LBNL-2001229

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August/2019

This work was supported by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

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September 4, 2019

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Hydrofluorocarbons (HFCs) are the fastest growing type of greenhouse gases (GHG) emissions, increasing at an annual rate of 10-15% [1]. HFCs are primarily used as refrigerants in air conditioning and refrigeration equipment and have a global warming potential (GWP) many thousands of times greater than CO_2. Their rapid growth has led to a global agreement to aggressively phase down their production by amending the Montreal Protocol on Substances that Deplete the Ozone Layer [2]. We quantify the GHG benefits implementing aggressive but economic energy efficiency measures (about 30% more efficient than current technology) in air-conditioning (AC) and large commercial refrigeration equipment (CRE) together with low-GWP refrigerants. Shifting the 2030 world stock of room ACs and CRE from current levels of energy-efficiency and high-GWP refrigerants to "economic" energy efficiency levels and low-GWP refrigerants by 2050 would avoid up to 240.1 GT CO_2e and shifting to "best-available technology" energy efficiency levels and low GWP refrigerants by 2050 would avoid up to 373 GT CO_2e with existing electricity grid emission factors. About two-thirds of this cumulative savings are from reduced electricity sector emissions from improved energy efficiency. Thus, it is highly beneficial to pursue high energy efficiency in concert with the transition to lower GWP refrigerants to achieve maximal GHG reductions with the least amount of equipment re-design and replacement.

Phasing down HFCs and other short-lived climate pollutants offer faster climate change mitigation than control of CO_2 emissions alone [3,4]. Simultaneously, energy efficiency market transformation programs are endeavoring to improve the energy efficiency of air conditioning and refrigeration equipment to provide life-cycle cost, energy, GHG, and peak load savings [5,6]. These two trends offer an opportunity to implement energy efficiency and refrigerant transition policies in concert to achieve much higher savings than either policy alone.

Data sources and methodology are described below and used to calculate the emissions reduction from efficiency improvement only, from refrigerant transition only, and from implementation of both of these policies together. Much of the discussion is focused on mini-split units for room air conditioning since this is the dominant source of projected GHG emissions and GHG emissions savings potential (almost 50% of the total savings). We report the benefits of implementing both policies separately and in conjunction, and conclude with a brief discussion for how these policies might be enacted and implemented.

Air conditioning represents about 30% of current and forecasted summer load (electricity demand) in warm climates such as California, about 40-60% of the total load in hot climates on typical summer days in metropolitan areas like Delhi, India and can even triple summer load in very hot areas such as New South Wales, Australia [7,8].

The global room air conditioner market is growing rapidly with increased urbanization and electrification, rising incomes, and falling AC prices in many developing economies. Room air-conditioner ownership in urban China grew from a few percent to over 100% (i.e., more than one room air conditioner (AC) per urban household), in about 15 years [9]. Air conditioner sales in many emerging high population economies such as India, and Indonesia are growing at 10-15% per year [10,11] and current penetration rates are still low. For example, AC penetration in India in 2011 was about 5% [12]. We assume conventional vapor compression-based technology will be used for this analysis, since new technologies while promising, still have cost and performance issues.

Based on IEA (2018) [13] estimates, an additional 1.21 billion un-ducted mini-split units will be added to the global AC stock by 2030 and 3.28 billion by 2050 compared to the stock in 2015 if current trends persist. Overall global unit demand for mini-split room air conditioning in 2050 is estimated to increase by a factor of 3.75 times over the demand in 2015. In the absence of mitigation policy, this growth is expected to have a large-scale impact on electricity generation capacity and peak load, particularly in economies with hot climates, and to contribute significantly to GHG emissions.

We also estimate the increase in adoption for other air conditioning equipment types, namely variable refrigerant flow (VRF) and ducted systems, air- and water-cooled chillers, packaged air conditioners and domestic and commercial refrigeration equipment. These other air conditioning product types are typically larger capacity systems than un-ducted mini-split systems that can be used in commercial buildings, industrial buildings, and multi-family residential buildings. The volume of these markets in numbers of units is much lower than that for mini-splits and in some cases the growth rates are lower than that for mini-splits (e.g., air- and water-cooled chillers).

There is limited modeling data on the increase of room air conditioning demand in the developing world. Aufhammer and Mansur 2014 [14] provides a detailed literature review and states that "what would be of great interest are studies, which project future air conditioner penetration by country by 2100 under different climate, income and price scenarios." We compare our estimates to four recent sources [15-18] and find that our estimates for mid-century cooling demand are at the high end but within the range of these earlier sources.

Davis 2015 [17] provides a detailed study using microdata from Mexico to describe the relationship between temperature, income, and air conditioning in that country. Their modeling projects estimated increases in overall electricity consumption from 2010 to 2100 but does not quote the demand for air conditioning or the number of times increase in air conditioning electricity demand in the future. Our best estimate of their reported data for the case of increased AC demand from greater income and a stabilized climate suggest an increase in air conditioning demand of about 8 to 16 times in 2100 from the level of 2010. Our estimate is about 10 times higher AC demand in Mexico in 2050 relative to 2010 is within the range of Davis' estimates.

Santamouris 2016 quotes a global cooling demand in 2050 for the residential sector in the range of 2.0 -15.7 PWh which spans the range of projected cooling demand estimates given by Isaac

2009 and Mima 2011. From Table 1 below it is seen that this work's reference case estimate of 13.9 PWh demand in 2050 is at the high end of estimates for the three prior references and is in between the Mima 2011 and Santamouris 2016 high demand cases.

This work's methodology to estimate recent and future demands (2005-2050) based upon equipment stock estimates from the IEA [13] for ten regions of the world (U.S, China, Japan and Korea, the European Union, India, Indonesia, Mexico, Brazil, the Middle East, and Rest of the World), estimates for operating hours by equipment type by country, and energy consumption per unit is described below.   Thus our estimates take into account more recent equipment growth data from the IEA that capture the recent and projected extremely high growth rates in air-conditioning in the developing world.

This work does not take into account a changing climate. As discussed in Davis 2015 [17], this is expected to boost demand at both the "intrinsic margin" (increased usage in existing units), and at the "extrinsic margin" (increased adoption of AC units). For the purpose of sensitivity analysis, we include two other cases in Table 1 for this work, a "low demand" case with 0.8 times the reference case's annual percent increase in demand for each country, and a "high demand" case where the annual increase in demand is 1.2 times the reference case's annual percent increase (i.e., if the baseline annual growth rate is 1%, the low and high demand cases would modify this to 0.8% and 1.2% per year, respectively).

Table 1. Projected cooling demand in the residential sector in 2050.

Source	2050 Projected Residential Cooling Demand (PWh)
Santamouris 2016 low [18]	2.0
Isaac 2009 low [15]	2.7
Isaac 2009 ref. case [15]	4.0
Santamouris 2016 avg. [18]	5.2
Isaac 2009 high [15]	6.0
Mima 2011 no climate change [16]	7.0
Mima 2011 avg [16]	9.2
This work, low demand	10.7
Mima 2011 High [16]	11.6
This work ref. case	13.9
Santamouris 2016 high [18]	15.7
This work, high demand	18.0

Commercial and domestic refrigeration includes many product types and sizes including commercial refrigerators and freezers, self-contained display cases (also known as integral units), refrigerated beverage vending machines, remote condensing units, large centralized equipment found in supermarkets and hypermarkets, and domestic refrigerators. Self-contained units or those that contain an evaporator, compressor, and hermetically sealed refrigerant lines in an enclosed case typically have much lower refrigerant charge sizes and much lower charge losses than non-self-contained equipment types [19,20].

Greenhouse gas emissions abatement over the lifetime of AC and CRE equipment can result from two effects: (1) "direct" GHG emissions savings from reduced refrigerant losses to the atmosphere (from leakage during equipment use and at end-of-life) and/or by using lower-GWP refrigerants; and (2) reduced "indirect" GHG emissions from the electricity grid due to lower electricity consumption from higher efficiency equipment, ceteris paribus. Transitioning from a high GWP refrigerant to a low GWP refrigerant can also impact the indirect GHG emissions if the new refrigerant shifts the equipment efficiency and/or cooling capacity. For example, Table 2 shows the global warming potential and energy savings for a set of alternative refrigerants compared to the baseline HFC refrigerant, R410a, for room AC. Reductions in 100-year GWP of 60% to 100% are achieved. The energy savings for "dropping in" new refrigerant into existing 1.5-ton AC equipment varies from +11% to -18%. The key point is that alternative refrigerants can achieve deep reductions in GWP with equivalent to better overall energy efficiency to the baseline refrigerant R-410a. R32, R290[1] and hydrofluoro olefin (HFO)/HFC blends such as DR5 or DR 55 all offer significant emissions abatement potential compared to the baseline refrigerant case of R410a. Meanwhile, other HFO blends offer reduction in emissions due to lower GWP, but increase indirect emissions compared to R410a from lower energy efficiency. This is due to lower cooling capacity (e.g. ARM70a), lower efficiency (e.g. R32/134a) or both (e.g. HPR1D). Note however that R290 (propane) is flammable and that all the other alternative refrigerants are mildly flammable ("A2L") whereas R410a is non-flammable.

These general considerations apply to other product types as well. For example, CRE equipment can transition to "natural refrigerants" such as ammonia (GWP = 0), hydrocarbons (GWP<10), and CO_2 (GWP = 1), often with equivalent to improved energy efficiency and with much lower direct CO_2-eq. emissions from refrigerant leakage since natural refrigerants have orders of magnitude lower GWP values than typical HFC-based refrigerants for CRE (e.g., R404a GWP = 3920; R407a GWP = 2107).

Table 2. Reduction in global warming potential (100-year GWP values) and energy savings for 15 alternative refrigerants vs. baseline R410a refrigerant for room AC for a 1-ton mini-split room air conditioner. [21-31]

Refrigerant	GWP	Flammability Rating	Cooling Capacity (% of baseline)	Efficiency (% of baseline)	Energy Savings (% of baseline)

[1] Note that R290 is a drop-in replacement for R-22 refrigerant, but requires a different compressor and modified refrigerant tubing when used to replace R-410a.

R410a (Baseline)	1924	A1	100%	100%	-
R290	3	A3	100%	105%	5%
DR5	490	A2L*	103%	104%	6%
R32/R152a	647	A2L*	109%	103%	11%
R32	675	A2L	108%	99%	6%
DR55	698	A2L	108%	99%	6%
L41-1	461	A2L	90%	100%	-11%
L41-2	583	A2L	93%	103%	-4%
L41a	494	A2L*	97%	103%	0%
L41b	494	A2L*	96%	103%	-1%
ARM70a	482	A2L*	89%	106%	-6%
ARM71a	460	A2L*	96%	103%	-1%
D2Y60	272	A2L*	87%	101%	-14%
R32/R134a	713	A2L*	105%	92%	-4%
HPR2A	600	A2L*	95%	101%	-4%
HPR1D	407	A2L*	91%	93%	-18%

A summary of GHG savings potential by equipment type assuming a simultaneous transition to economic and best-available-technology energy efficiency savings and low-GWP refrigerants is shown in Table 3 and Figure 1 below. A total savings potential of 240.1 Gtons CO_2e is projected for 2030-2050 for the case of economic energy efficiency and baseline (or static) electricity grid emission factors, and 177.8 Gt CO_2e in the case where annual electricity grid emission factors decrease at 2% per year. The most savings potential is from by mini-split air conditioners with 42-54% of the potential since the installed stock of mini-splits is so large and the lifetime leakage rate is relatively high. This is followed by two types of commercial refrigeration equipment (remote condensing units and large centralized refrigeration systems) at 18-30% of the overall savings and VRF/ducted systems at about 11-12% of the overall savings. Overall, air conditioning systems make up about 64% of the potential savings to 2050.

Table 3. Estimated total direct and indirect GHG reductions from air conditioning equipment and refrigeration equipment with economic energy efficiency savings and low-GWP refrigerants for 2030, 2040, and 2050 assuming static electricity emission factors to 2050

Product Type	Life-time	Capacity in tons	Pct. Leakage of Init. Charge	Hours - op./yr.	Total direct and indirect GHG reductions			
					2030 (GT CO2e)	2040 (GT CO2e)	2050 (GT CO2e)	2030 + 2040 + 2050 (GT CO2e)
Mini-split AC	10	1	170%	Varies by country	25.3	37.1	47.0	109.4
Remote Condensing units	15	Varies	239%	5500	10.6	14.1	17.5	42.2
VRF & Ducted AC	15	7.5	169%	3000	8.0	9.2	10.3	27.5
Supermarkets	15	100	263%	5500	5.5	6.9	8.4	20.8
Self-contained refrigeration units	10	Varies	28%	Varies by country	4.3	5.6	6.9	16.8
Chillers - Air cooled	15	15	99%	2000	1.9	2.8	3.7	8.4
Chillers- Water cooled	15	100	99%	2000	1.6	2.3	3.1	7.0
Domestic Refrigerators	15	Varies	40%	Varies by country	1.6	1.9	2.2	5.7
Packaged AC	15	10	136%	3000	0.6	0.8	1.0	2.3
Total					59.3	80.7	100.1	240.1

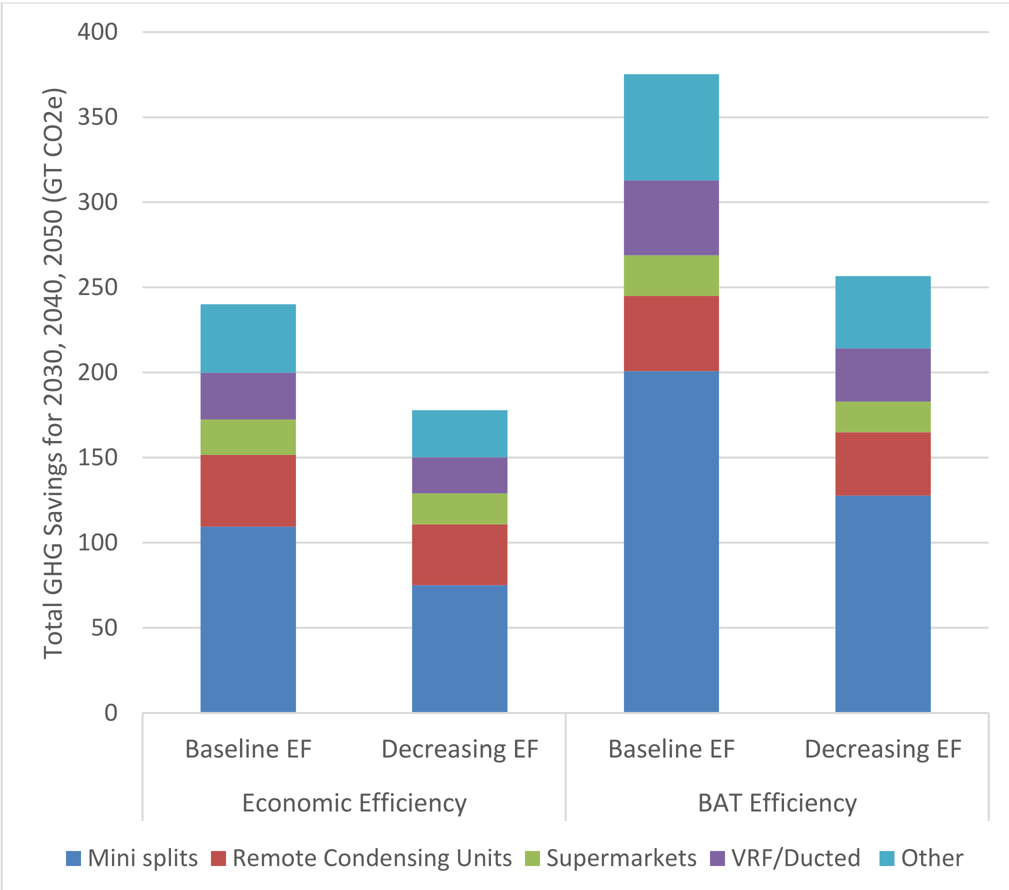

Figure 1. Estimated emissions abatement potential of AC and refrigeration equipment in 2030, 2040, and 2050 over equipment lifetime relative to baseline refrigerant and baseline energy efficiency. (Source: Author's calculations)

For best-available-technology (or "maximum" efficiency), total savings to 2050 are 373.0 and 257.6 $GtCO_2e$ for baseline (or static) electricity emission factors and decreasing emission factors, respectively (Fig. 1). Table S1 in the SI shows the GHG emissions for the reference case (no efficiency improvement and baseline HFC refrigerants) vs. the policy case of best-available technology (BAT) energy efficiency and low GWP refrigerants for 2030, 2040, and 2050 with static emission factors for both cases. Reference case cumulative GHG emissions are 587.1 Gt CO2e while the policy case is 214.1 Gt for an overall cumulative savings of 373.0 Gt CO2e.

Overall, indirect savings from improved energy efficiency contribute 50-61% of the overall savings for the economic efficiency case, and 67-76% of overall savings for the BAT case (Fig. 2).

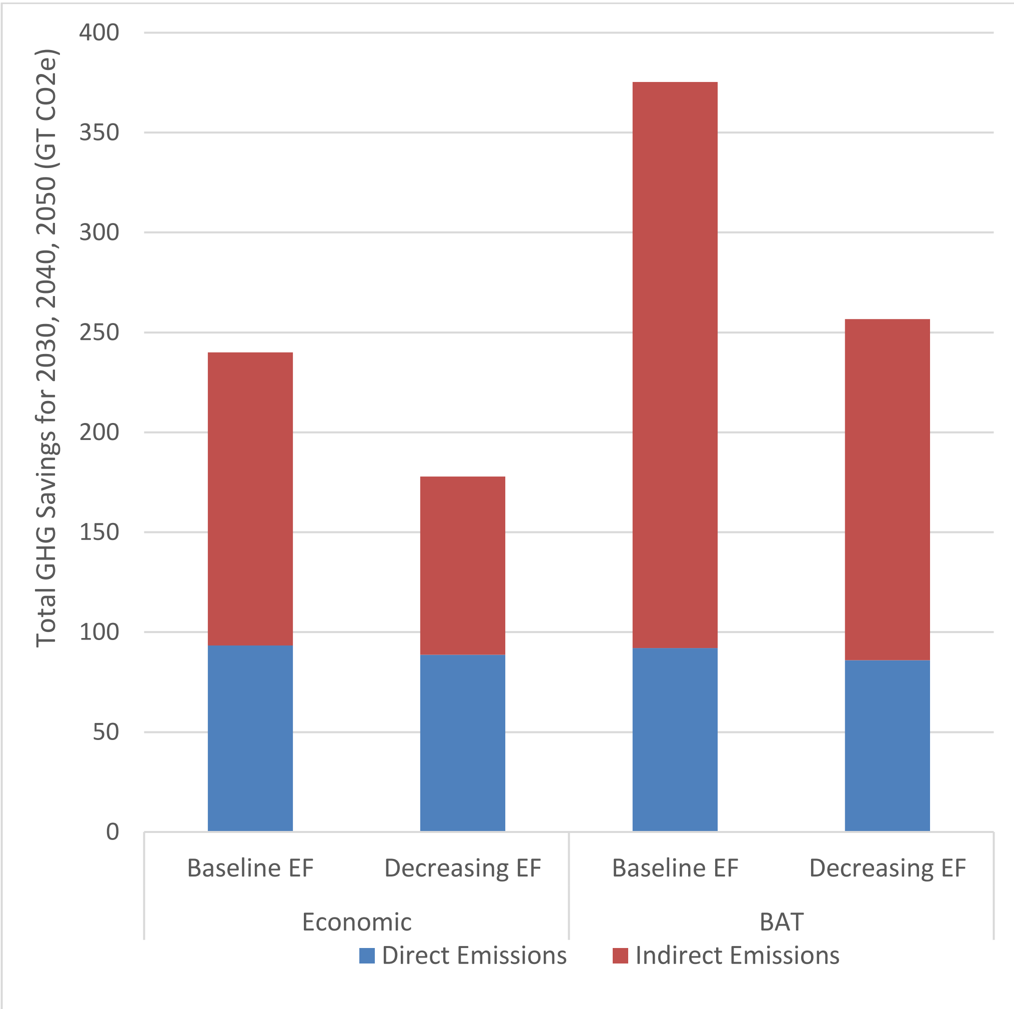

Figure 2. Direct and indirect savings potential for the total GHG savings potentials shown in Figure 1 above. (Source: Author's calculations)

Figure 3 shows the estimated emissions abatement over the lifetime of mini-split ACs if the global stock in 2030 is both 30% efficient (the level of economic energy efficiency) and uses lower GWP refrigerants. The blue and purple bars indicate the impact of switching the global stock of AC to the lower GWP refrigerant in 2030. The blue bar shows direct emissions abatement and the values here are directly related to the reduction in 100-year GWP values shown in Table 2. The purple bars show the indirect emissions abatement due to the impact of alternative refrigerants on equipment energy efficiency and equipment capacity as shown in Table 2. The green bars indicate the indirect emissions abatement over the lifetime of the AC if the global stock is made 30% more efficient from air conditioner re-design. We find that implementing energy efficiency improvement policies for room air conditioners in conjunction with conversion to lower GWP refrigerants, can more than double the benefit of a refrigerant-only policy implemented in isolation for the first five alternative refrigerants in Figure 3.

Note that these estimates show the emissions reduction potential that could be captured over the lifetime of the ACs for the ***global stock in 2030.*** The *cumulative* emissions reduction could be much higher than these estimates and would accrue higher total benefits if the transition policy is enacted earlier.

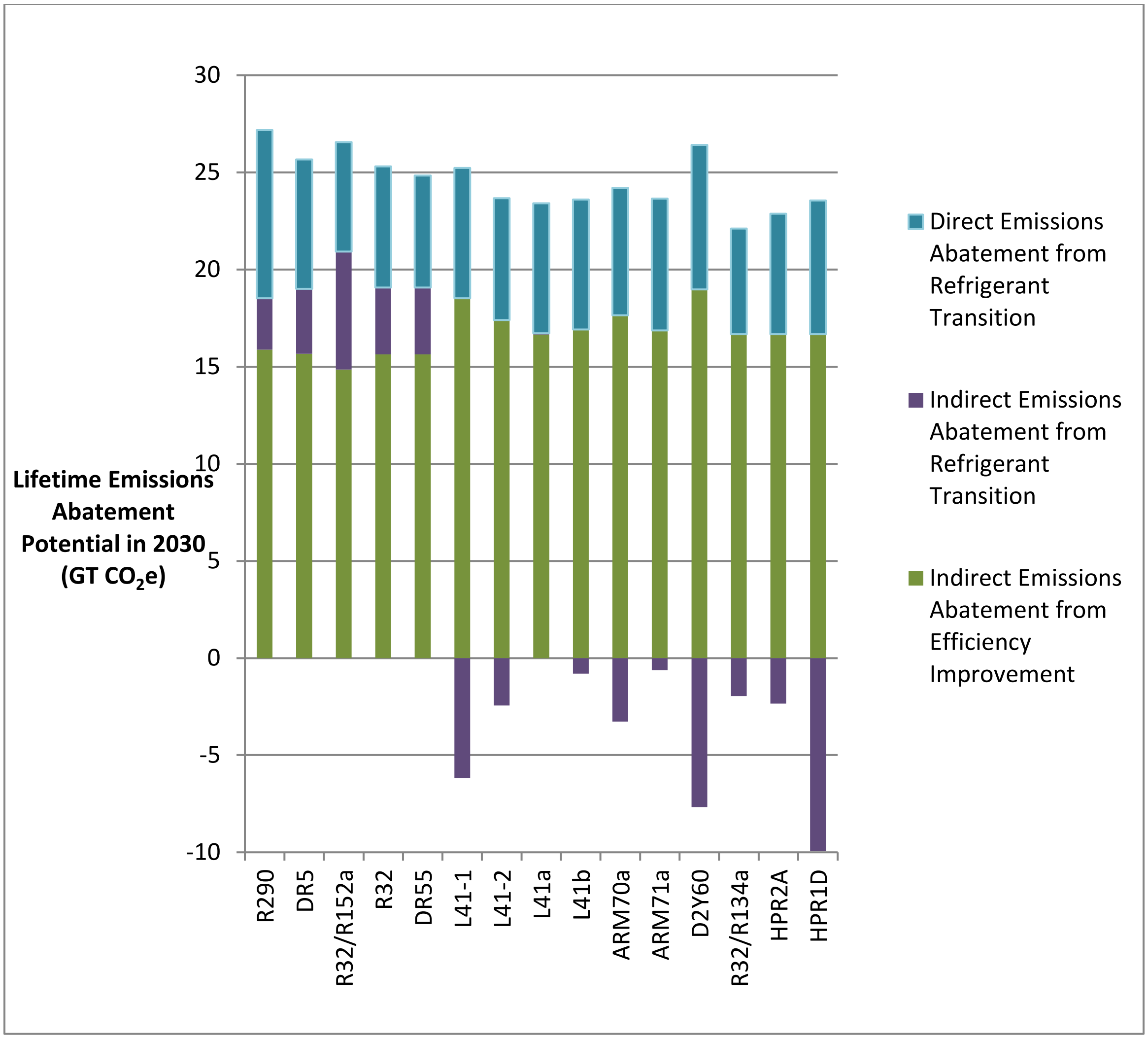

Figure 3. Estimated emissions abatement potential of mini-split room AC stock in 2030 over AC lifetime compared to baseline refrigerant R-410a. (Source: Author's calculations)

The AC system efficiencies quoted here for the set of alternative refrigerants are based upon the U.S. Air Conditioning, Heating, and Refrigeration Institute's (AHRI) Alternative Refrigerant Evaluation Program (AREP [11]; described in the Supplementary Information below) and these AC systems were not specifically designed and optimized for these low-GWP refrigerants. Hence these efficiency results should not be used to guide eventual choice of refrigerant. Results from systems optimized for the refrigerants could show more efficient performance with different refrigerants, since manufacturers typically optimize the system to obtain the best performance for the specific refrigerant. The intent of this report is not to prioritize one refrigerant over another but rather to impart the magnitude of total emissions savings from the different policies.

Figure 4 shows that estimated annual emissions abatement in a few of the largest developing economies (China, India and Indonesia) if their stock of room ACs in 2030 is switched to more efficient air conditioning equipment with lower GWP refrigerant.   GHG savings of 1.7 GT/year annually would result in China, equivalent to about 17 Three Gorges Dams and 0.4 GT/year annually in India, or more than double the annual savings than India's National Solar Mission.

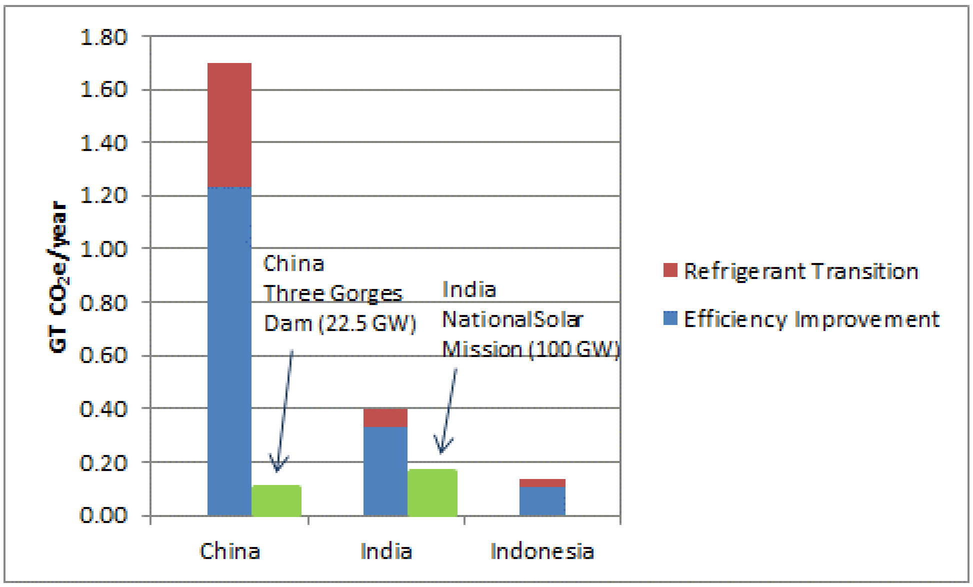

Figure 4 Estimated annual emissions abatement potential of air conditioning stock in 2030 (Source: Author's calculations)

Figure 5 shows that estimated annual emissions abatement for air conditioning equipment grows from 3.7 GT/year annually in 2030 to 7.1 GT/year in 2050 if the global stock of air conditioning equipment is switched to more efficient equipment and lower GWP refrigerants. Note that these savings assume that 100% of the global stock of air-conditioners are shifted to economic energy efficiency and low GWP refrigerants in 2030 and in all subsequent years.

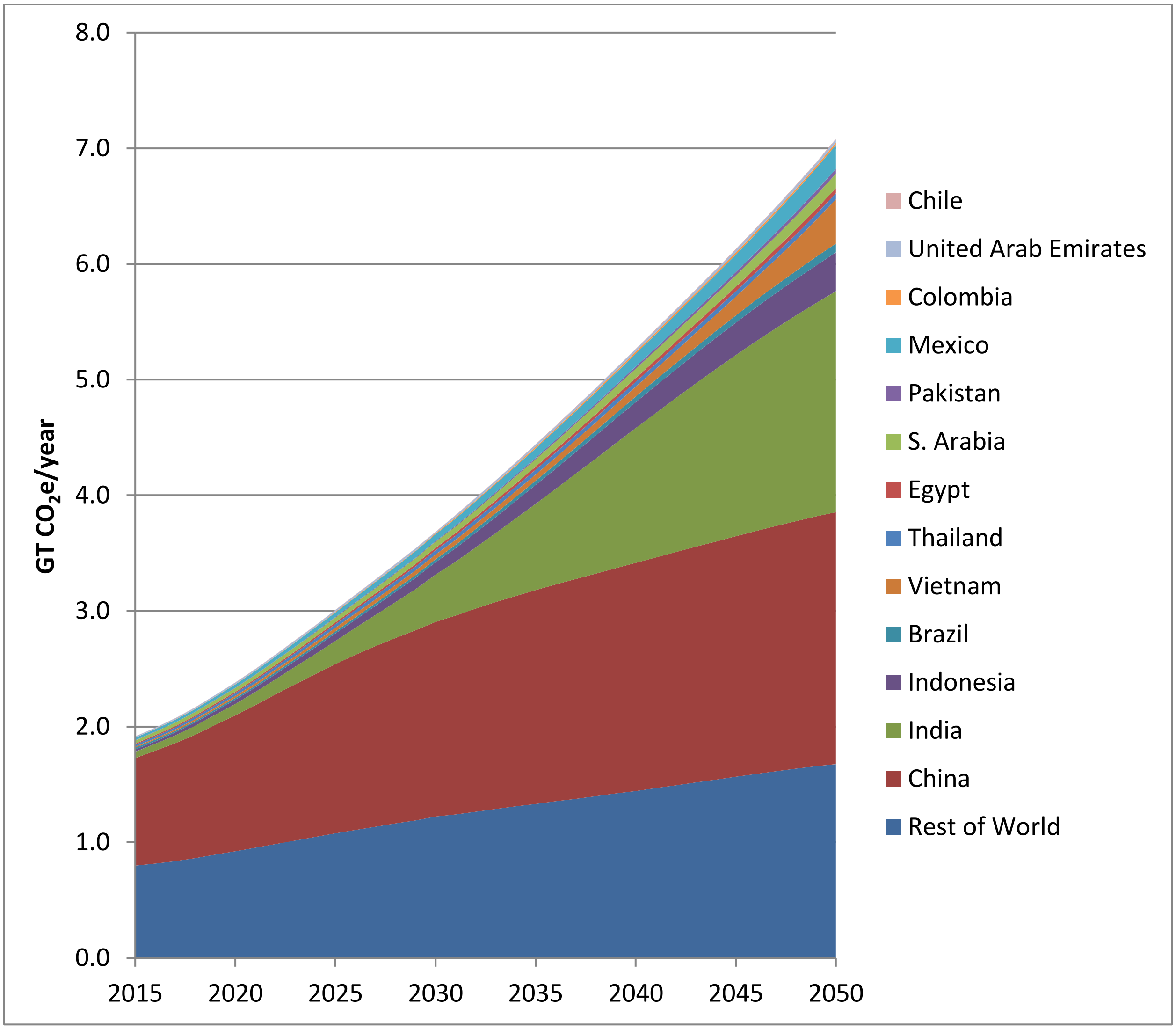

Figure 5. Estimated annual emissions abatement potential of more efficient and lower-GWP AC stock. (Source: Author's calculations)

Sensitivity of cumulative emissions reductions are shown in Tables S12 and S13 in the SI. Low growth scenarios are taken at 0.8 times the annual growth rate from the reference case, and high growth scenarios assume 1.2 times higher annual growth rate. A second sensitivity is provided for the electricity sector operating emission factor. In the reference scenario, this emissions factor is held constant for each country; while for this sensitivity case, the EF is decremented by 2% per year or to about 26% lower EF in 2030 and about 51% lower EF in 2050 from 2015 values (or roughly moving from coal-based systems to gas-based systems). Relative to the reference scenario of 240.1 Gt CO2e savings and assuming economic energy efficiency savings, the cumulative emissions reduction in GtCO2e is reduced to 145.1 Gt in the low growth and decreasing EF scenario and increased to 294.9 Gt in the high growth case (Table S12). For the best-available-technology energy efficiency case, the baseline growth cumulative savings ranges from 210.0 to 459.1 GtCO2e (Table S13).

Transition issues include the cost of alternative refrigerants, re-design/re-optimization of systems for energy consumption, overall performance, and the fact that the new air conditioning refrigerants are either slightly flammable (class A2L refrigerants) or flammable in the case of R-290. Standards and codes are in development to address the latter concern.

This work shows that combining aggressive energy efficiency in ACs and CRE can contribute to as much GHG reductions if not more than phasing out high GWP refrigerant gases. Thus, the combination of both aggressive energy efficiency and transitioning to lower GWP refrigerants can provide a significant contribution to the GHG mitigation required to avoid the 2° C threshold for increase in average global temperature. Global climate change is expected to bring greater extremes in weather conditions that could result in both higher peak and overall demand for air conditioning. Both of these topics should therefore be the subject of further study, policy mitigations, and technology planning.

Acknowledgements

This work was funded by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, and conducted at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231. The authors would also like to thank Omar Abdulaziz (Oak Ridge National Laboratory, USA), Steve Kujak (Ingersoll Rand/Trane, USA), Vaibhav Chaturvedi (Council on Energy, Environment and Water, CEEW, India), Rajendra Shende (TERRE Policy Center, India), Suely Carvalho (Instituto de Pesquisas Tecnológicas e Nucleares, IPEN, Brazil), and Karim Amrane (Air Conditioning Heating and Refrigeration Institute, AHRI) for peer review of this work and providing very useful and constructive suggestions and comments.

Author contributions: N.S. led the research team, greenhouse gas modeling and article writing; M.W. updated the greenhouse gas model, compiled data, and assisted in article writing; V.L. provided stock projections and hours of operation; A.P. provided research direction.

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Methods

The approach in this work is to construct a baseline scenario for global air conditioning and commercial refrigeration energy demand and associated GHG emissions in 2020, 2030, 2040 and 2050 and then to compare it to an alternative scenario which assumes much higher energy efficiency in cooling equipment and the use of much lower GWP refrigerants. Both scenarios assume strong growth in air conditioning and CRE demand from continuing economic growth, particularly in developing countries such as India and China. GHG emissions take into account both direct emissions related to refrigerant leakage and end-of-life refrigerant loss (i.e., venting to the atmosphere) as well as indirect emissions from the generation of electricity needed to power ACs. The impact of global warming on AC demand is not taken into account in this work but could be a very important factor in the future. We consider conventional or “in-paradigm” vapor-compression based AC equipment. Other emerging technologies, while promising, are highly uncertain in their market adoption and beyond the scope of this study.

We describe the analysis approach and assumptions for mini-split room ACs here and modeling assumptions for other products are found in the SI, For mini-splits, the base case here assumes a 1.0 ton (5.25 kW cooling capacity) mini-split air conditioner with R-410a refrigerant. A 1.0-ton unit size is a common cooling capacity in many of the markets under consideration. The baseline efficiency is assumed as an energy efficiency ratio (EER) of 2.9 W/W. Our assumption of a constant energy efficiency over time along with a fixed percentage efficiency improvement provides a result that would be similar if both the baseline efficiency and the efficiency improvement potential improved at the same rate. Other assumptions for the baseline mini-split air conditioners based on representative parameters from conventional equipment are described in the SI.

Alternative low-GWP refrigerants are being explored by industry for various sectors. For the purposes of this study, we use reported results on refrigerant performance from the Air-Conditioning, Heating, and Refrigeration Institute's Low-GWP Alternative Refrigerants Evaluation Program (AREP), augmented by sources in the general literature. (Wang and Amrane, 2014 [30]; Schultz and Kujak, 2012 [26]; Tio et al 2012 [29]; Lim and Hern, 2013 [25]; Alabdulkarem et al 2013 [22]). Alternative refrigerants include: R32, DR5, R290, ARM70a, D2Y60, HPR1D, L41a, L41b and two blends of 95% R32 with 5% R134a and 5% R152a respectively. All of these refrigerants except R290 are tested under the AREP.

Many standards and labeling programs identify the range of efficiency improvement options and quantify the total technically feasible potential and cost-effective potential for efficiency improvement in various appliances including air conditioners. Among these are the programs under the US Department of Energy (DOE, 2011), the European Commission's Ecodesign process (EuP, 2009) [6], and the Korean Energy Management Corporation (KEMCO 2015). In addition, product rating websites such as topten.info also provide a good indication of the range of efficiency improvement available for ACs. We use these sources as well as product literature and interviews with industry experts to identify the total possible efficiency improvement potential. To model feasible efficiency improvement options, we use a spreadsheet model developed for and described in more detail in Shah et al. (2013).

A separate spreadsheet model known as the Refrigerant Evaluation System- Next Generation (RESNG) was constructed to analyze the energy and greenhouse gas (GHG) benefits of refrigerant transition based on the AREP results [27. Figure 7 below shows the broad structure of the RESNG model.

The AREP test results (efficiency and cooling capacity) and results from the literature were used to calculate the annual energy consumption of the appliance with an alternate refrigerant. This was used with country-specific electricity grid CO2 intensity (is the average emission rate (kg) of CO2 emissions released per kWh of energy generated or used) and lifetime of the appliance to calculate indirect (energy related) emissions reduction from the alternate refrigerant. Separately, the GWP and charge of the alternate refrigerant, also reported by the AREP, along with assumptions on the leakage rate, end of life loss rate, base case charge size and lifetime were used to estimate the direct (leakage-related) emissions reduction. These were then added to calculate the total emissions reduction from switching to the alternate refrigerant.

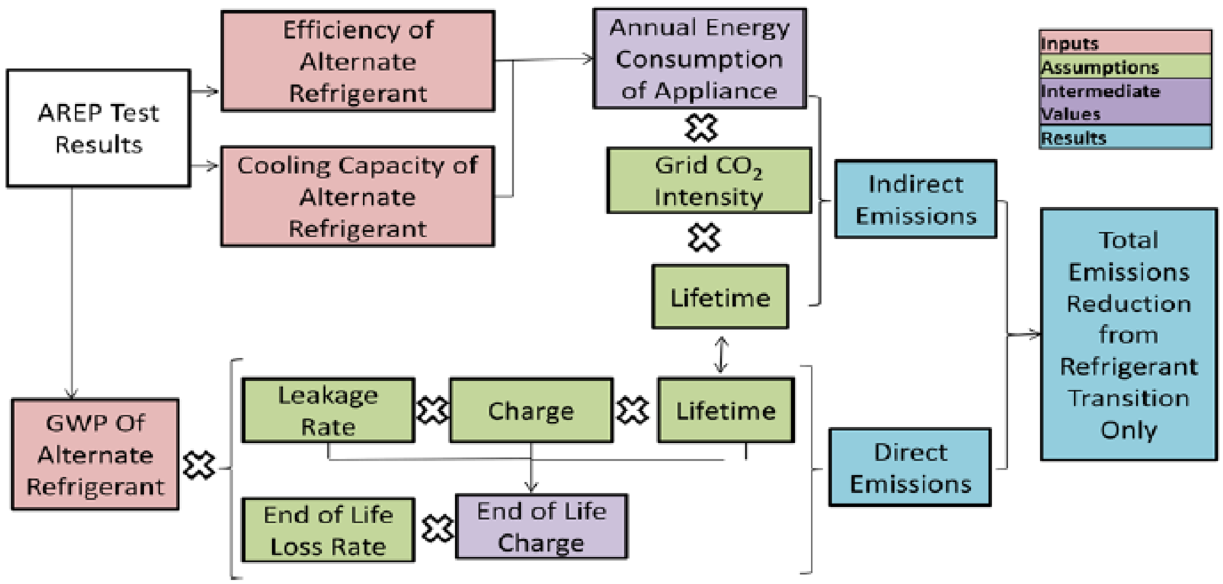

Figure 7. Structure of RESNG spreadsheet model. AREP refers to the Air-conditioning, Heating and Refrigeration Institute's (AHRI) Alternate Refrigerant Evaluation Program (AREP)

The results from these two models (efficiency and refrigerant transition) were combined for each country to give estimates of the greenhouse gas reduction benefits from:

1. Efficiency improvement only (based on 8 Shah, et al, 2013);
2. Refrigerant transition only (from RESNG modeling results for both direct and indirect emissions); and
3. Refrigerant transition and efficiency improvement implemented together (by combining the results of the first two items above.)

Since the tests conducted by the AREP are "drop-in" or "soft-optimization" tests, the results of efficiency improvement options modeled in the efficiency-only case are independent from the refrigerant transition-only case. Soft optimization testing refers to tests done on systems that are modified for the alternate refrigerants using standard production-line components. Therefore, the combined effect of both policies can be obtained by combining the results as discussed above.

References Used in Methods

Korea Energy Management Corporation (KEMCO). Database of Products registered in Energy Efficiency Standards and Labels. Accessed 15 June, 2015.
http://bpms.kemco.or.kr/efficiency_system/product/pd0020.aspx

Supplementary Information

Table S1. GHG emissions for the reference case of no efficiency improvement and baseline HFC refrigerants vs. the policy case of best-available technology (BAT) energy efficiency and low GWP refrigerants for 2030, 2040, and 2050 with static emission factors for both cases. Overall cumulative GHG savings is 373 Gt CO2e.

Sub-sector	Case	Case descriptor	Period	Cumulative GtCO2e indirect	Cumulative GtCO2e direct	Subtotal Gt CO2e	Total GtCO2e
Mini-split AC and packaged AC	Reference	Static emissions factors		246.3	37.8	284.1	587.1
VRF/ducted, chiller air-cooled, chiller water-cooled	Reference	Static emissions factors		122.2	19.5	141.7	
Domestic, Supermarket, CRE, remote condensing	Reference	Static emissions factors		121.1	40.2	161.3	
Mini-split AC and packaged AC	Policy	BAT + static EF		74.8	5.2	80.0	214.1
VRF/ducted, chiller air-cooled, chiller water-cooled	Policy	BAT + static EF		73.7	2.4	76.1	
Domestic, Supermarket, CRE, remote condensing	Policy	BAT + static EF	2030-2040 + 2040-2050 + 2050-2060	57.9	0.1	58.0	

Table S2. GHGs in CO2e split out by product sector for (1) the reference case with static grid emissions factors (conventional refrigerants and no efficiency improvement) and (2) best available technology energy efficiency and static grid emission factors. The time frame here is 2030-2050 inclusive.

Case descriptor	Sector	Sub-sector	Cumulative GtCO2e indirect	Time frame	Cumulative GtCO2e direct	TOTAL
Reference case; static emissions factors	Stationary space cooling	Mini-split AC and packaged AC	139.0	2030-2040 + 2040-2050	21.9	160.9
	Stationary space cooling	VRF/ducted, chiller air-cooled, chiller water-cooled	73.6		11.6	85.2
	Stationary Refrigeration	Domestic, Supermarket, CRE, remote condensing	89.6		24.1	113.7
BAT + static EF	Stationary space cooling	Mini-split AC and packaged AC	41.2		3.3	44.5
	Stationary space cooling	VRF/ducted, chiller air-cooled, chiller water-cooled	44.4		1.2	45.7
	Stationary Refrigeration	Domestic, Supermarket, CRE, remote condensing	51.9		0.5	52.4

1. Alternate Low-GWP Refrigerants

Since the 1830's, the air-conditioning and refrigeration industry has seen multiple transitions of refrigerants with a shift in the properties of refrigerants being sought with each generation of refrigerants, as shown in Figure S1 below. The second generation of refrigerants focused on safety and durability, the third focused on stratospheric ozone protection while the current and ongoing transition expanded this focus to climate protection, including lower global warming potential, short atmospheric lifetime and energy efficiency as key refrigerant properties. (Andersen et al. 2013; Calm, 2008)

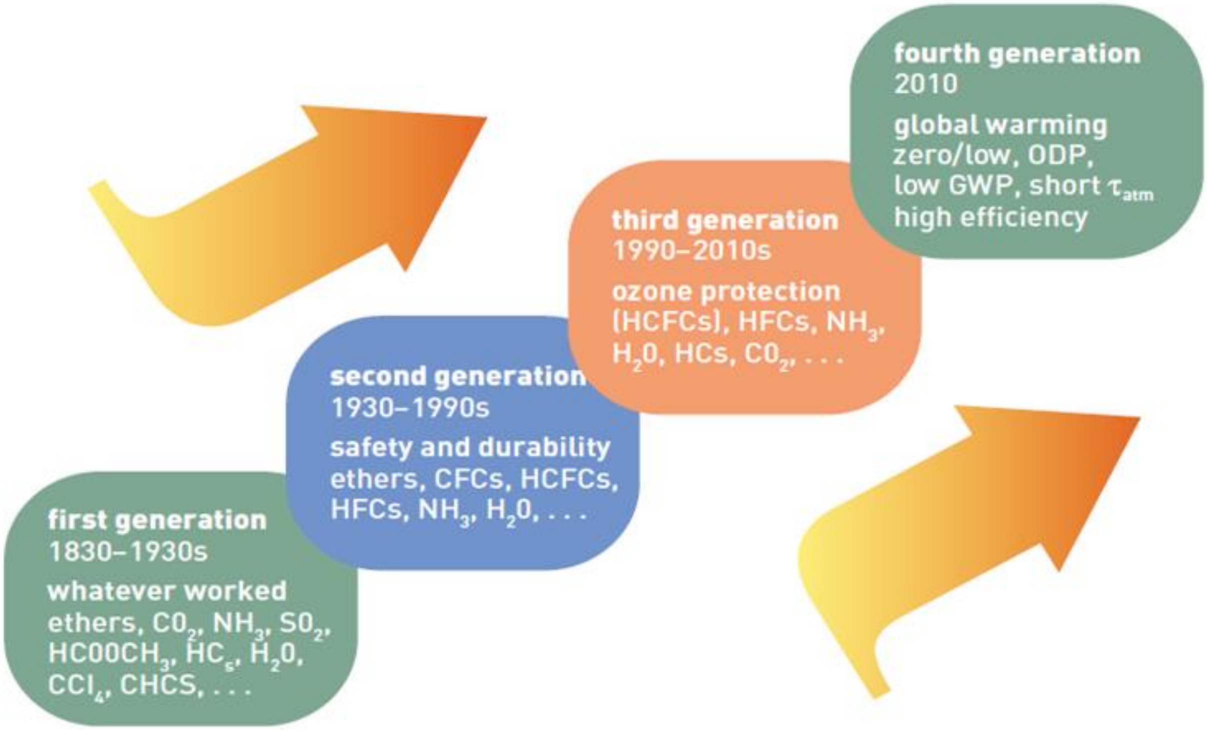

Figure S1 Evolution of refrigerant properties (Calm, 2008)

The transition from second to third generation of refrigerants under the Montreal Protocol focused on stratospheric ozone protection. This transition also indirectly led to a reduction in greenhouse gas emissions since the new alternatives to ODSs, including HFC refrigerants, typically had a lower GWP than the substances being phased out. The conspicuous exception is that R410a has a higher GWP than the HCFC R-22 it replaced in ACs. However, these HFCs still have high global warming potentials many thousands of times greater than CO_2. Table S3 below lists the most commonly used refrigerants, their corresponding global warming potentials, and sectors in which they are commonly used.

Table S3 Commonly used refrigerants and their Global Warming Potentials (GWPs)

Refrigerant	**IPCC AR5 Global Warming Potential (100-year)**	**Sectors**
R22	1760	Most refrigeration & air conditioning sectors
R134a	1300	Large chillers, refrigeration, mobile air conditioning
R404a (HFC blend)	3943	Industrial, commercial refrigeration
R410a (HFC blend)	1924	Unitary and commercial ACs,

As shown in Figure S2 below and also discussed by Velders et al. (2012), HFCs are now the fastest growing greenhouse gases in the world, growing at the rate of 10-15% per year. This trend, combined with their high global warming potential shown in Table S3 above, has led to national and regional regulations that restrict HFC uses and emissions, and a global consensus from island States, the EU-28, North America, India and the Africa group, to amend the Montreal Protocol to phase down HFCs.

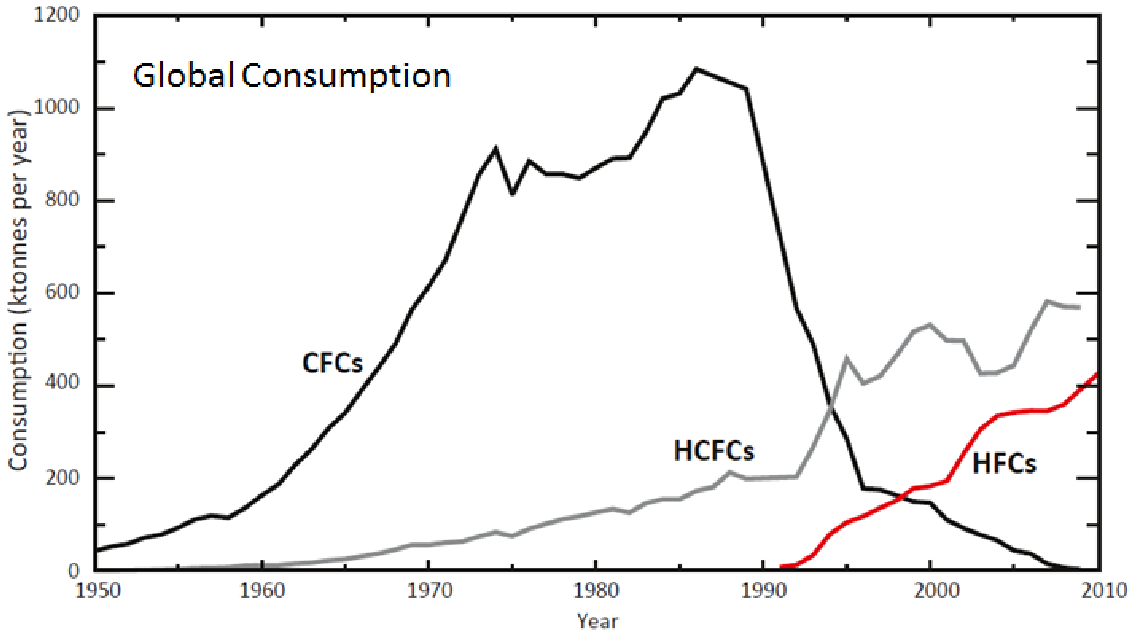

Figure S2. Global consumption of CFCs, HCFCs and HFCs (Source: UNEP, 2011)

The Kigali Amendment was approved in October 2016 and continues the practice under the Montreal Protocol of setting different control schedules for A5 and non-A5 Parties. Typically, non-A5 Parties have earlier and faster control schedules than A5 Parties that are allowed a "grace period" while new technology is commercialized and achieves economy of scale and competitive prices. The Kigali Amendment to the Montreal Protocol depicted in Figure S3 below begins the HFC phasedown in 2019 for non-A5 Parties and in 2029 for A5 Parties, providing a grace period of 10 years.

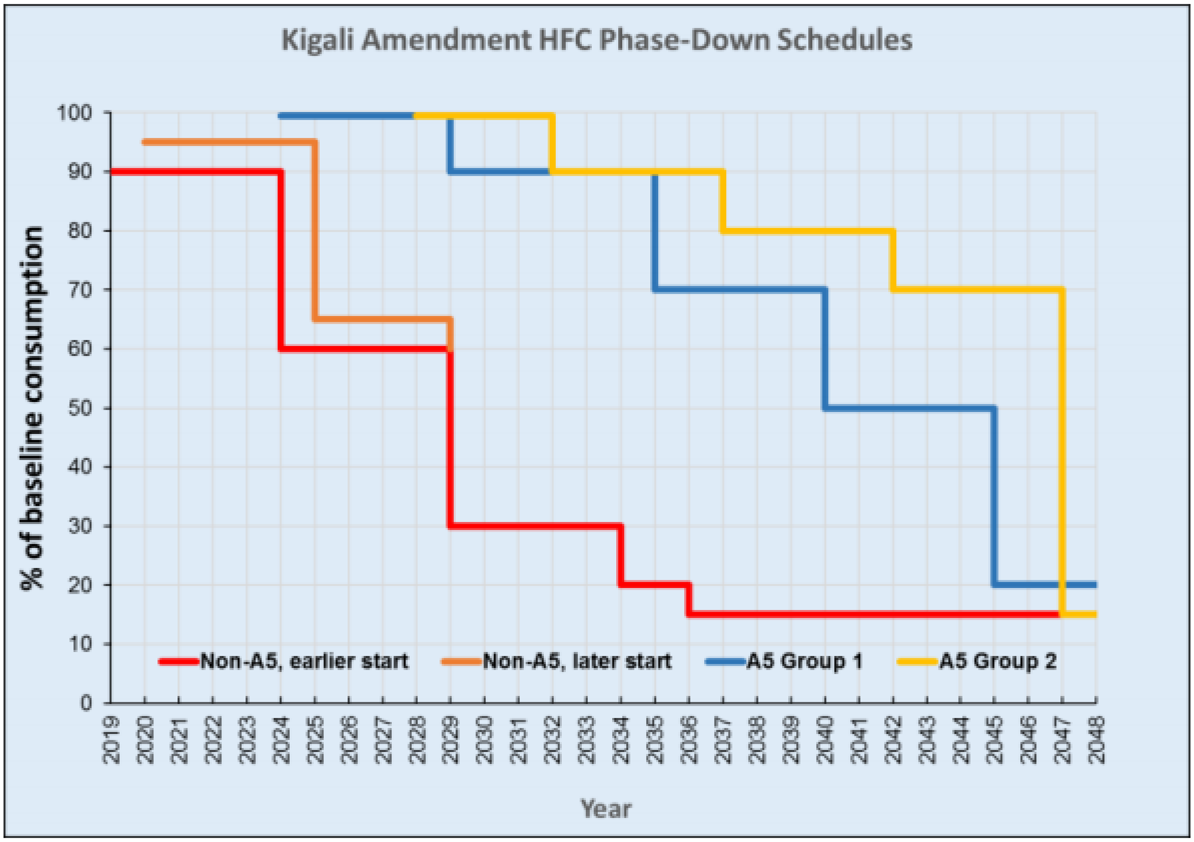

Figure S3. Kigali Amendment Schedule for HFC phasedown (ref: http://www.unep.fr/ozonaction/information/mmcfiles/7876-e-Kigali_FS01_Introduction.pdf, accessed December 13, 2018)

As a result of the growing concerns around the high global warming potential of the third generation, fast growing HFC refrigerants, in 2011, the US industry began the Air-conditioning Heating and Refrigeration Institute's (AHRI) low-GWP Alternate Refrigerant Evaluation Program (AREP). The AREP is a voluntary cooperative research and testing program to identify suitable alternatives to high-GWP refrigerants, to accelerate research on alternatives, to avoid duplicative work and to publish the results in a consistent format (Wang and Amrane, 2014). Phase 1 of the AREP was completed in 2013 and evaluated 38 candidate refrigerants through 41 tests on 31 different types of equipment. Navigant summarized the state of research, and development of alternative refrigerants in the various refrigeration and air conditioning sectors in a report for the US Department of Energy (Goetzler et al, 2014). Table S4 below summarizes the degree of development of alternative low-GWP refrigerants in the various sectors. Work is currently ongoing, both through the AREP and independently within the industry to identify suitable low-GWP candidate refrigerants. Much of the recent work ongoing activity both in the AREP and independently is to identify alternatives for residential and commercial air conditioning.

Table S4. Status of development of alternative refrigerants in various sectors (Goetzler, 2014)

Equipment Type	New Equipment				Service
	(1) Identify Refrigerants	(2) Develop Equipment	(3) Gain Regulatory Approval	(4) Address Servicing Needs	(5) Drop-in Solution Available?
Residential Refrigeration	●	●	●	○	○
Small Self-Contained Refrigeration	●	●	●	○	○
Large Self-Contained Refrigeration	●	◐	◐	◌	○
Walk-in Refrigeration	●	◐	◐	◌	○
Supermarket Refrigeration	●	◐	◐	◌	○
Residential and Light Commercial A/C	◐	◐	◐	◌	○
Large Commercial A/C	○	◌	◌	◌	○
Centrifugal Chillers	●	○	◌	◌	◐
Scroll/Screw Chillers	●	●	●	◌	○

Legend:
● = Challenge has been met ◐ = Work is on-going ○ = Immediate challenge ◌ = Future challenge

For example, of the 41 tests conducted in Phase 1 of the AREP, 18 tests were compressor calorimeter tests, 20 were system "drop-in" tests and 3 were "soft-optimization" tests.[2] Table S5 below shows the equipment types tested and the corresponding number of equipment tested under phase 1 of the AREP.

Table S5 Tests conducted under the AREP Phase 1 (Source: Wang and Amrane, 2014)

Equipment Type	Number of Equipment Tested under AREP Phase 1
Air conditioners and heat pumps	11
Chillers	4
Refrigeration	3 (1 commercial refrigerator and 2 ice machines)
Transport refrigeration	1
Bus air conditioning	2
Compressors	10

[2] Soft optimization testing refers to tests done on systems that are modified for the alternate refrigerants using standard production-line components.

Most of the current candidate refrigerants for air conditioning are either "medium-GWP", i.e., GWP in the range 400-750 or have ASHRAE flammability ratings of A2L (mildly flammable) or both (ASHRAE 2010). Tables S6 and S7 show the list of refrigerants considered and tested by the AREP as alternatives to R410a. It is important to note that *while these refrigerants indicate the compositions and kinds of refrigerant being explored, refrigerants other than these are also being explored* and may eventually be commercialized by the industry. However, for the purposes of estimating the direct and indirect emissions benefits from these refrigerants, the list of refrigerants below, along with R290, is sufficient, as the eventual choice of refrigerant(s) for ACs is likely to have similar properties and similar or lower global warming potential. In addition to the refrigerants listed below tested by AHRI, R290 (propane; GWP<5) is an additional low-GWP refrigerant we consider in this report.

Table S6. R410a alternatives tested under AREP Phase 1 (Source: AHRI, 2014)

Baseline	Refrigerant	Composition	(Mass%)	Classification	GWP_{100}
R410A GWP=1924 (IPCC AR5)	ARM-70a	R-32/R-134a/R-1234yf	(50/10/40)	A2L*	469
	D2Y60	R-32/R-1234yf	(40/60)	A2L*	271
	DR-5	R-32/R-1234yf	(72.5/27.5)	A2L*	491
	HPR1D	R-32/R-744/R-1234ze(E)	(60/6/34)	A2L*	407
	L41a	R-32/R-1234yf/R-1234ze(E)	(73/15/12)	A2L*	494
	L41b	R-32/R-1234ze(E)	(73/27)	A2L*	494
	R32	R32	100	A2L	677
	R32/R134a	R-32/R-134a	(95/5)	A2L*	708
	R32/R152a	R-32/R-152a	(95/5)	A2L*	650

* American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) flammability A2L designation is expected based on the refrigerant's properties, but has not yet been assigned by ASHRAE.

Table S7. R410a alternatives tested under AREP Phase 2 (Source: AHRI, 2016)

Baseline	Low-GWP Refrigerants	Composition	(Mass%)	Classification	GWP*
R-410A	ARM-71a	R-32/R-1234yf/R-1234ze(E)	68/26/6	A2L	460
	DR-5A (R-454B)	R-32/R-1234yf	68.9/31.1	A2L	466
	DR-55	R-32/R-125/R-1234yf	67/7/26	A2L	698
	HPR2A	R-32/134a/1234ze(E)	76/6/18	A2L	600
	L-41-1 (R-446A)	R-32/R-1234ze/R-600	68/29/3	A2L	461
	L-41-2 (R-447A)	R-32/R-1234ze/R-125	68/28.5/3.5	A2L	583

2. Energy Consumption and Energy Efficiency Assumptions by Product

Table S8. Economic potential and best-available-technology estimates for energy efficiency savings by product type utilized in this report.

Product Category	Countries	Product description	Year	UEC (kWh/yr) or (kWh/m2-yr for Remote and Integral Displays only)	Economic Potential UEC (kWh/yr)	Best Available Technology UEC (kWh/yr)	BAT Savings (%)	REF.
Mini-split AC	Brazil	1 ton	2014	2026	1418	608	70%	Shah et al. 2015, Park et al. 2017
	Chile		2014	925	648	278	70%	
	China		2014	1454	1018	436	70%	
	Colombia		2014	2335	1634	700	70%	
	Egypt		2014	2423	1696	727	70%	
	India		2014	2643	1850	793	70%	
	Indonesia		2014	2731	1912	819	70%	
	Mexico		2014	1982	1388	595	70%	
	Pakistan		2014	2114	1480	634	70%	
	S. Arabia		2014	5683	3978	1705	70%	
	Thailand		2014	2159	1511	648	70%	
	UAE		2014	5596	3917	1679	70%	
	Vietnam		2014	2863	2004	859	70%	
Packaged AC	Asia	10 ton AC	2015	27371	18755	14055	49%	G. Rosenquist 2016
	North America		2015	27371	18755	14055	49%	
	Europe		2015	27371	18755	14055	49%	
	Rest of World		2015	27371	18755	14055	49%	
VRF/ Ducted AC	Asia	7.5 ton HP	2015	11706	9950	7375	37%	G. Rosenquist 2016
	North America		2015	11706	9950	7375	37%	
	Europe		2015	11706	9950	7375	37%	
	Rest of World		2015	11706	9950	7375	37%	
Chillers, air cooled	Asia	500kW, 143 tons	~2012-2017	303,006	215,669	188,383	38%	IEA 4E (2015), DOE FEMP (2018), A. Lekov 2016
	North America	500kW, 143 tons	~2012-2017	275,460	215,669	188,383	32%	
	Europe	500kW, 143 tons	~2012-2017	162,098	107,835	94,191	42%	
	Rest of World	500kW, 143 tons	~2012-2017	243,883	215,669	188,383	23%	
Chillers, air cooled	Asia	1500kW, 429ton	~2012-2017	909,018	635,353	565,148	38%	
	North America	1500kW, 429ton	~2012-2017	826,380	635,353	565,148	32%	
	Europe	1500kW, 429ton	~2012-2017	486,293	317,676	282,574	42%	
	Rest of World	1500kW, 429ton	~2012-2017	731,649	635,353	565,148	23%	

Product Category	Countries	Product description	Year	UEC (kWh/yr) or (kWh/m2-yr for Remote and Integral Displays only)	Economic Potential UEC (kWh/yr)	Best Available Technology UEC (kWh/yr)	BAT Savings (%)	REF.
Chillers, water cooled	Asia	500kW, 143 tons	~2012-2017	181,804	125,023	89,260	51%	IEA 4E (2015), DOE FEMP (2018), A. Lekov 2016
	North America	500kW, 143 tons	~2012-2017	151,925	125,023	89,260	41%	IEA 4E (2015), DOE FEMP (2018), A. Lekov 2016
	Europe	500kW, 143 tons	~2012-2017	124,990	62,512	44,630	64%	IEA 4E (2015), DOE FEMP (2018), A. Lekov 2016
	Rest of World	500kW, 143 tons	~2012-2017	166,653	125,023	89,260	46%	IEA 4E (2015), DOE FEMP (2018), A. Lekov 2016
Chillers, water cooled	Asia	1500kW, 429ton	~2012-2017	535,671	340,973	230,907	57%	IEA 4E (2015), DOE FEMP (2018), A. Lekov 2016
	North America	1500kW, 429ton	~2012-2017	392,632	340,973	230,907	41%	IEA 4E (2015), DOE FEMP (2018), A. Lekov 2016
	Europe	1500kW, 429ton	~2012-2017	312,475	170,486	115,454	63%	IEA 4E (2015), DOE FEMP (2018), A. Lekov 2016
	Rest of World	1500kW, 429ton	~2012-2017	461,502	340,973	230,907	50%	IEA 4E (2015), DOE FEMP (2018), A. Lekov 2016
Domestic refrig-erators freezers	Asia	Average size	2015	398	334	160	60%	IEA 4E (2014); DOE (2011); Stricker (2013); UNEP (2017)
	North America		2015	495	386	263	47%	IEA 4E (2014); DOE (2011); Stricker (2013); UNEP (2017)
	Europe		2015	300	262	141	53%	IEA 4E (2014); DOE (2011); Stricker (2013); UNEP (2017)
	Rest of World		2015	349	298	151	57%	IEA 4E (2014); DOE (2011); Stricker (2013); UNEP (2017)

Product Category	Countries	Product description	Year	UEC (kWh/yr) or (kWh/m2-yr for Remote and Integral Displays only)	Economic Potential UEC (kWh/yr)	Best Available Technology UEC (kWh/yr)	BAT Savings (%)	REF.
Remote and integral display cabinets	Asia	Chilled, multi-deck (RVC2)	2014	7730	2382	1916	75%	Waide et al. (2014); DOE (2018)
	North America	Chilled, multi-deck (RVC2)	2014	5110	2382	1916	63%	Waide et al. (2014); DOE (2018)
	Europe	Chilled, multi-deck (RVC2)	2014	2738	2382	1916	30%	Waide et al. (2014); DOE (2018)
	Rest of World	Chilled, multi-deck (RVC2)	2014	3687	2382	1916	48%	Waide et al. (2014); DOE (2018)
	Asia	Frozen, open, island (RHF4)	2014	4195	3242	3242	23%	Waide et al. (2014); DOE (2018)
	North America	Frozen, open, island (RHF4)	2014	4672	3242	3242	31%	Waide et al. (2014); DOE (2018)
	Europe	Frozen, open, island (RHF4)	2014	3906	3242	3242	17%	Waide et al. (2014); DOE (2018)
	Rest of World	Frozen, open, island (RHF4)	2014	5621	3242	3242	42%	Waide et al. (2014); DOE (2018)
	Asia	Chilled, multi-deck (IVC2)	2014	11263	3866	2577	77%	Waide et al. (2014); DOE (2018)
	North America	Chilled, multi-deck (IVC2)	2014	7446	3866	2577	65%	Waide et al. (2014); DOE (2018)
	Europe	Chilled, multi-deck (IVC2)	2014	5512	3866	2577	53%	Waide et al. (2014); DOE (2018)
	Rest of World	Chilled, multi-deck (IVC2)	2014	5548	3866	2577	54%	Waide et al. (2014); DOE (2018)

Product Category	Countries	Product description	Year	UEC (kWh/yr) or (kWh/m2-yr for Remote and Integral Displays only)	Economic Potential UEC (kWh/yr)	Best Available Technology UEC (kWh/yr)	BAT Savings (%)	REF.
Remote and integral display cabinets	Asia	Chilled, glass door (IVC4)	2014	2336	1986	1635	30%	Waide et al. (2014); DOE (2018)
	North America	Chilled, glass door (IVC4)	2014	2336	1986	1635	30%	Waide et al. (2014); DOE (2018)
	Europe	Chilled, glass door (IVC4)	2014	2336	1986	1635	30%	Waide et al. (2014); DOE (2018)
	Rest of World	Chilled, glass door (IVC4)	2014	2336	1986	1635	30%	Waide et al. (2014); DOE (2018)
	Asia	Frozen, open, island	2014	9340	5548	5475	41%	Waide et al. (2014); DOE (2018)
	North America	Frozen, open, island	2014	10403	5548	5475	47%	Waide et al. (2014); DOE (2018)
	Europe	Frozen, open, island	2014	7300	5548	5475	25%	Waide et al. (2014); DOE (2018)
	Rest of World	Frozen, open, island	2014	12516	5548	5475	56%	Waide et al. (2014); DOE (2018)
	Asia	Frozen, glass lid, island (IHF6)	2014	2097	1424	1376	34%	Waide et al. (2014); DOE (2018)
	North America	Frozen, glass lid, island (IHF6)	2014	2336	1424	1376	41%	Waide et al. (2014); DOE (2018)
	Europe	Frozen, glass lid, island (IHF6)	2014	1639	1424	1376	16%	Waide et al. (2014); DOE (2018)
	Rest of World	Frozen, glass lid, island (IHF6)	2014	2409	1424	1376	43%	Waide et al. (2014); DOE (2018)

3. National and Global Market Analysis for Mini-Split ACs

We used IEA 2018 estimates for global mini-split stock projections by country and region as shown below (Fig. S4). Global stock is projected to grow from 1.19 billion units in 2015 to 4.47 billion in 2050.

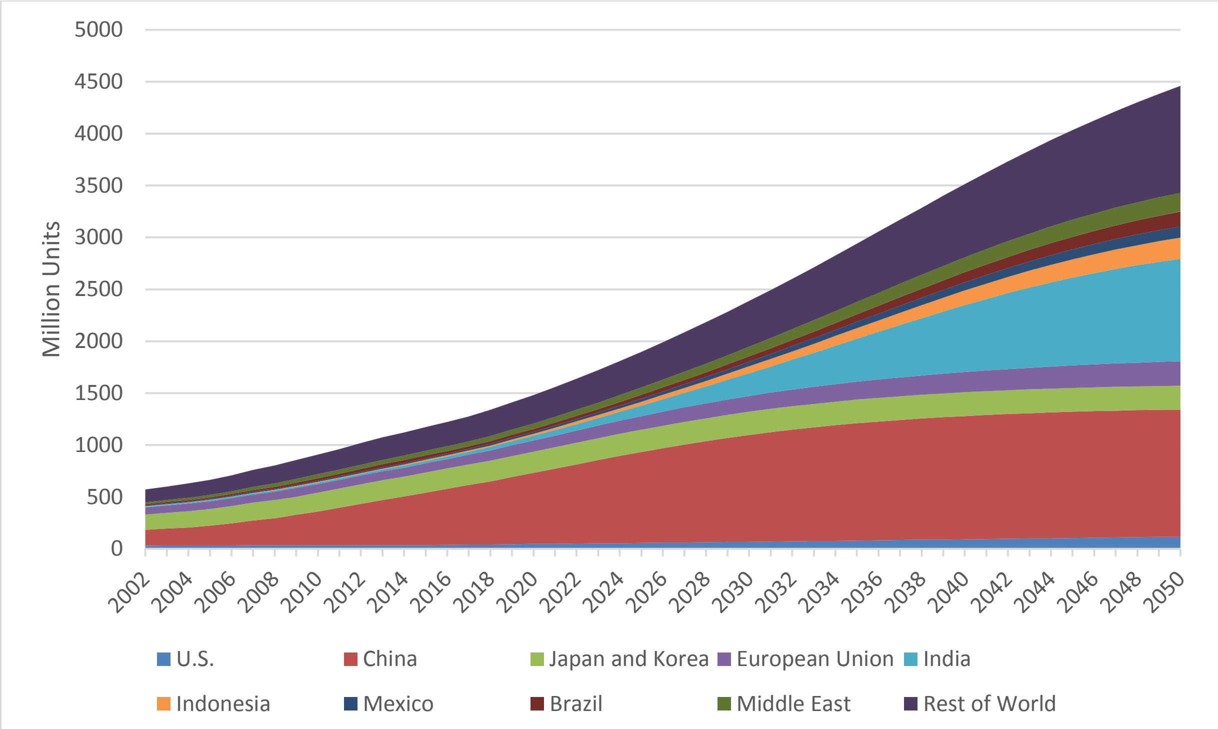

Figure S4. Estimated global growth of mini-split stock to 2050 (IEA 2018).

4. Mini-Split Energy Use Analysis

The energy use analysis provides an estimate of the annual energy consumption of a typical air conditioner for each of the countries analyzed in this study. The annual energy consumption is a function of the average cooling capacity, efficiency and hours of use.

The assumptions for baseline cooling capacity and efficiency are presented in the Methods section of the main text. The following describes the methodology to determine the hours of use in the country analyzed.

To the extent possible, we try to rely on published references to estimate the hours of use of ACs. When no data is available, we rely on a basic model of unit energy consumption developed by (McNeil and Letschert, 2010) in order to predict hours of use. The modeled UEC is a function of Cooling Degree Days and household income. In order to present equivalent hours of use, we divide the calculated UEC by the cooling capacity and efficiency. For the commercial sector, we assume 8 hours of use per business day except for very mild climate countries such as Chile. The results and sources/assumptions are presented in Table S9.

Table S9. AC usage characteristics used in BUENAS model by country

Country	Cooling Degree Days	Hours of use/day (for 365 days)	Source/Assumption
Brazil	2015	4.6	Residential Hours from UEC modeling (McNeil and Letschert, 2007), Assumes 8 hrs per day in commercial applications during half of the year
Chile	225	2.1	Residential Hours from UEC modeling (McNeil and Letschert, 2007), Assumes 8 hrs per day in commercial applications during half of the year
China	881	3.3	Residential Hours from (McNeil et al, 2012), Assumes 8 hrs per day in commercial applications
Colombia	2119	5.3	Residential Hours from UEC modeling (McNeil and Letschert, 2007), Assumes 8 hrs per day in commercial applications
Egypt	1836	5.5	Residential Hours from UEC modeling (McNeil and Letschert, 2007), Assumes 8 hrs per day in commercial applications
India	3120	6.0	Residential Hours from UEC modeling, Assumes 8 hrs per day in commercial applications
Indonesia	3545	6.2	Residential Hours from UEC modeling (McNeil and Letschert, 2007), Assumes 8 hrs per day in commercial applications
Mexico	1560	4.5	Residential Hours from UEC modeling (McNeil and Letschert, 2007), Assumes 8 hrs per day in commercial applications
Pakistan	2810	4.8	Residential Hours from UEC modeling (McNeil and Letschert, 2007), Assumes 8 hrs per day in commercial applications
S. Arabia	3136	12.9	Residential Hours from (Al-Sulaiman and Zubair, 1996); assumes 8 hrs per day in commercial applications
Thailand	3567	4.9	Residential Hours from UEC modeling (McNeil and Letschert, 2007), Assumes 8 hrs per day in commercial applications
UAE	3294	12.7	Residential Hours from UEC modeling (McNeil and Letschert, 2007), Assumes 8 hrs per day in commercial applications

Vietnam	3016	6.5	Residential Hours from UEC modeling (McNeil and Letschert, 2007), Assumes 8 hrs per day in commercial applications

Efficiency improvement has been extensively discussed in the literature and in previous studies (Shah et al, 2013, Phadke et al 2013, DOE 2011, EuP, 2009). In most of these studies efficiency improvement methods are outlined and the costs of these are estimated. Here we assume that efficiency improvement of 30% from a baseline of 2.9(W/W) EER (energy efficiency ratio) is possible based on the results of the Cooling the Planet study (Shah et al, 2013). While some fraction of the energy savings from efficiency will likely not be captured due to the "rebound effect", this result (30% efficiency improvement potential) is conservative, since we do not consider price or technological learning and since we also do not assume the maximum efficiency available on the market today.

For example, efficiency improvement of 40-50% is possible based on commercially available models on the Korean market today, as shown in Figure S5. Air conditioners that are over 50% more efficient than baseline models are available today on the global market at comparable prices to the inefficient baseline models.

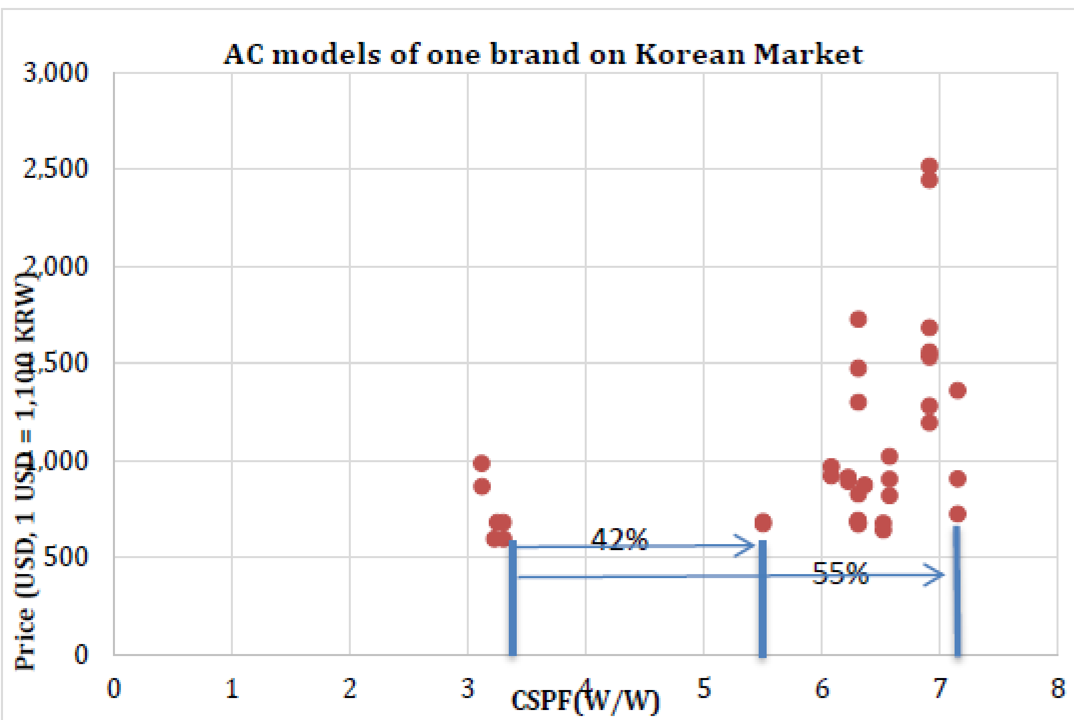

Figure S5. Efficiency of commercially available ACs of one brand on the Korean market (Source: KEMCO, 2015)[3]30

[3] Cooling Season Performance Factor (CSPF) is a metric of air conditioner energy efficiency that is calculated using a weighted average of performance at various load conditions in order to accurately reflect energy efficiency savings at part load conditions.

5. Mini-Split AC Refrigerant Charge, Leakage and End-of-Life Loss

Refrigerant Charge size

The baseline R410a mini-split air conditioning charge is taken at 1.2 kg/ton for a nominal 1-ton system, based on three mini-split specification sheets for R410a (ICP Navigator (2015), Trane Corporation (2015), American Mini-splits (2015)). Since there is a range of charge sizes found in representative systems, we utilize the average of three best fit-lines as shown in Figure S6 below.

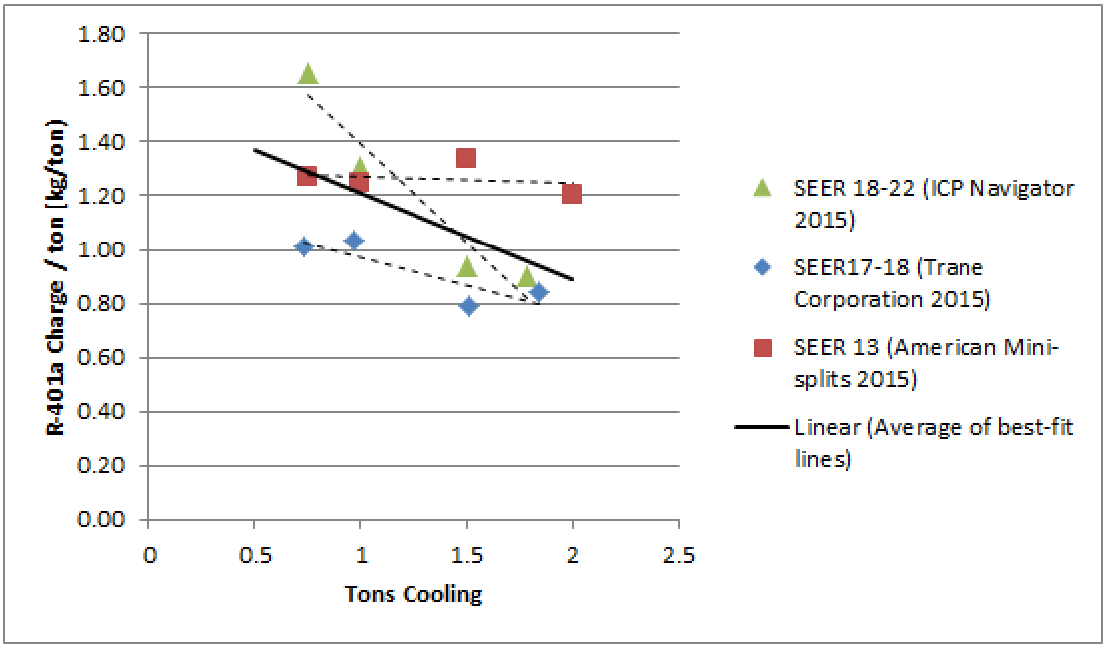

Figure S6. Charge/ton of cooling capacity for various mini-split units

The average of the three best-fit lines is shown and nominal R410a charge is found to be 1.2 kg at 1 tons cooling capacity.

Refrigerant Leakage and End of Life Charge loss

An installation emission factor of 1% and average annual operating emissions of 10% are assumed, based on Gallagher et al. (2014), and the Intergovernmental Panel on Climate Change (IPCC 2006). Operating emissions are the loss in refrigerant charge from leakage during equipment operation relative to the charge at the beginning of each year. End-of-life (EOL) charge loss is assumed to be 100% of remaining charge. This level of operating emissions is at the high end of the range of emissions given by the IPCC, but the IPCC notes that higher values of leakage (and lower values for equipment lifetime) are appropriate for developing countries. Gallagher assumes a charge loss at EOL of 56%, but we assume that no charge is recovered at EOL since these are small cooling systems and since regulations and enforcement for EOL charge recovery are lacking in virtually all countries. We note here that EOL charge recovery and handling are a very important and potentially powerful means of reducing direct emissions from refrigerants and could be pursued in conjunction with efforts to reduce the GWP of the refrigerants themselves, and our assumption of 100% loss at EOL is more an attempt to capture impact of current policies than an endorsement of them as such.

We found that many references (e.g., IIR (2015) and EPA (2014)) refer back to the IPCC (2006) data and the sources described therein for their quoted leakage loss numbers.

We present two analytical approaches for treating annual operating leakage as follows:

Gradual refrigerant loss for typical unit: In the first approach, we assume that each unit has an average operating emission loss percentage as stated (10%). We also assume that the system is recharged at 35% initial charge loss due to discernable performance loss, amounting to two recharges over the assumed 10 year lifetime of the AC. With these assumptions, the average total lifetime charge loss is 169% of initial charge.

Catastrophic refrigerant loss for a few units: In the second approach, operating emissions are assumed to be dominated by component failures such as corrosion, condenser failure, indoor or outdoor coil failure, etc. (see UNEP 2003, Section 10.3.2). The 10% annual operating emissions are thus attributed to 10% failure rate each year for an initial equipment population from a variety of failure mechanisms. When a component failure occurs, all refrigerant is assumed lost and subsequently the equipment is repaired and refrigerant is refilled to its initial value. With this set of assumptions, the average total refrigerant leakage loss is 160% of the initial refrigerant charge. Both approaches yield very similar results, and we adopt a total lifetime refrigerant loss of 170% of initial charge for new equipment. (A similar conclusion is found for a starting assumption of 5% annual operating emissions: 134% total charge loss over the equipment lifetime in the first approach and 137% in the second approach).

6. Electricity Grid CO_2 Intensity

Electricity emission factors (EFs) are shown in Table S10 by country. The 2012-2014 EF numbers are from the Institute for Global Environmental Strategies Clean Development Mechanism (IGES CDM) Project Database as of June 2, 2015 and reflect grid emission factors which have been reported for registered CDM project activities (IGES 2015). The operating EF is the kgCO_2/kWh emissions factor of current plants, and represents the EF for electricity produced at the generating source. The average of three years of data (2012-2014) was chosen to obtain a representative data set. These EFs were compared to earlier values reported by the Intergovernmental Panel on Climate Change (IPCC, 2011) and found to be in reasonable agreement. In this work we have taken the IGES CDM reported EF for most countries with the exception of Brazil. Brazil has anomalously high EF (0.408 kg CO_2/kWh) for recent data compared to the IPCC value of 0.087. A third reference source, the U.S EIA (Energy Information Administration) was consulted and the EF of 0.098 kg CO_2/kWh was found to be much closer to the IPCC value and utilized for this work (EIA 2015a). Transmission and distribution (T&D) losses and end-use EF are also shown in Table S10. T&D losses are from the World Bank (World Bank, 2015) and EF (end-use) represents the CO_2 emissions per end-use kWh or kWh at the electrical outlet.

Table S10. Electricity emission factors by country

	Operating EF, 2012-2014 ($kgCO_2e/kWh$)	Transmission and Distribution Losses (% of output) (2010-14, World Bank)	EF, End-use (kg CO2e/ kWh(end-use))
Brazil	0.098	16	0.117
Chile	0.751	7	0.807
China	1.002	6	1.066
Colombia	0.423	12	0.481
Egypt	0.592	11	0.666
India	0.981	21	1.242
Indonesia	0.808	9	0.888
Mexico	0.647	15	0.761
Pakistan	0.690	17	0.831
S. Arabia	0.654	9	0.719
Thailand	0.571	7	0.614
UAE	0.572	7	0.615
Vietnam	0.622	10	0.691

7. Additional Results for Mini-split Air Conditioning

Figure S8 shows the lifetime emissions abatement potential in 2050 if the global mini-split AC stock is transitioned to lower GWP refrigerants and a 30% energy efficiency improvement relative to current efficiency.

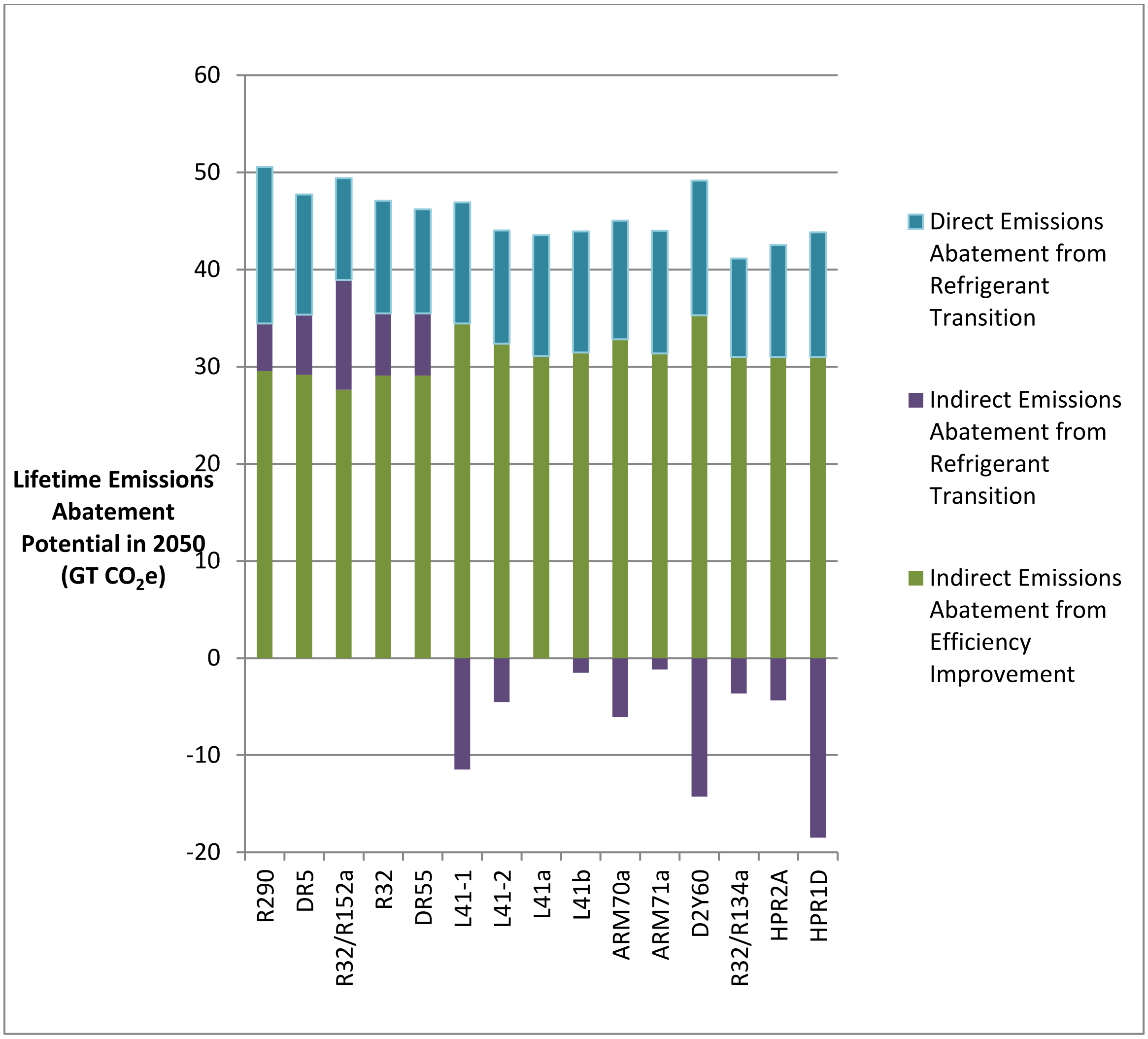

Figure S7. Estimated emissions abatement potential of mini-split AC stock in 2050 over AC lifetime compared to baseline refrigerant R-410a. (Source: Author's calculations)

Table S11 below shows the relative percent of abatement potential for mini-splits from efficiency improvement (economic energy efficiency or 30% energy efficiency improvement) and refrigerant transition for various economies. Implementing both policies together roughly doubles the GHG benefit when compared to either policy in isolation in several countries. Countries with higher hours of use and/or a more carbon-intensive grid benefit more from efficiency.

Table S11. Relative contribution to overall GHG benefits in 2030 from energy efficiency only versus refrigerant transition (Source: Author's calculations)

	% from Efficiency	% from Refrigerant Transition
Brazil	23%	77%
Chile	46%	54%
China	62%	38%
Colombia	55%	45%
Egypt	62%	38%
India	74%	26%
Indonesia	69%	31%
Mexico	61%	39%
Pakistan	64%	36%
Saudi Arabia	76%	24%
Thailand	59%	41%
United Arab Emirates	74%	26%
Vietnam	66%	34%
Global total	66%	34%

8. Assumptions for Other Types of AC Equipment

Variable Refrigerant Flow/Ducted AC systems

For VRF and ducted AC systems, baseline and low GWP alternative refrigerants and refrigerant leakage are assumed to be the same as for mini-split AC. A typical system size is assumed to be 7.5 tons based on BSRIA 2018 market reports. Baseline energy efficiency is taken as 14.6 IEER[4] with baseline UEC=11,700 kWh and economic maximum potential energy efficiency savings are estimated to be 15% and 37% respectively (Rosenquist 2016). Stock changes are projected in twelve developing countries (Brazil, Chile, China, Colombia, Egypt, India, Indonesia, Mexico, Saudi Arabia, Thailand, United Arab Emirates, and Vietnam) and the rest of the world based on IEA (2018) stock data and BSRIA (2016a).

[4] The Integrated Energy Efficiency Ratio (IEER) expresses cooling part-load EER efficiency for commercial unitary air conditioning and heat pump equipment on the basis of weighted operation at various load capacities.

Air-Cooled Chillers

For air-cooled chillers, a typical system size is assumed to be 15 tons based on BSRIA 2018 market reports. The refrigerant type for baseline chillers is taken to be R143a (GWP=1430) and an alternative refrigerant such as ARM-42A (GWP=117) [AREP 2014] is assumed for comparison. Total charge lost over the lifetime of the unit is estimated to be 99% of the initial charge. Baseline energy efficiency is taken as 10.41 IPLV[5] with baseline UEC=20,000 kWh and maximum potential energy efficiency savings estimated to be 35% [IEA 4E (2015), DOE FEMP (2018), Alex Lekov (2016)]. An economic energy efficiency savings of 27% is based on Table S8, and additional efficiency gain or loss may be realized depending on the alternative low-GWP refrigerant. Stock changes are projected in twelve developing countries (Brazil, Chile, China, Colombia, Egypt, India, Indonesia, Mexico, Saudi Arabia, Thailand, United Arab Emirates, and Vietnam) and the rest of the world based on IEA (2018) stock data and BSRIA (2016b).

Water-Cooled Chillers

For water-cooled chillers, a typical system size is assumed to be 100 tons based on BSRIA 2018 market reports. The refrigerant type for baseline chillers is taken to be R143a (GWP=1430) and an alternative refrigerant such as ARM-42A (GWP=117) [AREP 2014] is assumed for comparison. Total charge lost over the lifetime of the unit is estimated to be 99% of the initial charge. Baseline energy efficiency is taken as 20.8 IPLV with baseline UEC=67,000 kWh and maximum potential energy efficiency savings estimated to be 50% [IEA 4E (2015), DOE FEMP (2018), Alex Lekov (2016)]. An economic energy efficiency savings of 31% is based on Table S8, and additional efficiency gain or loss may be realized depending on the alternative low-GWP refrigerant. Stock changes are projected in twelve developing countries (Brazil, Chile, China, Colombia, Egypt, India, Indonesia, Mexico, Saudi Arabia, Thailand, United Arab Emirates, and Vietnam) and the rest of the world based on IEA (2018) stock data and BSRIA (2016b).

Packaged Air Conditioners

For packaged air conditioner, typical systems are assumed to be 10 tons based on BSRIA 2018 market data. Total charge lost over the lifetime of the unit is estimated to be 136% of the initial charge. Baseline and low GWP alternative refrigerants and refrigerant leakage are assumed to be the same as for mini-split AC. Baseline energy efficiency is taken as 11.0 IEER with baseline UEC= 39,500 kWh and maximum potential energy efficiency savings estimated to be 49% (Rosenquist 2016). As in mini-splits above, an economic energy efficiency savings of 30% is assumed from the baseline value here, and additional efficiency gain or loss may be realized depending on the alternative low-GWP refrigerant. Stock changes employ the same methodology as that for mini-splits above with annual stock projections based on IEA (2018).

5 IPLV stands for Integrated Part Load Value, and is a similar concept to IEER, where part-load performance is measured and rated

9. Assumptions for Commercial Refrigeration Equipment and Domestic Refrigerators

Large Centralized Refrigeration Systems (Supermarkets)

For large centralized refrigeration equipment and remote condensing units, country-level data for a large number of countries was not available. Using data for the number of supermarkets in the U.S.[6], China (USDA 2017), and India (USDA 2018), we estimated the number of supermarkets by economic development region[7] and the total number of supermarkets in the world in 2015 (n=272,000). We assume that a typical supermarket's refrigeration energy use is dominated by centralized refrigeration equipment since this configuration is typically the lowest cost implementation for these types of stores. We also assumed the following baseline parameters (NCI 2009; NCI 2015): average annual energy consumption = 900 MWh and average refrigeration charge = 909 kg. The refrigerant type for baseline systems is taken to be a mix of R-404a and R-507 (average GWP = 3953) [EPA, 2010] and the alternative refrigerant is assumed to be CO_2 (GWP=1) in a trans-critical CO_2 configuration. Total charge lost over the lifetime of the unit is estimated to be 296% of the initial charge assuming a 15-year lifetime, 18.6% annual operating loss, charge topping each year, and 20% charge loss at end-of-life (ARB 2018; ICF 2011). Economic and maximum potential energy efficiency savings estimated to be comparable to that for remote condensing units or 40% and 45%, respectively [CLASP (2014); DOE (2018)]. In the case of trans-critical all-CO_2 systems, improvements in energy efficiency have been reported in cool and mild climate with some loss in efficiency in hot climates (e.g., NCI 2015). However, recent modeling studies have indicated the possibility for equivalent to better efficiency even in very warm climates (Gullo et al. 2016; Purohit et al. 2017). Here we do not assume any additional efficiency improvement or penalty from systems based on CO_2 refrigerant that is incremental to the 30% baseline efficiency improvement assumption.

To estimate the global increase in the number of supermarkets we start with the baseline number of grocery stores in 2015, utilize annual market growth assumptions by global region until 2025 (Grandview 2018), and then assume annual growth projections as for remote condensing units from 2025 to 2050 or about 2.5% per year (Waide et al. 2014) since the Grandview study only estimates growth to 2025.

Remote Condensing Units

For remote condensing equipment, detailed country-level data was not available. EPA (2010) notes that there were approximately 34 million systems in use worldwide in 2010 with typical refrigerant charge sizes of about 10kg. We assume about 8 kg of charge per refrigeration ton (Emerson 2015); and 5500 hours of annual operation (NCI 2009). The refrigerant type for baseline systems is assumed to be the same as for centralized systems above (average GWP=3953) and the alternative refrigerant here is assumed to be a hydrocarbon such as propane (GWP=3) in a self-contained configuration. As with centralized systems, the baseline refrigerant leakage is high and lifetime charge loss is estimated to be 254% of initial charge (15% annual operating loss and 34% charge loss

[6] https://www.foodindustry.com/articles/how-many-grocery-stores-are-there-in-the-united-states/, accessed December 4, 2018.

[7] http://www.pewglobal.org/interactives/global-population-by-income/, accessed December 4, 2018.

end-of life (ARB 2018)). Economic and maximum potential energy efficiency savings is estimated to be 40% and 45% respectively [CLASP (2014); DOE (2018)]. Generally, hydrocarbon refrigerants will realize equivalent to improved energy efficiency compared to conventional HFC refrigerants. Global increases in the stock of this equipment type start with the baseline stock in 2010, utilize annual market growth assumptions by global region until 2025 (Grandview 2018), and then assume annual growth projections from 2025 to 2050 or about 2.5% per year taken from Waide et al. 2014.

Self-Contained Commercial Refrigeration Units (Integral CRE units)

For self-contained refrigeration equipment, country-level data for a large number of countries was not available. Using available data for the number of self-contained CRE units and the number of supermarkets and convenience stores in California[8] (ARB 2017) and the UK (ICF 2011, USDA 2016), we estimated the number of self-contained CRE units as a function of the number of supermarkets and convenience stores. Using data on the number of these store types in China (USDA 2017), and India (USDA 2018), we estimated the number of self-contained CRE units by economic development region across the world to estimate a total global stock of 87.4 million units in 2017.

To estimate the global increase in the number of self-contained CRE units, we started with the baseline number of units in 2017 and utilized annual market growth assumptions by global region until 2025 (Grandview 2018), and then assume annual growth projections as for remote condensing units from 2025 to 2050 or about 2.5% per year (Waide et al. 2014) since the Grandview study only estimated growth to 2025.

We assume that there are 10 million units in 2017 with hydrocarbon refrigerant[9] but that 75% of global units will utilize hydrocarbon refrigerant by 2050 in the reference case. This assumption is supported by a recent international standard development to increase the flammable charge size limit in self-contained refrigeration equipment. In May of 2019, the International Electrotechnical Commission (IEC) announced its approval of an increase in the charge limit for A3 (flammable) refrigerants to 500 g from 150 g – as well as a rise in the charge limit for A2 and A2L (low flammable) refrigerants to 1,200 g from 150 g – in self-contained commercial refrigeration cabinets under IEC standard 60335-2-89.10

Reference case refrigerants for non-R290 units are assumed to be R-134a (GWP=1430) for the 2030, 2040, 2050 savings calculations, all units are assumed to fully transition to R290.[11] Economic and technical potential savings for self-contained CRE is based on the values in Table S8. Leakage and lifetime are based on ICF 2011 and ARB 2014 (average 1 kg of refrigerant charge per unit, 0.8% annual operating loss, 70% charge loss at end-of-life, and 10 year lifetime).

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[8] https://www.foodindustry.com/articles/how-many-grocery-stores-are-there-in-the-united-states/, accessed December 4, 2018.

[9] https://www.truemfg.com/AboutUs/Natural-Refrigerant, accessed June 22, 2019

[10] http://www.hydrocarbons21.com/articles/8994/in_reversal_iec_approves_increase_of_charge_limit_for_flammable_refrigerants, accessed June 3, 2019.

[11] https://www.truemfg.com/AboutUs/Natural-Refrigerant, accessed June 22, 2019

The total GHG savings from transitioning self-contained CRE to high energy efficiency units and low GWP refrigerants is dominated by indirect emissions savings since annual charge loss is very small and since much of the production is shifting to on low GWP hydrocarbons in the near future.

Domestic Refrigerators

Unit growth for domestic refrigerators are based on the following assumptions: (1) growth in the developing world from 2015 to 2030 is based on UNEP (2017) projections; (2) there will be slowing growth in the developing world until 2050, and (3) growth in the developed world will be at the same rate as population growth. With these assumptions, units grow from 1.74 billion units in 2015 to 3.6 billion in 2050. In 2018, more than 700 million domestic refrigerators globally use R600a and by 2020, 75% of the global production will be based on R600a.[12] We assume that 75% of global stock will utilize R600a in 2050 in the reference case. Reference case refrigerants for non-R600a units are assumed to be R-134a (GWP=1430) and for the 2030, 2040, 2050 savings calculations, all units are assumed to fully transition to R600a. Annual electricity consumption, economic energy efficiency savings and best-available technology (or technical potential) savings for domestic refrigerators is based on the values in Table S8. Leakage and lifetime are based on ICF 2011 and ARB 2014 (average 0.13 kg of refrigerant charge per unit, 0.7% annual operating loss, 56% charge loss at end-of-life, and 15 year lifetime).

As in the case of self-contained CRE equipment, the total GHG savings from transitioning domestic refrigerators to high energy efficiency units and low GWP refrigerants is dominated by indirect emissions savings since overall charge size and annual loss is very small and since much of the production is expected to be based on low GWP hydrocarbons in the near future.

10. Sensitivity Analysis

Table S12. Sensitivity of cumulative emissions reductions with economic energy efficiency savings versus scenario assumptions

	Cumulative Emissions Reduction from 2030 to 2050 (billion tonnes CO_2e)	
	Baseline Operating EF (static over time)	For Operating EF decreasing at 2% per year
Low Growth	195.0	145.1
Baseline Growth	**240.1 (reference scenario in main text)**	177.9
High Growth	294.9	217.7

[12] https://www.secop.com/solutions/natural-refrigerants/, accessed 6/22/19

Table S13. Sensitivity of cumulative emissions reductions with best-available-technology energy efficiency savings.versus scenario assumptions

	Cumulative Emissions Reduction from 2030 to 2050 (billion tonnes CO_2e)	
	Baseline Operating EF (static over time)	For Operating EF decreasing at 2% per year
Low Growth	302.9	210.0
Baseline Growth	373.0	257.6
High Growth	459.1	312.4

Table S14. Total GHG reductions with economic energy efficiency savings by product type, growth scenario, and emissions factor scenario.

Product Type	Growth Scenario	Emissions Factor Scenario	Total direct and indirect GHG reductions			
			2030 (GT CO2e)	2040 (GT CO2e)	2050 (GT CO2e)	2030 + 2040 + 2050 (GT CO2e)
Mini-split AC	**Baseline**	**Baseline (static)**	**25.3**	**37.1**	**47.0**	**109.4**
	Baseline	Decreasing	20.1	25.9	29.1	75.1
	Low	Baseline	21.8	29.7	35.9	87.4
	High	Baseline	29.2	46.3	61.4	136.9
	Low	Decreasing	17.4	20.8	22.2	60.4
	High	Decreasing	23.3	32.3	38.0	93.6
Remote Condensing units	**Baseline**	**Baseline**	**10.6**	**14.1**	**17.5**	**42.2**
	Baseline	Decreasing	9.5	11.9	14.3	35.7
	Low	Baseline	9.0	11.2	13.4	33.6
	High	Baseline	12.5	17.6	22.6	52.7
	Low	Decreasing	8.1	9.6	11.0	28.7
	High	Decreasing	11.2	14.9	18.6	44.7
Supermarkets	**Baseline**	**Baseline**	**5.5**	**6.9**	**8.4**	**20.8**
	Baseline	Decreasing	5.0	6.1	7.2	18.3
	Low	Baseline	4.8	5.8	6.7	17.3
	High	Baseline	6.3	8.3	10.3	24.9
	Low	Decreasing	4.4	5.1	5.8	15.3

	High	Decreasing	5.8	7.3	8.9	22.0
VRF & Ducted AC	**Baseline**	**Baseline**	**8.0**	**9.2**	**10.3**	**27.5**
	Baseline	Decreasing	6.7	7.1	7.4	21.2
	Low	Baseline	6.8	7.6	8.3	22.6
	High	Baseline	9.5	11.1	12.7	33.3
	Low	Decreasing	5.7	5.8	6.0	17.5
	High	Decreasing	7.9	8.5	9.2	25.6
Self-contained CRE	**Baseline**	**Baseline**	***4.3***	***5.6***	***6.9***	***16.8***
	Baseline	Decreasing	3.2	3.6	3.9	10.7
	Low	Baseline	3.7	4.6	5.5	13.8
	High	Baseline	4.8	6.8	8.7	20.3
	Low	Decreasing	2.8	2.9	3.0	8.7
	High	Decreasing	3.6	4.2	4.8	12.6
Domestic Refrigerators	**Baseline**	**Baseline**	**1.6**	**1.9**	**2.2**	**5.7**
	Baseline	Decreasing	1.2	1.4	1.6	4.2
	Low	Baseline	1.3	1.5	1.8	4.6
	High	Baseline	1.9	2.3	2.6	6.8
	Low	Decreasing	1.0	1.2	1.3	3.5
	High	Decreasing	1.4	1.7	1.9	5.0
Chillers - Air cooled	**Baseline**	**Baseline**	1.9	2.8	3.7	**8.4**
	Baseline	Decreasing	1.5	2.0	2.4	5.9
	Low	Baseline	1.8	2.5	3.1	7.4
	High	Baseline	2.0	3.2	4.4	9.6
	Low	Decreasing	1.4	1.7	2.0	5.2
	High	Decreasing	1.6	2.2	2.9	6.7
Chillers- Water cooled	**Baseline**	**Baseline**	**1.6**	**2.3**	**3.1**	**7.0**
	Baseline	Decreasing	*1.3*	*1.8*	*2.2*	*5.3*
	Low	Baseline	1.5	2.1	2.7	6.3
	High	Baseline	1.6	2.6	3.7	7.8
	Low	Decreasing	1.3	1.6	1.9	4.8
	High	Decreasing	1.3	2.0	2.6	5.9
Packaged AC	**Baseline**	**Baseline**	**0.6**	**0.8**	**1.0**	**2.3**
	Baseline	Decreasing	0.4	0.5	0.6	1.5

	Low	Baseline	0.5	0.7	0.8	2.0
	High	Baseline	0.6	0.9	1.2	2.6
	Low	Decreasing	0.3	0.4	0.4	1.1
	High	Decreasing	0.4	0.6	0.7	1.7
Total	**Baseline**	**Baseline**	**59.3**	**80.7**	**100.1**	**240.1**
	Baseline	Decreasing	48.9	60.2	68.7	177.8
	Low	Baseline	51.2	65.6	78.2	195.0
	High	Baseline	68.3	99.0	127.5	294.9
	Low	Decreasing	42.4	49.1	53.6	145.1
	High	Decreasing	56.5	73.7	87.5	217.7

Table S15. Total GHG reductions with best-available-technology energy efficiency savings by product type, growth scenario, and emissions factor scenario.

Product Type	Growth Scenario	Emissions Factor Scenario	Total direct and indirect GHG reductions			
			2030 (GT CO2e)	2040 (GT CO2e)	2050 (GT CO2e)	2030 + 2040 + 2050 (GT CO2e)
Mini-split AC	**Baseline**	**Baseline (static)**	**46.4**	**68.1**	**86.3**	**200.8**
	Baseline	Decreasing	35.4	44.3	48.1	127.8
	Low	Baseline	40.1	54.6	65.9	160.6
	High	Baseline	53.6	84.9	112.6	251.1
	Low	Decreasing	30.6	35.5	36.7	102.8
	High	Decreasing	40.9	55.2	62.8	158.9
Remote Condensing units	**Baseline**	**Baseline**	**12.2**	**16.1**	**20.0**	**48.3**
	Baseline	Decreasing	11.0	13.8	16.5	41.3
	Low	Baseline	10.4	12.9	15.4	38.7
	High	Baseline	14.4	20.2	26.0	60.6
	Low	Decreasing	9.3	11.0	12.7	33.0
	High	Decreasing	12.9	17.2	21.4	51.5
Supermarkets	Baseline	Baseline	**5.7**	**7.2**	**8.7**	**21.6**
	Baseline	Decreasing	5.2	6.3	7.4	18.9
	Low	Baseline	5.0	6.0	7.0	18.0
	High	Baseline	6.6	8.6	10.7	25.9

	Low	Decreasing	4.5	5.2	5.9	15.6
	High	Decreasing	6.0	7.5	9.1	22.6
VRF & Ducted AC	**Baseline**	**Baseline**	**12.8**	**14.6**	**16.4**	**43.9**
	Baseline	Decreasing	10.2	10.4	10.7	31.3
	Low	Baseline	10.9	12.1	13.3	36.2
	High	Baseline	15.1	17.7	20.3	53.2
	Low	Decreasing	8.6	8.6	8.6	25.9
	High	Decreasing	12.0	12.6	10.5	35.1
Self-contained CRE	**Baseline**	**Baseline**	**5.3**	**7.0**	**8.7**	**21.0**
	Baseline	Decreasing	4.0	4.4	4.8	13.2
	Low	Baseline	4.7	5.8	6.9	17.4
	High	Baseline	6.1	8.5	10.9	25.5
	Low	Decreasing	3.5	3.6	3.8	10.9
	High	Decreasing	4.5	5.2	6.0	15.7
Domestic Refrigerators	**Baseline**	**Baseline**	**4.7**	**5.5**	**6.3**	**16.5**
	Baseline	Decreasing	3.5	4.1	4.7	12.3
	Low	Baseline	3.7	4.4	5.1	13.2
	High	Baseline	5.6	6.6	7.5	19.7
	Low	Decreasing	2.8	3.3	3.8	9.9
	High	Decreasing	4.1	4.9	5.6	14.6
Chillers - Air cooled	***Baseline***	***Baseline***	**2.4**	**3.6**	**4.8**	**10.8**
	Baseline	*Decreasing*	1.9	2.4	3.0	7.3
	Low	*Baseline*	2.3	3.2	4.0	9.5
	High	*Baseline*	2.5	4.1	5.7	12.3
	Low	*Decreasing*	1.8	2.2	2.5	6.5
	High	*Decreasing*	2.0	2.8	3.6	8.3
Chillers- Water cooled	**Baseline**	**Baseline**	2.4	3.6	4.9	**10.9**
	Baseline	Decreasing	1.9	2.5	3.2	7.6
	Low	Baseline	2.4	3.3	4.2	9.8
	High	Baseline	2.5	4.1	5.7	12.2
	Low	Decreasing	1.9	2.3	2.7	6.9
	High	Decreasing	2.0	2.8	3.7	8.5
Packaged AC	**Baseline**	**Baseline**	**0.8**	**1.1**	**1.4**	**3.3**

	Baseline	Decreasing	0.6	0.7	0.8	2.1
	Low	Baseline	0.8	1.0	1.2	2.9
	High	Baseline	0.8	1.3	1.7	3.8
	Low	Decreasing	0.6	0.6	0.7	1.9
	High	Decreasing	0.6	0.8	1.0	2.4
Total	**Baseline**	**Baseline**	**91.8**	**125.5**	**155.8**	**373.0**
	Baseline	Decreasing	72.6	87.6	97.5	257.6
	Low	Baseline	79.3	102.0	121.6	302.9
	High	Baseline	106.0	154.3	198.9	459.1
	Low	Decreasing	62.7	71.2	76.1	210.0
	High	Decreasing	83.7	107.2	121.4	312.4

Table S16. Summary data for 30% energy efficiency case, baseline growth and electricity grid emissions factors.

Product Type	Life-time	Cap-acity in tons	Pct. Leakage of Init. Charge	Hours - op./yr.	Total direct and indirect GHG reductions				Pct. of 2030 + 2040 + 2050	Direct savings	Indirect Savings
					2030 (GT CO2e)	2040 (GT CO2e)	2050 (GT CO2e)	2030 + 2040 + 2050 (GT CO2e)			
Mini-split AC	10	1	170%	Varies by country	25.3	37.1	47.0	109.4	44.5%	34%	66%
Remote Condensing units	15	7.5	169%	3000	11.3	12.9	14.5	38.7	*15.7%*	31%	69%
VRF & Ducted AC	15	Varies	239%	5500	9.6	12.7	15.7	38.0	15.5%	67%	33%
Supermarkets	15	100	263%	5500	5.0	6.4	7.7	19.1	7.8%	75%	26%
Self-contained refrigeration units	10	Varies	28%	Varies by country	3.3	4.3	5.4	13.0	5.3%	1%	99%
Domestic Refrigerators	15	Varies	40%	Varies by country	2.7	3.1	3.6	9.4	3.8%	2.1%	97.9%

Chillers - Air cooled	15	15	99%	2000	2.1	3.1	4.1	9.2	3.7%	27%	73%
Chillers- Water cooled	15	100	99%	2000	1.5	2.3	3.0	6.8	2.8%	26%	74%
Packaged AC	15	10	136%	3000	0.6	0.8	1.0	2.3	0.9%	11%	89%
Total					61.3	82.6	101.9	245.9	100%	38%	62%

Table S17. Summary data for 40% energy efficiency case, baseline growth and electricity grid emissions factors.

Product Type	**Life-time**	**Cap-acity in tons**	**Pct. Leakage of Init. Charge**	**Hours - op./yr.**	**Total direct and indirect GHG reductions**				**Pct. of 2030 + 2040 + 2050**	**Direct savings**	**Indirect Savings**
					2030 (GT CO2e)	**2040 (GT CO2e)**	**2050 (GT CO2e)**	**2030 + 2040 + 2050 (GT CO2e)**			
Mini-split AC	10	1	170%	Varies by country	30.5	44.9	56.8	132.2	44.9%	27%	73%
VRF & Ducted AC	15	7.5	169%	3000	13.5	15.4	17.3	46.2	*15.7%*	27%	73%
Remote Condensing units	15	Varies	239%	5500	10.6	14.1	17.5	42.2	14.3%	61%	39%
Supermarkets	15	100	263%	5500	5.5	6.9	8.4	20.8	7.1%	69%	31%
Self-contained refrigeration units	10	Varies	28%	Varies by country	4.4	5.7	7.1	17.2	5.8%	1%	99%
Domestic Refrigerators	15	Varies	40%	Varies by country	3.5	4.2	4.8	12.5	4.2%	1.6%	98.4%
Chillers - Air cooled	15	15	99%	2000	2.7	4.0	5.2	11.9	4.0%	25%	75%
Chillers- Water cooled	15	100	99%	2000	1.9	2.9	3.8	8.6	2.9%	22%	78%

Packaged AC	15	10	136%	3000	0.7	0.9	1.2	2.8	1.0%	9%	91%
Total					73.2	98.9	122.2	294.3	100%	32%	68%

Table S18. Summary data for 50% energy efficiency case, baseline growth and electricity grid emissions factors.

Product Type	Life-time	Cap-acity in tons	Pct. Leakage of Init. Charge	Hours - op./yr.	Total direct and indirect GHG reductions				Pct. of 2030 + 2040 + 2050	Direct savings	Indirect Savings
					2030 (GT CO2e)	2040 (GT CO2e)	2050 (GT CO2e)	2030 + 2040 + 2050 (GT CO2e)			
Mini-split AC	10	1	170%	Varies by country	35.8	52.6	66.6	155.0	45.2%	23%	78%
VRF & Ducted AC	15	7.5	169%	3000	15.7	17.9	20.1	53.6	15.7%	24%	76%
Remote Condensing units	15	Varies	239%	5500	11.7	15.4	19.2	46.3	13.5%	55%	45%
Supermarkets	15	100	263%	5500	5.9	7.5	9.0	22.4	6.5%	64%	36%
Self-contained refrigeration units	10	Varies	28%	Varies by country	5.4	7.2	8.9	21.5	6.3%	1%	100%
Chillers - Air cooled	15	12	99%	2000	3.25	4.83	6.41	14.49	4.2%	23%	77%
Domestic Refrigerators	15	Varies	40%	Varies by country	4.4	5.2	5.9	15.5	4.5%	1.3%	98.7%
Chillers-Water cooled	15	100	99%	2000	2.29	3.46	4.63	10.38	3.0%	19%	81%
Packaged AC	15	10	136%	3000	0.81	1.12	1.43	3.36	1.0%	8%	92%
Total					85.2	115.2	142.1	342.6	100%	27%	73%

Table S19. Summary data for Economic energy efficiency case, baseline growth and electricity grid emissions factors.

Product Type	Life-time	Cap-acity in tons	Pct. Leakage of Init. Charge	Hours - op./yr.	Total direct and indirect GHG reductions				Pct. of 2030 + 2040 + 2050	Direct savings	Indirect Savings
					2030 (GT CO2e)	2040 (GT CO2e)	2050 (GT CO2e)	2030 + 2040 + 2050 (GT CO2e)			
Mini-split AC	10	1	170%	Varies by country	25.3	37.1	47.0	109.4	45.6%	34%	66%
Remote Condensing units	15	Varies	239%	5500	10.6	14.1	17.5	42.2	17.6%	61%	34%
VRF & Ducted AC	15	7.5	169%	3000	8.0	9.2	10.3	27.5	11.4%	42%	58%
Supermarkets	15	100	263%	5500	5.5	6.9	8.4	20.8	8.7%	69%	31%
Self-contained refrigeration units	10	Varies	28%	Varies by country	4.3	5.6	6.9	16.8	7.0%	1%	99%
Chillers - Air cooled	15	15	99%	2000	1.9	2.8	3.7	8.4	3.5%	28%	72%
Chillers- Water cooled	15	100	99%	2000	1.6	2.3	3.1	7.0	2.9%	26%	74%
Domestic Refrigerators	15	Varies	40%	Varies by country	1.6	1.9	2.2	5.7	2.4%	3.5%	96.5%
Packaged AC	15	10	136%	3000	0.6	0.8	1.0	2.3	1.0%	11%	89%
Total					59.3	80.7	100.1	240.1	100%	39%	61%

Table S20. Summary data for Best Available Technology (BAT) energy efficiency case, baseline growth and electricity grid emissions factors.

Product Type	Life-time	Cap-acity in tons	Pct. Leakage of Init. Charge	Hours - op./yr.	Total direct and indirect GHG reductions				Pct. of 2030 + 2040 + 2050	Direct savings	Indirect Savings
					2030 (GT CO2e)	2040 (GT CO2e)	2050 (GT CO2e)	2030 + 2040 + 2050 (GT CO2e)			
Mini-split AC	10	1	170%	Varies by country	46.4	68.1	86.3	200.8	53.8%	16%	84%
Remote Condensing units	15	Varies	239%	5500	11.2	14.7	18.3	44.2	11.8%	58%	42%
VRF & Ducted AC	15	7.5	169%	3000	12.8	14.6	16.4	43.9	11.8%	28%	72%
Supermarkets	15	100	263%	5500	5.7	7.2	8.7	21.6	5.8%	66%	34%
Self-contained refrigeration units	10	Varies	28%	Varies by country	5.3	7.0	8.7	21.0	5.6%	1%	100%
Domestic Refrigerators	15	Varies	40%	Varies by country	4.7	5.5	6.3	16.5	4.4%	1.2%	98.8%
Chillers-Water cooled	15	100	99%	2000	2.41	3.64	4.86	10.910	2.9%	18.4%	81.6%
Chillers - Air cooled	15	15	99%	2000	2.42	3.59	4.77	10.78	2.9%	26.0%	74%
Packaged AC	15	10	136%	3000	0.79	1.1	1.41	3.3	0.9%	8%	92%
Total					91.8	125.5	155.8	373.0	100%	24%	76%

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