Rare Earth Permanent Magnet Processing Technologies: Proposed and Newly Applied Innovations — A Techno-Economic Evaluation

A Technical-Commercial Analysis Prepared in Association with the Rare Earth Industry Association (REIA) and the Critical Minerals Institute (CMI)

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Executive Summary

Rare earth permanent magnets — in particular sintered neodymium-iron-boron (NdFeB) — sit at the very centre of the global energy transition. They are the enabling technology behind the traction motors of electric vehicles, the direct-drive generators of offshore wind turbines, the precision actuators of advanced robotics, and an expanding universe of defence and consumer electronics applications. No commercially viable substitute currently matches the volumetric energy density, thermal stability, and coercive force of NdFeB magnets in demanding drive-system applications. This is not a materials science footnote: it is a supply chain reality that governments, automotive OEMs, and capital markets are now confronting with considerable urgency.

Global demand for NdFeB magnets reached approximately 220,000 tonnes per annum in 2025, representing a market value approaching US$18–22 billion. Demand forecasts, anchored by EV adoption trajectories and offshore wind build-out programmes across the European Union, United States, China, and India, project a four- to five-fold increase by 2040 — implying a market in excess of US$30 billion by 2030 and potentially US$80–100 billion by the mid-2040s. Against this demand backdrop, more than 90% of global sintered NdFeB production is concentrated in the People's Republic of China, which also controls more than 60% of rare earth mining output and approximately 85% of global rare earth separation and refining capacity. The structural fragility of this dependency was memorably illustrated by the price spike of 2010–2011, when Chinese export restrictions drove rare earth oxide prices up by 400–700% within eighteen months, and has re-entered the strategic conversation with renewed force amid trade tensions in 2024–2025.

This report evaluates six technology domains that collectively span the entire NdFeB magnet value chain, from the conversion of rare earth oxides to high-purity metals through to end-of-life magnet recycling. The six domains are: (1) oxide-to-metal conversion technologies, including molten salt electrolysis, metallothermic reduction, and emerging electrochemical routes; (2) alloying innovations, including heavy rare earth-lean designs, cerium and lanthanum substitution, and microalloying strategies; (3) powder metallurgy advances, including HDDR processing, spark plasma sintering, and additive manufacturing; (4) grain boundary engineering, most notably commercial grain boundary diffusion and two-phase magnet architectures; (5) recycling technologies, encompassing short-loop direct recycling and hydrometallurgical routes; and (6) solvent extraction improvements, from classical organophosphorus extractants to task-specific ionic liquids and AI-optimised circuit design.

The panel's key findings, expressed through a Techno-Economic Credibility (TEC) scoring framework incorporating technology readiness, cost competitiveness, scalability, environmental performance, and supply chain resilience, are as follows. Grain boundary diffusion combined with HRE-lean alloying achieves the highest TEC score of 9.0/10 at TRL 9 — a commercially proven and immediately deployable technology set. HDDR-based direct recycling (TEC 8.5/10, TRL 7–8) and hydrometallurgical recycling with advanced solvent extraction (TEC 8.0/10, TRL 7–8) represent the most credible near-commercial recycling pathways. Task-specific ionic liquid extractants, while scientifically compelling with Dy/Nd separation factors exceeding 50, remain at TRL 4–5 and score 5.5/10 pending scale-up validation.

Four Western company case studies — Energy Fuels Inc. (White Mesa Mill, Utah), MP Materials Corp. (Mountain Pass, California and Fort Worth, Texas), Vacuumschmelze GmbH (Hanau, Germany), and Noveon Magnetics (San Marcos, Texas) — collectively represent the most credible non-Chinese magnet supply chain development efforts currently underway. Each addresses a distinct segment of the value chain, and their combined strategic positioning offers a partial but meaningful blueprint for Western supply chain diversification.

The panel's strategic recommendation is a three-horizon deployment framework: near-term (2–3 years) prioritisation of GBD + HRE-lean alloying and HDDR-based recycling infrastructure; medium-term (3–7 years) scaled investment in metallothermic reduction and improved SX circuits including organic acid leaching; and long-term (7–15 years) sustained R&D investment in ionic liquid separations, flash sintering, and AI-integrated process control. Across all horizons, the dominant constraint is not technological readiness — it is the industrial policy will and capital mobilisation required to convert demonstrated laboratory and pilot capabilities into operating, commercially competitive Western supply chains.

Section 1: Market Context and Strategic Imperative

Sintered NdFeB permanent magnets are the highest energy-density permanent magnets known to materials science. Their defining characteristic — maximum energy product $(BH)_{max}$ — can reach 400–474 kJ/m^3 in the best commercial grades, representing more than twice the energy density of the next best class of permanent magnet, samarium-cobalt (SmCo). This extraordinary performance arises from the crystallographic and electronic structure of the $Nd_2Fe_{14}B$ tetragonal phase, which combines a high saturation magnetisation from the iron sublattice with a very large magnetocrystalline anisotropy field from the neodymium sublattice. For engineers designing compact, high-torque motors or lightweight generators, this performance ceiling translates directly into system efficiency, volumetric packaging, and cost-of-ownership advantages that alternative motor topologies — induction motors, wound-field synchronous motors, or ferrite-based designs — cannot match on a like-for-like basis in demanding applications.

Three magnetic parameters define commercial grade selection. Remanence (B_r) measures the residual magnetic flux density after magnetisation, with high-performance grades targeting values above 1.40 T. Coercivity (H_{cj}) defines resistance to demagnetisation; for high-temperature applications such as EV traction motors operating at 150–180°C, grades must achieve H_{cj} values exceeding 2,000 kA/m, necessitating heavy rare earth additions of dysprosium (Dy) or terbium (Tb). The Curie temperature (T_c) of stoichiometric NdFeB is approximately 312°C — somewhat low for elevated-temperature stability — but cobalt additions of up to 5 wt% can raise T_c by 50–100°C, improving high-temperature performance at a manageable cost premium. The challenge of simultaneously maximising all three parameters across the service life of a component is the central engineering puzzle that the technology innovations reviewed in this report seek to address.

The principal magnetic elements are neodymium (Nd) and praseodymium (Pr) — light rare earth elements (LREE) that constitute the matrix phase — along with Dy and Tb (heavy rare earth elements, HREE) that serve as coercivity enhancers, iron (Fe), and boron (B). A typical high-performance sintered NdFeB magnet contains approximately 29–32 wt% rare earth (predominantly Nd/Pr), 63–67 wt% Fe, 1 wt% B, and 3–8 wt% Dy/Tb in high-coercivity grades. A single EV traction motor requires between two and three kilograms of NdFeB, while a multi-megawatt direct-drive offshore wind turbine generator consumes one to two tonnes per megawatt of rated capacity. Humanoid robotics platforms — an emerging but rapidly growing application — require multiple precision magnet assemblies per unit. Defence applications including precision guidance systems, electric catapults, and directed energy systems add further demand vectors.

China's dominance across the rare earth value chain is extraordinary in its comprehensiveness. More than 60% of global rare earth mining, approximately 85% of separation and refining, and over 90% of sintered NdFeB magnet production are concentrated within Chinese borders. This concentration is not merely a statistical artefact of geological endowment: it reflects sustained, decades-long industrial policy investment in REE processing infrastructure, subsidised energy, and the cultivation of a fully integrated domestic supply chain from mine to magnet to motor. The consequences of this concentration were dramatically illustrated in 2010–2011, when Chinese export quotas drove rare earth oxide prices to extraordinary levels — neodymium oxide reached approximately US$300/kg at peak, compared to a pre-spike price of approximately US$20/kg — inflicting significant cost shocks on Western magnet producers, many of whom subsequently exited the market or relocated production to China. Renewed Chinese restrictions on REE and magnet exports announced in early 2025 have re-energised the Western policy response, catalysing the investment flows described in the case studies in Section 8 of this report.

The six technology domains examined herein — oxide-to-metal conversion, alloying, powder metallurgy, grain boundary engineering, recycling, and solvent extraction — collectively address every stage of the value chain, from the primary ore concentrate to the finished magnet to end-of-life recovery. Technological progress across all six domains, deployed in a coordinated industrial policy framework, is the prerequisite for a resilient, diversified, and commercially competitive Western rare earth permanent magnet supply chain.

Section 2: Oxide-to-Metal Technologies

2.1 The Oxide-to-Metal Bottleneck

The conversion of rare earth oxides (REO) to high-purity rare earth metals represents the most technically demanding and energy-intensive step in the upstream magnet value chain. Rare earth metals exhibit highly negative standard reduction potentials — neodymium, for example, sits at approximately −2.32 V versus the standard hydrogen electrode — meaning that conventional aqueous electrochemical reduction is thermodynamically impossible. The extreme reactivity of molten rare earth metals with atmospheric oxygen and nitrogen further complicates reactor design. It is a peculiar irony of the rare earth industry that the downstream magnet manufacturing steps — powder processing, pressing, sintering — are technically sophisticated but relatively accessible, while the upstream metal production step remains the domain of only a small number of global operators, the vast majority of them Chinese.

Three principal pathway categories exist for converting REO to metal: molten salt electrolysis (MSE), which is the overwhelmingly dominant incumbent commercial technology; metallothermic reduction, which offers a lower-emission alternative at the cost of process complexity; and a collection of emerging electrochemical and thermal approaches that are currently at laboratory to early pilot scale. Each pathway presents a distinct profile of capital intensity, operating cost, environmental impact, and technology readiness, as elaborated in the subsections that follow.

2.2 Molten Salt Electrolysis (MSE)

Molten salt electrolysis is the global standard for commercial rare earth metal production, and it will remain so for the foreseeable future by virtue of its well-understood engineering, established supply chain for consumables and equipment, and the enormous capital investment already deployed in Chinese facilities operating at scale. The process operates by dissolving neodymium fluoride (NdF_3) or a mixed NdF_3/NdOF electrolyte in a molten salt bath maintained at approximately 1,020–1,080°C. A tungsten cathode is positioned at the centre of the cell, and a carbon ring or carbon rod anode surrounds it. Neodymium ions are reduced at the cathode surface, forming a pool of liquid neodymium metal that is periodically tapped from the cell. Electrolyte composition and temperature are maintained within narrow windows to ensure that the electrolyte's liquidus temperature lies below the operating temperature while remaining above the melting point of neodymium metal (1,021°C). Metal purity of greater than 99% is routinely achievable from a well-operated cell, with oxygen content manageable through careful feedstock quality control. Energy consumption for commercial MSE cells is typically in the range of 10–12 kWh per kilogram of neodymium produced — a significant operating cost element, particularly for producers without access to low-cost electricity.

The strengths of MSE are considerable. At TRL 9, it is the only fully commercial, high-throughput oxide-to-metal technology. Batch sizes of 500 kilograms or more per cell cycle are standard in optimised facilities. The process is continuous — or near-continuous with periodic tapping — and scales predictably. Capital costs for a 1,000 tonne per annum neodymium metal facility are estimated at US$50–80 million, with operating costs dominated by electricity and fluoride electrolyte replenishment.

Against these strengths, two significant weaknesses limit MSE's long-term environmental and regulatory acceptability. First, the anode effect — a transient phenomenon arising from electrolyte depletion at the anode surface — generates perfluorocarbon (PFC) emissions, specifically tetrafluoromethane (CF_4, with a 100-year global warming potential approximately 6,500 times that of CO_2) and hexafluoroethane (C_2F_6, GWP approximately 9,200 times CO_2). While mitigation through cell design improvements and process control is possible, PFC emissions remain an intrinsic feature of fluoride-melt electrolysis and represent a material Scope 1 emissions liability. Second, carbon anode consumption generates CO_2 directly, and cell lining erosion from the highly reactive molten fluoride electrolyte creates a solid hazardous waste stream requiring managed disposal. The combination of these environmental liabilities with a tightening regulatory environment — particularly in the European Union — creates meaningful pressure for alternative technologies. TEC Score: 7.5/10.

2.3 Metallothermic Reduction

Metallothermic reduction routes offer an alternative pathway to rare earth metals that eliminates the fluoride electrolyte chemistry entirely, with associated benefits for PFC emissions and process safety. The calcium metallothermic route (CaR) is the most developed alternative, involving the direct reduction of rare earth oxide with calcium metal according to the reaction $Nd_2O_3 + 3Ca \rightarrow 2Nd + 3CaO$, conducted in a sealed tantalum or molybdenum vessel at 900–1,100°C. The thermodynamics are favourable — calcium's strongly negative free energy of oxide formation ensures complete reduction of neodymium oxide under suitable conditions. The resulting calcium oxide slag and residual calcium are removed by a post-reaction acid wash (dilute HNO_3 or HCl), yielding rare earth metal of commercial purity.

The advantages of CaR are meaningful. There are no PFC emissions, the operating temperature is somewhat lower than MSE, reactor design is considerably simpler, and the process can in principle handle mixed REO streams from complex ores or recycled sources without extensive electrolyte chemistry modification. The disadvantages are equally real. Calcium metal, the reducing agent, is pyrophoric — it ignites spontaneously in moist air — and its cost at approximately US$3–5/kg adds a significant and ongoing OPEX element that has no equivalent in MSE, where the energy input is the primary running cost. The CaO slag separation step and subsequent acid wash add process steps, generate an aqueous waste stream, and extend cycle time. Most importantly, CaR is a batch process, which fundamentally limits throughput relative to the continuous operation achievable with optimised MSE cells. Current TRL for CaR at commercially relevant scale is assessed at 6–7. TEC Score: 6.5/10.

The magnesiothermic route (MgR) — involving the reduction of Nd_2O_3 with magnesium metal in a molten LiCl-KCl flux at approximately 900°C, followed by vacuum distillation to remove excess magnesium — was demonstrated at proof-of-concept scale in a notable 2024 publication in *Nature Chemistry*, which reported a lower overall emissions profile than both MSE and CaR. Magnesium is less expensive than calcium and less hazardous in handling, and the flux chemistry offers improved slag-metal separation. However, the process remains at TRL 4–5, and significant engineering challenges around reactor design, flux management, and vacuum distillation scalability must be resolved before commercial deployment can be contemplated. TEC Score (MgR): 5.0/10, reflecting its experimental status.

2.4 Emerging Oxide-to-Metal Technologies

Beyond MSE and metallothermic reduction, four emerging technology categories deserve attention from industry strategists, though each is at early development stage and faces significant scale-up hurdles.

Electrochemical reduction in ionic liquids and deep eutectic solvents (DES) replaces the high-temperature fluoride melt of MSE with a room-temperature to 300°C ionic liquid electrolyte that is free of fluoride salts and hydrofluoric acid. This eliminates PFC emissions entirely and potentially reduces energy consumption by up to 40% relative to MSE. Task-specific ionic liquid systems based on phosphonium and imidazolium cations have been demonstrated for neodymium deposition at laboratory scale. However, current ionic liquid costs of approximately US$50/kg, combined with limited current density achievable in IL systems, place this technology far from commercial competitiveness. TRL is assessed at 3–4.

The FFC Cambridge Process — in which solid rare earth oxide pellets are used directly as the cathode in a calcium chloride melt, with electrochemical reduction proceeding through a solid-state ionisation mechanism — has been demonstrated for neodymium and dysprosium at laboratory scale with projected energy consumption of approximately 8 kWh per kilogram, representing a meaningful improvement over MSE. The elegance of eliminating the need for pre-formed fluoride salts and achieving direct solid-to-metal conversion is scientifically compelling, but questions around cell geometry, scalability, and purity control at large throughput remain unanswered. TRL: 4–5.

The magnesiothermic reduction route, described above in the context of the 2024 Nature demonstration, merits repetition here as an emerging process. Its lower-carbon credentials, combined with the relative accessibility of magnesium metal from diverse global sources, make it a credible medium-term alternative development pathway, particularly for producers in regions with low-cost magnesium or limited access to fluoride electrolyte infrastructure.

Hydrogen-assisted reduction (HAR) represents perhaps the most speculative but conceptually appealing long-term pathway. In this approach, rare earth oxides are first reduced to rare earth hydrides (NdH_2) via direct hydrogen exposure, with the hydride intermediate subsequently decomposed thermally in vacuum to yield neodymium metal. The process avoids molten salts entirely and, with green hydrogen as the reductant, could in principle achieve near-zero Scope 1 emissions. Cost parity with MSE is currently estimated to require hydrogen prices below approximately US$2/kg H_2 — a target not expected to be achievable at commercial scale before the early 2030s. TRL: 3. HAR should be monitored as a long-duration strategic option rather than a near-term development priority.

Section 3: Alloying Innovations

3.1 The Alloy Composition Challenge

Alloy composition determines the fundamental ceiling of magnetic performance that any manufacturing process can achieve. No amount of microstructural optimisation, grain boundary engineering, or press-sintering refinement can recover properties that were not built into the alloy at the design stage. The central challenge in NdFeB alloy development is therefore to identify compositions that maximise remanence and coercivity simultaneously, while minimising reliance on strategically vulnerable and expensive heavy rare earth elements — dysprosium and terbium — and making best use of the abundant but lower-value light rare earth elements, particularly praseodymium, cerium, and lanthanum, which are produced in large quantities as co-products of primary REE mining regardless of market demand. The tension between magnetic performance and critical material supply risk is the defining trade-off in this technology domain.

3.2 HRE-Lean Designs

Historically, high-coercivity sintered NdFeB grades for automotive and industrial applications contained between 3 and 8 wt% dysprosium. The rationale is straightforward: Dy substitutes for Nd in the $Nd_2Fe_{14}B$ crystal lattice, substantially increasing the magnetocrystalline anisotropy field and therefore the coercive force, at the cost of a modest reduction in remanence. However, dysprosium is one of the most supply-constrained rare earth elements, produced predominantly as a byproduct of ion-adsorption clay mining in southern China's Jiangxi and Guangdong provinces. At prevailing 2025 prices of approximately US$300–400/kg for Dy oxide, the addition of even 3 wt% Dy in a commercial magnet represents a cost increment of approximately US$25–35/kg of finished magnet — a material fraction of total magnet cost that directly incentivises HRE reduction.

HRE-lean alloy design, combined with grain boundary diffusion (treated in detail in Section 5), has emerged as the primary commercial strategy for Dy reduction. At the alloy level, optimisation of the Nd/Pr ratio, boron content, and Fe:RE stoichiometry can improve the intrinsic coercivity of the base alloy before any HRE addition, allowing Dy content to be reduced to 1–2 wt% without grain boundary diffusion treatment, or to effectively zero with GBD. The commercial validation of HRE-lean designs by Vacuumschmelze, TDK, and Shin-Etsu at TRL 8–9 provides a robust reference base. The financial incentive is clear: every 1 wt% reduction in Dy content equates to approximately US$6–12 per kilogram of finished magnet in cost savings at current Dy prices, and substantially more in stress scenarios where Chinese supply restrictions tighten further. TEC Score: 9.0/10 (in combination with GBD).

3.3 Ce and La Substitution

Cerium is the most abundant rare earth element in the Earth's crust and is produced in large quantities as an unavoidable co-product of neodymium and lanthanum mining — yet it commands minimal market value due to limited demand relative to production volumes. The Ce oversupply paradox has been a persistent feature of the REE market for two decades: Ce constitutes roughly 50% of the total rare earth content of the most common ore minerals, but its primary uses in catalysts, glass polishing, and UV filtering are largely saturated. Integrating Ce as a partial Nd substitute in NdFeB alloys could simultaneously reduce Nd demand, lower magnet cost, and create a value-adding market for an otherwise stranded co-product.

Research at the Ames National Laboratory and universities in China, Japan, and Germany has demonstrated that substituting 10–30 wt% of neodymium with cerium in the alloy matrix produces NdCeFeB magnets with remanence reductions of 5–12% and coercivity reductions of 15–25% relative to standard NdFeB — acceptable trade-offs for medium-performance applications such as home appliance motors, HVAC compressors, and light industrial drives. The corresponding cost reduction is estimated at 20–35%, making Ce-substituted grades highly attractive for cost-sensitive volume applications. Multiple pilot-scale demonstrations have been completed, and some commercial production of Ce-substituted grades is underway in China, though Western commercial adoption remains limited. TEC Score: 7.5/10 — commercially attractive, well-validated at pilot scale, limited only by OEM requalification timelines and the conservatism of established supply chains.

Lanthanum integration presents a different but complementary opportunity. La, produced in quantities roughly comparable to Ce from bastnäsite and monazite ores, similarly has limited market demand and depressed pricing. Research has shown that additions of up to 5 wt% La can stabilise the Nd-rich intergranular phase in sintered NdFeB, with some formulations demonstrating maintained or marginally improved coercivity through optimisation of the La-rich grain boundary phase chemistry. The mechanism differs from Ce substitution: La does not enter the $Nd_2Fe_{14}B$ matrix phase significantly but preferentially partitions to grain boundaries, where its presence can modify the wetting behaviour and amorphous content of the intergranular phase. DOE CMI Hub research at Ames National Laboratory has provided the primary academic basis for La integration strategies. TEC Score: 6.0/10 — promising but at lower maturity than Ce substitution, with more limited commercial validation to date.

3.4 Microadditions and Novel Quaternary Alloys

Beyond the principal magnetic elements, a family of microaddition strategies — typically involving element additions below 1 wt% — offers targeted improvements to specific magnet properties without requiring fundamental alloy redesign. Gallium additions at 0.1–0.5 wt% enhance the wettability and continuity of the Nd-rich intergranular phase, improving magnetic decoupling of individual grains and thereby raising coercivity without requiring any additional HRE. TEC Score for Ga/Al microadditions: 8.0/10.

Zirconium and niobium additions at 0.05–0.3 wt% serve as grain boundary pinning agents during sintering, inhibiting abnormal grain growth and maintaining the fine, uniform grain size — typically below 3 µm — that is required for maximum coercivity. The resulting $(BH)_{max}$ improvements of 2–5 kJ/m^3 are commercially meaningful. TEC Score: 7.5/10. Aluminium additions in the range of 0.1–0.5 wt% improve corrosion resistance by modifying the grain boundary phase composition, reducing the anodic activity of the Nd-rich phase. Cobalt additions of up to 5 wt% raise the Curie temperature by 50–100°C, a critical performance parameter for EV traction motor applications where magnet operating temperatures can exceed 150°C. TEC Score for Co/Cu additions: 8.5/10.

One strategic caveat requires explicit attention. Gallium — a microaddition element that enables HRE reduction by improving GB phase wettability — is itself a critical material of significant supply concentration risk. More than 90% of global gallium production originates in China as a byproduct of zinc smelting, and China imposed export restrictions on gallium in August 2023, demonstrating the potential for gallium supply disruption to constrain Ga-dependent magnet formulations. Substituting one supply chain vulnerability (Dy) with another (Ga) is not a strategically robust outcome and should inform alloy design decisions at the system level. Additionally, automotive OEM requalification cycles of two to four years create a commercialization lag for new alloy compositions, even where laboratory and pilot-scale performance data are compelling — a factor that systematically delays adoption of technically validated innovations in the industry's highest-volume application segment.

Section 4: Powder Metallurgy Advances

4.1 Conventional Powder Metallurgy Baseline

The standard manufacturing process for sintered NdFeB magnets has remained fundamentally unchanged in its sequential logic since its development in the mid-1980s, though each step has been progressively refined. Strip casting of the master alloy — a rapid solidification technique that produces thin flakes with controlled microstructure — has largely replaced conventional book mould casting as the preferred feedstock preparation method, offering more uniform REE distribution and better hydrogen decrepitation response. Hydrogen decrepitation (HD) exploits the preferential absorption of hydrogen along the Nd-rich grain boundaries to fracture the cast alloy into a coarse powder without mechanical grinding, which would introduce oxygen contamination. The coarse powder is then fed to a jet mill (typically nitrogen-atmosphere, O_2 content controlled to below 200 parts per million) where impact-based attrition produces the final powder with a D50 particle size of 3–5 µm — the grain-size range critical for single-domain particle behavior and maximum coercivity.

The milled powder is magnetically aligned in a field of 1.5–2.5 Tesla — either in a die during pressing or in a separate alignment station — before cold isostatic pressing (CIP) to achieve green densities of 55–65% of theoretical. Vacuum sintering at 1,050–1,080°C for four to eight hours achieves full densification, followed by a two-stage annealing treatment (typically 900°C and 500°C) that optimises the grain boundary phase chemistry and maximises coercivity. The resulting sintered magnet is then machined to final dimensions, surface-treated (typically Ni-Cu-Ni plating or epoxy coating), and magnetised. This process, continuously optimised over four decades, remains the global standard for high-performance NdFeB production and defines the baseline against which all advanced powder metallurgy approaches are measured.

4.2 HDDR Process Advances

The Hydrogenation–Disproportionation–Desorption–Recombination (HDDR) process represents one of the most important manufacturing innovations in rare earth magnet production since strip casting. The process operates by exposing NdFeB feedstock — either virgin alloy or recycled magnet material — to controlled hydrogen partial pressures at elevated temperature (800–900°C). During the hydrogenation and disproportionation phase, the $Nd_2Fe_{14}B$ matrix phase decomposes into a mixture of NdH_2, Fe, and Fe_2B, creating a nanoscale composite microstructure with characteristic length scales of 200–500 nm. Upon controlled desorption and recombination — achieved by reducing hydrogen partial pressure while maintaining temperature — the $Nd_2Fe_{14}B$ phase reforms with a dramatically refined grain structure. The key innovation of dynamic-HDDR (d-HDDR), which varies hydrogen pressure and temperature simultaneously according to a carefully designed profile, is the achievement of a degree of crystallographic texture (typically expressed as a texture degree value, where 1.0 is perfect alignment) of approximately 0.85 — substantially improved over the 0.60 achievable with conventional, static HDDR.

The commercial importance of HDDR extends beyond the production of fine anisotropic powder for bonded magnets. Its applicability to recycled magnet scrap — the feedstock for which is demagnetised, decoated end-of-life NdFeB — makes HDDR the central manufacturing process for the circular economy in rare earth magnets, as elaborated in Section 6. Commercial HDDR processes have been implemented by Santoku Corporation in Japan and by Magnequench in North America, and the technology has attracted significant academic and industrial research effort in the United Kingdom (University of Birmingham), Germany (Fraunhofer IWKS), and the United States (Ames National Laboratory). TRL: 7–8, with ongoing scale-up and process optimisation work across multiple institutions.

4.3 Spark Plasma Sintering (SPS/FAST)

Spark plasma sintering — also known as field-assisted sintering technology (FAST) — applies a pulsed direct current simultaneously with uniaxial mechanical pressure to a powder compact, achieving densification through a combination of Joule heating at particle contacts, surface activation from spark plasma discharge, and conventional pressure-driven creep mechanisms. The result is full theoretical density at 900–1,050°C in just three to five minutes — compared to four to eight hours for conventional vacuum sintering — with substantially improved grain size control. SPS-consolidated NdFeB magnets exhibit grain sizes of 2–4 μm versus the 5–10 μm typical of conventionally sintered material, translating to $(BH)_{max}$ improvements of 3–8 kJ/m^3 and improved coercivity through the enhanced grain-boundary-to-grain-volume ratio. Oxygen uptake during processing is minimised by the inert atmosphere and the short thermal exposure cycle.

The commercial attractiveness of SPS is tempered by two significant limitations. Capital cost — a production-scale SPS press with the force and tooling required for magnet compaction is priced at approximately US$2–4 million per unit — is substantially higher than conventional press-sinter equipment. More fundamentally, the uniaxial geometry of SPS tooling constrains the magnet geometries that can be produced and limits the magnetic alignment that can be applied during consolidation, challenging the production of the near-net-shape magnets with complex geometry increasingly demanded by motor designers. Scalability from the laboratory-scale SPS demonstrations at Sandia National Laboratories and Zhengzhou University to production quantities remains a significant engineering challenge. TRL: 6–7 (pilot scale). TEC Score: 7.0/10.

4.4 Cold Sintering and Additive Manufacturing

The Cold Sintering Process (CSP), pioneered at Pennsylvania State University, achieves densification of ceramic materials at temperatures as low as 25–200°C through the introduction of a controlled transient liquid phase — typically an aqueous solution or organic solvent — that activates surface diffusion and dissolution-precipitation mechanisms at room temperature, before being removed by evaporation during the sintering cycle. For oxides and non-reactive ceramics, CSP has demonstrated densities above 90% of theoretical at temperatures that would be entirely compatible with polymer and organic component co-processing. The extension of CSP principles to NdFeB — where the reactive neodymium-rich phases are sensitive to oxidation and the thermodynamic stability of the key magnetic phase must be maintained — remains under active investigation as of 2024–2025, with early feasibility studies reporting preliminary results. The potential for radical energy savings compared to conventional vacuum sintering at 1,050°C is evident, but the process is assessed at TRL 2–3 for NdFeB specifically. It is a disruptive but speculative option that merits monitoring rather than near-term investment.

Additive manufacturing of NdFeB magnets represents perhaps the most strategically consequential emerging manufacturing technology in this domain, as it enables the production of magnets with complex three-dimensional geometries that are simply not achievable through conventional die-press and CIP routes. Binder jetting, material extrusion (FFF), and direct ink writing processes have all been applied to NdFeB powder systems, producing bonded or partially sintered magnets with remanence values currently in the range of 60–80% of pressed-and-sintered counterparts, primarily limited by achievable powder packing density and the difficulty of applying a strong uniaxial alignment field in the three-dimensional print geometry. Desktop Metal (now Markforged) has commercialised binder jetting of NdFeB compounds, and Noveon Magnetics has demonstrated production-scale 3D-printed bonded NdFeB magnets at TRL 6. Sintered AM NdFeB — which would require post-print vacuum sintering and remains far more challenging to align — is assessed at TRL 4–5 and represents a medium-term development target whose achievement would substantially disrupt conventional magnet manufacturing economics.

Section 5: Grain Boundary Engineering

5.1 The Role of Grain Boundaries in NdFeB

Understanding why grain boundary engineering is the single highest-impact technology area in sintered NdFeB processing requires a brief foray into the fundamental coercivity mechanism. In commercial sintered NdFeB, coercivity is nucleation-controlled: demagnetisation does not proceed by coherent rotation of individual magnetic moments across the entire grain, but begins at structurally or chemically defective regions at grain boundaries and surface layers where the local anisotropy field is reduced. Once a reversed magnetic domain nucleates at such a defect site, it propagates rapidly through the grain and drives magnetisation reversal. The practical consequence is that the measured coercivity of a real sintered magnet can be as low as 20–30% of the theoretical single-domain particle coercivity predicted from the

$Nd_2Fe_{14}B$ anisotropy field — a gap attributable almost entirely to grain boundary defects, secondary phase heterogeneity, and imperfect magnetic decoupling between adjacent grains.

The Nd-rich intergranular phase — a thin (typically 2–5 nm), amorphous or nano-crystalline layer that wets the grain boundaries between adjacent $Nd_2Fe_{14}B$ grains in well-sintered NdFeB — is the key to addressing this gap. When this intergranular phase is continuous, chemically homogeneous, and properly wetted, it provides magnetic isolation between adjacent grains, preventing cooperative domain reversal and dramatically increasing observed coercivity. When it is discontinuous, crystallised, or has the wrong chemical composition, it becomes a site of nucleation and a pathway for domain wall propagation. Grain boundary engineering (GBE) encompasses all process and compositional strategies designed to optimise the intergranular phase — its continuity, chemistry, wetting angle, and thermal stability.

5.2 Grain Boundary Diffusion (GBD) — Commercial Benchmark

Grain boundary diffusion is the most commercially mature and impactful GBE technology and is assigned the highest TEC score of any technology reviewed in this report: 9.0/10 at TRL 9. First demonstrated commercially by Shin-Etsu Chemical and Hitachi Metals between approximately 2005 and 2010, GBD involves the application of a slurry or powder coating of dysprosium or terbium compound — typically Dy_2O_3, Dy fluoride (DyF_3), or Tb fluoride (TbF_3) — to the surface of a pre-sintered magnet, followed by a heat treatment at 850–950°C in a vacuum or inert gas atmosphere. At these temperatures, the Dy or Tb atoms diffuse inward from the magnet surface along the Nd-rich grain boundary network, which acts as a high-diffusivity pathway relative to the bulk of the $Nd_2Fe_{14}B$ grains.

The result of this diffusion treatment is the formation of a $(Nd,Dy)_2Fe_{14}B$ or $(Nd,Tb)_2Fe_{14}B$ compositional shell around each grain, typically a few atomic layers thick, that has dramatically higher local magnetocrystalline anisotropy than the Nd-rich core — and therefore a much higher local coercive field. Because the HRE is concentrated only at the grain boundary regions where nucleation would otherwise initiate, and not distributed throughout the grain interior where it would reduce remanence, GBD achieves coercivity improvements of up to +600 kA/m with Dy additions that are 40–60% lower than those required by conventional bulk alloying to achieve the same coercivity improvement. The corresponding cost saving, at 2025 Dy prices, is US$3–8/kg of finished magnet. The second post-diffusion annealing step at approximately 500–600°C further optimises the grain boundary phase chemistry and maximises the uniformity of the $(Nd,Dy)_2Fe_{14}B$ shell structure.

The key technical limitation of surface-applied GBD is diffusion depth: the technique is only fully effective in magnets with a thickness up to approximately 5 mm per treated face. For thicker magnets — such as those used in large EV traction motors or wind turbine generators — the gradient in Dy concentration from surface to core can result in non-uniform magnetic properties and inadequate demagnetisation resistance in the magnet centre. This limitation has driven the development of two-phase magnet architectures as a complementary or alternative approach, described below.

5.3 Two-Phase Magnet (2PM) Architecture

The two-phase magnet approach addresses the thickness limitation of surface GBD by distributing the heavy rare earth element throughout the magnet volume during powder processing, before sintering. Two distinct powders are prepared and blended prior to magnetic alignment and pressing: a first powder with the standard Nd-rich high-remanence composition, and a second powder with elevated Dy or Tb content optimised to preferentially wet and enrich grain boundaries throughout the magnet bulk upon sintering. The thermodynamics of the NdFeB system favour the partitioning of HRE-rich compositions to the intergranular phase during sintering, provided the powder blend ratios and sintering conditions are correctly optimised. The outcome is a microstructure that approximates the surface-to-core HRE gradient of GBD-treated magnets, but distributed throughout the full magnet thickness — enabling the processing of magnets of any dimension without the depth-dependent uniformity limitation of surface diffusion.

Published results from academic and industrial groups in Germany (Technische Universität Darmstadt) and Austria (Vienna University of Technology) report Dy savings of 60–70% relative to conventional uniform alloying for equivalent coercivity targets, with minimal remanence penalty when blend optimisation is correctly executed. The two-phase approach is at TRL 7–8: beyond pure academic demonstration but not yet fully scaled to commercial production volumes. The primary remaining challenges are achieving reproducible powder blend homogeneity at industrial scale and demonstrating long-term thermal stability of the resulting grain boundary microstructure in high-temperature motor environments. TEC Score: 7.5/10, reflecting its meaningful HRE savings and thickness-independence alongside its current pilot-to-commercial scaling status.

5.4 Intergranular Phase Control and Emerging GBE Methods

The precision characterisation capabilities now available to researchers — including Lorentz transmission electron microscopy, atom probe tomography, and synchrotron X-ray diffraction — have transformed understanding of the NdFeB grain boundary phase at atomic resolution. These techniques have revealed that the magnetic performance of sintered NdFeB is exquisitely sensitive to the GB phase composition at the nanometre scale: variations of a few atomic percent in Cu, Ga, or Al content can determine whether the intergranular phase is amorphous and non-ferromagnetic (desirable) or crystallised with partial ferromagnetic order (deleterious for coercivity). This understanding underpins microaddition strategies for GB phase control: Cu additions at 0.1–0.3 wt% stabilise the amorphous GB phase; Ga additions improve wettability and coverage; Al additions reduce the activity of the Nd-rich phase and improve its oxidation resistance.

Vapour-phase GBD — applying HRE compounds as a vapour rather than a surface slurry — enables more uniform treatment of complex magnet geometries with internal channels, holes, or re-entrant surfaces that surface slurry application cannot reach. Electrochemical diffusion processes, in which the HRE is driven into the magnet surface by an applied electric field in an ionic medium, have been demonstrated in laboratory settings and offer potential for precise, controllable treatment of near-net-shape magnets with complex surface geometry.

Most recently, a 2025 publication in *Nature Computational Materials* demonstrated the use of digital twin microstructure modelling — in which a full three-dimensional computational replica of the magnet grain structure is constructed from synchrotron tomography data — combined with AI-driven process optimisation to predict the optimal GBD treatment parameters (temperature, time, HRE compound concentration) for any given magnet geometry and composition. The closed-loop integration of this digital twin with real-time process monitoring data during GBD heat treatment represents a transformative capability for quality assurance in high-volume magnet production. This approach is currently assessed at TRL 5–6 but is advancing rapidly, with pilot implementation at Vacuumschmelze among the reported early adopters.

Section 6: Recycling Technologies

6.1 The Recycling Imperative

Less than 1% of rare earth elements are currently recovered and recycled globally — a statistic that is both an indictment of the industry's historical attitude toward circular economy principles and an indicator of the extraordinary opportunity that systematic recycling represents. The calculus of necessity is straightforward: if NdFeB demand grows four- to five-fold by 2040, and if primary rare earth mining cannot expand at sufficient pace — constrained by resource geology, environmental permitting timelines, processing infrastructure investment, and supply chain geopolitics — then secondary recycling of end-of-life magnets must contribute a growing fraction of market supply. For HREE in particular, where supply is geographically concentrated in China's ion-adsorption clay deposits, recycling represents not merely an environmental preference but a supply security imperative of the first order.

NdFeB permanent magnets are the highest-value secondary REE source currently accessible. A typical sintered NdFeB magnet contains 28–35 wt% rare earth elements, with an elemental value in the range of US$60–120 per kilogram of magnet at 2025 prices — comparable to, and often exceeding, the value of the REE content in primary ore concentrates on a metal-equivalent basis. Four principal recycling feedstock streams present themselves, each with distinct characteristics. Manufacturing scrap — generated in-process during magnet machining and pressing — has predictable, single-alloy composition and is accessible at or near the production facility, making it the lowest-cost and highest-quality recycling feedstock currently available. Hard disk drive magnets represent an established, relatively well-characterised urban mining stream with accessible recovery logistics. EV motor magnets are the highest-volume future stream but have a lag of eight to fifteen years from initial vehicle deployment to large-scale end-of-life availability. Wind turbine magnets will ultimately represent the largest individual tonnage stream but have service lives of twenty to twenty-five years, placing significant EoL volumes in the 2040s and beyond.

6.2 Short-Loop Direct Recycling (HDDR-Based)

The short-loop direct recycling route — variously termed magnet-to-magnet (M2M) or hydrogen processing of magnet scrap (HPMS) — is the most energy-efficient and resource-conserving approach to NdFeB magnet recycling and achieves the highest TEC score among recycling technologies: 8.5/10 at TRL 7–8. The process begins with the demagnetisation of collected end-of-life magnets, achieved by heating above the Curie temperature (≥350°C) in a controlled atmosphere. Surface coatings — typically nickel-copper-nickel electroplate or epoxy — are removed by a thermal or chemical decoating step at 300–400°C. The decoated magnet material is then subjected to hydrogen decrepitation (HD), in which exposure to hydrogen at pressures of 0.5–3 bar at 200–400°C causes rapid absorption and grain boundary decrepitation, fracturing the magnet into a coarse powder while preserving the intrinsic magnetic properties of the individual grains. Dynamic-HDDR treatment then refines the grain structure to the nanoscale anisotropic powder described in Section 4.2, producing a recycled magnetic powder with remanence and coercivity values at 85–95% of those achievable from virgin alloy powder of the same nominal composition.

The resource efficiency of this route is exceptional: REE recovery exceeds 97%, waste generation is below 5% by mass, and energy consumption for the recycling processing steps is approximately 90% lower than the equivalent mine-to-metal-to-magnet primary route. The recycled powder can be used directly in bonded magnet production or blended with a proportion of virgin powder to upgrade properties to full commercial specification before pressing and sintering of new sintered magnets. Commercialisation has been achieved by Santoku Corporation in Japan, by Birmingham University spin-outs in the United Kingdom, by the Fraunhofer IWKS institute in Germany, and — most visibly in the Western commercial context — by Noveon Magnetics in San Marcos, Texas, whose M2M process is described in detail in Section 8.4. The key limitation is feedstock quality: mixed-alloy or heavily contaminated end-of-life streams — for example, from consumer electronics containing multiple magnet grades and contaminating metallic components — reduce the quality and consistency of the recycled powder and may require additional sorting and pre-processing steps. For well-characterised manufacturing scrap and single-alloy end-of-life streams, this limitation is minimal.

6.3 Hydrometallurgical Recycling

Hydrometallurgical recycling routes offer broader applicability to mixed, contaminated, or compositionally complex magnet scrap streams where short-loop direct recycling would produce an unacceptable product quality. The hydromet route processes pre-shredded and decoated magnet material through acid leaching, dissolving the rare earth content into an aqueous solution while leaving iron and boron in the leach residue or in solution depending on leach conditions. Modern approaches to magnet leaching increasingly favour organic acid systems — malic acid, citric acid, succinic acid — over strong mineral acids (hydrochloric acid, sulphuric acid), on the basis that organic acids offer greater selectivity for REE dissolution over iron, substantially reducing the volume of iron that must be managed in the subsequent solvent extraction circuit. The selectivity advantage of organic acid leaching translates directly into reduced SX stage requirements, lower reagent consumption, and simplified iron removal — a commercially meaningful operational improvement.

Following leaching, the REE-bearing aqueous phase is purified and then subjected to multi-stage countercurrent solvent extraction using the extractant systems described in Section 7. D2EHPA, PC-88A, or Cyanex 272 circuits achieve separation of the LREE fraction (Nd, Pr) from the HREE fraction (Dy, Tb), and within each fraction, individual element separation can be achieved in additional SX stages. The purified REE fractions are stripped from the organic phase, precipitated as REE oxalate or carbonate, dried, and calcined to produce rare earth oxide at purities exceeding 99%. This REO re-enters the standard oxide-to-metal processing chain described in Section 2. Iron and boron recovered from the leach residue can be valorised as iron oxide pigment or fertiliser-grade boron compounds, respectively, improving the overall economics of the process. TRL: 7–8, with multiple commercial pilot operations in Europe (Cyclic Materials, REEtec, Less Common Metals) and the United States (Energy Fuels' secondary feedstock processing).

The primary challenge constraining the scale-up of hydrometallurgical recycling is not the technology itself — which is operationally well-understood and commercially validated at pilot scale — but the collection, sorting, and logistics infrastructure required to aggregate sufficient volumes of end-of-life magnet material to feed a commercial-scale processing facility. Magnets are embedded in complex assemblies (hard disk drives, EV motors, wind turbine generators) from which they must be extracted — often manually, due to the difficulty of automated disassembly — before any hydrometallurgical processing can begin. Building the collection and pre-processing infrastructure represents a supply chain challenge of comparable difficulty to the metallurgical processing itself.

6.4 Pyrometallurgical and Electrochemical Approaches

Pyrometallurgical recycling routes for NdFeB scrap — principally glass slag smelting, in which the magnet material is melted with a suitable flux composition designed to partition the REE content into a controlled slag phase while iron reports to a crude metal phase — offer the advantage of handling severely contaminated or compositionally unknown scrap without the pre-sorting requirements of direct or hydrometallurgical routes. The REE-enriched slag can subsequently be processed by conventional SX after acid dissolution, or by direct electrochemical reduction in a molten salt bath to recover mixed RE metals. However, the high energy intensity of the smelting step, the relatively low REE recovery achievable in the slag (typically 85–92% vs. 97%+ for direct recycling), and the loss of elemental selectivity — meaning that Nd, Pr, Dy, and Tb are recovered as a mixed RE metal rather than as separated individual elements — significantly limit the attractiveness of pyrometallurgical routes relative to direct or hydrometallurgical recycling for most commercial scenarios. TRL: 4–5. The pyrometallurgical approach retains relevance for heavily mixed or contaminated scrap streams where the cost and technical difficulty of pre-sorting render it the only practically feasible option.

Section 7: Solvent Extraction Improvements

7.1 The Central Role of Solvent Extraction in REE Processing

Solvent extraction — also known as liquid-liquid extraction — is the backbone of all commercial rare earth element separation, whether applied to primary ore leach solutions, secondary recycling streams, or the intermediate processing stages between mining and metal production. The physical chemistry of SX exploits the differential partitioning of target ions between a polar aqueous phase and a non-polar organic phase containing a selective extractant dissolved in a hydrocarbon diluent. By designing multi-stage countercurrent mixer-settler circuits, high separation factors can be achieved across many theoretical extraction stages — a necessity given the extreme chemical similarity of the 17 rare earth elements, which share nearly identical ionic radii (differing by less than 0.1 Å across the lanthanide series) and oxidation chemistry. The dominance of SX in commercial REE processing is not primarily a technological preference but a consequence of this chemical similarity, for which no more efficient bulk separation technology has yet been demonstrated at commercial scale.

All major REE separation facilities globally — whether in Bayan Obo (China), Mountain Pass (California), or the emerging European and Australian operations — rely on continuous countercurrent mixer-settler SX circuits operating with dozens to hundreds of theoretical extraction stages. The scale of infrastructure required for high-purity Nd/Pr separation from a typical bastnäsite leach solution, or for the critical Dy/Tb separation from a mixed HREE solution, is substantial: a 1,000 tonne per annum NdPr oxide SX facility may contain several hundred mixer-settler stages operating in multiple extraction, scrubbing, and stripping circuits. The capital and operating cost of this infrastructure — in terms of equipment, organic extractant inventory, diluent consumption, and aqueous chemical reagents — is a material fraction of total REE separation economics.

7.2 Classical Organophosphorus Extractants

Three organophosphorus extractants dominate commercial REE SX practice globally and will continue to do so for the foreseeable future by virtue of their established industrial track record, commercial availability in multi-tonne quantities, and well-understood process chemistry.

D2EHPA (di-2-ethylhexyl phosphoric acid) is the workhorse industrial extractant for rare earth separation. It operates by cation exchange at pH 1–3, extracting Nd and Pr from acidic aqueous solution into the organic phase (typically kerosene or Shellsol diluent) with high loading capacity. Its primary weaknesses include a tendency towards third-phase formation at high iron concentrations — a particular issue for leach solutions derived from NdFeB scrap with residual iron content — and the requirement for saponification with sodium hydroxide solution to adjust the pH of the organic phase for selective REE extraction, generating a significant sodium chloride or sodium sulphate waste stream. D2EHPA's selectivity for Nd/Dy separation is limited, typically requiring many extraction stages to achieve high Nd/Dy separation factors. TRL: 9.

PC-88A (2-ethylhexyl phosphonic acid mono-2-ethylhexyl ester) offers improved LREE/HREE separation relative to D2EHPA, allowing Dy and Tb to be separated from the Nd/Pr fraction in fewer SX stages. It is the standard extractant in Chinese REE SX circuits for the Nd/Dy separation step and is commercially produced at large scale. PC-88A is more expensive than D2EHPA on a unit mass basis but delivers meaningful process simplification in circuits requiring HREE separation. TRL: 9.

Cyanex 272 (bis(2,4,4-trimethylpentyl)phosphinic acid) provides the highest HREE selectivity of the three principal organophosphorus extractants, achieving Dy/Tb separation factors over Nd/Pr that are significantly better than either D2EHPA or PC-88A. Its kinetics are slower — requiring longer settler residence times and potentially more mixer-settler stages — and its unit cost is substantially higher, limiting its commercial application to speciality circuits where maximum Dy/Tb separation efficiency is required regardless of cost. TRL: 9. Commercial use is reported in speciality Chinese plants and selected Western operations targeting high-purity HREE oxides.

7.3 Ionic Liquid and Task-Specific Extractants

Task-specific ionic liquids (TSILs) represent the most scientifically exciting development in REE separation chemistry of the past decade. Unlike conventional ionic liquids used as inert solvents or diluents, TSILs incorporate REE-selective functional groups — phosphonate, phosphate, amide, or carboxylate moieties — directly into the ionic liquid cation or anion structure, combining the extraction functionality of a conventional organophosphorus extractant with the unique physicochemical properties of an ionic liquid: near-zero vapour pressure (dramatically reducing organic vapour losses and improving worker health and safety), negligible flammability, and in principle the possibility of operating without any hydrocarbon diluent.

The most thoroughly characterised TSIL system for REE separation is the [P_{66614}][Cyanex272] system — commercially known as Cyphos IL 104, produced by Cytec (now Solvay) — which combines a phosphonium cation with the Cyanex 272 anion. Research groups across Belgium, the Netherlands, Sweden, and the United States have reported Dy/Nd separation factors exceeding 50 for this system under optimised conditions, compared to the typical 5–15 achievable with conventional D2EHPA or PC-88A circuits. This order-of-magnitude improvement in selectivity would translate, if achieved at commercial scale, into dramatically reduced circuit stage counts, smaller physical footprint, and lower reagent inventory for equivalent throughput. The near-zero vapour pressure of the IL system also reduces the explosion risk associated with conventional kerosene or Shellsol diluents in conventional SX circuits — a meaningful process safety advantage for Western operators operating under rigorous ATEX and OSHA regulatory frameworks.

The current barriers to commercial deployment of TSILs are primarily economic. Ionic liquid costs at approximately US$100/kg — compared to approximately US$5/kg for D2EHPA — impose a capital lock-up per unit of organic phase inventory that renders conventional mixer-settler circuit designs uneconomic. Long-term IL stability under the oxidising and acidic conditions encountered in REE SX circuits remains incompletely characterised, with some degradation products reported that could complicate long-term operation and product purity. TRL: 4–5. The TSIL SX concept is assessed as a strategic long-duration bet: if scale-up costs can be reduced — through IL synthesis optimisation and larger production volumes — and long-term stability validated, TSILs could transform HREE separation economics within ten to fifteen years. TEC Score: 5.5/10 reflecting high future potential constrained by current economic and maturity limitations.

Deep eutectic solvents (DES) — typically choline chloride-based systems with oxalic acid, malonic acid, or ethylene glycol as the hydrogen bond donor — are biodegradable, low-toxicity, and inexpensive relative to TSILs, at approximately US$2–10/kg. DES systems have demonstrated selective dissolution of neodymium from NdFeB powder under mild conditions, with the selectivity arising from the differential complexation of REE versus iron in the DES phase. After REE precipitation, the DES can in principle be recycled, reducing reagent costs. TRL: 3–4. DOE-funded research under the Critical Materials Hub programme has been ongoing 2023–2026 with promising preliminary results. Supported ionic liquid phases (SILP) — in which ionic liquids are immobilised on solid silica or alumina supports, enabling column-based continuous extraction without the liquid-liquid emulsion management challenges of conventional SX — represent a further variant of potential relevance for small-scale urban mining operations, with REE loading capacities of 0.5–1.5 mmol/g reported at TRL 3.

7.4 AI-Optimised SX Circuit Design

The inherent variability of recycling-derived leach feed compositions — in which Nd:Pr:Dy:Tb ratios and total REE concentration fluctuate with feedstock provenance and pre-processing conditions — creates an operational optimisation challenge for conventional SX circuits designed and operated for constant feed compositions. Machine learning models trained on historical SX circuit operating data, combined with digital twin representations of the mixer-settler flowsheet, are now being deployed to predict and continuously update the optimal operating parameters — pH, aqueous-to-organic flow ratio, scrubbing acid concentration, temperature — in response to real-time feed composition measurements. Research groups at Ames National Laboratory and ANSTO (Australian Nuclear Science and Technology Organisation) have demonstrated saponifier (NaOH) consumption reductions of 20–30% and improved separation efficiency in pilot-scale SX circuit tests using ML-based process control, relative to conventional operator-adjusted fixed-parameter operation. The practical significance — beyond the operating cost saving — is that AI-optimised control enables commercial SX circuits to process variable-composition recycling feedstocks with the consistency and product quality assurance that were previously achievable only with homogeneous primary ore leach solutions. TRL: 5–6. Deployment as a standard feature of commercial REE SX process control systems is likely within five years as digital platforms from established process control vendors incorporate AI capabilities.

Section 8: Company and Project Case Studies

8.1 Energy Fuels Inc. (NYSE: UUUU) — From Uranium Mill to REE Hub

Energy Fuels Incorporated presents one of the most strategically creative pivots in the Western critical minerals industry: the conversion of the White Mesa Mill in Blanding, Utah — the only fully licensed and operating conventional uranium mill in the United States — into a hub for rare earth element processing. The White Mesa facility's existing infrastructure for handling and processing radioactive and chemically complex materials, combined with its licences for radioactive byproduct material processing, gives it a regulatory head start that would require years and hundreds of millions of dollars to replicate from a greenfield position. The company's rare earth processing programme commenced in 2021 with the introduction of monazite concentrate as a feedstock — a heavy mineral sands byproduct from titanium and zirconium mining in the southeastern United States and elsewhere — chosen in part for its relatively high content of heavy rare earth elements including dysprosium and terbium.

The commercial SX circuit for neodymium-praseodymium oxide production achieved commercial-scale throughput in April 2024, making Energy Fuels the first US company in decades to produce separated NdPr oxide from mined ore on American soil. The programme has since progressed rapidly: a dysprosium oxide pilot circuit commenced operations in July 2025, producing separated Dy_2O_3 at purities of ≥99.5%, with a terbium circuit scheduled to initiate in October 2025 and commercial HREE production targeted for the fourth quarter of 2026. The strategic significance of the HREE circuit cannot be overstated: dysprosium and terbium are the most supply-concentrated and price-volatile rare earth elements in the NdFeB magnet system, and Energy Fuels is uniquely positioned as the only US producer of separated HREE oxides from mined ore at any scale.

The Donald Project joint venture in Victoria, Australia — developed in partnership with Astron Corporation — provides the long-term primary feedstock for White Mesa's REE processing expansion. Phase 1 projections of approximately 92 tonnes per annum of separated dysprosium and 16 tonnes per annum of terbium from the Donald Project ore body are expected to cover approximately 34% and 23% of US annual demand for these elements respectively, representing a meaningful but partial domestic supply contribution. The critical gap in Energy Fuels' value chain position is the absence of metal production or magnet manufacturing capability — the company produces REO, which must be sold to a metal smelter or magnet manufacturer. A formalised offtake linkage with MP Materials or another US metal producer would materially enhance its supply chain significance. TEC Score: 7.5/10.

8.2 MP Materials (NYSE: MP) — America's Mine-to-Magnet Pioneer

MP Materials holds a unique position in the American rare earth supply chain as the operator of the Mountain Pass Mine in San Bernardino County, California — the only active rare earth mining operation of commercial scale in the United States, and one of the highest-grade bastnäsite deposits in the world. The company's 2024 production of 45,000 tonnes of rare earth oxide in concentrate represented an all-time high for US rare earth mining output, and positions Mountain Pass as a globally significant primary production source. The Mountain Pass orebody is characterised by a very high proportion of light rare earth elements — neodymium, praseodymium, cerium, and lanthanum

— consistent with its bastnäsite mineralogy, and the company has progressively built out its on-site processing capability to produce separated NdPr oxide at approximately 1,300 tonnes per annum as of 2024.

The most consequential milestone in MP Materials' development trajectory was the commissioning of commercial NdPr metal production at its Independence facility in Fort Worth, Texas, announced on January 22, 2025. This achievement — the first time rare earth metal smelting via molten salt electrolysis has operated at commercial scale in the United States in a generation — represents the critical bridge between oxide production and magnet manufacturing in the domestic supply chain. Trial production of automotive-grade sintered NdFeB magnets at the Independence facility was underway by mid-2025, with a target production rate of approximately 1,000 tonnes per annum of sintered NdFeB and initial deliveries to General Motors targeted for the end of 2025 or early 2026 under a previously disclosed supply agreement. Financial performance for fiscal year 2025 showed revenues of US$275.5 million, representing a 35.1% year-on-year increase, with a net loss of approximately US$85.9 million reflecting the capital intensity of the Independence facility build-out — a loss profile consistent with a company in the capital deployment phase of a major infrastructure investment cycle rather than indicative of fundamental commercial weakness. Key customers include Apple, General Motors, and the United States Department of Defense.

MP Materials' most significant strategic challenge is the LREE-dominant nature of the Mountain Pass orebody. Dysprosium and terbium — the HREE critical for high-coercivity magnet grades required in EV motors and wind turbines — are not present in meaningful quantities in bastnäsite from Mountain Pass. Sourcing HREE for its magnet products will require either supply agreements with HREE producers (most naturally Energy Fuels), imports from non-Chinese sources, or the development of HREE processing from alternative feedstocks. Resolving this HREE gap is the defining next chapter in MP Materials' mine-to-magnet integration story. TEC Score: 8.5/10 — the highest-conviction fully integrated Western rare earth project currently operating, with strong government backing and a clear commercial development trajectory.

8.3 Vacuumschmelze GmbH & Co. KG (VAC) — The GBD Benchmark

Vacuumschmelze, headquartered in Hanau, Germany, is Europe's premier permanent magnet manufacturer and the undisputed benchmark for commercial grain boundary diffusion technology in the Western world. With more than four decades of sintered NdFeB manufacturing experience, VAC has developed the comprehensive VACODYM® product range spanning remanence values from 1.03 to 1.42 Tesla and coercivity values from 875 to 3,220 kA/m — a performance envelope that covers the complete spectrum of commercial motor and generator applications from industrial servos to aerospace actuators to scientific undulator beamlines. The company operates a fully Western supply chain for its magnet production, maintaining supply chain independence from Chinese HREE through GBD-based coercivity enhancement rather than bulk HRE alloying, a strategic choice that has proved prescient given the increasing frequency and severity of Chinese rare earth export restrictions.

VAC's GBD process — commercially implemented across its VACODYM product range for over a decade — applies Dy/Tb fluoride or oxide coatings to pre-sintered magnet surfaces, followed by heat treatment at 850–950°C in vacuum to drive HREE diffusion along grain boundaries to depths of 1–5 mm per treated face. The coercivity uplift achievable through VAC's GBD process reaches up to +600 kA/m above the base sintered magnet value, enabling high-performance grades with dramatically lower total Dy/Tb content than conventionally alloyed equivalents. Three pressing variants — HR (isostatic pressing), TP (transverse pressing), and AP (axial pressing) — are offered within the VACODYM range, with HR and TP grades delivering 5–8% higher remanence than AP grades of equivalent composition by virtue of superior magnetic texture in the green compact.

The most significant commercial development from VAC in the review period was the announcement on September 9, 2025 of the VACODYM 902 TP — the first commercially available NdFeB sintered magnet at high performance levels produced without any dysprosium or terbium addition. With a guaranteed remanence of ≥1.40 T and intrinsic coercivity of ≥1,190 kA/m, the VACODYM 902 TP represents the inaugural product in VAC's progressive VACODYM 90X HRE-reduction roadmap, with the next generation targeting remanence up to 1.45 T and coercivity of 1,280 kA/m while maintaining zero HRE addition. The principal open question is the long-term demagnetisation resistance of HRE-free grades at temperatures above 150°C — the operating regime of demanding EV traction motor applications — for which extended validation data are pending. TEC Scores: GBD commercial benchmark 9.0/10 (TRL 9, fully proven); VACODYM 902 TP HRE-free grade 7.0/10 (TRL 7–8, commercial but high-temperature limits under validation).

8.4 Noveon Magnetics — The Urban Mining Pioneer

Noveon Magnetics, based in San Marcos, Texas, occupies a unique and strategically important niche in the rare earth magnet industry as the only US manufacturer of sintered NdFeB permanent magnets produced exclusively from recycled feedstock. The company's patented M2M (Magnet-to-Magnet) process — a commercial implementation of the HDDR-based direct recycling principles described in Section 6.2 — processes end-of-life NdFeB scrap sourced from hard disk drives, motors, EV components, and industrial appliances through demagnetisation, thermal decoating, hydrogen decrepitation, and d-HDDR treatment to produce anisotropic nanograin powder that is then pressed, sintered, and finished into commercial-grade EcoFlux™ brand sintered NdFeB magnets. The company reports 90% energy savings relative to conventional mine-to-magnet processing and a 50% reduction in environmental impact metrics, positioning EcoFlux magnets not only as a supply chain diversification option but as a premium sustainability credential for OEMs with decarbonisation commitments.

Two landmark commercial agreements defined Noveon's trajectory in the period under review. In February 2025, Nidec Motor Corporation — the Kyoto-headquartered global leader in small precision motors with an annual motor output exceeding 1 billion units — signed a five-year binding offtake agreement for EcoFlux magnets, with a potential cumulative volume exceeding 1,000 tonnes of sintered NdFeB over the contract term. Deliveries commenced in 2025 for automation, industrial, and defence applications. In January 2026, Noveon announced a joint venture with LG Electronics and Kangwon Energy to establish a closed-loop M2M recycling programme in which end-of-life NdFeB magnets recovered from LG appliances and electronics are processed back into new EcoFlux magnets for re-use in new LG products — a true circular economy implementation with a new South Korea processing facility under development via the Kangwon JV, adding an Asia-Pacific recovery and production node to what was previously a single-facility US operation.

The decentralised supply chain architecture of Noveon's model — which sources feedstock from multiple urban mining streams rather than depending on a single mining operation or country — offers a structural resilience advantage over primary-mining-dependent competitors. The principal risks facing Noveon are the logistics and economics of feedstock aggregation at industrial scale, the customer qualification timeline for recycled-content magnets in safety-critical automotive and defence applications (typically 2–4 years), and the single-facility concentration in Texas prior to the Korea JV becoming operational. EcoFlux magnet properties, at 85–95% of virgin material performance, are adequate for a wide range of industrial and consumer applications but may require composition adjustment or blending with a virgin powder fraction for the most demanding automotive and aerospace grades. TEC Score: 8.0/10.

Section 9: Techno-Economic Credibility Scorecard

The Techno-Economic Credibility (TEC) scoring methodology applied throughout this report provides a structured, comparative framework for evaluating technologies at disparate stages of development against a common set of commercially relevant criteria. Each technology is scored on a scale of 1 to 10 across five equally weighted sub-criteria: Technology Readiness Level (TRL) maturity, which assesses proximity to commercial deployment; capital expenditure risk, which reflects the magnitude and uncertainty of required investment; operating cost competitiveness, which evaluates cost position relative to incumbent technologies; environmental impact score, which incorporates emissions, waste generation, water consumption, and hazardous material handling; and supply chain resilience, which considers dependence on geographically concentrated input materials and process chemicals. The composite TEC score represents the unweighted arithmetic mean of the five sub-criterion scores.

It is important to note that the TEC score is not a pure measure of scientific maturity, commercial profitability, or environmental performance in isolation — it is an integrated judgment of readiness and attractiveness for investment and deployment decision-making as of June 2026. A high TRL technology with poor environmental credentials (such as MSE with PFC emissions) scores lower than a combined technology approach such as GBD + HRE-lean alloying, which achieves the highest score in this framework by virtue of proven commercial deployment, excellent supply chain resilience through Dy reduction, low capital incremental cost, and strong environmental credentials relative to high-Dy bulk alloying. Conversely, highly promising emerging technologies such as task-specific ionic liquid SX score lower despite their long-term transformative potential, reflecting the honest assessment that commercial-scale validation remains pending and economic barriers are currently significant.

Scores presented represent the consensus assessment of the REIA/CMI expert review panel as of June 2026, based on published literature, commercial disclosures, site visit assessments, and expert interviews conducted between January and May 2026.

Technology Area	TRL	CAPEX Risk	OPEX Competitiveness	Environmental Score	TEC Score (/10)
1. MSE Oxide-to-Metal	9	Low	Moderate (high energy, PFC)	Poor	7.5
2. Metallothermic Reduction (CaR)	6–7	Medium	Good	Good (no PFC)	6.5
3. HRE-Lean Alloying + GBD	9	Low	Excellent	Excellent	9.0
4. Ce/La Substitution	7–8	Low	Excellent	Excellent	7.5
5. SPS / Flash Sintering PM	6–7	High	Good	Good	7.0
6. HDDR Direct Recycling	7–8	Low–Medium	Excellent	Excellent	8.5
7. Hydromet Recycling + SX	7–8	Medium	Good	Good	8.0
8. TSIL / Ionic Liquid SX	4–5	High	Poor (cost)	Excellent	5.5

Near-Term Priorities (2–3 Year Horizon)

HRE-lean GBD alloying and HDDR-based direct recycling offer the clearest and most immediate paths to commercial deployment with demonstrated return on investment. Both are at TRL 7–9, require only modest incremental capital expenditure relative to greenfield alternatives, and address the twin strategic priorities of reducing HREE demand and closing the magnet recycling loop. For any Western company or government programme seeking to establish a commercially competitive sintered NdFeB position within a two-to-three-year timeframe, GBD-based manufacturing and HDDR-based urban mining should be treated as baseline, not as innovative additions.

Strategic Bets (5–10 Year Horizon)

Task-specific ionic liquid extractants, spark plasma sintering, and AI-optimised SX circuit control represent step-change technological opportunities whose commercial impact, if scale-up economics can be resolved, would be transformative. TSILs could reduce the HREE separation circuit stage count by an order of magnitude, with corresponding capital and operating cost reductions. SPS sintering could improve $(BH)_{max}$ by 5–10% in the same physical magnet volume. AI circuit control could make variable-feed recycling economics competitive with primary ore SX at commercial scale. Sustained government co-investment and industry consortium R&D are the appropriate delivery mechanisms for these longer-horizon bets, which carry too much scale-up risk and too long a capital payback period for unsubsidised private investment alone.

Section 10: Strategic Conclusions and Recommendations

The analysis presented across the preceding nine sections supports six principal strategic conclusions, each with direct implications for investment allocation, industrial policy design, and supply chain architecture decisions by Western governments, OEMs, and capital providers in the rare earth permanent magnet sector.

1. GBD + HRE-Lean Alloying Is the Immediate Commercial Priority. With a TEC score of 9.0/10 and TRL 9, the combination of grain boundary diffusion with HRE-lean alloy design represents the single most commercially mature, financially attractive, and strategically impactful technology set available to the industry today. Its proven deployment by Vacuumschmelze, TDK, Shin-Etsu, and others across millions of commercial magnets provides a validation base that no emerging technology can match. Every percentage point of dysprosium or terbium eliminated from the alloy composition is a direct and compounding benefit: a cost reduction of US$6–12/kg of magnet at current HREE prices, a reduction in Scope 3 supply chain emissions associated with Chinese ion-adsorption clay mining, and a reduction in exposure to the geopolitical supply disruption risk that China's near-monopoly on HREE production creates. GBD should be considered not an optional enhancement but a baseline process requirement for any new Western sintered NdFeB manufacturing facility established after 2026. VAC's VACODYM 902 TP, as the first commercially available high-performance HRE-free sintered NdFeB magnet, represents the logical endpoint of this technology trajectory and provides the aspirational benchmark for the industry's HREE reduction roadmap.

2. HDDR Direct Recycling Requires Scale-Up Investment Now. At TRL 7–8, with a TEC score of 8.5/10 and commercial validation by Noveon Magnetics and others, HDDR-based magnet-to-magnet recycling is not a speculative future technology — it is an under-deployed commercial capability whose primary constraint is feedstock logistics, not metallurgy. The technology delivers REE recovery rates above 97%, waste generation below 5%, and energy savings of approximately 90% relative to primary processing. The bottleneck is the collection, decommissioning, and pre-processing infrastructure required to aggregate sufficient end-of-life magnet volumes from hard disk drives, EV motors, and industrial applications. Industry consortia modelled on the European Battery Alliance — pooling OEM, recycler, and government resources to establish magnet take-back and pre-processing networks — and government investment in urban mining logistics infrastructure are the missing policy instruments. The technology investment has been made; the supply chain investment has not.

3. Hydrometallurgical Recycling + Improved SX Is Commercially Feasible. The combination of organic acid leaching with Cyanex 272 or PC-88A solvent extraction for end-of-life NdFeB processing is at TRL 7–8 with a TEC score of 8.0/10 and multiple pilot operations in Europe and North America providing operating reference data. Energy Fuels' White Mesa Mill demonstrates the SX technology component at commercial scale with primary monazite feedstock — the same extractant chemistry applies directly to magnet-derived leach solutions. Commercial-scale hydromet recycling is achievable within three to five years with available technology; the investment decision is fundamentally one of commercial economics and feedstock security rather than technical feasibility.

4. Metallothermic Reduction Deserves Sustained Investment. Eliminating perfluorocarbon emissions from molten salt electrolysis is not merely an environmental preference — it is a regulatory imperative that is approaching with increasing legislative velocity, particularly in the European Union where fluorinated greenhouse gas regulations are progressively tightening. Calcium metallothermic reduction at TRL 6–7, while not yet commercially competitive with MSE on a unit cost basis, is the most credible near-term alternative pathway for producing NdFeB-grade rare earth metals without PFC emissions. Government R&D co-investment programmes — analogous to the DOE ARPA-E funding that has advanced several oxide-to-metal technologies in the United States — directed specifically at scaling CaR reduction to commercial throughput, reducing calcium metal cost, and resolving CaO slag valorisation would materially advance this technology's commercial readiness within five to seven years.

5. The Energy Fuels → MP Materials Supply Chain Linkage Is the Most Credible Near-Term US HREE Solution. The complementary value chain positions of Energy Fuels and MP Materials are structurally compelling: Energy Fuels produces separated HREE oxides (Dy_2O_3, Tb_4O_7) from the Donald Project and White Mesa Mill, while MP Materials converts NdPr oxide to NdPr metal via MSE and to sintered NdFeB at the Independence facility. A formalised long-term offtake agreement — in which Energy Fuels supplies separated HREE oxides to MP Materials for incorporation into its magnet alloy, either as a GBD coating precursor or as a direct alloy addition — would constitute the first fully domestic US supply chain for HREE-containing NdFeB magnets. The two companies' geographies (Utah and California/Texas), licences, and processing capabilities are directly complementary, and the strategic case for formalised collaboration is compelling. We recommend that both companies and relevant government agencies (DoD, DoE) actively facilitate the commercial structuring of this linkage as a national supply chain priority.

6. Ionic Liquids and AI Process Control Are the Long-Duration Bets. Task-specific ionic liquids with Dy/Nd separation factors exceeding 50 represent a genuinely transformative technology for HREE separation if their economic and stability barriers can be resolved. With NdFeB demand projected at four to five times 2025 levels by 2040 — implying a correspondingly expanded HREE separation requirement — the absolute scale of separation infrastructure required under a business-as-usual extractant scenario is daunting. TSILs offer a path to achieving that separation in substantially smaller, cheaper, and more geographically distributed facilities. The appropriate investment vehicle is sustained government-industry co-funded R&D, targeting IL synthesis cost reduction, long-term stability validation, and small-scale pilot demonstration by 2030 as the gateway to commercial feasibility assessment. AI-optimised SX circuit control is a nearer-term deployment priority — already at TRL 5–6, it should be incorporated into the design specification of every new commercial REE SX circuit commencing engineering design after 2026.

Appendix A — Glossary of Key Terms

Term / Abbreviation	Definition
$(BH)_{max}$	Maximum energy product — the figure of merit for a permanent magnet's stored magnetic energy per unit volume, expressed in kJ/m^3. Higher values indicate greater performance in a given volume.
B_r (Remanence)	Residual magnetic flux density retained after magnetisation in the absence of an applied field, measured in Tesla (T). Higher B_r delivers greater flux density in motor/generator gaps.
H_{cj} (Coercivity)	Intrinsic coercive force — the reverse applied field required to reduce the magnet's intrinsic magnetisation to zero, expressed in kA/m. Higher H_{cj} confers resistance to demagnetisation at elevated temperatures and under adverse applied field conditions.
T_c (Curie Temperature)	The temperature above which a ferromagnetic material loses its permanent magnetism and becomes paramagnetic. For NdFeB, $T_c \approx 312°C$; Co additions can raise this to ~360–400°C.
GBD (Grain Boundary Diffusion)	A post-sintering process in which heavy rare earth compounds (Dy, Tb) are diffused along grain boundaries into a pre-sintered NdFeB magnet, achieving coercivity enhancement with 40–60% lower HRE usage than conventional bulk alloying.

Term / Abbreviation	**Definition**
HDDR	Hydrogenation–Disproportionation–Desorption–Recombination. A hydrogen-based process that produces fine anisotropic NdFeB powder suitable for bonded or sintered magnet production; central to direct magnet recycling technologies.
MSE (Molten Salt Electrolysis)	The dominant commercial process for converting rare earth oxides to high-purity metals using a fluoride-based molten salt electrolyte at approximately 1,050°C. Produces PFC greenhouse gas emissions as a process byproduct.
SX (Solvent Extraction)	Liquid-liquid extraction using an organic extractant dissolved in a hydrocarbon diluent to selectively partition and separate individual rare earth elements from mixed aqueous leach solutions. The universal REE separation technique.
D2EHPA	Di-2-ethylhexyl phosphoric acid. The most widely deployed commercial extractant for rare earth SX; high loading capacity but limited LREE/HREE selectivity. TRL 9.
Cyanex 272	Bis(2,4,4-trimethylpentyl)phosphinic acid. A commercially available organophosphorus extractant with superior HREE selectivity, particularly for Dy/Tb separation from Nd/Pr, at higher cost and slower kinetics than D2EHPA. TRL 9.
TSIL (Task-Specific Ionic Liquid)	Designer ionic liquid incorporating REE-selective functional groups in its ion structure, enabling Dy/Nd separation factors >50. Near-zero vapour pressure; diluent-free operation possible. Currently TRL 4–5 due to high cost and stability limitations.

Term / Abbreviation	Definition
DES (Deep Eutectic Solvent)	Low-melting-point solvent formed from a mixture of a hydrogen bond acceptor (e.g., choline chloride) and a hydrogen bond donor (e.g., oxalic acid). Biodegradable, inexpensive, and demonstrated for selective REE dissolution from NdFeB. TRL 3–4.
SPS (Spark Plasma Sintering)	Also called Field-Assisted Sintering Technology (FAST). Consolidates powder compacts to full density in 3–5 minutes using simultaneous pulsed DC current and uniaxial pressure. Achieves finer grain sizes and higher $(BH)_{max}$ vs. conventional sintering. TRL 6–7.
TRL (Technology Readiness Level)	A 1–9 scale, originally developed by NASA, measuring the maturity of a technology from basic principles (TRL 1) through laboratory demonstration (TRL 4–5), pilot validation (TRL 6–7), and full commercial deployment (TRL 8–9).
TEC Score	Techno-Economic Credibility Score (1–10). Composite metric used in this report, averaging equally weighted sub-scores for TRL maturity, CAPEX risk, OPEX competitiveness, environmental impact, and supply chain resilience.
HRE / HREE	Heavy Rare Earth Elements. In the NdFeB context, principally dysprosium (Dy) and terbium (Tb), used to enhance coercivity. Primarily sourced from ion-adsorption clay deposits concentrated in southern China.
LRE / LREE	Light Rare Earth Elements. In the NdFeB context, principally neodymium (Nd), praseodymium (Pr), cerium (Ce), and lanthanum (La). More widely distributed geographically than HREE; dominant in bastnäsite and monazite ores.

Term / Abbreviation	Definition
NdFeB	Neodymium-Iron-Boron. The class of rare earth permanent magnets based on the $Nd_2Fe_{14}B$ tetragonal intermetallic phase, first commercialised in 1984. The highest energy-density permanent magnets known to science.
M2M (Magnet-to-Magnet Recycling)	A closed-loop recycling process, exemplified by Noveon Magnetics' proprietary M2M technology, in which end-of-life NdFeB magnets are processed directly back into new sintered NdFeB magnets with >97% REE recovery and ~90% energy saving vs. primary processing.
REO (Rare Earth Oxide)	The calcined oxide form of a rare earth element (e.g., Nd_2O_3, Dy_2O_3), typically the commercial product of solvent extraction, precipitation, and calcination operations. REO is the feedstock for molten salt electrolysis and metallothermic reduction to produce rare earth metals.

Appendix B — Organization Profiles

Rare Earth Industry Association (REIA)

The Rare Earth Industry Association (REIA) is a Belgium-headquartered global non-profit industry association founded in 2019 with a membership of over 70 companies spanning the full rare earth value chain — from primary mining and ore processing through rare earth separation, metals production, alloy manufacturing, magnet production, and downstream applications in motor and generator systems. REIA's mandate is to advocate for sustainable, diverse, and commercially competitive rare earth supply chains on behalf of its membership and in dialogue with governments, regulatory bodies, and international institutions globally. REIA convenes technical working groups, publishes industry intelligence, and provides a structured forum for pre-competitive cooperation on supply chain resilience, environmental standards, and technology development priorities. This report has been prepared in association with REIA as part of its ongoing programme of industry education and technology intelligence publications.

Critical Minerals Institute (CMI)

The Critical Minerals Institute (CMI) is a global intelligence and advisory platform connecting companies, capital markets participants, and policymakers around the critical minerals economy. CMI provides research, market analysis, investor relations support, and industry intelligence across all critical mineral commodities including rare earth elements, lithium, cobalt, nickel, manganese, and graphite, with a particular focus on the intersection of mineral supply chains with the energy transition and defence industrial base. CMI's subscriber base spans mining companies, downstream manufacturers, financial institutions, sovereign wealth funds, and government agencies in North America, Europe, Asia-Pacific, and the Middle East. This report represents one component of CMI's Critical Minerals Intelligence Reports programme and reflects the analytical standards applied across CMI's broader body of work in the rare earth permanent magnet supply chain domain.

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All data, analysis, and TEC scores contained in this document were prepared in association with the Rare Earth Industry Association (REIA) and the Critical Minerals Institute (CMI) — June 2026.
TEC scores are based on published literature and expert panel analysis as of June 2026. This document is a companion to the 28-slide PowerPoint presentation of the same title.