Sustainable Energy & Environmental Systems Department
Energy Analysis & Environmental Impacts Division
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An assessment of the global cooling supply chain and implications for critical minerals

Opportunities and risks for the U.S., India, and the Quad

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Table of Contents

Table of Figures

List of Tables

Abstract

The global room air conditioner (AC) industry has undergone rapid growth, and the U.S. and India now face new supply chain risks due to China's dominant role in manufacturing and driving demand. As India's room AC market and related electricity consumption increases with continued economic development, it faces dual challenges of supply chain vulnerabilities and power grid blackouts from higher peak loads. To mitigate supply chain vulnerabilities for high-efficiency cooling equipment and critical mineral inputs to AC components, there is an increasing need to diversify the supply chain and address energy security and peak load risks to both the U.S. and India. This report assesses the potential for diversifying supply chains and scaling up manufacturing of highly efficient cooling equipment technologies and related critical mineral inputs in the U.S. and India. Successful cooperation on these technologies will enable the U.S., India, and their Quadrilateral Security Dialogue (Quad) partners to diversify AC supply chains while meeting India's large and growing demand for efficient cooling. In the similarly concentrated supply chain for critical minerals, the U.S. and India can work with Japan and Australia to leverage each country's strengths in diversifying mining, processing, and refining while pursuing alternatives to materials with high supply chain risks and supporting increased recycling and circular economy approaches.

1. Introduction

The global residential room air conditioner (AC[1]) industry has grown rapidly in recent decades. This growth has occurred within a supply chain architecture that remains overwhelmingly dominated by China, creating significant vulnerabilities for both the United States and India as major consumers and emerging manufacturers of cooling equipment. Both countries also face challenges in meeting growing electricity demand for cooling. In the U.S., air conditioning is responsible for 19% of residential electricity consumption (EIA, 2024), and nearly half of window and portable units are manufactured and imported from Asia (BSRIA, 2024a-d). India's rapidly growing AC market is starting to approach that of China in scale and being met through both domestic and foreign manufacturers. However, the rising electricity consumption is straining India's electric grid and threatening grid reliability on the hottest days. At the same time, escalating geopolitical tensions around regional conflicts and trade disagreements have distorted global prices and caused supply disruptions for critical mineral needed for compressors, motors, chips, and semiconductors used in the manufacture of high-efficiency ACs.

To mitigate growing supply chain vulnerabilities, there is an urgent need to diversify the cooling equipment supply chain and address energy security and peak load risks in both the U.S. and India. This report aims to assess the potential for supply chain diversification and the scale-up of manufacturing of highly efficient cooling equipment and related critical mineral inputs in the U.S. and India. Using data collected from industrial and trade associations and market research firms, we assess the latest global market trends in room AC manufacturing and associated demand. Geographical vulnerabilities in the global supply chain for key critical minerals are assessed using U.S. Geological Survey data, expert assessments, and the latest international critical minerals outlooks by BloombergNEF (BNEF) and the International Energy Agency (IEA).

This report begins with a global analysis of the current room AC market, highlighting the dominance of China in room AC production and demand while emphasizing potential growth and vulnerabilities in the U.S. and India markets. It identifies specific technologies and processes that are essential for scaling the manufacture of highly efficient, affordable room AC units, including those with advanced refrigerants. The report then highlights opportunities for the U.S. and India to become leaders in manufacturing the most valuable components in high-efficiency room ACs through diversifying supply chains away from China. It further assesses supply chain risks and vulnerabilities for other key inputs to high efficiency room ACs in the highly concentrated mining, refining, and processing of critical minerals and manufacturing of semiconductors. The findings shed light on broader implications and opportunities for U.S.-India collaboration with its two other Quadrilateral Security Dialogue (Quad) partners of Japan and Australia to secure the global cooling supply chain and lead in efficient AC manufacturing by leveraging their respective key strengths and India's large and growing demand for efficient cooling.

2. Room Air Conditioners Global Market Analysis

2.1 Room AC Production and Demand

The global residential room AC industry has grown rapidly in recent decades and continues to be dominated by China throughout the supply chain. In terms of production volume, China is the single-largest producer of room ACs globally: in 2021, China produced nearly 155 million units, accounting for 82% of the 189 million units produced globally, as shown in Figure 1 (China IOL, 2022). China's dominance in room AC manufacturing largely results from its ease and efficiency with manufacturing

[1] The product categories included in "room AC" differs by country. See country-specific market analysis for product types included.

and its low costs for inventory, capital, freight, energy, and real estate.

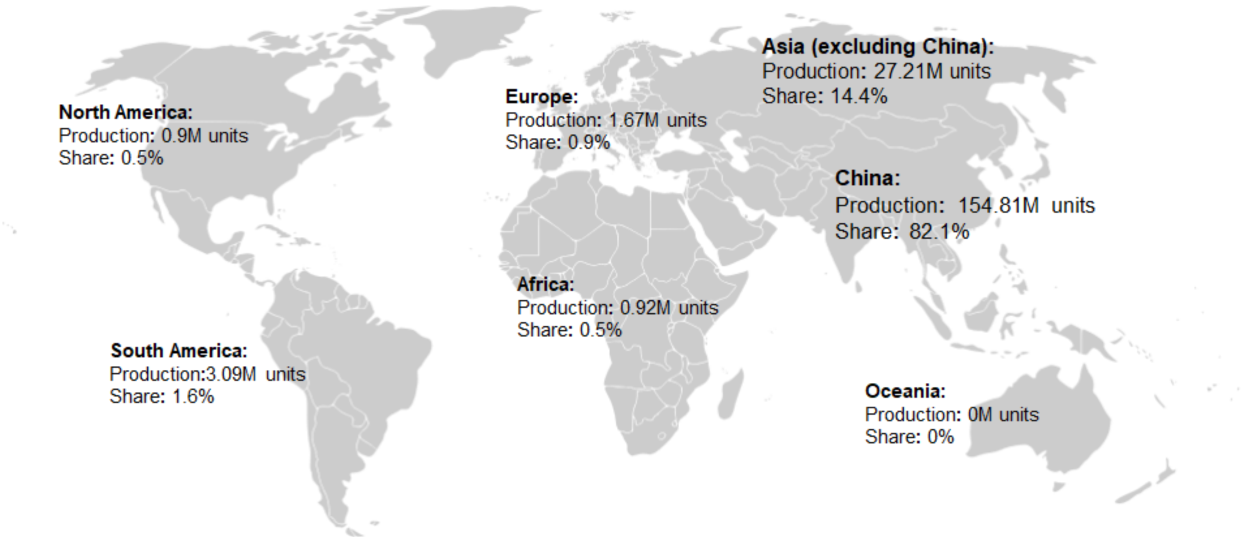

Figure 1. Global room AC production by region, 2021
Source: China IOL, 2022

Outside China, global residential AC production capacity continues to grow. Other parts of Asia accounted for 14.4% of global production in 2021 (Figure 2). Specifically, production in Southeast and South Asian countries like Thailand, India, Malaysia, and Indonesia has increased significantly in recent years. Thailand is positioning itself as a global manufacturing center for ACs, becoming the third-largest global AC exporter in 2024. In response to the China–U.S. trade war and considerations such as avoiding tariffs, some AC companies have begun shifting production to Southeast Asia. For example, leading multinational manufacturers are increasingly attracted by Thailand's location, infrastructure, and government investment incentives (Medina, 2025). Following Thailand, other key countries with high production volumes of room ACs include India, Japan, South Korea, Malaysia, and Indonesia.

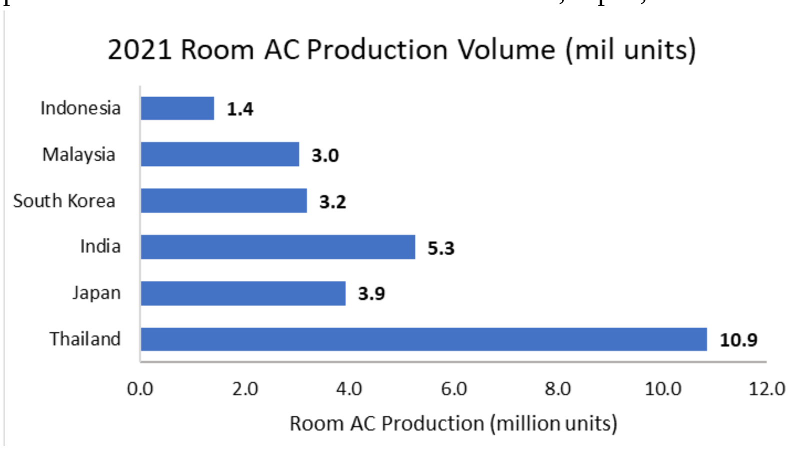

Figure 2. Room AC production volume by country, 2021
Source: China IOL, 2022

Outside Asia, Europe and South America together only produced 2.5% of global room ACs in 2021,

totaling nearly 5 million units. This highlights the undeniably large role that China—and increasingly, Asia—plays in global room AC production, as well as the broader supply chain.
China and Asia also account for most of the global demand for room AC units (Figure 3). China alone represented over half (51%) of total global room AC demand in 2021, followed by the rest of Asia (23%), North America (9%), and South America and Europe (7% each). Future demand in Asia is expected to grow with rising household incomes, continued population growth in many countries, and hotter and more humid conditions throughout parts of the region (IEA, 2024).

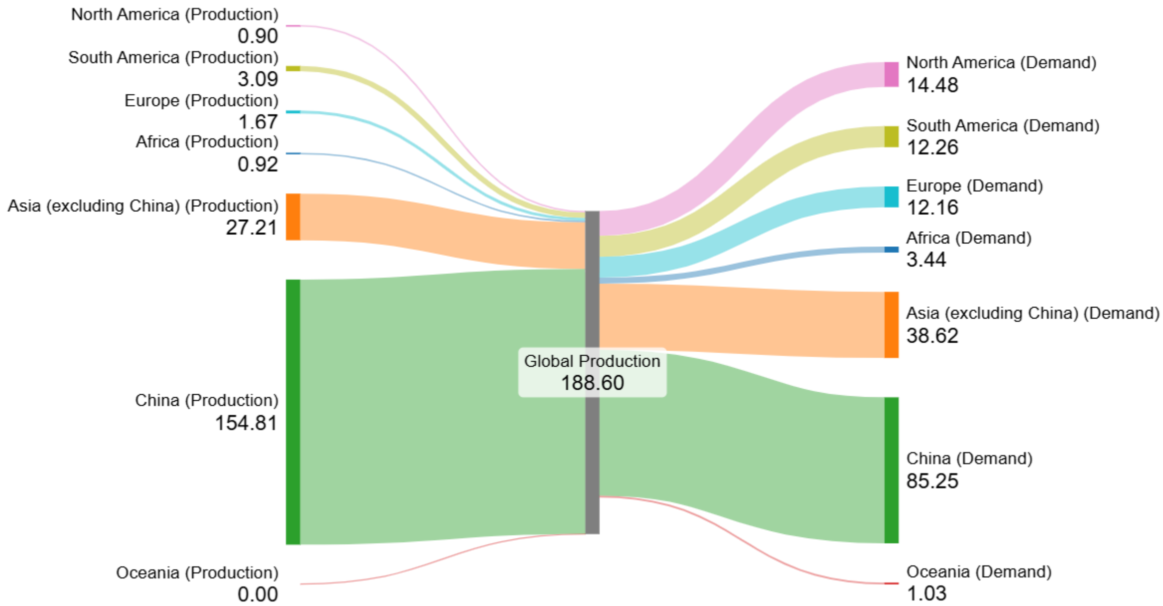

Figure 3. Global room AC production and demand flows (in millions of units), 2021
Source: China IOL, 2022

Surging demand for air conditioning—driven by rising temperatures and humidity, increased urbanization, and expanded access to cooling technologies in developing countries—is fundamentally reshaping electricity consumption patterns across the globe. According to our room AC stock turnover modeling estimates, global annual room AC sales are projected to grow to over 775 million units by 2050—a more than five-fold increase from current levels, reflecting the accelerating global demand for cooling (Figure 4). This explosive growth is already straining electrical grids; in the U.S., 37% of the increase in electricity demand from April to September 2024 relative to the prior year was driven by higher AC use (Ember, 2025). The impact on peak load is particularly severe, as room ACs' share on peak electricity load could reach 45% in 2050 in India and other countries, forcing utilities to invest heavily in new power generation and transmission infrastructure and driving up energy costs for consumers (IEA, 2018). IEA projects that air conditioning will drive more than 1,200 TWh of additional global electricity demand by 2035 (IEA, 2024a). Meanwhile, the manufacturing sector is experiencing unprecedented demand, creating both opportunities and supply chain challenges for AC manufacturers as the industry scales to meet massive market expansion while improving energy efficiency performance to moderate impacts on power grids.

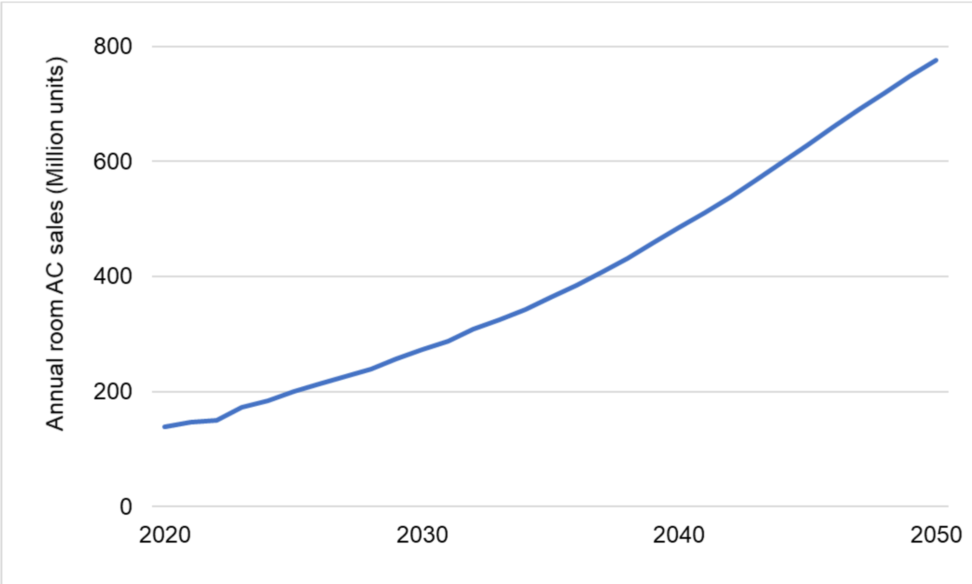

Figure 4. Global room AC sales projections, 2020–2050
Source: LBNL room AC stock turnover analysis

At the country level, a closer assessment of specific room AC markets illuminates emerging technological trends and the risks of continuing to rely on China-dominated supply chains. The U.S. and India offer two valuable examples.

2.2 Cooling Market Analysis: U.S.

In 2023, window units and ducted single-split systems together accounted for approximately 77% of U.S. cooling equipment sales by volume, with virtually identical shares (39% and 38%, respectively). Portable units have the third-largest share of sales, at 8%. By value, ducted single-splits represented about 47% of total U.S. cooling equipment sales of USD $24.6 billion.

The U.S. imported USD $14.2 billion of air conditioning equipment in 2023, including USD $2.8 billion from China alone (UN Comtrade, 2025). Notably, the U.S. imports *all* its window and portable AC units, primarily from China and South Korea. Imported multi-splits and variable refrigerant flow (VRF) units accounted for over three-quarters of U.S. sales in those categories (Figure 5).

Table 1 shows the major companies responsible for manufacturing and/or importing different types of air conditioning equipment, along with components and their associated headquarters and country of manufacturing or assembly. Daikin is the only manufacturer of mini-split systems in the U.S., while ducted splits are produced domestically by Trane, Carrier, Rheem, Goodman, Friedrich, and Amana. About half of rooftop units are imported, primarily from Mexico, by major manufacturing brands such as Lennox, Carrier, and Trane.

Table 1. Major room AC manufacturers by product type and location

	Windows	Portable	Split	VRF	Rooftop	Indoor Packaged	Chillers	AHUs	Fan Coils	Global HQ	Country of Manufacture/ Assembly
Smardt							I,M			Canada	USA, Canada
Gree (Watsco)			I	I						China	China
GE Appliances (Haier)	I	I								China	China, USA
Daikin			M	M	M	M	M	M	M	Japan	USA, China, Italy
Fujitsu			I	I						Japan	Thailand
Panasonic			I							Japan	Malaysia
Mitsubishi Electric			I	I						Japan	Thailand, China
Samsung			I	I						South Korea	South Korea, China
LG	I	I	I	I						South Korea	South Korea, China
Carrier			M, I	I	M, I	M	M	M	M	USA	China, USA, Mexico
Trane			M, I	I	I	M	M	M	M	USA	USA, China, France
JCI			I	I	M	M	M	M	M	USA	USA, China
Lennox			M, I	I	M, I					USA	USA, Mexico
Rheem			M, I		M					USA	USA, Mexico
Nortek					M			M		USA	USA

I: import
M: manufacture

Source: Authors' work based on BSRIA 2024a, 2024b, 2024c, 2024d and industry consultation

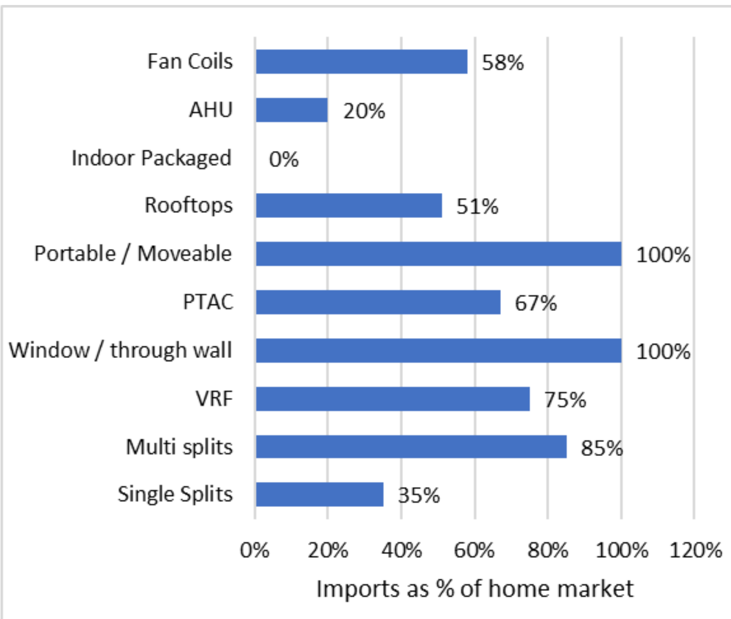

Figure 5. U.S. import shares by AC product type

Source: Authors' work based on BSRIA 2024a, 2024b, 2024c, 2024d and industry consultation

2.3 Room AC Market Analysis and Outlook: India

India's room AC market has undergone astounding growth over the last two decades, experiencing a 12-fold increase in total units sold between 2006 and 2023 (Figure 6). Key growth drivers include demographic factors (e.g., increasing household size and disposable income and rapid urbanization) as well as climatic ones (e.g., rising average temperatures, shifting rainfall patterns, and more frequent and severe heat waves and extreme weather). Continued rapid market growth is expected, with some estimates anticipating compound annual average growth rates of 15.8% and a domestic market size of USD $30 billion by 2030 (U.S. International Trade Administration, 2024).

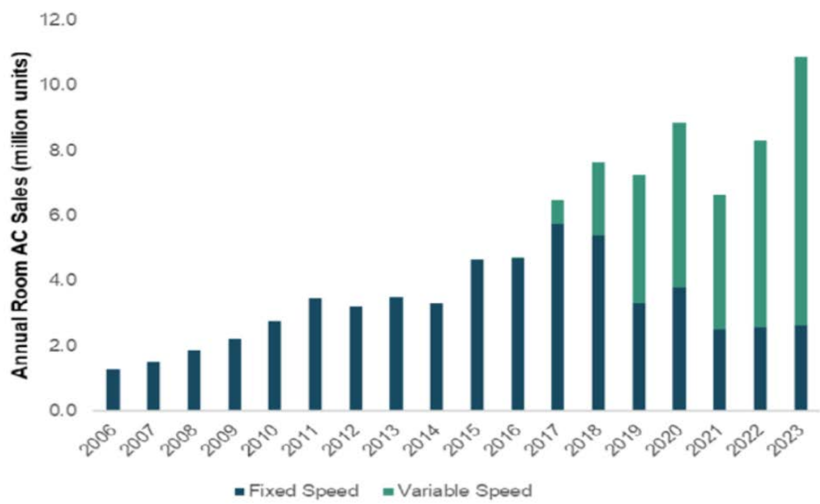

Figure 6. India annual room AC sales, 2006–2023
Source: Abhyankar et al., 2025

India's room AC market includes three main product types: portable units, split ACs, and window ACs. Over the last few years, the share of split units has risen due mainly to rising urbanization and disposable incomes along with preferences for improved air quality and energy efficiency (IEA, 2024a). By 2021, 82% of India's room AC units were split units (Figure 7). For these units, the industry's shift from fixed-speed (non-inverter) to primarily inverter-based compressor technology has significantly improved room AC energy efficiency (BSRIA, 2021, 2024). This shift has been partly driven by India's increasingly stringent minimum energy performance standards (MEPS).

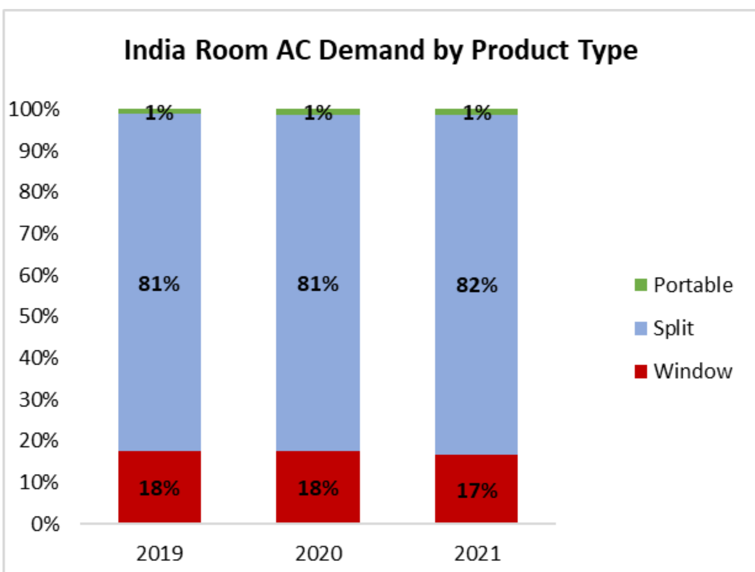

Figure 7. India demand for room AC products by type, 2019–2021
Source: data from China IOL, 2022

Between 2019 and 2021, the market share of high-efficiency room AC units increased for both split and window units, accounting for the largest share of products sold (Figure 8). These units are rated 3-stars and 5-stars, respectively, by India's energy label. The small number of old fixed-speed 5-star split units still being sold in 2019 were largely phased out by 2021, by which time the least efficient (1- and 2-star) split ACs had a negligible share. Similarly, inefficient 1- and 2-star window ACs are no longer available in India as of 2020. For window units, the share of 5-star sales grew rapidly in under two years, reaching one-fifth of the market. The shift toward energy-efficient ACs aligns with a growing consumer focus on premium comfort and connectivity features in home appliances.

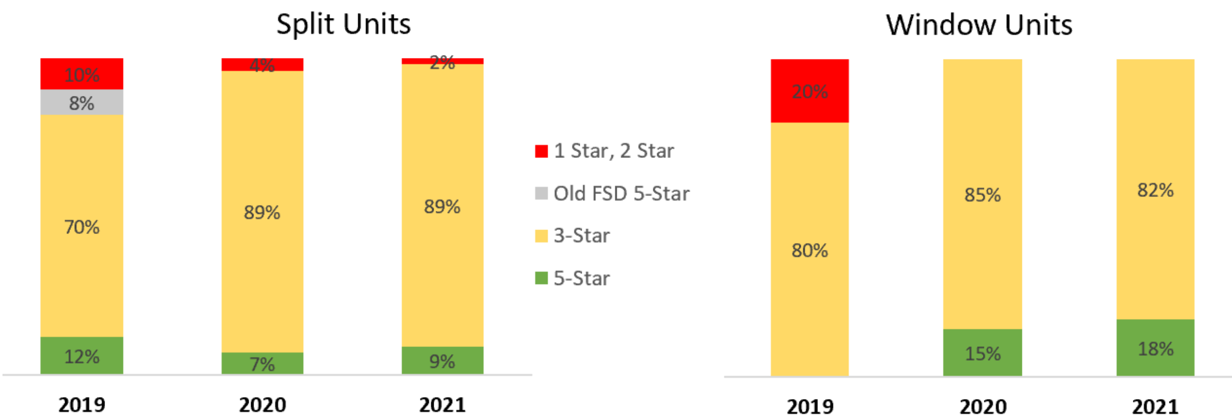

Figure 8. India room AC energy efficiency distribution by product type, 2019–2021
Source: data from China IOL, 2022

Looking ahead, India's room AC ownership is expected to skyrocket alongside increased population, urbanization, and income growth, potentially reaching 240 million units by 2050—a nearly 10-fold increase from 2030 levels (based on our room AC stock turnover modeling assumptions, Figure 9). As AC penetration and corresponding usage rise, India's cooling peak demand will increase, particularly on the hottest days. From 2019 to 2022, electricity consumption for space cooling grew by 20% despite relatively small increases in AC unit ownership and improvements in energy efficiency. Without policy interventions, Abhyankar et al. (2025) estimates that room ACs could contribute roughly 120–180 GW to India's peak electricity demand (currently 240 GW) by 2030–2035, and 800 GW by 2050. This would threaten the reliability of India's electricity grid, with power shortages occurring as soon as 2026 despite 50 GW of new generation and storage projects in the pipeline.

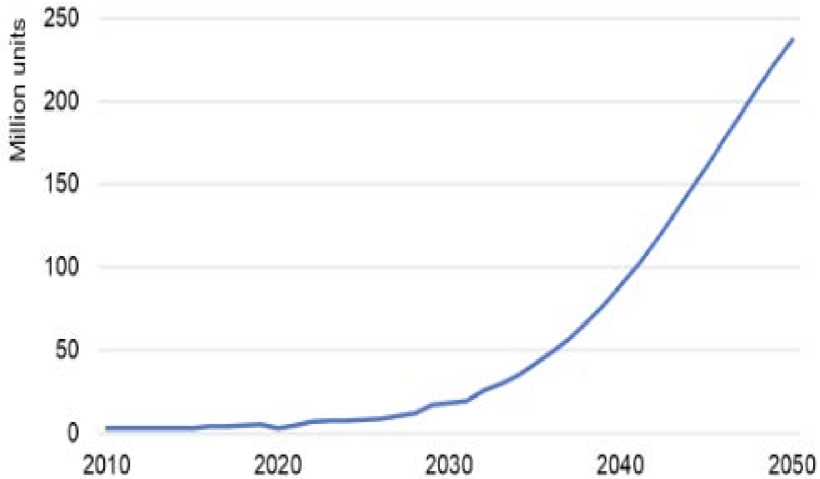

Figure 9. India historical and projected room AC stock, 2010–2050
Source: LBNL India room AC stock turnover modeling

In light of this daunting challenge, Abhyankar et al. 2025 find that more ambitious MEPS and energy labels can help mitigate peak power demand and black-out risks, with sizable net consumer savings. This could present opportunities for manufacturers in India (e.g., Voltas, Lloyd, BLUE STAR), Japan (e.g., Daikin, Johnson Controls/Hitachi, Panasonic), and South Korea (e.g., LG, Samsung), which together account for roughly three-quarters of India's ductless split AC sales (BSRIA, 2022). Even so, both domestic Indian and foreign multinational manufacturers already offer high-efficiency AC models with ISEER values above 6.0 in the Indian market (Figure 10).

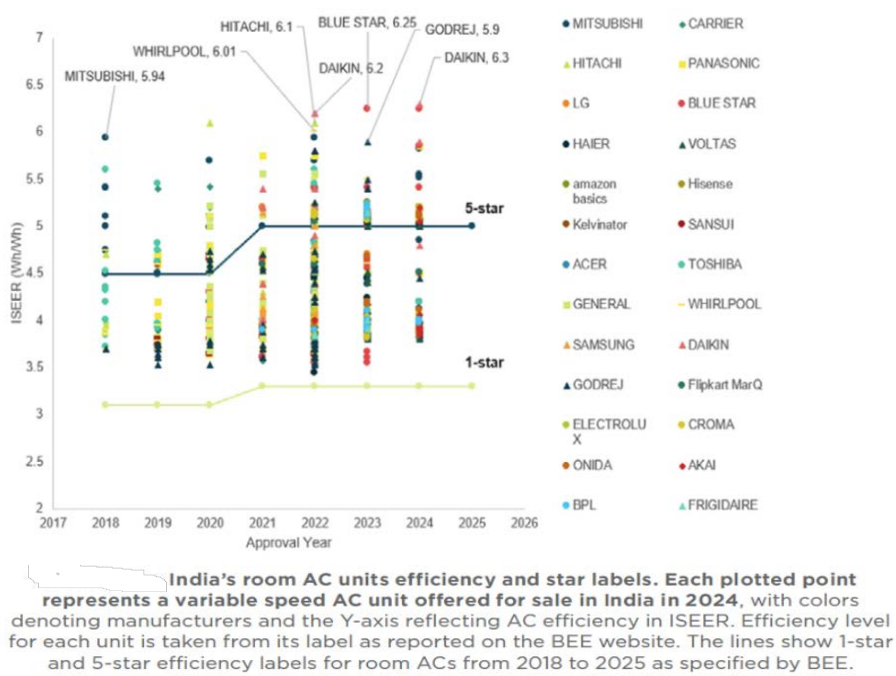

Figure 10. India room AC unit efficiency levels by manufacturer
Source: Abhyankar et al., 2025

3. Supply Chain Opportunities and Risks Analysis

The room AC manufacturing supply chain represents a sophisticated global network that spans multiple continents and involves dozens of specialized suppliers at each tier. The process begins with the extraction and processing of essential raw materials, including ferrous metals used to produce structural components and housing (steel), heat exchanger fins and condenser coils (aluminum), and refrigerant tubing and electrical wiring (copper). High-efficiency permanent magnet motors used in modern variable-speed compressors and fan systems require critical rare earth elements (REEs) like neodymium and dysprosium that are sourced primarily from China.

These raw materials flow to specialized component manufacturers who produce the core functional elements of air conditioning systems, as illustrated in Figure 11. The indoor unit houses the cold coil (evaporator), fan, motor, temperature sensor, filter, and electrical circuits that manage the cooling process and user interface. The outdoor unit contains the hot coil (condenser), compressor, fan, motor, and additional electrical circuits that handle the heat rejection and refrigeration cycle management.

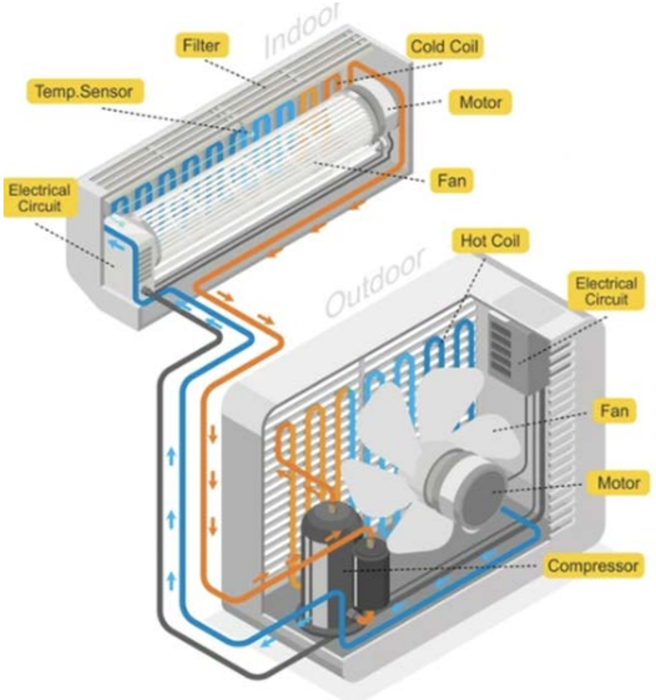

Figure 11. Cross-sectional view showing key components of a room AC system, including indoor and outdoor units

Compressor manufacturers are often located in countries like China, Japan, and South Korea. Heat exchanger specialized companies fabricate evaporator and condenser coils using advanced tube-and-fin designs, while electronics manufacturers produce sophisticated printed circuit boards (PCBs) that control everything from temperature regulation to energy management and smart connectivity features. Fan manufacturers create both axial and centrifugal fans optimized for airflow and energy efficiency, while refrigerant suppliers provide environmentally compliant cooling agents that meet evolving regulatory standards.

The assembly process typically occurs at manufacturing facilities strategically located near major consumer markets or in regions with favorable labor costs and logistics infrastructure. These plants integrate hundreds of components sourced from the upstream supply network. Quality testing can include refrigerant leak detection, electrical safety verification, and performance validation across various operating conditions before products move through multi-tiered distribution channels.

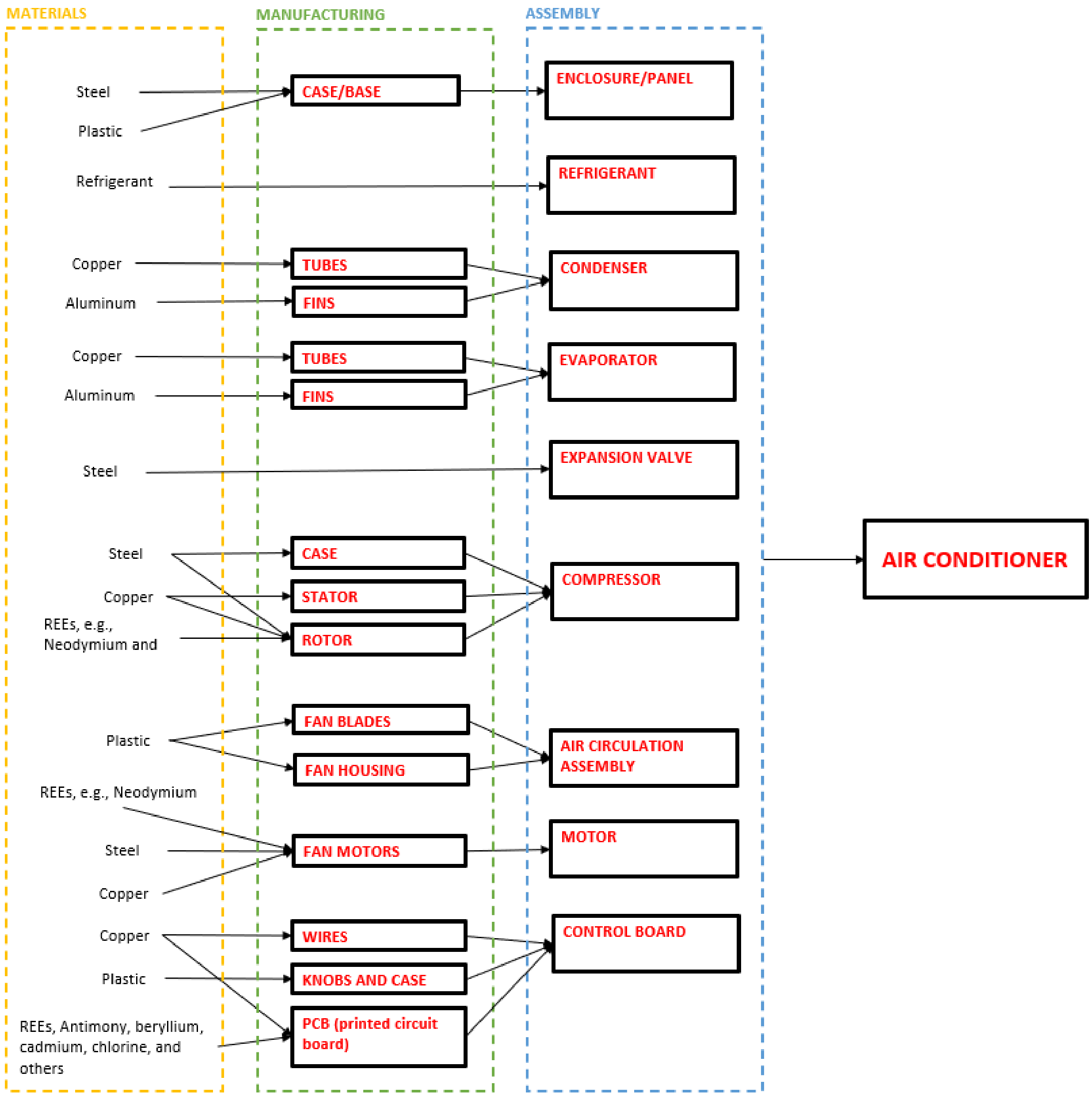

Figure 12. Room AC manufacturing supply chain example schematic
Note: REE = Rare Earth Element

The final distribution network encompasses regional warehouses, retail partners and, increasingly, direct-to-consumer e-commerce fulfillment centers, all coordinated to ensure timely delivery while managing seasonal demand fluctuations that can vary dramatically based on climate patterns and construction cycles.

3.1 Room AC Supply Chain Risk Analysis

The rapid expansion of cooling technologies is reshaping global supply chains and driving unprecedented demand for key equipment components and critical minerals—including copper, aluminum, REEs, and refrigerants—that are essential to their manufacture, efficiency, and environmental compliance. High-tech components such as compressors and printed circuit boards (PCBs) are concentrated in a handful of countries, while lower-tech parts like sheet metal and fans benefit from more localized production. This distribution creates both opportunities and vulnerabilities shaped by technological barriers and regulatory shifts.

China's dominance extends beyond finished products to encompass core components, with heat exchangers, PCBs, fan motors, and up to 90% of compressors sourced from Chinese manufacturers. This influence permeates even internationally branded units, which rely heavily on Chinese-made parts. Meanwhile, Chinese companies dominate global exports, reaching markets across Europe, Southeast Asia, South America, and Africa.

China's overwhelming market position creates profound vulnerabilities in global supply chains. Disruptions originating from geopolitical tensions, public health crises, or government-imposed export controls can rapidly cascade across international markets, triggering shortages, price volatility, and production delays. Recent export restrictions on REEs and magnets—crucial components for AC motors and compressors—demonstrate how China can leverage its position for strategic or retaliatory purposes. These actions threaten supply continuity for manufacturers in the United States, Europe, and beyond, highlighting the fragility of supply chains so heavily dependent on a single nation.

China's control extends to critical material processing, where it maintains a stranglehold on rare earths processing (90% of global capacity) and critical materials like gallium (98% supply share) (Karali and Shah, 2022) [2]. This dominance cements China's role in the supply chain, leaving global markets vulnerable to disruptions such as the 2022 germanium and gallium export controls that threatened smart AC semiconductor supplies.[3]

The United States and India remain deeply reliant on Chinese supply chains for AC equipment and components. While U.S. dependence has become less direct through third-country imports (which still rely on Chinese parts), India's dependence remains direct and acute, with critical shortages emerging whenever Chinese supply faces disruption. While India and other countries have begun developing manufacturing capacity, scaling up to match China's output and cost competitiveness will require years of sustained investment and development.

This dependence exposes the U.S., India, and the rest of the world to significant supply chain risks, including disruption and price volatility. U.S. imports of ACs from China totaled more than USD $3 billion in 2024, according to the United Nations (UN).[4] Reliance on imports has made the sector

[2] https://www.nytimes.com/2025/06/03/business/rare-earth-metals-china.html

[3] https://www.stimson.org/2025/chinas-germanium-and-gallium-export-restrictions-consequences-for-the-united-states/#:~:text=imply%20German%20reexport.-,Impact%20on%20the%20United%20States,materials%20has%20not%20apparently%20declined.

[4] https://tradingeconomics.com/united-states/imports/china/air-conditioning-machines-temp-hum-change

particularly vulnerable to trade policy changes. The U.S. domestic manufacturing base, featuring companies like Carrier, Trane, and other established HVAC manufacturers, struggles to compete with lower-cost imported units and components. Despite growing efforts to diversify corporate supply chains to countries like India and Vietnam, China's primacy remains largely intact.[5] Many components assembled in other countries still originate in China, making a complete decoupling from Chinese supply chains nearly impossible in the short term. China's value-added content in imports thus remains high, even as direct exports declined in 2025 due to tariffs.

India's air conditioning sector has traditionally exhibited high import dependency, with imported components constituting up to half of total AC costs (Figure 13). The country's AC industry relies heavily on Chinese imports for critical components, particularly compressors, PCBs, copper tubes, and fan motors (Figure 13). Local manufacturing covers only 10–25% of demand for these components, with Chinese imports filling the remainder. The acute product shortages and price increases seen in India during supply disruptions or trade tensions underscore the country's vulnerability (PWC, 2024). Other components like grooved copper tubes are also in short supply domestically, and despite government efforts to boost domestic manufacturing (Figure 13), India's trade deficit with China continues to expand. However, the landscape may be transforming due to government initiatives, particularly the Production Linked Incentive (PLI) scheme for white goods (Dixit and Bhasin, 2022).

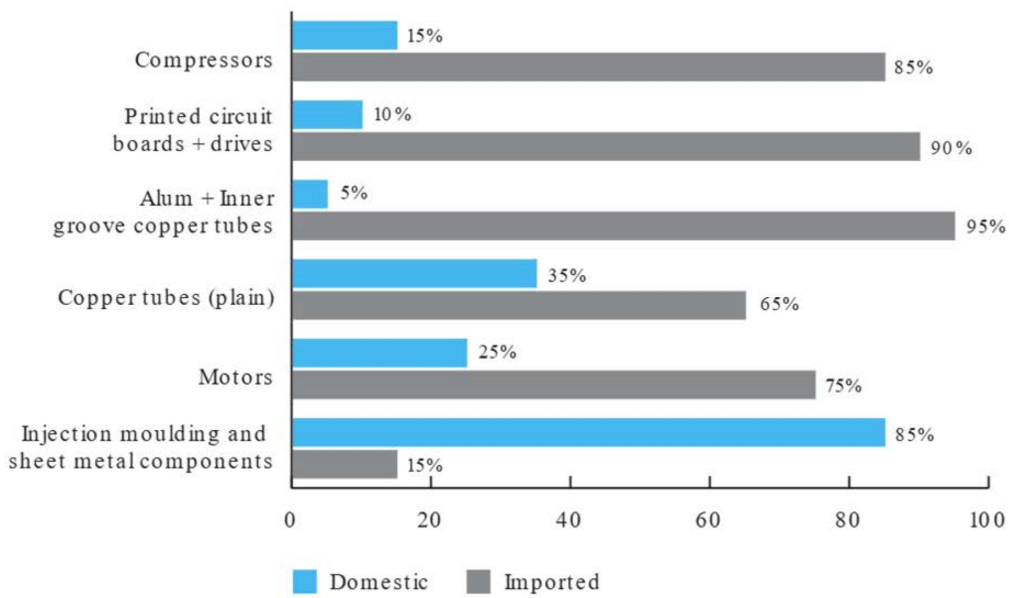

Figure 13. Share of imports and domestically manufactured AC components in India
Source: Dixit and Bhasin, 2022

The manufacturing of high-impact AC components faces significant knowledge gaps outside of China, requiring targeted technology transfer initiatives. For example:

- Compressors: Process know-how and intellectual property-linked designs remain concentrated in China. There is a significant lack of access to advanced manufacturing techniques, such as

[5] https://sccei.fsi.stanford.edu/china-briefs/friendshoring-nearshoring-reshoring-how-us-trade-relationship-china-evolving

precision machining for special compressors, while both the U.S. and India lack the technical expertise required for large-scale production. For example, manufacturing inverter compressors (which include the extra components of drives and controllers) in India largely depends on imports from China. This poses considerable supply chain dependence as inverter compressors are used in more than 55% of split room ACs sold in India, with shares increasing every year (Abhyankar et al., 2025). In addition, a state of self-sustaining domestic compressor production would require large scale, a threshold few domestic firms could meet without foreign partnerships or substantial state support.

- Heat exchangers: Economies of scale are key to making heat exchangers at competitive prices. Raw materials (e.g., high-grade copper and aluminum) must be procured at cheap prices. In India, grooved copper tube manufacturing faces obstacles from the absence of coating facilities and quality issues with recycled copper, forcing 100% import reliance (Dixit and Bhasin, 2022).
- PCBs and controllers: India, lacking a semiconductor manufacturing base, imports 95% of its semiconductors from countries like China, Taiwan, South Korea, and Singapore (Dixit and Bhasin, 2022). The U.S. faces similar challenges with domestic PCB fabrication for specialized HVAC controls (CRS, 2020). The complexity of these systems requires substantial investment in both equipment and skilled personnel.
- Low-GWP refrigerants: Partnerships with global chemical firms would be needed for the U.S. and India to develop production capabilities for next-generation refrigerants like R-454B, which demand advanced synthesis and purification processes available only in established manufacturing centers. Technologies utilizing advanced refrigerants often demand specialized manufacturing processes due to material compatibility requirements, safety protocols, and precision engineering capabilities currently concentrated in China:
    - HFO blends and low-GWP refrigerants (R-454B, R-448A): These require production facilities with strict contamination controls and advanced chemical synthesis processes to ensure purity and stability—capabilities needing significant capital investment and technical expertise.
    - Natural refrigerants (CO_2, ammonia): Systems using carbon dioxide (R-744) or ammonia (R-717) necessitate corrosion-resistant materials such as stainless steel for compressors and piping, along with sophisticated leak-detection systems and safety protocols for high-pressure or toxic environments.

3.2 Room AC Supply Chain Opportunities Analysis

The room AC supply chain presents compelling diversification opportunities as global manufacturers seek alternatives to China-centric production models. The U.S. can emerge as a particularly attractive destination for supply chain restructuring, driven by regulatory incentives. These policy frameworks create strong economic incentives for companies to establish manufacturing capabilities within the U.S., particularly for components requiring advanced materials science and precision engineering.

India represents another significant opportunity in the evolving room AC supply chain landscape, offering advantages in both cost-competitive manufacturing and rapidly expanding domestic market demand. The country's production-linked incentive schemes for white goods manufacturing creates favorable conditions for establishing regional supply chain hubs that can serve both domestic consumption and export markets.

India represents a significant opportunity in the evolving room AC supply chain landscape, offering advantages in both cost-competitive manufacturing and a rapidly expanding domestic market. Expanding markets provide opportunities to scale up manufacturing, resulting in a more cost-competitive environment. The country's production-linked incentive schemes for white goods manufacturing create favorable conditions for establishing regional supply chain hubs that can serve both domestic consumption and export markets.

The convergence of regulatory pressures for alternative refrigerants, geopolitical supply chain resilience imperatives, and the urgent need for energy-efficient cooling solutions in emerging markets positions both the U.S. and India as critical nodes in the next-generation room AC supply chain architecture.

4. Critical Minerals Supply Chain Implications

Room ACs, increasingly ubiquitous as modern-day home appliances, are mineral- and material-intensive equipment. As room AC technology evolves to offer users more new features and control options, critical minerals and semiconductors are becoming a key part of the highest-value supply chain for cooling. The key components of room ACs—particularly more efficient variable-speed ACs—include the following materials and minerals.

First, copper is a transition metal widely used in ACs, including in heat exchangers and wiring as an excellent conductor of heat. Aluminum, a lightweight alternative to copper, is used in heat exchangers, tubing, and electrical components. Second, rare earth elements, including specifically **neodymium, terbium, and dysprosium**, are used in magnets within compressors and motors that enhance AC energy efficiency performance and heat resistance. These rare earth elements are metallic and possess unique properties that are essential for many technological applications, including energy technologies and other high-tech devices. Third, semiconductors are used in variable-frequency drive circuits for AC motors to regulate alternating current voltage and frequency and enable precise control. Semiconductors are also used in temperature sensors within ACs and advanced control systems. Vital components in all electronic devices, semiconductors rely on critical minerals for their conductive and insulative properties. Specifically, semiconductors use **silicon** as the initial material for manufacturing chip wafers, while metals such as **gallium, germanium, palladium** are added later to change the wafers' conductivity (CSIS, 2024). Copper and cobalt are also used in integrated circuit wiring.

Figure 14 presents estimates from our global room AC e-waste model, illustrating the volume of materials discarded from used equipment worldwide. The figure highlights both the quantity of materials utilized in room ACs and the potential for material recovery through circular economy practices.

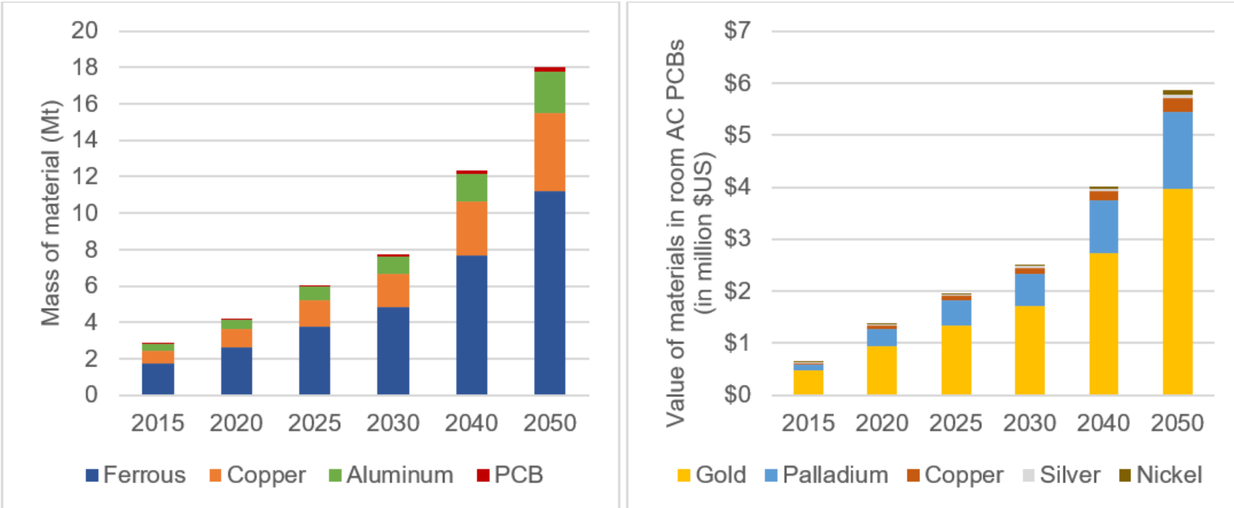

Figure 14. Mass of materials discarded with room AC e-waste and potential value of materials in PCBs in a BAU scenario

Source: LBNL room AC e-waste modeling estimates

4.1 Critical Minerals Supply Chain

4.1.1 Mining and Extraction

The key minerals used in room AC manufacturing, particularly critical minerals and rare earth elements, all face limited or concentrated supply chains encompassing the various stages of mining, refining, and processing, leading to supply chain vulnerabilities. For cobalt, silicon, and rare earth elements, existing reserves and mining production are highly concentrated in one geographical location (Figure 15). China dominates global mining for rare earths for magnets (i.e., neodymium, praseodymium, dysprosium and terbium) and raw silicon with 69% and 79% shares, respectively, while the Democratic Republic of Congo mines 80% of cobalt (BNEF, 2024). For copper, Chile and Peru together comprise over one-third of global mining production in 2023.

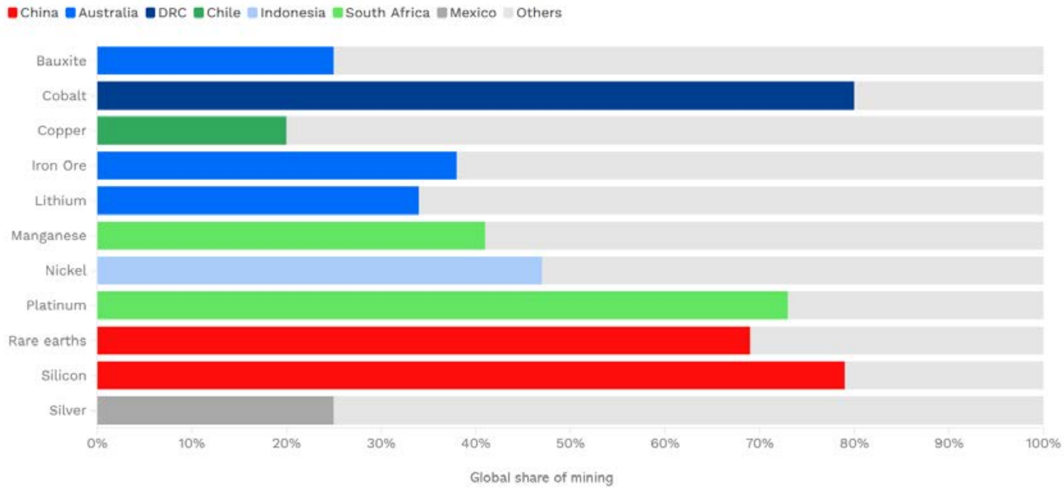

Figure 15. Global share of mining by country and mineral, 2023

Source: Adapted from Gurzu, 2025. Data from BNEF Transition Metals Outlook, 2024. Rare earths include neodymium, praseodymium, dysprosium, and terbium. DRC = Democratic Republic of Congo.

Based on operating and announced projects, total copper mining is expected to decline through 2040. Together, the three largest copper mining countries (Chile, Democratic Republic of Congo, and Peru) are expected to account for 54% of total output in 2040, up from 47% in 2023 (IEA, 2025). Similarly, cobalt mining is also expected to remain concentrated, with the top three countries continuing to produce more than three-quarters of the global total (IEA, 2025). Cobalt production is expected to ramp up in the near term due to new mines in the Democratic Republic of Congo and increased production from Indonesia before leveling off in the 2030s. While supply of mined rare earth elements for magnets is expected to increase by over 50% by 2040, the top three countries are still expected to account for more than three-quarters of the global total (IEA, 2025).

4.1.2 Processing and Refining

After mining and extraction, raw minerals and metals are transformed into refined materials by separation, purification, and processing. This occurs during the midstream processing and refining stage, the supply chain for which is even more concentrated than mining production where critical minerals are concerned. China is the world's largest importer of raw critical minerals, facilitated by its strategic investment in overseas mining projects; in 2023, Chinese firms invested USD $16 billion in overseas mining projects (CSIS, 2025). China has also made substantial investments to expand its domestic refining capacity and adopted related industrial policies. As the world's leading copper refiner, China accounted for 45% of the global market in 2023, up from 30% in 2015 (IEA, 2025). The country's control over global critical minerals production is reinforced by its capacity to process from 60% to more than 90% of the global supply of certain key minerals—including 73%, 92%, and 93% of cobalt, rare earth elements, and polysilicon, respectively, as seen in Figure 16 (BNEF, 2024). This geographic concentration in key minerals refining is expected to continue through 2040 (Figure 17). For magnet rare earths, the top three countries are expected to account for more than 90% of global refining through 2040, dominated by China and Malaysia (IEA, 2025).

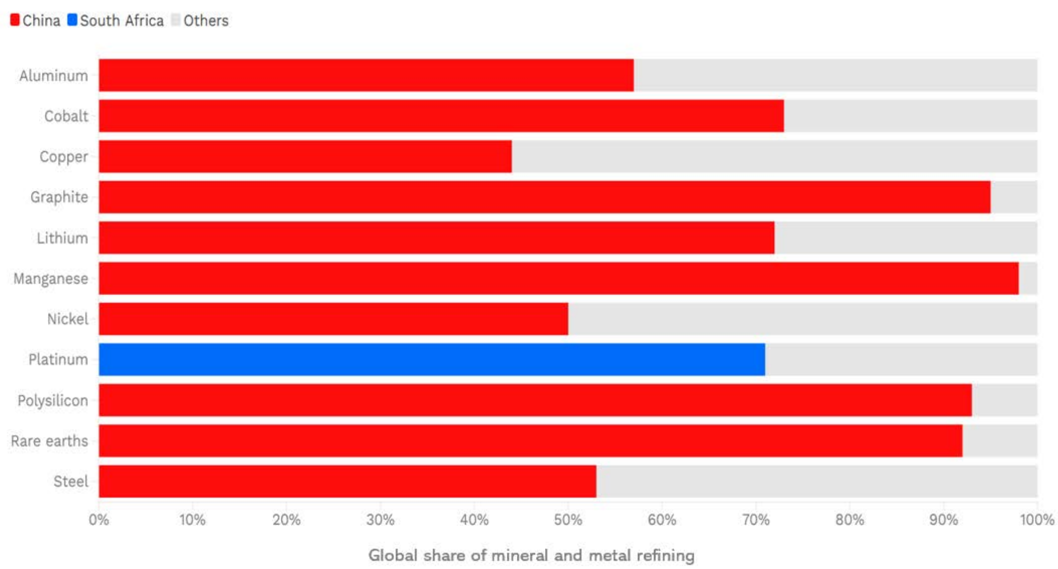

Figure 16. Global share of refining by mineral and top country, 2023
Source: Adapted from Gurzu, 2025. Data from BNEF Transition Metals Outlook, 2024.
Note: Rare earths include neodymium, praseodymium, dysprosium and terbium.

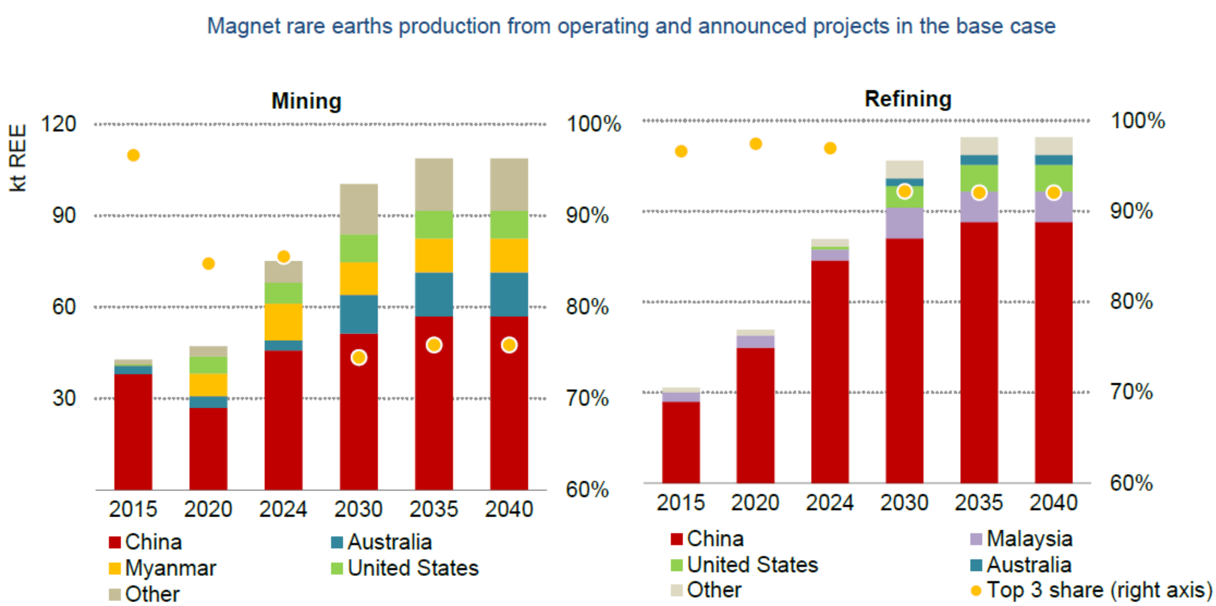

Figure 17. Magnet rare earths mining and refining output by country under IEA Base Case, 2015–2040
Source: IEA, 2025 and Global Critical Minerals Outlook, 2025
Note: Magnet rare earth elements include neodymium, praseodymium, dysprosium and terbium.

For other critical minerals and metals used in manufacturing semiconductors (i.e., gallium, germanium, and palladium), refining and production are dominated by China, Russia, and South Africa. Gallium is sourced only as a byproduct of bauxite mining, which is found in extremely limited quantities in Earth's crust. Australia and Guinea, half of the countries with highly concentrated bauxite reserves, are also two of the three countries that together mine nearly two-thirds of the world's bauxite; the other is China

(USGS, 2025). In 2022, the three largest bauxite exporters (with a combined 86% global export share) sent most of their bauxite to China for refining (CSIS, 2025). Consequently, China now accounts for almost all (98%) of global gallium production. China also accounts for 60% of the global supply of refined germanium, sourced as a byproduct of zinc ore processing (CSIS, 2025). Production of palladium, a platinum metal, is highly concentrated in Russia and South Africa, with global production shares of 40% and 34%, respectively (USGS, 2025), both of which poses geopolitical challenges as reliable trade partners.

4.2 Critical Minerals and Supply Chain Vulnerabilities

For room AC components and their critical mineral inputs, supply chain vulnerabilities and disruptions can significantly affect the availability and price of AC units. These vulnerabilities include supply risks, geopolitical risks, and a limited ability to respond to disruptions in supply chains. Supply risks include sudden spikes in demand that cause a supply/demand imbalance—for example, when demand for work-from-home digital products surged during the Covid-19 pandemic, contributing to a global shortage in semiconductor chips. The highly specialized supply chain for semiconductors and regionalized clusters for individual semiconductor components exacerbated this shortage (Mohammad et al., 2022).

The booming demand in critical minerals, spurred by the global clean energy transition, has led to price volatilities and spikes in the global market (Figure 18). Other factors—including lags in expanding supply and the high geographic concentration in mining and refining many minerals—have compounded these volatilities. Over the last decade, price spikes on the order of 200–300% have occurred for lithium, nickel, rare earth elements, copper, and silicon (UNCTAD, 2024). For rare earth minerals such as tellurium, gallium and germanium that are recovered during the processing of other ores, supply and pricing are closely tied to market dynamics for their associated primary commodities (IEA, 2025).

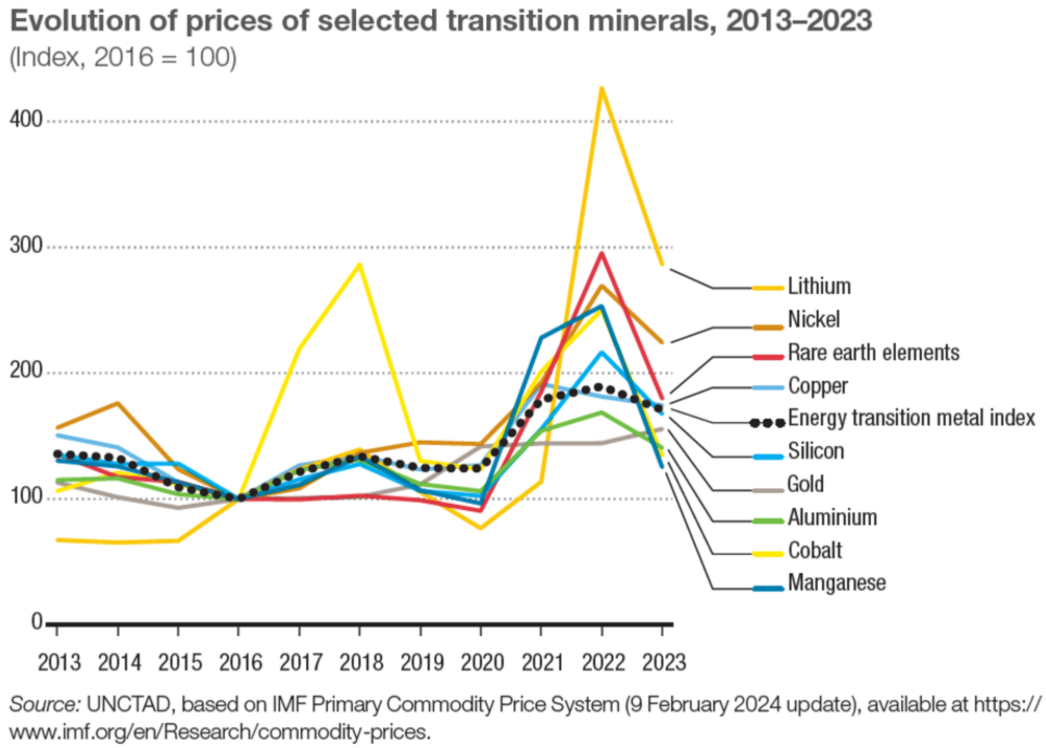

Figure 18. Price trends for selected critical and energy transition minerals, 2013–2023
Source: UNCTAD, 2024

Note: Energy Transition Metal Index is a price index based on a basket price of commodity metals associated with energy transition technologies and themes

Geopolitical risks and tensions have manifested in wars and trade disputes that affect production and supply, leading to supply chain disruptions and barriers such as export bans. For example, the war in Ukraine disrupted the supply of neon used in lasers to make semiconductor chips when two Ukrainian manufacturers, responsible for half of global supply, halted production in 2022 (Alper, 2022).
In 2019, Japan imposed restrictions on exports to South Korea, severely limiting the latter's access to key chemicals used in semiconductor manufacturing (Mohammad et al., 2022). In April 2025, amid an escalating U.S.-China trade war, China imposed export restrictions on seven rare earth elements required special export licenses for seven rare earth elements, including terbium and dysprosium, infor which it dominates global refining capacity. The inevitable resulting price spikes will cascade down the supply chain to drive up prices for end-use products (e.g., batteries, semiconductors, room ACs). Moreover, these price spikes could have wider economic impacts: if the gaps in manufacturing costs between China and other countries expand further, countries such as Europe, Japan, Korea, and the U.S., whose burgeoning manufacturing bases for advanced technologies all depend on critical minerals, could experience significant negative economic impacts (IEA, 2025).

Three strategies can mitigate these potential supply chain disruptions and vulnerabilities: diversification of sourcing and supply chains; identification of substitutes for high-risk minerals; and increasing secondary supply through material recycling and circular economy approaches. A comprehensive approach with strategies that concurrently tackle both the supply and demand-sides holds the greatest potential for mitigating risks from the current highly concentrated manufacturing in a realistic timeframe.

Diversifying supply chains faces challenges from high capital requirements, long-term price uncertainties, and potentially stringent requirements for addressing environmental, social and governance risks in establishing new projects for geographic diversification of supply chains (IEA, 2024b). For the U.S. domestically, Alaska holds critical mineral resources that are historically largely underexplored and underinvested but is now receiving greater attention, including federal grants to increase geological surveys and research and development (U.S. DOE, 2025). For semiconductors diversification, targeted investment in mineral-rich, economically competitive countries aligned with U.S. interests is one potential solution. Increasing investment in Australia's bauxite refining and Guinea's bauxite production to boost gallium production outside China is one option, as is investing in zinc and germanium production in Australia and Peru (CSIS, 2024).

Technology switching and innovation and identifying appropriate substitutes are two related strategies for moderating risks related to specific minerals. New technologies and innovations can moderate demand for key critical minerals, as illustrated by next-generation solar cells (which need less silicon) and alternative electric vehicle battery chemistries (which don't require cobalt). On the supply side, more research and development are needed to address the reality of limited substitutes for critical mineral inputs, particularly those used semiconductors. Specifically, no good substitutes exist for gallium, pallidum, germanium, or silicon in this application. For other magnet rare earths, cerium is emerging as a potential lower-cost substitute for neodymium but must overcome performance hurdles, while research and development for iron nitride is in its early in the research and development stages (McKenzie, 2023). No readily available substitute exists for terbium or dysprosium.

Circular economy approaches and recycling can also mitigate supply chain risks by increasing secondary sources of critical minerals and materials, but the potential for scaling up near- and mid-term circularity pathways must be better understood (IEA, 2024c). Specific solutions include improved technologies and processes such as advanced sorting, novel chemical and physical processes, and quality control methods for improving waste recovery and recycling efficiency. In addition, industry-specific policy tools—such as targets for material recovery, collection rates and economic incentives, and innovative pricing schemes and business models—will be needed to support the development of domestic supply chain ecosystems for the secondary sourcing of critical minerals (IEA, 2025). These targets should also align with environmental goals and a systems-thinking approach to meet environmental and social responsibility goals and avoid unintended consequences.

4.3 Critical Minerals Supply Chain Opportunities: Engaging the Quad

As partners in the Quadrilateral Security Dialogue, the U.S. and India can tap into each partner's distinct assets to diversify and secure the global cooling supply chain amid rising tensions with China. Since 2021, Quad partners have seen interests align in the Indo-Pacific region, particularly around technology innovation and supply chain resilience (as indicated by the establishment of related regional working groups). Looking forward, each partner country has distinctive advantages in helping secure the global cooling supply chain and enabling new manufacturing leadership away from China. The U.S. and India in particular can become leaders in manufacturing semiconductors and other components for high-efficiency room ACs.

4.3.1 Australia

Australia holds key critical minerals reserves and is open to cooperating to diversify its supply chain and expand its processing and refining of critical minerals. Its abundant reserves include silicon, lithium, cobalt, and rare earths as well as copper, iron ore, and gold. Although Australia has historically exported much of what it mines, it increasingly recognizes the need to diversify its supply chain by investing in its processing and refining capabilities. Domestically, Australia adopted its Critical Minerals Strategy for 2023–2030, which expands policy support for processing and refining via tax incentives, R&D investment, and international partnerships. Within the India and Indo-Pacific region, Australia established the India-Australia Economic Cooperation and Trade Agreement (ECTA), which eliminated tariffs on critical minerals and launched the Indo-Pacific Economic Framework Critical Minerals Dialogue to strengthen the supply chain.

4.3.2 Japan

As a longtime leader in electronics manufacturing, Japan is also a global leader on air conditioning technologies and a key player in critical materials processing and semiconductor manufacturing. In particular, Japan holds 26% of the manufacturing market for power semiconductors, an important input for room ACs enabling efficient motor control and electrical power conversion. Japan also provides 35% of semiconductor manufacturing equipment and nearly half the world's supply of semiconductor materials (CSIS, 2023). Domestically, Mitsubishi Electric accounts for one-third of the Japanese market for manufacturing AC power modules and holds intellectual property rights for a new mounting technology and an intelligent power module (Mitsubishi Electric, 2025). Along with Daikin, the company is leading development of advanced power semiconductors using silicon carbide and gallium nitride to improve AC performance and efficiency. Within critical minerals and materials, Japan holds leading expertise and global market shares in the processing of critical materials for manufacturing batteries, electronics, and semiconductors. Specifically, Japan processes 3% of the world's cobalt, 6% of copper, 9% of nickel, 17% of beryllium, and 20% of selenium (Centre for Social and Economic Progress, 2024).

4.3.3 United States

The U.S. is a growing player and consumer in global semiconductors. Home to three of the five principal semiconductor equipment companies—Applied Materials, Lam Research, and KLA—the U.S. now has 8% of global semiconductor fabrication capacity. This share is expected to grow, as Taiwan's TSMC (responsible for 80-90% of advanced semiconductor manufacturing) recently invested USD $100 billion to expand its capacity in Arizona. This investment will support development of three new fabrication plants, two advanced packaging plants, and a major R&D center (Sacks and Segal, 2025). In addition, the U.S.-India TRUST Initiative, established in early 2025, gives India the opportunity to increase its production and export of legacy node chips, used both in HVAC equipment controls and semiconductor supply chains, in order to mitigate Chinese dominance.

5. Conclusion

The global room AC industry is at a critical juncture, characterized by explosive demand growth, concentrated supply chains, and mounting geopolitical tensions that threaten energy security and grid reliability in major markets. China's overwhelming dominance—accounting for 82% of global room AC production and controlling up to 90% of critical components like compressors—creates profound vulnerabilities for both the U.S. and India. With global room AC sales projected to increase more than five-fold by 2050, these supply chain risks will only intensify. According to our analysis, this increase could result in cumulative energy consumption exceeding 61,000 TWh and a global peak load of over 3,000 GW by 2050.

While India's AC market is shifting towards higher-efficiency models, including those with premium features, projected increases in AC ownership and usage will dramatically increase peak load and the risk of blackouts in the near future. India faces particularly acute challenges, with room AC peak demand potentially reaching up to 180 GW by 2030–2035 (vs. today's system peak of 240 GW), threatening grid stability and more frequent blackouts as early as 2026. Ambitious energy efficiency standards for room ACs can help mitigate this rise in peak power demand and concerns about grid reliability. At the same time, this expected market growth can improve manufacturing economies of scale in India by serving as a key demand driver for the country to bolster its domestic cooling supply chain.

This report identifies specific high-impact components where knowledge transfer and manufacturing scale-up are most urgently needed: variable-speed compressors (particularly inverter technology), advanced heat exchangers with specialized copper tubing, PCBs and semiconductor controllers, and systems compatible with low-GWP refrigerants. These components represent the highest-value segments of the supply chain and offer the greatest potential for reducing dependence on China.

Successful cooperation requires focused technology transfer in critical areas: inverter compressor manufacturing (addressing India's market share and growing demand), specialized heat exchanger production including grooved copper tube manufacturing, PCB and semiconductor controller fabrication (addressing India's 95% import dependency), and low-GWP refrigerant system integration. These technologies represent the highest-impact opportunities for reducing supply chain vulnerabilities while meeting India's massive cooling demand.

Leadership by the U.S. and India in addressing energy security and grid reliability can help alleviate emerging supply chain risks and vulnerabilities all Quad partners face by continuing to rely on China for both finished ACs and components. Manufacturing high-value room AC components (e.g., compressors, heat exchangers, PCB boards, and alternative refrigerants) faces significant knowledge gaps outside of China, requiring targeted technology transfer initiatives. The U.S. and India can lead on efficient AC manufacturing by focusing on their respective strengths and India's cooling demand. The U.S. may offer a particularly attractive locus for supply chain restructuring, driven by substantial regulatory incentives, growing investment in manufacturing, and capabilities in advanced materials science and precision engineering—which could particularly benefit next-generation refrigerant system and semiconductor manufacturing. India holds market advantages in cost-competitive manufacturing and exploding product demand, further strengthened by its recent production-linked incentive schemes for white goods that could facilitate establishing global supply chain hubs.

Building manufacturing ecosystems that can achieve economies of scale comparable to Chinese production while maintaining competitive pricing is of critical importance. This work includes developing supplier networks, establishing quality standards and testing facilities, and creating workforce training programs that support advanced manufacturing capabilities. India's ambitious energy efficiency standards trajectory can act as a demand driver for its domestic manufacturing investments.

The supply chain for critical minerals used in ACs is similarly geographically concentrated, with China controlling most of the world's mining and refining. China's recent export restrictions on key materials like terbium and dysprosium illustrate the problem of China dependence—namely, the potential for cascading supply disruptions and price volatility that impacts manufacturing dynamics worldwide. In response, the U.S. and India can work with Japan and Australia to leverage domestic reserves, expand processing and refining capacities, and support the onshoring of semiconductor manufacturing. Beyond diversification of sourcing, addressing supply chain risks can be further complemented by finding appropriate substitutes and enabling greater material recycling and circular economy approaches.

Transforming global room AC supply chains is fundamental to building supply chain resilience, energy and critical minerals security, and economic competitiveness in an era of growing cooling demand. U.S.-India collaboration can catalyze broader technology partnerships that address shared challenges while reducing supply chain dependence. Regulatory incentives, market demand, and geopolitical imperatives could create opportunities for the U.S. and India to lead the next generation of efficient cooling technologies while strengthening energy and materials security for themselves and their Quad partners.

The ultimate goal is to establish resilient, diversified supply chains that reduce global dependence on single-country production while advancing cooling efficiency to address a host of manufacturing, energy, and mineral security challenges. This also involves developing circular economy approaches for critical materials recovery, advanced research into substitute materials, and technology innovation partnerships that maintain global leadership on efficient cooling technologies.

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