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# Dysprosium Under Supply Constraint: A Critical Review of Demand Growth, HREE Supply Concentration, Magnet-Efficiency Strategies, Recycling, and the Potential Supply–Demand Gap

**Antonio Clareti Pereira, PhD**
PhD in Chemical Engineering
Federal University of Minas Gerais (UFMG))
Belo Horizonte, Minas Gerais, Brazil
E-mail: claretipereira@gmail.com
ORCID: https://orcid.org/0000-0001-8115-4279

## Abstract

Dysprosium (Dy) occupies a disproportionate strategic position in the rare-earth economy because small additions can sustain the coercivity and high-temperature performance of neodymium–iron–boron (NdFeB) permanent magnets used in traction motors, wind generators, industrial drives, aerospace systems, and other demanding applications. This critical review examines the 2020–2026 literature through a supply–demand lens that explicitly separates geological occurrence, marketable primary supply, midstream conversion capacity, technological Dy intensity, secondary supply, and demand avoided through substitution or redesign. The central argument is that Dy supply risk cannot be assessed from resource tonnage or gross technology deployment alone. Market availability depends on mineralogical deportment, beneficiation and cracking performance, difficult heavy-rare-earth-element (HREE) separation, conversion to qualified metal/alloy and magnet products, geographic concentration, trade policy, and the time required to qualify new supply. At the same time, future demand is endogenous to magnet engineering: grain-boundary diffusion, microstructure control, hybrid magnet concepts, HREE-free magnets, and motor redesign can reduce Dy intensity even as electric mobility and wind capacity expand. Recycling can provide a strategically valuable but temporally delayed secondary stream, with outcomes governed by collection, sorting, magnet access, process choice, separation selectivity, product quality, and loop closure. An integrated accounting framework defines effective demand as gross service-driven demand minus avoided demand, while available supply includes qualified primary and secondary output adjusted for recovery, separation, and trade constraints. The review concludes that the most credible response to the Dy constraint is a portfolio combining upstream diversification, separation/refining capacity, material efficiency, recycling, product qualification, and transparent scenario analysis rather than reliance on any single new mine, recycling process, or substitution technology.

**Keywords:** Dysprosium; NdFeB permanent magnets; Heavy rare-earth elements; Supply security; Grain-boundary diffusion; Recycling.

## Highlights

- Dy risk is governed more by qualified midstream supply than by geological abundance alone.
- Future Dy demand must be modeled with technology-dependent magnet intensity rather than a fixed kg-per-vehicle factor.

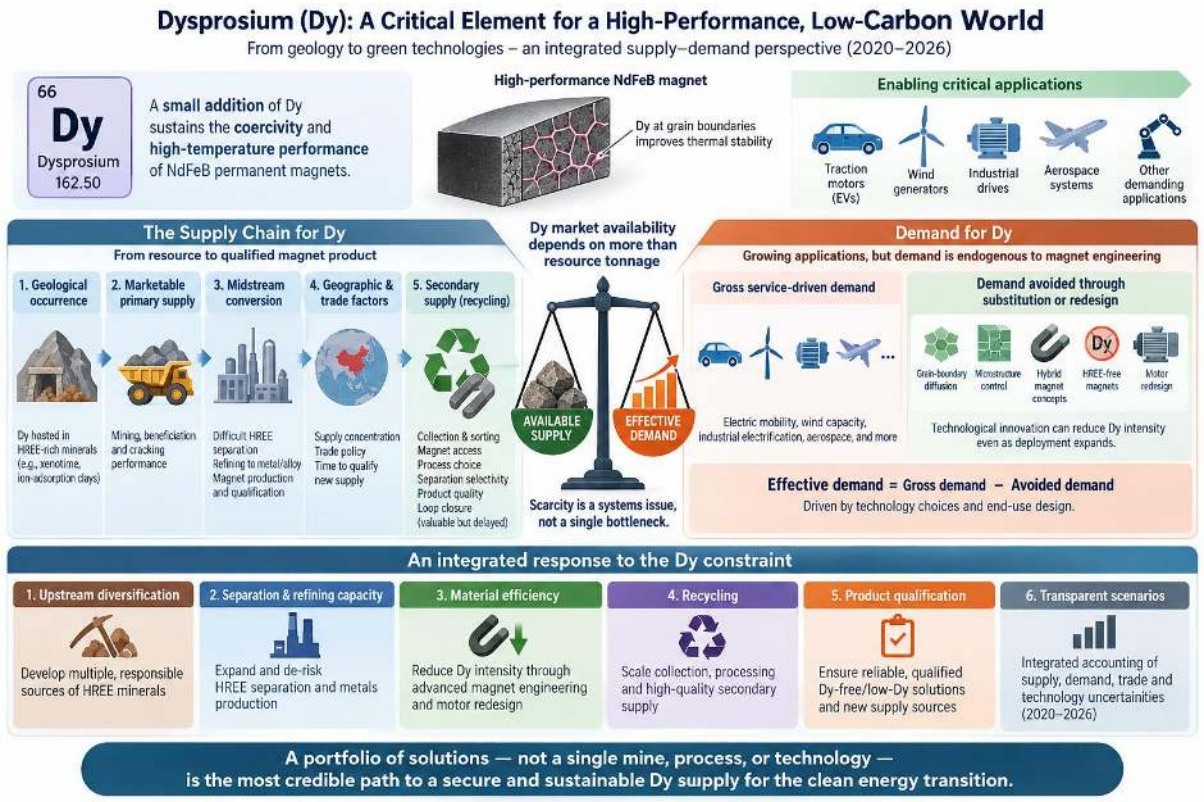
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- Grain-boundary diffusion, HREE-lean magnets, motor redesign, and recycling act as complementary demand- and supply-side levers.
- A portfolio framework integrating primary supply, secondary supply, avoided demand, trade exposure, and qualification risk is proposed.

**Graphical abstract**




## 1. Introduction: Why Dysprosium Is Different from Other Rare Earths

Dysprosium is not the dominant mass component of neodymium–iron–boron (NdFeB) magnets, yet it can determine whether a magnet retains sufficient coercivity at elevated temperatures and under demagnetizing fields. This asymmetry between small material fraction and high functional importance is the first reason Dy should be analyzed separately from aggregate rare-earth-element (REE) markets. The permanent-magnet literature consistently identifies Dy as a material whose strategic relevance is tied to high-performance NdFeB applications rather than to bulk consumption alone (Coey, 2020; Heim et al., 2023; J. Li et al., 2021; Nishino et al., 2022). In parallel, energy-transition studies show that deployment of electric mobility and wind power can amplify exposure to magnet rare earths, while supply-chain analyses emphasize that vulnerability depends on where material is

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processed and transformed, not merely where ore is mined (Alves Dias et al., 2020; Ballinger et al., 2020; Dai et al., 2023; Junne et al., 2020; Klimenko et al., 2021).

The second distinguishing feature is concentration. The 2026 IEA assessment treats Nd, Pr, Dy, and Tb as strategic magnet rare earths and reports that demand for this group doubled from 2015 and will continue to expand toward 2030. It also shows a much higher Chinese share in refining and permanent-magnet manufacturing than in mine production, suggesting the main bottleneck is a chain of conversion capabilities rather than a single geological constraint (International Energy Agency, 2026). This distinction is crucial: a new heavy-rare-earth-element (HREE)-bearing deposit does not immediately create marketable Dy oxide, metal, alloy, or qualified magnet feed. Mineralogy, beneficiation, cracking, leaching, separation, metalmaking, alloying, magnet fabrication, and customer qualification each introduce yield losses, lead times, capital intensity, environmental burdens, and strategic dependencies (Cheng et al., 2024; He et al., 2026; McNulty et al., 2022; Shuai et al., 2024).

A third feature is demand endogeneity. A simple projection that multiplies electric-vehicle sales by a fixed Dy content can materially overstate or understate future consumption because magnet chemistry and motor architecture evolve. Grain-boundary diffusion (GBD) can localize HREE additions where they most improve coercivity, while microstructure engineering, HREE-free magnet concepts, hybrid-magnet machines, and reduced-rare-earth motor topologies can lower Dy use per unit of delivered torque or power (Chang et al., 2026; Chen, 2020; Chen et al., 2026; Cui et al., 2026; Durgun et al., 2026; Hioki, 2023; Kautsar et al., 2025; Khonongbua et al., 2026; Kumar et al., 2026; Liu et al., 2026; Luk et al., 2020; Rangarajan et al., 2025; Tang et al., 2026). Consequently, increasing EV or wind deployment does not imply a proportional increase in Dy demand.

The fourth feature is the interaction between supply security and circularity. NdFeB process scrap and end-of-life magnets contain Dy in a far more concentrated form than most primary ores, but this theoretical advantage is reduced by collection losses, component integration, coating and alloy heterogeneity, demagnetization requirements, sorting, and the need to recover a product that can re-enter a demanding magnet supply chain (Bacchetta et al., 2024; Baghel et al., 2025; Guo et al., 2025; Habibzadeh et al., 2023; Kumari & Sahu, 2023; Mishra et al., 2023; Nayebossadri et al., 2024; Rudnik, 2026; Zheng et al., 2025). Secondary supply

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therefore matters, but its contribution must be evaluated as qualified recovered Dy rather than as gross Dy contained in scrap.

This review adopts the title above because it frames Dy as a constrained system rather than a conventional commodity with an independent supply curve. The aim is to integrate geology, mineral processing, separation, magnet engineering, demand forecasting, recycling, market concentration, policy, and economics within a single accounting logic. The article asks four linked questions: (i) what controls the conversion of geological Dy into market-available Dy; (ii) how rapidly could service demand for high-performance magnets translate into Dy demand under changing technology intensity; (iii) how much can recycling and material-efficiency strategies offset primary supply pressure; and (iv) where do concentration, price, and qualification bottlenecks make nominal supply diversification less effective than it appears.

## 2. Review Methodology and Supply–Demand Accounting Framework

This review is a critical integrative synthesis of literature published from January 2020 through 20 September 2026 rather than a formal PRISMA meta-analysis. The final evidence base comprises 133 unique cited sources and matches the final bibliography. Because the review was not prospectively registered as a systematic review, we did not log database-specific raw hit counts or an exact excluded-record total; we also do not claim a retrospective PRISMA-style flow count. For the revision audit, literature discovery was organized into six Boolean families covering primary supply/resources, separation/refining, gross demand, Dy-intensity reduction and magnet strategies, recycling/secondary supply, and supply-chain/market/geopolitical exposure. Broad discovery used Google Scholar, supplemented by targeted publisher/DOI searches and direct searches of authoritative institutional sources, including the International Energy Agency (IEA), U.S. Department of Energy (DOE), International Monetary Fund (IMF), and the Ministry of Commerce of the People's Republic of China (MOFCOM). We used backward and forward citation chasing from key reviews and Dy-specific studies to identify additional relevant records. Searches were conducted in English; authoritative English versions of institutional or policy documents were used where applicable. Candidate records were excluded when duplicated, outside the review window without a clear foundational role, insufficiently relevant to a Dy-specific bottleneck, superseded by a more authoritative version, lacking traceable technical or market evidence, or

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available only as an unverified preprint. We retained general rare-earth-element (REE) literature only when it informed a Dy-specific bottleneck or a transferable magnet–REE system variable. Table 1 reports the reproducibility audit and evidence-selection rules (Chen et al., 2023; Eheliyagoda et al., 2023; Eheliyagoda et al., 2025; Graedel et al., 2022; International Energy Agency, 2026; Kosajan et al., 2025; Li et al., 2023; Mathur et al., 2024; P. Wang et al., 2024; Wang et al., 2022; Xiao et al., 2022; Zhong et al., 2026).

Table 1. Search strategy and reproducibility audit for the critical integrative review

| Method element | Revised specification |
|---|---|
| Review design | Critical integrative review; no claim of PRISMA systematic-review compliance or meta-analysis. |
| Coverage and final update | January 2020–20 September 2026. Retained older sources only when needed for foundational mechanisms or context. |
| Search platforms | Google Scholar for broad discovery; targeted publisher/DOI searches; direct institutional searches of IEA, U.S. DOE, IMF, and MOFCOM records. |
| Representative Boolean families | (1) (dysprosium OR Dy) AND ("supply chain" OR supply OR demand OR criticality); (2) (dysprosium OR "heavy rare earth*") AND (separation OR refining OR leaching OR "solvent extraction"); (3) (NdFeB OR "Nd-Fe-B") AND (dysprosium OR Dy) AND ("grain boundary diffusion" OR coercivity OR "HREE-lean"); (4) (dysprosium OR NdFeB) AND (recycling OR scrap OR "end-of-life" OR circular*); (5) (dysprosium OR "rare earth*") AND ("electric vehicle*" OR wind OR motor OR generator) AND (intensity OR demand); (6) (dysprosium OR "rare earth*") AND ("export control*" OR concentration OR price OR "supply security"). |
| Language and citation chasing | Searches were conducted in English. We applied backward and forward citation chasing to key reviews, material-flow studies, process papers, and technology studies. We used authoritative English versions of policy documents where available. |
| Eligibility and exclusions | Retained sources had direct Dy relevance or a clearly transferable HREE/magnet-system role and traceable technical or market evidence. Duplicates, non-relevant records, superseded versions, unverified preprints, and out-of-window papers without a foundational role were excluded. |
| Institutional and market evidence | We used authoritative institutional documents for time-sensitive market, policy, and supply-chain claims; we prioritized peer-reviewed literature for technical mechanisms and process performance. Opaque commercial forecasts were not used as sole evidence for scientific claims. |
| 2026 online-first treatment | Advance-online papers were retained only when a permanent DOI and publisher record were verifiable. We rechecked all 2026 advance-online DOIs and institutional URLs cited in the manuscript during the 20 September 2026 audit. |
| Final corpus | 133 unique cited sources, identical to the final bibliography. Raw search-hit and exact excluded-record counts were not prospectively logged and are therefore |

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| Method element | Revised specification |
|---|---|
| | not retroactively invented. |

Note. The table documents the final reproducibility audit used for revision. The review remains a critical integrative synthesis; the 133-source final corpus is the cited bibliography, not a retrospectively reconstructed PRISMA screening count.

Table 2. Evidence architecture for the critical review of dysprosium supply and demand

| Analytical domain | Central question | Preferred indicators | Typical evidence |
|---|---|---|---|
| Primary supply | Can geological Dy become separated, saleable Dy? | Dy grade/deportment; beneficiation recovery; leach extraction; separation recovery; ramp-up | Resource/mineralogy studies; process reviews; project-cost and criticality studies |
| Conversion & separation | Where is Dy lost or bottlenecked after mining? | Stage yield; impurity burden; separation stages; product purity; qualification | Hydrometallurgy; solvent extraction; adsorption; electrochemistry; mixer-settler work |
| Gross demand | How much magnet service is deployed? | EVs; wind MW; motor output; magnet mass per application | Technology-demand forecasts; motor/generator studies |
| Dy intensity & avoided demand | How much Dy is required per unit of service? | Dy wt% in magnet; GBD penetration; magnet mass; substitution share | Magnet microstructure; GBD; HREE-free magnet and motor-design studies |
| Secondary supply | How much recovered Dy actually displaces primary Dy? | Collection; sorting; metallurgical yield; product purity; closed-loop qualification | Short-loop and long-loop recycling; LCA; urban mining |
| Market & geopolitical exposure | Can nominal supply reach the user when needed? | Concentration; trade controls; regional price spread; inventory; elasticity | IEA/DOE assessments; export-control documents; market and resilience studies |

Note. Compiled and adapted from the evidence categories represented by (Chen et al., 2023; Demir et al., 2026; Eheliyagoda et al., 2023; Eheliyagoda et al., 2025; Graedel et al., 2022; International Energy Agency, 2026; Kosajan et al., 2025; Li et al., 2023; Mathur et al., 2024; Nassar et al., 2025; U.S. Department of Energy, 2023; P. Wang et al., 2024; Wang et al., 2022; Xiao et al., 2022; Zhong et al., 2026).

Table 2 makes two methodological choices explicit. First, supply is not equated with resources or mine output. In this review, qualified supply means Dy-containing material that has completed the processing, product-specification, and availability steps required to enter its intended downstream market without depending on conversion capacity that is unavailable to that market. Chemical/product qualification refers to requirements such as oxide purity, impurity limits, metal/alloy composition, physical form, batch consistency, and manufacturability. Customer/component qualification refers to downstream approval of magnets or components for the intended application, including performance, reliability, traceability, and quality-system requirements. A scenario should therefore state the

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qualification boundary being counted—separated oxide, metal/alloy, magnet-grade feed, finished magnet, or approved component. Second, demand does not equal the number of vehicles, turbines, or motors produced. It depends on service deployment, magnet use, magnet mass, and Dy intensity, reduced by substitution and design choices. These choices align material-flow approaches with technology-sensitive demand forecasting and avoid a recurring error in critical-mineral scenarios: treating both conversion yields and material intensity as fixed (Dai et al., 2023; Della Bella et al., 2023; Eheliyagoda et al., 2023; Heim et al., 2023; Mathur et al., 2024; P. Wang et al., 2024; P. Wang et al., 2026).

Equations 1–4 are conceptual accounting identities and a scenario architecture, not calibrated or validated predictive or econometric equations. Quantitative application requires scenario-specific parameterization, empirical calibration where data permit, and explicit uncertainty ranges or probability distributions for high-impact variables such as project commissioning, process recovery, Dy intensity, recycling availability, trade accessibility, and qualification delay.

For year *t*, gross Dy demand can be represented conceptually as (Equation 1)

$$D_{g,t} = \Sigma_i (Q_{i,t} \times m_{i,t} \times d_{i,t}) \quad (1)$$

where $D_{g,t}$ is gross Dy demand in year t [kg Dy y−1 or t Dy y−1]; $Q_{i,t}$ is the deployed quantity of application class i in year t [application units y−1 or MW y−1, as appropriate]; $m_{i,t}$ is average NdFeB magnet mass per application or service unit [kg magnet per unit or kg magnet MW−1]; $d_{i,t}$ is Dy mass per unit magnet mass [kg Dy kg−1 magnet]; and the summation is over application classes i. Harmonize unit bases within each scenario.

Effective demand is then defined as (Equation 2)

$$D_t = D_{g,t} - A_t \quad (2)$$

where $D_t$ is effective Dy demand [kg Dy y−1 or t Dy y−1], and $A_t$ is avoided Dy demand on the same basis. For transparent scenarios, disaggregate $A_t$ into four non-overlapping mechanisms: material-efficiency reduction (including GBD, downsizing, and thermal-management effects), magnet-chemistry substitution, component redesign, and technology substitution. Parameterize the categories separately to avoid double counting and to reflect different adoption rates and qualification constraints.

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On the supply side, available supply is represented as (Equation 3)

$$St = Pt + Rt + It - Lt \quad (3)$$

where St is market-available Dy supply in year t [kg Dy y−1 or t Dy y−1]; Pt is qualified primary supply; Rt is qualified secondary supply; It is the net inventory/trade contribution; and Lt represents processing, specification, trade, logistics, or other losses/unavailable material, all expressed on the same Dy mass-per-time basis. Primary capacity should be traced explicitly as announced capacity → commissioned capacity → operating capacity → recovered separated Dy → qualified marketable product. Secondary supply is cohort- and time-dependent: manufacturing scrap can enter with a short lag, whereas end-of-life (EoL) supply derives from earlier deployment cohorts and product lifetimes. Quantitative implementations therefore require time-lag or cohort functions for collection, recovery, and qualification.

The annual supply–demand balance is therefore (Equation 4)

$$Bt = St - Dt \quad (4)$$

A negative Bt indicates a nominal physical deficit; a positive Bt indicates a nominal supply buffer or surplus; and Bt close to zero indicates a tightly balanced market. These states describe the aggregate physical accounting balance and do not, by themselves, establish supply security because accessibility, product form, qualification, inventories, contracts, logistics, and geographic concentration can prevent nominal supply from reaching a specific user.

Figure 1 formalizes this accounting framework. Its purpose is not to prescribe a single forecast, but to force scenario builders to state assumptions for the supply-conversion chain, qualification boundary, technology-dependent Dy intensity, avoided-demand mechanism, and secondary-supply timing. That is especially important when comparing 2025, 2030, 2035, and 2050 scenarios because upstream project timing, separation/refining capacity, recycling availability, product lifetimes, magnet and motor design, and policy access evolve on different clocks (Dai et al., 2023; Eheliyagoda et al., 2025; Klimenko et al., 2021; Samuel et al., 2026; Savvidou et al., 2026; P. Wang et al., 2024; P. Wang et al., 2026).

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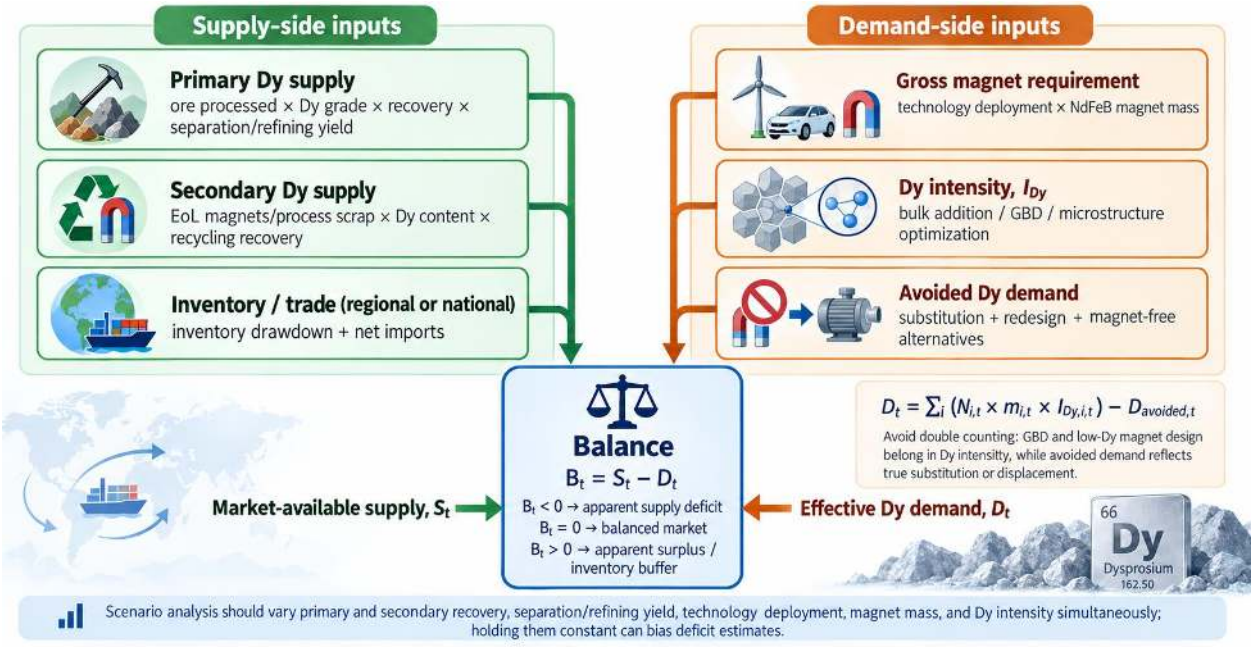



Figure 1. Supply–demand accounting framework for dysprosium.

Note. Conceptually adapted from material-flow, demand-scenario, and circularity approaches in (Dai et al., 2023; Eheliyagoda et al., 2023; Eheliyagoda et al., 2025; Heim et al., 2023; P. Wang et al., 2024; P. Wang et al., 2026; Wang et al., 2022; Xiao et al., 2022).

After Figure 1, the central analytical implication is that a credible Dy scenario should report sensitivity or uncertainty ranges for at least primary-supply commissioning and ramp-up, separation/refining yield and qualification, Dy intensity per magnet and per application, secondary-supply collection/recovery and time lag, and trade accessibility. A forecast that varies only EV sales or only announced mine capacity produces a narrow uncertainty band for a system whose dominant uncertainty is often structural. When numerical forecasting is attempted, propagate distributions or bounded ranges through the accounting identities rather than presenting a single deterministic path.

## 3. Geological Occurrence and Primary Dysprosium Supply

### 3.1 Ion-adsorption clays and regolith-hosted HREE resources

Ion-adsorption clay and regolith-hosted systems are central to the HREE discussion because REEs can occur partly as exchangeable ions associated with clay surfaces rather than only as refractory mineral lattices. Experimental and mineral-systems studies emphasize adsorption/desorption behavior, clay mineralogy, weathering, fluid–rock interaction, and deposit architecture as controls on recoverability (Borst et al., 2020; Russo et al., 2025; Wu et al., 2023). For Dy, this creates an apparent advantage: low-temperature leaching can avoid

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some energy-intensive cracking steps. However, grades may be low, spatial variability can be high, water and reagent management is important, and the environmental burden of in-situ or heap-like leaching can dominate project acceptability (He et al., 2026; Li et al., 2024).

### 3.2 Xenotime, monazite-associated Dy, and hard-rock HREE resources

Xenotime is a valuable HREE host because it can be richer in Y and HREEs than many light-rare-earth-element (LREE)-rich feeds such as bastnäsite or monazite. However, high HREE content does not eliminate processing challenges like liberation, phosphate chemistry, impurity deportment, and separation of Nd–Dy or LREE–HREE. Studies show Dy recovery is a selective-separation issue, and mineralogy impacts whether physical beneficiation can reject gangue before hydrometallurgy (Cheng et al., 2024; McNulty et al., 2022; Takip et al., 2025).

Monazite and mixed hard-rock deposits can supply Dy, often as a minor part of a larger REE mix. This creates a rare-earth balance problem: increasing Dy output also means producing other elements with different demand and prices. Reviews of monazite decomposition highlight the link between cracking, impurity removal, recovery, residue management, and separation (Shuai et al., 2024; B. Wang et al., 2026; Zhao et al., 2025). Complex hard-rock systems can increase HREE resources, but mineral complexity, fine grain size, and multi-element deportment may shift challenges from geology to beneficiation and separation (Pereira, 2025).

### 3.3 From resource tonnage to marketable Dy

Primary Dy supply should therefore be evaluated through a conversion chain rather than a resource table. Table 3 compares the principal occurrence classes using variables that matter for marketability: Dy enrichment mechanism, physical upgrading potential, hydrometallurgical burden, impurity/separation challenge, environmental sensitivity, and likely scale-up constraint (Banerjee et al., 2026; Borst et al., 2020; Cheng et al., 2024; He et al., 2026; Li et al., 2024; McNulty et al., 2022; Russo et al., 2025; Shuai et al., 2024; B. Wang et al., 2026; Wu et al., 2023).

Table 3. Primary dysprosium occurrence classes and their translation into marketable supply

| Occurrence class | Dy occurrence/enrichment | Potential advantage | Main bottleneck | Supply implication |
|---|---|---|---|---|
| Ion- | Exchangeable | Mild leaching; no | Low grade, | Can be strategically |

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| Occurrence class | Dy occurrence/enrichment | Potential advantage | Main bottleneck | Supply implication |
|---|---|---|---|---|
| adsorption/regolith clays | REEs on clays; HREE-enriched weathering profiles | high-temperature cracking for exchangeable fraction | heterogeneity, reagent/water management, environmental control | important if leaching and downstream HREE separation are integrated |
| Xenotime-rich feeds | $YPO_4$ structure with HREE substitution | High HREE proportion relative to many LREE ores | Liberation, phosphate chemistry, impurity control, Nd–Dy/HREE separation | High Dy value per TREO tonne but separation remains decisive |
| Monazite/bastnäsite-associated Dy | Dy as minor part of mixed REE basket | Large established REE resource base | Low Dy share; co-production balance; cracking/residue burdens | More total REE output does not necessarily create proportionate Dy supply |
| **Peralkaline/complex** hard-rock HREE | Multiple HREE-bearing silicates/phosphates and complex associations | Potential new geographic diversification | Fine mineralogy, difficult beneficiation, complex hydrometallurgy | Strategic value depends on recovery to separated Dy, not resource tonnage |
| Secondary/unconventional resources | Dy concentrated in magnets, process scrap, some tailings/residues | High contained grade and potentially shorter project lead time | Collection, heterogeneity, access, sorting, selective recovery | Best viewed as complementary qualified supply rather than a complete substitute for mines |

Note. Compiled and adapted from (Adu et al., 2026; Banerjee et al., 2026; Borst et al., 2020; Cheng et al., 2024; He et al., 2026; Julapong et al., 2023; Li et al., 2024; McNulty et al., 2022; Pereira, 2025; Russo et al., 2025; Shuai et al., 2024; Takip et al., 2025; B. Wang et al., 2026; Wu et al., 2023; Zhao et al., 2025).

Table 3's comparison explains why resource diversification does not automatically diversify supply. A resource may be geologically attractive yet strategically weak if it produces a mixed concentrate requiring separation in an already concentrated midstream. Conversely, a modest resource linked to local separation, metal/alloy conversion, and magnet qualification can have disproportionate strategic value. For Dy, project evaluation should therefore report not only total rare-earth-oxide (TREO) grade and HREE distribution but also expected Dy recovery to separated product, co-product balance, impurity penalties, reagent recycle, residue closure, and the intended downstream product specification.

## 4. The Dysprosium Supply Chain: Where Availability Is Created or Lost

Figure 2 presents the mine-to-motor Dy chain and highlights a central distinction of this review: geological availability is not market availability. Multiple conversion steps lie

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between a Dy-bearing resource and a traction motor, each with its own technology, capital, environmental, and qualification risks (Cheng et al., 2026; Cheng et al., 2024; He et al., 2026; International Energy Agency, 2026; McNulty et al., 2022). Strategic exposure is often concentrated after mining, particularly in chemical separation, metal/alloy production, and permanent-magnet manufacturing. This is why national mine-development strategies can leave downstream users exposed if concentrates must still enter a geographically concentrated separation and magnet ecosystem.

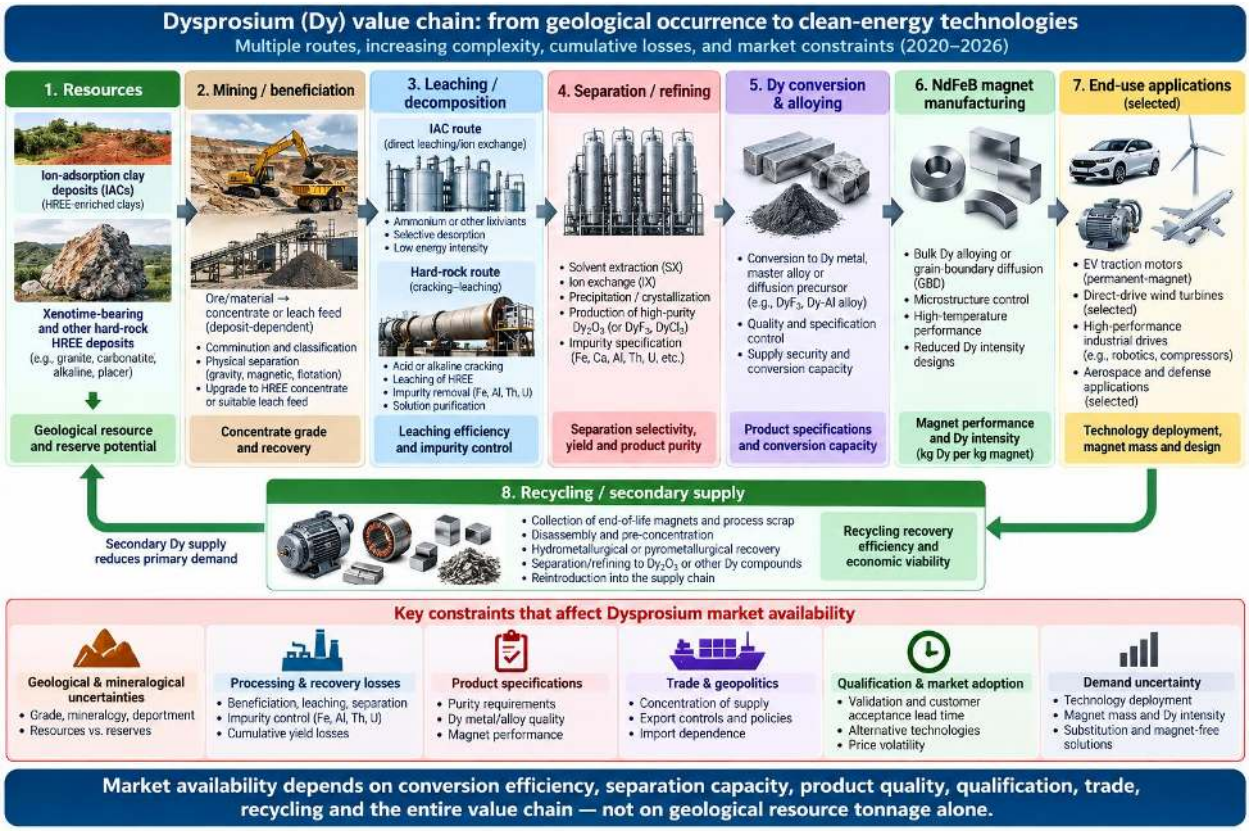



Figure 2. Dysprosium value chain from resource to motor/generator, emphasizing midstream and downstream exposure.

Note. Conceptually adapted from REE processing and supply-chain analyses in (Cheng et al., 2026; Cheng et al., 2024; He et al., 2026; International Energy Agency, 2026; McNulty et al., 2022; Shuai et al., 2024).

The processing chain begins with mineralogical characterization and beneficiation. The objective is not simply maximum total rare-earth-oxide (TREO) recovery but a concentrate whose mineralogy and impurity burden support economical cracking and leaching. Fine-grained or ultrafine feeds can undermine conventional upgrading, while broad REE processing studies show that comminution, gravity, magnetic, electrostatic, and flotation

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stages must be selected around actual liberation and mineral associations (Adu et al., 2026; Cheng et al., 2024; Julapong et al., 2023; Shuai et al., 2024). For Dy-bearing feeds, beneficiation is more valuable because every unit of gangue carried into chemical processing increases reagent consumption and residue generation without increasing scarce HREE output.

Cracking and leaching then transfer REEs to a form that can be separated. Depending on mineralogy, this may involve acid or alkaline decomposition, direct leaching of exchangeable REEs, or other routes. Yet extraction is only an intermediate metric. Dy marketability requires selective recovery from chemically similar lanthanides. Solvent extraction remains central because large separation factors can be accumulated across many stages, but stage count, phase behavior, solvent inventory, entrainment, and scrub/strip design become important scale-up variables. Nonaqueous systems, ionic-liquid-assisted extraction, electrodialysis, selective precipitation, adsorption, and electrochemical routes are being explored to reduce reagent or stage burdens and create more compact separations (Dewulf et al., 2020; Dewulf et al., 2022; Ding & Azimi, 2023; Gao et al., 2024; Hua et al., 2022; Hua et al., 2025; Koshani et al., 2026; Riaño et al., 2020; Q. Wang & Subban, 2024; Zuo et al., 2022).

Purified Dy compounds must then be converted to metal or alloy and incorporated into magnet production. Electrochemical studies in fluoride melts illustrate the technical specificity of producing Dy-containing alloys, while magnet studies show that the relevant product is not merely chemically pure Dy but Dy delivered in a physical and chemical form compatible with alloying or diffusion (Liao et al., 2020; Zuo et al., 2022). This requirement introduces a qualification layer often omitted from resource forecasts.

The 2026 IEA value-chain assessment reinforces the strategic importance of this midstream/downstream concentration, reporting substantially higher Chinese shares in refining and sintered permanent-magnet production than in mining (International Energy Agency, 2026). Thus, diversification should be measured at several nodes: mine output, separated oxide, metal/alloy, magnet, and qualified component. A country that diversifies only the first node may reduce geological dependence while retaining conversion dependence.

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## 5. Current and Projected Dysprosium Demand

Dy demand comes mainly from applications that require high coercivity and thermal stability in NdFeB magnets. Major demand drivers include EV and hybrid traction motors, wind generators, industrial motors, robotics, aerospace and defense systems, selected electronics, and other high-temperature permanent-magnet uses (Alves Dias et al., 2020; Ballinger et al., 2020; Heim et al., 2023; Junne et al., 2020). The composition of this demand matters because operating temperature, torque density, reliability, cooling design, and demagnetization margin determine whether a given application requires Dy-rich magnets, Dy-lean magnets, or no Dy at all.

Electric mobility receives the greatest attention because vehicle production can scale rapidly and traction motors impose stringent performance requirements. However, motor design is heterogeneous. Reviews of EV motors cover interior permanent-magnet machines, synchronous reluctance concepts, ferrite machines, wound-rotor machines, and hybrid configurations that alter rare-earth requirements (Abdel-Wahed et al., 2025; Gobbi et al., 2024; Khonongbua et al., 2026; Kumar et al., 2026; Liu et al., 2026; Luk et al., 2020; Rangarajan et al., 2025; Rom et al., 2024; Yang et al., 2025). Consequently, forecasts should not assign one universal Dy coefficient to every EV. A realistic model needs shares by motor topology, magnet grade, power class, thermal design, and regional technology choice.

Wind power creates a different demand profile. Direct-drive or permanent-magnet generator choices can raise NdFeB use per unit of capacity, while geared architectures and alternative generator designs change material intensity. Earlier energy-system studies already identified possible mismatches between critical REE supply and ambitious wind deployment, and later circularity work demonstrates that narrowing and closing material flows can substantially alter long-run requirements (Li et al., 2020; Ren et al., 2021; Savvidou et al., 2026). The same logic applies to industrial drives and robotics: service growth does not translate directly into Dy growth when efficiency, motor architecture, and magnet design change.

Table 4 summarizes the major demand drivers and, importantly, the variables that should replace a fixed Dy-per-unit assumption in scenario models (Alves Dias et al., 2020; Cui et al., 2026; Gobbi et al., 2024; Heim et al., 2023; Junne et al., 2020; Khonongbua et al., 2026; Kumar et al., 2026; Liu et al., 2026; Luk et al., 2020; Mathur et al., 2024; Rangarajan et al., 2025; Rom et al., 2024; Yang et al., 2025).

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Table 4. Dysprosium demand drivers and the variables required for technology-sensitive forecasting

| Demand segment | Why Dy may be used | Variables that control Dy intensity | Main forecasting error if simplified |
|---|---|---|---|
| EV/hybrid traction motors | High torque density, thermal stability, demagnetization margin | Motor topology; power; cooling; magnet mass; magnet grade; GBD; hybridization | Applying one fixed kg Dy per vehicle |
| Wind generators | Permanent-magnet generator performance and reliability | Drive train; generator topology; magnet mass per MW; temperature; lifetime | Equating installed MW directly with fixed Dy intensity |
| Industrial motors/robotics | Compactness, efficiency, precise torque control | Duty cycle; thermal load; rotor design; substitution options | Ignoring heterogeneous motor architectures |
| Aerospace/defence | High performance under severe thermal/mechanical conditions | Qualification standards; temperature; redundancy; coercivity margin | Assuming rapid substitution where qualification is slow |
| Electronics/other magnets | Miniaturization and specialized magnet grades | Product mix; magnet grade; recovery at end-of-life | Using aggregate REE demand as a proxy for Dy demand |

Note. Compiled and adapted from (Abdel-Wahed et al., 2025; Alves Dias et al., 2020; Ballinger et al., 2020; Cui et al., 2026; Gobbi et al., 2024; Heim et al., 2023; Junne et al., 2020; Khonongbua et al., 2026; Kumar et al., 2026; Li et al., 2020; Liu et al., 2026; Luk et al., 2020; Mathur et al., 2024; Nwokolo, 2025; Park et al., 2021; Rangarajan et al., 2025; Ren et al., 2021; Rom et al., 2024; Romani et al., 2026; Swaminathan et al., 2026; Yang et al., 2025).

After Table 4, two implications follow. First, separate gross deployment scenarios from material-intensity scenarios. Second, uncertainty in Dy demand should be asymmetric: aggressive GBD adoption, better thermal management, lower-HREE magnet grades, or alternative motors can reduce demand faster than a static-intensity model suggests, whereas continued reliance on high-HREE designs in high-temperature segments can preserve demand even if some mass-market vehicles move toward alternative architectures. This is why bottom-up valuation and design studies complement macro demand forecasts (Cui et al., 2026; Heim et al., 2023; Mathur et al., 2024; Romani et al., 2026).

## 6. NdFeB Magnet Technology as the Main Demand-Intensity Driver

### 6.1 Why Dy raises coercivity

Dy is introduced into NdFeB systems because substituting Dy for part of Nd can increase anisotropy and improve resistance to reverse-domain nucleation, especially at elevated temperatures. The penalty is that Dy can reduce remanence and is expensive and supply-constrained, so the engineering problem is not 'maximize Dy' but 'place the minimum

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necessary Dy where it produces the largest coercivity benefit.' Mechanistic and microstructural studies of Dy substitution and diffusion therefore underpin the economics of demand reduction (Dai et al., 2024; Fliegans et al., 2021; J. Li et al., 2021; W. Liu et al., 2021; Nishino et al., 2022).

### 6.2 Grain-boundary diffusion and localized HREE use

GBD is the most important near-term Dy-thrifting strategy because it decouples coercivity enhancement from homogeneous bulk alloying. Dy- or Tb-containing sources are applied to a magnet and diffused preferentially along grain boundaries, creating HREE-enriched shells or interfacial regions while leaving much of the grain core relatively HREE-lean. Research from 2020–2026 has progressed from process reviews and coating methods to alloy-source design, shell-structure control, temperature-dependent diffusion, thick-magnet treatment, and synergistic Dy/Tb diffusion (Chang et al., 2026; Chen, 2020; Chen et al., 2026; Cheng et al., 2025; Dai et al., 2024; He et al., 2021; Huang & Mo, 2024; Huang & Mo, 2026; Kan et al., 2025; Korent et al., 2021; Kou et al., 2026; Pan et al., 2025; Xiao et al., 2025; Zeng et al., 2026).

The strategic consequence is profound. If GBD achieves equivalent service coercivity with a smaller total Dy inventory, then technology growth can continue while Dy intensity declines. This is precisely the type of endogenous response that commodity-balance models must capture. It also means that Dy demand can be influenced by magnet manufacturing know-how, coating uniformity, diffusion depth, magnet geometry, and quality control, not only by ore supply.

### 6.3 HREE-lean, HREE-free, and alternative motor pathways

Beyond GBD, microstructure engineering has produced high-coercivity magnets with little or no HREE addition. Hot-deformed magnets, Pr-Cu diffusion, fluoride/eutectic modifications, and other boundary-phase approaches show that coercivity can be improved by controlling grain size, boundary chemistry, exchange coupling, and electrical resistivity (Hioki, 2021; Hioki, 2023; Kautsar et al., 2025; Lee et al., 2025; Tang et al., 2026; Volegov et al., 2020; Zhang et al., 2026). These advances do not mean Dy becomes unnecessary in all high-temperature duties, but they expand the design space and set a competitive ceiling on Dy intensity.

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At the motor level, hybrid-magnet arrangements, ferrite assistance, PM-assisted synchronous reluctance, wound-rotor machines, and other rare-earth-reduced or rare-earth-free architectures can substitute engineering complexity, control strategies, rotor volume, or other materials for HREE content (Abdel-Wahed et al., 2025; Cui et al., 2026; Khonongbua et al., 2026; Kumar et al., 2026; Liu et al., 2026; Luk et al., 2020; Park et al., 2025; Rangarajan et al., 2025; Rom et al., 2024; Yang et al., 2025). The trade-off is application-specific: lower critical-material exposure may come with changes in efficiency, mass, power density, cost, thermal behavior, or manufacturing complexity.

Figure 3 organizes these magnet- and motor-level pathways as a qualitative direction of declining Dy intensity. It deliberately avoids assigning universal percentage reductions because the achievable savings depend on magnet geometry, operating temperature, coercivity target, diffusion source, motor duty cycle, and system design (Chang et al., 2026; Durgun et al., 2026; Hioki, 2023; Kautsar et al., 2025; Korent et al., 2021; Kumar et al., 2026; Liu et al., 2026; Tang et al., 2026).

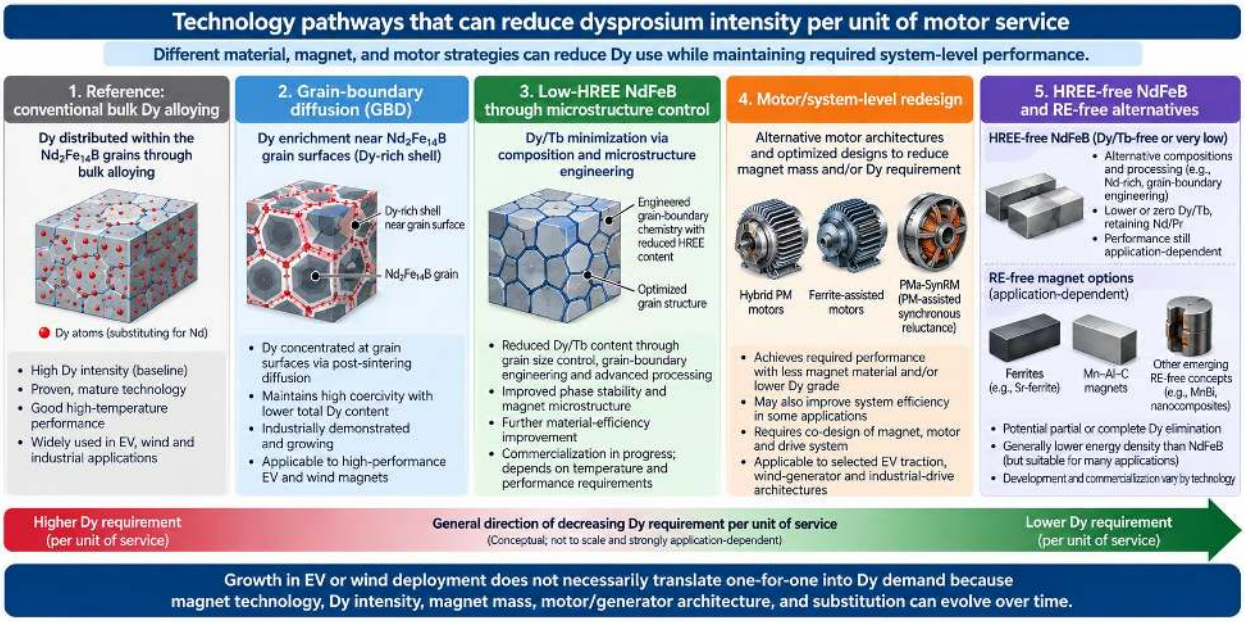



Figure 3. Technology pathways that can reduce dysprosium intensity per unit of magnet or motor service.

Note. Conceptually adapted from GBD, HREE-lean magnet, and reduced-rare-earth motor studies in (Chang et al., 2026; Chen, 2020; Chen et al., 2026; Durgun et al., 2026; Hioki, 2023; Kautsar et al., 2025; Khonongbua et al., 2026; Korent et al., 2021; Kumar et al., 2026; Liu et al., 2026; Rangarajan et al., 2025; Tang et al., 2026; Zhang et al., 2026).

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Table 5 translates Figure 3 into a decision framework. The critical point is that the measures are not mutually exclusive. A motor can combine GBD magnets, lower magnet mass, improved cooling, and a hybrid rotor architecture, multiplying the reduction in Dy per unit of service (Cui et al., 2026; Durgun et al., 2026; Khonongbua et al., 2026; Kumar et al., 2026; Liu et al., 2026; Samuel et al., 2026).

Table 5. Technology pathways for lowering dysprosium demand per unit of magnet or motor service

| Strategy | Intervention level | Expected Dy effect | Key trade-off / limitation |
|---|---|---|---|
| Bulk Dy optimization | Magnet chemistry | Incremental reduction | Still distributes Dy through much of magnet volume; remanence penalty can persist |
| Grain-boundary diffusion | Magnet processing | Strong Dy-thrifting potential | Diffusion depth, geometry, coating/source control and process uniformity |
| HREE-lean microstructure engineering | Magnet microstructure | Further reduction or elimination in some grades | Processing complexity; duty-specific performance |
| Hybrid-magnet / PM-assisted designs | Motor rotor/system | Reduces magnet and/or Dy requirement | Rotor volume, control, efficiency, cost and manufacturability trade-offs |
| Ferrite, wound-rotor or RE-free architectures | Motor system | Potential near-total Dy displacement | Power density, efficiency, mass, system redesign and qualification |
| Thermal management/downsizing | System integration | Indirectly lowers required coercivity margin and magnet inventory | May shift cost/complexity to cooling, electronics or mechanical design |

Note. Compiled and adapted from (Chang et al., 2026; Chen, 2020; Chen et al., 2026; Cui et al., 2026; Dai et al., 2024; Durgun et al., 2026; He et al., 2021; Hioki, 2023; Kautsar et al., 2025; Khonongbua et al., 2026; Korent et al., 2021; Kumar et al., 2026; Lee et al., 2025; J. Li et al., 2021; Liu et al., 2026; Z. Liu et al., 2021; Luk et al., 2020; Nishino et al., 2022; Nwokolo, 2025; Park et al., 2021; Rangarajan et al., 2025; Samuel et al., 2026; Swaminathan et al., 2026; Tang et al., 2026; Volegov et al., 2020; Yang et al., 2025; Zhang et al., 2026).

After Table 5, treat future Dy intensity as a scenario variable with technology diffusion rates rather than a constant. A conservative scenario can assume slow adoption and persistently high HREE grades in demanding segments; a transition scenario can allow broad GBD and hybridization; and an accelerated-efficiency scenario can combine HREE-lean magnets with motor redesign. This structure makes assumptions transparent and prevents a forecast from embedding an outdated magnet recipe.

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## 7. The Supply–Demand Balance: From Gross Demand to Effective Constraint

Material-flow studies of Dy show why the balance must be evaluated dynamically. Dy moves through mining, separation, alloy and magnet manufacture, product use, in-use stocks, scrap generation, recycling, trade, and loss reservoirs; regional systems differ in the timing and location of these flows (Chen et al., 2023; Eheliyagoda et al., 2023; Li et al., 2023; Wang et al., 2022; Xiao et al., 2022). A large in-use stock is not current supply, and a large resource is not current output. Similarly, process scrap can be available quickly, while end-of-life (EoL) EV and wind magnets arrive only after product lifetimes.

On the demand side, climate and technology scenarios have repeatedly identified Dy as a possible constraint for rapid expansion of clean-energy technologies. Studies focused on China and global low-carbon pathways indicate that gross demand can exceed conventional supply trajectories if material intensity remains high, but also show that circularity and material-efficiency measures can materially narrow potential imbalances (Dai et al., 2023; Eheliyagoda et al., 2025; Junne et al., 2020; Klimenko et al., 2021; Y.-F. Liu et al., 2025; P. Wang et al., 2024; P. Wang et al., 2026). This review therefore treats avoided demand as a first-class accounting term and separates it into material-efficiency reduction, magnet-chemistry substitution, component redesign, and technology substitution rather than combining interventions with different engineering feasibility and adoption timing.

On the supply side, project announcements should not be treated as equivalent to annual qualified Dy supply. Scenario construction should track the sequence announced capacity → commissioned capacity → operating capacity → recovered separated Dy → qualified marketable product, with explicit assumptions for commissioning probability, ramp-up, metallurgical recovery, separation capacity, product specification, and qualification. A mine that produces mixed concentrate but depends on external separation does not add the same resilience as a vertically integrated source. Mining-cost models help screen potential future supply, but cost alone cannot capture processing complexity, qualification delay, or strategic value (O'Brien & Alonso, 2025).

Secondary supply must also be time-indexed by feedstock cohort. Manufacturing scrap can contribute earlier and generally with shorter collection and qualification lags than dispersed EoL products. EoL magnets represent a larger long-run reservoir, but their availability is delayed by product lifetime and constrained by collection, access, sorting, process yield, and

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economics (Bacchetta et al., 2024; Baghel et al., 2025; R. Liu & Zeng, 2025; Y.-F. Liu et al., 2025; Zhao et al., 2024). A quantitative 2030 scenario therefore cannot assume the same secondary-supply pool as a 2050 scenario; it should link retirement cohorts to lifetime distributions and then apply collection, metallurgical-recovery, product-qualification, and closed-loop-displacement efficiencies.

A useful first-order physical coverage indicator is the ratio $C_t = S_t/D_t$. It compares aggregate market-available supply with effective demand before regional access, product-form compatibility, customer qualification, inventory mobility, contractual restrictions, logistics, or concentration are represented. Accordingly, $C_t > 1$ indicates only nominal aggregate physical coverage and must not be interpreted as evidence of supply security. Accessibility and concentration should remain conceptually distinct through a separate index, vector, or scenario constraint unless a formal combined metric is defined. Agent-based and macroeconomic studies of REE disruptions show how network structure and bottlenecks propagate beyond simple tonnage balances (C. Bogmans et al., 2026a; C. Bogmans et al., 2026b; Riddle et al., 2021).

The central inference is that Dy deficit risk emerges from synchronization failure: demand growth, new mines, separation capacity, magnet-efficiency adoption, recycling availability, and policy responses do not mature at the same rate. Scenario analysis should therefore focus less on a single 'deficit year' and more on the duration and depth of periods when qualified supply fails to keep pace with effective demand.

## 8. Geographic Concentration, Export Controls, and Supply Security

Geographic concentration changes what a balanced global market means. Dy-bearing feed, separation/refining capacity, metal/alloy production, and magnet manufacturing can be concentrated in different places, but the greatest exposure arises where capacity is both concentrated and difficult to replicate. The 2026 IEA assessment emphasizes the exceptionally high concentration of refining and permanent-magnet production, while criticality studies treat Dy as important precisely because substitution is imperfect in some high-performance applications and supply risk is elevated (International Energy Agency, 2026; Kosajan et al., 2025; Nassar et al., 2025; U.S. Department of Energy, 2023).

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Terminology is kept explicit because the concepts are not interchangeable. Geological scarcity refers to limited economically relevant occurrence or resource availability; market scarcity refers to insufficient market-available material relative to demand over a defined horizon; supply-chain concentration describes the geographic or organizational concentration of conversion, manufacturing, or logistics capacity; supply security concerns whether users can obtain the required quantity and specification when needed under normal and disrupted conditions; and material criticality is a broader assessment combining economic or strategic importance with supply risk and substitutability. A material can therefore be geologically abundant yet supply-insecure or strategically critical (Graedel et al., 2022; Kosajan et al., 2025; Nassar et al., 2025; U.S. Department of Energy, 2023).

China's April 4, 2025 export-control announcement explicitly included dysprosium metal, Dy-containing alloys, targets, Dy-containing NdFeB permanent-magnet materials, dysprosium oxide, and Dy-containing compounds and mixtures. The measure requires exporters of controlled items to apply for a license under the relevant export-control provisions (Ministry of Commerce of the People's Republic of China & General Administration of Customs of the People's Republic of China, 2025). For scenario analysis, the key distinction is that trade controls can alter accessible market supply, timing, and regional product availability without changing geological resources or necessarily changing mine production. Product forms should therefore be modeled separately because oxide, alloy, and magnet users can face different access constraints.

Policy-data cutoff: 20 September 2026. Trade-control conditions and licensing practice are time-sensitive; the status of all policy measures should be reverified immediately before production or online publication. The April 2025 measure is retained here because the cited official announcement is the primary documentary source for the Dy-related controlled-item categories discussed in this review.

Historical and recent work on export quotas, geopolitical risk, and informational statecraft shows that rare-earth markets can exhibit price and availability responses larger than annual production changes alone suggest (Binzat & Dilek, 2026; Depraiter et al., 2025; Woods, 2025). The 2026 IEA analysis further reported large regional price premia for Dy and Tb outside China during a period of constrained trade, reinforcing the idea of geographically bifurcated markets (International Energy Agency, 2026).

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Supply security therefore has at least four dimensions: source diversity, processing diversity, product-form diversity, and contractual/logistical diversity. A nominally diversified mining portfolio can still depend on one separation center; multiple separation plants can still depend on one metal/alloy route; and several magnet plants can still rely on the same Dy feedstock. Business-strategy and resilience analyses accordingly emphasize network diversification rather than simple supplier counts (Logožar, 2026).

Policy responses should be evaluated by which bottleneck they address. Strategic inventories can buffer short disruptions but do not create new production. Mine financing expands upstream capacity but may leave separation dependence unchanged. Separation and magnet incentives address midstream/downstream capability but require secure feed. Recycling improves circularity but depends on scrap access and qualified outlets. International partnerships can spread risk but require compatible standards, permitting, financing, and long-term offtake. The appropriate policy unit is therefore the chain, not the individual commodity.

## 9. Price, Elasticity, and the Rare-Earth Balance Problem

Dy pricing is shaped by scarcity, concentration, co-production, substitution options, inventories, and policy. The rare-earth balance problem is fundamental: ores contain baskets of REEs, so raising output of a scarce element can simultaneously increase production of more abundant elements. This weakens the analogy with commodities whose output can be expanded independently. Criticality and alloy-level analyses consequently argue for evaluating materials in the context of co-produced systems and functional applications rather than as isolated elements (Graedel et al., 2022; Kosajan et al., 2025).

Supply elasticity is constrained by long mine-development timelines, mineralogical complexity, separation-capacity requirements, permitting, and qualification. Demand elasticity is also unusual: in the short run, high-temperature magnet users may have limited ability to redesign products, while in the longer run, GBD, HREE-lean magnets, alternative motors, and recycling can materially change Dy demand. Empirical work on non-fuel-mineral elasticities and rare-earth market disruptions supports the view that short-run price responses can be strong when both supply and substitution are constrained (Binzat & Dilek, 2026; Shojaeddini et al., 2025).

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Price therefore performs two roles. It rations scarce material in the short run and accelerates technology response in the medium run. High Dy prices increase the economic value of GBD, lower-HREE grades, recycling, improved scrap sorting, and alternative motor architectures; they can also improve the viability of lower-grade or more complex primary resources. Bottom-up analysis of rare-earth value in EV motors shows why willingness to pay can be substantial when the material enables a high-value system-level performance function (Romani et al., 2026).

However, a price-only solution can create undesirable feedback. Very high prices may encourage substitution that permanently reduces Dy intensity, undermining new mines' revenue assumptions. Conversely, expectations of future substitution can deter investment in supply that is still needed during the transition. The result is a coordination problem in which project finance, technology roadmaps, offtake agreements, recycling infrastructure, and strategic policy must align across different time horizons.

Table 6 summarizes the principal market mechanisms and the direction in which they act on the Dy balance (Binzat & Dilek, 2026; Depraiter et al., 2025; Graedel et al., 2022; International Energy Agency, 2026; Kosajan et al., 2025; O'Brien & Alonso, 2025; Romani et al., 2026; Shojaeddini et al., 2025; Woods, 2025).

Table 6. Market mechanisms that alter the apparent dysprosium supply–demand balance

| Mechanism | Short-run effect | Longer-run response | Recommended modeling treatment |
|---|---|---|---|
| Export **controls/licensing** | Reduces accessible supply; creates regional scarcity | Diversification, inventories, alternative sourcing, redesign | Model regional availability, not only global production |
| Price spikes / regional premiums | Rationing and higher magnet cost | GBD, substitution, recycling, new project incentives | Use technology-switching thresholds and regional prices |
| Co-production / balance problem | Limits independent Dy supply response | Basket-value optimization; new HREE-rich feeds | Link Dy output to co-produced REE mix |
| Low supply elasticity | Slow response to demand shocks | Mine/separation investment with long lead times | Use commissioning probability, ramp-up and qualification lags |
| Demand elasticity through engineering | Limited immediate substitution in qualified designs | Material efficiency and motor/magnet redesign | Allow Dy intensity to decline endogenously |
| Strategic inventory/contracting | Buffers temporary disruptions | Can stabilize financing and offtake | Separate stock draw from sustainable annual production |

Note. Compiled and adapted from (Binzat & Dilek, 2026; C. Bogmans et al., 2026a; C. Bogmans et al., 2026b; Depraiter et al., 2025; Graedel et al., 2022; International Energy Agency, 2026; Kosajan et

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al., 2025; Logožar, 2026; Ministry of Commerce of the People's Republic of China & General Administration of Customs of the People's Republic of China, 2025; O'Brien & Alonso, 2025; Riddle et al., 2021; Romani et al., 2026; Shojaeddini et al., 2025; Woods, 2025).

After Table 6, the main analytical caution is that a forecast based on a single long-term equilibrium price can obscure the dynamics that make Dy critical. Scenario models should consider regional price spreads, temporary trade frictions, capacity bottlenecks, and technology switching thresholds rather than assume frictionless arbitrage.

## 10. Secondary Supply, Recycling, and Selective Recovery

### 10.1 Feedstock hierarchy: process scrap before complex end-of-life products

Recycling is frequently presented as an immediate answer to Dy scarcity, but the quality and timing of secondary resources differ. Manufacturing scrap is relatively homogeneous, concentrated, and available without waiting for product retirement. End-of-life (EoL) magnets are more heterogeneous and embedded in motors, drives, electronics, and other assemblies. Sorting technologies that identify magnet-containing motors without destructive opening, and methods for recovering magnets from end-of-life products, can therefore be as strategically important as the downstream chemical process (Baghel et al., 2025; Nayebossadri et al., 2024).

Short-loop recycling aims to preserve more of the magnet or alloy value by demagnetizing, hydrogen decrepitation, reprocessing, or otherwise returning material to magnet production with limited elemental separation. Studies on hydrogen-assisted recycling and repeated recycling of sintered magnets show the attraction of this approach when feed chemistry is known, and contamination is controlled (Bacchetta et al., 2024; Habibzadeh et al., 2023; Mishra et al., 2023; Nayebossadri et al., 2024; Schönfeldt et al., 2023; Schönfeldt et al., 2025). Its limitation is feed specificity: mixed grades, coatings, corrosion products, Cu, Al, or other additions can accumulate and make product specification harder to maintain.

### 10.2 Long-loop hydrometallurgical, solvometallurgical, and electrochemical routes

Long-loop routes dissolve or otherwise chemically transform the magnet, allowing recovery and separation of individual REEs. Their advantage is feed flexibility and the potential to produce high-purity Dy products; their disadvantage is a larger chemical flowsheet with leaching, Fe removal, separation, precipitation or crystallization, reagent regeneration, wastewater, and residue management. Reviews of NdFeB recycling and Dy recovery show a

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broad technology set including mineral-acid and organic-acid leaching, solvent extraction, ion exchange/adsorption, ionic liquids, precipitation, crystallization, biohydrometallurgy, and electrochemical routes (Brião et al., 2022; Guo et al., 2025; Kumari & Sahu, 2023; X. Li et al., 2021; Pereira, 2026b; Rudnik, 2026; Zheng et al., 2025).

Selective Nd–Dy separation is particularly important because magnet scrap contains both light and heavy REEs. Solvent-extraction studies demonstrate separation using neutral extractants, ionic liquids, and mixer-settler flowsheets; other work explores electrodialysis, chelator-assisted precipitation, functionalized resins, nanocellulose, and flow-enhanced separations (Dewulf et al., 2020; Dewulf et al., 2022; Ding & Azimi, 2023; Gao et al., 2024; Islam et al., 2026; Koshani et al., 2026; Mohammed & Zhang, 2026; Pereira, 2026a; Riaño et al., 2020; Q. Wang & Subban, 2024). Molten-salt electrolysis provides a different route in which selective electrochemical behavior can support direct separation or alloy production, potentially shortening parts of the conventional aqueous chain (Hua et al., 2022; Hua et al., 2025; Liao et al., 2020; Zuo et al., 2022).

Crystallization is another potentially valuable finishing or recovery operation because it can combine product formation with solvent/reagent recovery. Scale-up and life-cycle analysis of antisolvent crystallization from NdFeB-derived streams illustrates the need to evaluate not only laboratory recovery but also solvent circulation, energy, purity, and environmental burdens at process scale (Pawar et al., 2026).

### 10.3 Circularity is a system property

Figure 4 shows the circular Dy loop from magnet manufacture through use, collection/sorting, preprocessing, recovery/separation, and return to production. The key message is that metallurgical extraction recovery is only one efficiency in a longer system. Collection losses, exports of EoL products, inability to access embedded magnets, mixing of grades, product-specification failures, and customer-qualification failures can dominate the fraction of recovered Dy that actually returns to qualified use (Bacchetta et al., 2024; Baghel et al., 2025; Li et al., 2026; R. Liu & Zeng, 2025; Y.-F. Liu et al., 2025; Rudnik, 2026; Zhao et al., 2024). The strongest circularity endpoint is therefore functional displacement of virgin Dy, not extraction yield alone.

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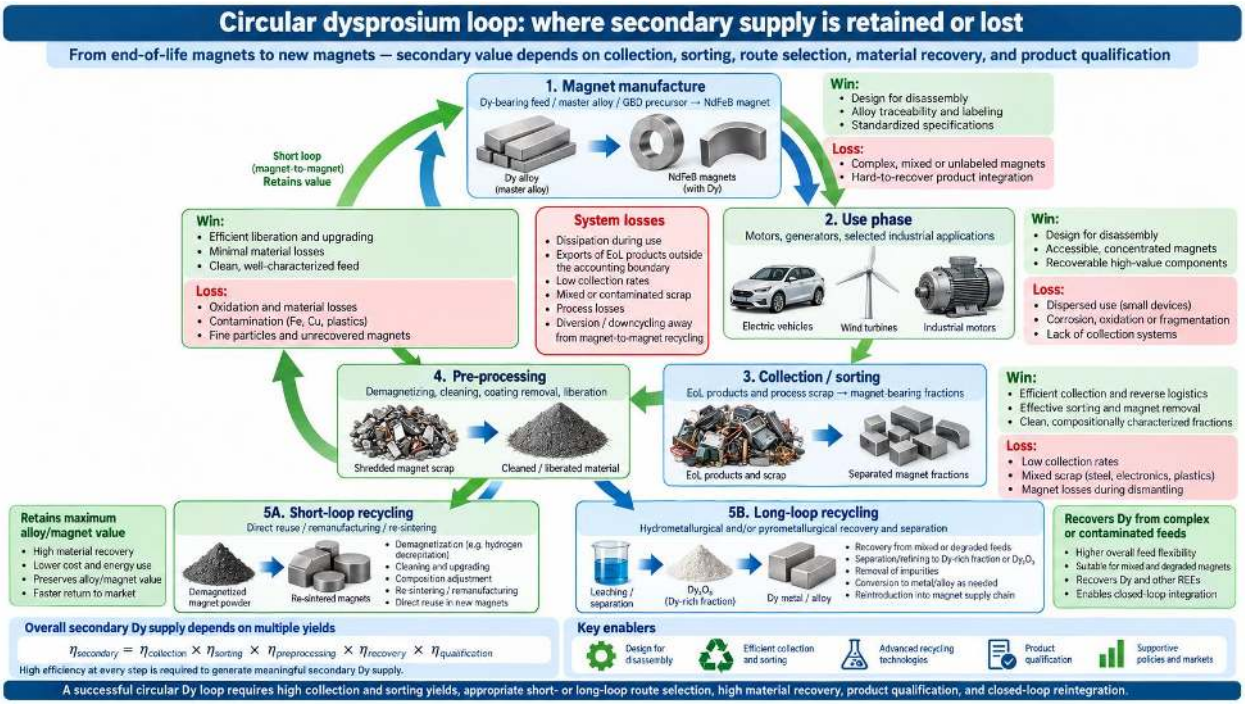



Figure 4. Circular dysprosium loop showing where secondary supply is recovered or lost.

Note. Conceptually adapted from NdFeB recycling and circularity studies in (Bacchetta et al., 2024; Baghel et al., 2025; Guo et al., 2025; Habibzadeh et al., 2023; Li et al., 2026; R. Liu & Zeng, 2025; Y.-F. Liu et al., 2025; Mishra et al., 2023; Nayebossadri et al., 2024; Rudnik, 2026; Schönfeldt et al., 2023; Schönfeldt et al., 2025; Zhao et al., 2024; Zheng et al., 2025).

Life-cycle studies add another constraint: a recycling route should not be treated as automatically preferable simply because it is circular. Environmental performance depends on energy mix, acid and solvent consumption, reagent regeneration, recovery yield, coproduct credits, wastewater treatment, and the avoided burden assigned to primary production (Bailey et al., 2021; Langkau & Erdmann, 2021; Wang et al., 2025). This is especially relevant for Dy because its disproportionate environmental and economic burden within NdFeB systems can make material-efficiency measures highly valuable even before full closed-loop recycling is achieved (Samuel et al., 2026).

Circularity evidence is also geographically uneven. Collection infrastructure, in-use stock age, product access and disassembly, regulation, electricity mix, reagent and waste-treatment infrastructure, and downstream magnet-making capability vary substantially among regions. Recycling potentials estimated for China or selected industrialized regions should therefore not be transferred directly to another region without re-parameterizing collection, retirement

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cohorts, energy mix, industrial capacity, and qualification pathways (Chen et al., 2023; Eheliyagoda et al., 2023; Eheliyagoda et al., 2025; Wang et al., 2025; Zhao et al., 2024).

Table 7 compares secondary-supply pathways by feed flexibility, selectivity, product form, principal bottleneck, and strategic role (Bacchetta et al., 2024; Baghel et al., 2025; Brião et al., 2022; Dewulf et al., 2020; Dewulf et al., 2022; Ding & Azimi, 2023; Guo et al., 2025; Habibzadeh et al., 2023; Hua et al., 2022; Hua et al., 2025; Islam et al., 2026; Koshani et al., 2026; Kumari & Sahu, 2023; Li et al., 2026; X. Li et al., 2021; Mishra et al., 2023; Mohammed & Zhang, 2026; Nayebossadri et al., 2024; Pawar et al., 2026; Pereira, 2026b; Riaño et al., 2020; Rudnik, 2026; Schönfeldt et al., 2023; Schönfeldt et al., 2025; Q. Wang & Subban, 2024; Wang et al., 2025; Zheng et al., 2025; Zuo et al., 2022).

Table 7. Secondary dysprosium pathways: process role, selectivity, and strategic contribution

| Pathway | Feed flexibility | Dy selectivity / product | Main bottleneck | Strategic role |
|---|---|---|---|---|
| Direct/short-loop magnet recycling | Low–moderate; best for known grades | Preserves alloy/magnet functionality rather than isolating Dy | Contamination, grade mixing, coatings, property restoration | Fastest route for clean process scrap and selected EoL magnets |
| Hydrometallurgy + solvent extraction | High | High-purity separated Dy possible | Acid/reagent use, Fe removal, multistage SX, wastewater | Flexible long-loop route for mixed scrap |
| Adsorption / ion exchange | Moderate–high | Selective polishing or Dy/Nd separation possible | Capacity, kinetics, elution, resin life, scale-up | Useful for purification and smaller/variable streams |
| Precipitation/crystallization | Moderate | Can combine separation and product formation | Selectivity, solvent/reagent recycle, crystal handling | Potentially compact finishing and recovery route |
| Molten-salt / electrochemical recovery | Moderate | Direct selective recovery or alloy production possible | High-temperature salt handling, purity, scale-up | Can shorten aqueous flowsheets and produce alloy directly |
| Integrated closed-loop route | Feed-specific | Qualified magnet or separated Dy returned to manufacture | Collection + processing + product qualification must all work | Highest strategic value when virgin Dy is demonstrably displaced |

Note. Compiled and adapted from (Bacchetta et al., 2024; Baghel et al., 2025; Brião et al., 2022; Dewulf et al., 2020; Dewulf et al., 2022; Ding & Azimi, 2023; Gao et al., 2024; Guo et al., 2025; Habibzadeh et al., 2023; Hua et al., 2022; Hua et al., 2025; Islam et al., 2026; Koshani et al., 2026; Kumari & Sahu, 2023; Li et al., 2026; X. Li et al., 2021; R. Liu & Zeng, 2025; Y.-F. Liu et al., 2025; Mishra et al., 2023; Mohammed & Zhang, 2026; Nayebossadri et al., 2024; Pawar et al., 2026;

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Pereira, 2026b; Riaño et al., 2020; Rudnik, 2026; Schönfeldt et al., 2023; Schönfeldt et al., 2025; Q. Wang & Subban, 2024; Wang et al., 2025; Zhao et al., 2024; Zheng et al., 2025; Zuo et al., 2022).

Table 7 clarifies the strategic hierarchy. Near-term circular supply will likely be dominated by manufacturing scrap and accessible high-grade EoL streams; medium-term growth depends on collection and disassembly; and long-term contribution depends on whether recycled Dy qualifies into products that actually displace virgin Dy. Reporting a single 'recycling rate' without distinguishing collection, preprocessing access, metallurgical extraction, separation/product yield, qualification, and functional substitution can therefore overstate closed-loop circularity.

## 11. Integrated Mitigation Portfolio, Research Gaps, and Decision Priorities

No single intervention resolves the Dy constraint. New mines expand primary supply but face long lead times and may still depend on concentrated separation capacity. New separation plants address the midstream bottleneck but need reliable feed and qualified outlets. GBD and material efficiency can act relatively quickly in magnet manufacturing but cannot eliminate Dy from every duty. Alternative motors and HREE-free magnets reduce exposure but involve system-level trade-offs. Recycling creates domestic or regional secondary supply but is limited by product lifetimes and collection. The appropriate response is therefore a portfolio (Cui et al., 2026; Eheliyagoda et al., 2025; Ghorbani et al., 2025; He et al., 2026; International Energy Agency, 2026; Li et al., 2026; Liu et al., 2026; Logožar, 2026; Rangarajan et al., 2025; Samuel et al., 2026; P. Wang et al., 2024; P. Wang et al., 2026).

Figure 5 maps representative mitigation options by potential contribution and near-term deployability. Positioning is qualitative and is informed by five dimensions: evidence of commercial deployment, technical maturity, expected lead time, supply-chain scale, and qualification burden. To make evidence maturity explicit, the discussion uses four descriptors—commercially established, industrially emerging, pilot/demonstration, and laboratory/research stage—without treating them as formal technology-readiness-level scores. Representative mature or commercially deployed measures include selected GBD practices, process-scrap recycling, sourcing diversification, and inventory policies; industrially emerging or pilot-stage options include expanded EoL loops, new separation capacity, and some hybrid magnet/motor strategies; several HREE-free high-performance magnet concepts and emerging separation chemistries remain application-specific and at

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lower maturity. These categories are indicative rather than universal because maturity varies by process configuration, application, region, and qualification pathway (Chang et al., 2026; Guo et al., 2025; International Energy Agency, 2026; Kautsar et al., 2025; Logožar, 2026; Mishra et al., 2023; Tang et al., 2026).

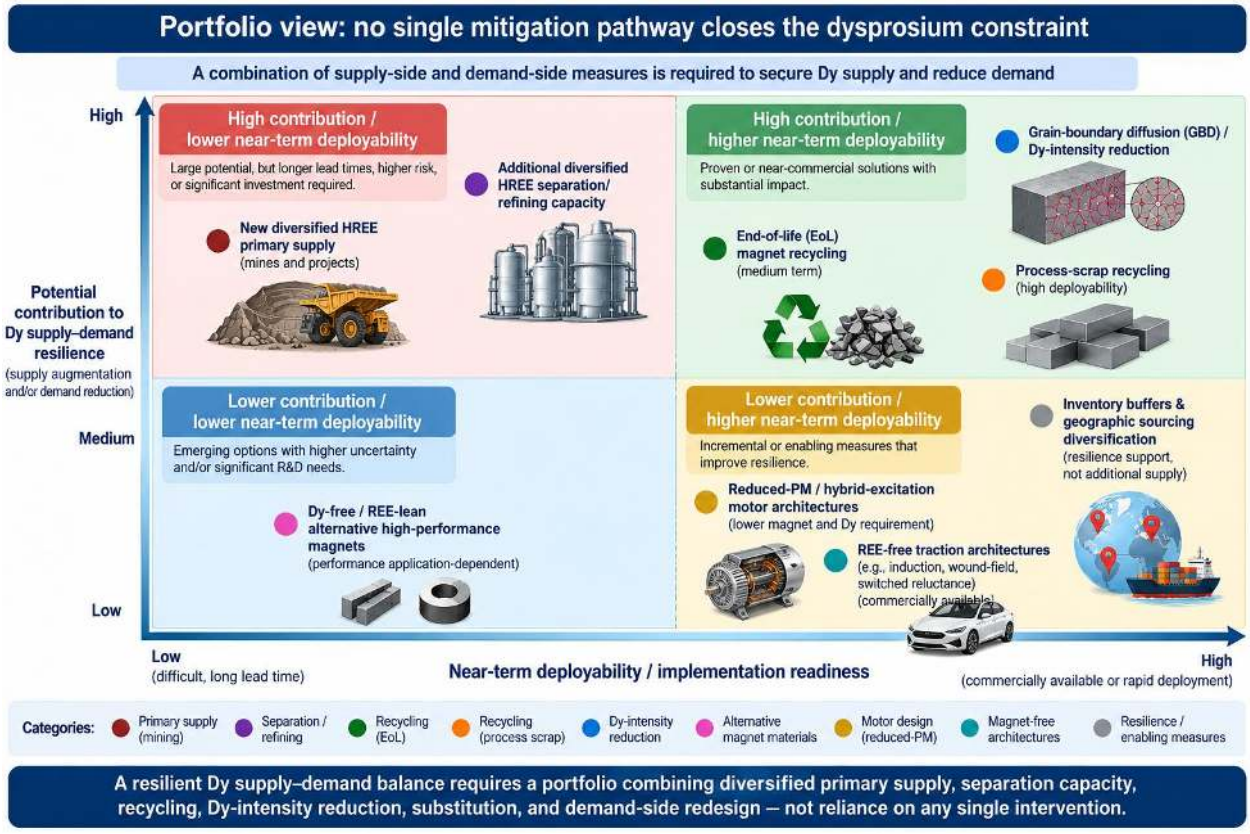



Figure 5. Qualitative portfolio of mitigation options for dysprosium supply security.

Note. Original author synthesis based on supply diversification, magnet efficiency, recycling, and resilience literature (Eheliyagoda et al., 2025; Ghorbani et al., 2025; He et al., 2026; International Energy Agency, 2026; Li et al., 2026; Liu et al., 2026; Logožar, 2026; Samuel et al., 2026; P. Wang et al., 2024; P. Wang et al., 2026). Positioning is qualitative and informed by commercial deployment, technical maturity, expected lead time, supply-chain scale, and qualification burden; it is not a formal TRL or multi-criteria score.

Five research gaps deserve priority. First, public Dy supply data should move from total REE mine output toward product-form data: separated Dy oxide, metal/alloy, magnet-grade feed, and qualified magnet output. Second, demand models should publish the assumed magnet mass and Dy intensity by motor or generator architecture. Third, primary project assessments should report Dy recovery to separated product and not merely TREO recovery. Fourth, recycling studies should report functional displacement of virgin Dy in addition to extraction yield. Fifth, market studies should integrate regional trade constraints and qualification lead

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times with physical material flows (Chen et al., 2023; Eheliyagoda et al., 2023; Li et al., 2023; Riddle et al., 2021; Wang et al., 2022; Xiao et al., 2022).

A sixth cross-cutting gap is scale-up. Many separation and recycling studies demonstrate selectivity at batch scale, while industrial feasibility depends on continuous operation, impurity accumulation, phase disengagement, resin or solvent lifetime, reagent recycle, crystallizer hydrodynamics, product filtration, and specification stability. Mixer-settler testing, multistage adsorption-elution, crystallization scale-up, and process integration studies are therefore disproportionately valuable because they close the distance between a separation factor and a bankable flow sheet (Dewulf et al., 2022; Mohammed & Zhang, 2026; Pawar et al., 2026; Riaño et al., 2020).

A seventh gap is environmental comparability. Primary and secondary Dy routes are often assessed with different system boundaries. A consistent framework should include energy, water, reagent production, neutralization, residues, emissions, coproduct allocation, transport, and avoided primary production. Circular-economy and LCA studies show that the answer can change with regional energy mix and process configuration (Della Bella et al., 2023; Langkau & Erdmann, 2021; Samuel et al., 2026; Savvidou et al., 2026; Wang et al., 2025).

Finally, policy should distinguish strategic capacity from nominal capacity. A facility contributes to resilience only when it can access feed, operate economically, meet product specifications, complete relevant qualification, and serve downstream users under realistic disruption conditions. Critical-material assessments and supply-chain studies support a move toward stress testing rather than static criticality rankings (C. Bogmans et al., 2026a; C. Bogmans et al., 2026b; International Energy Agency, 2026; Nassar et al., 2025; U.S. Department of Energy, 2023). A useful policy dashboard would therefore combine concentration, operating and qualified capacity, qualification status, inventory days, recycling availability, regional access, and technology-adjusted demand.

The portfolio perspective also changes how projects should be prioritized. A smaller integrated Dy separation or recycling project located near magnet manufacturing may improve resilience more than a larger upstream project that exports mixed concentrate. Conversely, a new mine can be highly strategic if paired with local separation and long-term offtake. The investment question is not simply 'how many tonnes of Dy?' but 'how many

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tonnes of qualified, geographically accessible Dy can this intervention add or avoid, how quickly, and at what environmental and economic cost?'

## 12. Conclusions

Dysprosium is a small-volume material with system-level importance because it can determine whether NdFeB magnets meet coercivity and temperature requirements in demanding applications. Its criticality arises from the interaction of growing magnet-dependent technologies, difficult HREE separation, concentrated midstream and downstream capacity, long supply-development lead times, and limited short-run substitution in some high-performance uses.

The central conclusion of this review is that Dy availability should be measured at the point of qualified market supply, not at the level of geological resources or mixed rare-earth production. Likewise, future Dy demand should be modeled as a technology-dependent variable rather than a fixed function of EV, wind, or motor deployment. Grain-boundary diffusion, microstructure engineering, hybrid and rare-earth-reduced motor architectures, and improved thermal design can materially lower Dy intensity, while recycling can add a secondary stream whose contribution is delayed by product lifetimes and depends on closed-loop qualification.

A robust supply–demand assessment therefore requires coupled treatment of conversion-adjusted qualified primary supply, cohort- and time-lagged qualified secondary supply, gross service-driven demand, and avoided demand separated into material efficiency, magnet-chemistry substitution, component redesign, and technology substitution. Geographic concentration, product form, qualification, contracts, logistics, and trade restrictions must then be considered separately from the physical coverage balance because globally adequate tonnage can still coexist with severe regional or application-specific inaccessibility.

The most credible strategy is a diversified portfolio combining upstream projects, separation and refining, metal/alloy and magnet capability, Dy-thrifting magnet technologies, alternative motor designs, process-scrap and end-of-life recycling, strategic inventories, and international sourcing partnerships. The research priority is to replace headline resource and recycling numbers with transparent, product-specific, time-resolved metrics that show how much qualified Dy is actually added to—or removed from—future demand.

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### Conflict of Interest

The author declares no conflict of interest.

### Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

### Author Contributions

Conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation: the author.

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