrical steel and ferrosilicon as strategic chokepoints, including the quality risks created by scrap-based steelmaking. The conclusion considers the implications for energy-security frameworks and their treatment of midstream manufacturing capabilities.

Box 1. Manufactured Criticality Across the Transformer Supply Chain

Laing et al. (forthcoming) illustrate the three mechanisms through separate cases, including GOES as an example of quality criticality. This paper examines how these mechanisms can co-occur within a single industrial chain. High-purity ferrosilicon illustrates intermediary criticality, because GOES production depends on a specialized upstream input; transformer-grade GOES illustrates quality criticality, because application-specific magnetic and metallurgical requirements narrow the range of usable material; and qualification and supplier-approval processes illustrate institutional criticality because technically suitable products may not be immediately admissible to established transformer supply chains. The chain therefore illustrates three distinct but interacting constraints on effective supply: dependency on a specialized intermediary input, application-specific quality requirements, and institutional barriers to supplier substitution. Greater reliance on scrap-based electric arc furnace (EAF) steelmaking may deepen quality criticality by narrowing suitable feedstocks for premium GOES (see Appendix F).

From Grid Reliability to Industrial Bottlenecks: Reframing Transformer Supply Chains

02

Transformers are highly customized electrical devices that enable voltage conversion through electromagnetic induction and are essential components of electricity transmission and distribution networks, facilitating the efficient transfer of electricity across different voltage levels (see Appendix A). Unlike typical generation assets or modular energy technologies, transformers are tailored to specific operating and environmental conditions and are difficult to substitute across voltage classes.

As a result, transformer failures or supply constraints may not be addressed solely through diversification or rapid replacement (NIAC 2024). Transformer supply disruption can lead to prolonged outages, delayed grid expansion, and deferred connection of new generation and loads (Chopra and Boucher 2024). With accelerating electrification and increasingly time-sensitive grid expansion, transformer availability has become a critical determinant of electricity system resilience.

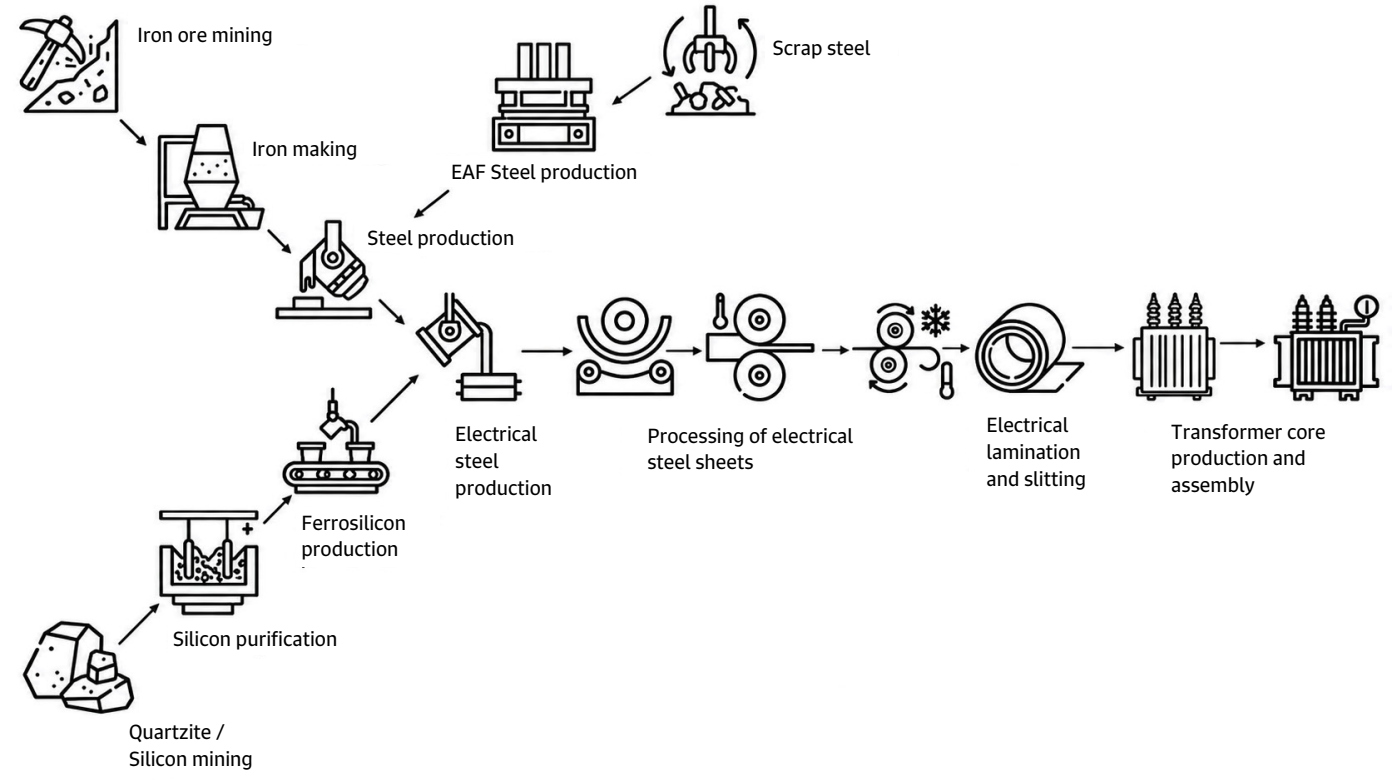
The IEA (2025) estimated that in 2024, approximately 1,650 GW of solar and wind projects in advanced development stages were awaiting grid connections due to a lack of transmission capacity, including transformers. Addressing this issue requires an understanding of how existing analytical frameworks have conceptualized infrastructure vulnerability and why transformer supply chains have received limited systematic attention.

2.1 The Ferrosilicon-GOES-Transformer Process Chain

Figure 1 traces the process chain from raw material extraction to finished transformer assembly. Two independent upstream pathways converge at the electrical steel production stage. The first progresses from iron ore mining through ironmaking and steel production, including scrap-based EAF. The second begins with the mining of quartzite and silicon-bearing ores, which are refined through silicon smelting before being alloyed with iron to produce ferrosilicon.

Specialization begins at the point where the production pathways merge: ferrosilicon is introduced as a precise alloying input into the steel melt, and the resulting material undergoes a series of technically demanding downstream processes (cold rolling, annealing, lamination, slitting, and chemical treatments, among others) before the finished grain-oriented electrical steel (GOES) is ready for transformer core production and further assembly. Each of these midstream processing stages requires proprietary equipment, decades of accumulated process expertise, and capital investment that takes years to build and master (DOE 2024b).

Figure 1. Transformer supply chain.



Source: Author's interpretation.

Note: Transformer assembly is shown as the terminal stage; upstream material inputs other than ferrosilicon and electrical steel are not depicted.

2.2 Literature Review: Grid Resilience, Material Criticality, and Transformer Supply Chains

The literature spans five overlapping strands: grid resilience, critical minerals, energy-transition materials, transformer markets, and government policy. Each addresses part of the problem, but none integrates material dependencies, manufacturing concentration, and geopolitical exposure within a single analytical frame. Table 2 maps the literature and the specific gap addressed here.

Three gaps emerge from this literature. First, transformers remain underexamined as standalone infrastructure assets, treated as generic components of aggregate transmission models rather than as a source of structural vulnerability. Second, transformer-grade GOES is often neglected in critical materials and industrial policy frameworks despite meeting their usual criteria, having only recently been included in the U.S. critical materials list. Third, no existing strand integrates material dependencies, manufacturing concentration, trade exposure, and governance conditions within a single frame, particularly at the scale that accelerating electrification implies. The manufactured criticality framework addresses this conceptually, but illustrates each mechanism separately (Laing et al., forthcoming).

This paper addresses these gaps by tracing chokepoints from transformer assembly through GOES to ferrosilicon. It shows how different forms of constraint can interact and propagate across a single industrial value chain, creating effective supply vulnerabilities that are not apparent from resource availability or nominal production capacity alone.

Table 2. Review of comparative literature and related studies.

Thematic literature	Framework covered	Main findings and relevance
Grid resilience studies: Redefining Resource Adequacy Task Force (2021); Mohanty et al. (2024); Cochran et al. (2015); Khan et al. (2022); Berg and Fritze (2015)	Operational reliability, generation adequacy, grid flexibility, and asset management to ensure system stability under variable renewable integration and evolving load patterns.	Establishes the importance of infrastructure robustness; studies do not examine how manufacturing constraints shape equipment availability or system expansion timelines.
Critical minerals frameworks: Graedel et al. (2015); Ku et al. (2024); Nuss et al. (2014)	Upstream mineral extraction, supply and processing concentration, geopolitical exposure, and substitution limits for resource materials essential to energy technologies.	Provides analytical tools for assessing resource security but focuses exclusively on ores and resource materials; studies do not extend to processed specialty materials or manufactured components like GOES.
Energy transition materials: Valero et al. (2018); Deetman et al. (2021); Collins et al. (2024)	Aggregate material demand projections for energy infrastructure buildout, including steel, copper, and aluminum requirements.	Quantifies material volumes needed for electrification but treats steel as an undifferentiated commodity; does not account for specialized processing requirements or a limited supplier base for GOES.
Transformer market studies: Kivrak (2019a, 2019b); Christoffersen (2025); Aubertin (2019); Hirschberg, Reus, and Schleyer (2026)	Supply-demand dynamics, manufacturing capacity, market forecasting, price evolution, and lead time trends in transformer markets.	Documents supply and capacity constraints with empirical rigor, but provides limited analysis of geopolitical dimensions or commodity governance frameworks.
Government policy reports: DOE (2024b); Nguyen et al. (2022); Kaboli (2025); NIAC (2024); IEA (2023, 2026b)	National infrastructure vulnerabilities, import dependencies, critical infrastructure protection, and domestic manufacturing capability.	Identifies transformer supply constraints as a strategic concern and recognizes GOES as a critical material; provides actionable policy recommendations, but focuses primarily on national solutions with limited attention to global supply chain coordination.
This paper	Application of the manufactured-criticality framework to the ferrosilicon-GOES-transformer supply chain, examining interacting intermediary, quality, and institutional constraints.	Applies the manufactured criticality framework to show how different forms of midstream constraint interact within a single industrial value chain.

Industrial Fragility in Transformer Supply Chains

03

The midstream constraints identified in Section 2 are reflected in the broader challenges facing transformer supply chains and manifest across three interrelated axes.

First, accelerating transformer demand has outpaced manufacturing capacity expansion, creating persistent supply deficits and extended lead times. This comparison is best understood as directional evidence of growing pressure rather than a precise supply-demand balance. Demand growth reflects modeled end-market requirements, whereas capacity expansion reflects estimated nameplate capacity, not realized production (Christoffersen 2025). While grid operators maintain N-1 and N-2[2] redundancy standards for critical infrastructure, extended transformer replacement times may prolong the period during which a system operates with diminished redundancy after a contingency and may increase its exposure to a subsequent failure.

Second, transformer production depends on grain-oriented electrical steel (GOES), a specialty steel produced by a handful of mills concentrated primarily in Japan, South Korea, and China, creating a structural concentration that transformer manufacturing expansion cannot easily bypass.

Third, these material and manufacturing dependencies reconfigure the geography of energy security, extending vulnerability from traditional fuel supply concerns to electrical equipment supply chains (Mishra 2021; Mitchell 2024; Bazilian and Baker 2025).

3.1 Demand Acceleration vs. Manufacturing Inertia

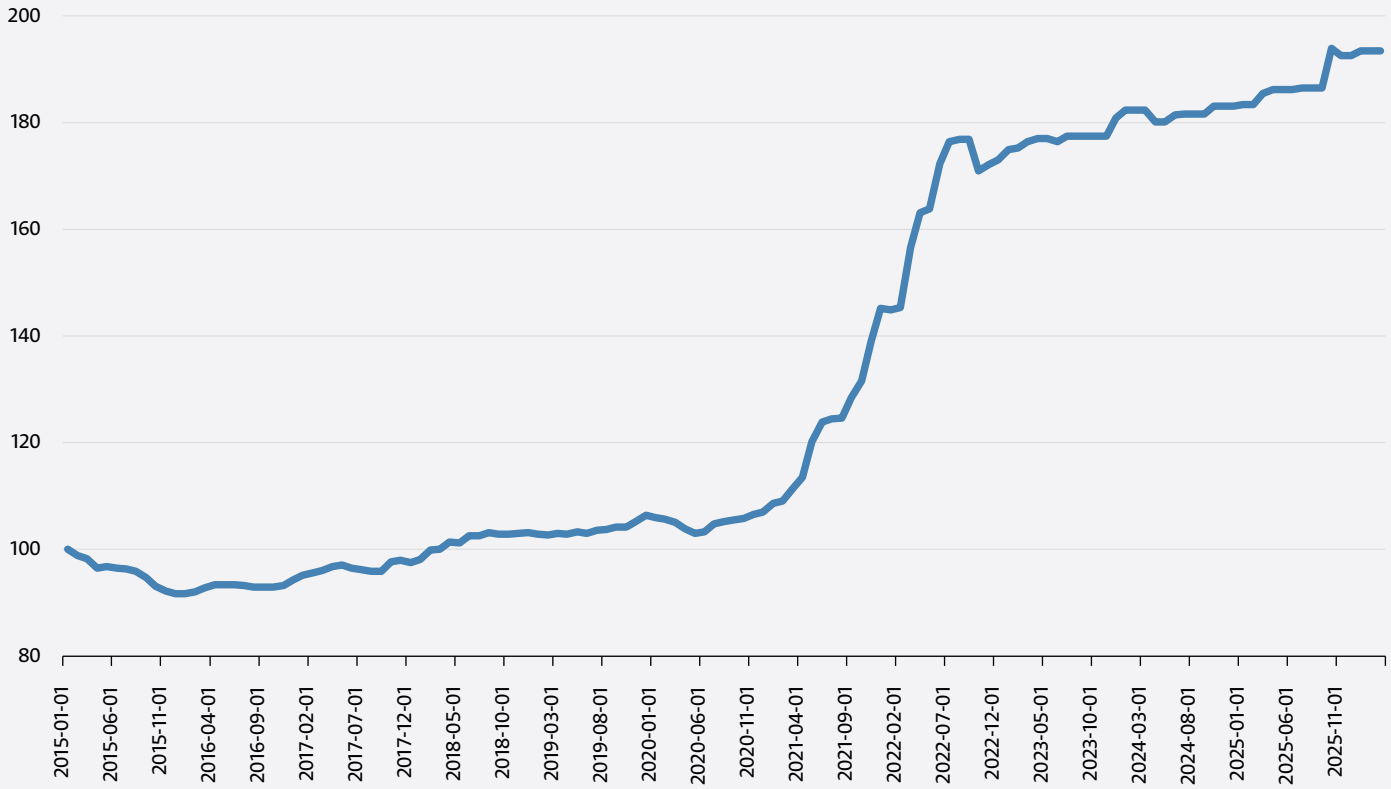
The global transformer market reveals a fundamental mismatch between accelerating demand and constrained manufacturing expansion: between 2019 and 2024, transformer demand grew by 23%, while manufacturing capacity expanded by less than 5%, with post-COVID labor shortages and material constraints further limiting effective production growth (Christoffersen 2025).

Price escalation has accompanied these delays. The figures below reflect U.S. market data, which, alongside European data, provide some of the most consistently disclosed price series globally, illustrating the data opacity that this paper identifies as a structural feature of the supply chain (see Appendix E). Since 2019, unit costs have increased by 77% for power transformers, 45% for generator step-up units, and 78%-95% for distribution transformers in the U.S. market (Thomas et al. 2025).

Precise quantification of the supply-demand gap, however, remains constrained by data opacity: original equipment manufacturer (OEM) capacity utilization rates and production

2 N-1 and N-2 are contingency planning standards in power system reliability engineering. The N-1 standard requires that a power system remain fully operational following the unexpected loss of any single component, such as a transmission line, transformer, or generating unit. The N-2 standard extends this requirement to the simultaneous or sequential failure of any two components and is typically mandated for critical facilities where supply interruption is unacceptable, including hospitals, data centers, and major power plants. Most transmission grids globally operate to N-1 as a baseline, with N-2 reserved for the most critical infrastructure nodes.

Figure 2. PPI by commodity: machinery and equipment: power distribution transformers, except parts (January 2015 = 100).



Source: U.S. Bureau of Labor Statistics (2026).

volumes are not systematically disclosed, meaning aggregate capacity figures rely on facility-level estimates rather than reported data (see Appendix E for a detailed explanation).

Figure 2 shows the U.S. Producer Price Index (PPI) for power and distribution transformers remaining flat through mid-2020, then rising in two stages to nearly double by late 2025, a pattern consistent with structural supply imbalance. However, the price series alone does not disaggregate the contributions of input cost inflation, demand-pull pressure, and supply-side constraints (Chopra and Boucher 2024).

The manufacturing response, while significant, remains insufficient to close these gaps in the near term. Since 2023, manufacturers have announced major investments. Still, these facilities typically require three to five years from groundbreaking to full production, indicating that announced capacity expansion may not reach full production before 2030. Several facilities also remain subject to financing, permitting, and qualification timelines that could cause further delays (NIAC 2024; Barlow 2026; DLS Cold Rolled Grain Oriented Steel 2026). Capacity expansion also faces persistent constraints: skilled labor shortages limit the scaling of production even in new facilities, given the years of training required for specialized winding, assembly, and testing, and manufacturers remain cautious about overcapacity (Christoffersen 2024, 2025).

Table 3. Average annual transformer capacity additions required in NZE Scenario.

Time period	Average annual transformer capacity additions
2012-2021	2,400 GW/year
2022-2030	4,900 GW/year
2031-2040	6,700 GW/year
2041-2050	4,900 GW/year

Note: The IEA (2023) reports transformer capacity additions in GW as a system-expansion metric, while transformer market studies often report equipment demand or shortfalls in megavolt-amperes, GVA, or dollar terms. These measures are not directly interchangeable without assumptions about voltage class, power factor, loading rates, and system configuration. The table is therefore used to indicate the scale and direction of future transformer requirements, not to calculate a precise supply-demand balance.

Source: IEA (2023).

The scale of the challenge extends well beyond the current supply disruption cycle. The IEA's Net Zero Emissions by 2050 Scenario (Table 3) requires average annual transformer capacity additions to more than double from 2,400 GW per year (2012-2021) to 4,900 GW per year through 2030, peaking at 6,700 GW per year in the 2031-2040 decade (IEA 2023). Because the IEA scenario figures and market shortfall estimates use different units and methodologies, they should be interpreted as complementary indicators of pressure on transformer supply rather than as directly comparable measures.

Quantifying the current supply-demand gap precisely remains difficult, reflecting the data opacity that characterizes the sector. Rystad Energy (Christoffersen 2025) estimates that demand growth outpaced capacity expansion by more than 18 percentage points between 2019 and 2024, while Citi Research's supply-demand modeling projects a 2025 annual shortfall of 708 GVA, narrowing but not closing the gap to 292 GVA by 2030 (DLS Cold Rolled Grain Oriented Steel 2026). McKinsey (Hirschberg et al. 2026) projects that accumulated unmet transformer demand in Europe and North America could rise from 1,137 GVA in 2025 to 1,689 GVA by 2030, despite announced capacity expansions and increasing imports. Closing this gap through domestic production alone could require approximately 40 additional capacity-expansion projects and $6.1 billion in further investment (Hirschberg et al. 2026). These estimates suggest that incremental capacity additions may not be sufficient to eliminate accumulated shortages, reinforcing the distinction between nominal capacity expansion and effective supply.

The divergence between these estimates, with Rystad's grounded in facility counts and the other two (Citi Research's and McKinsey's) in demand modeling, reflects the absence of standardized capacity reporting across the industry: neither OEM utilization rates nor grade-specific output volumes are systematically disclosed, meaning all aggregate gap estimates carry methodological uncertainty that complicates both market assessment and policy design. Even if current market estimates point to a narrowing of the near-term supply gap, the manufacturing base will still need to absorb a further step-change in demand, requiring additional investments.

> “Demand for transformers is accelerating over months, while the supply of critical materials, particularly high-grade grain-oriented electrical steel (GOES), responds over years.

However, manufacturing capacity expansion alone cannot resolve transformer supply constraints: production remains constrained by the availability of core materials, particularly high-grade GOES, a dependency that manufacturing investment alone cannot overcome (further examined in Section 4). Demand is accelerating over months, while material supply responds over years. This persistent mismatch reflects long investment cycles, specialized production capabilities, and high barriers to entry rather than resource scarcity.

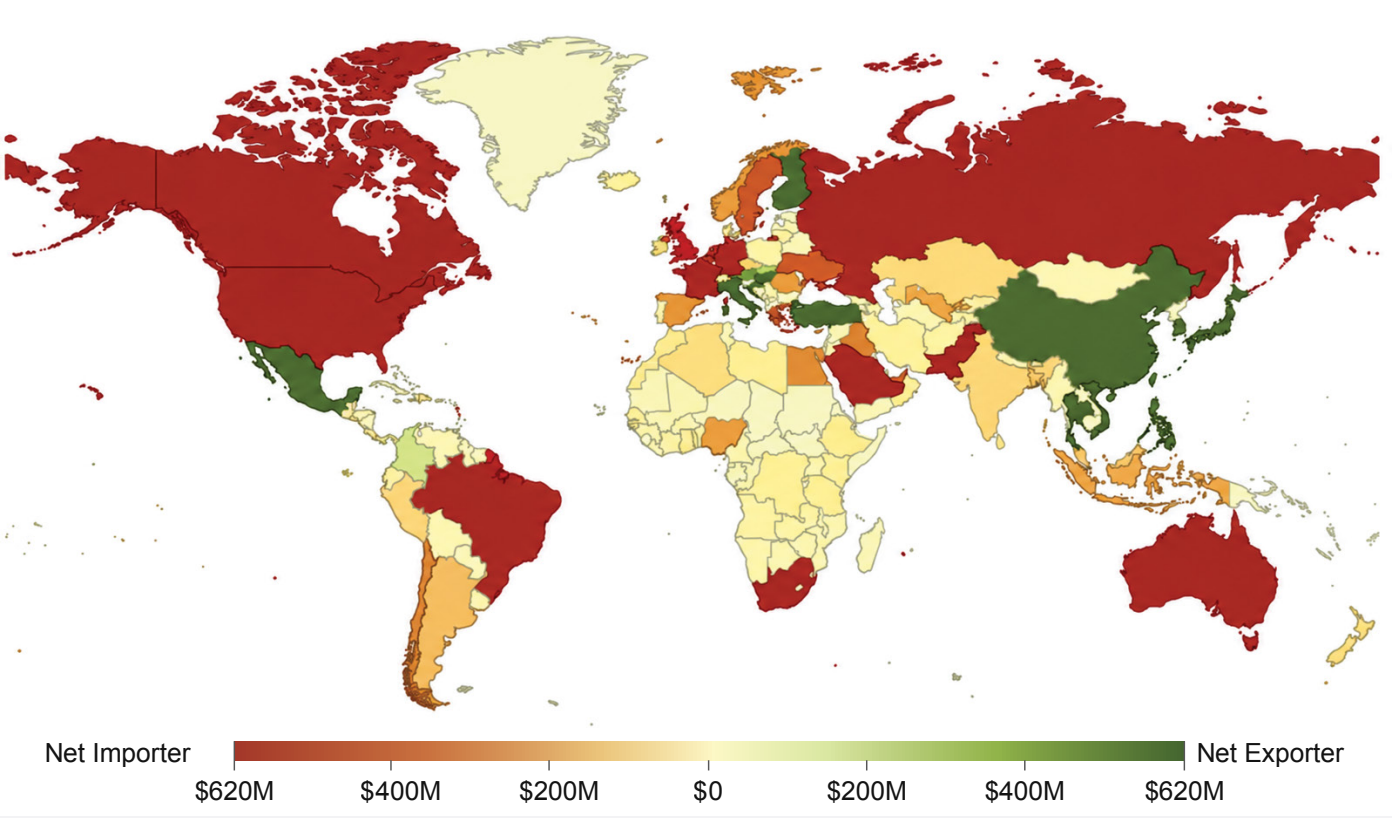
3.2 Trade Dependencies and the New Geography of Energy Security

The geographic concentration of production capacity further compounds manufacturing inertia: the regions facing the fastest demand growth are overwhelmingly dependent on imports from a narrow set of exporting economies. Figure 3 shows the 2024 global net trade balance for electrical transformers.

Trade concentration does not by itself establish vulnerability; its significance arises when import dependence coincides with long qualification periods, limited substitutability, concentrated upstream inputs, and simultaneous demand growth. Export surpluses are concentrated in a narrow group of manufacturing economies, led by China. At the same time, substantial import dependence extends across the U.S., Australia, South America, Africa, and South Asia (IEA 2026b). Except for Mexico, which primarily exports to the U.S., the Western Hemisphere remains deeply import-dependent, highlighting energy security challenges (Sobczak and Behr 2019; Smith 2020).

The U.S. imports approximately 80% of its large power transformers, primarily from Canada, Mexico, and increasingly China (Thomas et al. 2025). Europe collectively occupies a paradoxical position: a net importer by value (approximately $2.3 billion in exports versus $2.5 billion in imports in 2024), yet a key exporter of high-voltage transformers (IEA 2026b). Germany is a net exporter, reflecting its concentration of high-voltage, high-specification transformer manufacturers. At the same time, France and Italy are net importers, relying more heavily on lower-cost imports for volume segments. The

Figure 3. Global trade balance of electrical transformers (2024).



Note: The figure shows the net trade balance.

Source: OEC (2024a).

split between value- and volume-based trade reflects market segmentation, not balanced exchange: European manufacturers dominate high-value, low-volume segments such as large power transformers above 100 megavolt-amperes (MVA), while utilities increasingly procure high-volume distribution transformers from China and Türkiye, where costs are substantially lower (Bloomberg 2026; New Fortune Times 2026).

European transformer manufacturers, even when exporting premium units, depend on imported GOES: thyssenkrupp's approximately 150 kt/year capacity cannot meet Europe's estimated 400 kt/year demand, requiring imports from Japan and South Korea (Transformers Magazine 2025). European anti-dumping duties on Chinese GOES, implemented to protect domestic production, have increased costs for European manufacturers without resolving the underlying import dependency in high-volume segments (T&D Europe 2020; Virchenko 2025; Livraghi and Peereboom 2026; Steven 2026).

This industrial geography differs fundamentally from traditional fuel-based energy security. Transformer markets are characterized by long-term contracts, producer-specific technical specifications, and prequalification processes that can extend over several years for new suppliers (DOE 2012). Nations controlling GOES production or transformer manufacturing expertise possess influence over the pace of global electrification, a dynamic examined further below (Boucher 2025; Howland 2025). However, the trade dependencies documented above exist in the absence of any coordinating governance architecture capable of formally managing them.

3.3 Policy Fragmentation and the Governance Gap in Grid Equipment Supply

Transformer supply-chain governance appears fragmented across procurement, trade, industrial policy, and national-security domains. The policy examples reviewed in this paper suggest that transformer availability is not consistently treated as an integrated strategic constraint. However, transformers differ from ordinary electrical components because they combine system-wide indispensability, limited substitutability, long manufacturing and qualification cycles, limited spare inventories, and dependence on specialized upstream inputs such as GOES and high-purity ferrosilicon. Delays can therefore affect grid expansion, renewable integration, outage recovery, and aging-asset replacement.

Standardization challenges are especially acute in the distribution-transformer segment. The U.S. alone has more than 80,000 varieties of distribution transformers, reflecting utility-specific requirements, regulatory fragmentation, and historical procurement practices that prioritize customization over interoperability (NIAC 2024; DOE 2024a). This increases manufacturing complexity, limits economies of scale, extends lead times, and complicates emergency mutual aid for distribution equipment. While large power transformers face different customization and qualification constraints, the distribution-transformer case shows how fragmented specifications can intensify supply-chain stress.

Policy contradictions further undermine resilience: decarbonization mandates are accelerating demand while trade and domestic-content policies simultaneously constrain supply, as detailed in Section 4. These contradictions reflect a deeper institutional gap: the current global architecture, designed around resource extraction and commodity flows, does not extend to create a market for manufactured components or processing-stage materials, leaving disruptions to be addressed through bilateral or unilateral action rather than coordinated governance mechanisms (DOE 2024b; Walton 2024).

These governance gaps – institutional fragmentation, standardization failures, policy contradictions, and absent international coordination – mean that the systemic fragility documented in this section persists not for want of recognition but for want of an institutional architecture adequate to the challenge.

Manufactured Criticality in the Transformer Supply Chain

04

The transformer supply chain provides a useful application of the manufactured criticality framework because intermediary, quality, and institutional constraints arise at successive stages of the same industrial system. GOES is particularly important because its production sits between upstream ferroalloy inputs and downstream transformer manufacturing. Although electrical steel accounts for only about 1% of global crude steel output, and transformer-grade GOES is a fraction of that, its engineered structure is essential to transformer efficiency (IEA 2023; Long and Pan 2024; WSA 2026). Iron and silicon are abundant, but the specialized manufacturing capabilities, application-specific material requirements, and supplier-qualification processes required to produce and deploy transformer-grade GOES narrow effective supply.

The subsections below examine GOES production concentration and supplier qualification (institutional criticality), transformer-grade GOES (quality criticality), and high-purity ferrosilicon (intermediary criticality), before turning to the know-how and trade-policy conditions that reinforce them.

4.1 GOES Production Concentration and Institutional Constraints

GOES production exhibits a degree of geographic and industrial concentration that exceeds even that of transformer manufacturing, with very few specialized mills worldwide possessing the metallurgical capabilities, proprietary technologies, and capital investment required to produce high-grade GOES at scale. Japan (Nippon Steel, JFE Steel), South Korea (POSCO), and China (Baosteel, others) collectively account for roughly two-thirds of nominal GOES capacity (Table 4). The U.S. retains limited capacity through Cleveland-Cliffs, while Europe's meaningful production is confined to a few producers. Russia historically contributed significant capacity through Novolipetsk Steel (NLMK), but sanctions imposed following Russia's 2022 invasion of Ukraine have complicated its participation in Western markets.

Quantifying this concentration precisely is constrained by data opacity: GOES producers do not publish production figures systematically, and aggregate electrical steel statistics routinely conflate grain-oriented and non-grain-oriented grades, indicating that current GOES capacity estimates carry inherent uncertainty (see Appendix E). The production of high-permeability transformer-grade GOES is rarely reported, further contributing to opacity regarding availability (see Appendix D for GOES grades). Because comparable public capacity data are not regularly updated, the 2020 figures are used here to show the structure of GOES production rather than to calculate current supply availability.

Table 4. Global GOES manufacturing capacity.

Country	Capacity (2020) (kt/year)	Companies (GOES production)
China	1,780	Baowu/Baosteel, Anshan, Beijing Shougang, TISCO, Guangdong Yingquan
European Union	400	thyssenkrupp Electrical Steel (currently not operational), Stalprodukt, ArcelorMittal, Cogne Acciai Speciali
Japan	480	JFE Steel, Nippon Steel
South Korea	300	POSCO
Russia	330	NLMK
United States	300	Cleveland-Cliffs
Other countries	190	Aperam (Brazil), JSW-JFE Steel (India)
Global	~3,780	

Note: Table 4 uses 2020 capacity estimates because updated, comparable, publicly available country-level GOES capacity data are not systematically reported. The figures should therefore be interpreted as indicative of the structure of global GOES capacity, not as current realized output. Subsequent ownership changes, plant outages, utilization rates, product mix, and grade-specific production may alter effective supply availability. This limitation reinforces the paper's data-opacity argument and means that Table 4 should not be read as a precise measure of 2024-2026 supply capacity. JSW-JFE Steel (India) is the current owner of thyssenkrupp's operations in India.

Source: IEA (2023).

Substituting GOES grades or switching suppliers is technically difficult and commercially costly, requiring extended qualification processes, transformer design adjustments, and multi-stage performance testing. This represents institutional criticality: technically suitable material may not constitute effective supply until the producer and product have completed the relevant qualification and approval processes. These requirements constrain supply flexibility even when alternative capacity nominally exists, making approved-supplier lists resistant to rapid expansion.

Each GOES specification requires design qualification, testing, and process adjustment over several months. Even if transformer assembly capacity were expanded, GOES availability could constrain output. Furthermore, transformer-grade GOES production is often not prioritized by steel producers who prefer to focus on non-grain-oriented electrical steel (NGOES) used for motors in electric vehicles (Anton 2022; Berns et al. 2025).

While global GOES nameplate capacity is expected to meet current transformer demand on a tonnage basis, actual usable production is constrained by utilization rates, quality requirements, and the qualification barriers mentioned above. Utilization rates across GOES mills are not publicly reported, meaning the gap between nameplate and effective capacity cannot be precisely quantified from external sources. Investment cycles extend three to five years from facility planning to full production and require substantial capital investments. GOES producers hesitate to expand precisely because transformer demand is historically cyclical: memories of boom-bust consolidation in the 2000s and earlier periods continue to deter capital commitment, even during acute supply disruptions (Aubertin 2018; Kivrak 2019a).

The market consequently exhibits oligopolistic characteristics, with a small number of vertically integrated producers exercising significant pricing power, expanding capacity, and generating margins that reflect market structure rather than production costs alone (Chopra and Boucher 2024; Thomas, Boucher, and Mendrek-Laske 2025; Johnson 2026).

Most crucially, alternatives to GOES remain limited. Amorphous metal cores offer lower no-load losses but are mechanically brittle, comparatively expensive, and cannot yet be manufactured in the sizes required for large power transformers; their adoption is confined to distribution transformers in efficiency-focused markets (Walton 2023a, 2023b; NIAC 2024).

Table 5. Average annual GOES requirement for power transformers (based on NZE Scenario).

Time period	Average annual GOES requirements
2012-2021	3 Mt/year
2022-2030	6 Mt/year
2031-2040	8 Mt/year
2041-2050	6 Mt/year

Note: Because publicly available GOES production statistics remain incomplete and historical capacity estimates are not updated systematically, the historical capacity data in Table 4 and the scenario-based demand projections in Table 5 should be interpreted independently rather than as a direct supply-demand balance.

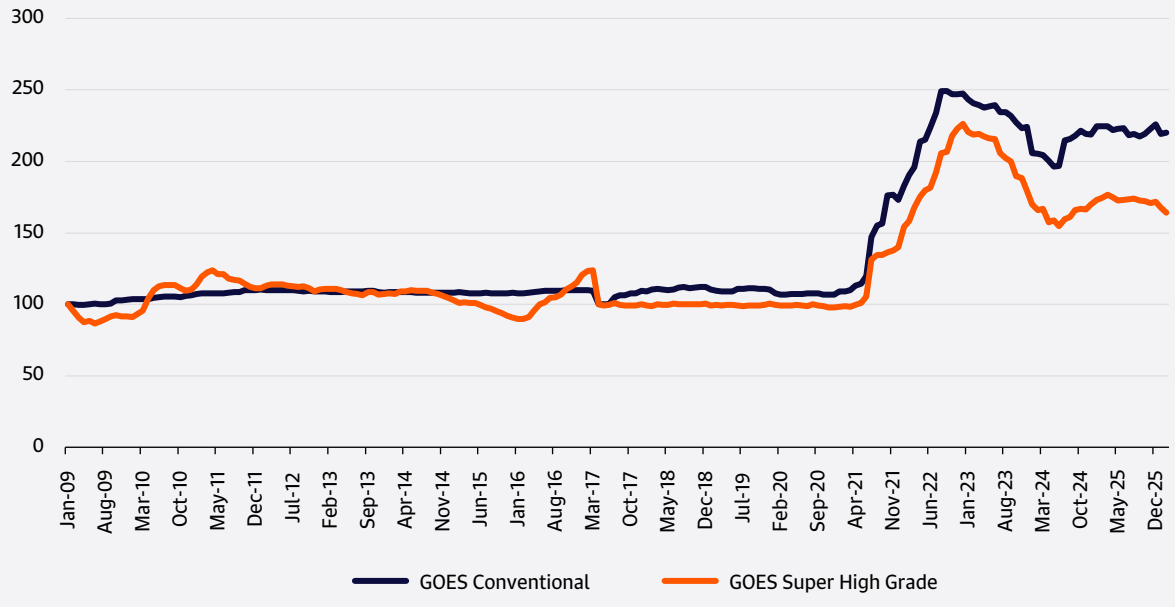
Source: IEA (2023).

4.2 GOES as a Quality Criticality Chokepoint

The demand trajectory for GOES is steep. Under the IEA's Net Zero Emissions by 2050 Scenario, average annual electrical steel requirements for power transformers are projected to double from approximately 3 Mt per year (2012-2021) to 6 Mt per year through 2030, peaking at 8 Mt per year in the 2031-2040 period, before easing to 6 Mt per year as the installed base matures (Table 5).

Figure 4 shows GOES price indices remaining within a narrow band from 2009 to 2020, then rising sharply from mid-2021, with conventional GOES prices doubling and Super High-Grade prices rising further before partially retracing without returning to pre-2021 levels, a pattern consistent with structural supply-side constraints. However, energy input cost inflation, post-pandemic demand recovery, and currency movements represent confounding factors that the price indices alone cannot disaggregate. The sustained failure to return to pre-2021 levels is, however, more consistent with structural than cyclical explanations. Super High-Grade's greater volatility is consistent with tighter supplier concentration at the premium end of the market, where prices respond more sharply to qualification constraints and order-queue dynamics than those of the broader-based conventional grade.

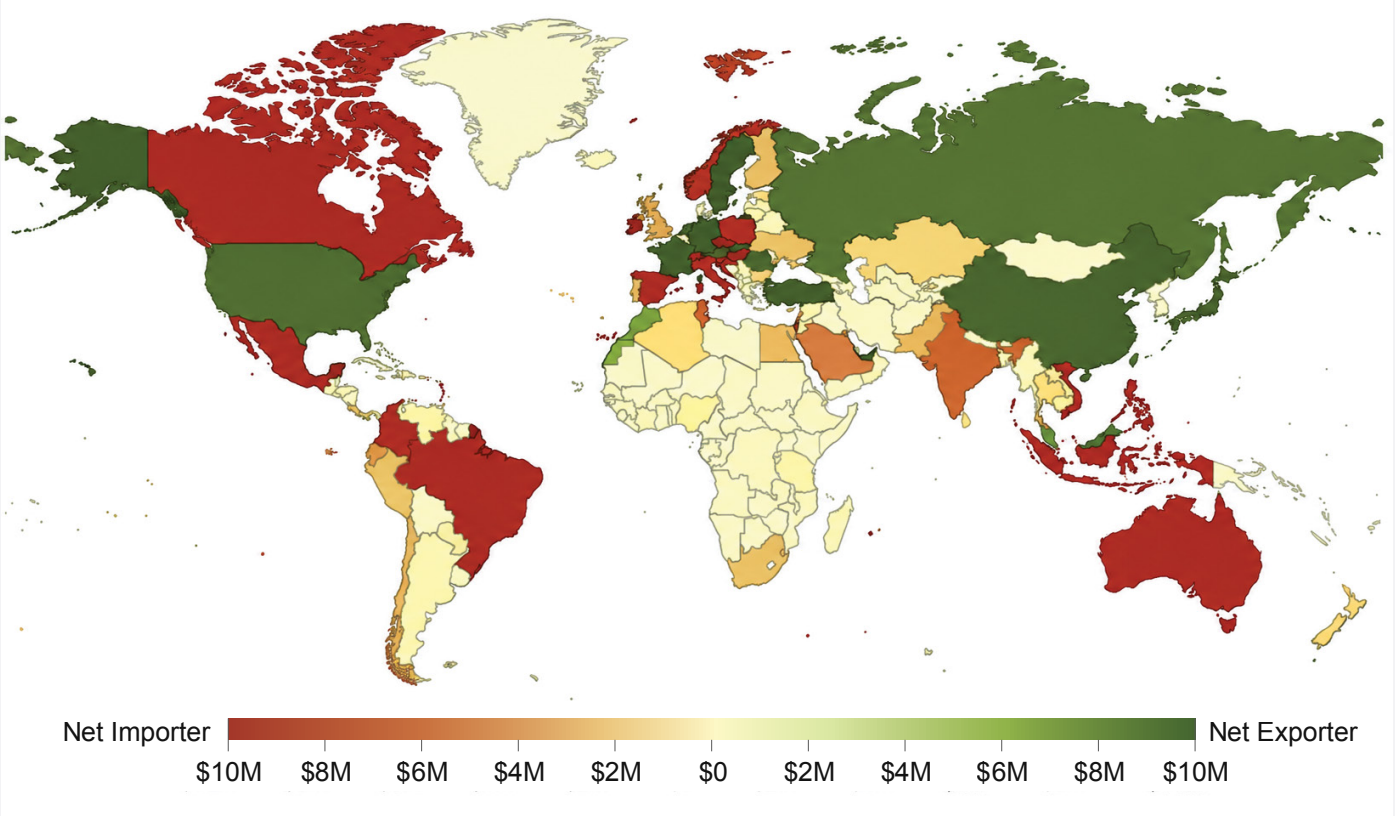
Figure 4. GOES price index.



Source: T&D Europe (2026).

Global trade flows in electrical steel highlight the geographic concentration underpinning this constraint. Figures 5 and 6 map trade balances for GOES in narrow-width (< 600 mm) and wide-width (> 600 mm) categories, respectively. Wide-width GOES is particularly relevant to large transformer-core manufacturing.

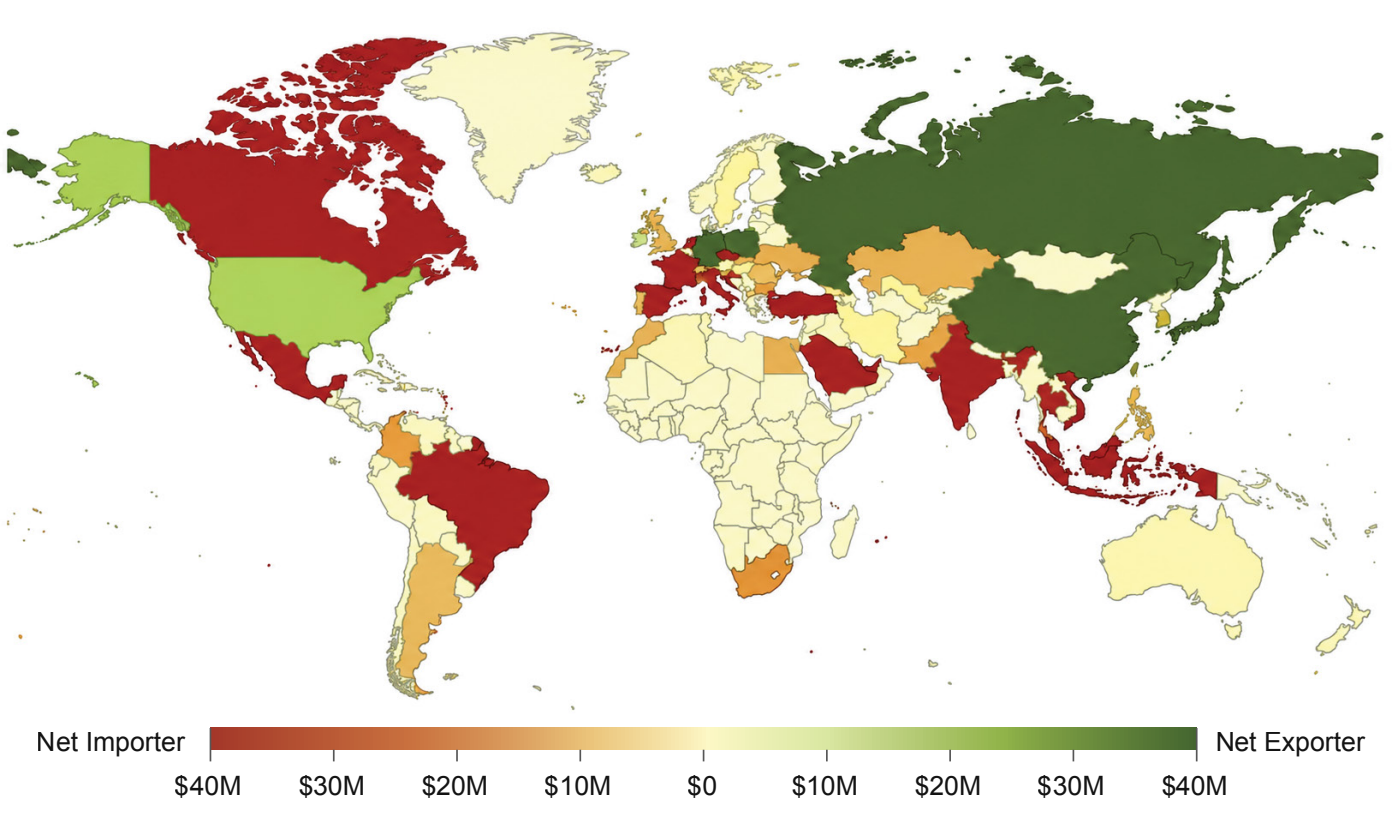
Figure 5. Global trade balance of GOES (width < 600 mm).



Note: The figure shows the net trade balance.

Source: OEC (2024b).

Figure 6. Global trade balance of GOES (width > 600 mm).



Note: The figure shows the net trade balance.

Source: OEC (2024b).

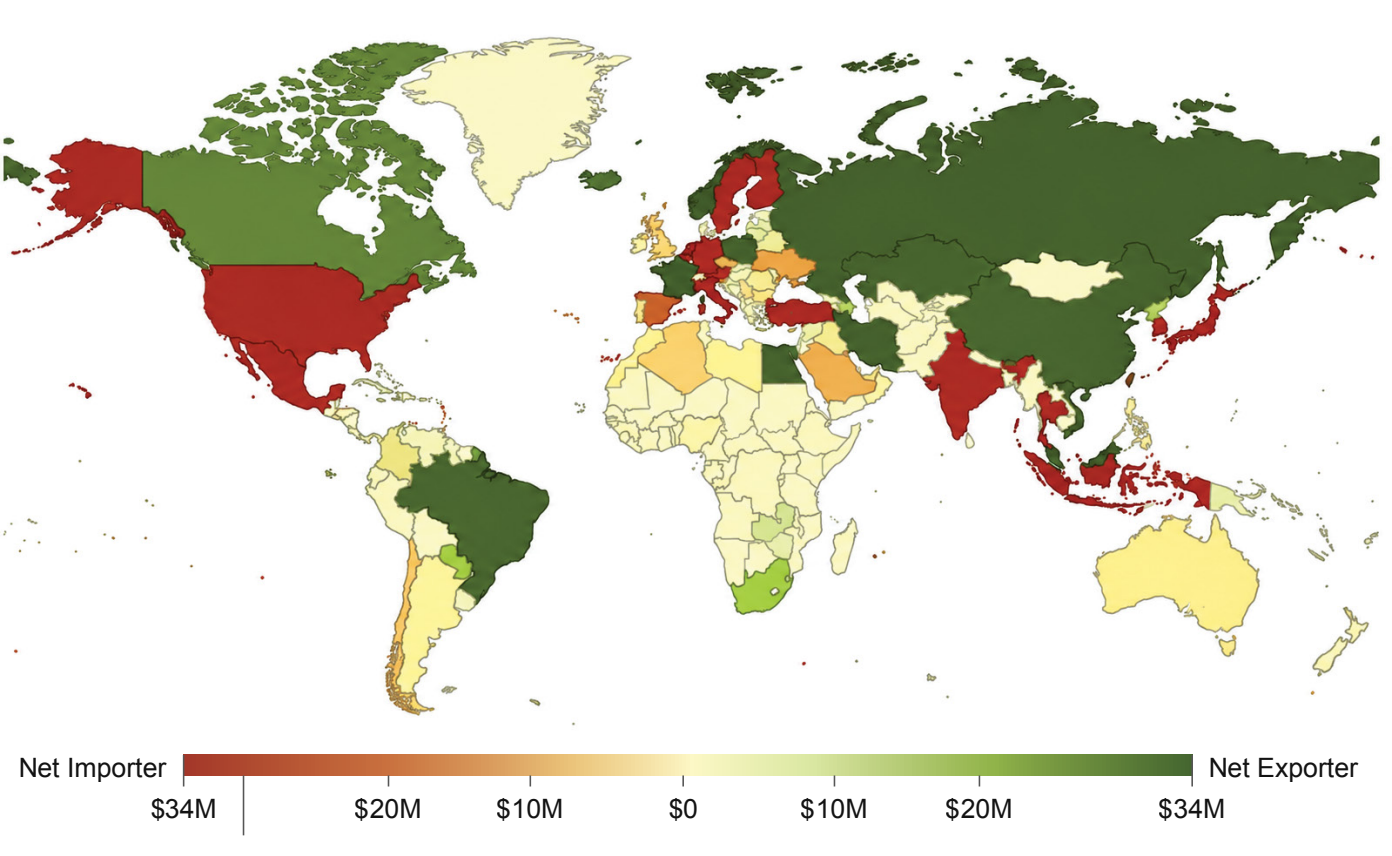
Export surpluses in wide-width electrical steel (Figure 6) are concentrated overwhelmingly in Japan and South Korea, with China remaining a secondary exporter despite its large nominal capacity. Import dependence is deepest across Europe, South and Southeast Asia, and the Americas, precisely the regions experiencing the most acute transformer supply disruptions. The narrow-width trade balance (Figure 5) shows a different geographic pattern, with China more prominent among exporters of GOES below 600 mm in width (Sazzini 2025).

The implication is that transformer manufacturing capacity is not homogeneous: access to narrower-width electrical steel does not guarantee access to the wider grades required for large power transformers. Assembly-stage expansion therefore does not eliminate upstream GOES dependence.

4.3 Ferrosilicon as an Intermediary Criticality Chokepoint

Ferrosilicon represents a form of intermediary criticality within the transformer supply chain because GOES production depends on a specialized upstream input whose supply is also geographically concentrated. Ferrosilicon imparts the electrical resistivity and magnetic properties that distinguish GOES from commodity steel (see Appendix B). At the same time, China accounts for approximately 70% of global production, with Russia, Norway, and Brazil supplying most of the remainder (see Appendix C).

Figure 7. Global trade balance of ferro-silicon, > 55% silicon (2024).



Source: OEC (2024c).

Public statistics do not distinguish high-purity ferrosilicon suitable for GOES production from standard metallurgical grades; Figure 7 therefore uses ferrosilicon containing more than 55% silicon as the closest available trade proxy. Export surpluses are concentrated in China, while the U.S., Europe, Japan, and South Korea remain import-dependent, indicating that major GOES producers are themselves exposed to upstream ferrosilicon concentration. High-purity production is also energy-intensive, requiring approximately 8-11 MWh per ton, reinforcing concentration in regions with relatively low-cost electricity (Mukhambetgaliyev et al. 2020). The result is an upstream dependency that is not visible in conventional GOES capacity assessments.

The ferrosilicon-GOES-transformer sequence therefore demonstrates how manufactured criticalities can interact across successive stages rather than operating as isolated vulnerabilities. Constraints at one stage can propagate downstream, while simultaneous constraints at several stages can compound supply pressure. This cumulative effect is not a separate form of criticality but a consequence of multiple constraints operating within an interconnected supply chain.

India's 2024 certification requirements for GOES imports illustrate how qualification can add a further constraint: reported license-renewal delays contributed to a 30% shortfall, with domestic production meeting only 10%-12% of demand (Srivastava 2024). The case also shows why mitigation is not interchangeable across the chain: transformer stockpiling does not resolve material shortages, GOES diversification does not remove ferrosilicon dependence, and new ferrosilicon capacity faces structural energy-cost constraints.

4.4 Proprietary Know-How, Patent Barriers, and Technological Lock-In

Geographic concentration of GOES production is reinforced by the concentration of formal and tacit know-how. Patent and technology-transfer studies indicate that competitive production depends on specialized process knowledge in texture control, coatings, annealing, and domain refinement,

raising the time and cost required for entry even where equipment and raw materials are available (Taguchi 1977; Takamiya et al. 2016; You and Park 2018). Technology licensing can provide access but may involve significant fees, production limitations, and geographic restrictions (Makman 2012; Saoshiro and Inoue 2012; Kim 2025). These formal, tacit, and equipment-related barriers reinforce the intermediary, quality, and institutional constraints identified above by limiting the speed at which alternative capacity can become operational and qualified.

Beyond formal patents, GOES production depends critically on tacit knowledge: process expertise, troubleshooting capabilities, and yield optimization techniques accumulated over decades of production experience and embedded in organizational routines and personnel. This knowledge cannot be transferred solely through documentation or equipment purchases; it must be developed through operational experience. Even well-capitalized steelmakers with strong cold-rolling and metallurgical capabilities require years to reach consistent, cost-competitive GOES yields.

Equipment procurement adds a further constraint. Precision cold-rolling mills capable of achieving thickness uniformity to within micrometers cost millions of dollars and carry long procurement lead times from a handful of global suppliers (Kellermayr and Westermayer 2016; Haentjes 2018; Hidayat 2026). Incumbent GOES producers often maintain preferred relationships with these equipment suppliers, limiting access for new entrants. International technology transfer faces additional headwinds from export controls on advanced manufacturing equipment and strategic reluctance to enable competitors (Nakamoto and Song 2012; Obayashi and Cho 2015; NSC 2023). A government announcing plans to build domestic GOES capacity faces realistic timelines of several years before achieving operational, quality-competitive production, assuming technical success and an absence of unforeseen complications.

4.5 Trade Conflicts, Policy Misalignment, and Institutional Constraints

Trade policy has increasingly targeted the GOES and transformer supply chain, frequently with effects that contradict energy transition objectives. U.S. Section 232 tariffs on electrical steel imports, initially imposed at 25% in 2018 and extended and broadened in 2024-2025 to include copper, increased transformer costs by 20%-50%, depending on the specification (Rogers 2020; Lee 2025). European anti-dumping measures on Chinese GOES restricted access to a lower-cost supply, while domestic European production remained inadequate to compensate. China, in turn, has discussed export controls on specialty steel and related materials in response to Western complaints of Chinese overcapacity.

Beginning in January 2026, China introduced an export licensing system covering a broad range of steel products, including flat products, ferroalloys, and semi-finished steel (Gemmell 2025). While this does not constitute an export restriction, it establishes an administrative mechanism through which strategically important industrial products can be monitored and, if necessary, regulated. Alongside earlier export controls on gallium, germanium, graphite, antimony, tungsten, and other critical materials, the measure illustrates how strategic oversight is expanding from raw materials toward manufactured industrial products and processing capabilities (Kern 2026).

Most recently, China announced export controls on lithium-ion battery manufacturing equipment and synthetic graphite anode materials under the Ministry of Commerce of the People's Republic of China's Announcement No. 58 (October 2025), which were subsequently suspended following diplomatic pressure but not rescinded, extending the export control logic to clean energy manufacturing technology itself (Lau et al. 2025a, 2025b; MOFCOM and GACC 2025). Collectively, these measures illustrate how supply vulnerability can arise beyond geological resources, extending to manufactured intermediates, processing capabilities, equipment, and production technologies.

These actions reflect legitimate national industrial policy objectives, but jointly create market instability and undermine supply-chain predictability. The structural contradiction is acute: decarbonization mandates, renewable energy targets, and electric vehicle incentives accelerate transformer demand, while import tariffs on raw materials simultaneously raise costs and constrain supply options. Domestic content requirements create analogous tensions across multiple geographies. In the U.S., such provisions have delayed grid projects where domestic transformer capacity has failed to meet procurement timelines (Vock 2024; Jao 2023; Thomas, Boucher, and Mendrek-Laske 2025). India's localization drive has not prevented shortages of GOES, with supply tightness already placing renewable deployment timelines at risk (Srivastava 2024, 2026).

This reflects institutional fragmentation: energy transition goals are set by environmental and energy ministries; trade policy responds to manufacturing competitiveness concerns; procurement policy prioritizes cost optimization. The coordination mechanisms to bridge these domains remain inadequate.

Conclusion

05

Transformer supply chains pose energy-security risks distinct from traditional fuel-supply and generation-adequacy risks. The ferrosilicon-GOES-transformer chain demonstrates how intermediary, quality, and institutional forms of manufactured criticality can interact across successive stages of a single industrial system. Geographic concentration, long investment cycles, limited substitutability, qualification barriers, and specialized manufacturing capabilities can therefore combine to restrict effective supply even where underlying resources and nominal production capacity are available.

Because these constraints sit at different stages, mitigation measures are not interchangeable across the chain: transformer stockpiling does not resolve GOES shortages, diversifying GOES supply does not remove ferrosilicon dependence, and new ferrosilicon capacity remains constrained by energy costs. Demand is accelerating faster than manufacturing capacity and supply chains can respond, contributing to persistent pressures on lead times and equipment availability.

Contemporary brittleness therefore has an additional industrial dimension: it increasingly resides not only in fuel supply but also in industrial capacity whose geographic concentration, technological lock-in, and investment inertia can create new supply-chain chokepoints. Extraction-focused critical-minerals frameworks and operational grid-resilience approaches do not fully capture these forms of supply insecurity. Data opacity compounds the problem by limiting visibility into production volumes, utilization rates, inventories, and grade-specific output.

The policy implication is correspondingly structural, and its difficulty lies less in identifying the required interventions than in the institutional misalignment between them. Energy planning operates on decadal horizons; trade and industrial policy respond to electoral and business cycles; procurement decisions are made on a project-by-project basis. Supply-chain investment in GOES and transformer manufacturing requires multiyear demand visibility that these cycles currently do not provide. These findings point to the need for stronger coordination across domains that are currently governed in isolation.

Energy policy sets decarbonization targets; trade policy governs tariffs and export controls; industrial policy shapes manufacturing investment; financial policy determines which capital structures can absorb long-cycle manufacturing risk; and procurement policy establishes whether utilities face incentives to prioritize supply security over cost efficiency.

> For Saudi Arabia, transformer supply resilience cannot be built through final assembly alone.

The paper does not test specific institutional designs. Instead, it identifies the need for future research on governance mechanisms that could better connect energy planning, trade policy, industrial strategy, finance, and utility procurement in support of transformer supply-chain resilience.

For Saudi Arabia and other import-dependent electricity systems, the implication is that transformer supply resilience cannot be built through final assembly alone. Localization strategies need to account for upstream dependencies on GOES and high-purity ferrosilicon, as well as requirements for testing capabilities, supplier qualification, and long-term procurement visibility.

More broadly, midstream industrial capacity should be treated as an integral component of energy-system resilience rather than an ancillary procurement issue. The transformer case illustrates how electricity-centered systems depend not only on securing raw materials but also on maintaining the specialized manufacturing, quality, and qualification capabilities that convert those materials into deployable infrastructure.

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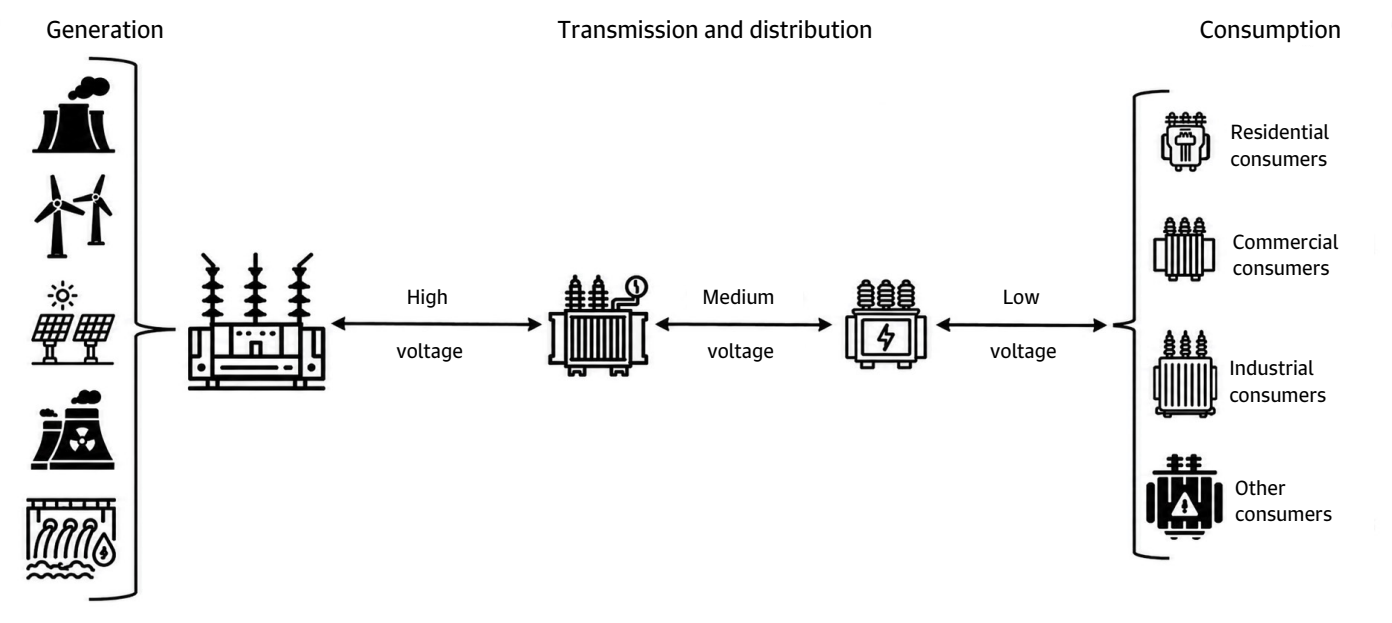
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Appendices

Appendix A. The Materiality of Transformers

The transformer is a static device designed to transfer electrical energy between circuits through electromagnetic induction, serving as an indispensable link between generation, transmission, distribution, and consumption (Figure A1). Its primary function is to step up voltage for efficient long-distance transmission and subsequently step it down for safe distribution and end use. High-voltage transmission minimizes energy losses over long distances, while low-voltage distribution ensures electricity can be used in residential, commercial, agricultural, transportation, and industrial applications (Atwa 2019). Figure A1 illustrates why transformers are present at every stage of the power system, making shortages difficult to localize and easy to propagate.

Figure A1. Transformers' role in the electricity grid.



Source: Adapted by the author from Kuntawong (2024).

Structurally, transformers comprise a magnetic core made of laminated electrical steel (also referred to as silicon steel), an iron-silicon alloy containing roughly 1%-6.5% silicon that increases the steel's electrical resistivity and improves its magnetic properties. This core, together with copper or aluminum windings that conduct electrical current, enables efficient magnetic flux transfer and voltage conversion (Hayakawa 2022). The value of electrical steel lies in its ability to minimize energy losses while maintaining favorable magnetic properties. Higher silicon content, however, increases brittleness and complicates downstream processing. Reducing losses requires the steel to be rolled into thin laminations and coated with insulating films. In some applications, laser scribing is also used to reduce magnetic domain-related losses. These requirements make the manufacturing and processing of electrical steel more technically demanding, especially when producing thinner sheets.

Electrical steel is produced in two primary forms: NGOES, used in rotating machines such as motors, and GOES, designed for static equipment, such as transformers, where its directional magnetic properties are critical for efficient grid operation.

Appendix B. Ferrosilicon Grades (Indicative and Non-Exhaustive)

Table B1. Examples of commercial specifications for ferrosilicon alloys.

	Silicon (%)	Aluminum (% max)	Titanium (% max)	Phosphorus (% max)	Sulfur (% max)	Carbon (% max)	Application
FeSi72	72	2		0.02	0.02	0.2	General steelmaking
Standard FeSi75	75	1.5		0.02	0.02	0.1	Stainless steelmaking
High Grade FeSi	65-75	0.1	0.02	0.035	0.02	0.2	Electrical steelmaking
Low Al FeSi	75-78	0.1	0.03	0.04	0.01	0.07	Electrical steelmaking
High Purity FeSi	75-78	0.04	0.02	0.02	0.003	0.03	Electrical steelmaking
HP FeSi 75	75-77	0.05	0.05	0.015	0.003	0.02	GOES steelmaking
Ultra Low Al FeSi	75-78	0.02	0.02	0.02	0.001	0.02	GOES steelmaking
Ultra-High Grade FeSi90	90	1		0.01	0.01	0.05	High-performance alloys

Note: All values are expressed as percentages by weight.

Source: Elkem (n.d.); Tennant Metallurgical Group (n.d.); IspatGuru (2018); Elsevier (n.d.).

Appendix C. Global Ferrosilicon Production Shares

Table C1. Global ferrosilicon production (%).

Country	2021	2022	2023	2024	2025
China	70	69	70	67	72
Russia	11	11	9	9	9
Bhutan	1	2	2	2	2
Kazakhstan	2	2	2	3	2
Malaysia	2	2	2	3	2
India	1	1	1	1	1
Norway	4	4	3	3	3
Iceland	1	2	1	2	1
Spain	1	1	1	1	1
Brazil	4	4	4	3	3
Other countries	4	3	5	5	2

Note: Country shares are calculated from USGS country-level ferrosilicon production estimates. For 2025, U.S. production was withheld; shares are therefore based on the sum of disclosed non-U.S. country estimates. 'Other countries' aggregates smaller producing countries and the USGS residual category. Figures are estimates and may not total 100% because of rounding. Production data do not distinguish between ferrosilicon grades.

Source: Author's calculations; USGS (2025).

Appendix D. Transformer Grade Electrical Steel Specifications (Indicative)

Table D1. GOES grades for transformer manufacturing (non-exhaustive).

Grade	Iron loss (W/kg)	Thickness (mm)	Use (indicative)
M2 (Higher-Efficiency)	0.90-1.10	0.23-0.27	For higher-efficiency transformer applications
M3	1.10-1.30	0.23-0.27	Power and distribution transformer applications
M4	1.30-1.50	0.27-0.30	Medium transformer applications
M5	1.50-1.70	0.30-0.35	Distribution transformer applications
M6 (Lower-Efficiency)	1.70-1.90	0.35	For less demanding, small transformer applications

Note: Lower core-loss grades are typically used in higher-efficiency transformer designs. Additional grades, such as domain-refined and high-permeability, are also used for transformer applications.

Source: Promisteel (2024).

Appendix E. Data Opacity Across the Transformer Supply Chain

Publicly available data on transformer supply-demand dynamics and GOES manufacturing capacity relative to energy transition requirements remain fragmented, inconsistent, and often opaque. Across the ferrosilicon-GOES-transformer supply chain, limited disclosure of production, utilization, and contractual information, combined with commercial sensitivities and proprietary market structures, constrains transparency. As summarized in Table E1, these data gaps force market intelligence providers and price-reporting agencies to rely heavily on estimates rather than reported figures, reinforcing rather than resolving uncertainty across the supply chain.

Table E1. Summary of data opacity by supply-chain stage.

Supply chain stage	Data gap	Specific limitations	Sources
Transformer manufacturing	Nameplate capacity vs. realized output, impact of capacity utilization	Customization dynamics, variable utilization (utilization declines following boom-and-bust cycles), cumulative transformer numbers in terms of overall volume without segregation	Christoffersen (2025); Aubertin (2016, 2017, 2018); Kivrak (2019a); Maqsood et al. (2023)
Transformer manufacturing	Market size estimation methodology	Differences in dollar-to-MVA conversion introduce numerical variation in transformer market estimates; inconsistent scope definitions across studies prevent reliable comparisons.	Aubertin (2019); Blauvelt and Carlen (2022); Carlen and Blauvelt (2023)
Electrical steel production (GOES/NGOES)	GOES/NGOES production data are not separately reported	Major producers do not publish GOES and NGOES output separately; aggregate electrical steel figures conflate transformer-grade and motor-grade steel, rendering supply assessments inaccurate and reliant on estimates	IEA (2023); WSA (2025); Fastmarkets Pricing Team (2026); European Commission (2022)
Electrical steel grades (GOES/NGOES)	GOES production data are not reported by grade	Premium GOES grades for large power transformers are not reported; no public database tracks their output separately from standard cold-rolled grain-oriented steel	Blauvelt and Carlen (2022)
Ferrosilicon grades	Commodity-grade data conflate standard and high-purity grades	Trade databases and national statistics track ferrosilicon as a single commodity; specific grades required for GOES/NGOES are not publicly reported	USGS (2025)
Ferrosilicon production and offtake	Producer-to-plant supply relationships are not publicly disclosed	Ferrosilicon producers do not disclose customer volumes, grade specifications, and other proprietary details	USGS (2025)

Source: Author's compilation.

Transformer Manufacturing: The Nameplate vs. Realized Output Gap

Nameplate capacity systematically overstates realized output in the transformer industry for structural reasons specific to transformer procurement cycles. Transformers are made to order: each unit is engineered to the customer's specifications, requiring custom core dimensions, winding configurations, and insulation systems. This means that facilities cannot simply run at full capacity when demand is high; order lead times, design and engineering bottlenecks, and specialist workforce availability all constrain actual throughput independently of nameplate production capacity (Kivrak 2019a, 2019b; European Commission 2022).

The gap between nameplate and realized capacity is further influenced by the industry's history of cyclical demand. Following the 2015-2016 renewables-driven investment cycle, OEM capacity utilization dropped to 40%-50% as demand did not sustain the levels that had prompted expansion (Maqsood, Fayyaz, and Sheppard 2023). Two cycles within a decade, including the post-2008 bust and the post-2015 bust, created rational institutional caution. Manufacturers now discount demand signals and are slow to commit to new capacity, even amid currently elevated prices and lead times. Announced capacity expansions should therefore be treated as a ceiling on potential output growth, not a floor (Aubertin 2018, 2019).

A further methodological challenge concerns market size estimation. Transformer market size is typically estimated by applying MVA multipliers to installed generating capacity, a method that introduces significant uncertainty at the distribution transformer level, where the dollar-to-MVA conversion varies depending on assumptions about voltage class and unit size. Scope inconsistencies across studies make cross-study comparisons unreliable without explicit reconciliation, further complicating the reliability of market size estimates.

Grain-Oriented Electrical Steel: The GOES/NGOES Conflation Problem

Publicly available electrical steel production data do not disaggregate GOES and NGOES grades. The two materials serve entirely different end markets: GOES is used for transformer cores, while NGOES is used for motors, generators, and electric vehicle traction systems. They also have distinct supply-chain structures. Conflating them produces data that are unreliable for assessing transformer-grade material availability.

This conflation is pervasive. The World Steel Association's electrical steel production figures, national industry association data, and most commercial market intelligence reports aggregate GOES and NGOES without distinction. The U.S. DOE's 2023 Critical Materials List includes electrical steel as a category covering GOES, NGOES, and amorphous steel collectively (Kaboli 2025), reflecting the same aggregation problem at the policy level.

The problem is compounded at the premium end of the GOES market. The grades required for large power transformers and generator step-up transformers operating at the highest voltage and efficiency specifications are produced using proprietary processes by a limited set of companies. These producers do not publish output volumes for premium grades separately from standard cold-rolled grain-oriented production.

Ferrosilicon: Commodity Aggregation and Grade Invisibility

Ferrosilicon is tracked as a single commodity category in major public databases and national trade statistics. This aggregation obscures a critical quality distinction. Standard ferrosilicon used in bulk steelmaking is a widely traded commodity. High-purity ferrosilicon, the grade required for GOES production, is a specialty product produced by a small number of facilities capable of maintaining the low impurity levels and high silicon purity that GOES metallurgy demands (see Appendix B for grade specifications).

This means that the upstream dependency identified in Section 4 – the requirement for high-purity ferrosilicon as a precondition for GOES production – is invisible in every standard commodity tracking mechanism. Supply relationships between qualified ferrosilicon producers and GOES mills are commercially confidential; no public mapping exists of which producers supply which mills or under what grade specifications.

Opacity as a Governance Challenge

The three layers of opacity documented above reflect a common underlying structure: a supply chain composed of made-to-order manufacturers, proprietary-process materials producers, and specialty input suppliers, none of whom report production volumes and all of whom have rational incentives to limit public disclosure of commercially sensitive information.

The collective effect is a supply chain that is structurally difficult to monitor, model, and govern. Critical minerals frameworks that rely on publicly reported production and trade data are not equipped to capture the quality- and grade-specific vulnerabilities that characterize the ferrosilicon-GOES-transformer chain. Before supply-chain vulnerabilities can be effectively mapped and tracked, the reporting infrastructure needed to make them visible must first be established.

Appendix F. The Decarbonization Paradox: Tramp Elements and the GOES Feedstock Dilemma

The risk described here is a prospective deepening of quality criticality within the manufactured criticality framework: tramp-element accumulation narrows the range of technically acceptable feedstocks and production routes for GOES, without any reduction in the availability of iron or steel. Decarbonization pathways in steelmaking may create a feedstock-quality constraint for high-performance electrical steel production.

Box F1. The Decarbonization Paradox in Electrical Steel Production

GOES manufacturing depends on an exceptionally controlled metallurgical environment, requiring carefully selected steel and tightly managed melt chemistry to maintain extremely low concentrations of residual (tramp) elements. Unlike conventional structural steels, GOES is extremely sensitive to impurities such as copper, tin, chromium, nickel, phosphorus, and sulfur, which can disrupt secondary recrystallization, alter magnetic domain development, and increase core losses. Because these residual elements cannot be economically removed during steelmaking and progressively accumulate through successive recycling cycles, greater reliance on insufficiently segregated recycled steel feedstocks may create an additional constraint on expanding premium GOES production.

As steel recycling, motivated by decarbonization policies, intensifies over the coming decades, a structural tension may emerge between circular economy objectives that promote higher scrap utilization and the stringent feedstock-quality requirements essential for manufacturing transformer-grade electrical steel. Policies encouraging higher scrap utilization may create a feedstock-quality trade-off where residual-element accumulation is not adequately controlled.

Background: Steelmaking Routes and the Decarbonization Imperative

Steel production accounts for approximately 7%-9% of global CO_2 emissions (WSA 2025). The primary production route, the blast furnace-basic oxygen furnace (BF-BOF) process, uses coking coal as both a fuel and a reducing agent and is responsible for the majority of these emissions. The principal decarbonization pathway involves transitioning from BF-BOF to EAF steelmaking, either using steel scrap as feedstock or direct reduced iron.

EAF steelmaking produces approximately one-third of the greenhouse gas emissions of BF-BOF per ton of steel produced (Su 2025). Globally, EAF steelmaking currently accounts for approximately 30% of global steel production and is projected to rise substantially, driven by decarbonization measures (WSA 2025).

The risk operates through several impurity and process mechanisms that may make GOES tolerances difficult to achieve when scrap quality and melt chemistry are not sufficiently controlled.

Tramp Elements: The Irremovable Contaminants

Table F2. Selected tramp element challenges for GOES production via scrap-based EAF steelmaking.

Element	Primary scrap source	Metallurgical challenges	Risk trajectory/Source
Copper	Electric motors, wiring, and appliances	Cannot be removed from molten steel; segregates to grain boundaries; causes hot shortness (surface cracking during rolling)	Increasing as scrap streams become richer in electronic waste, driven by circularity mandates. Over time, recycled material may accumulate more copper as a tramp element. Gramlich et al. (2023); Daehn, Cabrera Serrenho, and Allwood (2017); Qin et al. (2025); Dworak et al. (2022)
Tin	Electronic solder, food packaging tinplate, bearing alloys	Segregates to grain boundaries during annealing; exacerbates hot shortness; interferes with Goss texture development	Increasing as end-of-life electronic scrap volumes grow with accelerating electrification. Gramlich et al. (2023); Daehn, Cabrera Serrenho, and Allwood (2017)
Antimony	Flame retardants in plastics, lead-acid batteries, and specialty alloys	Segregates to grain boundaries during annealing; interferes with grain growth control required for Goss texture	Increasing as flame-retardant use in plastics grows with the proliferation of electronics; shredded scrap streams are becoming increasingly contaminated. Gocnik et al. (2025); Hatzenbichler et al. (2025); Glushko and Schnitzer (2026); Littringer et al. (2026)

Sources: Author's compilation, based on indicated sources.

Copper: The Principal Contaminant

Copper is the most consequential tramp element for GOES production. Unlike most metallic impurities, copper cannot be removed from molten steel through conventional refining, as it is not oxidized by oxygen blowing and therefore accumulates in the steel melt as scrap is recycled multiple times, increasing its concentration with successive recycling cycles (Daehn et al. 2017; Gramlich et al. 2023).

Copper, as an alloying element, can contribute to grain growth and strength when present at certain concentrations (Lobanov et al. 2013; Wu and Zeng 2015). However, uncontrolled residual copper from recycled scrap is undesirable. Copper content in steel scrap in Organization for Economic Co-operation and Development countries already ranges from 0.20% to 0.25% by weight, and from approximately 0.30% to 0.35% by weight in the U.S. (Panasiuk et al. 2022; Sartor et al. 2022). Given the proprietary nature of electrical steel compositions, the actual copper concentrations that might be tolerable for effective application in GOES remain undisclosed. The primary sources of copper contamination are electric motors and wiring in automotive shredder residue, end-of-life consumer electronics, and construction and demolition waste.

The scale problem is compounding rather than static. As electrification accelerates, increasing the number of electric vehicles, motors, and electronic components in manufactured products, the copper content of post-consumer, end-of-life scrap streams is rising. The energy transition that is driving transformer demand is simultaneously degrading the quality of the scrap feedstock used to produce EAF steel.

Tin and Antimony: Slow Creep

Tin and antimony create analogous and, in some respects, more severe problems for GOES specifically. Both are surface-active elements that segregate to grain boundaries during annealing, interfering with the precise inhibitor dissolution and control of grain growth required to produce the Goss texture, thereby affecting the directional magnetic properties of GOES (Gocnik et al. 2025; Littringer et al. 2026).

The sources of tin and antimony contamination are growing. Tin is used extensively in electronic solder, food packaging (tinplate), and bearing alloys; antimony is used in flame retardants in plastics (which contaminate shredded scrap streams), lead-acid batteries, and various alloys.

As the end-of-life scrap stream becomes increasingly electronics-rich, driven by higher electrification rates, faster product obsolescence cycles, and expanding circularity mandates, tin and antimony contamination is rising alongside copper contamination. Stringent end-user tolerances for tramp elements could further constrain steel recycling for applications such as GOES, even with closed-loop recycling. Such issues highlight that decarbonization pathways relying increasingly on scrap-based steelmaking must recognize that not all steel applications have identical metallurgical requirements, a distinction highlighted by Dworak et al. (2022), but not examined in detail in the existing academic literature.

While higher recycled content is appropriate for many products, applications such as transformer-grade GOES require exceptionally narrow impurity tolerances and carefully controlled process chemistry. This trajectory highlights a narrower, more tractable need: grade-segregated scrap collection and tramp-element tracking at the point of recycling, without which GOES-grade feedstock could become scarcer as the broader scrap pool degrades.

About the Author



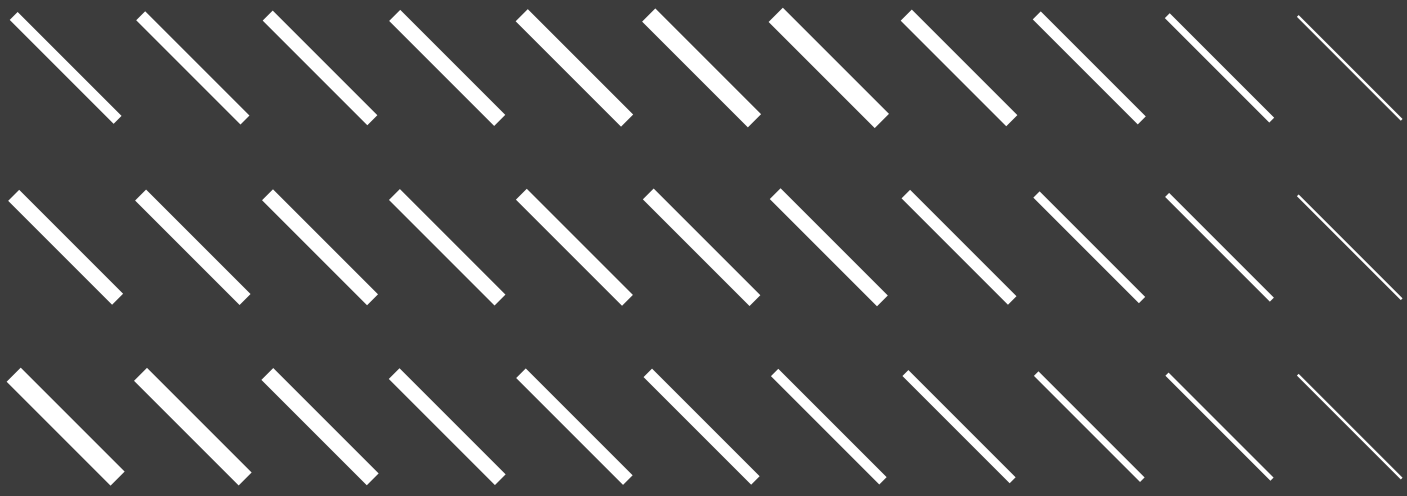
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About the Project

The importance of critical minerals to the deployment of energy transition technologies has been increasingly recognized in recent years. Given Saudi Arabia's plans to integrate renewable energy and low-carbon transportation options into its future energy system, understanding the interactions between technologies and critical minerals is vital. Furthermore, with ambitions to scale up mining, the question arises as to how resources can be best utilized to meet the Kingdom's goals. This project aims to develop literature relevant to both the country and the world in these areas.





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