The International Symposium on New Refrigerants and Environmental Technology 2025,
October 23 - 24, 2025,
Kobe International Conference Center

TS016

Scenario analysis of the effect of reducing HFC emissions for residential air conditioners

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Background

Rapid growth in global cooling demand

By 2050, 3 times equipment capacity, 3 times electricity consumption (baseline), cooling-related GHG emissions projected to reach 6.1 billion tons of CO_2eq, according to UNEP and IEA reports

Current Policy Trends

- Global Cooling Pledge at COP28 (the targets of 68% of cooling-related GHG emission reduction by 2050)
- Kigali Amendment(KA): phase-down of HFC emissions scheduled

Research necessity

- Need for quantitative evaluation of combinations effects of **lifecycle refrigerant management (LRM)** and refrigerant substitution on GHG emission reductions

LRM: a comprehensive approach focused on managing refrigerants throughout the entire lifecycle to reduce environmental impacts such as greenhouse gas emissions

Research Objectives

Research Objectives

- Quantitative assessment of combined effects of **refrigerant substitution** and **LRM**
- Long-term scenario analysis through **2070**
- Detailed regional and process-specific analysis

Scope

- GHG emissions from refrigerants for residential air conditioners(ACs)
- Global analysis framework: **seven** regional classifications
- LRM levels involving leakage reductions during operation and recovery improvements at end-of-life(EOL)

Contents

- Methodology and assumptions
  - Emission estimation formula by process of residential ACs
  - Assumed scenarios with combined refrigerant substitution and LRM levels
  - Assumptions on refrigerant transition schedule
  - Assumptions on leakage rates during operation and recovery rates at EOL

- Results (Impacts of LRM enhancement and refrigerant substitution)
  - Global refrigerant emissions from residential ACs
  - Global mean surface temperature

- Conclusion and future study

Methodology 1

An approach consistent with UNFCCC GHG inventories(2006 Guidelines) and Gi et al.(2018)
(1) Socio-economic indicators(population, GDP, households), CDDs *(under 2 °C target)
(2) Stocks of residential ACs (54 regions) by using (1)
(3) Refrigerant substitution, leakage rates during operation, and recovery rates (7 regions)
(4) Emission for three processes (during manufacturing and operation, and at EOL) (7regions)

Residential AC stocks estimation

- Residential AC stocks estimated from annual cooling capacity (TWh) and per-unit annual capacity (TWh/unit)
  - ✓ Annual cooling capacity are estimated from household (population) scenarios, and (b) annual capacity per household based on logistic functions of per-capita GDP and CDDs.
  - ✓ Per-unit annual capacity are estimated from unit capacity (kW/unit) and annual operating hours. The operating hours are estimated from the operating hours of the base year and changes in CDDs (relative to the base year).
  - ✓ Future population, household and GDP projections are based on "middle of the road" scenario (SSP2)

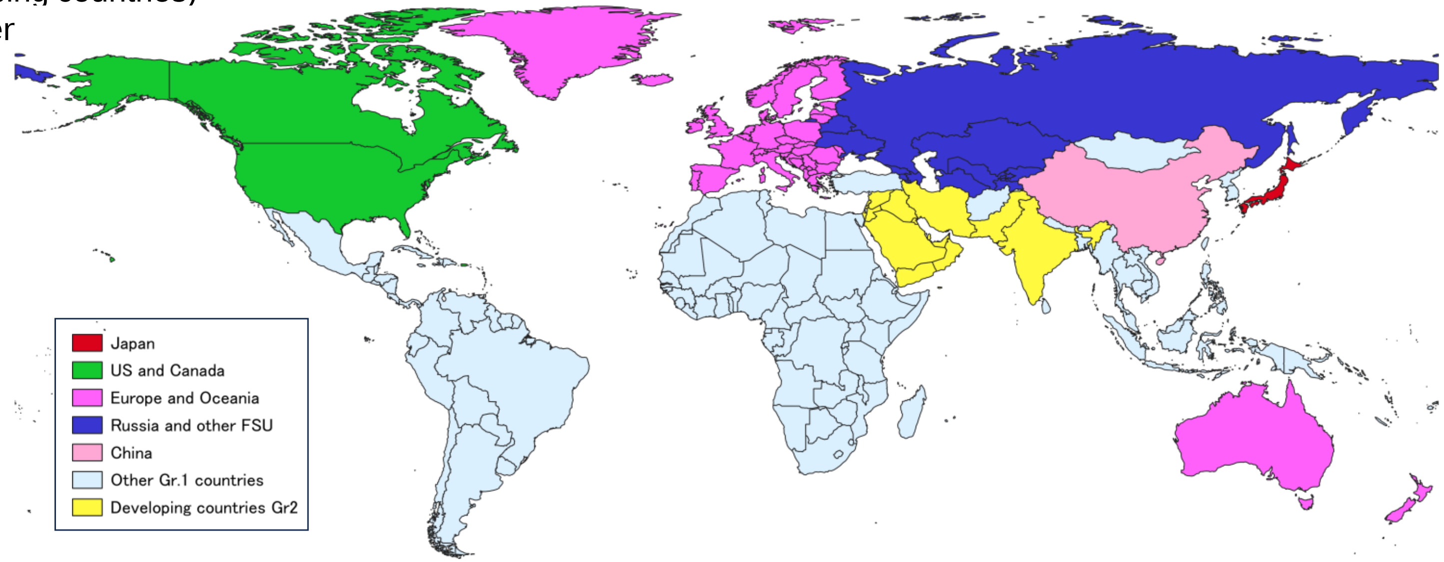
Equipment Lifetime and Disposal Estimation

- Average lifetime: 15 years (developed countries), 10 years (developing countries)
- Disposal number estimation using Weibull distribution probability der

Regional Classification (Seven regions)

- Japan
- US and Canada
- Europe and Oceania
- Russia and other FSU

- China
- Other Gr1** developing countries
- Gr2** developing countries



*CDDs: Cooling Degree Days
**Gr1 and Gr2 are based on the country classification of the KA.

Methodology 2

Emission estimation formulas for three processes

$$EM=\sum NP*MM*XM \quad (1)$$
$$EO=\sum NO*MO*XO \quad (2)$$
$$ED=\sum (ND*MD)-RE \quad (3)$$

- EM, EO, and ED are the refrigerant emissions at the manufacturing stage, during operation, and at the EOL stage, respectively.
- NP, NO and ND are the number of units produced, in operation, and disposed of, respectively.
- MM, MO and MD are the average amounts of refrigerant in each of the three processes.
- XM and XO are the refrigerant leakage rates during each of the processes.
- RE is the amount collected, based on the relevant IPCC guidelines.

Scenario design

Scenario		Ultimately dominant refrigerant (representative)	Leakage Reductions	Recovery Improvements
S 1	High-GWP (Reference)	R410A [GWP1920]	Normal	Normal
S 2-1	Medium-GWP and Flammable Gas	R32 [GWP677]	Normal	Normal
S 2-2	Medium-GWP and Flammable Gas	R32	Enhanced	Normal
S 2-3	Medium-GWP and Flammable Gas	R32	Enhanced	Enhanced
S 2-4	Medium-GWP and Flammable Gas	R32	Enhanced	Strongly Enhanced
S 3	Ultralow-GWP and Extremely Flammable Gas	R290 [GWP0.02]	Enhanced	Strongly Enhanced

Assumed time for refrigerant transition

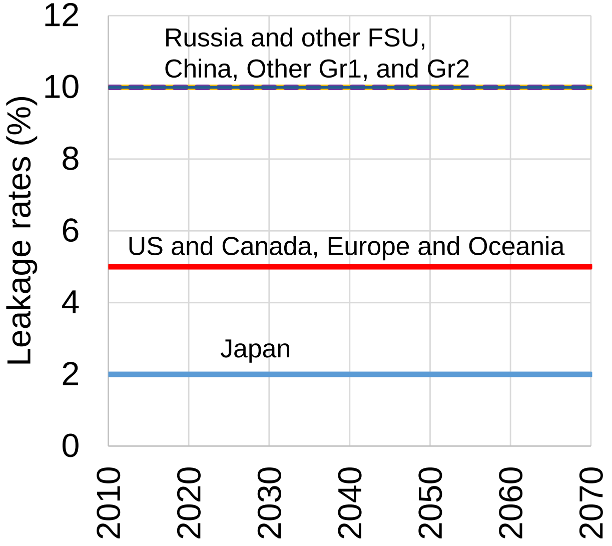
Region category	Country / region	R410A (S1)		R32 (S2-1—S2-4 and S3)		R290 (S3)	
		A1	A2	B1	B2	C1	C2
Developed countries	Japan	1998	2001	2013	2016	2035	2040
	US and Canada	2008	2011	2024	2028	2040	2045
	Europe and Oceania	1999	2002	2016	2020	2040	2045
	Russia and other FSU	1999	2002	2025	2030	2040	2045
Developing countries Gr1	China	2013	2017	2017	2026	2040	2050
	Other countries	2013	2014	2014	2026	2040	2050
Developing Countries Gr2	India and Pakistan	2010	2013	2013	2024	2045	2055
	Middle-east countries	2013	2025	2025	2030	2045	2055

Note: Note: A1 and A2 represent the year when R410A refrigerant exceeds **20% and 80% shares of new installations**, respectively. B1 and B2 represent the period when R32 refrigerant exceeds 20% and 80% shares of new installations, respectively, in the scenarios except for S1. C1 and C2 represent the period when R290 refrigerant exceeds 20% and 80% shares of new installations, respectively.

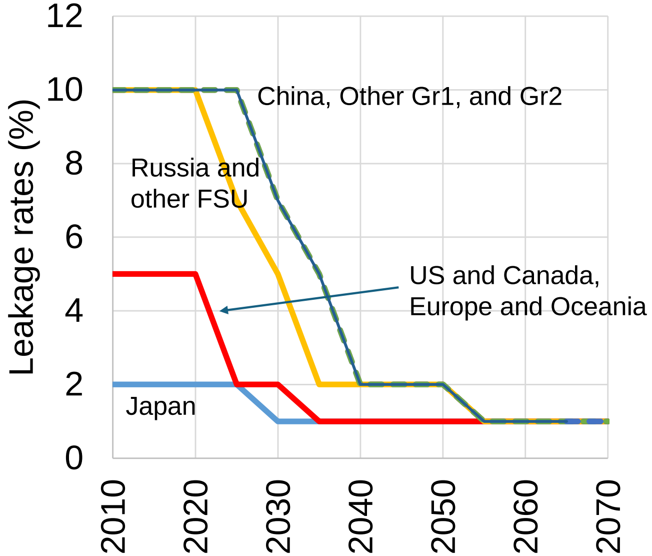
Assumed leakage rates during operation and recovery rates at EOL

Leakage rates

(a) Normal LRM (Leakage)
S1 and S2-1

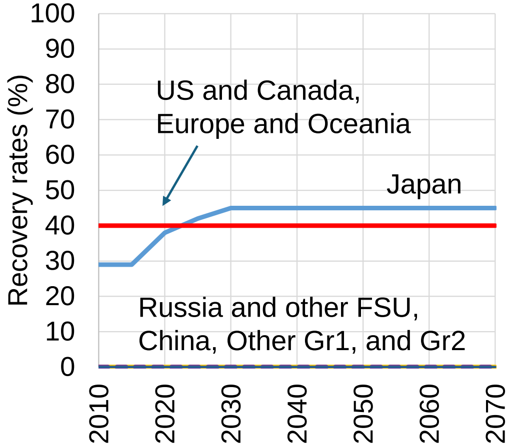


(b) Enhanced LRM (Leakage)
S2-2, S2-3, S2-4 and S3

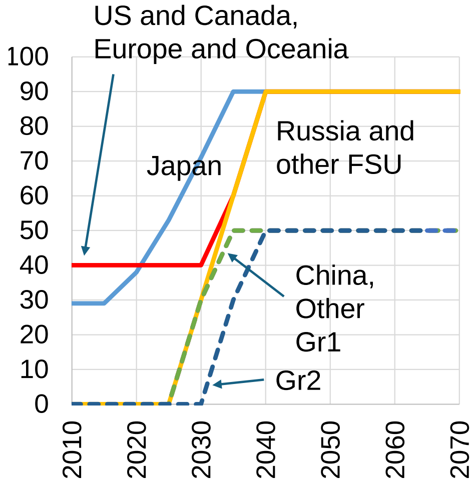


Recovery rates

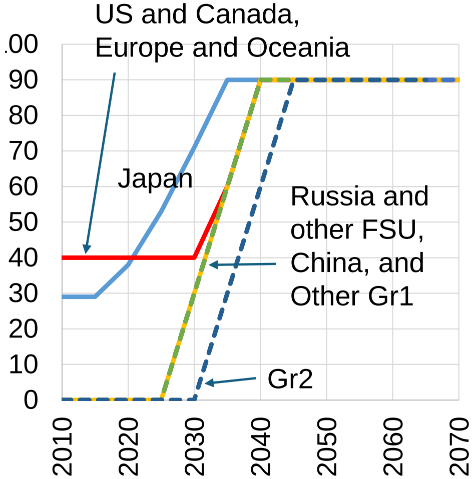
(a) Normal LRM (Recovery)
S1,S2-1 and S2-2



(b) Enhanced LRM (Recovery)
S2-3

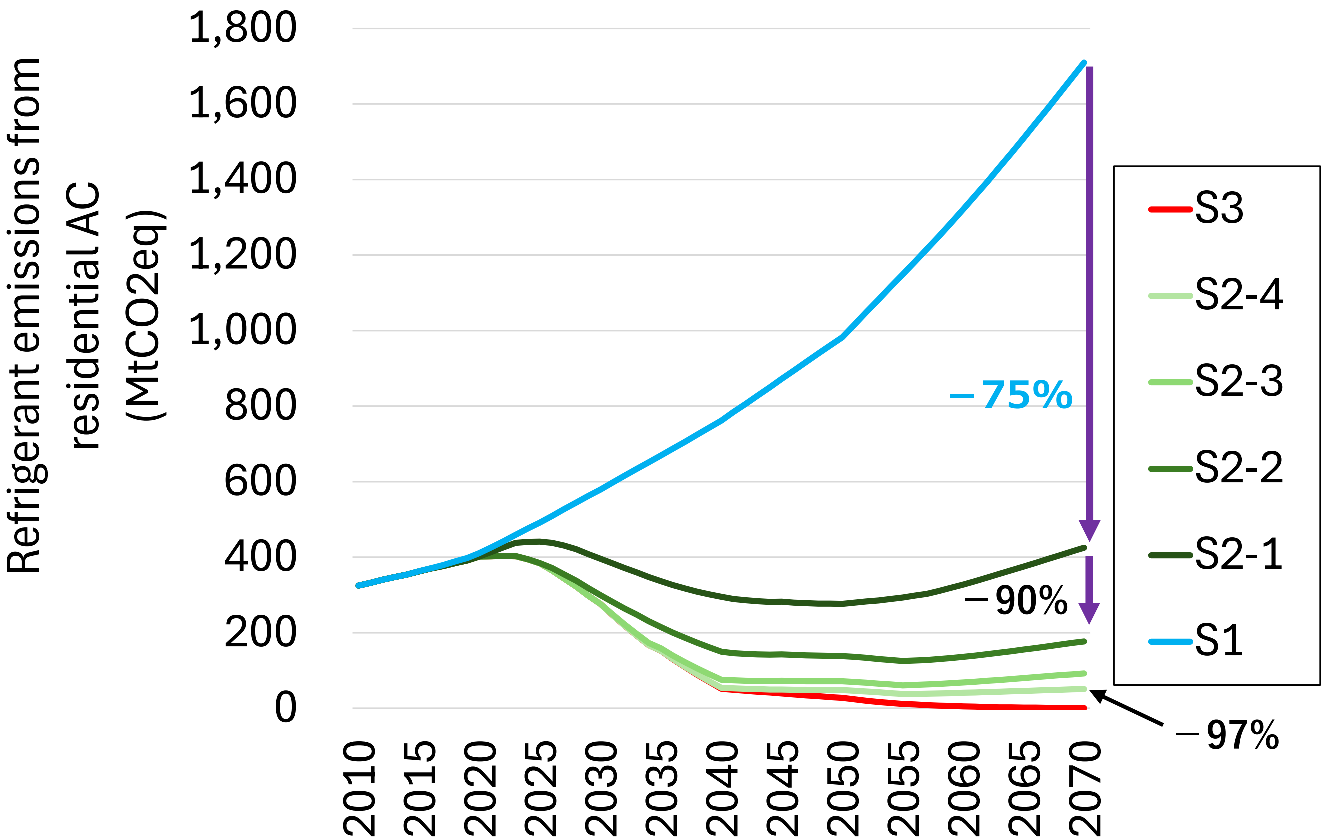


(c) Strongly Enhanced LRM
(Recovery)
S2-4 and S3



Source:
Homma et al. (2025)

Result 1: Global refrigerant emissions from residential ACs



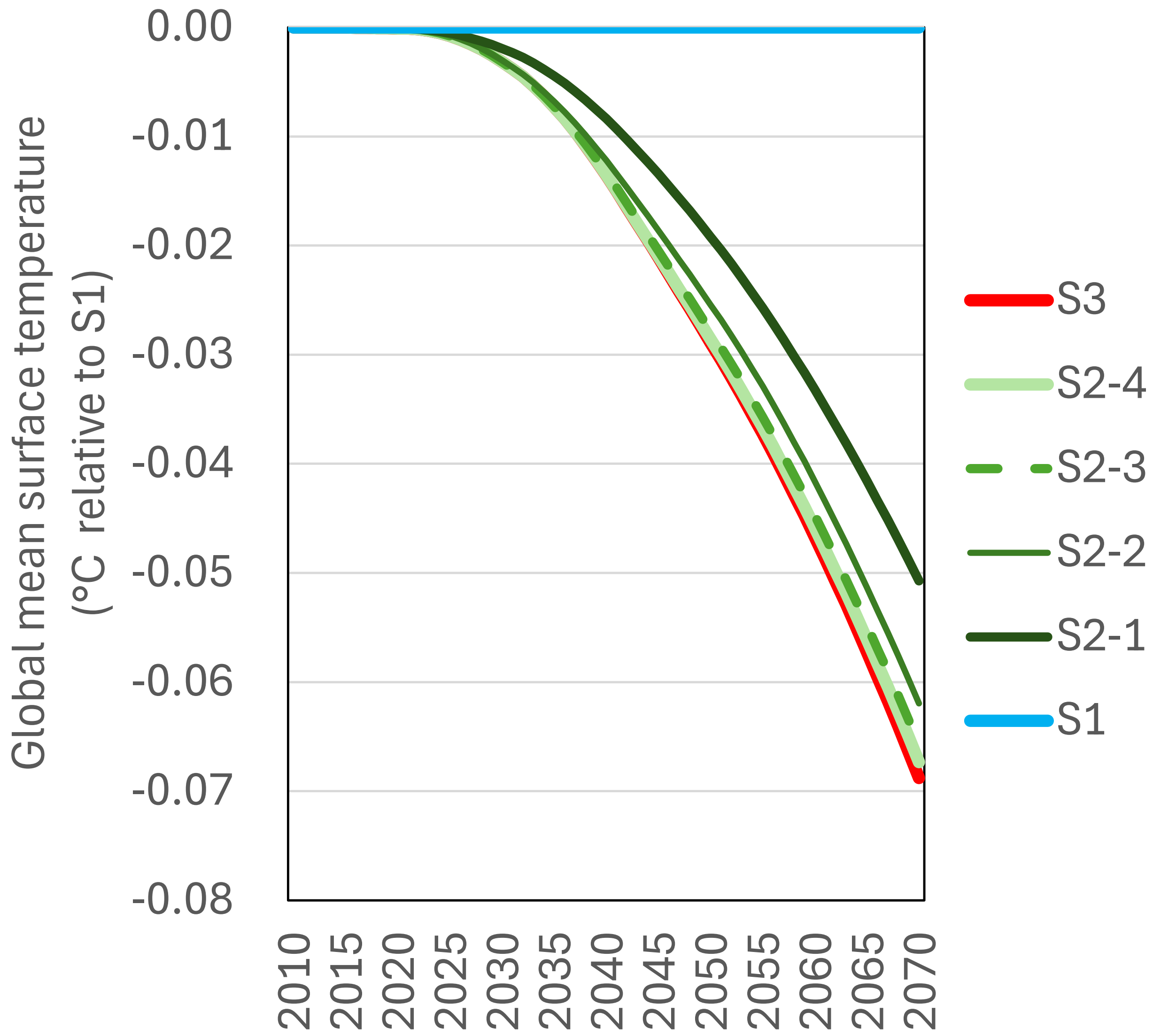
Source: Homma et al. (2025)

Refrigerant Substitution Effect from R410A to R32 (S2-1): －75% in 2070 (compared to S1)

LRM Enhancement Effects(S2-2,S2-3, and S2-4):
S2-2: － 90% in 2070, S2-3: － 95% , and S2-4: － 97%

Most enhanced LRM + ultralow-GWP refrigerant (S3):
[Ultralow-GWP refrigerant + Most enhanced LRM scenario] achieves nearly 100% reduction by 2070

Result 2: Changes in global mean surface temperature(°C relative to S1)



Source: Homma et al. (2025)
(estimates by MAGICC6)

Temperature decrease effects
(2070, relative to S1)
S2-1: 0.051℃
S2-4: 0.067 ℃
S3: 0.069 ℃

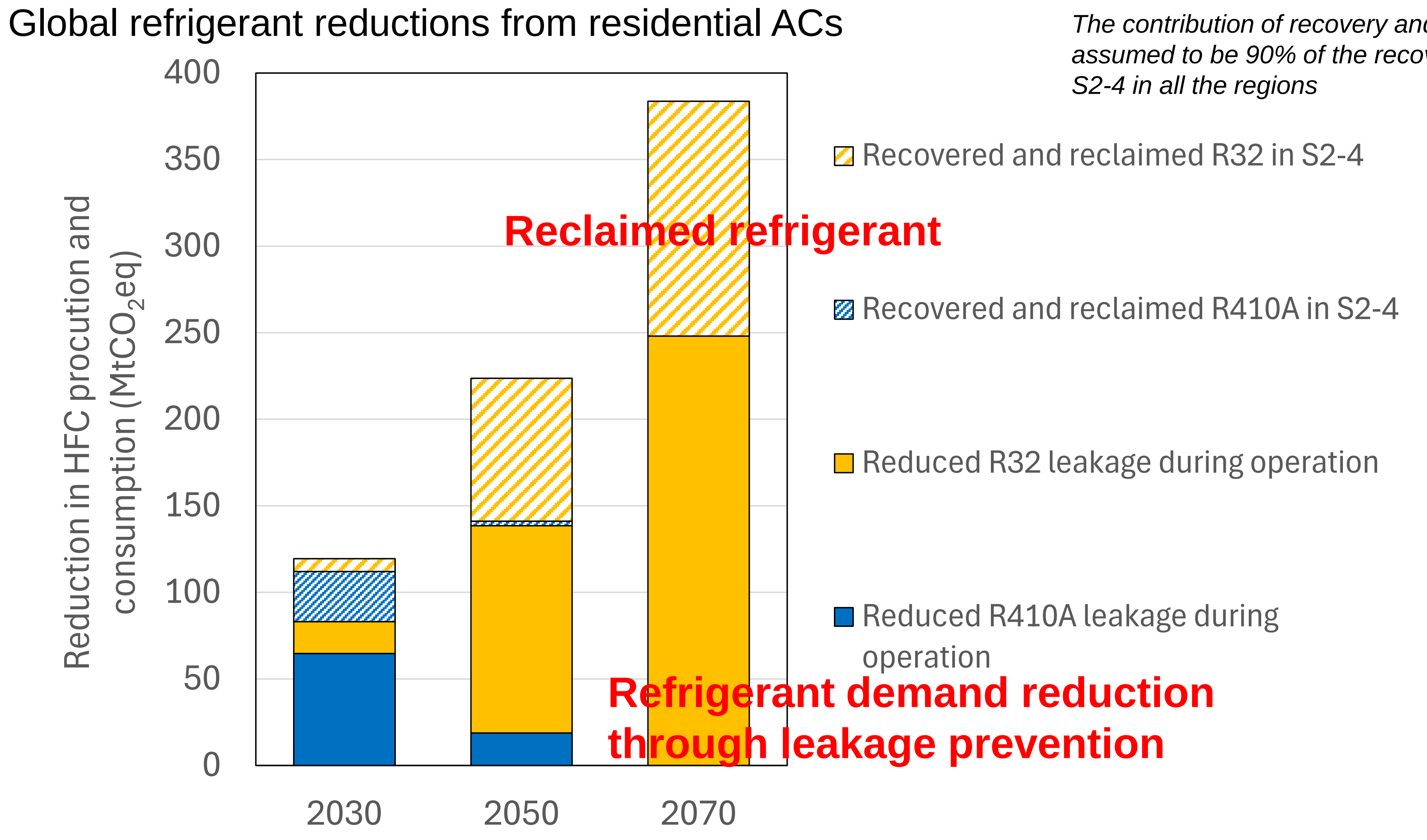
- Very small difference between S2-4 and S3 effects (only 0.002 ℃)
- [Medium-GWP+ most enhanced LRM] achieves climate effects almost comparable to ultralow-GWP

- Effectiveness of multiple pathway approach of enhanced LRM and refrigerant substitution

- Significant environmental improvement possible with medium-GWP refrigerants through enhanced leakage reduction and recovery rates

Result 3: Reducing HFCs production through most enhanced LRM

The contribution of recovery and reclamation at EOL is assumed to be 90% of the recovered emissions estimated in S2-4 in all the regions



The global cumulative reduction will be achieved by approximately 10.8 GtCO2eq between 2020 and 2070.

Source:
Homma et al. (2025)

Conclusion

- Combined approach of refrigerant substitution and LRM improvement is quite effective way of reducing GHG emissions.
- [R32 + most enhanced LRM scenario] can achieve 97% emission reduction by 2070, compared to reference scenario (R410A).
- [R32 + most enhanced LRM scenario] will achieve reduction in global HFCs cumulative production by approximately 10.8 GtCO2eq for 2020-2070.
- [Medium-GWP refrigerant + most enhanced LRM scenario] is considered as practical and effective climate change mitigation strategy. (Refrigerant transition is not the only solution)
- For social implementation, effective LRM technology and the relevant institutional design are necessary.

<Future study>

- Estimations on investments required for LRM enhancements and the cost-effectiveness analysis
- Measures to enhance LRM in developing countries and the effective international support systems

More information on this report

Combined Effects of Refrigerant Substitutions of Residential Air Conditioners and Improvement in Lifecycle Refrigerant Management on Reduction of Global Greenhouse Gas Emissions
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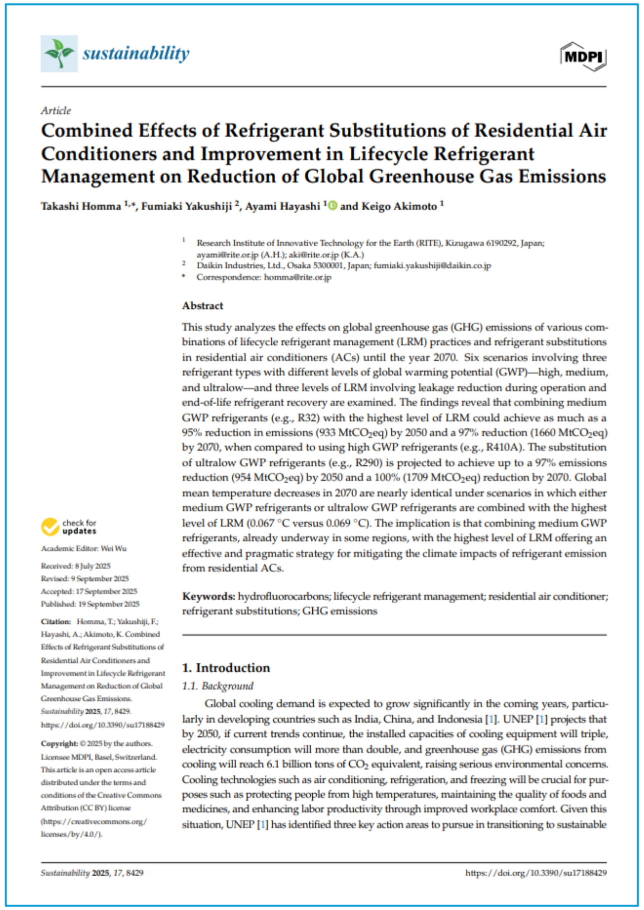
Sustainability 2025, 17(18), 8429 https://doi.org/10.3390/su17188429



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Article

Combined Effects of Refrigerant Substitutions of Residential Air Conditioners and Improvement in Lifecycle Refrigerant Management on Reduction of Global Greenhouse Gas Emissions

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Abstract

This study analyzes the effects on global greenhouse gas (GHG) emissions of various combinations of lifecycle refrigerant management (LRM) practices and refrigerant substitutions in residential air conditioners (ACs) until the year 2070. Six scenarios involving three refrigerant types with different levels of global warming potential (GWP)—high, medium, and ultralow—and three levels of LRM involving leakage reduction during operation and end-of-life refrigerant recovery are examined. The findings reveal that combining medium GWP refrigerants (e.g., R32) with the highest level of LRM could achieve as much as a 95% reduction in emissions (933 $MtCO_2eq$) by 2050 and a 97% reduction (1660 $MtCO_2eq$) by 2070, when compared to using high GWP refrigerants (e.g., R410A). The substitution of ultralow GWP refrigerants (e.g., R290) is projected to achieve up to a 97% emissions reduction (954 $MtCO_2eq$) by 2050 and a 100% (1709 $MtCO_2eq$) reduction by 2070. Global mean temperature decreases in 2070 are nearly identical under scenarios in which either medium GWP refrigerants or ultralow GWP refrigerants are combined with the highest level of LRM (0.067 °C versus 0.069 °C). The implication is that combining medium GWP refrigerants, already underway in some regions, with the highest level of LRM offering an effective and pragmatic strategy for mitigating the climate impacts of refrigerant emission from residential ACs.

Keywords: hydrofluorocarbons; lifecycle refrigerant management; residential air conditioner; refrigerant substitutions; GHG emissions

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Academic Editor: Wei Wu

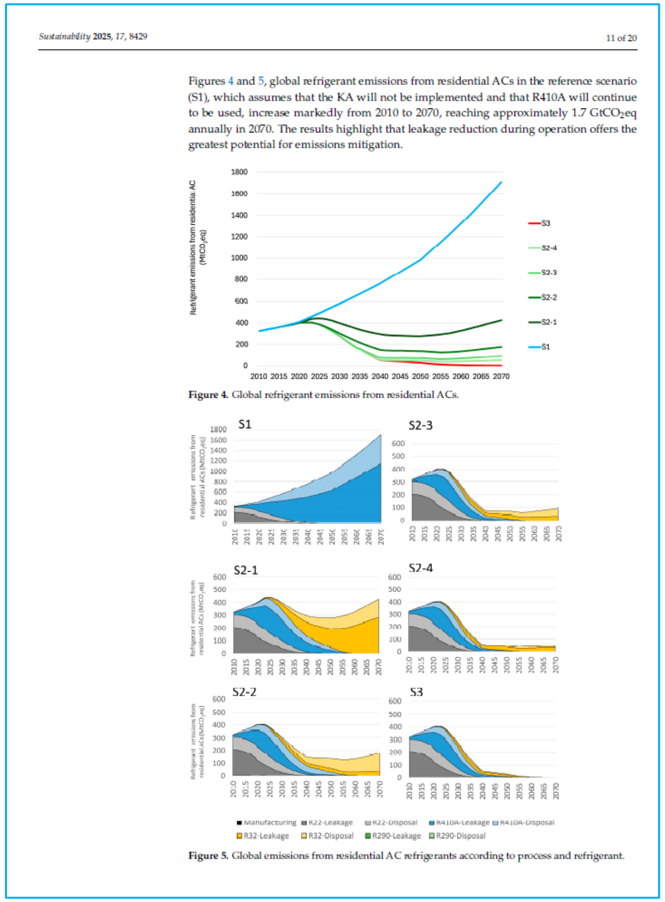
Received: 8 July 2025
Revised: 9 September 2025
Accepted: 17 September 2025
Published: 19 September 2025

Citation: Homma, T.; Yakushiji, F.; Hayashi, A.; Akimoto, K. Combined Effects of Refrigerant Substitutions of Residential Air Conditioners and Improvement in Lifecycle Refrigerant Management on Reduction of Global Greenhouse Gas Emissions. *Sustainability* **2025**, *17*, 8429. https://doi.org/10.3390/su17188429

1. Introduction

1.1. Background

Global cooling demand is expected to grow significantly in the coming years, particularly in developing countries such as India, China, and Indonesia [1]. UNEP [1] projects that by 2050, if current trends continue, the installed capacities of cooling equipment will triple, electricity consumption will more than double, and greenhouse gas (GHG) emissions from cooling will reach 6.1 billion tons of CO_2 equivalent, raising serious environmental concerns. Cooling technologies such as air conditioning, refrigeration, and freezing will be crucial for purposes such as protecting people from high temperatures, maintaining the quality of foods and medicines, and enhancing labor productivity through improved workplace comfort. Given this situation, UNEP [1] has identified three key action areas to pursue in transitioning to sustainable



Figures 4 and 5, global refrigerant emissions from residential ACs in the reference scenario (S1), which assumes that the KA will not be implemented and that R410A will continue to be used, increase markedly from 2010 to 2070, reaching approximately 1.7 $GtCO_2eq$ annually in 2070. The results highlight that leakage reduction during operation offers the greatest potential for emissions mitigation.

Figure 4. Global refrigerant emissions from residential ACs.

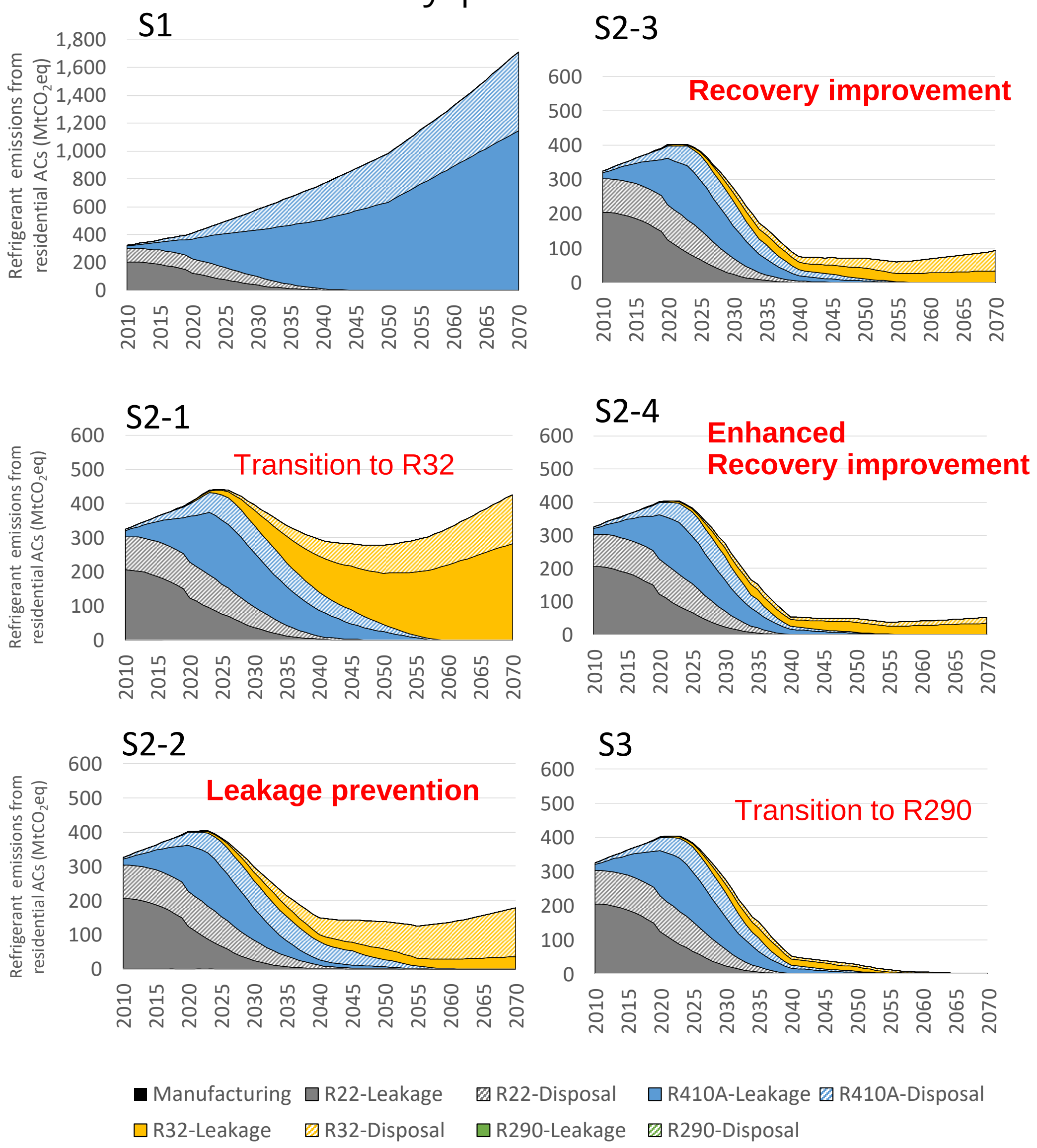
Figure 5. Global emissions from residential AC refrigerants according to process and refrigerant.

Appendix

Appendix a: Global refrigerant emissions from residential ACs

Source: Homma et al. (2025)

By process



By region