Magnets First: A Practical Path to Domestic Rare-Earth Security

Douglas C. Youvan

doug@youvan.com

www.youvan.ai

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The fastest, cleanest way to ease U.S. rare-earth dependence is to start where concentrations are already highest: permanent magnets. Sintered NdFeB parts in hard-disk drives, appliances, tools, industrial motors, wind turbines, and EV drivetrains typically contain ~27–32 wt% rare earths (mostly Nd/Pr, with Dy/Tb in high-temperature grades). That's orders of magnitude richer than mixed municipal waste or even most mine tailings. A magnets-first strategy focuses on capturing these parts before shredding or landfilling, then channeling them into proven recycling routes—hydrogen decrepitation for direct magnet-to-magnet re-sintering, or chemical flowsheets to recover high-purity RE oxides and re-alloy. The approach is modular, policy-friendly (labeling, right-to-repair, procurement standards), and immediately scalable through retail take-back, IT asset disposition, and scrapyard partnerships. It also returns exactly the constrained elements—Nd/Pr and, when present, Dy/Tb—needed for defense, EVs, and electrification. This paper lays out a field-ready playbook: where magnets sit in today's waste and product streams, how to collect and process them safely, what the unit economics look like, and which policies convert small pilots into reliable national tonnage. Compared with digging mixed trash or waiting on greenfield mines, magnets-first offers lower capex, faster ramp, and real supply-chain resilience right now.

Keywords: rare earths, NdFeB, magnet recycling, hydrogen decrepitation, grain-boundary diffusion, dysprosium, terbium, e-waste, right-to-repair, magnet passport, procurement standards, ITAD, appliance take-back, circular economy, domestic supply chain.

Outline

1. Problem Statement and Thesis

1.1 Strategic risk from REE dependence

The United States sits at the end of a long, fragile chain for the very elements that enable electrification and defense: neodymium and praseodymium for high-performance permanent magnets, and dysprosium/terbium to hold coercivity at high temperatures. The risk is three-fold:

- Concentration risk: A single geography dominates separation and magnet making. A tariff, license pause, or export quota can bottleneck downstream industries (EVs, wind, precision servos, missiles) within months.
- Temporal risk: Even when mines operate domestically, the *processing* and *magnet fabrication* steps are the rate limiters. Commissioning separation plants and magnet lines is measured in years and billions, not quarters and millions.
- Compositional risk (HREEs): Heavy REEs (Dy/Tb) are the true chokepoint for high-temp grades; substitutes are partial, not complete. If HREEs hiccup, high-spec magnets disappear first, throttling sectors with the least tolerance for derating.
  Net effect: the national exposure is not abstract—it's "motors on backorder," "turbines delayed," and "readiness degraded," driven by a supply chain that can be pinched at a few valves.

1.2 Why magnets are the pivotal choke point

Rare earths move through many forms (ores, concentrates, separated oxides, metals), but value, specificity, and switching costs condense inside the magnet:

- Highest useful concentration: Finished NdFeB parts contain ~27–32 wt% REEs; no upstream waste stream comes close. Each kilogram of magnet embodies the exact elements industry needs, already alloyed for performance.
- Function, not commodity: A magnet's value is its coercivity, remanence, and thermal stability—properties born of composition, grain size, diffusion profiles (Dy/Tb shells), and sintering history. You don't just "swap in ferrite" without losing torque density, efficiency, and form factor.
- Irreversibility of shredding: Once devices are shredded, magnets fragment, oxidize, and contaminate. The physics that made them valuable becomes a processing headache. Therefore, pre-shred capture of intact magnets is the golden hour.
- HREE stewardship lives here: Dy/Tb are applied as grain-boundary diffusion or bulk additions in specific parts (e.g., traction motors). Recovering those magnets yields the

scarcest atoms in the form most readily reincorporated into new high-temp grades. In short: magnets are where scarcity meets functionality. Secure the magnet layer, and you secure the capability layer above it.

1.3 Thesis: magnets-first beats landfill mining and long-lead greenfield projects

Magnets-first is a pragmatic thesis grounded in grade, time, and risk:

- Grade advantage: Mixed landfill fines sit at tens to low hundreds of ppm total REEs; incinerator ash at ~10^2–10^3 ppm. By contrast, magnets are ~300,000 ppm (30%). That's a three to four-order-of-magnitude head start in recoverable content. Grade drives opex and capex.
- Time-to-tonnage: Magnet capture leverages existing flows—appliance returns, IT asset disposition, data-center HDD refreshes, decommissioned industrial drives, OEM scrap—so pilot lines can scale in quarters, not years. Mines and separation plants remain essential, but their clocks run long and their risk is construction, permitting, and market.
- Process optionality: With intact magnets you can choose hydrogen decrepitation → re-sinter (lowest energy, preserves alloy) or chemical recovery → REOs/metals (most flexible for mixed scrap). That optionality de-risks investment and allows modular, regional build-out.
- HREE focus where it counts: Targeted pull of high-temp grades returns Dy/Tb to the loop—precisely where new supply is hardest. Landfill mining cannot selectively surface HREE-bearing materials at scale; greenfields cannot conjure HREE orebodies where they don't exist.
- Policy leverage: Simple rules (magnet labeling, design-for-disassembly, right-to-repair, deposit-refund "magnet bounties," recycled-content procurement) flip collection economics quickly—something you can't do to geology or global geopolitics.

Therefore: For near-term resilience and meaningful import displacement, prioritize pre-shred magnet capture and recycling. Keep building mines and separation capacity, yes—but don't wait for them to solve today's bottleneck. Magnets-first is the fastest, lowest-risk bridge from vulnerability to capability.

2. Where the Magnets Are: A National Inventory

Below, each stream is framed as (a) stock/flow, (b) capture points, (c) unit ops & safety, (d) purity/yield notes, and (e) quick KPIs. Ranges are field-typical rules of thumb to guide pilots (not hard forecasts).

2.1 IT/e-waste: HDD voice-coil magnets and fans

(a) Stock/flow. Client PCs, workstations, servers, and data-center drives. Voice-coil magnet (VCM) sets are consistent: typically 10–20 g NdFeB per 3.5″ HDD, 6–12 g for many 2.5″ drives. Server/PC fans add 1–3 g each.
(b) Capture points. ITAD providers, data-center refreshes, corporate liquidations, municipal e-waste events, college move-outs.
(c) Unit ops & safety.

- De-mag or hydrogen decrepitation (HD) first to tame strong fields.
- Pop VCM “clam shells” with a simple jig; retain keeper plates to reduce stray fields.
- Separate Ni–Cu–Ni coated pieces; minimize steel carry-over.
  (d) Purity/yield. Uniform geometry and alloy = best direct HD → re-sinter feed. Coatings/adhesives are predictable.
  (e) KPIs. A pallet of 1,000 3.5″ HDDs → ~12–18 kg magnets (~3.6–5.4 kg REO). One technician can safely depop 300–400 drives/shift with proper tooling.

2.2 Appliances & white goods: compressors, actuators, small motors

(a) Stock/flow. Refrigerators, HVAC blowers, washing machines, dishwashers, microwaves: numerous small PM motors/actuators with 1–30 g magnets each; some premium/high-efficiency units carry larger rotor segments (50–150 g).
(b) Capture points. Retail take-back, hauler transfer stations, appliance recyclers, municipal bulky-waste days.
(c) Unit ops & safety.

- Demag or HD before opening sealed rotors; beware oil/foam in compressors (EHS).
- Use fixtures and shears to expose end-bells and slide out rotor stacks; collect magnet arcs/rings.
  (d) Purity/yield. Mixed motor families = chem-route friendly (to REOs) unless you batch by model line. Expect varnish/epoxy contamination; plan a burn-off or solvent step (with controls).
  (e) KPIs. A box truck (4–5 tons) of mixed appliances typically yields 8–25 kg of NdFeB, highly variable by intake mix. Throughput wins via pre-triage (model lists with known PM motors).

2.3 Tools, speakers, and small devices

(a) Stock/flow. Cordless tools (drill/driver/angle grinder), DIY shop gear, Bluetooth speakers, headphones, toys. Magnet sizes sub-gram to ~20 g each; speakers can carry ferrite or NdFeB (confirm).
(b) Capture points. Hardware store take-back, thrift/charity sorting centers, electronics recyclers, pawn/repair shops (end-of-life bins).
(c) Unit ops & safety.

- Battery removal first (fire risk).
- Simple press-out jigs for driver motors; pry-plates for speaker gap assemblies.
  (d) Purity/yield. Very heterogeneous; best routed to chemical recovery hubs unless you can segregate by brand/series.
  (e) KPIs. 1 gaylord of mixed smalls (~200–250 kg): expect 1–5 kg NdFeB after triage; economics hinge on pairing with Cu/Al recovery to pay the sorting bill.

2.4 Industrial, wind, and EV rotors (fewer units, high mass)

(a) Stock/flow. Industrial servo motors, robotics, elevators, MRI peripherals; EV traction motors (IPM/SPM, many now magnet-based); direct-drive wind turbines (rare but magnet-heavy).

- EV traction motors: commonly 1–3 kg NdFeB per motor (model/chemistry dependent).
- Industrial servos: 50–800 g per unit is typical.
- Direct-drive wind: hundreds of kg up to ton-scale per nacelle, but units are scarce and logistics heavy.
  (b) Capture points. Fleet/utility decommissioning, auto dismantlers, insurer total-loss auctions, OEM service depots, refurb shops.
  (c) Unit ops & safety.
- High-energy magnets: mandate controlled demag (thermal/AC) or HD in inert/vented vessels.
- Mechanical splitting jigs for rotor stacks; strict pinch/attraction hazard controls.
  (d) Purity/yield. Often high-temp grades with Dy/Tb diffusion shells—strategic feed for HREE stewardship. Thick coatings and adhesive stacks are common; plan pre-processing.
  (e) KPIs. 100 EV motors can yield 100–300 kg NdFeB. A single industrial line change-out (robot/servo farm) can supply 50–200 kg in a day with minimal transport miles.

2.5 Manufacturing scrap: swarf, offcuts, rejects

(a) Stock/flow. Magnet grinding swarf (oily fines), green-state rejects, broken segments, end-of-run inventories from magnet shops and motor/magnet OEMs.
(b) Capture points. Direct OEM contracts, Tier-1 motor factories, magnet finishers, sintering houses.
(c) Unit ops & safety.

- Pyrophoric fines: handle under inert atmosphere or wet; controlled HD can aid de-oiling.
- Filtration/centrifuge for coolant recovery; magnetic separation to boost solids grade.
  (d) Purity/yield. Highest average grade, most uniform chemistry; ideal for both magnet-to-magnet and chem routes. Trace Ni/Cu/Co from coatings is predictable.
  (e) KPIs. 1 tonne of clean swarf at ~30% REE → ~300 kg REO-equivalent; most cost-effective tonnage when secured on multi-year offtake.

Practical cross-cutting notes (for all streams)

- Golden hour = pre-shred. Once shredded, magnets oxidize and contaminate—capture intact wherever possible.
- Demag policy. Standardize a demag-first rule at yards/ITADs to cut injuries and speed disassembly.
- Two-bin routing. Bin A: clean, uniform parts → HD → re-sinter. Bin B: mixed/dirty → chem hub (oxalate/IL/halide).
- Data & traceability. Track source, weight, alloy guess (if known), Dy/Tb flags. This supports recycled-content claims and quality control.
- Localization. Urban hubs (IT/e-waste, appliances) favor high-throughput light disassembly; regional hubs focus on industrial/EV and chem processing.

Back-of-envelope sampler (helps size pilots)

- Data-center refresh (one mid-scale site): 10,000 HDDs → ~120–180 kg magnets → 36–54 kg REO in a few shifts.
- Auto dismantler network (per 10,000 end-of-life EVs/year): 10–30 tonnes NdFeB.
- Appliance recycler (50,000 units/year): 0.4–1.2 tonnes NdFeB depending on mix and model-year efficiency.

These streams together form a reliable, domestic, continuous feed. Start with IT/HDD + appliance take-back for quick wins, then layer industrial/EV programs and OEM swarf contracts to build tonnage and raise average grade.

3. Collection Architecture

Goal: move magnets pre-shred into two streams—Bin A (clean, uniform) for HD→re-sinter; Bin B (mixed/dirty) for chem-to-REO—using simple fixtures, standard SOPs, and modest incentives. Below is a field-ready blueprint.

3.1 Retail take-back and hauler integration

Targets: appliances, small electrics, tools, speakers, home IT.

Footprint

- Front-of-store pods: locked carts for "magnet-bearing" returns; QR for drop-off bounty.
- Back-dock triage table: screwdriver set, small shear, demag wand, VCM pop-jig.
- Regional consolidation cage: stackable totes (A/B bins), tamper seals, pallet scale.

SOP (10–15 min per unit typical)

1. Verify item class; remove batteries first.
2. Demag (AC wand 120–240 s) if strong fields are present.
3. Pop magnet modules (HDD VCMs, fan motors, drivers) using jigs.
4. Weigh, tag (source, device class, est. alloy), place in Bin A (clean) or Bin B (mixed).
5. Issue digital bounty; scan to ledger.

Staffing & training

- 1–2 store associates per large site; 1 roving tech per 15–20 stores for QA/EHS.
- 2-hr micro-training: magnet hazards, battery safety, demag use, sorting rules.

Incentives & economics

- Consumer bounty: $1–$5 per qualifying item (HDDs, power tools, fans).
- Hauler uplift: $50–$100 per filled pallet (verified mass & purity).

- Retailer KPI: $/sq-ft from take-back, % items diverted pre-shred.

KPIs

- Recovery rate (kg magnets / 100 returned items)
- Purity split: Bin A ≥ 70% by mass within 90 days
- Injury rate: 0 recordables; near-miss logs weekly
- Cost to recover (CTR): target <$2/kg magnet at maturity

EHS & compliance

- Battery isolation, lock-out for corded items, eye/hand PPE.
- Magnet pinch signage; AC-demag only in marked zone.
- Chain-of-custody tags; serialized tamper seals on pallets.

3.2 Scrapyards/MRFs: demagnetize-and-pop stations

Targets: appliances, motors, speakers at yards; IT peripherals at e-MRFs.

Micro-cell layout (8’ x 10’)

- AC demag coil + thermal cabinet (300–350 C) for stubborn rotors
- Bench with torque tools, vices, prybars, shears, VCM jig
- Steel-free staging table; A/B totes; fume hood for adhesive warm-off

Throughput model

- Light-duty line: 150–250 units/shift (mixed smalls) → 4–10 kg magnets
- Motor day: 40–60 small motors/hr with two techs → 10–20 kg/shift
- Add-on: “HDD hour” block—300–400 HDDs/shift by one trained operator

Operational rules

- Golden hour: magnets removed before shred/smelt.
- Two-bin standard: clean modules → A; mixed fragments/fines → B.
- Adhesive removal: 120–150 C softening; capture fumes; or controlled burn-off cabinet with scrubber.

Commercials

- Yard paid on verified net magnet mass + purity bonus (+5–10% for Bin A).
- Monthly scorecard: contamination demerits (steel, ferrite, Cu coils > threshold).
- Optional: gate-fee credit for magnets recovered from inbound municipal loads.

KPIs

- Pull-through: % motors entering line that yield magnets
- Contaminants: Ni/Cu/steel ppm in sample lots
- Cycle time per motor/HDD; overtime vs throughput
- CTR target at yards: $0.50–$1.50/kg (labor-led)

EHS

- Pinch-point SOPs; demag mandatory for parts >100 kA/m.
- Thermal handling SOP; fire watch for burn-off; Class D extinguisher for fines.

3.3 ITAD and data-center workflows (bulk HDD pulls)

Targets: HDD voice-coil magnets (VCM), fans, select server motors.

Process integration

- Add "Magnet Pull" to standard NIST 800-88 or on-site shred workflows.
- Two options:
  - A) Keep platter destruction (hammer mill / punch), extract VCMs pre-mill with jig.
  - B) Full disassembly lane (higher labor, higher purity).

Standard work sequence (HDD)

1. Intake log (drive make/model/serial), chain-of-custody seal.
2. Remove PCB, top cover; jig-pop VCMs; drop keepers back on to neutralize force.
3. Route platters to certified destruction; fans to small-motor bin.
4. Weigh and tag magnet sets; Bin A (uniform HDD VCMs).

Security & traceability

- Camera coverage; sealed totes; co-signed custody forms.
- Magnet lots cross-referenced to drive serial ranges (for audits).
- Data-center SLA: magnet mass per 1,000 drives; purity report monthly.

Commercials

- Per-drive service fee unchanged; credit for magnets ($/kg) offsets bill.
- Premium for same-model bulk pulls (uniform alloy, best for HD→re-sinter).

KPIs

- Pull efficiency: ≥95% of VCMs recovered from processed drives
- Operator rate: 300–400 HDDs/shift per lane
- Bin A purity: ≥95% HDD VCM parts by count
- CTR: $0.30–$0.80/kg (scale effect, minimal adhesives)

EHS

- Cut-resistant gloves, eyewear; magnet pinch SOPs.
- Demag wand available; jigs designed to keep fingers out of flux path.

3.4 OEM line-scrap offtakes and contracting models

Targets: grinding swarf, green rejects, broken segments, end-of-run inventories.

Material control

- Provide dedicated drums (oily swarf, dry swarf, green parts, coated parts).
- On-site de-oiling option (centrifuge/filtration) to raise solids grade.
- Weekly weigh-and-scan pickup; moisture % measured; solids assay quarterly.

Offtake models

- Indexed pricing: $/kg = a*(REE basket index) + b*(purity premium) − c*(moisture penalty).
- Floor-and-share: minimum $/kg plus upside sharing above index band.

- Tolling: recycler returns alloy or REOs to OEM at fee/ton; OEM retains commodity risk.

Quality specs (illustrative)

- Swarf: REE content ~30 wt%, Fe/Co balance; oil <10%; moisture <5%.
- Green rejects: alloy per drawing; coating absent; size/shape per bin.
- Coated segments: Ni/Cu/Ni mass fraction documented for contaminant budget.

Logistics & compliance

- DOT-approved drums for pyrophoric risk; inert gas blanket for fine swarf if needed.
- Hazard data sheets exchanged; emergency response card on each pallet.

KPIs

- Variability (stdev of REE wt% per month) → target <2 wt% for swarf, <1 wt% for green parts
- Yield to product: >90% for magnet-to-magnet routes on clean rejects
- Contract uptime: missed pickups <1 per quarter; disputes resolved <10 business days

EHS

- Class D extinguishers; no open flame near swarf.
- Grounding/anti-static mats at consolidation area.

Cross-cutting enablers (apply to all 3.x)

- Magnet passport (labeling): weight, composition class (e.g., NdPr-Dy, NdPr-no-Dy), coating, location in product, extraction notes.
- Data layer: per-pallet QR linking to source, mass, bin, photos, timestamps; export CSV for recycled-content claims.
- Two-market routing:
  - Bin A → HD→press→sinter lines (Texas/Midwest hubs).
  - Bin B → chem hubs (oxalate/IL/halide) with Fe/Co recovery.
- Performance cadence: 30-60-90 day ramp goals; monthly purity/CTR reviews; quarterly re-training.

Indicative ramp (single metro, 12 months)

- Q1: Stand-up 10 stores + 1 yard cell + 1 ITAD lane → 8–12 t/yr magnets run-rate
- Q2: Double stores, add 2nd yard, sign 1 OEM swarf contract → 20–30 t/yr
- Q3–Q4: Add auto dismantlers + industrial motor partner → 40–60 t/yr, Bin A ≥ 65%

This architecture is intentionally modular: start with ITAD/HDD (fastest wins), bolt on retail/haulers (volume), then capture industrial/EV and OEM swarf (grade and Dy/Tb).

4. Disassembly and Safety

Objective: remove magnets pre-shred with high yield and low incident risk, routing clean modules to HD→re-sinter and mixed/dirty material to chem hubs. Below are field-tested options, decision rules, and shop-floor details.

4.1 De-mag options: AC demag vs thermal vs hydrogen decrepitation (HD)

Choosing a method (quick rule-of-thumb):

- Small, uniform parts (HDD VCMs, fan rotors): AC demag first (fast, repeatable).
- Bonded/epoxy-heavy parts, thick arcs/rings: Thermal demag to soften adhesives + neutralize pull.
- Preparation for re-sinter or for brittle breakup: HD (demag + crack into friable powder in one step).

A) AC demagnetization

- What: Time-varying alternating field gradually reduced to zero.
- Pros: Seconds to minutes; minimal heat; preserves coatings; great for repeat lanes.
- Cons: Large parts need bigger coils; residual magnetization if cycle is rushed.
- Typical settings: 50/60 Hz coil; start field ≥ part's coercivity; 60–180 s taper; keep part centered and slowly withdraw on ramp-down.
- Safety: Keep ferromagnet clutter out of coil zone; pinch-hazard signage; hearing protection if coil hum >85 dBA.

B) Thermal demagnetization

- What: Heat above the magnet's Curie/operating threshold (often 300–350 °C for many NdFeB grades) to erase magnetization; also softens epoxies.
- Pros: Strong parts made safe; adhesives manageable; good for rotor stacks.
- Cons: Energy use; risk of oxidation/fume; can degrade alloy for direct re-use (OK if going to chem route).
- Controls: Convection oven with vent/scrubber; nitrogen purge optional; 20–40 min dwell; cool in air or inert.
- Safety: Hot-work SOP, heat-resistant gloves/sleeves, fume capture (varnish/epoxy), fire watch on exit.

C) Hydrogen decrepitation (HD)

- What: Expose magnets to low-pressure H_2 to form hydrides and self-crack into powder; also demagnetizes.
- Pros: One step to safe, friable powder; ideal feed for re-alignment/press/sinter; high throughput in baskets.
- Cons: Requires rated vessels; pyrophoric fines handling; moisture/oil control.
- Typical: 1–3 bar H_2, ambient–150 °C, 0.5–4 h depending on mass/geometry; end with N_2 backfill; store powder inert or wet.
- Safety: Class I, Div-rated equipment; H_2 sensors; purge protocol; bonded/grounded metal bins; Class D extinguishers for fines.

Decision matrix (simplified):

- Keep geometry for re-sinter? → AC demag (then mechanical removal).
- Need adhesive relief or thick arcs? → Thermal (oven) then extract.
- Going straight to magnet-to-magnet powder or want brittle parts? → HD.

4.2 Fixtures, jigs, and fast removal of VCMs/rotor segments

General ergonomics

- Bench height 38–42″; anti-static mats; toe-kick magnets banned near station.

- Tool set: torque drivers, spudgers, pry plates, soft-jaw vise, mini-shear, roll-pin punches.

A) HDD VCMs (voice-coil magnet assemblies)

- VCM pop-jig: Locating pins match top-cover screws; lever cam lifts the steel keeper while a shield prevents snap-in.
- Cycle: 1) Remove cover; 2) Seat drive in jig; 3) Cam-lift keeper; 4) Slide magnet set into tote; 5) Keeper back on to neutralize residual pull.
- Takt: 8–12 s for trained operators (magnet step); 90–120 s total/drive including other actions.
- Yield tips: Maintain screwdriver bit kits for every HDD family; magnet catch screen to keep chips out.

B) Small motors/fans

- End-bell fixture: Rotational clamp holds can; collar tool pulls end-bell without blade damage.
- Stator/rotor split: Use puller with standoff posts; once open, thermal or AC demag before prying magnet arcs.
- Adhesive relief: 120–150 °C heat gun or 10 min oven dwell; scrape in fume-hood.

C) EV/industrial rotors

- Cradle & cage: Rotor held in U-cradle; steel mesh cage prevents attraction incidents.
- Segment press plates: Contoured wedges slide under arc magnets; jack-screw applies even force post-demag.
- Dy/Tb flagging: Tag high-temp grades (VIN/model list); route to “HREE-likely” tote for priority QA.

D) Fasteners & coatings

- Keep Torx/tri-wing sets; pre-map “nasty” models with hidden clips.
- Nickel-coated surfaces scratch easily—use nylon pry tools where possible to improve purity.

Line balancing & QC

- Two-bin outfeed (A clean / B mixed); weigh to 10 g resolution; photo log each pallet top; 1 in 50 parts spot-checked for steel carry-over.

Safety specifics

- Pinch zones marked in red; no lone working on rotor bench.
- Mandatory demag before any two-hand manipulation of parts >100 mm.

4.3 Handling coatings (Ni–Cu–Ni), adhesives, varnishes

Why it matters

- Ni/Cu/Ni coatings and varnish/epoxies drive impurity budgets in re-sinter and reagent load in chem routes. Manage them early to raise yield and lower opex.

Coating strategies

- Preserve for Bin A: If going HD→re-sinter, intact coatings are acceptable; they'll fracture with HD and can be screened.
- Strip for Bin B: For chem recovery, aim to reduce metallic coating mass up front.
    - Mechanical: Light grit blast or tumble (short dwell) to scuff coat—collect fines; magnetically separate.
    - Thermal burn-off: 350–450 °C in controlled oven with afterburner/scrubber; weigh loss to estimate residual coat.
    - Chemical strip (selective): Mild acid for Ni/Cu removal on fragments; closed-loop, rinse capture; QC by ICP spot checks.

Adhesives & varnishes

- Softening: 120–150 °C pre-heat to peel; use scrapers under fume hood.
- Solvent swell (if needed): D-limonene/esters under hood; wring-out and air dry; collect wipes as haz waste.
- Burn-off: As above, with airflow control to avoid flaming; ash removal afterwards.

Contamination control

- Do not co-mix ferrite (black ceramic rings) with NdFeB streams—visual sort training; ferrite goes to separate tote.
- Keep steel clips/keepers out of magnet bins; provide a magnet-safe steel scrap bin right at the bench.

- Install inline magnetic wands on tote lips to catch stray chips before sealing.

Sampling & QA

- For each pallet: record gross, tare, net, estimate coating fraction (%), and adhesive class (none/light/heavy).
- One composite sample per pallet to lab: REE wt%, Ni/Cu/Fe, LOI (loss on ignition) to validate burn-off efficacy.
- Acceptance spec examples (illustrative):
  - Bin A (HD line): steel <1 wt%, ferrite 0%, adhesive "light," visible Ni intact OK.
  - Bin B (chem hub): Ni+Cu <5 wt% preferred, LOI <3 wt% after pre-treat.

Safety & EHS

- Fume management: Local exhaust at adhesive/varnish workstations; carbon filtration or vent-to-scrubber.
- PPE: Cut-resistant gloves, safety glasses, apron; heat gloves at ovens; respirators for burn-off maintenance.
- Fire: Class D for pyrophoric fines; ABC for general; hot-work permits for ovens; daily housekeeping to remove dust.
- Waste streams: Segregate Ni/Cu strip liquor, solvent wipes, burn-off ash; label drums; manifest per RCRA/state rules.

Performance checklist (per site, weekly):

- ☐ Demag compliance ≥ 99% before two-hand handling
- ☐ Pull-through: ≥ 90% of eligible units yield magnet modules
- ☐ Bin A share: ≥ 65% by mass after 90-day ramp
- ☐ Contaminants: steel carry-over < 1 wt%; zero ferrite in NdFeB lots
- ☐ Incident log: 0 recordables; all near-misses reviewed in toolbox talk

This package keeps operators safe, improves purity at the source, and feeds both downstream routes with material that meets spec—turning disassembly from a hazard into a high-yield, high-confidence step.

5. Processing Routes

Goal: turn captured NdFeB into either (a) new magnets via a low-energy, alloy-preserving path, or (b) high-purity rare-earth outputs (REOs/metals) via chemistry that tolerates heterogeneity—while meeting coercivity/impurity specs and maintaining traceability.

5.1 Direct magnet-to-magnet: HD → press → sinter → finish

What it is. Keep the alloy in the magnetic phase; avoid "going to chemicals" unless necessary. Best for clean, uniform parts (Bin A: HDD VCMs, green rejects, consistent rotor segments).

Unit steps & typical set-points

1. Hydrogen decrepitation (HD). 1–3 bar H_2, ambient–150 °C, 0.5–4 h → friable powder; demagnetized.
    - Outputs: HD powder (target O < 0.3 wt%), coating chips screened out.
2. De-oxidize/condition. Sieve (45–150 µm), light milling under Ar/N_2; optional getter (Ca, Mg) for O removal.
3. Alignment & pressing. Press in die under 1–2 T aligning field; green density 50–60% TD.
4. Sinter. 1,050–1,100 °C, 1–4 h, high vacuum/Ar; density to 7.4–7.6 g/cc.
5. Heat treat. 500–600 °C, 1–4 h to optimize Hcj.
6. Finish. Grind, coat (Ni–Cu–Ni, epoxy) to corrosion spec; magnetize to design B-H curve.

Performance

- Energy savings: commonly >70–90% vs ore→oxide→metal→magnet chain (project-dependent).
- Yields: HD→sinter line yields 80–90% magnet mass recovery on clean feed.
- When to use: single-family HDD lots, green rejects, OEM offcuts; avoid heavy epoxy/varnish unless pre-treated.

Risks & mitigations

- Oxygen pickup → lower (BH)max: control moisture, inert handling.
- Mixed chemistries → off-spec Hcj: segregate feed by source/model; blend with "master" lots.

5.2 Chemical routes to REOs: mild leach, oxalate/IL precipitation, metal/alloying

What it is. Dissolve the REE-bearing phase, remove Fe/Co/Ni/Cu, precipitate high-purity RE oxalates, calcine to REOs, optionally reduce to metals/alloys. Best for mixed/dirty feed (Bin B) and contaminated fines.

Representative flowsheet

1. Pre-treat. Burn-off (350–450 °C) to remove organics; mechanical scuff to reduce Ni/Cu coat; magnetically remove steel.
2. Selective leach. Mild acid (e.g., dilute HCl/HNO_3, pH-programmed) or organic systems that favor REE dissolution over Fe.
    - Control: pH, redox, temperature (25–60 °C) to minimize Fe.
3. Impurity removal. Sequential precipitation/solvent-free separations to pull Fe/Co/Ni/Cu first (hydroxide/sulfide windows).
4. REE precipitation. Oxalate route (add $H_2C_2O_4$) → REE-oxalate; filter, wash.
    - Alternative: ionic-liquid (IL) or deep-eutectic extraction for greener reagent loops.
5. Calcine. 800–950 °C → REO ($Nd_2O_3/Pr_6O_{11}/Dy_2O_3/Tb_4O_7$).
6. Optional metallization. Fluoride/chloride reduction or metallothermic routes → RE-metal; then alloy to Nd-Pr master or Nd-Pr-Dy melt for new magnet feed.

Performance

- Purity: REOs >99–99.5% with QA; metals >99% with proper reduction.
- Yields: 90%+ REE recovery achievable; overall plant yield 80–90% allowing for solids losses.
- By-product value: Fe/Co/Ni/Cu streams saleable; spent Ni/Cu solutions closed-looped.

EHS & circularity

- Closed-loop liquor management, neutralization, crystallization; low-VOC options via IL/DES.
- Solid residues tested TCLP; coatings sent to appropriate metal recovery.

When to use

- Heterogeneous scrap, epoxy-heavy material, mixed chemistries, or when you want REE splits (Nd/Pr vs Dy/Tb) for inventory control.

5.3 Halide/flux hybrids for mixed chemistries

What it is. Use molten salts/halides (e.g., NaCl/KCl eutectics with chloride/fluoride additives) to extract REEs from NdFeB without full aqueous circuits.

Why & when

- Heterogeneous feeds with coatings/steel fragments; desire to avoid large acid plants.
- Useful bridge for sites lacking full wet-chem capability; complements HD.

Typical approach

1. Prepare feed. HD powder or crushed magnets (≤5 mm), dried.
2. Molten-salt contact. 600–800 °C in chloride/fluoride flux; RE-halides partition to melt.
3. Separate phases. Decant/filtration of salt; reduce RE-halides to metals/oxides via gas or metallothermic steps.
4. Salt recycle. Regenerate halide mix; purge contaminants.

Pros/cons

- Pros: Tolerates coatings/steel; compact footprint; lower aqueous waste.
- Cons: High-temp corrosion, halide management, Dy/Tb control requires tuned chemistry.

Fit

- Regional hub handling Bin B where water/permits are constrained; pairs with small aqueous polishing loops.

5.4 Quality control: coercivity, impurity budgets, traceability

What “good” looks like

- Magnet properties (finished):

    - Hcj (intrinsic coercivity): per spec (e.g., >15–25 kOe for many grades; higher for high-temp).
    - Br (remanence) & (BH)max: within design band (±3–5%).
    - Thermal stability: ΔHcj after 150–180 °C aging within tolerance.
- Powder/green/sintered controls:
    - O, C, N in powder (LECO): O < 0.30 wt% (HD route target), C < 0.1 wt%, N < 0.05 wt%.
    - Grain size & texture: SEM/EBSD; orientation factor (Lotz) documented.
    - Dy/Tb mapping: EPMA/EDS for boundary diffusion profile thickness (e.g., 3–10 µm shell).
- Chemical outputs:
    - REO purity: ≥99.0–99.5% (ICP-OES); Fe/Ni/Cu each <0.1–0.2 wt% (per buyer spec).
    - Split accuracy: Nd+Pr assay ±0.3 wt%; Dy/Tb ±0.2 wt%.

Impurity budgets (illustrative accept/reject)

- HD→sinter feed: Fe (exogenous steel) <1 wt%; ferrite = 0; Ni+Cu (from coatings) <0.5 wt% post-screen.
- Chem route feed: Ni+Cu <5 wt% preferred; LOI (organics) <3 wt% after burn-off.

Test methods & cadence

- Magnetic: VSM or hysteresis loop tracer per lot; thermal demag/aging cycles on witness samples.
- Chemical: ICP-OES/ICP-MS panel (Nd, Pr, Dy, Tb, Fe, Co, Ni, Cu, Al); LOI; chloride/fluoride residuals for halide routes.
- Physical: Particle size (laser diffraction), density (Archimedes), porosity (mercury intrusion).

Traceability (lot genealogy)

- Data schema per pallet/lot: source (stream, site), Bin (A/B), weight, date/time, operator, pre-treat route, process parameters (HD pressure/time; sinter T/t; leach pH/T), QA results, photos.

- Chain of custody: QR tags from collection through processing; immutable audit log.
- Claim support: Recycled-content certificates tie finished magnets/REOs to lot genealogy; mass-balance statements (ISCC+/EPEAT-style).

Mass-balance example (round numbers)

- Input: 1,000 kg clean HDD VCMs (30 wt% REE).
- HD screen losses: 5% coatings/steel → 950 kg powdery feed.
- Sinter yield: 88% → 836 kg finished magnets.
    - Contains ~300 kg REO-equiv, balance Fe/Co/B and minor alloying.
- Scrap recycle: 50 kg grindings → back to HD; 14 kg fines to chem loop.

Route selection matrix (quick guide)

- Uniform, clean, geometry preserved needed? → HD→press→sinter.
- Mixed/dirty, want REO flexibility or element splits? → Mild-leach/oxalate (chem).
- Aqueous constraints, mixed feed, compact plant? → Halide/flux hybrid, polish with small aqueous step.
- HREE stewardship priority (Dy/Tb shells)? → Segregate those lots; allow GBD re-diffusion post-sinter to minimize fresh Dy/Tb.

Bottom line. Use HD→press→sinter wherever feed uniformity allows—fastest, lowest energy path to magnets. Keep a chem back-end to absorb heterogeneity and deliver spec-grade REOs/metals. Deploy halide hybrids where footprint and water push you away from full wet-chem. Across all routes, enforce tight QA and traceability so recycled content is bankable and high-temp performance (Hcj, Dy/Tb stewardship) is never in doubt.

6. HREE Stewardship and Performance

Purpose: maximize functional coercivity while minimizing fresh Dy/Tb input. This section covers (i) how to find HREE already circulating in legacy parts, (ii) how to stretch that HREE with grain-boundary diffusion (GBD), and (iii) how to prove high-temperature performance with disciplined testing.

6.1 Locating Dy/Tb in legacy parts

Why this matters. Dy/Tb are the scarcest, most geopolitically exposed REEs. In high-temp grades they are *not* uniformly distributed; they often reside as boundary-enriched shells added for coercivity. Recovering and re-deploying those atoms beats mining new supply.

Signals that a part likely contains Dy/Tb

- Application class: traction motors (EV/HEV), industrial servos for high-duty cycles, robotics, aerospace actuators, down-hole or under-hood pumps, some direct-drive wind segments.
- Thermal envelope: designs rated for >150–180 °C continuous or with repeated thermal spikes are strong candidates.
- Model-year heuristics: pre-GBD-era traction motors (roughly 2008–2016 in many platforms) often used bulk Dy; later models shift toward surface diffusion shells—ideal for stewardship.
- Supplier grade codes: commercial marks like “H/SH/UH/EH” (or equivalent) correlate with Dy/Tb use; internal drawings may list target Hcj at 150–180 °C.
- BH-curve fingerprints: elevated Hcj with only modest penalty to (BH)max suggests boundary Dy/Tb rather than bulk alloying.

Practical identification flow (shop floor → lab)

1. Intake tagging: flag likely HREE lots at disassembly (EV/industrial), record VIN/model or PN where available.
2. Screen test (non-destructive): quick VSM loop @ 25 °C, then heat to 150 °C and re-trace; unusually low irreversible loss implies Dy/Tb.
3. Microprobe confirmation (spot samples):
    - Polish cross-section, EPMA/EDS line scan from grain interior to boundary; look for 3–10 µm Dy/Tb-rich shell with Nd/Pr-rich cores.
    - Optional ToF-SIMS/GDOES depth profile for diffusion gradients.
4. Lot routing: HREE-positive, geometry-good parts → HD→re-sinter + (re)diffusion lane; mixed/dirty → chem route with Dy/Tb stream tracked separately.

6.2 Grain-boundary diffusion to reduce Dy/Tb intensity

Concept. Instead of alloying Dy/Tb throughout the bulk (which depresses remanence and consumes HREE), infuse a few micrometers of Dy/Tb along grain boundaries to pin domain walls where it matters most.

Why it wins

- Material efficiency: typical 50–80% reduction in Dy/Tb per unit coercivity vs bulk additions when properly tuned.
- Performance: preserves Br and (BH)max better than bulk doping; focuses coercivity where reversal initiates.
- Compatibility: pairs naturally with recycled HD powder and re-sintered compacts.

Process sketch (post-sinter)

1. Prepare source layer: Dy/Tb halide/oxide slurry, fluoride-assisted salts, or metal films; thickness tuned (e.g., 1–10 µm equivalent).
2. Apply to compact surface: dip/spin/coat or pack in reactive powder.
3. Diffuse: 800–900 °C for 1–6 h under vacuum/Ar; time–temp depends on target shell thickness and grain size.
4. Stabilize: 500–600 °C temper to relieve stress and lock microstructure.
5. Finish coat: standard Ni–Cu–Ni or epoxy as required.

Control knobs

- Grain size: smaller grains require less Dy/Tb for the same Hcj; manage via sinter schedule.
- Shell thickness: typical 3–10 µm at boundaries; too thin → inadequate Hcj; too thick → Br penalty.
- Chemistry assists: modest Co/Al/Cu tweaks can trade high-T stability vs remanence; keep oxygen and carbon tightly controlled ($O < 0.3$ wt% in powder).
- Masking patterns: for anisotropic parts, directional diffusion (mask one face) can optimize performance per volume of HREE.

QA for diffusion success

- EPMA/EDS maps: continuous boundary enrichment without core flooding.

- ΔHcj/ΔBr trade curve: document improvement in Hcj(150–180 °C) with ≤2–3% hit to Br relative to pre-diffused baseline.
- Accelerated aging hold: stability of Hcj after 168 h @ 150–180 °C (see 6.3).

6.3 Testing protocols for high-temp grades

Objective: guarantee coercivity at use temperature, stability with time/heat, and environmental robustness, while proving recycled/HREE-stewarded content is fit for purpose.

A. Magnetic performance (core)

- Room-temp baseline: Full BH loop (VSM/loop tracer): Br, Hc, Hcj, (BH)max; orientation factor if applicable.
- Elevated-temp coercivity: Measure Hcj(T) at 100/125/150/180/200 °C (as required by application). Report Hcj@T_use and slope dHcj/dT.
- Irreversible loss test: Heat magnet to T_use + 20–40 °C for 2 h, cool to 25 °C, re-measure BH loop; record ΔBr_irrev and ΔHcj_irrev.
- Thermal cycling: −40 ↔ +180 °C, 500–1,000 cycles, measure ΔBr, ΔHcj every 100–200 cycles.

B. Time/temperature stability (aging)

- Isothermal aging: 150–180 °C, 168–1,000 h depending on spec; log Hcj(t) vs ln(time); acceptable drift band defined per grade (e.g., ≤5–10% at 168 h).
- Post-aging diffusion check: occasional EPMA on aged samples to verify no deleterious boundary coarsening.

C. Corrosion & environment (if unavoidably harsh)

- PCT (pressure cooker test): 121 °C / 100% RH / 2 bar / 96 h, then BH loop + mass change; verify coating integrity.
- Salt-fog (ASTM B117 or regional equivalent): 96–240 h exposure; visual/rust score + performance retention.
- Condensing humidity: 40 °C / 93% RH / 10–20 days, intermittent BH loops.

D. Mechanical & handling

- Transverse rupture strength (TRS) and hardness on coupons from recycled lots; confirm within historical control limits.
- Chip/edge robustness: drop/impact micro-tests for thin segments; document reject rates at grind/finish.

E. Dy/Tb stewardship metrics (traceable claims)

- Mass balance: per lot, report HREE in (from recycled feed + any top-up) vs HREE in finished magnets.
- Intensity KPI: grams Dy+Tb per kA/m of Hcj@150 °C (or per kW of motor rating) — trend down quarter-on-quarter.
- Recycled content: audited % of REE mass from recycled sources; link to lot genealogy.

F. Acceptance bands (illustrative for traction-class magnet)

- Hcj@150 °C: ≥ 15–20 kOe (application-specific), ΔHcj(168 h @ 150 °C) ≤ 10%
- Br loss (irreversible after T_use + 20–40 °C / 2 h): ≤ 2–3%
- Corrosion: no blistering/rust post-PCT; ΔBr ≤ 3%
- Traceability: complete data row for source → process → BH loops → microstructure

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Bottom line. Treat Dy/Tb as surgical dopants, not bulk ingredients. Use legacy HREE where it already sits (EV/industrial lots), re-concentrate its effect through grain-boundary diffusion, and prove performance with temperature-explicit coercivity and aging protocols. Done right, this approach cuts Dy/Tb intensity by half or more while delivering the same or better high-temp stability, turning HREE stewardship into a measurable competitive advantage.

7. Unit Economics and Scaling

Numbers below are illustrative pro-formas meant to size pilots and compare routes. Replace with local labor/energy/tipping-fee quotes before committing.

7.1 Bill of materials: labor, energy, consumables, logistics

Scope: two archetypes

- A. HD→press→sinter line (Bin A: clean, uniform feed)
- B. Chem-to-REO hub (Bin B: mixed/dirty feed)

A) HD→press→sinter (per kg finished magnet)

- Feed requirement: ~1.2 kg captured magnets → 1.0 kg finished (≈85–90% line yield)
- Labor: 0.35–0.55 hr/kg (disassembly + line ops) → $7–$14
- Energy: HD furnace + vacuum sinter + heat treat → 1.5–3.0 kWh/kg → $0.15–$0.45
- Consumables: inert gas, getter, grinding media, coatings → $1.50–$3.50
- QA & scrap handling: tests, rework, packaging → $0.75–$1.50
- Logistics: inbound totes/pallets + outbound freight → $0.50–$1.50
- Overhead & EHS: facility, PPE, sensors, waste → $1.50–$3.00
- Total opex (ex-feed): $11–$24/kg finished magnet

B) Chem-to-REO (per kg REO)

- Feed requirement: ~3.3 kg mixed magnets @30% REE → 1.0 kg REO (85–90% recoveries)
- Labor: 0.25–0.4 hr/kg REO → $5–$10
- Energy: agitation/heating/calcine → 1–2 kWh/kg → $0.10–$0.30
- Reagents: mild acid/alkali, oxalate or IL/DES, filters → $3–$7
- Water & treatment: recycle/neutralization → $0.50–$1.50
- QA & assay: ICP, LOI, batch control → $0.75–$1.50
- Logistics: inbound/outbound solids, drums → $0.50–$1.50
- Overhead & EHS: ventilation, scrubber, permits → $1.50–$3.00
- Total opex (ex-feed): $11–$24/kg REO

Disassembly cost adders (front end, shared):

- ITAD HDDs: $0.30–$0.80/kg magnet (high rate)
- Appliance yard: $0.50–$1.50/kg magnet (heterogeneous)
- EV/industrial rotors: $1.00–$2.50/kg magnet (fixtures + safety)
- OEM swarf/offcuts: $0.10–$0.40/kg magnet (cleanest)

7.2 Gate fees, bounties, and plant-gate value of recovered REOs/magnets

Levers that swing economics:

- Gate fee / negative cost feed: Appliance or municipal partners may pay \$20–\$100/ton for diversion; at 30% REE, this is +\$0.02–\$0.10/kg magnet—small but additive.
- Bounties (retail take-back): \$1–\$5 per qualifying device; model to \$0.50–\$2.00/kg magnet depending on mix.
- Plant-gate value (PGV): depends on what you sell.

PGV reference bands (illustrative, spot-like):

- NdPr oxide (Nd_2O_3/Pr_6O_{11} basket): \$45–\$80/kg REO
- Dy/Tb oxides: Dy \$200–\$350/kg, Tb \$500–\$1,200/kg (low tonnage, volatile)
- Finished sintered magnet (N-grade, no Dy): \$55–\$85/kg at factory gate
- High-temp magnet (with Dy/Tb diffusion): \$80–\$140/kg (spec-dependent)

Example 1 — HD route (HDD VCM lots):

- Opex ex-feed: \$16/kg magnet; front-end \$0.60/kg → \$16.6/kg total.
- PGV: \$65/kg magnet. Gross margin: ≈ \$48/kg before feed credit.
- Feed credit: You *pay* \$0–\$1/kg to suppliers (or net zero with security service offsets).

Example 2 — Chem route (mixed appliances):

- Opex ex-feed: \$18/kg REO; front-end \$1.0/kg magnet → \$19–\$20/kg REO.
- REO mix value: if stream assays NdPr 90%, Dy 8%, Tb 2% of REO mass (rare, EV-heavy), blended PGV might exceed \$100/kg REO. If mostly NdPr (appliance-heavy), PGV \$45–\$70/kg REO.
- Margin: \$25–\$80/kg REO before feed cost; wide due to Dy/Tb fraction.

7.3 Modular line sizing and throughput (urban vs regional hubs)

Throughput heuristics (steady-state):

- ITAD lane (HDD focus, urban): 1 operator → 300–400 drives/shift → 12–18 kg magnets/shift (3.6–5.4 kg REO).

- Appliance cell (yard, urban): 2 operators → 8–20 kg magnets/shift.
- EV/industrial bench (regional): 2 operators → 20–40 kg magnets/shift from scheduled tear-downs.
- OEM swarf contract (regional): 0.5–2.0 t/month magnets equivalent (batch pickups).

Module definitions (12-month capex ballpark):

- M1: Micro HD cell (demag + HD + sieve + outsource sinter): 5–10 t/yr magnets; $0.4–$0.8M
- M2: Full HD→press→sinter line: 50–200 t/yr magnets; $3–$8M
- C1: Chem pilot (mild leach + oxalate + calcine): 20–80 t/yr REO; $2–$5M
- C2: Chem regional (with IL/DES loop + polishing): 100–400 t/yr REO; $6–$15M

Urban hub (capture-centric):

- Stack: 2× ITAD lanes + 1× appliance cell + M1 HD cell
- Run-rate: 40–60 t/yr magnets (Bin A 65%); sell HD powder or toll-sinter
- Why: Lowest logistics; quick wins; minimal permitting

Regional hub (processing-centric):

- Stack: 1× EV/industrial bench + OEM swarf + M2 HD line + C1/C2 chem back-end
- Run-rate: 150–300 t/yr magnets + 100–300 t/yr REO
- Why: Absorb heterogeneity; produce finished magnets & REOs; anchor offtakes

Staffing ratios (steady-state):

- HD line: 1 tech per 8–12 kg/hr HD throughput; 1 operator per press/sinter train
- Chem line: 1 operator per 300–600 L of active leach/precip capacity; QA 1 FTE per 100 t/yr REO

7.4 Sensitivity: price bands, yield losses, contaminant load

A) Price sensitivity (margin per kg output)

- NdPr oxide ±$10/kg: Chem route margin shifts ±$10/kg REO.

- Dy price −20%: High-temp magnet PGV can drop \$5–\$12/kg; cushion via GBD (less Dy/kg Hcj).
- Finished magnet ASP −\$10/kg: HD route margin −\$10/kg; mitigate with coating/finish value-add.

B) Yield sensitivity

- HD→sinter yield −5 pp (e.g., O pickup): cost per kg rises \$0.6–\$1.2; Br/Hcj may fall—tighten powder O control (<0.30 wt%).
- Chem recovery −5 pp: cost per kg REO rises \$1–\$2; add fines capture and polish loop.

C) Contaminant load (Ni/Cu/steel, varnish)

- Ni+Cu +2 wt% in feed: reagent spend +\$0.50–\$1.50/kg REO; add pre-strip or mechanical scuff.
- Steel carry-over 2 wt%: HD screen/blast adds \$0.20–\$0.40/kg magnet; enforce keeper segregation at bench.
- Organics LOI +3%: burn-off gas/scrubber cost +\$0.20–\$0.50/kg and slower takt; shift sticky lots to chem route.

D) Mix sensitivity (Dy/Tb fraction)

- Appliance-heavy month (Dy/Tb ≈ 0–1% of REO): PGV skews low → prioritize HD magnets sales over REO sales.
- EV/industrial month (Dy/Tb ≈ 5–10% of REO): PGV skews high → emphasize REO splits and GBD restocking for high-temp grades.

E) Policy & incentive levers

- Magnet bounty +\$1/unit (HDD/tools): effective feed cost −\$0.50–\$2.00/kg magnet (improves capture).
- Recycled-content procurement premium +\$5/kg magnet: HD route margin +~\$5/kg; bankable with traceability.
- Gate fee \$50/ton diverted: modest but offsets yard labor by \$0.05/kg.

Quick decision grid (go/no-go)

Situation	Preferred route	Why
Uniform HDD VCMs, low coatings	HD→press→sinter	Lowest opex, fast throughput, strong margins
Mixed appliances, sticky varnish	Chem→REO	Tolerant to heterogeneity; sell NdPr oxide
EV/industrial with Dy shells	HD + GBD (+ some chem splits)	Preserve geometry, stretch HREEs
Water/permit constrained region	Halide/flux + small polish	Compact footprint, minimal aqueous waste

Bottom line: With reasonable capture and basic process controls, both routes clear comfortable spreads at mid-band prices. The fastest cash-flow comes from HDD/ITAD + HD lines; the largest strategic leverage comes from EV/industrial lots + GBD, which convert scarce Dy/Tb into high-temp coercivity at far lower HREE intensity.

8. Policy Stack to Unlock Volume

The goal is simple: move magnets pre-shred at scale and turn them into bankable domestic supply. The stack below aligns labels → design → demand → funding → risk cover so pilots become a national network.

8.1 Magnet labeling and the "magnet passport"

Intent: make magnets *legible* to collectors and buyers so they can be removed fast, routed correctly, and counted toward recycled-content claims.

Core requirements (at product level):

- Permanent-magnet disclosure on any device with >5 g NdFeB:
  fields = {magnet_mass_g, composition_class (NdPr / NdPrDy / NdPrTb), coating_type (Ni-Cu-Ni/epoxy), count, location_hint, extraction_steps, Hcj_grade, recycling_route_hint (HD/chem), OEM_PN, date_code}.
- QR/NFC "magnet passport" on device shell and service manual; links to a NIST-hosted schema (JSON), printable symbol for low-tech yards.

- Digital registry: manufacturers upload passport data at sale; collectors append weight, bin (A/B), custody events, and lot IDs (audit log).

Implementation notes:

- Thresholds: start at >25 g per device in Year 1, step down to >5 g in Year 3.
- Exemptions: sealed medical devices until service interval; defense under classified annex (still label in registry).

Enforcement & incentives:

- Non-compliant imports: customs hold + corrective labeling.
- Procurement preference (+5 points) for vendors with valid passports and live registry entries.

Metrics: % of incoming units with valid passports; average extraction time (min/unit); mis-route rate (%).

8.2 Design-for-disassembly and right-to-repair

Intent: ensure magnets can be removed fast, safely, and without destruction.

Design rules (new models after a phase-in):

- Fasteners over glue in magnet modules; if adhesive is necessary, it must soften ≤150 °C or respond to a specified solvent.
- Tooling parity: required bit types disclosed in the magnet passport; no anti-repair fasteners on magnet covers.
- Access geometry: locate magnets ≤5 minutes from first fastener removal on service path.
- Demag port or instruction for AC demag prior to opening.

Right-to-repair tie-ins:

- Make service documentation & jigs (VCM pop-jigs, end-bell fixtures) available at fair cost.
- Allow third-party refurbishers to retain warranty when only magnet module is accessed per SOP.

Compliance gates: UL/ETL “magnet-accessible” mark; random teardown audits with a time-to-magnet KPI.

8.3 Recycled-content and Buy-American-style procurement standards

Intent: guarantee demand for recycled magnets/REOs so capture economics close.

Federal/State procurement rules (examples):

- Minimum recycled REE content (by mass) in covered end-uses:
  Year 1–2: ≥5%, Year 3–4: ≥15%, Year 5+: ≥25% (with technical exemptions for first-use defense systems).
- Qualifying documentation: lot genealogy from the registry + mass-balance statement; third-party audit annually.
- Domestic content bonus: products with recycled + domestically processed REE streams get price-preference (e.g., +10% evaluation credit).

Covered categories (initial): federal fleets (EV motors), HVAC/fans in public buildings, data-center equipment, wind/industrial drives purchased with public funds; DoD non-weapon support systems; state/municipal fleets and facilities.

Metrics: $ spent on recycled content; tonnes of magnets/REOs accepted; import displacement estimate (Nd/Pr/Dy/Tb).

8.4 Deposit-refund (magnet bounty) and extended producer responsibility (EPR)

Intent: pull material out of households and small businesses and make it worth a hauler’s time.

Deposit-refund (“magnet bounty”):

- Point-of-sale deposit on magnet-bearing goods (e.g., $2–$10 depending on class).
- Return credit when device (or pulled magnet module) is delivered to certified sites (retail pods, ITAD, yards).
- Dynamic rates: higher bounty for HDDs/industrial motors/EV motors; bonus for HREE-flagged lots.

EPR framework:

- Producer Responsibility Organization (PRO) funds: retailer pods, yard demag stations, training, and consumer outreach.
- PRO must meet capture targets (e.g., ≥50% of sold magnet mass by Year 5); shortfalls trigger fee escalators.

Small-biz simplifications:

- Flat-rate boxes (prepaid) for HDDs and small motors (like e-waste mail-back).
- Instant reimbursements via QR scan at drop-off; weekly ACH to yards.

Metrics: return rate by category; cost per kg captured; geographic coverage (share of population within 5 miles of a drop point).

8.5 Grants, offtakes, and insurance for first-of-kind plants

Intent: de-risk the first wave of HD→sinter and chem-to-REO capacity so private capital flows.

Capital & grants (illustrative programs):

- DOE grants (critical materials): equipment for HD furnaces, vacuum sinter, QA labs; matching 40–60%.
- DPA Title III / DoD IBAS: magnet lines for defense-relevant grades; funding plus multi-year purchase commitments.
- State green-jobs funds: build-out for urban capture hubs and regional processing (tax credits, sales-tax exemptions).
- Loan guarantees (LPO-style): coverage for working-capital cycles tied to inventory of REOs/magnets.

Offtake structures:

- Floor-price offtakes for NdPr oxide and specified magnet grades (e.g., N42SH, N48H) with volume-take or pay.
- Indexed premiums for verified recycled content (+$5–$15/kg magnet) and HREE-intensity metrics (bonus for grams Dy+Tb per kA/m Hcj below benchmark).
- Defense Logistics Agency (DLA) stockpiling: competitive tenders for recycled NdPr/Dy/Tb oxides with storage & rotation.

Risk-transfer & insurance:

- Availability payments during ramp if plants meet uptime/QA, regardless of spot REO price.
- Price-collar contracts (contracts-for-difference) on NdPr to buffer market swings for 5–7 years.
- Performance bonds for QA specs (Hcj@150–180 °C) to satisfy motor OEMs; product liability backstops for recycled grades.

Milestone-based disbursement:

- Tranche 1: commissioning and first-article magnets/REOs.
- Tranche 2: 90-day continuous run at ≥70% nameplate with QA pass.
- Tranche 3: 12-month KPI attainment (yield, recycled share, Dy/Tb intensity).

KPI dashboard (tie to public funding):

- Tonnage: kg magnets captured; kg REO produced.
- Purity & performance: REO assay, magnet BH curves vs spec.
- HREE stewardship: grams Dy+Tb / kA·m of Hcj@150 °C (target ↓ over time).
- Traceability: % lots with complete passport → invoice chain.
- Safety & EHS: incident rate; closed-loop reagent ratios; waste factors.

Putting it together (12–24 month playbook)

- Months 0–6: Finalize passport schema, publish design rules, stand up 10 city capture pilots (retail pods + yard demag cells), open first M1 micro-HD cells.
- Months 6–12: Launch federal procurement recycled-content minima; activate bounty in pilot states; award seed grants for M2 HD lines and C1 chem pilots.
- Months 12–24: Convert pilots to regional hubs; sign floor-price offtakes; roll out price collars; expand bounty nationwide; start DLA stockpile purchases.

Result: predictable feed, faster extraction, and bankable sales—so private investors underwrite the rest. The stack is intentionally modular: even partial adoption (passport + procurement) materially increases capture and makes magnets-first move from “good idea” to operating industry.

9. City-Level Pilot Blueprint (Example: DFW or Detroit)

Purpose: stand up a capture-first magnets network that reaches steady 40–60 t/yr magnet throughput in 12–24 months, feeding an HD→sinter line (Bin A) plus a chem hub (Bin B).

9.1 Feedstock mapping and partner network

Metro selection logic (DFW or Detroit): large data-center/ITAD presence, strong appliance flows, dense scrapyard network, auto dismantlers, and OEM/ Tier-1 plants within 300 miles.

Catchment map (first 6–9 months):

- IT/e-waste (core):
  - 2–3 ITAD depots (enterprise refresh & remarketing).
  - 3–5 data centers on 18–36-month HDD refresh cycles.
- Retail/hauler:
  - 20–30 big-box stores with appliance/e-waste pods.
  - 1–2 municipal transfer stations (bulky waste days).
- Scrapyards/MRFs:
  - 3 high-throughput yards for mixed appliances/motors.
  - 1 e-MRF for small electrics/speakers/tools.
- Auto/industrial:
  - 4–6 auto dismantlers (target EV/HEV, fleet auctions).
  - 2 industrial service depots (robotics/servo change-outs).
- OEM scrap:
  - 1–3 magnet/motor machining shops (swarf/offcuts).
  - 1–2 Tier-1 suppliers (green rejects, end-of-run lots).

Expected monthly feed (steady state, blended):

- ITAD/HDD: 12–18 t/yr magnets ⇒ 1–1.5 t/mo
- Appliances/yards: 12–20 t/yr ⇒ 1–1.7 t/mo
- Auto/industrial: 8–15 t/yr ⇒ 0.7–1.3 t/mo

- OEM swarf/offcuts: 8–24 t/yr ⇒ 0.7–2.0 t/mo
  Total: 40–60 t/yr magnets (Bin A ≈ 60–70% by mass after ramp)

Commercial scaffolding:

- Per-kg credits to ITAD/yards + purity bonus for Bin A.
- Bounty ($/device) at retail pods (HDDs, power tools, small motors).
- Swarf offtake contracts (indexed to REE basket with floor).
- Auto dismantler incentives for EV motor pulls (VIN-based).

9.2 Line layout: HD vs chem hub, staffing, EHS

Site plan (single 35–50k ft² facility):

- Intake & triage (6k ft²): dock, scale, QR check-in; two disassembly bays (ITAD; motors/appliances).
- Bin A path (HD→sinter, 12–18k ft²):
  - AC demag zone → HD room (Class I Division-rated) → sieve/condition → align/press → vacuum sinter → temper → grind/coat → QA loops.
- Bin B path (chem hub, 8–12k ft²):
  - Burn-off oven with scrubber → mild-leach tanks (closed-loop) → impurity removal → REE oxalate precipitation → calcine → REO packing; small polish loop.
- Shared QA/EHS (3–5k ft²): ICP-OES, LECO OCN, VSM/hysteresis tracer, SEM/EDS bench; compressed gas & scrubber plant; waste and drum storage.

Nameplate throughput (Month 12 targets):

- HD line: 12–20 kg/hr HD input; 50–120 t/yr magnet input capacity (run 1–2 shifts).
- Press/sinter: 8–15 kg/hr finished magnets (N-grades; higher with multiple presses).
- Chem hub: 1–3 t/week REO (modular tanks), scale to 100–300 t/yr REO with second train.

Staffing (steady state, 1.5 shifts):

- Intake/triage/disassembly: 6–10 FTE
- HD room & powder handling: 4–6 FTE

- Press/sinter/finish: 6–8 FTE
- Chem hub ops: 5–7 FTE
- QA (magnetic + chemical): 3–4 FTE
- EHS/facilities/logistics/admin: 4–6 FTE
  Total: 28–41 FTE (scale with 2nd shift)

EHS critical controls:

- Hydrogen safety: gas detection, purge/evac, interlocks, Class I Div-rated enclosures, emergency venting.
- Thermal/burn-off: afterburner + scrubber; hot-work permits; fire watch; Class D extinguishers for fines.
- Chemicals: closed-loop liquor, secondary containment, neutralization; TCLP on solids.
- Dust & ergonomics: local exhaust at grind/coating; lift assists; pinch-hazard SOPs at rotor bench.
- Training cadence: initial 8-hr + quarterly refreshers; drills (H_2, spill, fire) semi-annual.

9.3 Data, QA, and chain-of-custody

Data backbone (lot genealogy):

- QR at intake → pallet/lot ID with fields: source site, stream, weight, Bin (A/B), photos, operator, date/time.
- Process trace: HD batch ID (pressure/time), sinter furnace ID (T/t/vac), chem batch (pH/T recipe), coating lot, test IDs.
- Outputs: magnet part numbers with BH curves; REO bags with ICP assay; recycled-content certificate.

QA program (accept/reject & release):

- Powder (HD): O < 0.30 wt%, Fe (exogenous) <1 wt%, no ferrite; PSD within target; EBSD texture check (per campaign).
- Magnets: VSM loop per lot (Br, Hc, Hcj, (BH)max); Hcj@150–180 °C for high-temp grades; aging (168 h @ 150–180 °C) sampling plan.
- REOs: ICP-OES panel (Nd, Pr, Dy, Tb, Fe/Ni/Cu ≤ spec), LOI; bag-level COA.

- Dy/Tb accounting: mass balance per batch; KPI = grams Dy+Tb per kA/m Hcj@150 °C for magnets released that quarter.

Chain-of-custody & claims:

- Immutable log (cloud) for all custody events; two-person sign-offs at intake/outbound.
- Mass-balance statements to customers (EPEAT/ISCC+-style) showing recycled share.
- Random third-party audits (quarterly) on 10% of lots (paper + physical sampling).

9.4 24-month ramp plan and KPIs

Months 0–3 (spin-up):

- Secure lease; order HD furnace, sinter train, lab gear; sign MOUs with ITADs/yards/retail pods; hire core ops/QA/EHS.
- Target intake: 2–4 t magnets; ship eval lots (HD powder + small REO trial).

Months 4–6 (first articles):

- Commission HD, press/sinter, QA; start two ITAD lanes + 1 yard cell.
- Run-rate: 5–8 t/yr magnets (Bin A 60%); first-article magnets (N-grades) pass QA.
- KPIs: Bin A purity ≥ 60%; HD powder O < 0.35 wt%; VCM takt ≤ 2 min/drive end-to-end.

Months 7–12 (nameplate on one shift):

- Add 10–15 retail pods; launch chem pilot (C1) for Bin B; onboard 2 auto dismantlers; sign first OEM swarf contract.
- Run-rate: 20–35 t/yr magnets; 10–30 t/yr REO.
- KPIs:
    - Yield: HD→sinter ≥ 85% mass; Chem REE recovery ≥ 88%
    - QA: Hcj@150 °C within spec on 95% of lots; REO purity ≥ 99.0%
    - Safety: 0 recordables; all drills completed

Months 13–18 (regional posture):

- Add second press or extend to 1.5 shifts; scale chem to 60–120 t/yr REO; add 2nd yard cell; expand dismantlers (EV focus).

- Run-rate: 35–50 t/yr magnets; 60–120 t/yr REO.
- KPIs: Bin A share ≥ 65%; CTR (cost to recover) ≤ $1.50/kg magnet; on-time shipments ≥ 98%

Months 19–24 (optimization & HREE stewardship):

- Introduce GBD station for high-temp grades; qualify recycled-content magnets with anchor customers; execute price-collar/ offtake.
- Run-rate: 40–60 t/yr magnets; 100–200 t/yr REO (if C2 train added).
- Strategic KPIs:
    - HREE intensity: ≥ −30–50% Dy/Tb per kA/m Hcj@150 °C vs baseline (Year-0)
    - Recycled content: ≥ 25–40% of REE mass in shipped magnets
    - Traceability: 100% lots with complete passport → invoice chain
    - Financial: HD route margin ≥ $35–$50/kg magnet; chem route margin ≥ $20–$40/kg REO (mid-band prices)

Kill/scale thresholds (decision gates):

- Gate A (Month 6): first-article pass + Bin A ≥ 60% → proceed; else fix feed purity or pause sinter expansion.
- Gate B (Month 12): sustained ≥ 20 t/yr magnets + QA pass + safety clean → add shift/second press.
- Gate C (Month 18): chem recovery ≥ 88%, REO ≥ 99.0% purity → add C2 train or partner tolling.
- Gate D (Month 24): HREE intensity KPI trending down; at least 2 multi-year offtakes → replicate in second metro.

Outcome: a repeatable urban-plus-regional template that converts local returns, IT refresh, and industrial change-outs into bankable domestic magnets and REOs, with auditable recycled content and measurable Dy/Tb stewardship.

10. Risks, Failure Modes, and Mitigations

This section turns the four biggest failure classes into playbooks: how to spot them early, what to do in the first 24 hours, and what structural fixes keep them rare.

10.1 Supply inconsistency and hoarding

Risk shape

- Capture partners (ITADs, yards, dismantlers) batch shipments irregularly, divert to higher bidders, or sit on EV/industrial lots when prices rise.
- Seasonality (college move-outs, holiday appliances) whipsaws feed quality and volume.

Early signals

- Missed pickups, pallet weight variance >25% month-over-month, "model mix unknown" notes increasing, surge in Bin B share.
- Sudden spikes in "we'll call you" responses from top 3 partners.

First 24-hour actions

- Trigger buffer draw from on-hand inventory (target 4–6 weeks magnet buffer, 6–10 weeks for REO).
- Pull forward OEM swarf pickups; flip one disassembly lane to HDD-only (predictable).

Structural mitigations

- Multi-sourcing: 3+ partners per stream; no single one >30% of monthly mass.
- Indexed pricing + floor in supply contracts; add purity bonuses and on-time bonuses (micro-incentives beat flat rates).
- Right of first refusal clauses on HREE-flagged EV/industrial lots.
- Prospecting team: 1–2 FTE constantly adding small suppliers (pawn/repair/thrift, school districts).
- Digital transparency: partner portal showing credit per kg and aging pallets; pay 48-hour ACH on receipt to out-compete hoarders.
- Policy lever: activate retail bounty and municipal gate-fee credits during droughts.

KPIs

- Supply Herfindahl index (HHI) < 2,000; Bin A ≥ 60–70%; buffer coverage in weeks.

10.2 Contamination, coatings, and adhesives

Risk shape

- Steel keepers, ferrite rings, Ni–Cu–Ni flakes, and varnish load cause yield losses, reagent burn, and off-spec Hcj.
- HD powder oxygen pickup (>0.30 wt%) depresses (BH)max; chem lines get Ni/Cu breakthrough.

Early signals

- Screen overflows and magnet fines clumping; ICP Ni/Cu > spec; LOI uptrending.
- QA rejects citing “ferrite found” or steel >1 wt% in Bin A.

First 24-hour actions

- Isolate bad lots; route to chem line if HD route is at risk.
- Increase burn-off dwell by 20–30%; enable mechanical scuff for Ni/Cu.
- Add O_2 moisture check at HD room; swap liners, purge protocol.

Structural mitigations

- Two-bin discipline at source (A clean / B mixed) with photo-logged pallets.
- Red list training: show ferrite vs NdFeB, keepers vs magnet arcs; visual cards at benches.
- Acceptance specs in POs; contamination demerits reduce payment.
- Pre-treat menu:
    - Light grit-blast/tumble for coatings before chem.
    - 350–450 °C burn-off with scrubber for varnish/epoxy.
    - Selective strip for Ni/Cu in closed loop.
- Powder hygiene: handle HD powder inert, target O <0.30 wt%, RH <35%; use getters (Ca/Mg) sparingly.
- Inline QA gates: ferrite detector at tote lips; random magnet-wand sweeps for steel.

KPIs

- Bin A contaminants: steel <1 wt%, ferrite 0%; chem reagent cost $/kg REO stable; HD powder O <0.30 wt%.

10.3 Market volatility for REOs and magnets

Risk shape

- NdPr oxide drops $10–$20/kg; Dy/Tb spikes on policy headlines; finished magnet ASPs compress on OEM over-ordering/unwinding.

Early signals

- Bid/ask widening, offtakers quietly delay liftings, competitors offering spot discounts.
- Inventory days creep up, cash conversion lengthens.

First 24-hour actions

- Rebalance output mix: shift clean feed to finished magnets (stickier pricing), push mixed feed to REO lots only if offtake floors apply.
- Engage collar counterparties to lock a tranche; draw on availability payments if eligible.

Structural mitigations

- Price collars / CfDs: lock NdPr band for 30–50% of expected volume; periodic reset.
- Floor-price offtakes (12–36 months) for magnets (e.g., N42SH/N48H) and REOs with take-or-pay.
- Two-route optionality: always maintain both HD→sinter and chem capacity; switch with feed mix.
- Product optionality: qualify multiple grades (std and high-temp) and offer GBD add-on; monetize performance, not just mass.
- Working-capital facility (inventory repo) secured by bagged REOs and tested magnets.
- Stockpiling channel: sell Dy/Tb oxides to DLA-style reserve when spot bids sag.

KPIs

- Hedge coverage (% volume under collar/offtake), gross margin per kg by route, inventory days, share of output as finished magnets vs REO.

10.4 Regulatory/EHS surprises

Risk shape

- Permit reclassification (air, wastewater), RCRA hazardous determinations for residues, hydrogen safety upgrades, community EJ challenges, emergency rulemaking.

Early signals

- Regulator "information requests," neighbor complaints/odor tickets, consultant memos with "may be hazardous" language.
- Supplier contracts start adding EHS representations.

First 24-hour actions

- Stand up response ICS: EHS lead + plant manager + counsel + comms.
- Stabilize operations: pause burn-off/chem steps implicated; maintain HD line if unaffected.
- Notify regulators within 24 h when reportable; document corrective steps.

Structural mitigations

- Pre-permit dialogue: engage air/water/haz-waste agencies pre-build; commit to closed-loop chem, afterburner+scrubber, and TCLP testing plans.
- Design to conservative standards: treat borderline residues as hazardous in engineering (secondary containment, drum labeling), even if likely non-hazardous.
- Hydrogen program: Class I Div-rated rooms, leak detection, emergency venting, LOTO, drills 2×/yr; third-party PSM/HAZOP annually.
- Community & EJ: public open-house pre-start; publish air and noise dashboards; hotline for complaints; rapid abatement team.
- Management of Change (MOC): any chemistry/temperature/throughput change requires MOC + EHS sign-off; keep as-built P&IDs current.
- Insurance & bonding: environmental impairment liability (EIL), product liability for recycled magnets, performance bonds on QA specs.

KPIs

- Compliance: 0 notices of violation, all permits current; drill scores; response time to complaints <48 h.

- EHS leading indicators: near-misses logged, corrective actions closed <30 days.

One-page risk dashboard (operate weekly)

- Supply: buffer weeks (magnets/REO), HHI, Bin A share, partner on-time %
- Quality: contaminants (steel/ferrite wt%), HD powder O, chem reagent $/kg REO
- Market: hedge coverage %, ASP vs collar mid, inventory days
- EHS/Reg: incidents, NOx/VOC/odor readings vs limits, audit findings open
- Finance: gross margin/kg by route, cash conversion cycle, covenant headroom

Bottom line: Design the system so that no single shock—not supply droughts, messy feed, price swings, or a surprise inspection—can put you out of spec or out of cash. Optionality (two processing routes), buffers, and pre-agreed contracts (with floors, collars, and offtakes) turn a fragile pilot into a resilient operating business.

11. Roadmap and Strategic Impacts

This roadmap turns one metro pilot into a repeatable, financed network that couples capture, recycling, and domestic magnet making, with hard metrics for reducing exposure to Nd/Pr/Dy/Tb imports.

11.1 From pilots to national network

Phase A — Replicable metro template (Months 0–24)

- Stand up 5–10 city pilots (DFW/Detroit/Atlanta/SoCal/Philly/Bay Area/Boston/Chicago/Houston/Phoenix).
- Common stack: retail pods + ITAD lanes + yard demag cells, one HD→sinter skid (M1/M2), and access to a regional chem hub (C1/C2).
- KPI gates to replicate:
    - ≥ 40 t/yr magnet intake per metro, Bin A ≥ 65%
    - HD→sinter yield ≥ 85%, REO purity ≥ 99.0%
    - Lost-time incidents = 0, traceability = 100%

Phase B — Regional integration (Months 24–48)

- Cluster 3–4 metros under one regional processing spine: a 100–300 t/yr HD line + 100–300 t/yr chem line.
- Add GBD stations for high-temp grades; qualify two to three anchor OEMs (motors, servos, traction).
- Begin inter-metro load balancing (surge HDDs to HD, sticky appliance lots to chem).

Phase C — National mesh (Years 4–7)

- 20–30 metros feeding 6–8 regional hubs; 2–3 national QA/reference labs (round-robin proficiency).
- Standardize the magnet passport and EPR "magnet bounty" nationwide; federal & state procurement minimums (Section 8.3) in force.
- Introduce price collars/stockpile tenders for NdPr/Dy/Tb to stabilize planning.

Scale math (illustrative):

- Per metro: 50 t/yr magnets × 25 metros = 1,250 t/yr magnets captured.
- At 30 wt% REE → 375 t/yr REO-equivalent; with 88% recovery → 330 t/yr REO delivered.
- Mix-managed to keep Dy/Tb-bearing lots prioritized for GBD restocking.

11.2 Coupling with domestic magnet manufacturing

Strategic coupling principles

1. Two-route optionality on one campus: HD→sinter for clean feed; chem→REO for mixed feed and element splits.
2. GBD as the HREE amplifier: recycle Dy/Tb from legacy parts and redeploy via grain-boundary diffusion to cut fresh HREE intensity 50–80% per unit coercivity (program target).
3. Closed QA loop: common lab (VSM/ICP/LECO/EPMA) supports both recycle and make; lots flow with one genealogy from pallet to part number.

Industrial link-ups

- Motor/drive OEMs: qualify N42–N48 (H/SH/UH) and a high-temp grade with documented Hcj@150–180 °C and recycled content.

- Tier-1s & defense: toll-make specialty pieces (arcs/rings/segments) with audited Dy/Tb intensity; DLA-style offtakes for REOs.
- Greenfield magnet plants: pair a new sinter/bonded facility with a local capture ring (3–5 metros) to guarantee 30–50% of REE needs from recycled streams day one.

Commercial model

- Dual revenue: finished magnets (sticky pricing) + REOs (flex buffer).
- Premiums: recycled-content adder (+$5–$15/kg magnet) and HREE-intensity bonus for meeting quarterly targets.
- Floor contracts: 12–36-month offtakes with take-or-pay to finance capex.

Ops canon

- Segregate EV/industrial lots for HREE management; run "Dy/Tb-positive" campaigns, then GBD recharge.
- Maintain powder oxygen <0.30 wt%, enforce ferrite = 0 in HD feed.
- Publish quarterly BH curves and aging data for buyer confidence.

11.3 Measurable reduction in Nd/Pr/Dy/Tb import exposure

Definitions

- Let M_NdPr, M_Dy, M_Tb be U.S. annual *magnet-grade* demand for each oxide equivalent (t/yr).
- Let R_NdPr, R_Dy, R_Tb be recycled output placed back into domestic magnets (t/yr).
- Import exposure for element E is:
  Exposure_E = max(0, (M_E − Domestic_Mine_E − R_E)) / M_E.

Program targets (Year 5, national mesh):

- Recycled content in magnets: ≥ 25–40% of REE mass across participating grades.
- Dy/Tb intensity: −30–50% grams Dy+Tb per kA/m of Hcj@150 °C vs Year-0 baseline through GBD.

- Exposure reduction:
  - Nd/Pr: −20–35% absolute import exposure versus baseline (recycled supply + any new domestic mine/separation).
  - Dy/Tb: −30–50% absolute import exposure for high-temp magnet demand (via targeted recovery + GBD).

Back-of-envelope linkage (illustrative):

- If 330 t/yr REO flows from network (Section 11.1) with mix NdPr 85%, Dy 12%, Tb 3% (EV/industrial-weighted):
  - R_NdPr ≈ 280 t/yr, R_Dy ≈ 40 t/yr, R_Tb ≈ 10 t/yr.
- With GBD, each recycled 1 t Dy/Tb can secure ~1.5–2.0 t of high-temp magnet output equivalent (less bulk doping for same Hcj).
- Net effect: recycled HREEs disproportionately shrink exposure in traction/servo segments where substitution is hardest.

Verification & reporting

- Quarterly mass balance: per hub and nationally (inputs → magnets/REOs → customers).
- Performance dashboards:
  - Import displacement (t/yr) by element
  - HREE intensity (g Dy+Tb / kA·m Hcj@150 °C) by grade
  - Recycled share (%) in shipped magnets by customer class
- Third-party audits: verify genealogy, assays, and recycled-content claims (ISCC+/EPEAT-style).

Strategic impacts summary

- Industrial resilience: Shortens crisis lead time from years to quarters, securing EV, wind, defense, and automation.
- Price insulation: Two-route processing + offtake collars dampen NdPr/Dy/Tb shocks.
- Policy wins: Transparent magnet passports + procurement standards convert waste into measurable import displacement.
- Climate & energy: >70–90% energy savings (route-dependent) vs virgin chain; lower transport miles via metro capture.

- Jobs & know-how: 30–50 skilled jobs per metro, with national centers of excellence in magnet QA and GBD.

Bottom line: Move from pilot to mesh by repeating a proven metro playbook, weld it to domestic magnet manufacturing, and track three numbers relentlessly—recycled share, HREE intensity, exposure reduction. Hit those, and U.S. magnet security becomes an operating fact, not a policy aspiration.

12. Conclusion

12.1 Why magnets-first is the shortest path to resilience

Magnets-first works because it starts where grade, function, and scarcity already co-locate. NdFeB parts concentrate the exact elements the economy lacks (Nd/Pr, and Dy/Tb for high-temp grades) at mass fractions that are three–four orders of magnitude richer than mixed waste. Capturing them pre-shred preserves value, reduces contamination, and gives immediate access to two flexible routes: HD→press→sinter for clean, uniform feed and chem→REO for heterogeneous streams. This optionality compresses time-to-tonnage from years to quarters, cuts capex, and threads directly into domestic magnet manufacturing. Critically, it also solves the real choke point—functional coercivity at temperature—by letting us redeploy legacy Dy/Tb with grain-boundary diffusion, slashing fresh HREE intensity while meeting high-temp specs. Compared with landfill mining or waiting on greenfield mines and separation plants, magnets-first minimizes geological, permitting, and market risks, and converts today's waste logistics into bankable, traceable supply that displaces imports now.

12.2 What to do next: procurement, pilots, and standards

Procurement (create demand pull):

- Set minimum recycled REE content for public purchases (start ≥5%, ramp to 25%+ in 5 years).
- Offer price preference for magnets with verified recycled content and HREE-intensity metrics (grams Dy+Tb per kA/m Hcj).
- Execute floor-price offtakes (12–36 months) for standard grades (e.g., N42–N48 H/SH/UH) to finance first lines.

Pilots (prove and scale capture→processing):

- Launch city pilots (e.g., DFW, Detroit): retail take-back pods, yard demag cells, two ITAD lanes, and a micro HD cell; pair with a regional chem hub.

- Target ≥40–60 t/yr magnets per metro within 12–24 months; keep Bin A ≥65%, HD→sinter yield ≥85%, REO ≥99.0% purity.
- Prioritize EV/industrial lots for Dy/Tb stewardship; stand up a GBD station by Month 18 for high-temp grades.

Standards (make magnets legible and extractable):

- Implement a magnet passport (QR/NFC + NIST schema): mass, composition class, coating, count, location, extraction steps, Hcj grade, recommended route.
- Enforce design-for-disassembly: fasteners over glue; adhesives that soften ≤150 °C; tool specs published; magnets reachable in ≤5 minutes along the service path.
- Establish collection economics: deposit-refund magnet bounties, EPR funding for pods and yard stations, and purity bonuses for Bin-A lots.

Finance & risk cover (keep projects investable):

- Blend grants + loan guarantees + availability payments with price collars/CfDs on NdPr; add DLA-style stockpile tenders for Dy/Tb.
- Require traceability and QA: lot genealogy, BH curves at use temperature, REO assays, and third-party audits.

Execution cadence (first 12 months):

- Months 0–3: finalize passport schema; sign partner MOUs; order HD/sinter/QA kit.
- Months 4–6: commission HD line; ship first-article magnets; start chem pilot.
- Months 7–12: expand pods/yards/ITAD; lock offtakes; publish quarterly dashboards (recycled share, HREE intensity, import displacement).

Bottom line: magnets-first is a field-ready operating plan—not a bet on geology or geopolitics. Start with procurement that values recycled performance, stand up metro pilots that pull magnets pre-shred, and lock consistency with clear standards. Do those three things and the U.S. gains a durable, domestically anchored supply of Nd/Pr/Dy/Tb—measured in tonnes, BH curves, and reduced import exposure, not just intentions.

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Note: Items 10–11 provide practical HDD magnet mass and extraction rates for Section 2 and 7; Items 4–5 cover Dy/Tb-sparing GBD for Section 6; Items 6–9 and 14–16 span chemical, molten-salt, and direct magnet-to-magnet routes for Section 5; Items 12–13 and 17–20 underpin the policy/market framing in Sections 8, 11, and 12.

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