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Leapfrogging to Super-efficiency and Low Global Warming Potential Refrigerants in Air Conditioning

Recent Results and Further Work

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May 17, 2016

EXPERTS' GROUP ON R&D PRIORITY-SETTING AND EVALUATION

International Energy Agency, Paris, France

Introduction to Lawrence Berkeley National Laboratory

Managed by the University of California for
the United States Department of Energy

BERKELEY LAB
Lawrence Berkeley
National Laboratory

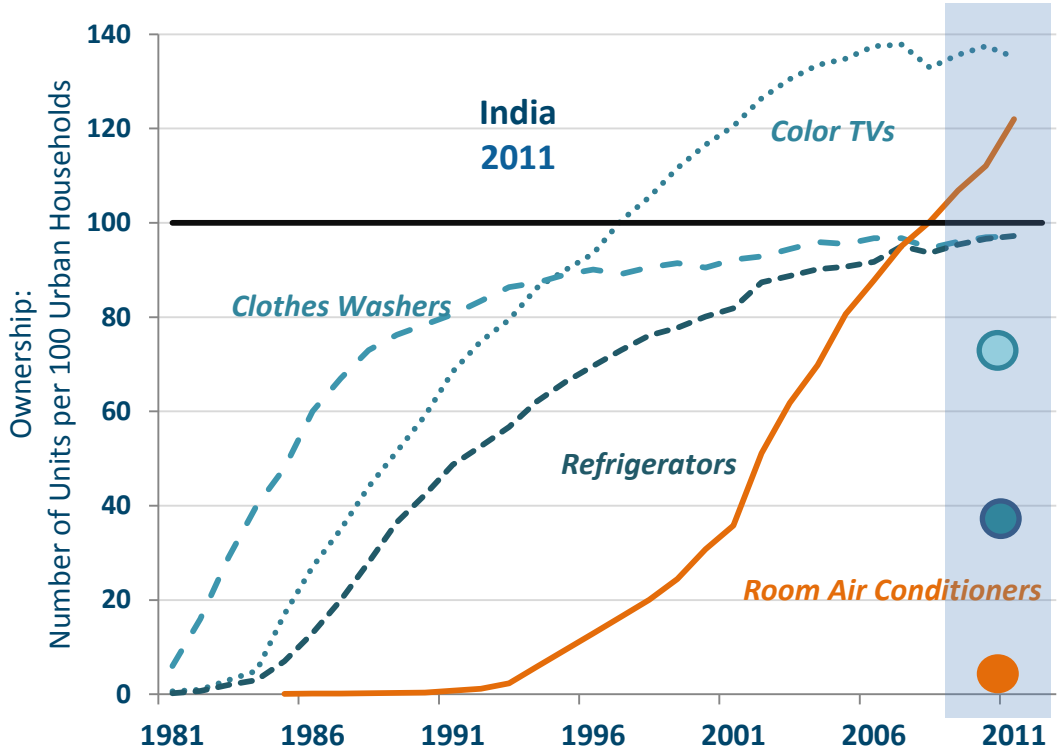
13 — Nobel Prizes
13 — National Medal of Science recipients
4,200 — Employees
200 — Site acreage

- **Dedicated to solving the most pressing scientific problems facing humankind**
- **Research, technical assistance on clean energy technologies and policies**
- **More than two decades of history of work internationally on power, appliances, industry, buildings, transport, air quality, and climate policy**
- **Significant focus on energy efficiency**
- **Technical Support to US DOE Appliance Standards Rulemakings**

Outline

- Motivation and Recent Trends
- Methodology and Assumptions
- Draft Results
- Summary, next steps, discussion

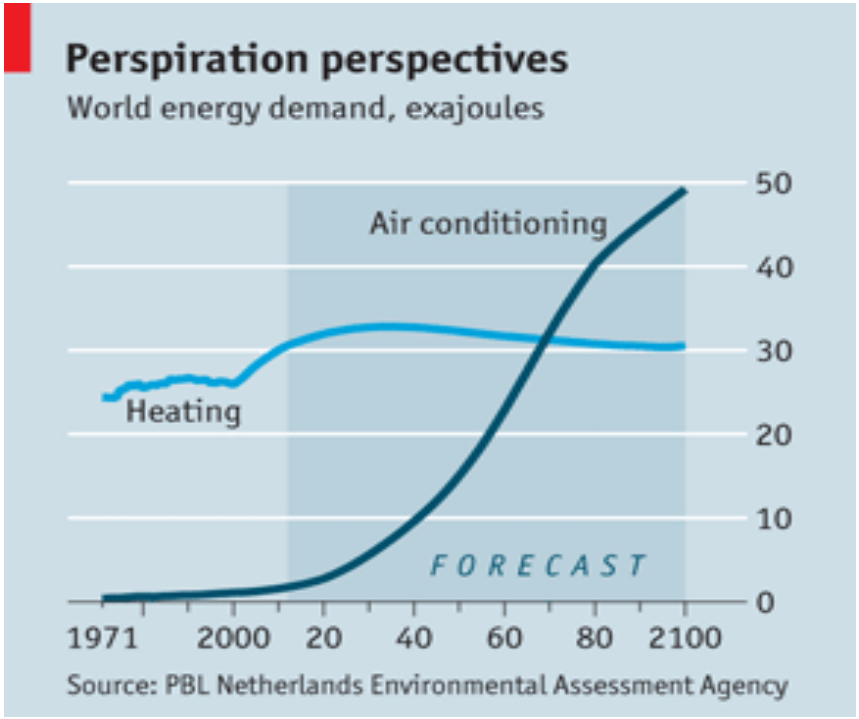
Growth in China's AC market

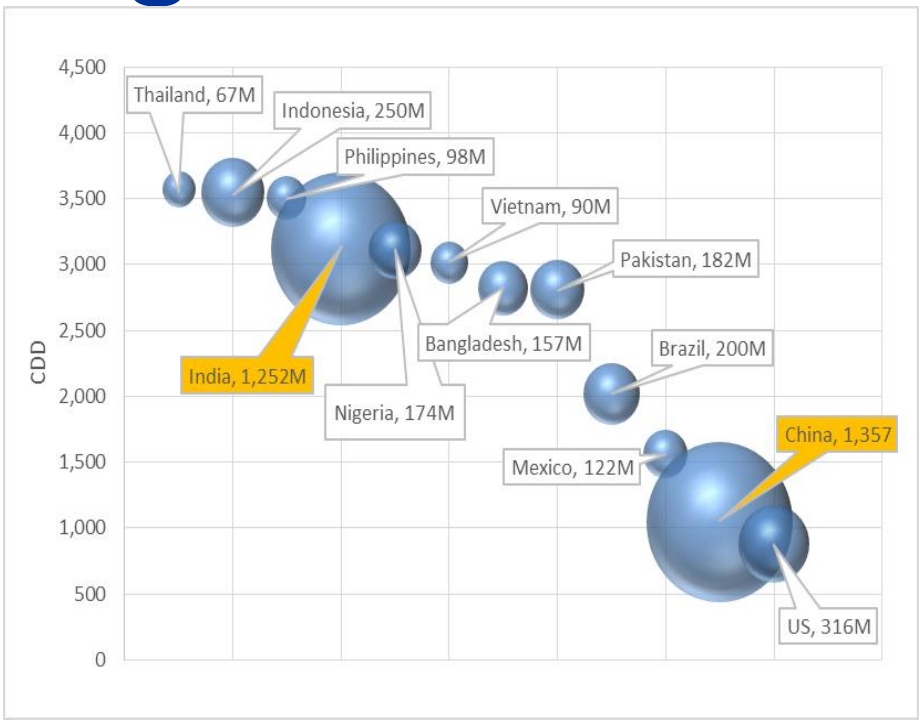


Source: NSSO, 2012, Fridley et al., 2012

- The AC ownership rate in urban China went from almost 0% in 1990s to over 100% in ~15 years(Fridley, 2012, 2015).
- AC sales in major emerging economies are growing at rates similar to China circa 1994–1995, e.g., India room AC sales growing at ~10-15%/year, Brazil at ~20%/year (Shah et al., 2013).

Future cooling needs

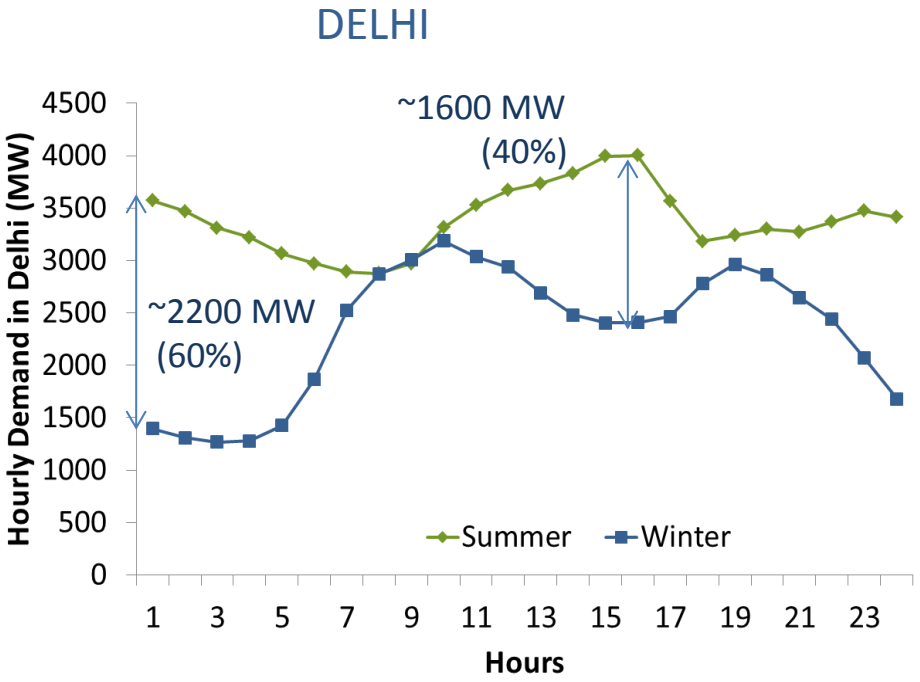




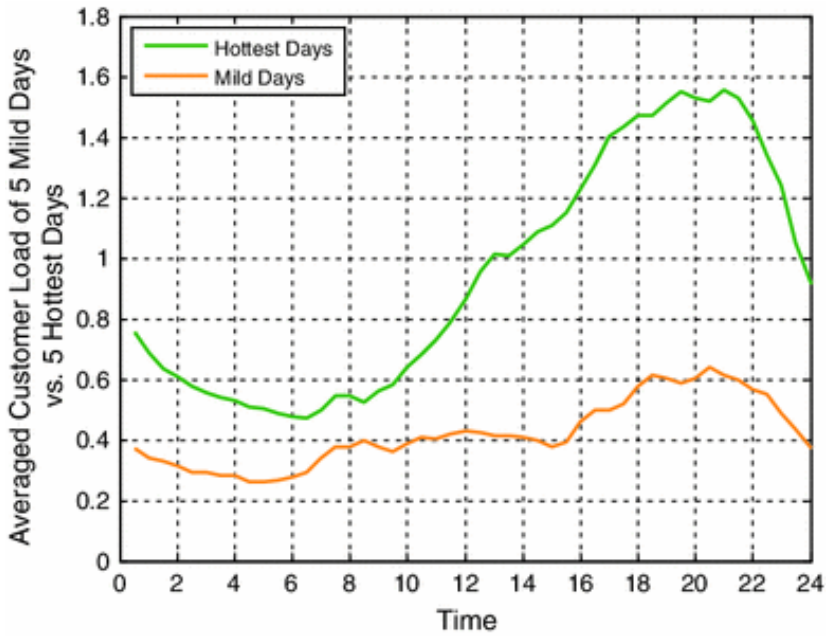
Source: Davis et al, Proceedings of the National Academy of Sciences, 2015

- India, South East Asia, and Brazil all have much higher cooling needs (indicated as cooling degree days) compared to China.
- China today is a ~50 million/year AC market, ~80GW of connected load added per year, ~120 ACs per 100 urban households

Cooling has a Significant Peak Load Impact



Source: DSLDC, 2012



Ausgrid, Australia

Source: Smith et al., 2013

Cooling comprises 40%–60% of summer peak load in large metropolitan cities with hot climates, such as Delhi, India …

…and can triple load on the hottest days in some areas, e.g., New South Wales, Australia.

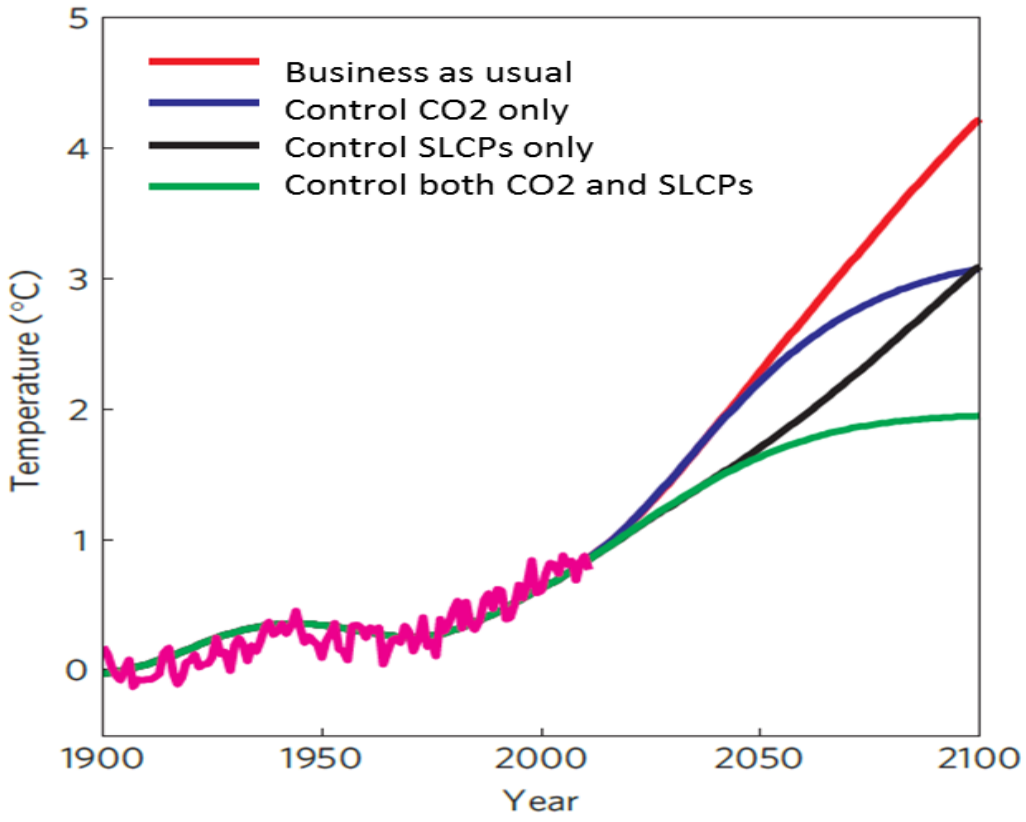
North American Proposal to the Montreal Protocol

Refrigerant	100 yr GWP
R134a (HFC)	1430
R404A (HFC)	3900
R410A (HFC)	2100
R22 (HCFC)	1810

Source: 2013 Proposed amendment to the Montreal Protocol submitted by Canada, Mexico and the United States of America
http://conf.montreal-protocol.org/meeting/oewg/oewg-33/presession/PreSession%20Documents/OEWG-33-3E.pdf

- Canada, Mexico and the US as well as the Federated States of Micronesia proposed amendments to the Montreal Protocol to phasedown HFCs in 2013, followed by the EU.
- Montreal Protocol seen as a successful model of international environmental treaty with financing, implementation in place and universal ratification.
- **Large AC markets, high ambient temperatures have concern over availability of alternate refrigerants for airconditioning.**

Control of CO_2 *and* HFC emissions needed



Source: Hu et al, 2013, Nature Climate Change

Does the Dubai pathway bring a win-win opportunity to reduce *both CO_2 and HFC emissions* in air conditioning?

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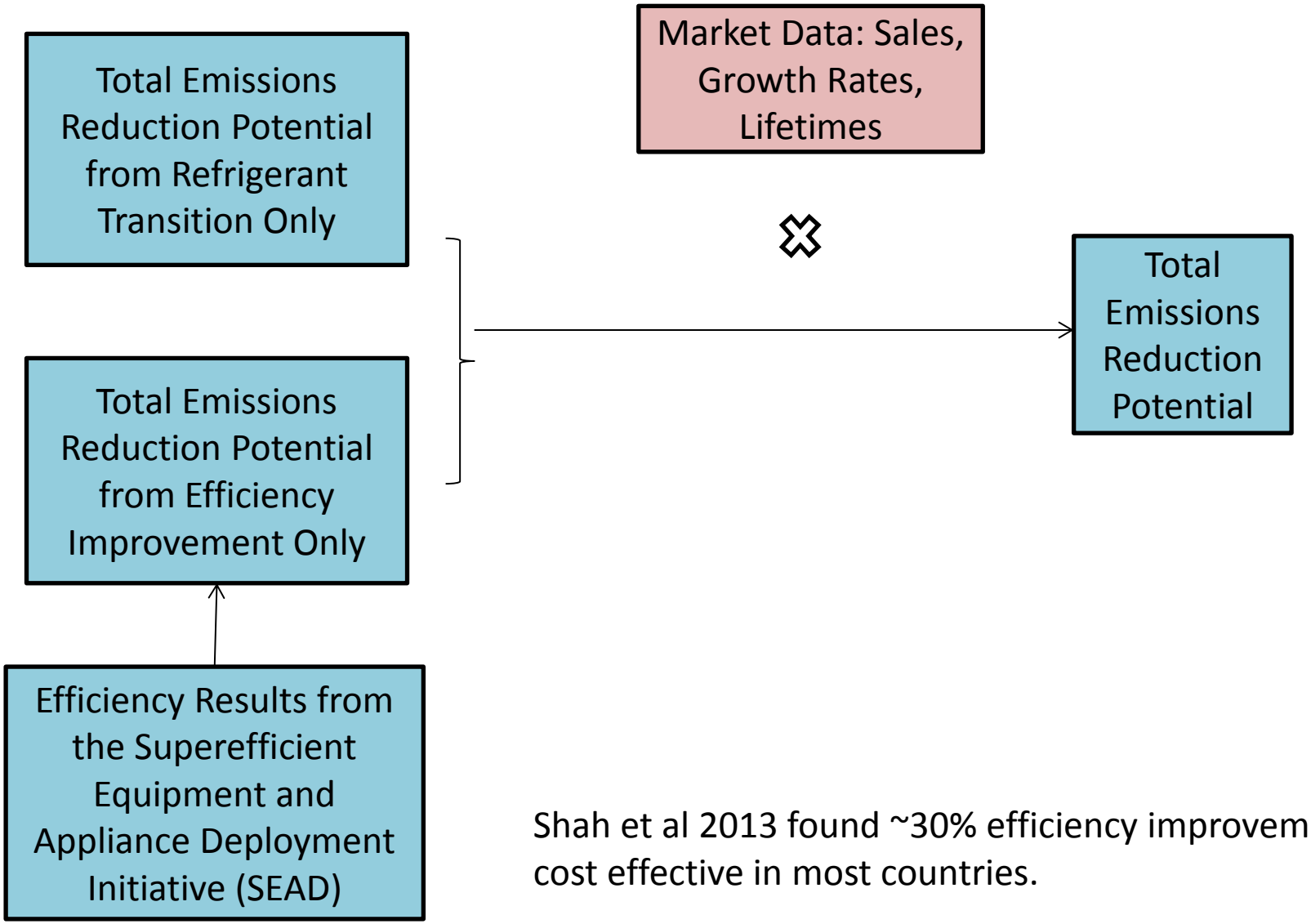
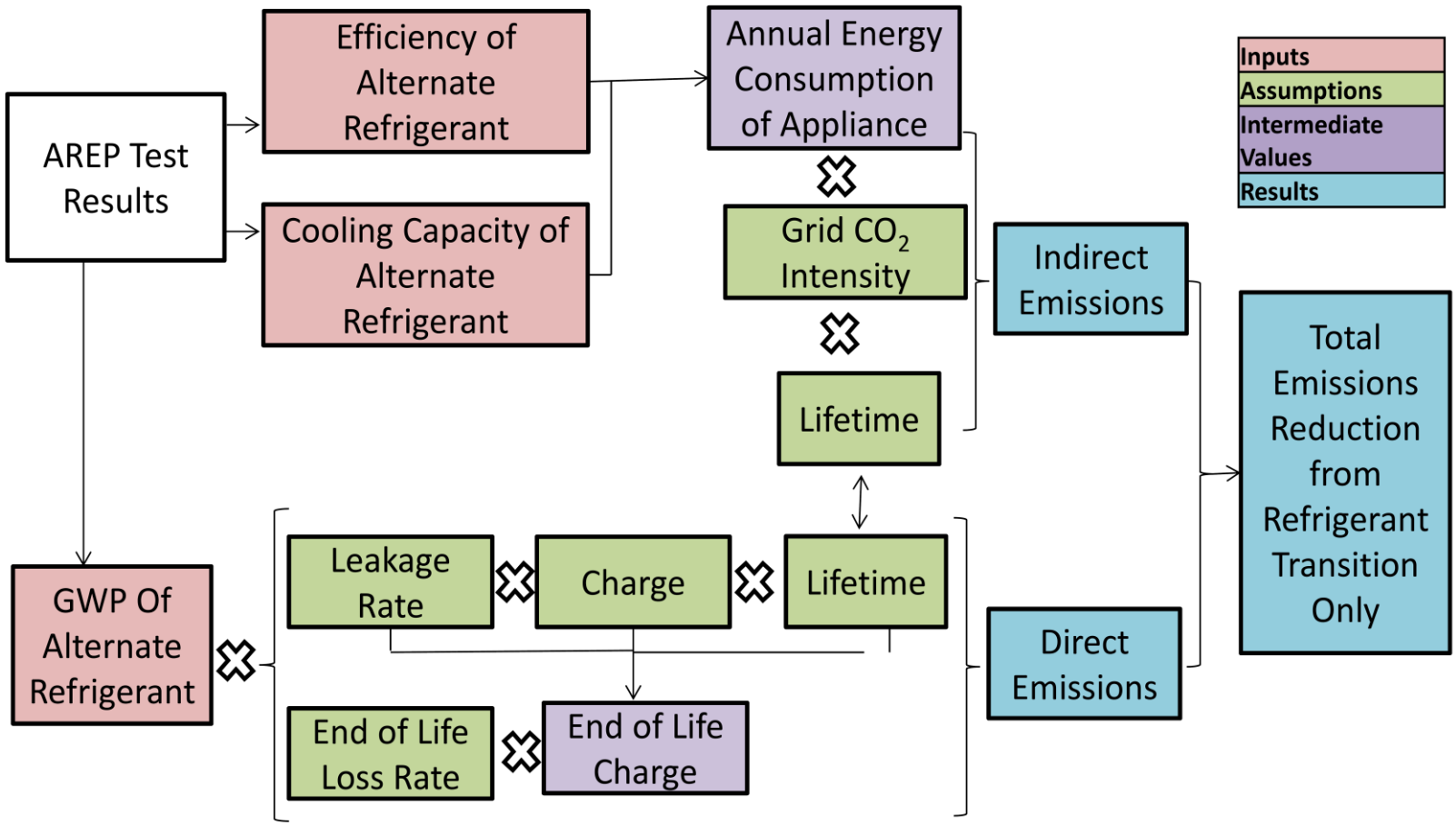
Structure of Model



Shah et al 2013 found ~30% efficiency improvement cost effective in most countries.

Structure of Model



GWP: Global Warming Potential

AREP: Air-conditioning, Heating and Refrigeration Institute (AHRI) Low Global Warming Potential (GWP) Alternate Refrigerant Evaluation Program (AREP)

Base Case Assumptions

Cooling Capacity (tons)	1.5
Appliance Lifetime	10
Power Consumption (kW)	1.81
Energy Efficiency Ratio (W/W)	2.9
Refrigerant Charge (kg)	1.7
Refrigerant Leakage Rate(%/year)	10.0%
End of Life Refrigerant Loss Rate (kg)	100%
Recharge at % loss	35%
Charge/ton of AC capacity (kg/ton)	1.10
Number of recharges	2
Total Lifetime Charge Emitted (kg)	2.81
Total % Charge Emitted	170%

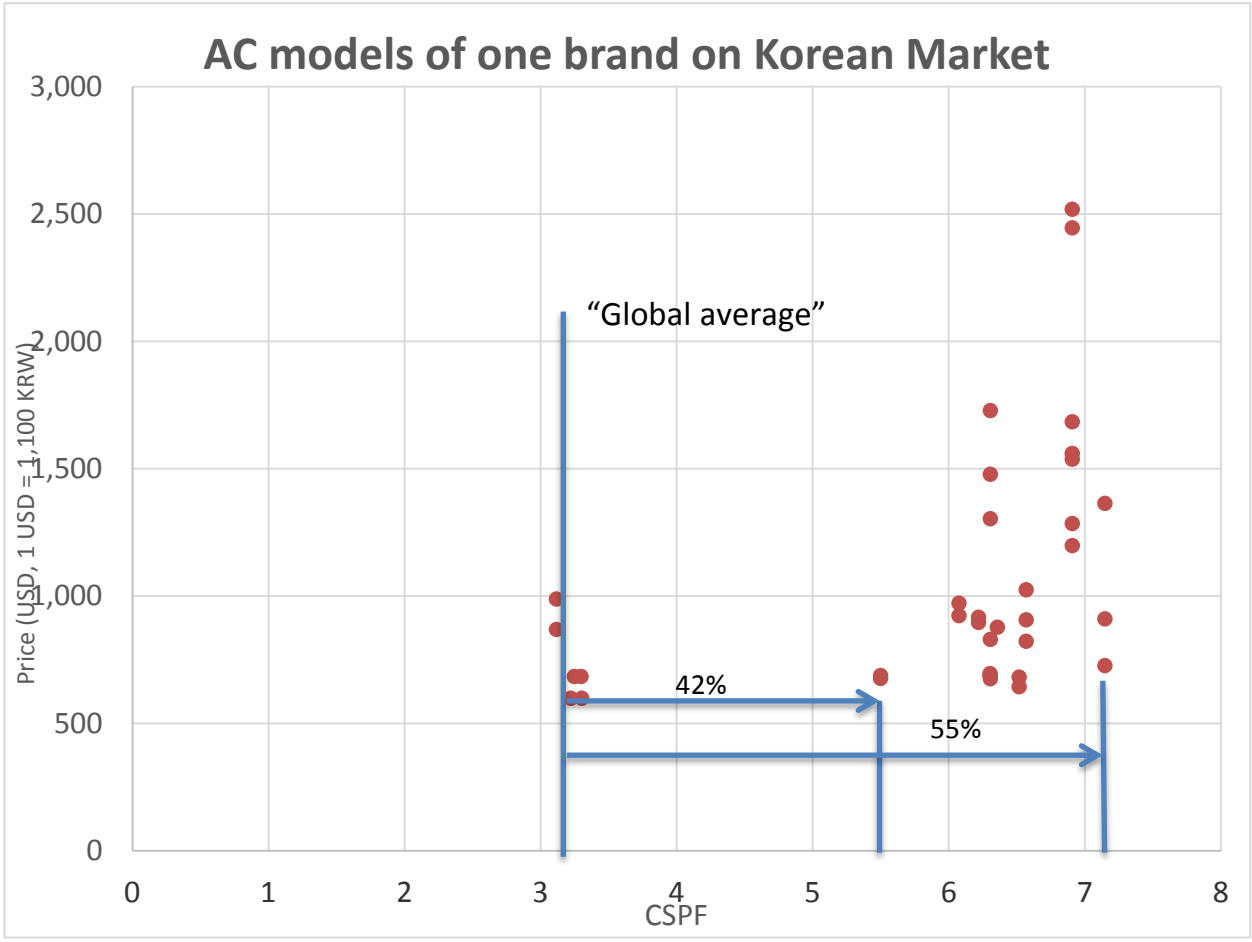
- R410A 1.5 ton mini-split AC with 2.9 W/W Energy Efficiency Ratio(EER).
- Mini-splits most common type of AC globally (60-95%)
- 1.5 tons is most popular cooling capacity in many global markets e.g. 60-65% of market in India.
- 2.9 EER representative of "average" efficiency found on global market, close to many minimum standards (e.g. 2.7 EER in India and 3.1 in China)

"Types" of efficiency improvement

		Explanation	Factors	Magnitude
A	Refrigerant	Alternate Low-GWP refrigerants being considered are more efficient		~5%
B	Replacement	New ACs are more efficient than old ACs	• decline in performance over the life • Current standards are more stringent • Current technology is more efficient	~10-50%
C	Market Transformation (e.g. standards, labeling, incentives, awards etc.)	Best performing ACs on the market are 40-50% more efficient than average	• Best available technology is significantly more efficient • Variable speed drives	~20-40%
Total			1-(0.95x0.7x0.7)	>50%

Only A and C considered for this study: more certain, less variation

Significant efficiency improvement potential



Source: KEMCO, 2015

Efficiency improvement of ~40% is commercially possible today!

AHRI Low-GWP Alternate Refrigerant Evaluation Program (AREP) Phase 1(2012-2014) & Phase 2 (2015-2016)

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

*estimated safety group rating, a safety group has not yet been assigned by ASHRAE in accordance with requirements of ASHRAE Standard 34-2013

Source: AHRI, 2014

- Voluntary co-operative research and testing program to identify suitable alternatives to high-GWP refrigerants.
- Standard reporting format for candidate refrigerants strongly desired by industry.

AHRI Low-GWP Alternate Refrigerant Evaluation Program (AREP) Phase 1(2012-2014) & Phase 2 (2015-2016)

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

Source: AHRI, 2016

- **Phase 2 also did not test very low-GWP refrigerant.**
- **Lowest GWP >450**
- **Some R32 HFO blends e.g. DR 55 appears to be optimized for flammability, very low burning velocity**

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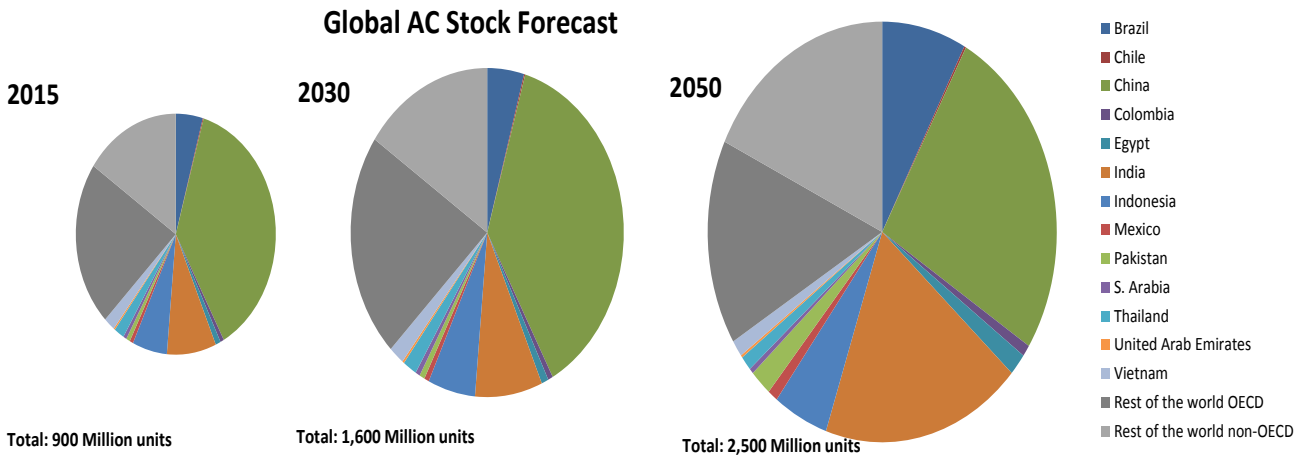
Results – Current and Future Estimated Stock

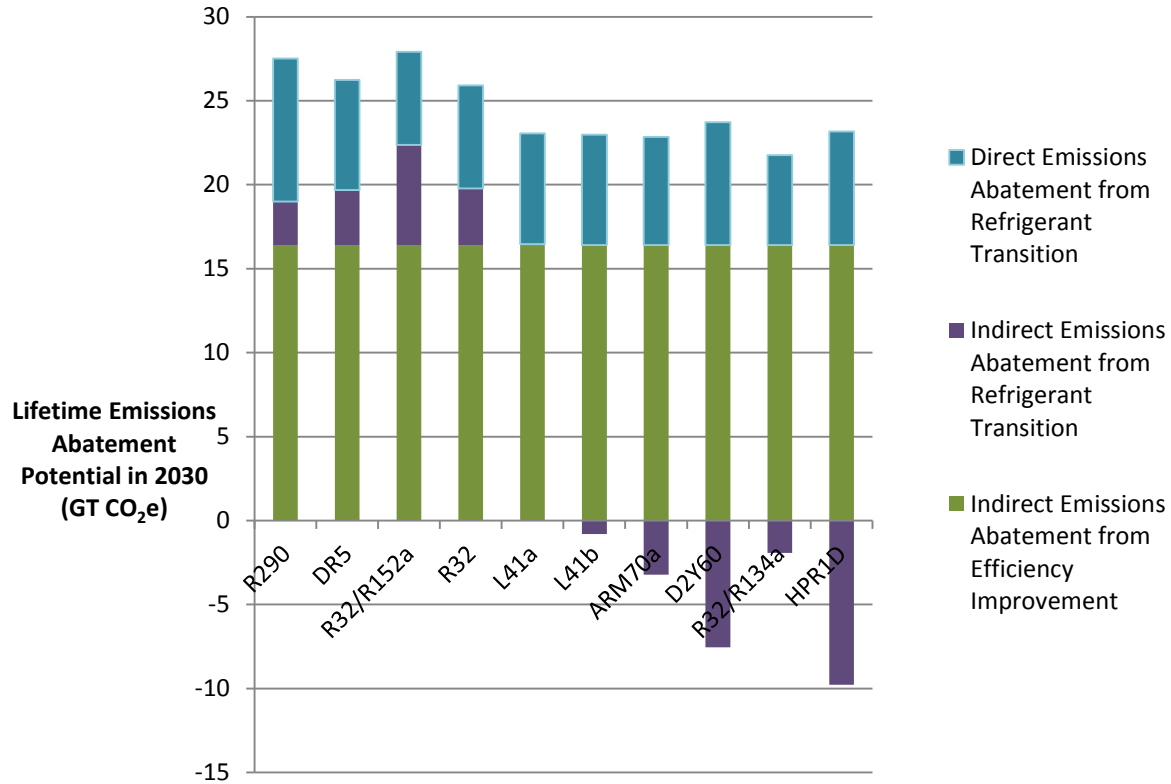
	Sales-based 2015 Stock (Millions)		
	Residential	Commercial	Total
Brazil	17.5	11.6	29.1
Chile	0.4	0.7	1.1
China*	326.7	146.8	473.5
Colombia	0.8	0.6	1.4
Egypt	3.1	2.1	5.2
India	14	4.7	18.7
Indonesia	10.5	7	17.6
Mexico	4.1	0.9	5.1
Pakistan	1.7	0.6	2.2
S. Arabia	4.7	1.2	5.9
Thailand	8.4	5.1	13.5
United Arab Emirates	2.1	0.6	2.7
Vietnam	5.1	2.1	7.2
Total	399.3	183.9	583.2



Global Room AC stock is estimated to grow significantly from now till 2050 with much of the growth in major emerging economies such as India, Brazil and Indonesia

Results from LBNL's Bottom-Up Energy Analysis System (BUENAS) model, Discussions ongoing about co-ordinating with IEA's WEO work.

Results – Global Lifetime Emissions Reduction in 2030



	Efficiency	Ref 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%
S. Arabia	64%	36%
Thailand	76%	24%
United Arab Emirates	59%	41%
Vietnam	74%	26%
Pakistan	66%	34%
Average	61%	39%

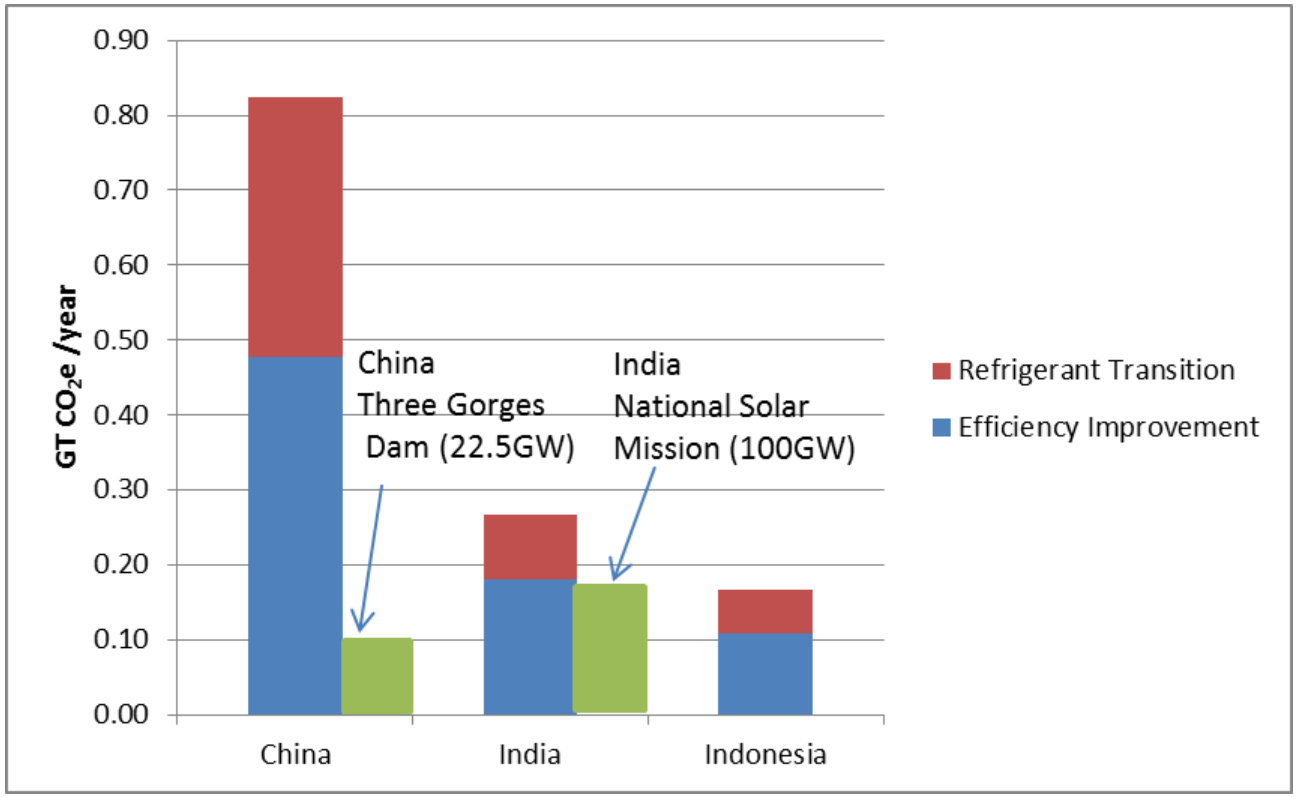
- **Efficiency improvement of ACs along with refrigerant transition roughly *doubles the emissions benefit* of either policy undertaken in isolation.**
- **Countries with higher hours of use or a more carbon-intensive grid benefit more from efficiency.**

Results – Reduction in 2030 and 2050 Peak Load (GW)

	2030				2050			
	Efficiency improvement	Refrigerant transition	Efficiency Improvement & Refrigerant transition	Number of Avoided 500 MW Peak Power Plants	Efficiency improvement	Refrigerant transition	Efficiency Improvement & Refrigerant transition	Number of Avoided 500 MW Peak Power Plants
Brazil	14-32	2.3-5.4	15.4-36	31-72	41.3-96.4	6.9-16.1	46-108	92-216
Chile	0.44 -1.0	0.1-0.2	0.5-1.1	1-2	0.9- 2.2	0.2-0.4	1.0-2.0	2-4
China	118 -277	20-46	132-310	264-620	138.5-323.2	23.1-54	155-361	310-720
Colombia	1.9-4.3	0.3-0.7	2.1-4.8	4-10	4.7-10.9	0.8-1.8	5.0-12.0	10-24
Egypt	2.6-6.2	0.4-1.0	3.0-7.0	6-14	9.0-21.0	1.5-3.5	10.0-23.0	20-46
India	27.3-63.8	4.56 -10.63	31-71	61-142	98-229	16.4-38.2	110-256	219-511
Indonesia	17.8-41.5	3.0-7.0	20-46	40-92	27-63	4.5-10.5	30-71	60-140
Mexico	1.8-4.2	0.3-0.7	2.0-4.7	4-10	5-11.6	0.8-1.9	5.5-13	11-26
Pakistan	1.2-2.9	0.21-0.48	1.0-3.0	2-6	8.0-19	1-3.0	9.0-21	18-42
Saudi Arabia	1.7-4.0	0.3-0.7	2-4.4	4-9	2.2-5.1	0.4-0.9	2.4-6	5-12
Thailand	5.2-12.2	0.9-2.0	6-13.7	12-28	6-13.8	1-2.3	6.6-15	14-30
UAE	0.71-1.7	0.1-0.3	0.8-1.9	2-4	1-2.3	0.2-0.4	1.1-3	2-6
Vietnam	5.8-13.4	1-2.2	6.4-15	13-30	6.7-15.7	1.1-2.6	7.5-18	15-36
Global	302-705	50-117	338-788	676-1576	487-1137	81-190	544-1270	1090-2540

- **Efficiency improvement of ACs along with refrigerant transition has a significant peak load reduction potential.**
- **Countries with higher hours of use, and larger AC markets show more peak load reduction.**

Results - Annual GHG Impact of AC policies in 2030



Transformation of the AC industry to produce super –efficient ACs and low GWP refrigerants in 2030 could provide GHG savings of 0.85 GT/year annually in China equivalent to over **8 Three Gorges dams** and over 0.32 GT/year annually in India, roughly **twice India's solar mission.**

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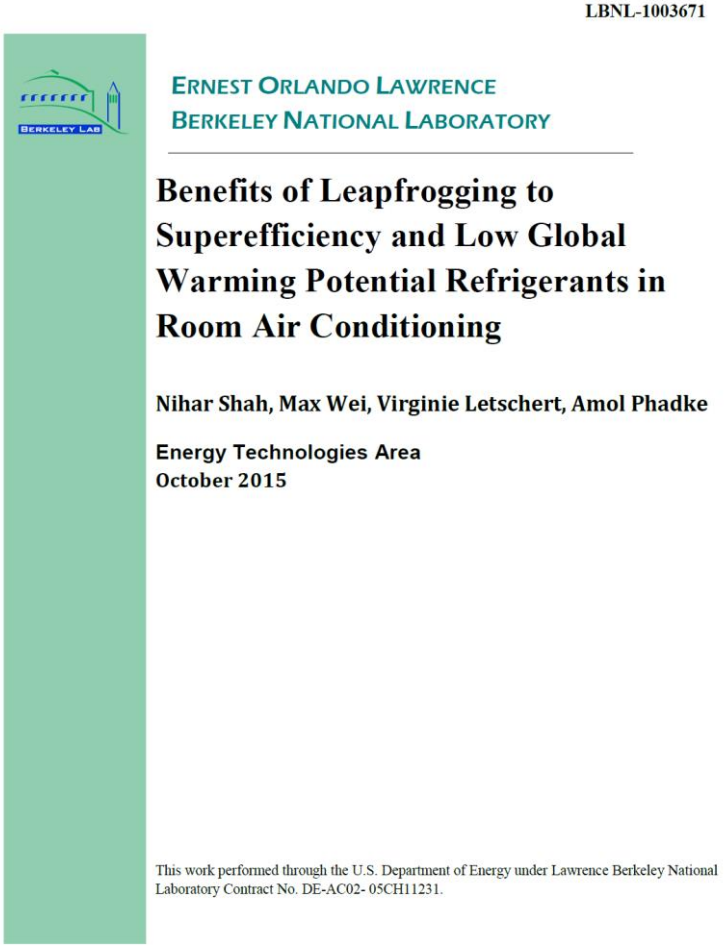
Current Status

- LBNL's results along with high ambient temperature testing results by ORNL helped facilitate Dubai Amendment to the Montreal Protocol to phase down HFCs.
- Montreal Protocol third "extraordinary MOP" in Vienna, 22nd-23rd July 2016- decisions on financing and schedule of HFC phasedown.
- AHRI low GWP AREP Phase 2 has found that HFO blends –e.g. DR55 manufactured by Chemours (DuPont) is ~5-10% more efficient than R410A. (Kujak and Schultz, 2016)
- DR55 is drop-in replacement for R410A, costs likely to be similar.
- Upcoming LBNL report in May with latest AHRI results including DR55

Summary

- Trends show significant estimated growth in the AC market particularly in major emerging economies.
- Large scale impact of air conditioning on electricity generation and peak load, particularly in hot climates and populous countries.
- Efficiency improvement of ACs along with refrigerant transition roughly doubles the emissions impact rather than either policy implemented in isolation.
- Efficiency improvement of ACs along with refrigerant transition shows significant peak load reduction.
- An opportunity to maximize climate, energy and peak load benefits by:
  - design *refrigerant transition projects* to have an efficiency improvement requirement
  - design *efficiency improvement projects* to have a low-GWP refrigerant requirement
- LBNL can assist with program design.

Questions, Suggestions?



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Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning

Nihar Shah, Max Wei, Virginie Letschert, Amol Phadke

Energy Technologies Area
October 2015

This work performed through the U.S. Department of Energy under Lawrence Berkeley National Laboratory Contract No. DE-AC02- 05CH11231.

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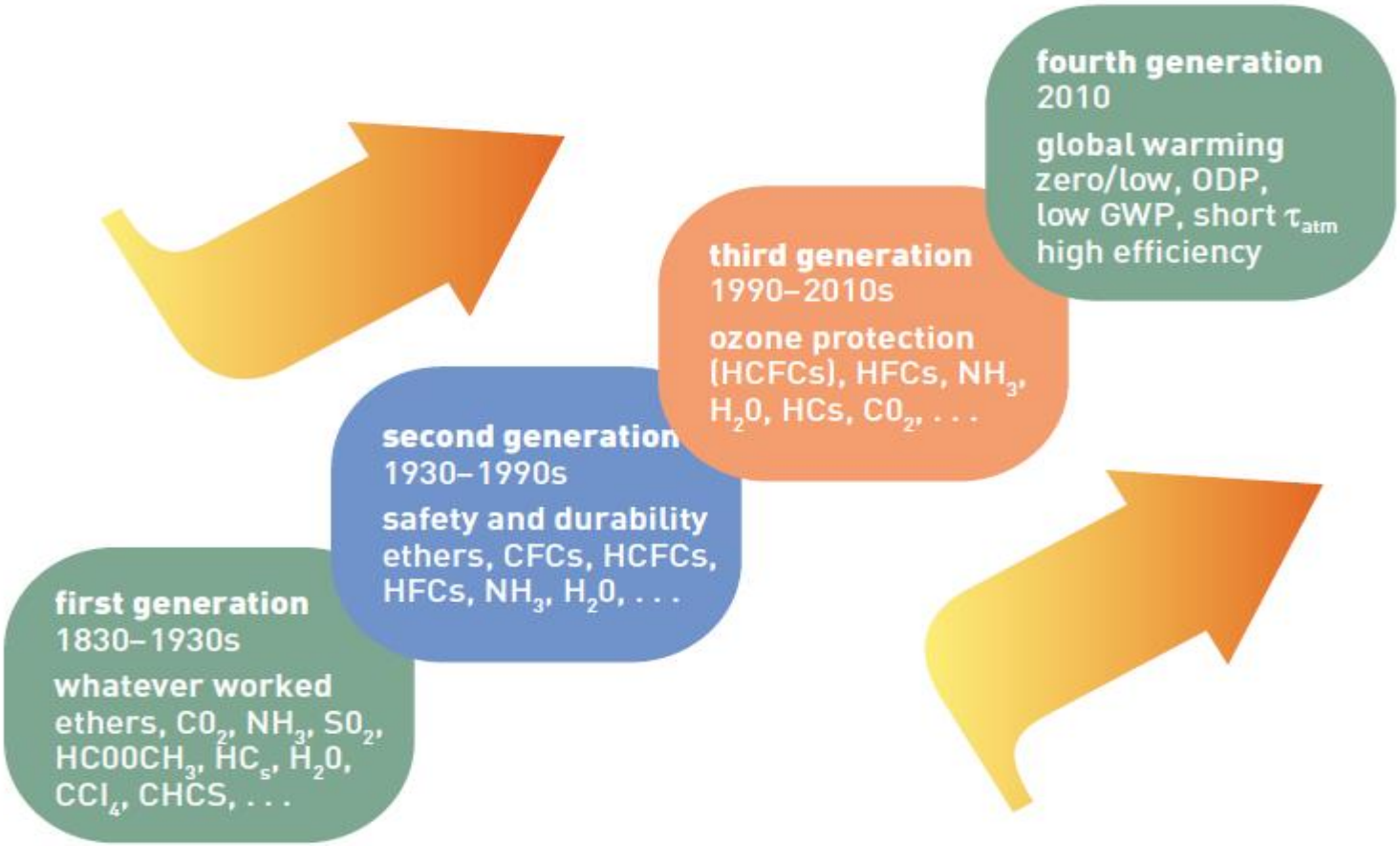
http://eetd.lbl.gov/publications/benefits-of-leapfrogging-to-superef-0

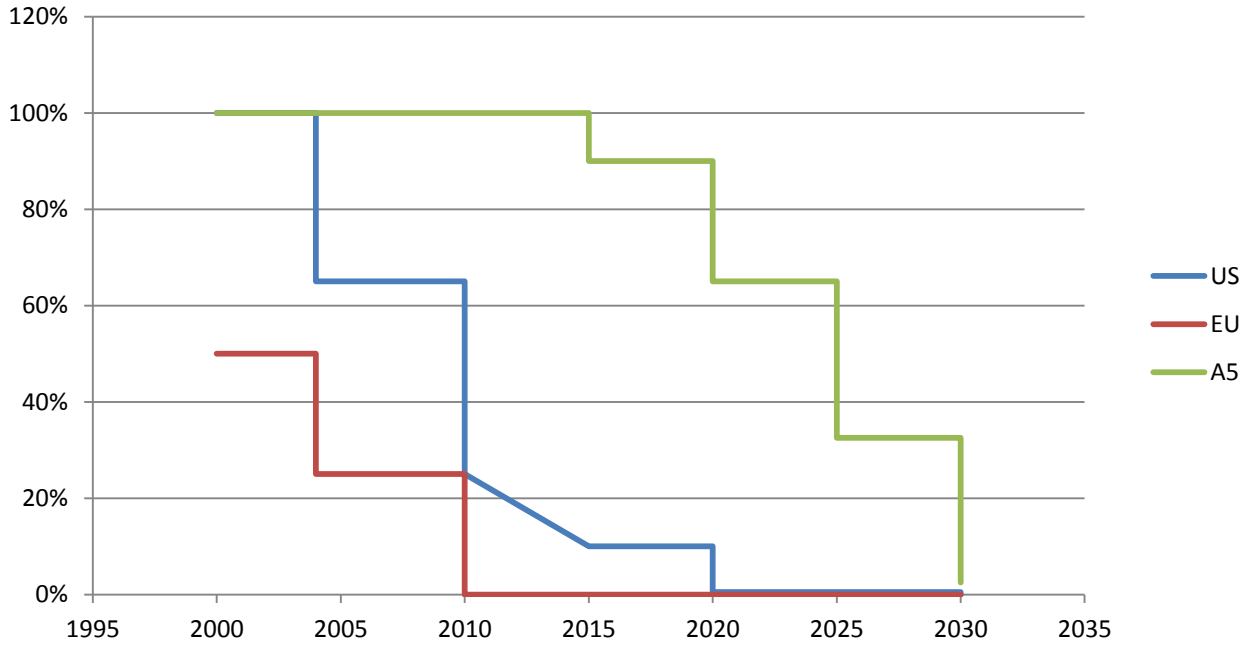
Background Slides

Evolution of Refrigerant Use



Source: Adapted from Calm, *International Journal of Refrigeration*, 2008, http://www.sciencedirect.com/science/article/pii/S0140700708000261

Recent History of the Montreal Protocol: Ozone Depletion

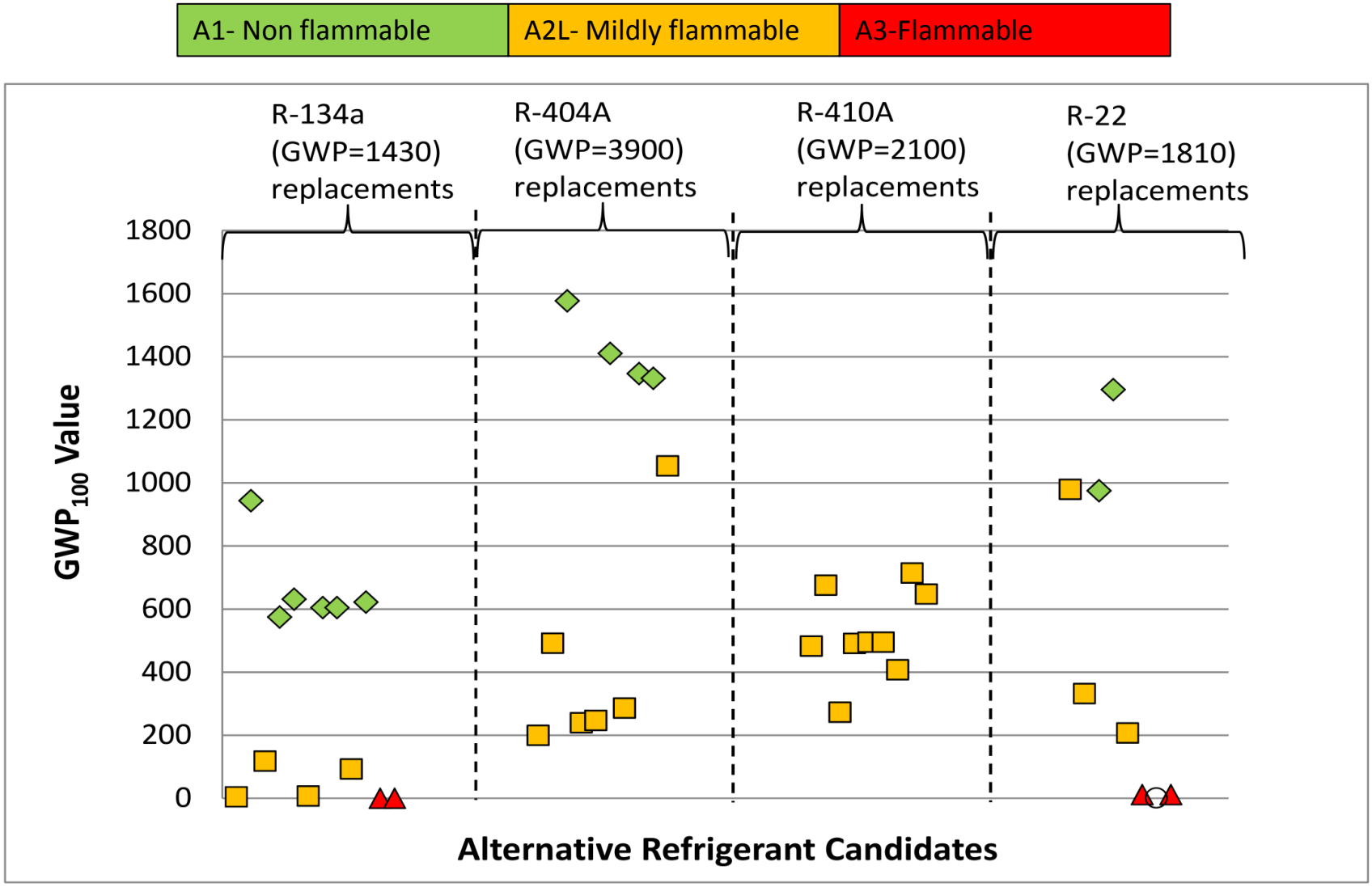


Montreal Protocol Phaseout Timeline for HCFC R22

- Beginning in the 1990's, the Montreal Protocol successfully targeted phase-out of Ozone Depleting Substances such as ChloroFluoroCarbons (CFCs) and HydroChloroFluoroCarbons (HCFCs) in favor of refrigerants such as HydroFluoroCarbons (HFCs).
- The EU and US phase-out is nearly complete while the Article 5(A5) countries began CFC phaseout in 2010 and HCFC phase-out in 2015.

Deliberative draft—Not for distribution

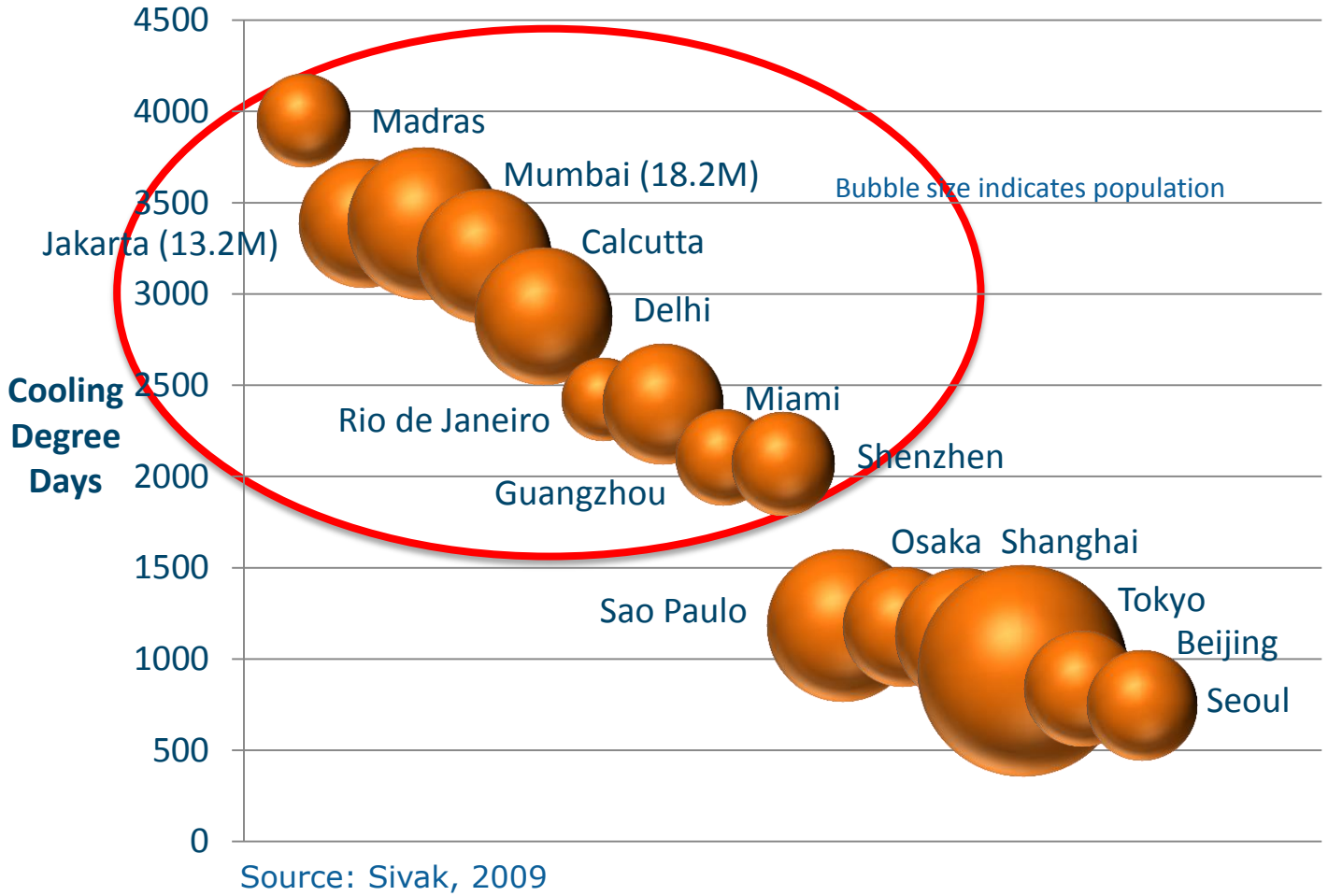
100-Year GWP and Flammability of Commonly Used Refrigerants



Source: http://www.unep.org/ozonaction/Portals/105/documents/webinar/2013/14August2013_Ppt_Karim%20Amrane.pdf

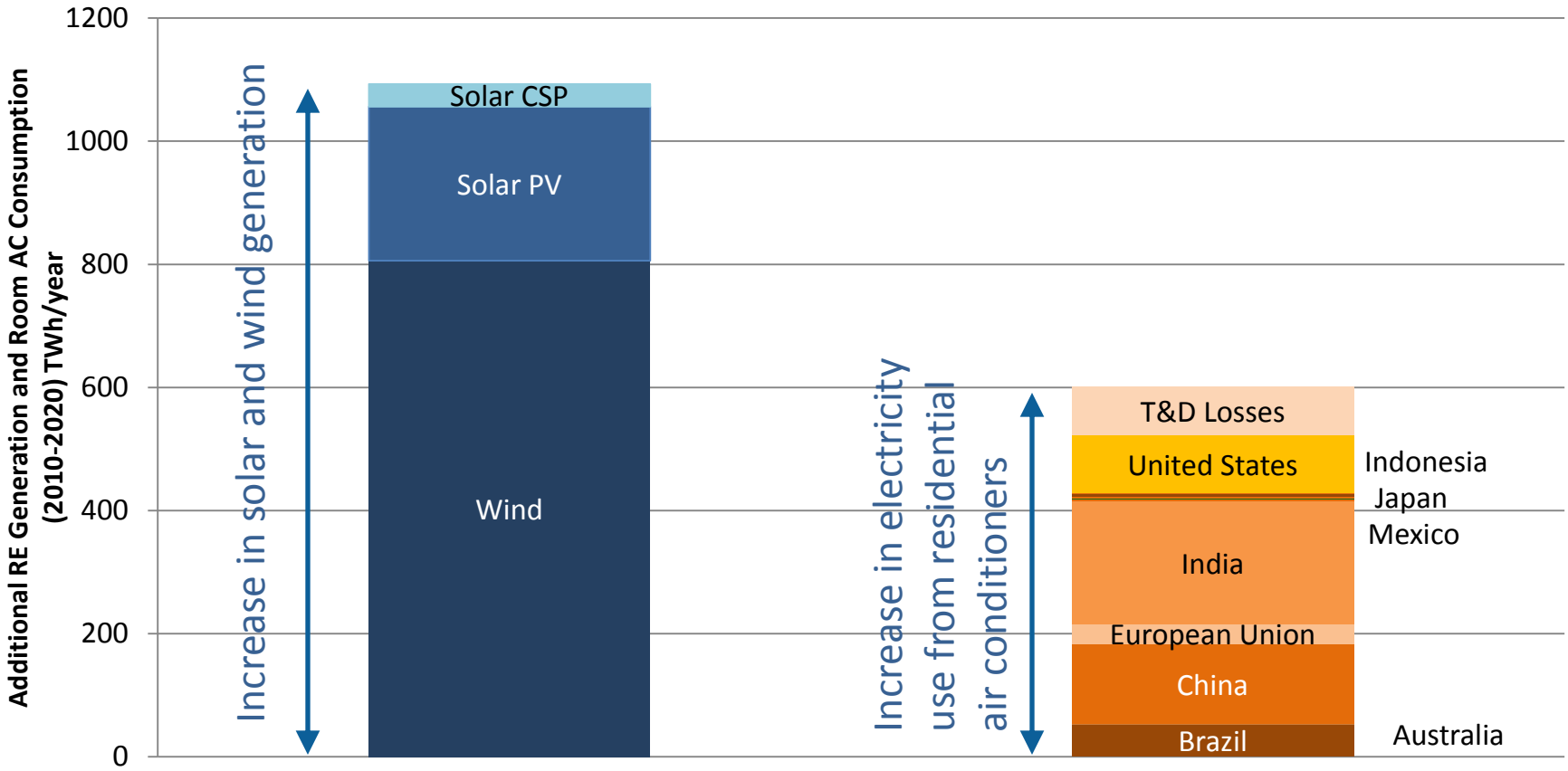
Deliberative draft—Not for distribution

High Cooling Energy Consumption in Largest Metros



Many of the world's most populous metropolitan areas have hot climates

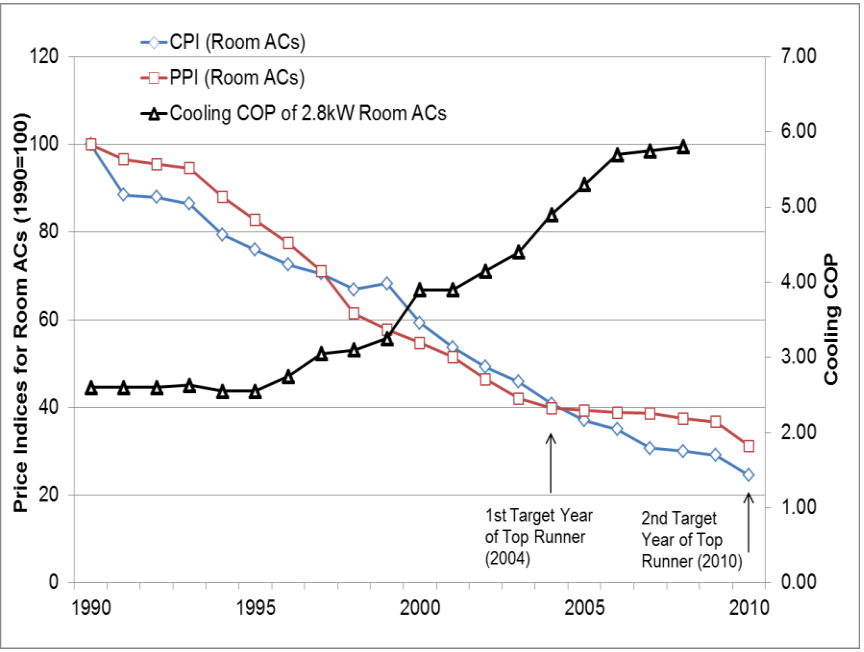
Growth in Renewable Generation and Cooling Energy, 2010–2020



Renewable energy generation: IEA World Energy Outlook 2012 (Current Policies scenario). Residential air conditioning consumption: Shah et al. (2013); LBNL's Room AC analysis for the SEAD initiative; and V. Letschert et al. (2012), LBNL's BUENAS model.

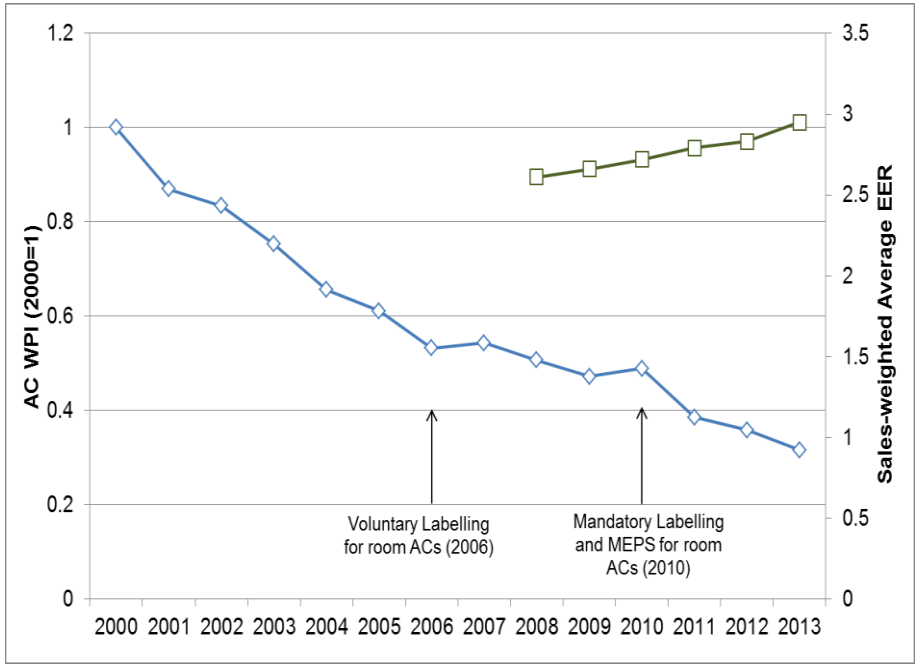
Incremental electricity consumption from residential ACs alone is >50% of solar and wind generation projected to be added between 2010 and 2020.

Falling Prices



Source: Kimura 2010 and Shibata, 2012

Japan



Source: OEA, 2013

India

AC prices continue to fall globally, even when efficiency improvement policies are implemented.