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A Chilling Prospect: Climate change effects of mismanaged refrigerants in China

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Potential Climate Impact from Obsolete RAC in China
Abstract:
The global community has responded to the dual threats of ozone depletion and climate change from refrigerant emissions (e.g., chlorofluorocarbons, CFCs, and hydrofluorocarbons, HFCs) in refrigerators and air conditioners (RACs) by agreeing to phase out the production of the most damaging chemicals and replacing them with substitutes. Since these refrigerants are ‘banked’ in products during their service life, they will continue to impact our environment for decades to come if they are released due to mismanagement at the end of life. Addressing such long-term impacts of refrigerants requires a dynamic understanding of the RACs’ life cycle, which was largely overlooked in previous studies. Based on field surveys and a dynamic model, we reveal the lingering ozone depletion potential (ODP) and significant global warming potential (GWP) of scrap refrigerants in China, the world’s largest producer (62%) and consumer (46%) of RACs in 2015, which comes almost entirely from air conditioners rather than refrigerators. If the use and waste management of RACs continue with the current trend, the total GWP of scrap refrigerants in China will peak by 2025 at a level of 135.2 ±18.9 Mt CO\textsubscript{2}e (equal to approximately 1.2%±0.2% of China’s total greenhouse gas emissions or the national total of either the Netherlands and Czech Republic in 2015). Our results imply an urgent need for improving the recycling and waste management of RACs in China.

Key words: climate change | sustainability | refrigerants | e-waste | industrial ecology

Introduction
Chlorofluorocarbons (CFCs) were synthesized as refrigerants in the 1920s for use in refrigerators and air conditioners (RACs). It was not until 1974 that the negative impact of fugitive CFC emissions on the Earth’s protective ozone layer was identified \(^{(1)}\). Many
alternative refrigerants, such as hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), were determined to be powerful agents in climate change, often hundreds to thousands of times the power of CO$_2$\(^{(2)}\). The global community has responded to the dual threats of ozone depletion and climate change from refrigerant emissions by agreeing to phase out the production of the most damaging chemicals and replace them with substitutes. However, a massive challenge remains because the older classes of refrigerants are still contained in RACs reaching their end of life (EoL). If these obsolete products are not properly managed, the harmful gasses will continue to be released into the atmosphere\(^{(3)}\).

Despite extensive studies on the consumption and environmental impact of ozone depleting substances (ODS) and their substitutes\(^{3-7}\), relatively few have examined these chemicals in devices reaching the EoL or put forward measures for control and impacts reduction. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories\(^{(8)}\) includes guidance on estimating emissions of fluorinated substitutes for ozone depleting substances; reporting requirements for non-Annex 1 countries including China are limited, and China’s reporting to the United Nations Framework Convention on Climate Change (UNFCCC) are solely aggregate production-based impacts. In Japan, Nakano et al. (2007)\(^{9}\) adopted the material flow analysis (MFA) approach to evaluate the global warming potential (GWP) reduction as a result of implementing the household appliance recycling. In our previous work (Zhao et al., 2011\(^{7}\)), the amount of residual ODS refrigerants from refrigerators in China was investigated, however the GWP and ODP impacts were not analyzed. Similarly, Xue et al. (2017a and 2017b)\(^{4-5}\) examined the GWP impact of the household refrigerator sector in Japan over
decades via a stock model. In addition, some studies were undertaken to evaluate the characterization of ODS refrigerants released from the recycling (e.g. dismantling and shredding) of RAC (cited and summarized Table S11). These emission factors have been taken as the key parameters to quantify refrigerant flows during EoL stages. The approach to select the appropriate methods to quantify the generation of obsolete RAC and their impacts is discussed in the Method section.

As the world’s largest producer (62% in 2015) and consumer (46% in 2015) of RACs, China generated 2.6 Kt of waste CFCs in 2005, which accounted for half of its total waste refrigerants. Addressing this, China signed the Vienna Convention for the Protection of the Ozone Layer in 1989, signed the Montreal Protocol on Substances that Deplete the Ozone Layer (Protocol) in 1991, and incorporated a strategy into a 1993 National Action Plan (updated in 1999). Remarkably, the Protocol was universally ratified by all 197 UN parties as of 2009. It was most recently amended in Kigali in 2016 to phase out HFCs beginning in 2019; the reduced use of these potent greenhouse gases (GHGs) is expected to avoid over 80 billion tonnes of CO$_2$e through 2050.

According to the Kyoto Protocol and the UNFCCC, a few countries and regions have already introduced laws to restrict the use of HFCs since 2005, including China. China’s efforts here have proven to be effective at reducing the domestic consumption (see Figure 1c) and subsequent release of ODS from RACs in China, especially of CFCs in refrigerators which was down to about 0.6 Kt of waste in 2015 (see Figure 1d).

Despite the progress in phasing out classes of refrigerants in production, there could be lingering ozone depletion potential (ODP) and significant global warming potential (GWP)
from mismanaged scrap refrigerants in China. Here we use field surveys and a dynamic Sales Obsolescence Model (SOM) (see details in the Method) to project that possibility.

Methods

The Sales Obsolescence Model. We employed a dynamic Sales Obsolescence Model (SOM) to quantify the waste RACs and their refrigerants generation and flows. The SOM built upon official government statistics and a set of surveys targeting the behavior of RAC consumers, collectors and recyclers from 2015 to 2016. Additional calculations are conducted between 2005 and 2035 in order to observe trends and to conduct the scenario analysis.

The calculation steps are as follows: (1) Determining the sales data (units) of RACs over a given time period; (2) Estimating the mass of initial refrigerants and their substitutes per RAC appliance, with a consideration of the diversity of blowing agents and compressor refrigerants, and accounting for leakage during use; (3) Modeling the lifespan of each type of RAC; (4) Estimating and predicting the total quantity of waste refrigerants generated in the given period; (5) Characterizing the GWP and ODP impacts derived from released refrigerants; (6) Further calculating the aggregated or individual GWP and ODP impacts at various end-of-life stages, with allocations to informal and formal e-waste recycling sectors. Various scenarios were developed to evaluate the ODP and GWP reduction potentials.

Field survey and data collection. (1) Sales data. Sales related data are retrieved from various official statistics from the Chinese government (listed in Table S1 in section 2.4 by Supporting Information). These include the production, export and import, sales by size, use...
of refrigerants and their substitution rate (by fractions). (2) **End-of-Life stage data.** We conducted a survey (n=1200) to analyze lifespan distribution of RACs and explore the household generation (Figure S5 and S6). In addition, we conducted field investigations on informal recyclers at home appliance repair shops (n=50) who collected scrap RACs from peddlers and consumers, to understand the treatment of RACs and their refrigerants in the informal sector (Figure S9 and Table S13). Licensed recyclers (n=7) in six provinces were investigated to characterize the collected amount of RACs, the treatment of RACs, and their refrigerants by formal recyclers. For validation, we also recorded the actual lifespans and refrigerant type of RACs (n=300) which were ready for processing at the formal recyclers (Table S4-6). The collection rate of waste RACs by formal sectors were determined from official statistics (Table S12). (3) **Refrigerant impact.** Other key parameters, including the residual rates of different refrigerants in scrap RACs and the GWP and ODP factors are drawn from literature.

**Model uncertainty.** Monte Carlo (MC) simulation was performed to capture uncertainty in each dataset at each calculation stage; MC simulations create results with a randomly drawn combination of values following reasonable probability distributions for each variable. The SOM results embed variability assigned to lifespan distribution parameters, reuse pathway likelihoods, future sales, and collection rates in the MC simulations. Variables pertaining to refrigerants include the fraction of each substitute used in production, mass per appliance of a given size, leakage rate in use, release rate in each recycling activity (Table S1-3 shows all
parameters). We reduce the model uncertainties and enhance the robustness of our results by using disaggregated data such as sales and refrigerants content according to various factors such as size, manufacturing year, manufacturer, and surveys distinguishing rural and urban consumers.

The system definition, model details, and data sources are all elaborated in Supplementary Information.

Results and Discussion

Quantifying the threat. Nearly all of the future climate change (89% in 2015 and 99% in 2020) impact is derived from scrap air conditioners (ACs); refrigerators played a larger role in the past (see Figure 1e and 1f). The use of transitional HCFCs, which are less ozone depleting than CFCs but have high GWP factors (see Table S10), has peaked in recent years in RACs (see Figure 1b and 1c). annual sales of RACs in China will continue to grow slightly in coming decades (see Figure 1a and 1b, from 4.1% in 2016 to 1.1% in 2025), the consumption of refrigerants will drop from a peak of over 100 thousand metric tons (Kt) per year at about year 2017 to about 10 Kt per year in 2035. This is because that newly developed and modern non-halogen refrigerants such as Hydrocarbons (HCs, including isobutane -R600a and propane-R290) will be increasingly substituted and are much less dense. They are considered a greener alternative to the fluorocarbons due to lower ODP and GWP factors. The peak of RAC waste generation will come in the next 5 to 10 years (see Figure 1d) (18). RACs normally have a long life span (e.g., 8-15 years) and the refrigerants are ‘banked’ inside (see Table S7). As a result, China might not end ODS releases from scrap RACs until
approximately 2035 due to banked HCFCs. HFCs, which have no ozone impact but
significant GWP, have had a drastic increase in use in the RACs sector as HCFCs declined.
Without an aggressive EoL management strategy, we forecast that the GHG emissions derived
from RACs will peak by 2025 at 135.2 ±18.9 Mt CO$_2$e. This is approximately equivalent to
approximately 1.2% (±2%) of China’s total GHG emissions in 2012, or the national total
GHG emissions of many other countries in the world, e.g., the Netherlands and Czech
Republic in 2015 (see Figure S18).
Figure 1 Sales of RACs and refrigerants consumption in RACs, and their ODP and GWP (without consideration of recycling for reuse or direct destruction) in China (average values), 2005-2035.
Current mismanagement of refrigerants. Much of these refrigerant emissions can be avoided through proper management systems at the end of life EoL. Our field investigations of informal and formal recyclers’ aid in characterizing the current EoL processes and pathways for scrap RACs in China. The informal recycling sector refers to recycling facilities where EoL equipment is manually dismantled by unskilled and ill-equipped labor, for example in Figure 2 (See Figure S9 and S10 as well). Refrigerant gasses are colorless and odorless; these workers likely perceive no harm by releasing them to the atmosphere. By contrast, the formal recycling sector refers to licensed recyclers where EoL equipment is centrally managed (see detailed descriptions in SI Section 1.1).

While it is feasible to properly recover compressor refrigerant from RACs with basic machinery, there are significant challenges for the cost-effective separation and collection of blowing agent refrigerants from polyurethane (PUR) foam in refrigerators. The metal fractions are recycled through shredding of the units. Similarly, the scrap foam is subsequently cut into small pieces that may be recycled, incinerated, or landfilled in a majority of cases. Both shredding process and landfill of PUR foam waste will release refrigerants (elaborated in SI Section 1.1).

Our results show that the potential climate change impact of China’s scrap refrigerants from RACs in 2015 was approximately 48.3 ±15.5 Mt CO$_2$e, and less than 4% of that was avoided through proper management (Figure 2). The climate change impacts are mainly derived from
the informal recycling activities (approximately 95%), with improper dismantling of compressors accounting for over 70%. Surprisingly, we found that formal recyclers rarely control the release of compressor gasses and refrigerator foam blowing agents. Therefore, a key to mitigate the potential climate impacts of RACs will be to enhance the capacity of recyclers to properly capture these gasses with technology and training.

![Diagram showing emissions along reverse supply chain](image)

**Figure 2** GWP impact (baseline, average values) derived from releasing refrigerants from obsolete RACs at various end-of-life stages, 2015. Refrigerants leakage during use and storage, approximately 18.9 Mt in 2015, are not considered in our scope.
RACs have largely been overlooked since toxicity was the main focus of previous efforts to tackle the e-waste issue in China\(^{(19)}\). Since 2009, the Chinese government has continuously promulgated a series of regulations and standards on the management of e-waste and a preliminary system based on extended producer responsibility (EPR) principles was established. Producers and importers of electric and electronic products are required to contribute to subsidizing the operation cost of formal licensed recyclers\(^{(19)}\) (Figure S23). A few types of e-waste, including RACs, have been given priority as a special waste stream for recycling and ultimate disposal in order to prevent adverse environmental impacts (e.g., toxicity and ODP) in China. Since then, a growing proportion of e-waste has been collected and treated by formal recyclers in China (Table S12). The current formal recycling rate of refrigerators is still low, but has grown from 1% in 2009 to 17% in 2015. By contrast, the current formal recycling rate of ACs is still less than 1%. Considering that ACs and the informal recycling create the vast majority of the growing climate change impacts, this is a clear area to target for rapid improvement.

**Proposed formal-informal sector collaboration.** The existing formal scrap RAC management system should be expanded in some form to include existing informal sectors in a bid to reduce improper recycling activities and consequently improve the recovery rate of refrigerants\(^{(20,21)}\). For a new system to succeed, the informal workers whose livelihoods are dependent on these RACs should be included as stakeholders in a participatory planning process. One option could be to aggressively incentivize the flow of obsolete RACs directly toward the formal sector. There is growing evidence that the percentage of formal sector on
e-waste collection is comparable to the informal sector if sufficient subsidies are in place, such as scrap TVs and PC (see Table S12)\(^{(19)}\). Existing subsidy levels appear to be inadequate as evidenced by the very low formal RAC recycling rates (illustrated in Figure S23 to S25).

A compromise could be for formal recycling businesses to connect closely with the current informal e-waste recycling routes in order to avoid competition in acquiring obsolete RACs. Perhaps the formal sector would be subsidized to pay a higher price for an intact compressor than the scrap metal market would for a dismantled compressor, allowing the informal workers to profit from minimal dismantling. The sectors’ collaboration to manage the refrigerants contained in the devices would thus mimic a Best-of-2-Worlds style approach\(^{(22)}\).

In recent years, the world’s most infamous e-waste dump sites, including Guiyu and Taizhou in China, Kolkata in India, and Agbogbloshie in Ghana\(^{(23-26)}\), have attracted global attention from the media and public on their environmental and health impacts, which consequently led to mitigation actions\(^{(27)}\). The southeastern town of Guiyu, nestled in China’s main manufacturing zone, for example, was once the largest hub for e-waste disposal on earth, with 5,000 or more informal e-waste workshops and dismantling facilities\(^{(23,28)}\). Since 2014, the local government has established an industrial park that concentrates on e-waste processing facilities to reduce their potential environmental and health impacts by using cleaner solutions and equipment\(^{(21)}\). Such ‘Guiyu model’ could offer a useful precedent for RAC refrigerant management developing countries.
Emission pathways against national targets. To evaluate the GWP reduction potentials in future, we have developed several scenarios for the projection of GWP impacts of obsolete RACs over the next two decades from 2016–2035 (Table 1).

Table 1 ODP and GWP reduction opportunity (scenarios setting)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Formal Recycling Rate of EoL RACs</th>
<th>Targeted year</th>
<th>Release Rate of Compressor Refrigerant</th>
<th>Release Rate of Blowing agent</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 (Business as usual)</td>
<td>17.36% (Rft) 0.67% (AC)</td>
<td>N/A</td>
<td>100% (Informal) 95% (Formal)</td>
<td>100% (Informal) 100% (Formal)</td>
</tr>
<tr>
<td>S2</td>
<td>85% (Rft) 85% (AC)</td>
<td>2035</td>
<td>100% (Informal) 10% (Formal)</td>
<td>100% (Informal) 10% (Formal)</td>
</tr>
<tr>
<td>S2a</td>
<td>17.36% (Rft) 85% (AC)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>85% (Rft) 85% (AC)</td>
<td>2025</td>
<td>100% (Informal) 10% (Formal)</td>
<td>100% (Informal) 10% (Formal)</td>
</tr>
<tr>
<td>S3a</td>
<td>17.36% (Rft) 85% (AC)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Scenario 1 is business-as-usual (BAU) with 2015 as a baseline, Scenario 2 increases the formal recycling rate linearly to 85% by 2035, which aligns well with the EU recycling target in the WEEE-Directive 2012/19/EU, while scenario 3 achieves the same goal (to 85%) by 2025. In Scenarios 2 and 3, the release rate of compressor refrigerant and foam blowing agent drops to 10%; the other 90% were assumed to be well managed, and any destruction impacts were neglected (detailed explanation in SI section 4). The baseline results of this analysis indicate the future dominance of environmental impacts from ACs relative to refrigerators. Therefore, scenarios 2a and 3a consider implementation of a policy where the proper recycling of ACs is prioritized while refrigerators’ formal recycling rates remain unchanged. In the case of a limited budget to support RAC recycling, this reflects allocating...
the bulk of the budget to ACs (see Figures S23-S24). Figure 3 shows that within two
decades, Scenarios 2 and 3 could achieve a cumulative reduction of 650 and 1,010 Mt of
CO$_2$e, respectively, compared to BAU.

![Graphs showing ODP, GWP, and carbon intensity reduction](image)

*Figure 3 Reduction potentials of ODP (a), GWP (b), and carbon intensity (c) in the three
scenarios (S1-S3).* Scatter plots of S2a and S3a are partially overlapped with S2 and S3
(respectively) due to the close values, suggesting refrigerators are insignificant. Figure 3c
illustrates carbon intensity (metric ton CO$_2$e per unit of GDP) reduction in three scenarios
against the national targets. Triangles show carbon intensity reductions compared to 2015
levels; China’s 13th Five-Year Plan target (18% below the 2015 level by 2020) is solid grey.
Circles show carbon intensity reductions compared to 2005 levels; China’s Intended
Nationally Determined Contributions (INDC) targets (up to 40%, 50%, and 60% by 2020,
2025, and 2030 respectively) are solid grey.

*Note: The ‘overlap’ between S2 (Orange) and S2a (Purple) plots is due similar modeling results.*
As the largest emitter of GHGs in the world, China is under mounting pressure surrounding climate change mitigation. China has already pledged to reduce its carbon intensity — the CO$_2$e per unit of gross domestic product (GDP) — by 60-65% by 2030 compared to 2005 levels (Figure 3c). This is defined in China’s Intended Nationally Determined Contribution (INDC) submitted to the United Nations Framework Convention on Climate Change (UNFCCC) (29). Meanwhile, China has made its own short-term commitment to reduce its energy and carbon intensity by 15% and 18% by 2016 and 2020 compared to 2015 level, respectively, within its 13$^{th}$ Five-Year Plan (30) (Figure 3c).

We have consequently evaluated if the proposed scenarios for the RACs sector can contribute proportionally to, or aligns well with, these national goals. The results (Figure 3c) show that, by 2020, the 13$^{th}$ Five-Year Plan target could not be met in any of these scenarios. However, both Scenarios 2 and 3 could meet the INDC goals by 2025 and 2030. This is because the GHG emissions peak earlier by around 2025, and then decrease to a low level by 2030. In other words, the long-term goal could be achieved by the RACs sector if the national target is equally distributed across all sectors. On the contrary, it is difficult to meet the upcoming short-term mitigation task if the formal recycling rate grows gradually. This implies that great efforts should be made to promote the environmentally sound recycling of EoL RACs, as well as enhancing the refrigerant release control. This short window of opportunity calls for urgent action.

**Policy recommendations.** In order to address the challenges of obsolete RACs management
and associated impacts, the following urgent actions are recommended.

- **Prioritize ACs over refrigerators.** Our results show that the GWP impacts are almost entirely derived from scrap ACs (89% in 2015 and 99% in 2020, on average), which currently have an abysmal formal recycling rate (approximately 1% in 2015). Our scenario estimates demonstrated similar performance if the AC recycling rate grows regardless if the refrigerator rate does the same. While refrigerators deserved priority in the past, going forward ACs certainly deserve focus, in case of a limited budget to subsidize and support RACs management. In order to formally collect ACs, there will have to be a higher subsidy than currently exists; funds currently allocated to refrigerator collection should be shifted to ACs.

- **Promote sound formal recycling of EoL RACs in collaboration with the informal sector: from collision to collaboration.** The allocation of responsibilities for proper management between formal and informal sectors will be a key aspect to ensure the economic and logistical viability of the overall management system. The specific structure of system should be designed with the active participation of all stakeholders. Since neither the current formal or informal recycling processes effectively capture fugitive refrigerant gasses, investments should be made in capacity building. Overall, regulations (or financial incentive policies) must be inclusive, building on existing realities.

- **Classify the refrigerants as hazardous waste.** China needs to classify the ODS and the refrigerants with high GWP factors as hazardous waste (HW), including CFCs, HCFCs, HFCs, and refrigerants-containing PUR foam. Low GWP alternatives such as
R290, R600a and cyclopentane could be exempted from the HW list. Following the adage “you can’t manage what you don’t measure”, enforceable rules, the cornerstone for HW management, can enable the tracking of refrigerant flows. These rules include records retention for the generation and transportation, along with permits for treatment and disposal \(^{(31)}\). From the Chinese institutional perspective, refrigerants are a typical HW that has been largely overlooked. Except for European Union (EU) \(^{(32)}\) and the US \(^{(33)}\), relatively few countries have classified scrap refrigerants as HW in the waste management system (elaborated in SI Section 6). This is particularly the case in the less-developed countries including China.

• *Enhance the destruction rate of refrigerants.* Several destruction technologies are available for the refrigerants, whether gases or PUR foam, and should be more extensively utilized in China. These include: rotary kiln, the cement kiln, and the plasma decomposition methods, as recommended by the United Nations Environment Program (UNEP) and approved by the Meeting of the Parties to the Montreal Protocol \(^{(34,35)}\). In contrast to incinerators and other treatment techniques, high temperature cement kilns are already in place in virtually every country and can, if found technical feasible, be retrofitted and adapted cost-efficiently to destroy chemicals like CFCs \(^{(36)}\). Actually, co-processing of solid wastes in cement kilns has already started in China \(^{(37)}\). There are currently nearly 250 plants in China with cement kilns and Chinese cement capacity accounts for over 60% of total worldwide capacity \(^{(38)}\). Therefore, there is high potential for development in the field of refrigerants treatment, particularly when cement plants are located close to or are easily accessible to sources of refrigerants.
Increasing population, rapid urbanization, and improving living standards have greatly accelerated electronic and electrical device purchases and subsequent e-waste generation in many less developed economies where adequate e-waste management is still lacking. The management of obsolete RACs has thus become a significant challenge for the climate-resilient transition of not only China but many other countries as well. For example, India is second only to China for processing imported e-waste and the world’s fifth largest country in domestic generation. However, only approximately 5% of India’s e-waste (including scrap RACs) is safely recycled due to poor infrastructure, incomplete legislations, and unenforceable regulatory frameworks\(^{(39)}\). In West Africa, e-waste recycling is dominated by informal activities, which include collection, manual dismantling, open burning, and open dumping of residual fractions. More advanced or costly treatment processes, such as degassing and recovering refrigerants from RACs are not available\(^{(26)}\). As the world’s largest producer and consumer of RACs, China has the responsibility to create effective scrap RAC management systems that ensure the collection and destruction of these waste refrigerants. China’s approach to address the ODP and GWP impacts of refrigerants in RACs could consequently benefit other countries as well.

**Supporting Information.**

The Supporting Information contains more detailed background, literature review, methods, survey results, limitations, calls for future research, and comparison with other countries. Supporting Information is available free of charge on the ACS Publications website at ***.
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