

U.S. Permanent-Magnet Supply Concentration and the Strategic Potential of Sm–Fe–N: Element-Level Exposure, Bonded-Magnet Substitution, and High-Performance Research Targets

Joshua Chukwuemeka Ejeka | Independent Researcher | ORCID 0009-0005-5885-5073 |
joshuaejeka@gmail.com

Abstract

The United States depends on internationally concentrated supply chains for permanent magnets, but trade statistics rarely distinguish the critical-element content of individual magnet chemistries. We combine U.S. import records for 2015–2025, exporter-reported mirror data, stage-specific rare-earth supply estimates, manufacturer magnetic-property data, and a 20,000-draw Monte Carlo model to assess the strategic opportunities offered by samarium–iron–nitrogen (Sm–Fe–N) magnets. China’s share of U.S. metal-magnet import value increased from 64.7% in 2015 to 72.7% in 2025, after reaching 79.8% in 2023; the estimated trend was 1.54 percentage points per year (95% confidence interval 0.78–2.30). Customs code HS 8505.11 combines several magnet chemistries, so these figures describe supplier concentration for loose metal magnets rather than Sm–Fe–N-specific trade. At equal nominal magnetic energy, commercial bonded Sm–Fe–N requires a median 0.72 times the volume of bonded NdFeB and reduces total rare-earth mass by 146 g per kilogram of incumbent magnet replaced, while eliminating 266 g of Nd and Pr. These gains coexist with an important exposure trade-off: samarium is itself subject to Chinese export controls. A simplified demagnetization model indicates that binder ratings often limit commercial bonded Sm–Fe–N before the modeled magnetic working-point limit, conditional on adequate demagnetization-curve squareness. A separate, explicitly prospective analysis identifies dense anisotropic Sm–Fe–N with an energy product near 300 kJ/m³ and room-temperature intrinsic coercivity of approximately 0.79–1.18 MA/m as a target for high-temperature traction-motor applications; this is not a demonstrated bulk magnet. Estimated samarium contained in current global mine output could theoretically support approximately 29.3 kt/year of bonded Sm–Fe–N, subject to recovery, separation, processing and competing demand. Together, the results identify demonstrated opportunities in bonded magnets and quantify research targets for expanding the role of Sm–Fe–N in supply-chain diversification.

Keywords: Sm–Fe–N; permanent magnets; supply concentration; samarium; bonded magnets; critical elements; anisotropy; traction motors

1. Introduction

Permanent magnets are essential to motors, generators, actuators, sensors and other energy technologies. Their performance depends on magnetic materials, but their availability also depends on the geography and organization of mineral extraction, separation, alloy production and magnet manufacturing. Rare-earth permanent magnets are especially important because their high magnetic energy product enables compact and efficient devices [1,2].

Samarium–iron–nitrogen (Sm–Fe–N) offers a distinctive materials pathway. Nitrogenation of Sm₂Fe₁₇ produces a phase with strong uniaxial anisotropy and a higher Curie temperature than the parent compound [3–5]. A second family, metastable TbCu₇-type Sm–Fe–N, can exhibit high intrinsic magnetization and anisotropy, although its processing and magnetic properties must be

evaluated separately from those of $\text{Th}_2\text{Zn}_{17}$ -type $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ [5–7]. Unlike NdFeB, these Sm–Fe–N chemistries do not require neodymium or praseodymium in their nominal composition, and they provide a route to reduce reliance on dysprosium and terbium in appropriate applications.

The present study focuses on two connected questions: what advantages can Sm–Fe–N already offer in commercially relevant bonded-magnet applications, and which measurable material properties would make higher-performance applications plausible? It does not attempt a comprehensive ranking of every existing Sm–Fe–N form against all sintered NdFeB grades. That broader comparative feasibility assessment is reserved for separate work. The high-temperature traction-motor case is retained here only to define a transparent research target, not to claim an existing commercial substitute.

II. Data and analytical framework

A. Trade data and interpretation

Annual U.S. import values for HS 8505.11 (permanent magnets of metal) and HS 8505.19 (other permanent magnets) were obtained from UN Comtrade for 2015–2025, together with exporter-reported shipments to the United States for eight major suppliers [8]. HS 8505.11 includes NdFeB, samarium–cobalt, alnico and Sm–Fe–N. It excludes magnets incorporated into imported motors and finished products. Accordingly, the trade analysis describes customs-class supplier concentration, not the country of origin of the rare-earth inputs and not the import share of any single chemistry.

For each year, partner value shares were calculated as 100 times partner imports divided by total imports. The Herfindahl–Hirschman index (HHI) was calculated as the sum of squared percentage shares. The 1,800 benchmark is retained as a descriptive merger-review reference, not as a validated supply-security threshold [9]. Trends were characterized using ordinary least squares, Theil–Sen slopes [10] and Mann–Kendall statistics [11]. Where U.S. shipment weights were imputed, exporter-reported weights and explicitly varied assumptions for suppliers lacking weights were used to explore mass-based shares.

B. Material compositions and exposure

The element-level model considers Nd+Pr, Dy+Tb, Sm and Co. Published composition ranges and manufacturer datasheets provide critical-element mass per kilogram of finished magnet [12–14]. Stage-level China shares are applied separately for mining, refining/separation and magnet production [2,15–18]. Samarium-specific stage data are not available in the cited sources; samarium is therefore assigned labeled proxies based on broader rare-earth supply estimates. These proxy exposures are scenario indicators rather than measurements of the actual geographic origin of the samarium in individual magnets.

C. Bonded-magnet comparison

The principal substitution comparison is between commercial bonded Sm–Fe–N and bonded NdFeB, evaluated at the same nominal magnetic-energy capacity and at the bonded NdFeB class operating temperature of 120 °C. The model uses manufacturer-reported ranges for remanence, intrinsic coercivity, maximum energy product and density [5,19–22], with 20,000 Monte Carlo draws. Required magnet volume is approximated by the ratio of the incumbent to substitute (BH)_{max} at operating temperature. This is a screening metric, not a complete magnetic-circuit equivalence test: geometry, demagnetizing field, irreversible loss, thermal history and device-level efficiency remain application-specific.

D. Temperature and future-performance targets

Remanence and intrinsic coercivity are modeled as linear functions of temperature using published coefficients. The simplified working-point condition requires the knee field $sH_c(T)$ to exceed $B_r(T)/[\mu_0(P_c+1)]$, with permeance coefficient P_c and knee squareness s . The model neglects external armature fields, complex demagnetization curves and time-dependent degradation. Its comparison with manufacturer operating-temperature ratings is a plausibility check rather than an independent proof of safe operation.

The high-performance scenario is deliberately distinct from the commercial bonded-magnet analysis. A dense, anisotropic Sm–Fe–N magnet with $(BH)_{\max}$ near 300 kJ/m^3 is used as a prospective benchmark, informed by the intrinsic potential of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$. Its modeled coercivity requirements of roughly 0.79 MA/m at $P_c = 2$ and 1.18 MA/m at $P_c = 1$ for the high-temperature traction-motor case are design targets, not measured performance of an existing bulk Sm–Fe–N magnet.

E. Samarium availability

A theoretical material-balance ceiling is estimated using 2025 global rare-earth oxide mine output, a historical 1.97% samarium-oxide share, conversion from Sm_2O_3 to elemental Sm and a range of existing samarium demand [15,23]. The result estimates samarium contained in mined material. It does not establish how much can be economically recovered, separated, refined or delivered to magnet manufacturers.

III. Results

A. Import concentration

The U.S. customs-value share attributed to China for metal permanent magnets rose from 64.7% in 2015 to a peak of 79.8% in 2023 and was 72.7% in 2025 (Fig. 1). The ordinary least-squares trend was $+1.54$ percentage points per year (95% CI 0.78–2.30); the Mann–Kendall trend test gave $p = 0.003$. The value-based HHI was at least 4,123 throughout the period and was 5,364 in 2025. In contrast, the China share of HS 8505.19 declined from 61.4% to 42.9%. These patterns show that the two customs categories have different supplier-concentration histories.

Mirror records suggest that China's estimated share by shipment mass can exceed its share by customs value. Under the central unit-value assumptions, China's mass share was 81.5–87.5% in the six years with usable Chinese export weights. However, the low rest-of-world unit-value assumption yields a share as low as 55.4%. Thus, the mass-based result is sensitive to missing-weight assumptions and should not be reported as a directly observed share.

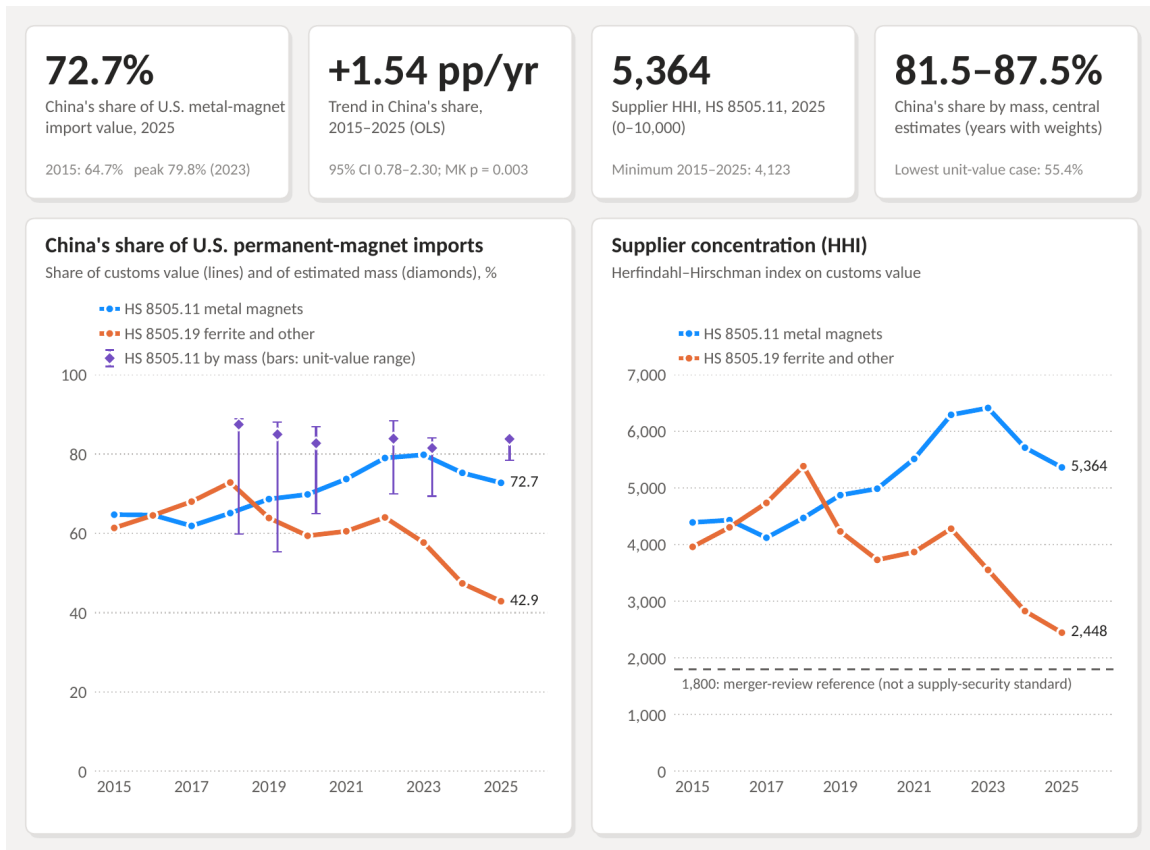


Figure 1. Concentration of U.S. permanent-magnet imports from 2015 to 2025. The top panels summarize the main indicators. The left graph shows China's share of U.S. imports by customs value for HS 8505.11 (metal magnets) and HS 8505.19 (other permanent magnets). For HS 8505.11, estimated mass shares are also shown for the six years with reported Chinese export weights. Diamonds indicate the central estimates, while error bars show the range obtained using different unit-value assumptions for other suppliers. The right graph presents the Herfindahl–Hirschman index (HHI) based on import value. The dashed line at 1,800 is included as a reference from U.S. merger guidelines and does not represent a supply-security threshold. Source: UN Comtrade [8].

B. Advantages of commercial bonded Sm–Fe–N

Commercial bonded Sm–Fe–N contains approximately 208 g of samarium per kilogram of finished magnet in the central model. Its critical-element intensity was estimated at 9.85 g/J of nominal (BH)maxV, compared with 21.14 g/J for bonded NdFeB (Fig. 2). The units refer to the model's normalized magnetic-energy metric, not measured delivered energy in an operating device.

At equal nominal magnetic energy and 120 °C, commercial bonded Sm–Fe–N required a median 0.72 times the volume (90% interval 0.63–0.85) and 0.58 times the mass of bonded NdFeB. For each kilogram of bonded NdFeB replaced, the model estimated removal of 266 g of Nd+Pr, addition of 120 g of Sm and a net reduction of 146 g in total rare-earth mass (90% interval 122–166 g reduction). The estimated reduction in China-refined critical-element content was 145 g. These are model-based comparisons for the specified bonded-magnet class, not universal substitution factors.

Table 1. Comparison of bonded NdFeB and commercial bonded Sm–Fe–N magnets at 120 °C, based on equal nominal magnetic energy. Values are medians from 20,000 Monte Carlo simulations, with 90% intervals shown in parentheses. Changes in elemental composition are expressed per kilogram of bonded NdFeB replaced.

Metric	Bonded NdFeB	Commercial bonded Sm–Fe–N
Critical-element intensity (g/J)	21.14	9.85
Relative volume at equal nominal energy	1.00	0.72 (0.63–0.85)
Relative mass	1.00	0.58
Change in Nd+Pr per kg replaced	Reference	–266 g
Change in Sm per kg replaced	Reference	+120 g
Change in total rare earth per kg	Reference	–146 g

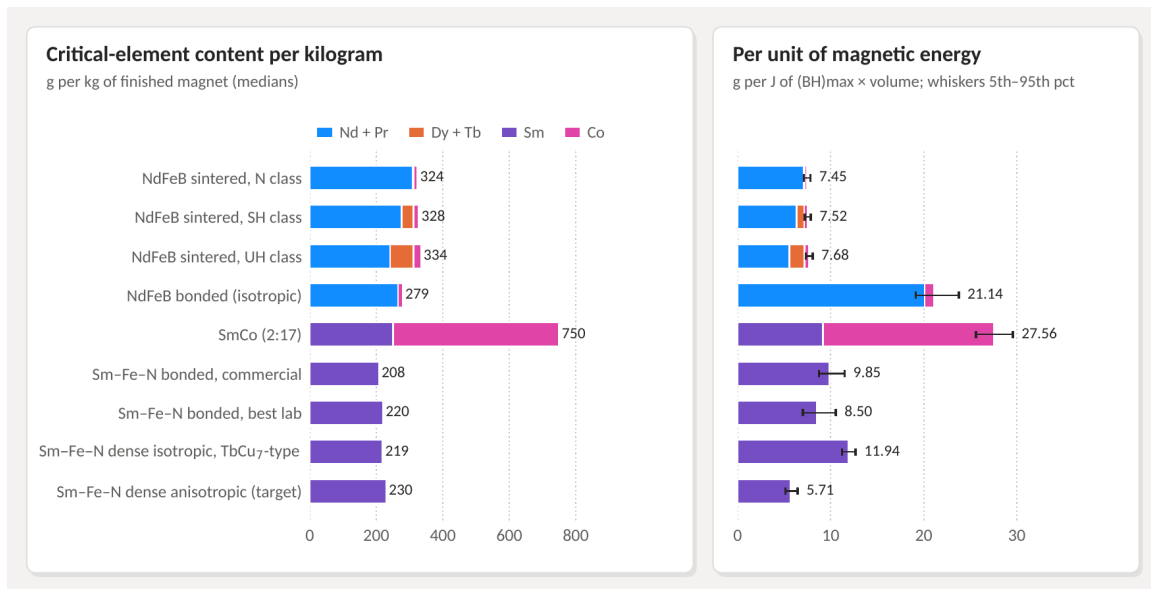


Figure 2. Critical-element content of different permanent-magnet materials, expressed per kilogram of finished magnet (left) and per joule of nominal magnetic energy, calculated as $(BH)_{\max} \times V$ (right). The bars show median values from 20,000 Monte Carlo simulations, with contributions separated by element group. Error bars in the right panel represent the 5th–95th percentile range for total critical-element content. The dense anisotropic Sm–Fe–N magnet represents a proposed performance target rather than an experimentally demonstrated material. Ferrite contains none of the critical elements considered in this analysis.

The compositional shift does not eliminate geopolitical risk. Samarium was included in China’s April 2025 export controls [15,16], so the replacement increases the mass of export-controlled samarium even as it reduces total rare-earth use and modeled China-refined content. This trade-off is central to a balanced supply-chain interpretation.

C. Temperature behavior of bonded grades

The simplified working-point model reproduced the rated temperatures of 11 sintered NdFeB grades [24] with a mean absolute error of 13.7 °C at $P_c = 2$ and $s = 0.9$ (Fig. 3), although the model is not a complete lifetime or irreversible-demagnetization assessment. For commercial bonded Sm–Fe–N grades with sufficiently high coercivity and knee squareness, the modeled magnetic limit can exceed the reported polymer binder rating of approximately 140–160 °C [21]. For example, the model indicates that a grade near 800 kA/m requires a squareness factor of about 0.74 at $P_c = 1$ to remain above the knee at 160 °C (Fig. 4). Since the underlying commercial datasheets generally do not report measured knee squareness, the binder-limited interpretation is conditional and requires experimental confirmation.

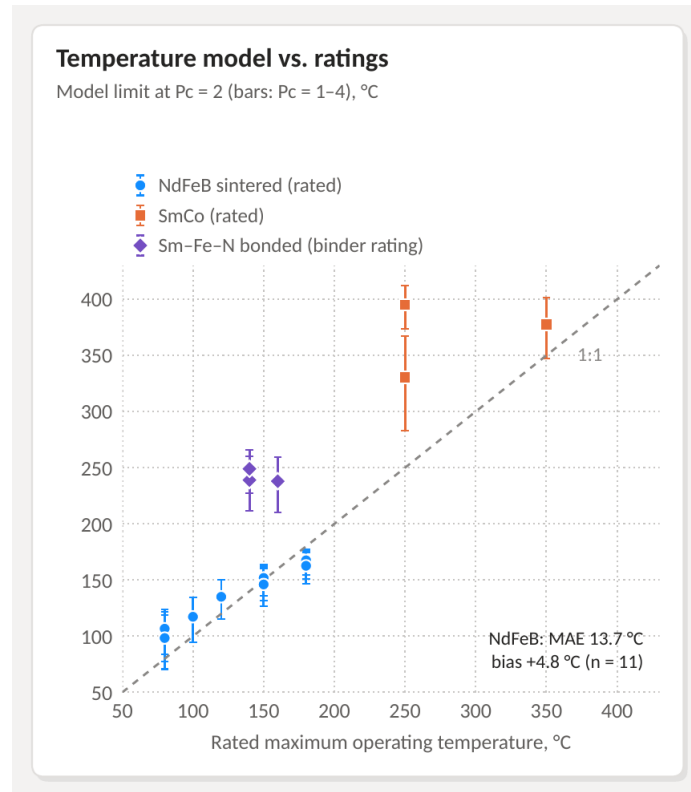


Figure 3. Comparison of modeled temperature limits with manufacturers' maximum operating-temperature ratings for sintered NdFeB [24] and samarium-cobalt magnets [25], and with binder temperature ratings for commercial bonded Sm–Fe–N magnets [21]. Model predictions use a permeance coefficient of $P_c = 2$ and a squareness factor of $s = 0.9$, with error bars showing the results for $P_c = 1-4$. Points above the dashed 1:1 line indicate that factors other than the modeled magnetic working-point criterion may determine the operating-temperature limit. This comparison provides a check on the model's plausibility rather than a complete assessment of safe operating conditions.

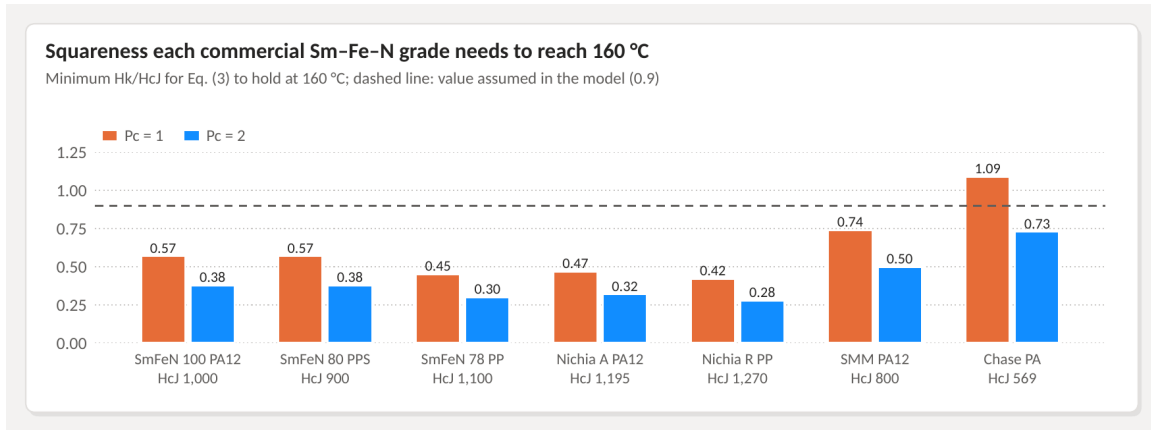


Figure 4. Minimum demagnetization-curve squareness factor ($s = H_k/H_cJ$) required for each commercial bonded Sm-Fe-N grade to satisfy the magnetic working-point condition at 160 °C, the highest binder temperature rating considered. Results are shown for permeance coefficients of $P_c = 1$ and $P_c = 2$. The dashed line indicates $s = 0.9$, the value assumed in the main model. Values greater than 1 indicate that the working-point condition cannot be satisfied by any physically possible squareness factor under the stated assumptions. Measured squareness values are not provided in the manufacturer datasheets. Grade data: [5,21,22].

D. A prospective route to high-temperature traction motors

The intrinsic properties reported for $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ and TbCu_7 -type Sm-Fe-N motivate investigation of dense, textured magnets beyond present bonded grades [4,5,7]. For a hypothetical dense anisotropic material with a maximum energy product near 300 kJ/m^3 , the model gives a relative volume near 0.93 in the 180 °C sintered UH-class benchmark and an estimated reduction of 101 g in total rare-earth content per kilogram of incumbent magnet replaced. The corresponding required room-temperature coercivity is approximately 0.79–1.18 MA/m across the stated load-line assumptions (Fig. 5). These numbers define a conditional target; no bulk Sm-Fe-N magnet with this full property combination has been reported.

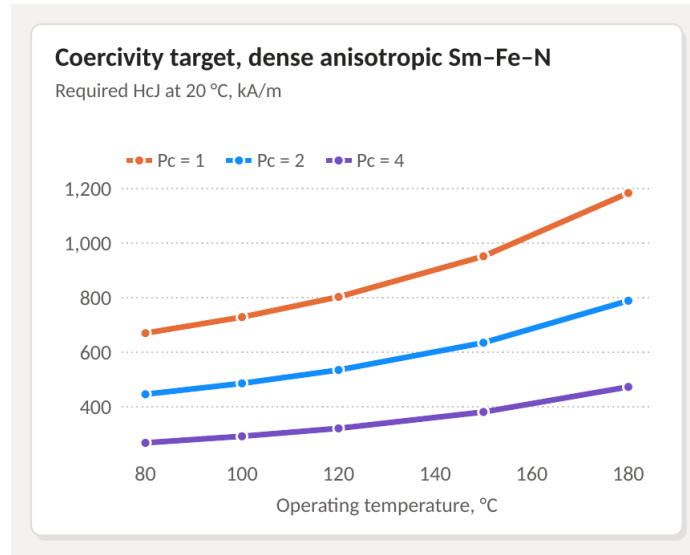


Figure 5. Estimated room-temperature intrinsic coercivity required for a proposed dense anisotropic Sm₂Fe₁₇N₃ magnet to satisfy the magnetic working-point condition at different operating temperatures. The calculations assume a maximum energy product of 300 kJ/m³, remanence of 1.23 T, temperature coefficients of $\alpha = -0.07\%/K$ and $\beta = -0.37\%/K$, and a squareness factor of $s = 0.9$. Results are shown for permeance coefficients of $P_c = 1, 2$ and 4 . These values represent proposed design targets and should not be interpreted as experimentally demonstrated properties of bulk Sm–Fe–N magnets.

Achieving such performance would require concurrent control of phase stability, interstitial nitrogen uptake, crystallographic texture, grain size, intergranular phases, density and coercivity. The metastable TbCu₇-type pathway is scientifically relevant because high intrinsic magnetization and anisotropy have been reported, but extrapolating thin-film intrinsic properties to dense bulk magnets remains an unresolved materials challenge. The 300 kJ/m³ scenario is therefore presented as a research roadmap rather than a forecast of commercial substitution.

E. Samarium material-balance opportunity

The model estimates approximately 6,576 t of samarium contained in 2025 world rare-earth mine output, existing demand near 490 t and a nominal surplus near 6,076 t. At the assumed samarium fraction in bonded Sm–Fe–N, this corresponds to a theoretical ceiling of about 29.3 kt of bonded magnet production per year (Fig. 6), equivalent to roughly 21% of current global rare-earth magnet tonnage [1]. This is a contained-metal upper bound. Actual deployment would depend on ore composition, samarium recovery, separation capacity, competing uses, fabrication yields, economic incentives and the location of processing infrastructure.

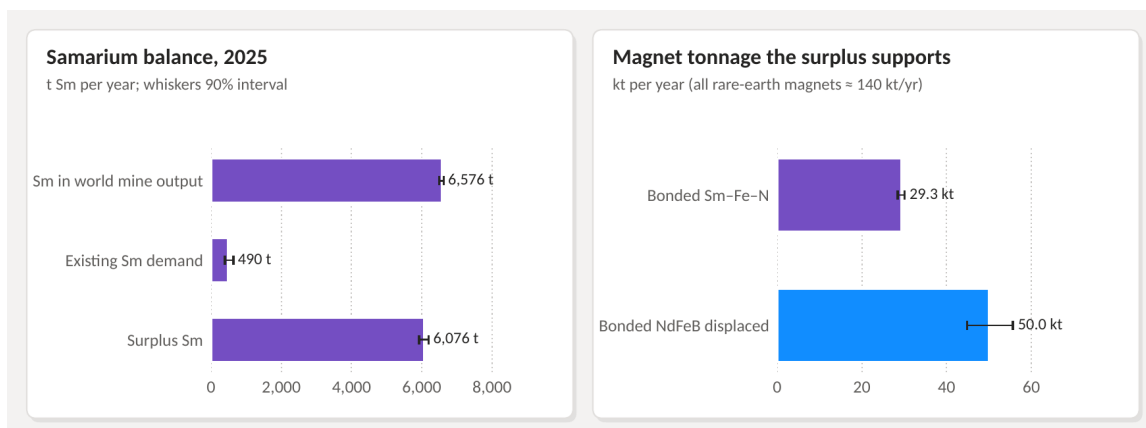


Figure 6. Estimated samarium availability and its potential contribution to bonded-magnet production. The left panel compares the samarium contained in global rare-earth mine output in 2025 with estimated existing demand and the remaining nominal surplus. The right panel shows the amount of bonded Sm-Fe-N that this surplus could theoretically support and the corresponding quantity of bonded NdFeB it could replace at equal nominal magnetic energy. Bars represent median estimates, with error bars showing 90% intervals. The calculations use the production-weighted samarium oxide fraction reported for 2010–2014 [23]. The uncertainty intervals account for variations in mine output and existing demand but do not include limitations associated with recovery, separation or competing uses.

IV. Discussion

The analysis identifies two different types of opportunity. First, commercial bonded Sm-Fe-N already offers a quantified materials-efficiency advantage over bonded NdFeB in the specified application class: less magnet volume at equal nominal energy, lower total rare-earth consumption and elimination of Nd and Pr from the substitute chemistry. Second, the intrinsic properties of Sm-Fe-N justify continued research into higher-density, anisotropic forms with the potential to expand the range of applications. The first conclusion rests on reported commercial-grade data and the stated model; the second is a forward-looking research proposition.

These opportunities should not be confused with automatic independence from concentrated supply chains. China's participation in rare-earth separation and magnet manufacture remains substantial [2] (Fig. 7), and samarium itself is subject to export controls. Diversification therefore requires not only alternative magnet chemistry but also viable separation, alloying, powder processing, consolidation and manufacturing pathways.

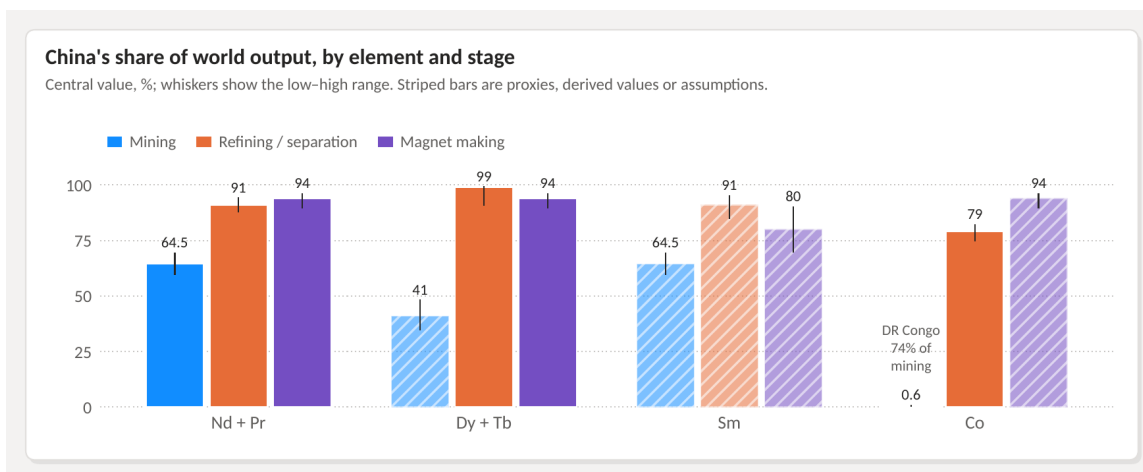


Figure 7. China's estimated share of global production for selected critical elements at three stages of the permanent-magnet supply chain: mining, refining or separation, and magnet manufacturing. Bars show central estimates, while error bars indicate the low-high ranges used in the analysis. Striped bars identify values based on proxies or derived estimates rather than direct measurements. Because samarium-specific data are limited, its shares are estimated using broader rare-earth production statistics. Cobalt differs from the rare-earth elements considered, as its mining is concentrated primarily in the Democratic Republic of the Congo rather than China. Sources: [2,15–18].

A practical research program would report the crystal structure and nitrogen stoichiometry of each powder; measure room- and elevated-temperature Br, HcJ, (BH)max and knee squareness; document texture and density; and test magnetic circuits under realistic operating fields. For metastable TbCu₇-type alloys, processing–structure–property relationships are especially important because the synthesis route can determine phase formation and the eventual coercivity of the magnet.

V. Limitations

The import data combine magnet chemistries and exclude magnets embedded in finished products. Supplier-country shares do not identify the mining or refining origin of constituent elements. Several stage-level estimates, especially those for samarium, are proxies. Mass-based import concentration depends on assumed unit values for partners without measured weights. The bonded-magnet substitution model equates nominal (BH)maxV rather than full device performance, and its temperature criterion assumes a simplified demagnetization curve and uncertain knee squareness. The Monte Carlo intervals reflect the chosen input ranges and do not account for every source of structural uncertainty. The samarium supply estimate is a contained-metal ceiling, not available industrial output. Finally, the dense anisotropic 300 kJ/m³ case is hypothetical and must not be interpreted as demonstrated bulk performance.

VI. Conclusions

U.S. metal permanent-magnet imports remained concentrated over 2015–2025, highlighting the value of material substitution alongside supply-chain diversification. Within the bonded-magnet application studied, commercial Sm–Fe–N offers a model-supported reduction in total rare-earth consumption and can replace Nd+Pr with samarium while requiring less magnet volume at equal nominal magnetic energy. These advantages are meaningful but do not remove exposure to samarium-related export controls or processing concentration.

A distinct long-term opportunity is the development of dense anisotropic Sm–Fe–N approaching 300 kJ/m³, with sufficient coercivity and thermal stability for high-temperature motor duty. That target is not yet a demonstrated magnet. By separating current bonded-magnet advantages from prospective high-performance objectives, the analysis offers a focused basis for materials research and supply-chain planning without overstating the evidence.

Data availability

The datasets, analysis code and interactive calculator supporting this study are publicly available on Zenodo (<https://doi.org/10.5281/zenodo.23486598>) [26]. The project repository is maintained at <https://github.com/johemeks/us-magnet-exposure>, and the interactive calculator can be accessed at <https://johemeks.github.io/us-magnet-exposure/calculator/>.

All quantitative results reported in this manuscript were checked against the archived version 1.0.0 results. Raw UN Comtrade records are not redistributed in accordance with the database's terms of use. Instead, the repository provides a script for retrieving the records and verifying them against the stored data fingerprints.

Use of AI tools

The author conceived the study, developed the research framework, directed the analysis, prepared the manuscript and independently verified the data, code, results and references. Claude (Anthropic) was used as an AI-assisted tool to support the retrieval of publicly available trade data, development of analysis scripts, preparation of figures, reference checking and editorial refinement of the manuscript. All AI-assisted outputs were reviewed and verified by the author, who takes full responsibility for the accuracy, interpretation and content of the work.

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