National Laboratory of the Rockies

Critical Minerals Use in Data Centers: Supply Chain, Lifecycle, and Circularity Implications for U.S. Artificial Intelligence Infrastructure

Lead Author, PI: Sherif Khalifa, Ph.D.,

Co-authors: Sam Reese, Tapajyoti Ghosh, Julien Walzberg, Alberta Carpenter

AMMTO Innovation Impact Seminar Series

April 22nd, 2026

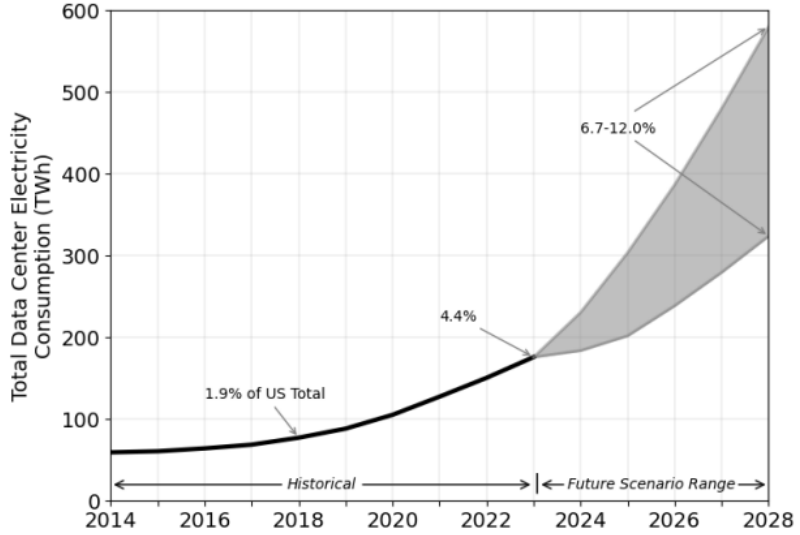
Photo from Adobe Stock 256750697

America's Digital Footprint is Growing Fast → Vast Energy and Materials are Needed

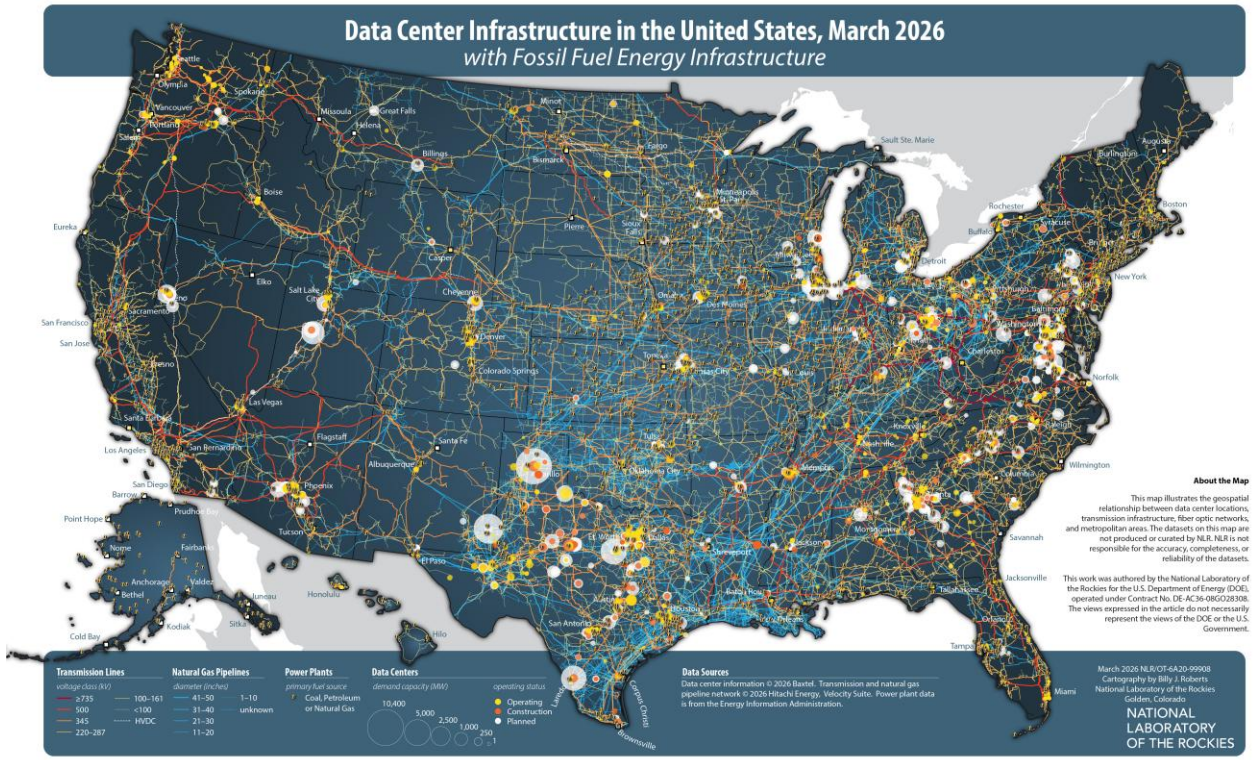
Data centers underpin the U.S. digital economy, including cloud services, AI, e-commerce, finance, defense, healthcare, scientific computing, and communications.

- Lawrence Berkley National Lab estimates electricity usage from US data centers were estimated to consume 4.4% of total electricity in 2023 and projected to increase to 12% by 2028.

- The growth is being driven by AI-accelerated servers, cloud computing, hyperscale facilities, model training, and high-bandwidth networking.



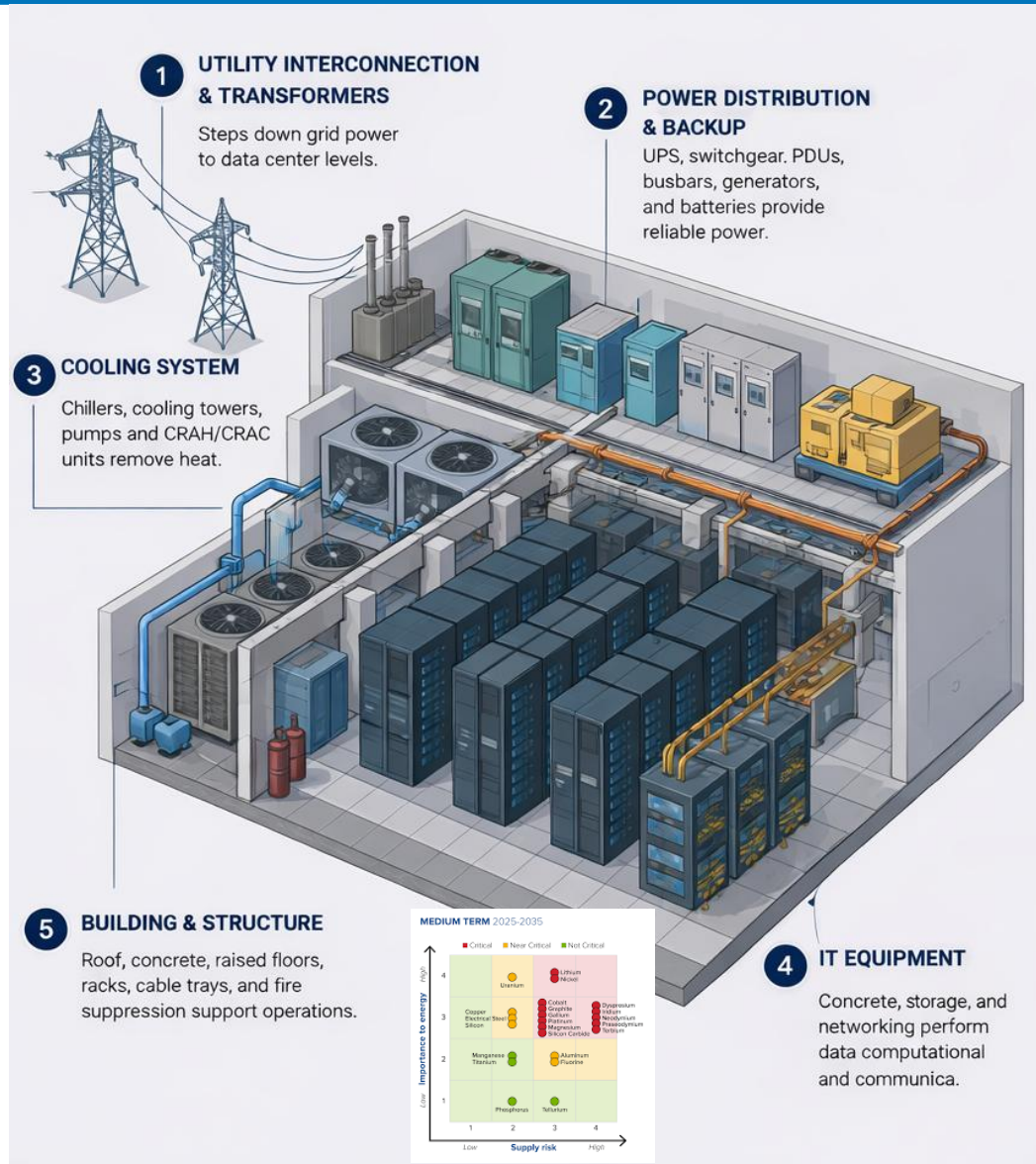
Source: Shehabi et al. (2024), LBNL-2001637, 2024 United States Data Center Energy Usage Report



Source: Billy J. Roberts, National Lab of the Rockies (NLR), NLR/OT-6A20-99908. March 2026.

Rapid data center growth is not only an electricity challenge — it is also a manufacturing, supply chain, and critical minerals challenge for the nation.

Data Center Anatomy – Critical Minerals and Materials Sink



Source: Adapted from LBNL Data Center Report (2016) and DOE Critical Materials Framework.

Critical Minerals and Metals by System

System	What It Includes	Key CMM-Beari Metals
1 Utility Interconnection & Transformers	Transformers, switchgear, grouding cabling	Copper (Cu)
2 Power Distribution & Backup	UPS, PDUs, busbars, generators, batteries	Copper (Cu), Lithium (Li), Nickel (Ni), Cobalt (Co), Tantalum (Ta)
3 Cooling System	Chillers, pumps, fans, CRAH/CRAC, heat exchangers	Copper (Cu), Aluminum (Ai) Neodymium (Nd) Dysprosium (Dy)
4 IT Equipment (Servers, Storage, Networking)	CPUs, memory, SSDs, HDDs, PCBs, NICs, cables, power supplies	Copper (Cu), Silicon (Si), Gald (Au), Galium (Ga), Neodymium (Nd), cid.O2a, Praecodymium (Pr), Tantalum (Ta)
5 Building & Structure	Steel. Aluminum	Aluminum (Al)

KEY TAKEAWAY

Data centers depend on a broad set of critical minerals.

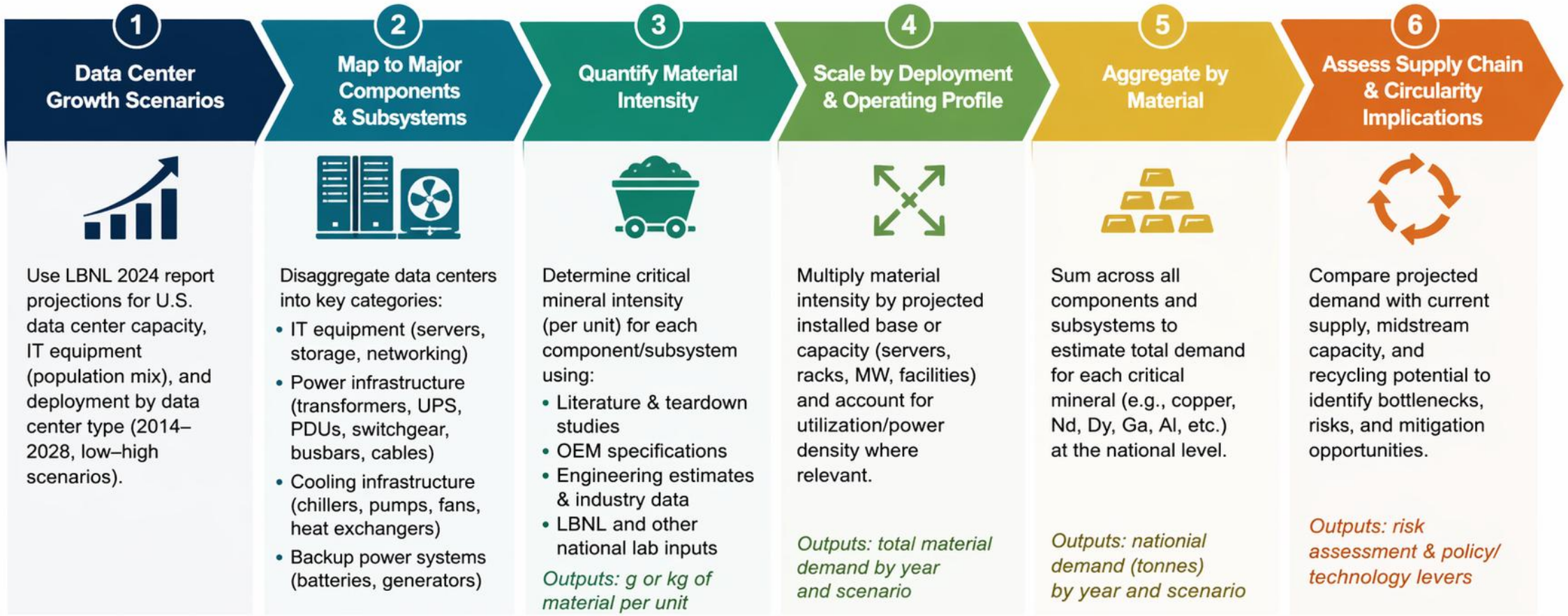
Copper underping power delivery and cooling, while rare earths gatium, willcon, and tanalure are esssential to high-performance computing and reliable operations.

We used LBNL's data center deployment scenarios to quantify demand for Cu, Nd, Dy and Ga. LBNL focused primarily on Information Technology (IT) (i.e., computing) equipment characterization.

Beyond IT hardware, data centers also require extensive power and cooling infrastructure, greatly increasing demand for Cu, Al and power electronics.

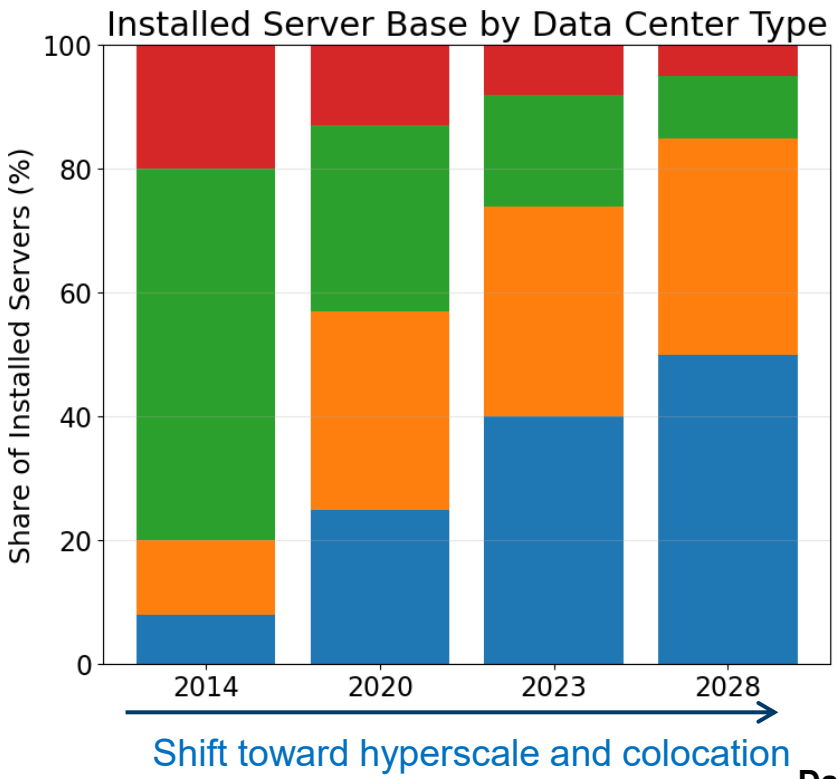
From Component-Level Material Intensity to Sector-Wide Critical Mineral Demand

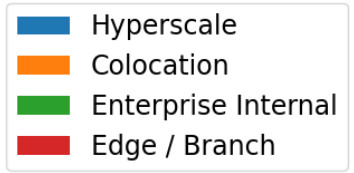
Methodology: From Data Center Growth to Critical Minerals Demand

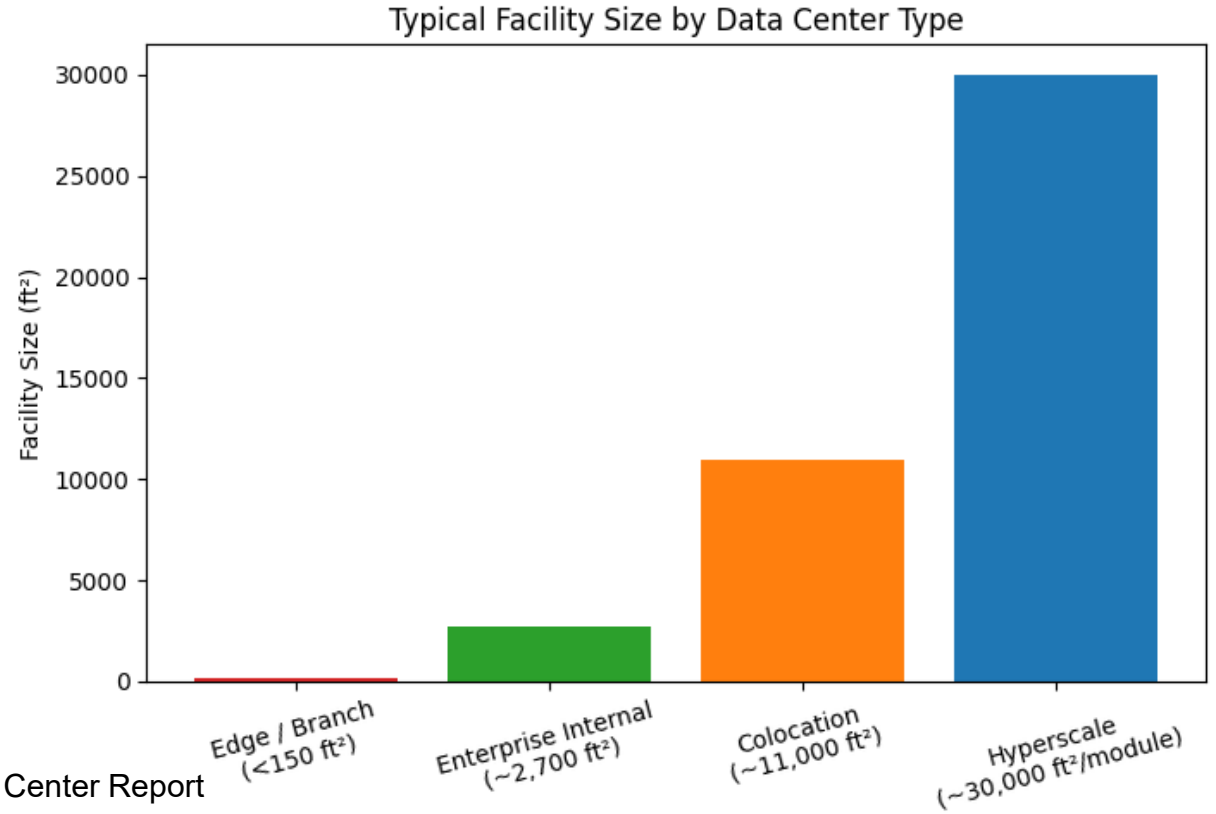


Abbreviations: UPS (Uninterruptible power supply); PDU(Power distribution unit); OEM (Original Equipment Manufacturer); MW (Megawatt).

Installed Server Base is Shifting Toward Hyperscale and Colocation







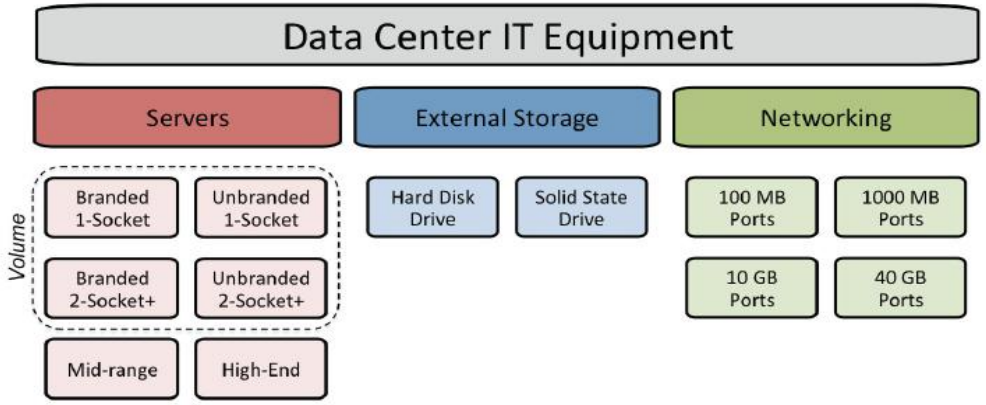
Data from: 2024 LBNL Data Center Report

- Hyperscale facilities are growing due to cloud computing, storage, streaming, SaaS, enterprise migration, and AI.
- AI workloads reduce the number of servers needed for some tasks, but higher rack power densities shift demand toward more material-intensive cooling and electrical infrastructure at the facility level.

Neodymium and Dysprosium Quantification

Rare Earth Elements (Nd, Pr, Dy) are primarily embedded in bonded permanent magnets used in rotating equipment and precision actuators in servers and storage drives of IT equipment.

- Servers, storage devices, and networking equipment are the primary IT hardware categories driving critical mineral demand in data centers.
- Within servers, rare earth magnets may be found in cooling fans, Hard Disk Drives (HDD), motors, and liquid-cooling pumps, while semiconductors and power electronics rely on materials such as gallium and copper.
- Storage systems can vary significantly between HDD-heavy architectures and Solid State Drives (SSD)-based systems, with hyperscale AI facilities increasingly shifting toward SSDs for performance and reliability.



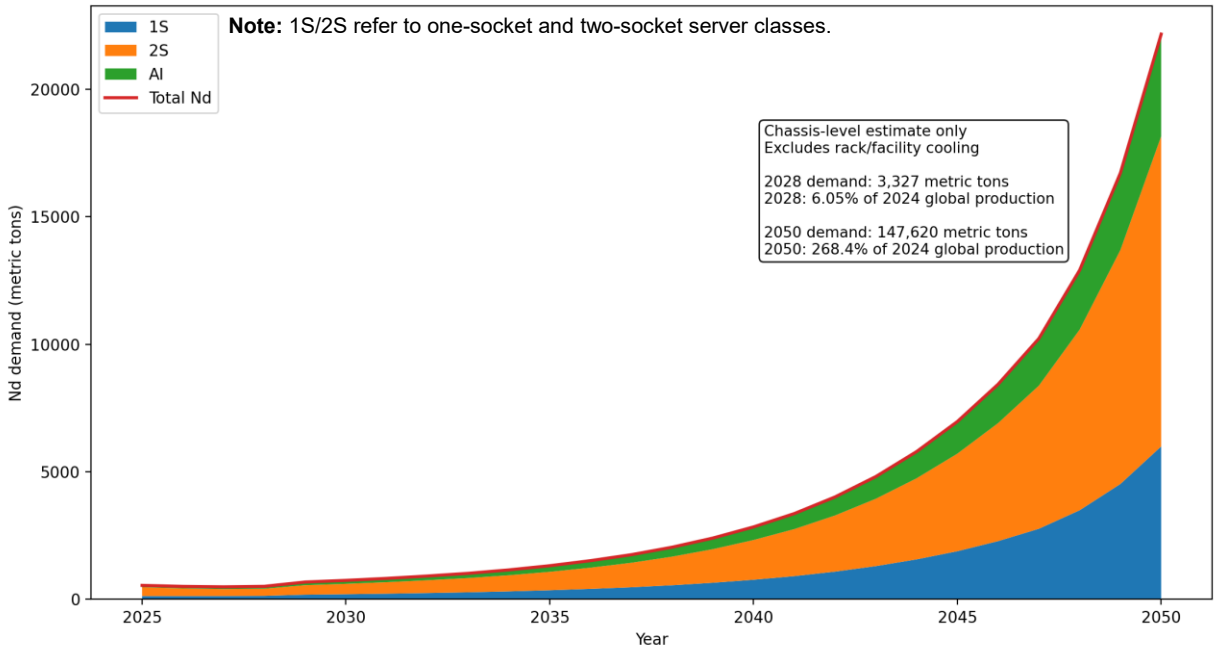
Source: 2016 LBNL Data Center Report

Subcomponent	REE-bearing function	Main REEs
Cooling fans	Permanent magnet motors	Nd, Dy
HDD spindle motor	Rotational motor	Nd, Dy
HDD voice coil actuator	Read/write head positioning	Nd, Dy
Small motors / actuators	Motion control	Nd, Dy

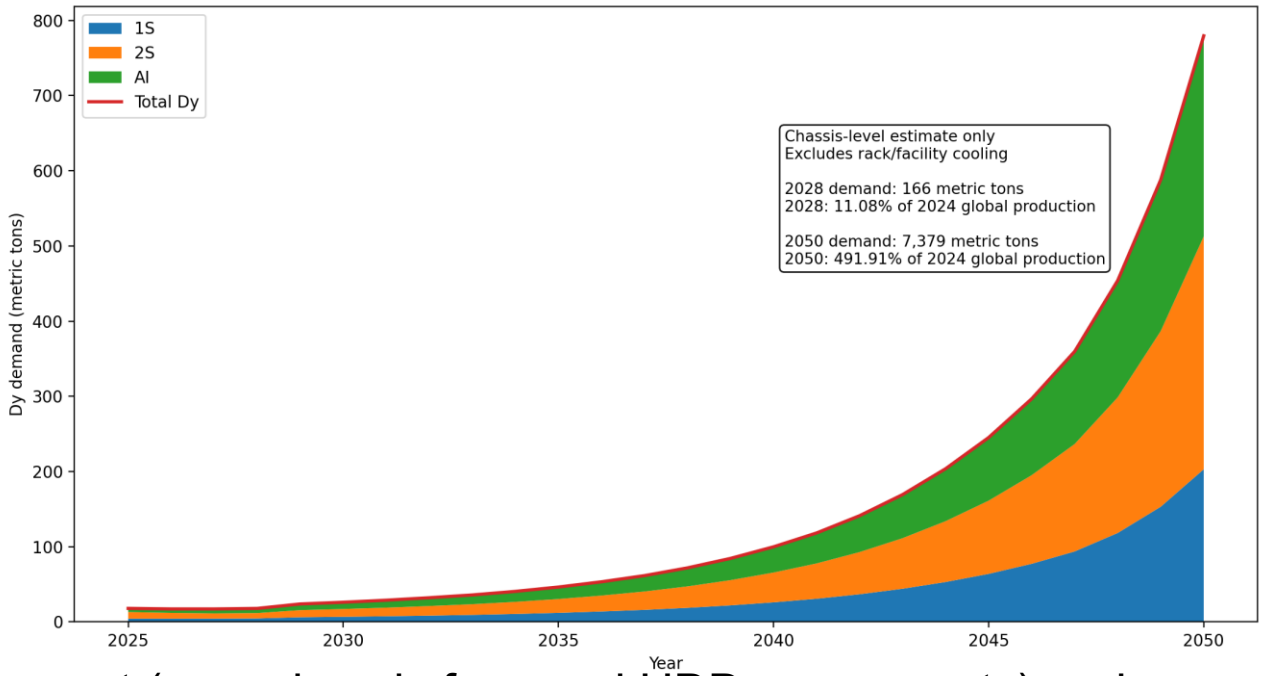
The mix of IT equipment varies by data center type, workload, and server architecture, which ultimately influences the material intensity per MW or per server deployed.

Rare Earths Estimates in IT Equipment

Nd

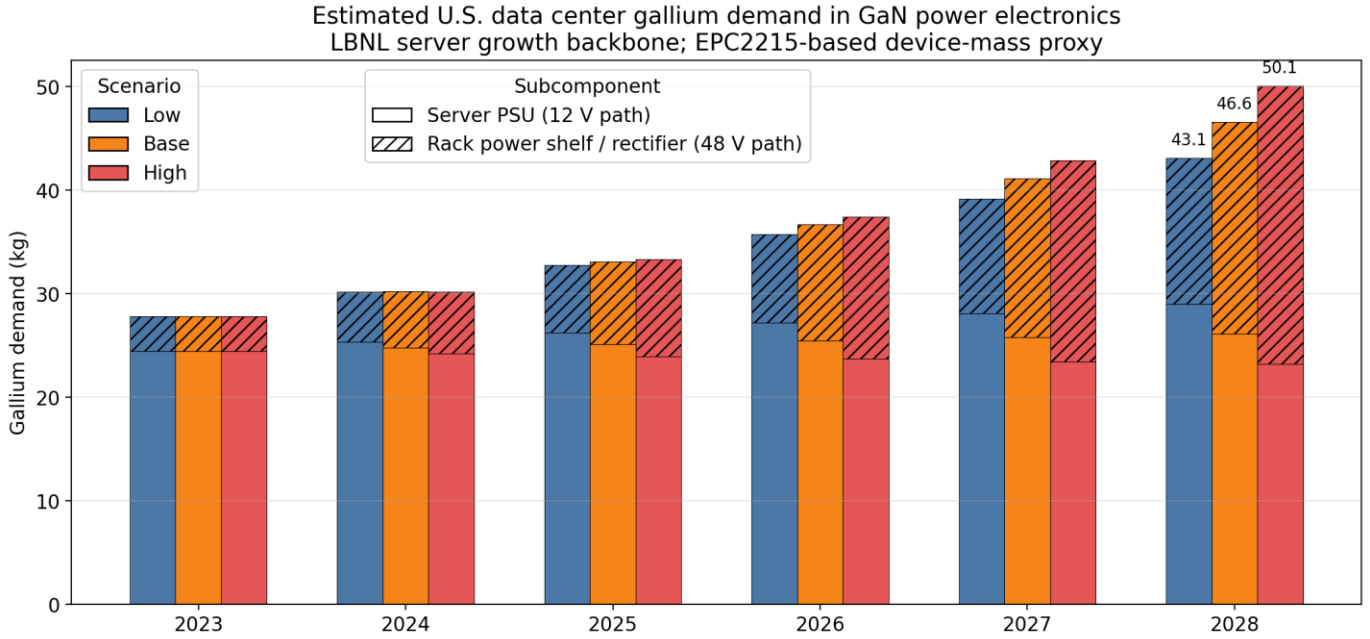


Dy



- Estimates shown here only include server-level IT equipment (e.g., chassis fans and HDD components) and do not include REEs embedded in facility-side cooling infrastructure such as CRAH/CRAC units and cooling.
- Even at the chassis level alone, projected U.S. data-center demand for Nd and Dy becomes substantial relative to current global production by 2028 and potentially exceeds today's global output by 2050.
- Facility-side cooling infrastructure likely adds materially to total Nd and Dy demand, but server-level fans and HDDs are expected to remain the primary REE-bearing components.

Gallium Nitride (GaN) Power Electronics Drive Limited Near-Term Demand



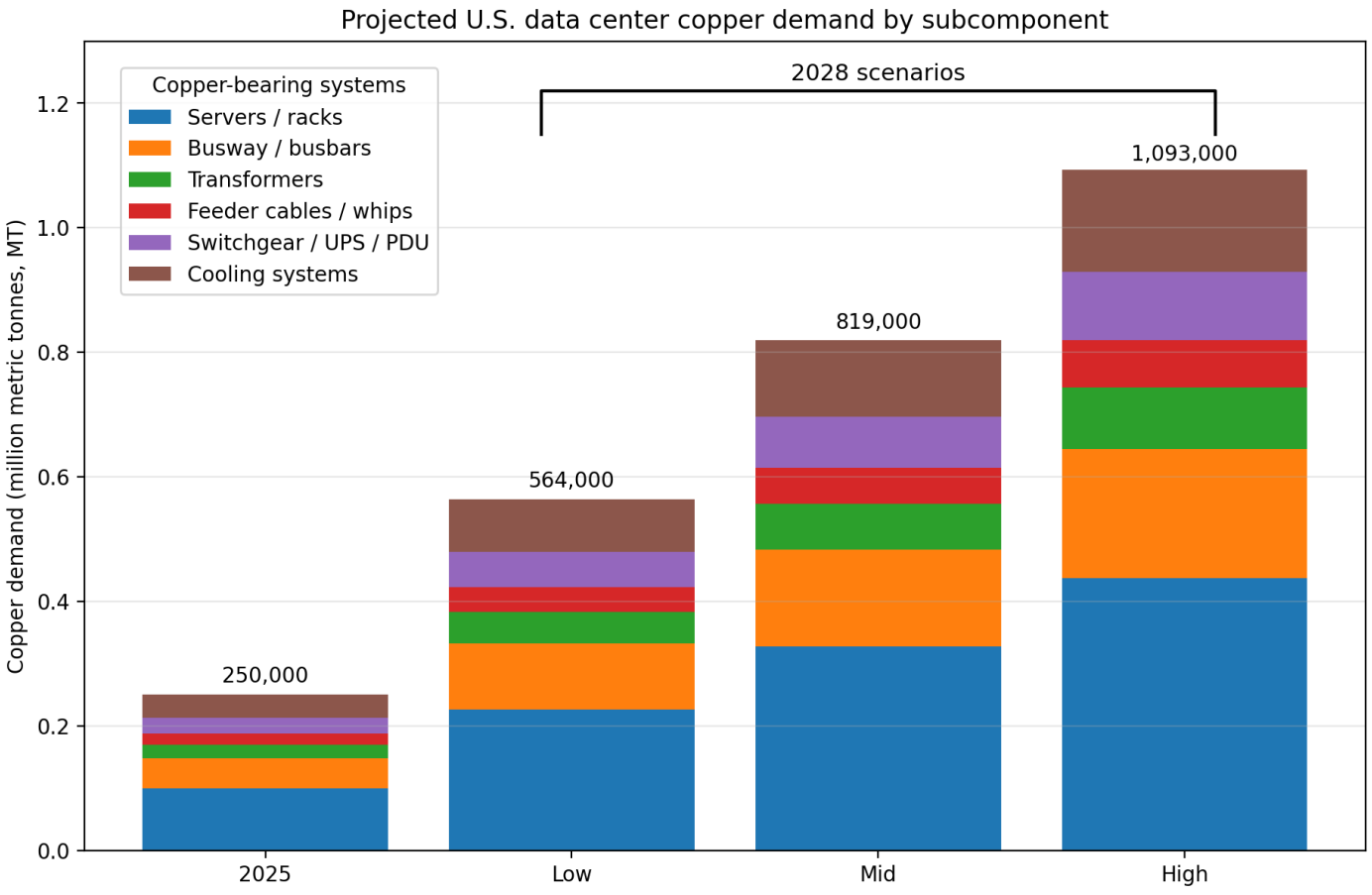
- Ga demand from data centers is primarily tied to gradual adoption of GaN power electronics in server PSUs and rack-level power shelves.
- Traditional silicon Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFETs) remain dominant through 2029, but GaN gains share in high-efficiency, high-power-density AI systems.
- Estimations could be reasonably higher if wider adoption of GaN in facility-side UPS systems, rectifiers and more aggressive rack-level power architectures.

Staggering Copper Demand from U.S. Data Centers Growth

- Copper demand for US Data Centers is expected to rise with AI-driven infrastructure growth, reaching roughly 0.6-1.1 million MT by 2028, based on LBNL's data center deployment scenarios.

- U.S. currently mines 1.1 million MT of Cu annually but has only two primary copper smelters and relies on imports for roughly half of refined copper. Deficits are covered by imports from Chile, Canada and Peru.

- Global refined copper demand is 28 million MT as of 2025 and could grow by 40% by 2040. Copper mine supply alone may meet less than 70% of projected 2035 demand. (USGS 2025, UNCTAD)

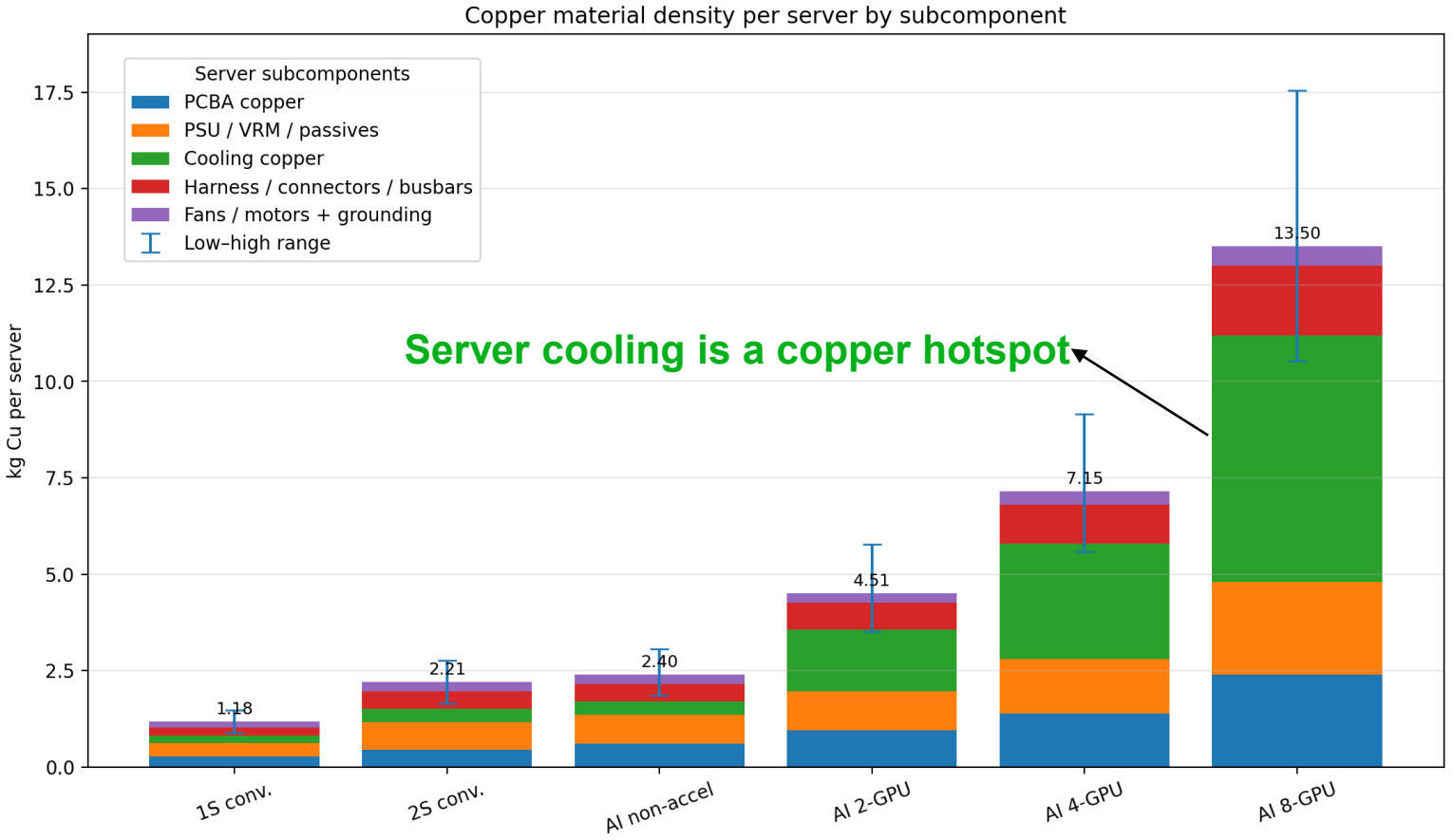


Low, mid and high cases reflect LBNL deployment scenarios.

Sources:
Shehabi et al. (2024), LBNL-2001637, 2024 United States Data Center Energy Usage Report
USGS Mineral Commodity Summaries 2025 – Copper: https://pubs.usgs.gov/periodicals/mcs2025/mcs2025-copper.pdf
UN Global Trade Update: Focus on Critical Minerals – copper in the new green and digital economy: https://unctad.org/publication/global-trade-update-may-2025-critical-minerals-copper

Copper Estimates in Data Center Servers

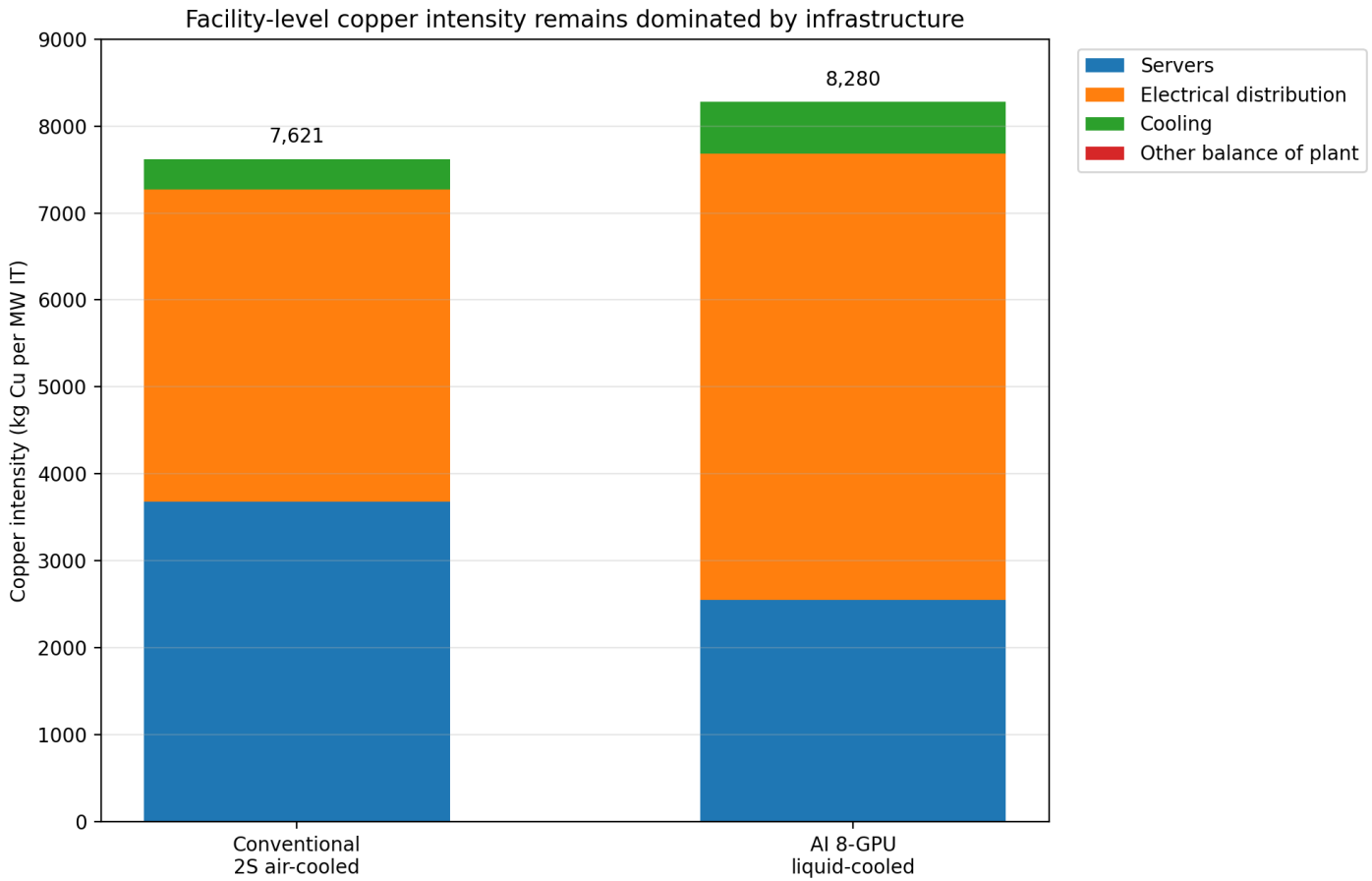
- AI server architectures can contain 5–10X more copper per server than conventional systems, driven primarily by liquid cooling and high-current power electronics rather than Printed Circuit Boards (PCB) copper.
- Advanced liquid cooling, cold plates, Voltage Regulator Module (VRMs), PSU windings, and internal busbars become dominant copper drivers in hyperscale AI systems.
- Copper demand scales faster than server count alone and is increasingly linked to AI rack power density and cooling strategy.



Low and high ranges reflect variation in board count, PSU sizing, VRM density, GPU count, cooling design, and use of copper-rich cold plates or busbars. AI servers show the widest range because copper content scales strongly with accelerator density and cooling strategy.

Still Copper Growth is Primarily driven by Sector Growth Per MW IT Rather than servers alone

- AI servers increase rack-level copper intensity, but facility-level copper demand remains dominated by electrical distribution and balance-of-plant infrastructure → higher node power density compresses the server-side Cu intensity per MW IT.
- Reduction in wiring at rack/server level is partly offset by heavier electrical distribution equipment (larger busbars, more transformer capacity, more cooling).
- Therefore, future copper demand is driven more by total deployed MW and sector growth than by AI servers alone.

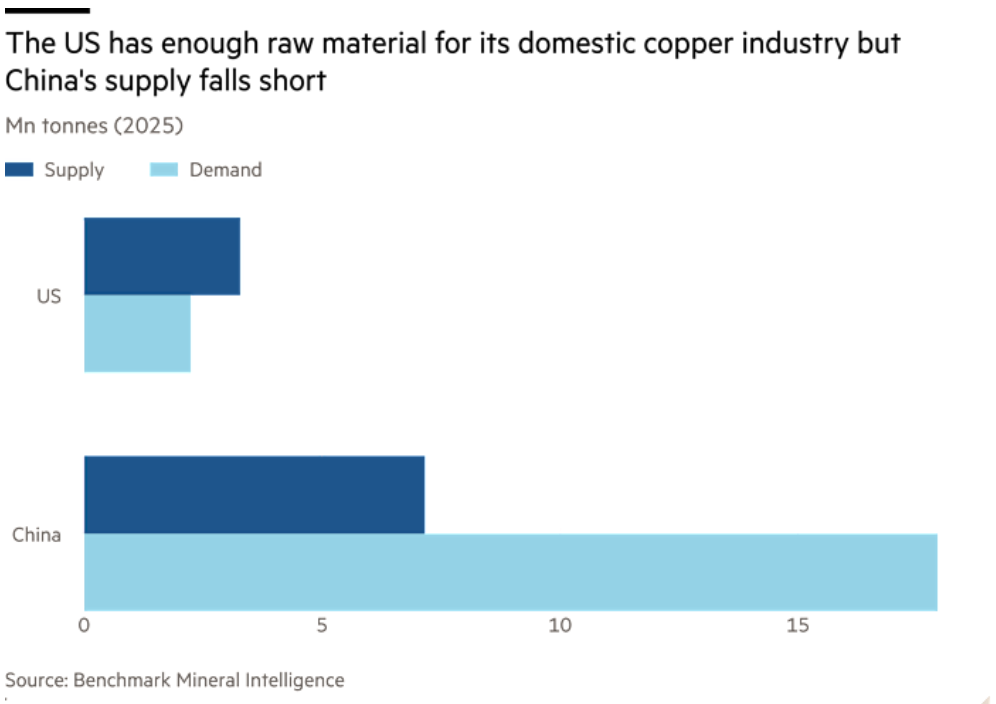


AI data centers are dramatically more copper-intensive per node and per rack, but on a per annual-average MW basis, facility-level copper intensity is only modestly above conventional air-cooled halls, and future high-voltage architectures could further reduce copper density.

Supply Chain Bottlenecks for Meeting U.S. Copper Demand

U.S. has currently roughly 48 million MT of copper reserves, while mining only ~1.1 million MT per year (USGS 2026). Proven reserves could theoretically provide several decades of domestic supply.

- U.S. exported nearly 957,000 MT of copper scrap to China or its intermediaries due to lack of domestic smelting → Losing nearly 580,000 MT of high-purity copper after refining.
- U.S. lacks enough domestic facilities to process low-grade, mixed, contaminated, or alloyed scrap into refined copper cathode.
- New investments are needed to develop advanced copper-sorting technologies from complex waste streams, pyrometallurgical and hydrometallurgical facilities for recovering copper, and refining capacity for impure copper into cathode-grade copper.



Copper ore availability is not the primary constraint for the U.S.; smelting, refining, scrap processing, value recycling, and downstream manufacturing capacity are the true bottlenecks.

Potential RD&D Pathways for Reducing Copper Demand in Data Centers

RD&D lever	Current maturity in U.S. markets	Approximate Cu reduction vs baseline (0.6-1.1 million MT)	Key RD&D need
Higher-voltage DC distribution	Emerging	~10–25% ; up to ~45% in conductor-heavy subsystems	Standardization, safety codes, connector design, arc protection, interoperability with existing AC systems
Solid-state transformers	Early-stage / pilot	~2–10%	Reliability, cost reduction, thermal management, grid-scale demonstration, long-duration testing
GaN / SiC power electronics	Commercially emerging	~2–5%	Larger substrates, lower defect density, lower cost, domestic wafer growth, packaging, thermal reliability
Direct-to-chip liquid cooling	Commercializing	~3–8%	Coolant compatibility, leak detection, maintenance, standardization, recyclability of cooling loops
Aluminum substitution	Mature in selected applications	~5–15% in selected conductors, busbars, and transformer windings	Better connection reliability, corrosion resistance, compact designs for high-density environments
Optical interconnects	Mature in some applications	<1–3%	Lower cost, lower power transceivers, closer integration into server and rack architectures
Modular / prefabricated systems	Commercial	~2–5%	Faster permitting, standardized interfaces, improved recycling and reuse pathways
Recycling / reuse	Mature but fragmented	Does not reduce total Cu demand; can offset ~10–40% of primary Cu demand depending on scrap recovery rates	Scrap sorting, secondary refining, recovery from e-waste, closed-loop reuse of transformers and cables

Near-term copper reductions are most likely to come from higher-voltage architectures, direct liquid cooling, and improved power electronics rather than a single disruptive technology.

Estimated reductions are not additive because several measures affect overlapping portions of the same electrical and cooling systems.

Impact of Demand on U.S. and Global CMM Supply Chains

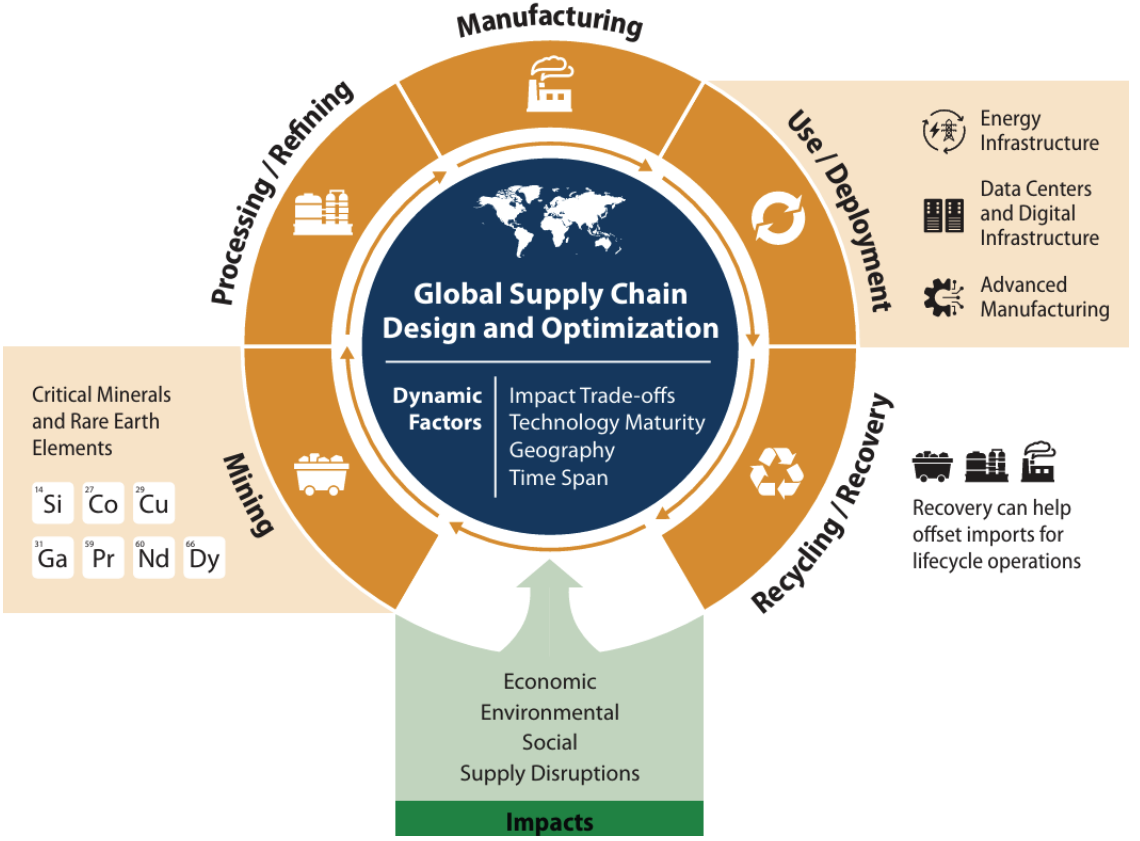
Case Study from AMMTO's BLEECAM™ Tool

Integrated Decision Support For Critical Minerals Supply Chains

The Benchmarking Life Cycle Environmental, Economic, and Social Metrics for Critical and Advanced Minerals and Materials (BLEECAM™) tool is an integrated decision-support platform that enables U.S. Department of Energy and industry to evaluate, optimize, and de-risk the deployment of materials, processes and emerging technologies in critical mineral supply chains across all life cycle stages.

- BLEECAM™ integrates dynamic supply chain optimization, life cycle assessment, technoeconomic- and life cycle costing analysis, and social life cycle assessment in a single platform.
- Evaluates the impacts of emerging materials and technologies before large-scale deployment, including new processing routes, recycling pathways, substitutions, and domestic supply chain expansion.
- Designed to inform decisions across sectors including energy generation, data centers, and grid infrastructure.
- Current applications include rare earths, permanent magnets, gallium, copper, AI data centers, grid infrastructure and recycling pathways.

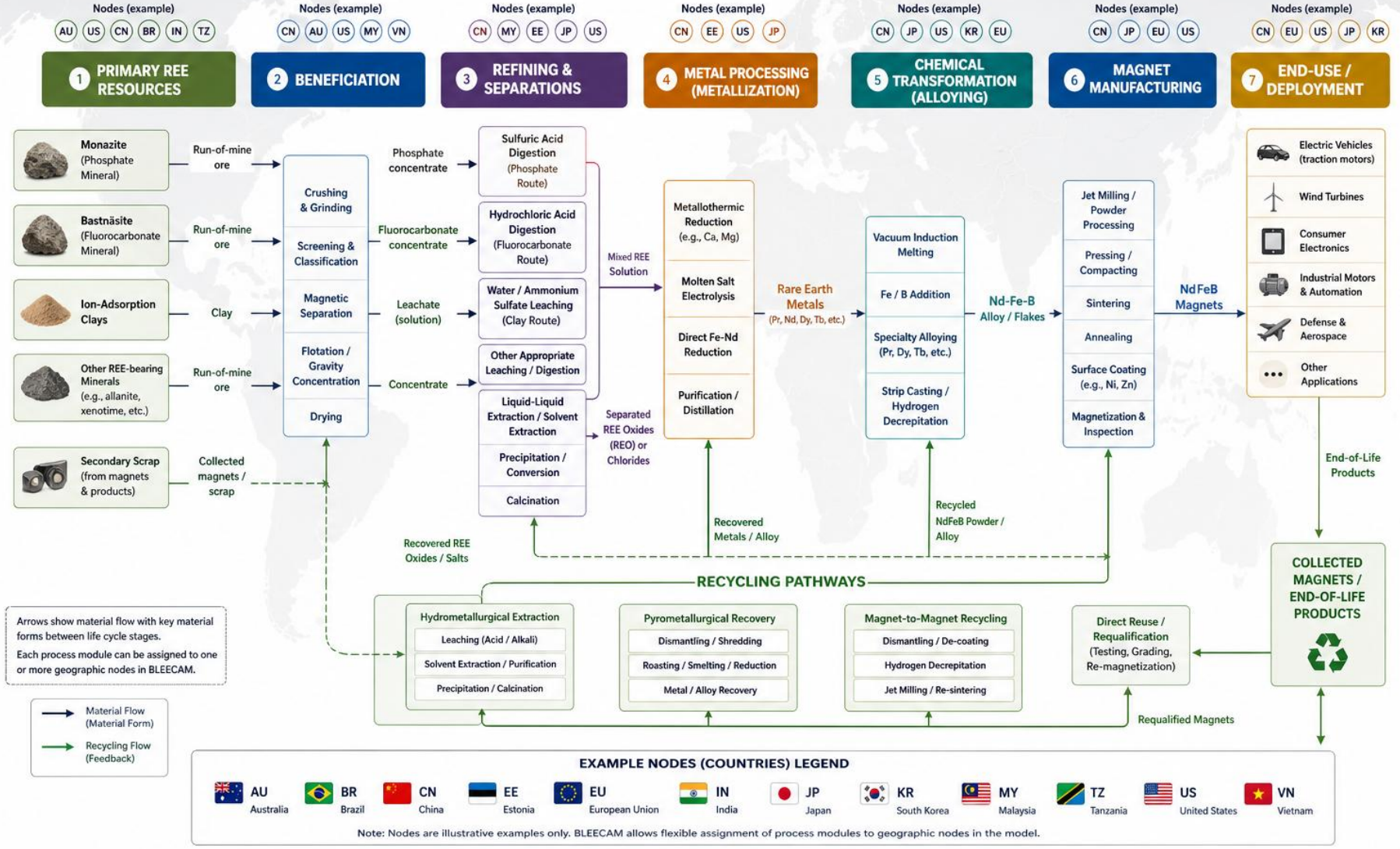
Decision Support Across the Critical Materials Lifecycle



DOE Contact: Helena Khazdozian (AMMTO)
NLR Contact: Sherif Khalifa

BLEECAM™ is a software funded by U.S. Department of Energy, Critical Minerals and Energy Innovation Office's Advanced Materials and Manufacturing Office. All rights reserved. 2026.

The REE Global Supply Chain Model



All cross-border pathways are built into BLEECAM tool including US and foreign countries

Upstream Dy Supply Shock Analysis

Research Question:

If China restricts Dy supply to the world now, could US still meet demand for REEs to build its data center infrastructure through 2028?

If Yes, under what conditions and supply configurations? How much does it cost?

If Partially, how much demand is unmet? Why?

If No, what should the U.S. response to technology innovations should be?

China Controls 4 Critical Nodes in Global Dy Supply

🔴 Chinese Dy Supply Restriction (Staged, 100% → 5%)

A staged restriction across four upstream Chinese Dy nodes — modeling export controls or production caps applied progressively over five planning periods.

Process Node	t=0	t=2	t=4
CN Metallothermic Reduction (Dy)	100%	50%	5%
CN Sulfuric Acid Digestion (DyOx)	100%	50%	5%
CN Clay Refining (DyOx)	100%	50%	5%
CN HCl Digestion (DyOx)	100%	50%	5%

New LCI alert! ←

Why 5% still matters: CN capacity is ~133× US demand. A 50% cut still leaves 66× overcapacity. Only sub-1% scenarios bring CN below the binding constraint — the 5% endpoint represents genuine deep disruption.

US and Allied Country Ramp-up Response

BLEECAM optimizer results for supply shock disruption

🟢 US Response + Allied Expansion (Ramp-Up)

Simultaneous ramp-up of US domestic recycling capacity and allied metallothermic capacity to offset the Chinese restriction.

Effective 3-year response plan

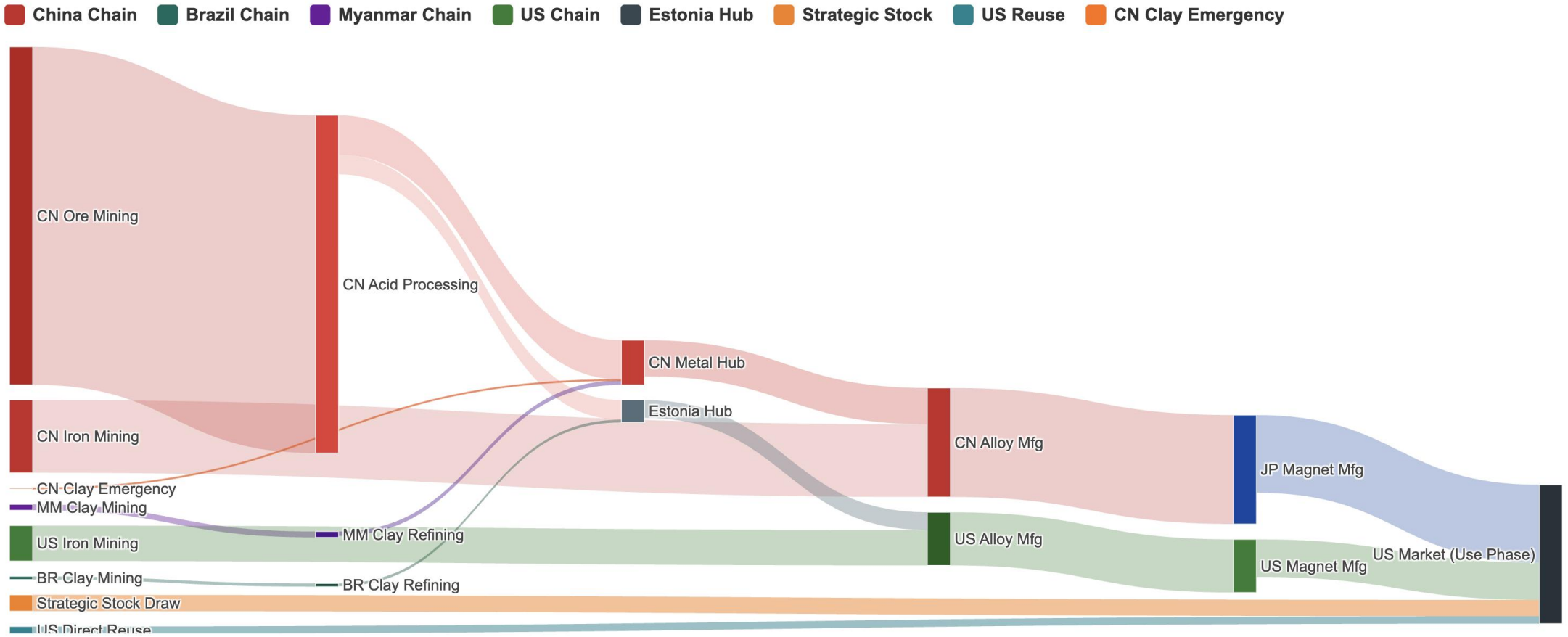
Pathway	t=0	t=4
US Hydro/Pyro/Cryo recycling (alloy)	0 t	**1,000 t each**
US Direct Reuse (hp_magnet)	0 t	**500 t**
US Magnet-to-Magnet Recycling	0 t	**500 t**
Estonia Metallothermic Reduction	40 t (×1)	**320 t (×8)**
Japan Metallothermic Reduction	400 t (×1)	**1,800 t (×4.5)**

Allied peak capacity (t=4): 2,120 t Dy — still far below the ~18,600 t Chinese gap. Brazil, Myanmar clay chains, and US recycling are structurally needed to close the supply balance.

Near term, the fastest and cheapest diversification path is allied expansion plus U.S. recycling.

With Aggressive Yet Plausible Plan…

US can meet 100% of its NdFeB demand for Data Centers

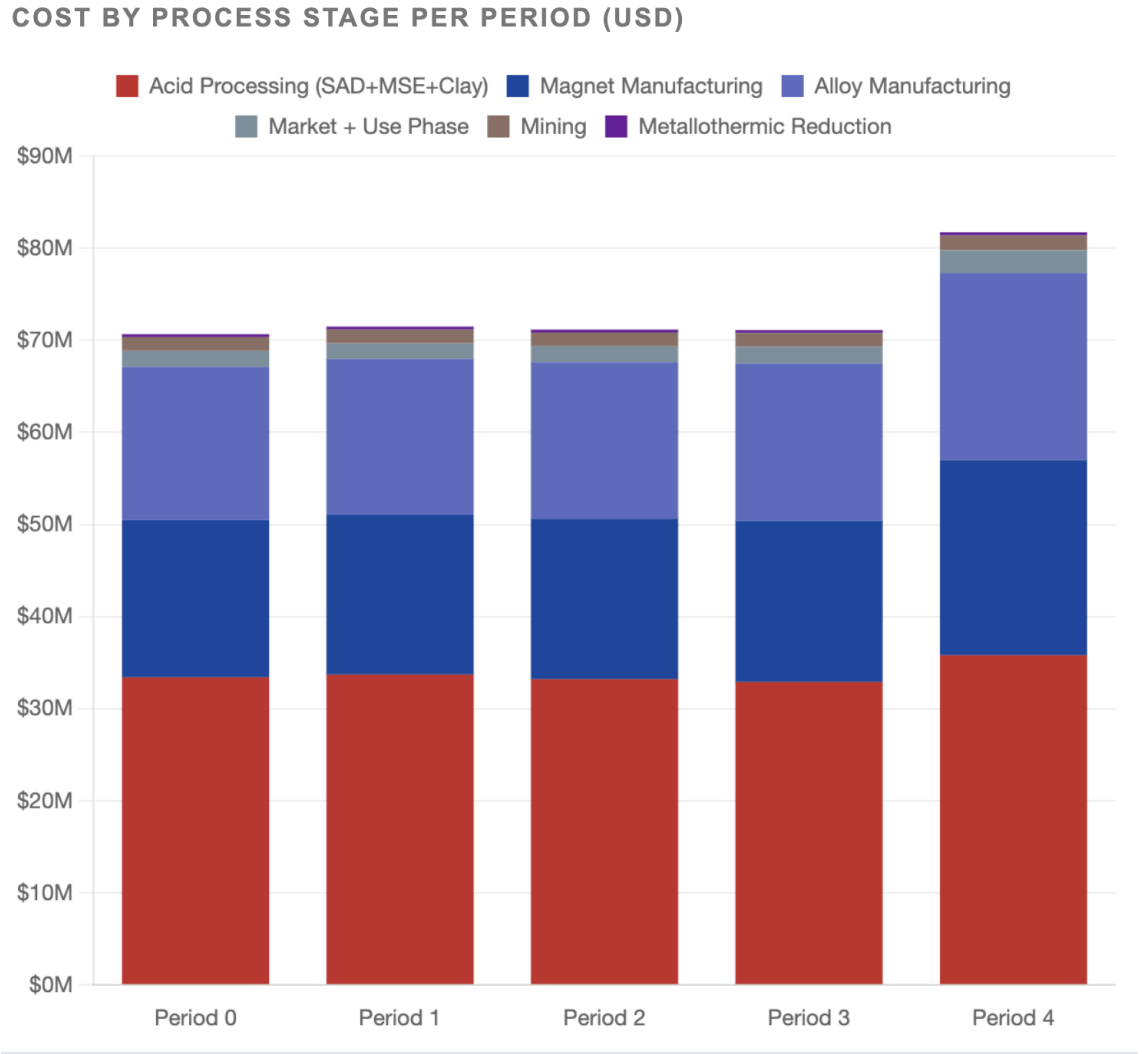


BLEECAM confirms that a strategic reserve of finished magnet blocks is needed to avoid unmet demand until capacity comes online in allied countries. For this scenario, the modeling tool suggested building a total of 306,000 kg of NdFeB magnets by 2027.

Scenarios examining China's restriction to Japan and Estonia have not been examined yet.

$398 Million Over 4 Years is Needed to Build New Supply Mix

- BLEECAM suggests that a total investment of $398 M is needed to build the capacity expansion needed.
- About 47% of the total cost is attributed to acid processing capacity build-up to refine clays and carry-out sulfuric acid dissolution.
- Global sourcing strategies and expanding midstream capacity are key interventions to meet U.S. demand.
- Sourcing from Chinese clays is up to 7 times more expensive than Brazilian rate.



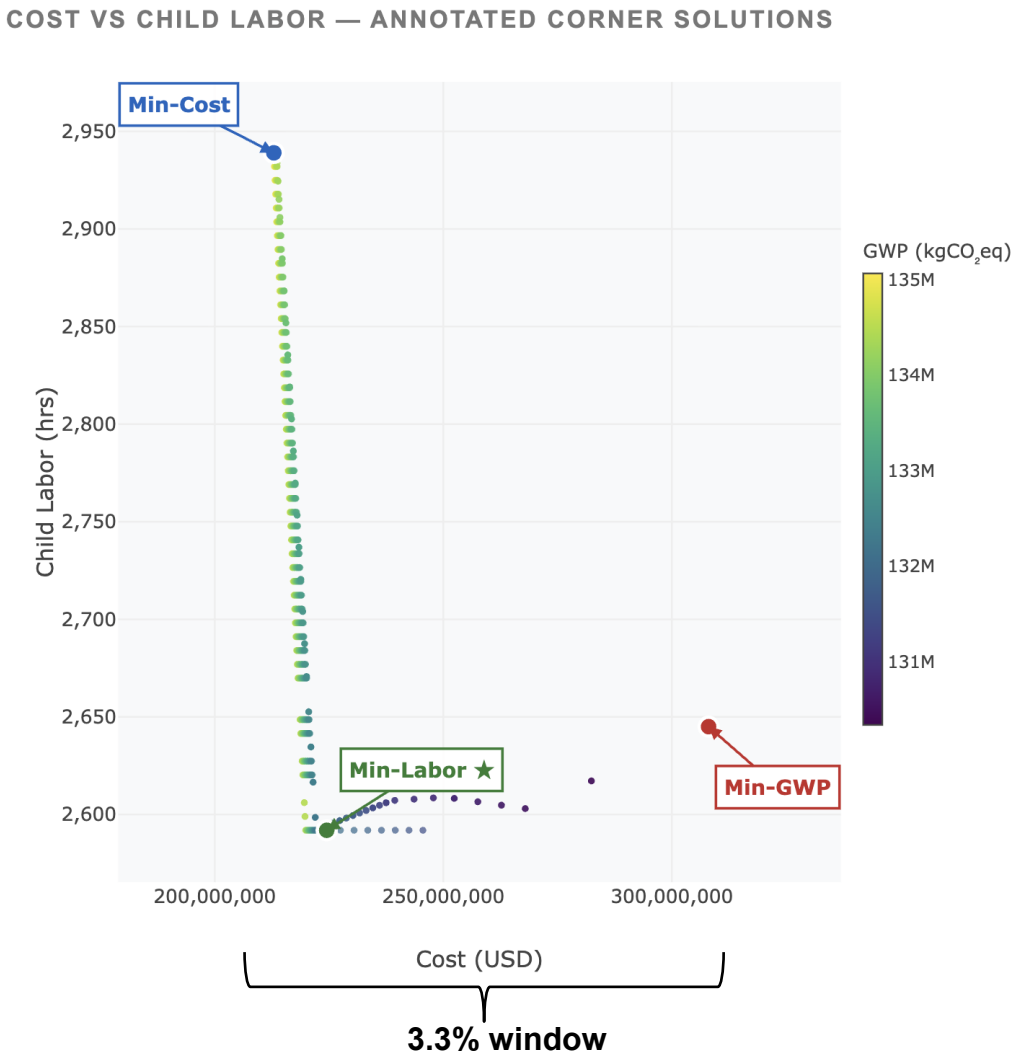
Cost, Forced Labor and Emissions Tradeoffs in Rare Earths Supply Chains

- All 803 combinations of global supply chain configurations to secure US demand of Dy clustered in 3.3% cost window

- Min-labor solution: +5% cost, –12% child labor, slight Greenhouse gases (GWP) benefit
- Min-GWP solution: +45% cost, only modest emissions reduction

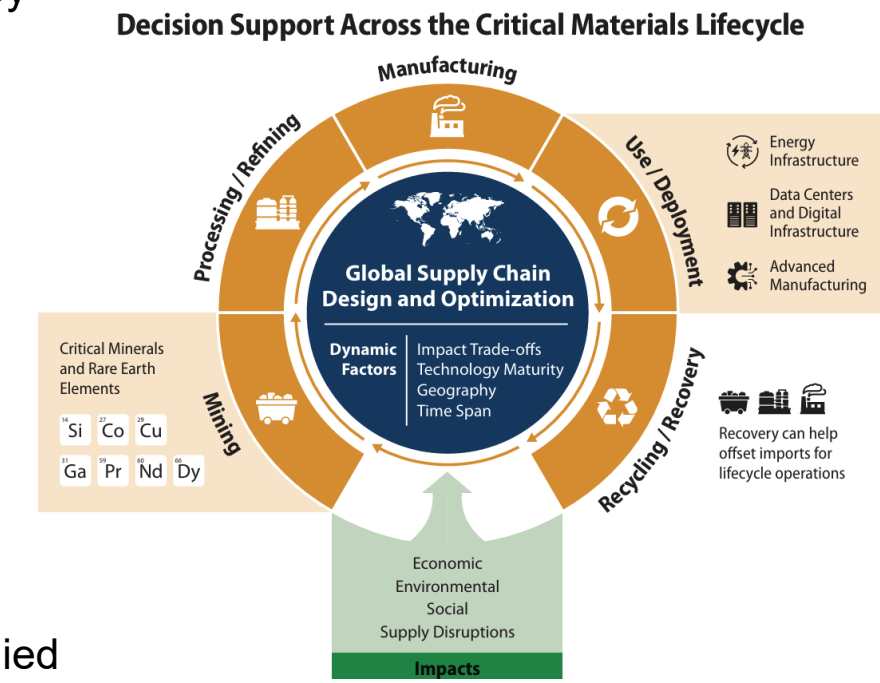
Labor outcomes are routing-sensitive
Emission outcomes are process-sensitive

Key Takeaway:
- procurement, sourcing, and ally-shoring for labor improvements
- Advanced chemistry and processing technology for emissions improvements
- Small cost increases can unlock major labor and emissions improvements.



Key Takeaways

- AI data centers are becoming a major new source of demand for copper, rare earths, gallium, batteries, and power electronics.
- Copper is likely the dominant near-term bottleneck because demand is driven more by power delivery, cooling, transformers, and grid infrastructure than by servers alone
- The main U.S. challenge is not resource availability, but limited refining, recycling, transformer manufacturing, and midstream processing capacity.
- Higher-voltage systems, liquid cooling, aluminum substitution, and better power electronics can reduce copper intensity, but not eliminate the need for major copper buildout.
- Recycling, reuse, domestic processing, and allied manufacturing will all be needed to meet future demand.
- BLEECAM shows that under a Dy supply shock, the fastest near-term response is allied expansion, U.S. recycling, and a temporary strategic reserve of finished magnets.
- Labor risks can be reduced at relatively low cost through sourcing decisions, while emissions reductions require advanced process technologies rather than rerouting alone.



Next steps include building pathways for Copper and Gallium in BLEECAM tool

Thank You!

Contact: Sherif Khalifa, Ph.D.

skhalifa@nlr.gov

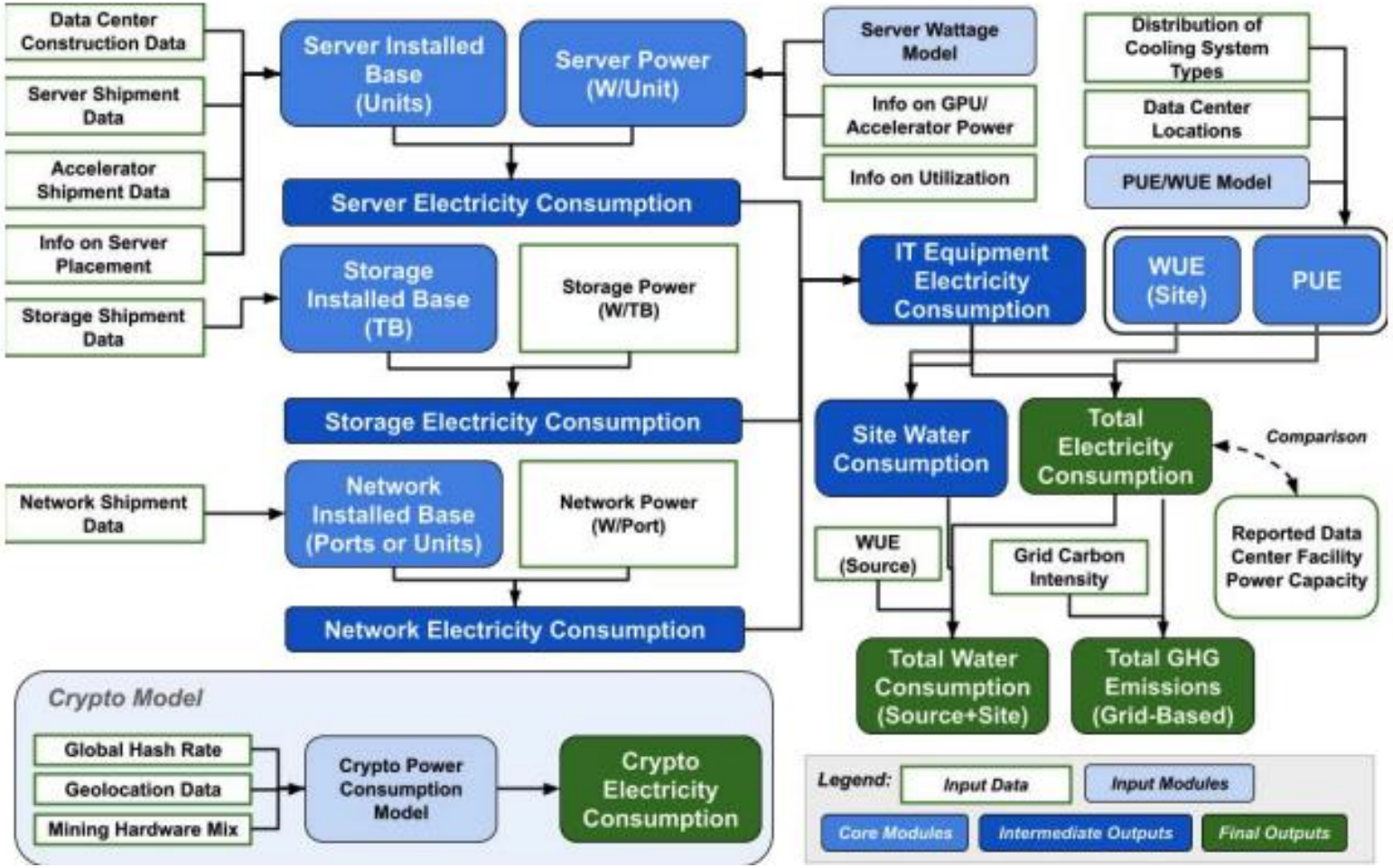
National Laboratory of the Rockies

NLR/PR-6A20-100743

This work was authored by NLR for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy's Office of Critical Minerals and Energy Innovation's Advanced Materials and Manufacturing Technologies. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Photo from Getty Images 181828180

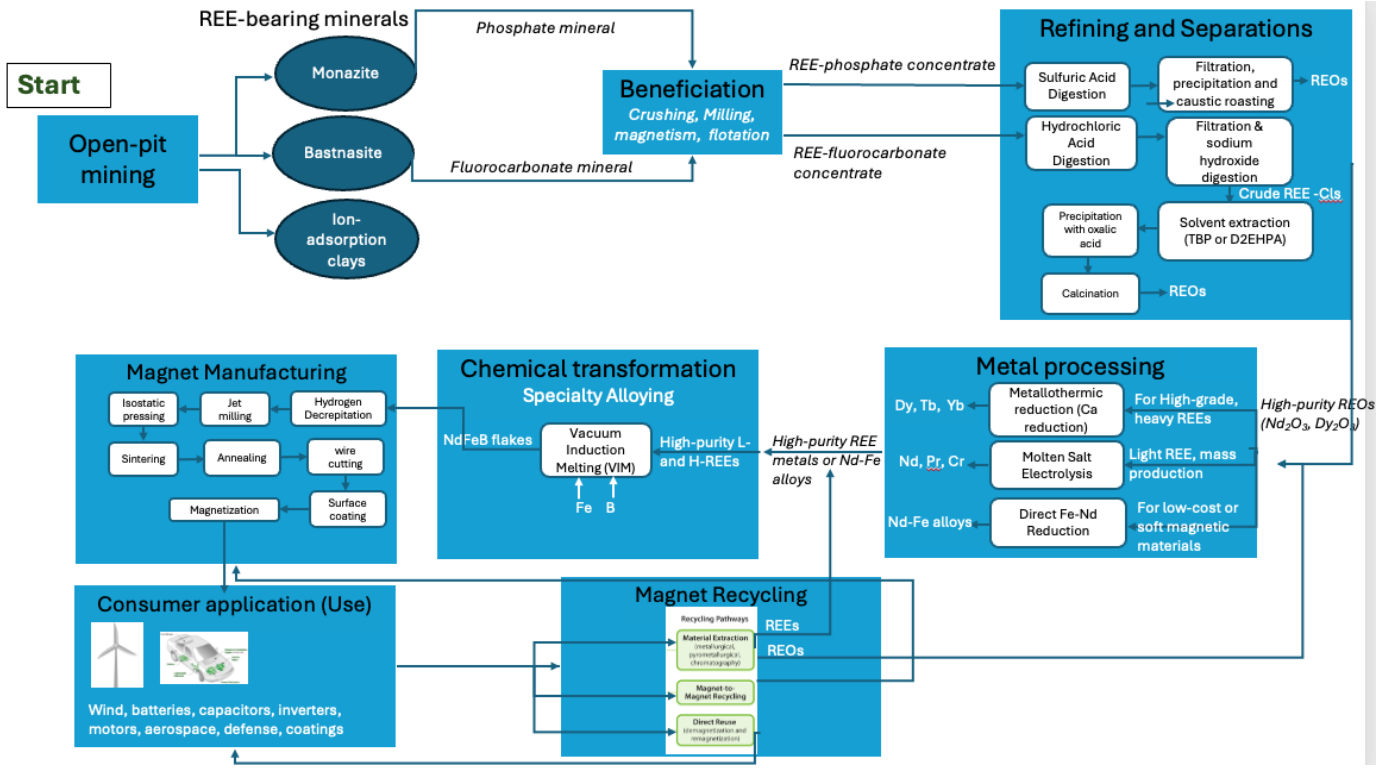
LBNL Data Center Flowchart for Electricity Model Studied



Source: Shehabi et al. (2024), LBNL-2001637, 2024 United States Data Center Energy Usage Report

Baseline Establishment
Materials, processes and technologies

NLR team established a comprehensive US-focused baseline for the entire value chain materials, processes and technologies present for target critical minerals. The team collected process designs including mass and energy balances to develop lifecycle inventories along literature review. The team proceeded to collect global production capacity data per each process step, analyzing global trade flows that feed target US energy systems.



Global Trade Flows of Neodymium			
Mining and Beneficiation			
	Global production:	350000	
	US production	43,000	(all bastnasite)
Ore shares:	**production (MT)**	**% of pathway allocation**	**Market shares**
Bastnasite	240000	68	China (53%), US (18%), Mynamar (16%), Australia (8%)
Monazite	90000	26	China (56%), India (3%), high-risk unknown small producers (40%)
Ion-adosprtion clays	22000	6	China (95%), Mynamar (5%)
Refining and separations			
Refining shares:	China (t)	Malaysia (t)	USA (t)
HCl digestion (bastnasite)	180000	24000	0
H2SO4 digestion (monazite)	45000	40000	0
NH4Cl leaching (IACs)	19000	0	0
	244000	64000	0
Metal processing			
Process	Country	Capacity (t/year)	Share (%)
Molten Salt Electrolysis (MSE	China	46000	92
Molten Salt Electrolysis (MSE	USA	1500	3
Molten Salt Electrolysis (MSE	Japan	1250	2.5
Molten Salt Electrolysis (MSE	UK	1250	2.5
Metallothermic Reduction (M	China	19600	98
Metallothermic Reduction (M	Japan	400	2
VIM	China	55200	92
VIM	Japan	3000	5
VIM	EU	1200	2
VIM	USA + UK	600	1
VIM	Total	60000	100
Magnet Manufacturing			
Country	Capacity (t/year)	Share (%)	
China	240000	87.5	
Japan	10000	3.6	
Europe	6000	2.2	
USA	1000	0.4	
Total	257000	100	

Further Power assumptions – Ga / GaN

- GaN devices used for end application voltages – 12V or 48V.
- Determine total current needed for 12V (Higher) and 48V (Lower).
- Number of switches needed for power processing
  - 8 devices for 48V application
  - 10 devices for 12V application
- Choosing a baseline GaN device from EPC
  - EPC 2307 (200V 62A switch)
  - EPC2215 (200V 32A switch)
- Estimate how many switches are needed (V,I variation)
  - 12V, 48V
  - 32A, 62A
- Material declaration is used for estimating total amount of GaN and Ga
  - Ga = 83% mass of GaN

EFFICIENT POWER CONVERSION

Material Composition Declaration

EPC2307

Company Name	Efficient Power Conversion (EPC)	Issue Date:	2024/11/1
Contact Name:	Yanping Ma	Contact Title:	VP Quality
Contact Phone:	(310) 615-0280	Contact Email:	yanping.ma@epc-co.com
Part Weight:	30.3 mg	Type of Product:	eGaN FET in FCQFN package

Construction Element	Substance	CAS No. If Applicable	Weight (mg)	Mass (%)	Sum (%)	Mass (ppm)
Chip	Silicon	7440-21-3	4.9489	16.3373	17.2447	163373
	Silicon oxide	7631-86-9	0.0342	0.1128		1128
	Silicon nitride	12033-89-5	0.0238	0.0786		786
	Gallium nitride	25617-97-4	0.0501	0.1655		1655
	Aluminum	7429-90-5	0.0643	0.2123		2123
	Aluminum nitride	24304-00-5	0.0118	0.0389		389
	Titanium	7440-32-6	0.0020	0.0065		65
	Titanium nitride	25583-20-4	0.0131	0.0432		432
	Copper	7440-50-8	0.0011	0.0035		35
	Tungsten	7440-33-7	0.0060	0.0197		197
	Polyimide		0.0686	0.2264		2264
Under Bump Metal	Titanium	7440-32-6	0.0005	0.0016	0.0175	16
	Copper	7440-50-8	0.0048	0.0159		159
Solder Bump	Copper	7440-50-8	0.4057	1.3394	1.8302	13394
	Nickel	7440-02-0	0.0288	0.0951		951
	Tin	7440-31-5	0.1177	0.3885		3885
	Silver	7440-22-4	0.0022	0.0071		71
Package	Copper	7440-50-8	11.7262	38.7103	80.9076	387103
	Iron	7439-89-6	0.3007	0.9926		9926
	Mold Compound		11.7959	38.9403		389403
	Tin	7440-31-5	0.6859	2.2644		22644
Sum in total:			30.2922	100.0000	100.0000	1000000

Neodymium, and Dysprosium – Assumptions

- Nd and Dy quantity depends on the temperature of the application.
- NdFeB magnets used in HDD cooling fans and data center facility can be assumed to be operating at 80°C.
- HDD drive-based motors can be assumed to be operating at 100°C.
- Each HDD drive has 10-15 grams of NdFeB.
- The facility motor loads can be assumed to be 40% of data center loads.

Table 4. Maximum operating temperature, associated Dy content, and example applications of NdFeB magnet grades

Grade suffix	Max operating temp. (°C) [54]	Approx. Dy content (wt. %) [55]	Approx. Nd+Pr content (wt. %)[3]	Example spplications
No suffix	80	<0.5%	29.5%	Toys, games, advertising, etc.
M	100	1.4%	28.6%	Hard disk drives, CD/DVD, MRI machines, sensors, refrigeration, etc.
H	120	2.8%	27.2%	Gauges, hysteresis clutch, magnetic separation, etc.
SH	150	4.2%	25.8%	**Wind power generators**, electric bicycles, energy storage systems, magnetic braking, industrial motors, general automotive applications, etc.
UH	180	6.5%	24.5%	Commercial and industrial generators, wave guides, undulators, etc.
EHz/AH	200/220	8.5% - 11%	19% - 21.5%	**Hybrid and electric traction drives**, high temp. motors and generators, etc.

Smith, Braeton J., et al. *Rare earth permanent magnets: supply chain deep dive assessment*. USDOE Office of Policy (PO), Washington DC (United States), 2022.