SPACE COOLING: RECOVERY, REUSE, RECYCLING AND SUPPLY CHAIN IMPACTS

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Abstract

The global cooling sector has undergone tremendous growth in recent years, and cooling demand is projected to double or triple by 2050. Surging air conditioning demand will continue to be driven by increased populations, incomes and occurrences of extreme heat and humidity events. Cooling equipment growth has important pollution and material implications as they are made up of critical metals and precious raw materials - including ferrous metals, copper, aluminum and printed circuit boards composed of copper, silver, gold and palladium - that generate significant electronic waste at end-of-life. Air conditioning equipment also contains fluorinated gas (F-gas) refrigerants, which are potent gases that are thousands of times more heat-trapping than carbon dioxide (CO_2). While recovery, reuse, and recycling strategies have been assessed for cold chain and refrigeration, there is currently limited analysis on how these strategies could be adopted for the global space cooling industry and potential supply chain implications.

This paper aims to address this research gap by qualitatively evaluating product and material recovery, reuse and recycling frameworks from both demand and supply-side perspectives and with the support of cooling-specific case studies. It also focuses on quantitatively assessing potential energy, emissions and resource benefits of such strategies for space cooling equipment. This paper first analyzes how existing recovery, reuse and recycling frameworks can be applied to space cooling, with emphasis on the demand-side enablers (e.g., innovative business models, supporting policies and regulations) and changes in supply-side production network throughout the supply chain (e.g., design, production and distribution, end-of-life recovery) needed to overcome existing barriers. It will present case studies of innovative business models for space cooling technologies, including reuse and recycling, and how effective refrigerant reclamation and recovery programs have been operationalized. Lastly, the paper will highlight global modeling results of energy, emissions and material recovery from scenario analysis of selected strategies for air conditioners. The findings of this paper are intended to inform the development of product and material recovery, reuse and recycling strategies for a rapidly growing stock of space conditioning equipment by addressing existing organizational, economic and regulatory barriers and potential supply-chain bottlenecks.

Introduction and Motivation

The global space cooling sector has undergone tremendous growth in recent years, and cooling demand is projected to double or triple by 2050 (IEA, 2024a). This growth is driven by rising temperatures and humidity, increased urbanization, extreme heat and humidity events, and expanded access to cooling technologies in developing countries. Future cooling demand in Asia, for example, is expected to grow with rising household incomes, continued population growth in many countries, increasingly affordable air conditioning systems, and more frequent hot and humid weather conditions throughout the region (Karali et al., 2022; Shah et al., 2025). Space cooling equipment growth also has material implications as they are made up of critical metals, rare earth elements (REEs), and precious raw materials - including ferrous metals, copper, aluminum and printed circuit boards (PCBs) composed of copper, silver, gold and palladium - that generate significant waste at the equipment's end-of-life (EOL). Cooling equipment's end-of-life waste is responsible for 21% of global e-waste generated in 2022 (Khosla et al., 2022; Balde et al., 2024).

AC equipment that provides space cooling contains fluorinated gas (F-gas) refrigerants, which are potent greenhouse gases that are thousands of times more heat-trapping than carbon dioxide (CO_2). While F-gas banks (i.e., equipment and storage tanks filled with refrigerant) are declining following a global phaseout of F-gas refrigerants under the Montreal Protocol, the hydrofluorocarbon (HFC) bank is still growing. Velders et al. (2022) show that total HFC emissions (from leakage during normal operation and from end-of-life banks) continued to increase through 2019 to about 0.8 $GtCO_2e$ per year. Although the Montreal Protocol addresses the production and consumption of new equipment, it does not address refrigerants in existing equipment, highlighting that end-of-life TEE products will continue to emit HFCs for decades.

While recovery, reuse, and recycling strategies have been assessed for cold chain and refrigeration applications, there is currently limited analysis on their adoption in the wider space cooling industry and the associated supply chain implications (Palafox-Alcantar et al. 2022). This paper aims to address this research gap by qualitatively evaluating product and material recovery, reuse and recycling frameworks from both demand and supply-side perspectives, and incorporates cooling-specific case studies of demand-side enablers and supply chain challenges. The paper also presents an updated quantitative assessment of room AC e-waste generation, refrigerant emissions, and material recovery potential under a baseline scenario for future assessments of the potential material or emissions benefits.

Review of Related Work

Recovery, Reuse and Recycling Frameworks and Implementation Barriers

In existing literature, recovery, reuse and recycling frameworks for space cooling equipment have evolved from a broader sustainable cooling solutions framework in Khosla et al. 2020 to a theoretical circular economy framework that maps the different lifecycle stages of cooling products and interventions. This proposed circular framework links the end-of-life stage back to earlier stages of production and use through strategies including recycling, repurposing, remanufacturing, and reusing/repairing/refurbishing along with phasing-out of ozone-depleting and high-Global Warming Potential (GWP) refrigerants (Khosla et al. 2022). A more recent framework in Palafox-Alcantar et al. 2022 expands by integrating and differentiating the supply and demand aspects in terms of potential applications, phases and stakeholders. The supply perspective follows a Global Production Network (GPN) of leading cooling product manufacturers and service providers, spanning across the design, optimized production and distribution, use and end-of-life stages. In the design stage, products are designed to help facilitate reuse, maintenance and repair to extend the product lifetime and to enable proper waste management. For example, modularity in design can help optimize production and distribution networks, while proper maintenance and repair during the use and operational stage can extend product lifetimes. Once waste is generated, its remaining value is also captured, such as by considering waste as resources applicable for a secondary use. Refrigerants and trace components such as plastics, metals and rare earth found in circuit boards and other electronic components can be recovered for financial and environmental value.

From the demand perspective, different enablers are needed to support recovery, reuse and recycling interventions in the GPN that include policy, technology, business models and consumers. Socio-political and economic enablers directly influence the demand for cooling and help shape cooling equipment production, including through regulatory approaches, innovative business models, and technical tools. From national or subnational governmental perspective, regulatory frameworks that can help drive recovery and recycling strategies include extended producer responsibility (EPR) requirements, waste management or sustainability standards, and rebates or pay-as-you-throw policies. In the U.S., a New York state assembly bill is proposing to establish a state-wide EPR program for household appliances and refrigerants by the end of 2027. Technical enablers include digital platforms for buying and selling reused products and traceability systems for tracking a product’s origin, geographical path, and chain of custody to improve supply chain transparency and meet recycled content requirements (Michaels et al. 2025).

Extending from the theoretical frameworks for recovery, reuse and recycling to actual implementation of circular supply chain management that can facilitate greater recovery, reuse and recycling currently faces a multitude of challenges. To achieve the fundamental shifts needed, existing literature identified the top five barriers as regulatory and financial barriers, followed by other technological and market barriers. Regulatory barriers include a lack of supporting regulations to incentivize businesses to shift towards circular supply chain management and adopt new circular business models (Çıkmak, Sinan, and Buşra Kesici, 2023). For financial barriers, companies are concerned with the high investment costs needed for circular supply chain management processes and impact on market competitiveness with limited short-term financial benefits (Çıkmak, Sinan, and Buşra Kesici, 2023). Some firms are also limited by insufficient financial resources and perception of risky investments that requires longer time to reach the break-even point, particularly those that are founded based on a linear economy model (Ayati et al. 2022).

For repair and refurbishment, specific market barriers also exist. First, the recovery of cooling units for repair and refurbishment often presents additional costs, such as transportation and logistical costs from collection centers to repair and refurbishment sites, that affect manufacturers’ participation (Khosla et al. 2022). Second, the persistence of informal markets for resale, particularly in developing and transitional economies, hampers the inclusion of reuse and resale as an additional revenue stream for cooling manufacturers and limits the removal or repair of inefficient or unsafe units (Khosla et al. 2022). Unclear costs of refurbished cooling units, stemming from lack of market data and uncertainty about future sales prices, also undermine the refurbishment market.

Technological barriers are another important category of barriers for recovery, reuse and recycling. In the design stage, compatible technologies and processes to design recoverable cooling products and products with prolonged use life could be an important barrier. In the end-of-life stage, supporting technologies are needed to collect and track products and sort waste for recovery, and to assess the quality or control the condition of end-of-life products (Ayati et al. 2022). The lack of reliable information systems that can integrate and share data between entities and provide information on a product's life-cycle conditions is another key obstacle for circular supply chains.

Technical Approach and Discussions

To explore how these theoretical frameworks and barriers can be addressed in real-life applications, we assess the supply chain implications of AC refrigerant lifecycle management and examine innovative business models and case studies that support space cooling recovery, reuse and recycling. We include quantitative modeling of existing and projected baseline energy, emissions and material recovery impacts from growth in the global room AC sector and AC e-waste generation to highlight the potential for future reductions through recovery, reuse and recycling.

Supply Chain Implications: Refrigerant Lifecycle Management Example

A cooling supply chain segment that has made more progress towards circularity is in the lifecycle management of AC refrigerants, and particularly in end-of-life refrigerant management. Refrigerant leakages occur throughout the air conditioning equipment's life-cycle, particularly during the installation or operation due to improper installation practices or cracks formed over time from exposure to corrosive environmental conditions (Kumar et al. 2023). At the end-of-life, proper recovery of refrigerants from used equipment for further processing via recycling, reclamation or destruction is crucial to preventing refrigerant emissions from being released into the atmosphere. Once recovered, refrigerants may be recycled or reclaimed and used as an alternative to new (virgin) refrigerants, thereby supporting a circular approach to refrigerant management. For recovered refrigerants that may not be technically or cost-effectively feasible for recycling or reclamation, destruction using approved technologies such as cement kilns or plasma arc incinerators can help neutralize refrigerants and prevent unwanted or harmful emissions (Kumar et al. 2023).

To improve refrigerant recovery and address unfavorable economics of recovery for reclamation or recycling, jurisdictions have introduced rebates and other recovery programs to provide financial incentive and/or designated reverse supply chains to support refrigerant recovery. Australia and New Zealand have implemented a rebate programs for returned refrigerants, including Australia's industry-supported refrigerant takeback program and New Zealand's Cool-Safe program funded by carbon credits. Australia has achieved some of the highest national refrigerant recovery rates of 50-70% (Kumar et al. 2023). New York City charges manufacturers a $15/unit fee to fund a refrigerant recovery program operated by the city's Department of Sanitation, prior to sending air conditioner units to recycling (Kalanki et al. 2024). The European Union extends incentives to recycling and reclamation by providing exemptions of reclaimed refrigerant from F-gas quotas, and exemption of recycled gas from refrigerant taxes in Norway, Denmark and France (Kalanki et al. 2024).

Innovative Business Models and Applications for Recovery, Reuse and Recycling

Business models define how companies create, deliver and capture value, and is key to driving and facilitating circularity by bridging consumer demand and production networks (Woldeyes 2025). Taking both upstream and downstream businesses into consideration, recent literature has developed archetypes and categorizations of general business models for circular economy based on value creation, delivery and capture (see Figure 1).

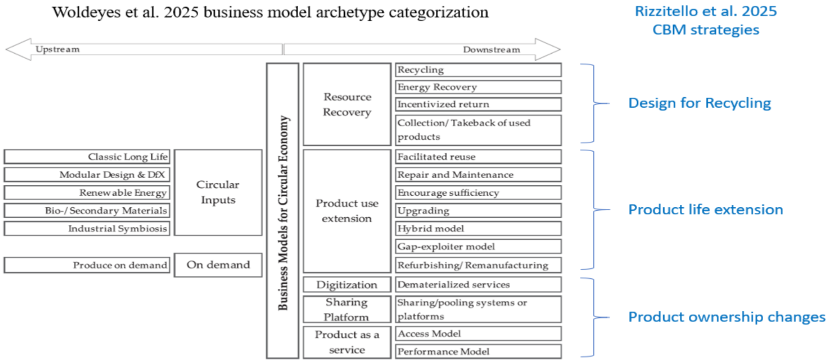

Figure 1. Circular economy business model archetypes: categorization mapping

Source: Figure based on Woldeyes et al. 2025 with authors' mapping from Rizzitello et al. 2025

The first category of circular business models is focused on product ownership changes and includes servitization and "product as a service," sharing/pooling systems or platforms, and decentralized service provision through digitalization. One specific example of servitization is the "cooling-as-a-service" business model, where commercial end-users such as data centers, retail and commercial spaces contract with a cooling-as-a-service provider to use cooling services by paying a fixed fee based on usage (NAB-CCM, 2025). One real-life CaaS example is Kaer Air's fixed pay-as-you-use rate for building customers that uses a modular design approach to add or remove AC units coupled with artificial intelligence and Internet-of-Things technology for optimized operations. Reported benefits of Kaer's CaaS service have included 20-70% reductions in cooling energy consumption and costs, and reduction in space requirements due to the equipment's flexible and modular designs (Ellen MacArthur Foundation, 2021).

The second category of circular business models focuses on extending the use and lifetime of existing product or equipment throughout different stages of a product's lifecycle to reduce waste and delay the need for new products. These business models extend from design considerations to repair and proper maintenance during operation to refurbishing and repurposing products at end-of-life. For the cooling sector, the Daikin Loop program in the European Union is one example of product life extension where Daikin recovers refrigerants from existing cooling units, reclaims the refrigerant and then uses the reclaimed refrigerant in new and certified Loop by Daikin units.

The third category of circular business models target the EOL stage for products by facilitating greater recycling and resource recovery with the goal of achieving a closed loop supply chain that minimizes waste, conserves resources and creates value. These include collection, take-back and incentivized return business models with designated processes to collect and handle returned items for repairs, refurbishment, or recycling. In the cooling sector, one specific example is the Danish HVAC pump manufacturer Grundfos's take-back program on pump circulators operating in seven EU countries. The program's success has included reported reductions in landfill waste by 32% from the baseline year with 64 tons of pump circulators collected (Itanola et al. 2025).

Modeling Approach

To quantify the existing and projected baseline waste, emissions and material impacts of growth in the global room AC sector, we developed a modeling framework to estimate global room AC e-waste generation with regional details. This modeling framework is based on an extended and updated version of the room AC stock turnover model previously developed by the authors (Karali et al. 2020 and Phadke et al. 2020) that also assesses the EOL refrigerant banks and leakage, annual atmospheric accumulation of refrigerant, and the valuable materials embedded in the e-waste (see Figure 2). The modeling approach used in this analysis to calculate refrigerant banks and materials from room AC e-waste is similar to those used in existing literature for EOL television sets, end-use devices, and refrigerators, but none of the earlier analyses track the refrigerant banks and leakage from TEE e-waste.

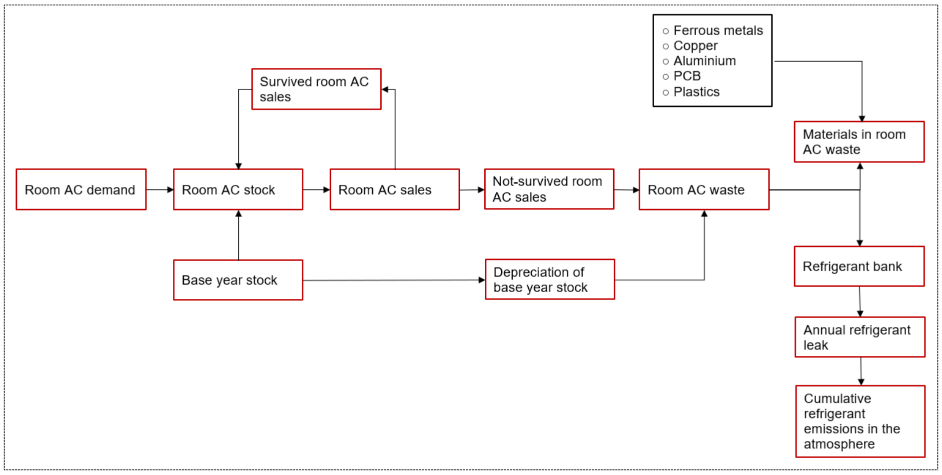

Figure 2. Room AC e-waste modeling framework

The stock turnover model first estimates new AC sales based on annual AC demand and scrappage of existing and new stock. Annual room AC stock in year t, St_t, is assumed to be equal to annual room AC demand, D_t. In this study, annual regional room AC demand growth is calibrated against IEA (2025) projections.

$$D_t = St_t \text{ (Eq. 1)}$$

Annual room AC stock is the sum of new sales in year t, S_t, and prior-year sales of units that are still in service. Room AC-specific survival rates are calculated through a logistic function as follows:

$$St_t = S_t + \sum_{u=1}^{t-1} S_u * survival_{t,u} + basestock_t \text{ (Eq. 2)}$$

$$survival_t = 1 - 1/(1 + e^{-\beta(t_{age} - t_0)}) \text{ (Eq. 3)}$$

where $basestock_t$ is the discounted stock in year t from the base year, t_0 is the median lifetime of the AC, t_{age} is the age in year t, and β is a growth parameter that determines how fast the ACs are retired around t_0.

Annual room AC e-waste generated, W_t, is the scrapped stock in year t and calculated as follows:

$$W_t = \sum_{u=1}^{t} S_u * (survival_{t-1,u} - survival_{t,u}) + (basestock_{t-1} - basestock_t) \text{ (Eq. 4)}$$

The model uses manufacturing-specific parameters such as average product weight and material content to calculate the end-of-life material composition and volume.

$$Ww_t = W_t * m \quad \text{(Eq. 5)}$$
$$M_{i,t} = Ww_t * \alpha_i \text{ (Eq. 6)}$$

where Ww_t is the total weight of room AC e-waste in year t, m is the average weight of room ACs on the market, $M_{i,t}$ is the total weight of material i discarded in e-waste at year t, and α_i is the share of material i in a room AC in terms of weight. In the absence of sufficient data, we assume that average product weight and material composition of room AC products remain constant over time.

The model also calculates the annual total end-of-life refrigerant banks in year t, Rb_t, as a function of the equipment scrapped in year t.

$$Rb_{t,r} = \sum_{u=1}^{t} S_u * (survival_{t-1,u} - survival_{t,u}) * charge_r * (1 - leak_r)^{t-u} * GWP_r + (basestock_{t-1} - basestock_t) * charge_r * (1 - leak_r)^{average\ lifetime} * GWP_r \text{ (Eq. 7)}$$

$$Rb_t = \sum_r Rb_{t,r} \text{ (Eq. 8)}$$

where $charge_r$, $leak_r$, and GWP_r are the charge amount of refrigerant, r, in a room AC, the annual average leakage rate from room ACs in use, and the GWP potential of the refrigerant charged into the equipment, respectively. Refrigerant leakage in a year, Rl_t, and refrigerant accumulated in the atmosphere in a year, Ra_t, are calculated as follows.

$$Rl_t = \sum_r Rb_{t,r} - Rb_{t-1,r} \quad \text{(Eq. 9)}$$

$$Ra_t = Rl_t + \sum_{u=1}^{t+lifetime_r} Rl_u * (1 - EOLleak_r)^{t-u} \text{ (Eq. 10)}$$

$EOLleak_r$ is the average leakage rate from end-of-life e-waste.

Our analysis estimates the existing and projected baseline waste, refrigerant emissions, and material impacts of growth in the global room air conditioning sector under a Business-as-Usual (BAU) scenario. This BAU scenario establishes a baseline to quantify the maximum potential for material and refrigerant recovery that circular economy interventions could capture, rather than representing a likely future trajectory. Table 1 presents the main BAU assumptions.

Table 1. Main assumptions used in the BAU scenario analysis for room ACs

Parameters	Model Value	Source
Demand growth	Annual regional room AC demand growth calibrated against IEA (2025) projections to account for population growth, rising household incomes, urbanization rates, and climate factors across regions.	IEA (2025)
Average lifetime	8 years for all regions	Karali et al (2020)
Median lifetime (t_0)	5 years for all regions included analysis, except 6.5 years for India; 11 years for Europe; 8 years for Brazil.	Karali et al (2020); Phadke et al. (2020)

Refrigerant trends	Based on 2023 market data, 23% of room ACs use HFC-410A, 73% use HFC-32, and the remainder use low-GWP alternatives such as HC-290	BSRIA country reports, (2025)
Beta parameter (β)	0.85 for all regions included analysis, except 0.7 for Europe	Karali et al (2020) ; Phadke et al. (2020)
Average weight of room ACs (m)	49 kg for all regions, constant through 2050 as conservative assumption not considering lightweighting or substitution trends	Heubes (2017)
Collection and recovery rates	Current global collection rate of 22.3% for EOL room ACs through 2050; 20% of collected units are processed for recovery of refrigerant and base metals	Balde et al (2024); Project Drawdown (2014)
Average annual refrigerant leakage during use ($leak_r$)	2% for all regions and refrigerants included in analysis	CARB (2017)
Refrigerant charge ($charge_r$)	1 kg for both HCFC-22 and HFC-R410A; 0.75 kg for HFC-32; average 1 kg for other low-GWP refrigerants considered	Heubes (2017) for HCFC-22, HFC-410A; Pramudantoro et al. (2018) for HFC-32; and assumed same as HFC-410A for other low-GWP refrigerants
Refrigerant lifetime ($lifetime_r$)	11.9 years for HCFC-22; 30 years for HFC-R410A; 5.4 years for HFC-32; average 5.4 years for other low-GWP refrigerants considered	IPCC (2022); and assumed same as HFC-32 for other low-GWP refrigerants

Note: This study assumes that there will be no refilling of room ACs during the use phase since the equipment lifetime is a defined parameter of the model. For this analysis, results are presented under different leakage rates to capture the impact of various leak patterns and to investigate the uncertainty bounds. The 2% leakage rate assumes refrigerant will leak at the same rate as 'during use'. The leakage rate of 100% per year aims to simulate the case with a full release of the refrigerant to the atmosphere. The other leakage rates, i.e., 10% and 50%, are used to represent any trend in between.

Modeling Results

Figure 3a compares room AC e-waste to total e-waste for the calibration years (2016, 2019, and 2022) and presents global e-waste projections for the period 2025–2050. Our modeling shows that 6.3 million metric tons (Mt) of annual room AC e-waste in 2023 increases more than four-fold by 2050. Globally, room AC e-waste generated annually is about 70–82.5% of new sales. This rate suggests a secondary material supply from room ACs and material demand for room AC production could increase proportionally with a proper collection and recycling infrastructure and a well-functioning secondary raw material market. More than half of the annual e-waste came from China in 2022, followed by rest of Asia (excluding India)(Figure 3c, left). But India significantly increases its share of total room AC e-waste generation by 2050, following the pace of demand growth in the region (Figure 3b, right). By 2050, China and India together generate over 60% of the total global e-waste, and the rest of Asia generates another 15%. Historically, these regions include significant informal sector operations (Figure 3c, right).

Figure 4 shows the rapid growth of room AC e-waste materials discarded that could be recovered and used as secondary raw materials with proper collection and recycling infrastructure under a baseline or Business-as-Usual (BAU) scenario. By 2050, recoverable material includes 11.3 Mt of ferrous metals, 4.3 Mt of copper, and 2.3 Mt aluminum. Similarly, the potential value of PCB materials is 3.5 times higher in 2040 and 6.3 times higher in 2050 compared to the 2022 value, totaling more than US$8 billion by 2050 based on the current per unit value of gold, silver, palladium, nickel and copper.

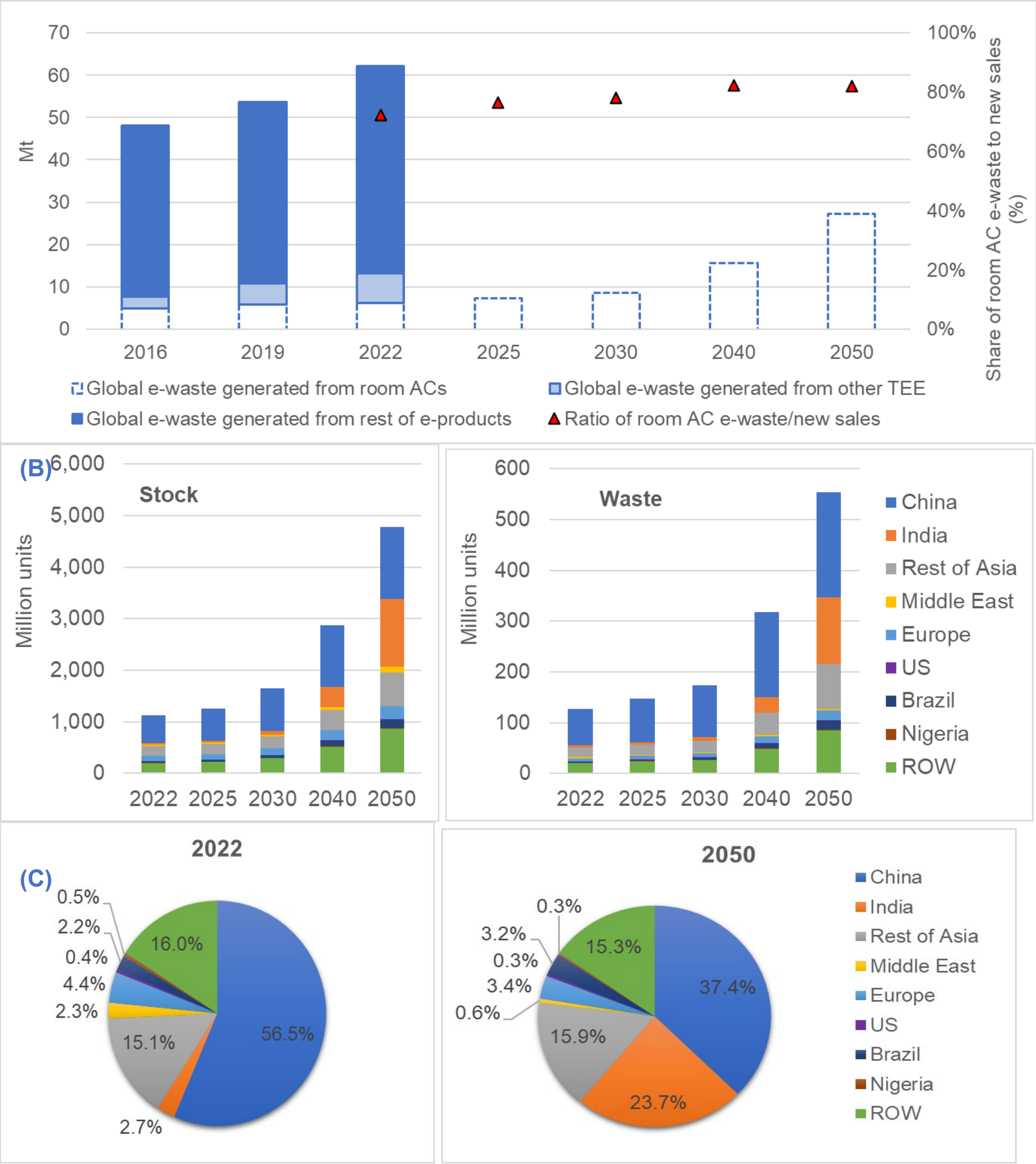

Figure 3. Room AC e-waste projections (A) global e-waste between 2015 and 2050. (B) Regional distribution of stock and e-waste, 2022-2050. (C) Regional share of room AC e-waste, 2022-2050. Source: Balde et al. (2024) for total e-waste generation between 2015 and 2022. BSRIA country reports (2025) for stock at 2022. ROW: Rest of the World

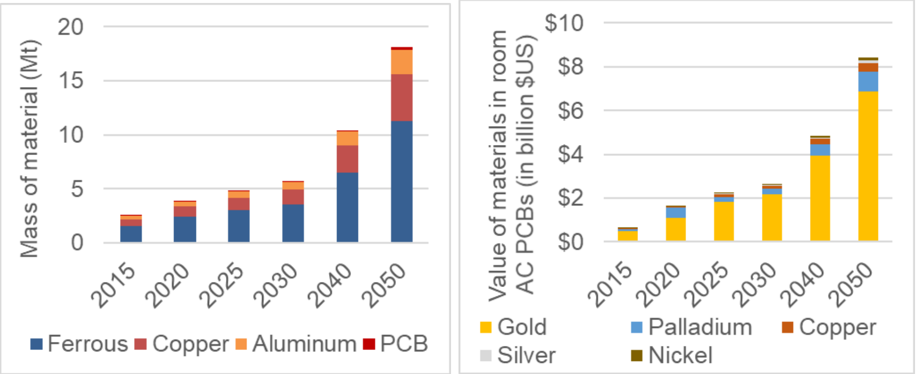

Figure 4. Mass of materials discarded with room AC e-waste and potential value of materials in PCBs in BAU scenario

The total refrigerant banks change significantly under different annual leakage rates (i.e., 2%, 10%, 50%, and 100% per year) as shown in Figure 5. The results suggest that room AC refrigerant banks from e-waste could increase to 7.1 GtCO$_2$e by 2050 under a 2% per year leakage rate. The refrigerant bank volumes decline to 1.0 GtCO$_2$e in the same year if the leakage rate is 10%. Total cumulative emissions from refrigerant leakage could reach about 4.5-16.3 GtCO$_2$e by 2050 (from 2015 onward) depending on the leakage rate. This result shows that emissions from the e-waste continue to grow even when the equipment is no longer in use and HFC consumption is significantly phased down following the Kigali Amendment schedule.

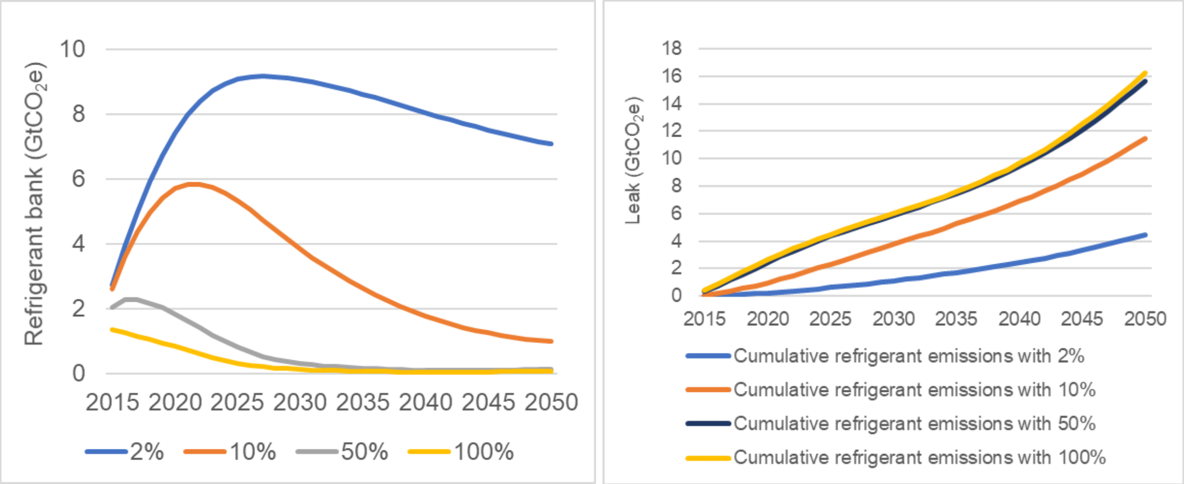

Figure 5. Global room AC refrigerant banks with different annual end-of-life leakage rates in the BAU scenario

Conclusions

As cooling demand continues to surge, recovery, reuse and recycling approaches are emerging as promising strategies for tackling the related environmental challenges of material waste and refrigerant emissions while capturing strategic value through improved supply chain and energy security and industrial competitiveness. Recent literature on circular cooling frameworks have coalesced around a supply-side perspective focused on circular actions that cooling product manufacturers, service providers, and other non-economic stakeholders can take throughout the product life-cycle stages of changing design principles (i.e. modularity), optimized production and distribution, extended use through repair and maintenance, and proper end-of-life management. However, the transformation of a linear to circular supply chain management faces many obstacles and barriers, including primarily regulatory and financial barriers but also technological barriers.

In refrigerant management specifically, progress has been made toward adopting circular lifecycle approaches for AC refrigerants, including proper refrigerant servicing and recovery during use, and recycling, reclamation, or destruction at end-of-life. Region-specific initiatives have been established to incentivize recovery, recycling, and reclamation, alongside innovative business models for servitization, product life extension, resource recovery, and design for recycability.

Our baseline modeling of room AC stock and e-waste generation reveals that annual room AC e-waste will increase more than four-fold from 6.3 Mt in 2023 to over 25 Mt by 2050, with three-quarters concentrated in China, India and the rest of Asia. With proper collection and recycling infrastructure—even maintaining only current global collection and recovery rates—up to 11.3 Mt of ferrous metals, 4.3 Mt of copper, 2.3 Mt of aluminum, and US$8 billion worth of printed circuit board materials could be recovered by 2050. While increasing recovery, reuse and recycling rates could increase the strategic value of room AC e-waste, additional research and modeling are needed to assess the full potential impact of different circularity strategies on reducing emissions and waste.

The paper's findings are intended to inform the development of product and material recovery, reuse and recycling strategies for a rapidly growing stock of end-of-life space conditioning equipment by addressing existing organizational, economic and regulatory barriers and potential supply-chain bottlenecks such as limited workforce development. Our results quantifying energy consumption, emissions, and material recovery potential help highlight the scale and urgency for coordinated public-private actions needed to increase recovery, reuse and recycling while improving and securing supply chains for the cooling sector.

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