Improved Life-Cycle Climate Performance (LCCP) Metrics: Room AC Carbon Footprint

Vienna OEWG Side Event

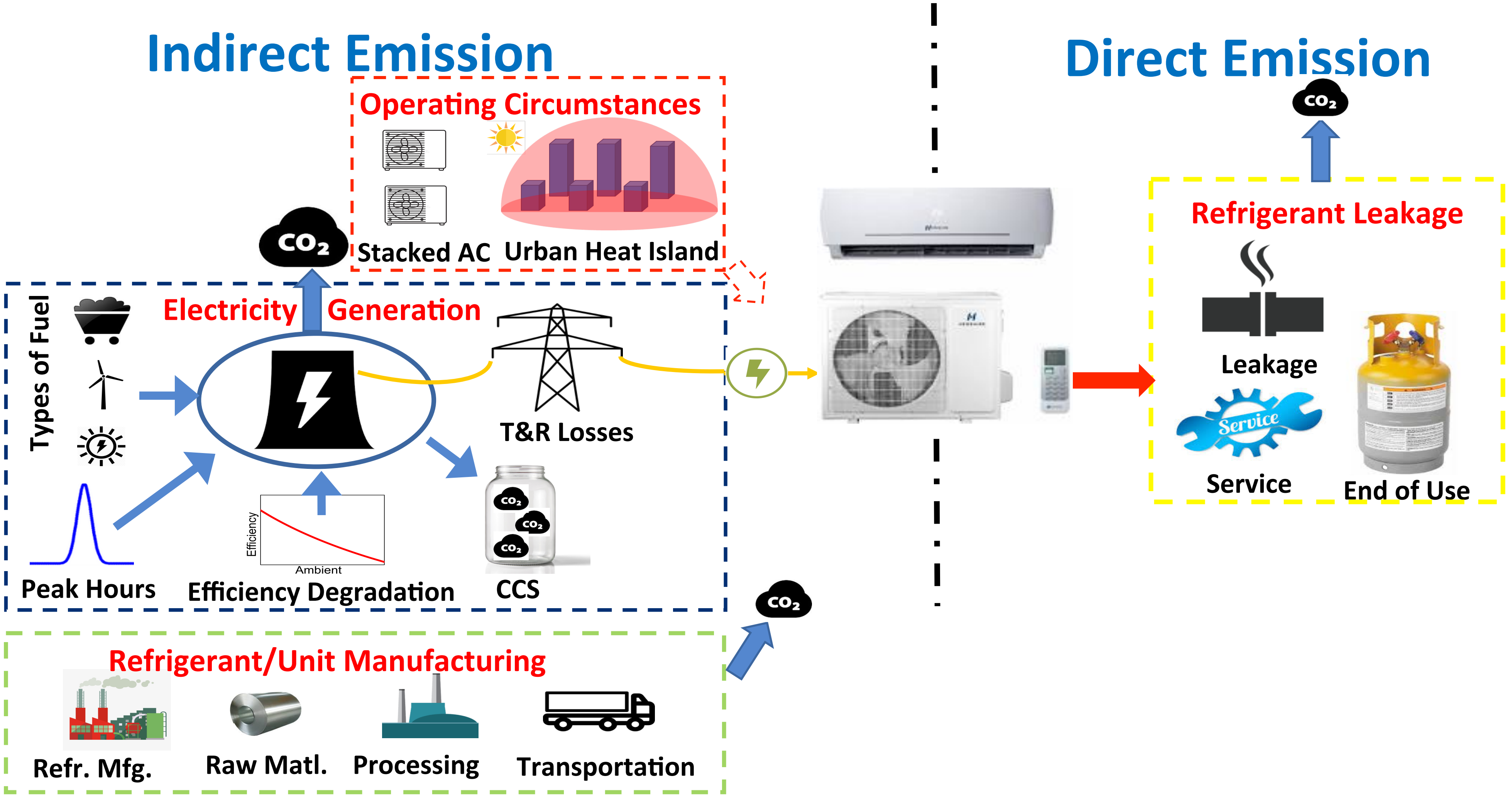
Dr. Stephen O. Andersen, Institute for Governance & Sustainable Development (IGSD)

Mr. James Wolf, Global Policy Associates

Abstract and Approach

- Imagine the ideal carbon metric if essential data were available, there were no limits on computation, and the ambition was to tailor the carbon estimate to the local real-world situation of the installation and use
- Assemble a "***Tiger Team***" of respected and influential experts to invent, elaborate and ultimately promote the metric
- Partner with *Center for Environmental Energy Engineering at University of Maryland* to push modelling with data sets for climate and carbon intensity of electricity

Life-Cycle Climate Performance (LCCP) of AC



RAC Carbon Metrics Tiger Team: Respected and Influential Experts

- Co-Chairs:
  - Dr. Stephen O. Andersen (IGSD) and James Wolf (Global Policy Associates; former ASHRAE President)
- LCCP Modelling Engineers and Members:
  - Dr. Yunho Hwang and Dr. Jiazhen Ling (University of Maryland – UMD)
- Expert Members:
  - Dr. Suely Carvalho, IPEN/University of Sao Paulo, Brazil
  - Didier Coulomb, International Institute of Refrigeration (IIR)
  - Hilde Dhont, Daikin Europe
  - Michel Farah, Daikin Middle East
  - Dr. Gabrielle Dreyfus, IGSD
  - Marco Gonzalez, Executive Director of the Montreal Protocol Ozone Secretariat (Retired)
  - Alex Hillbrand, Natural Resources Defense Council (NRDC)
  - Dr. Jinxing Hu, Beijing University
  - Dr. Nancy Sherman, IGSD
  - Mike Thompson, Trane
  - Viraj Vithoontien, World Bank
  - Stephen Yurek, Air-Conditioning, Heating, & Refrigeration Institute (AHRI)
  - Zhong Zhifeng, Ministry of Environmental Protection Foreign Economic Cooperation Office (MEP/FECO)

RAC Carbon Metric Goals: Big Data, Comprehensive Modelling, and Digital Label

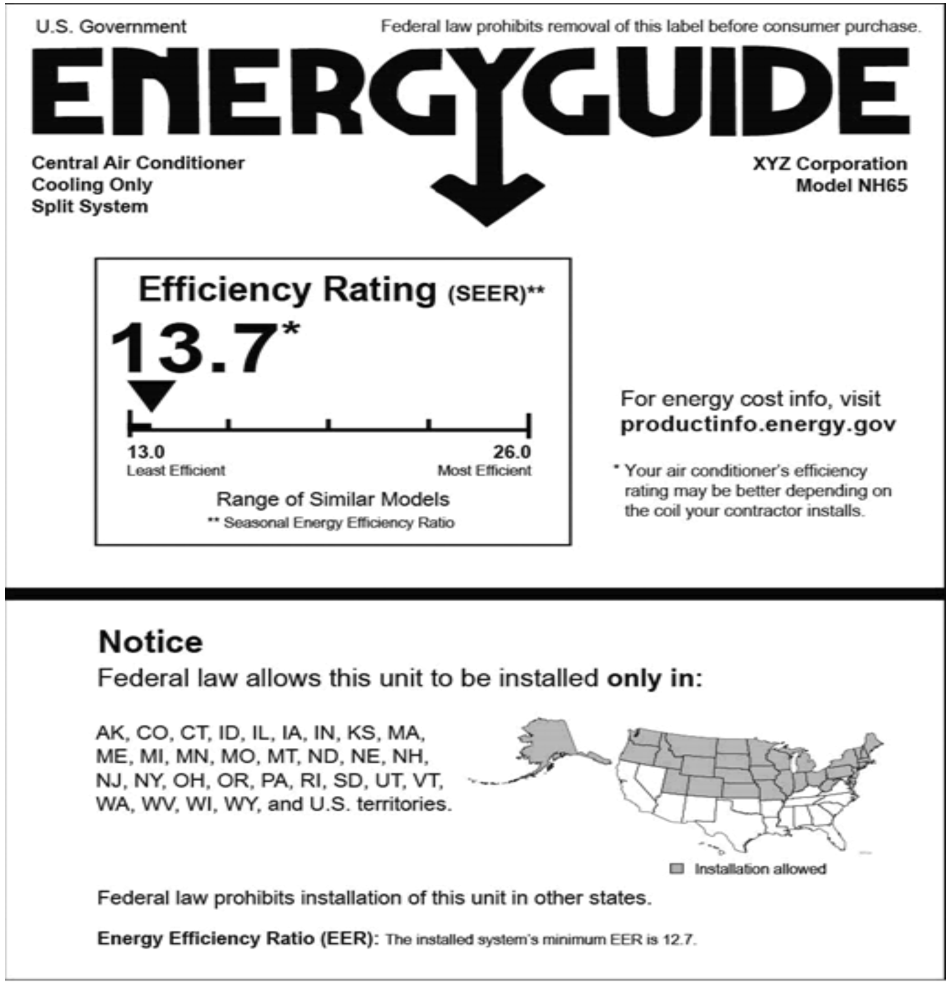
- Specified Equipment with Digital Label
  - Bar code could be linked to temperature-specific test data
  - Modelling could account for installation
    - solar incidence, shading, refrigerant line diameter and length, condenser clusters/stacking…
- Local Climate Data (Including temperature, humidity, cloud cover)
- Local Time-of-Day Carbon Intensity of Electricity as Delivered
  - Mindful of Carbon Intensity of Incremental Power
    - Seasonal, Time of Day, Accounting for Backup Power if frequent
  - Adjusted for Distribution/Transmission Loss (cost and carbon footprint)
- Accommodating Likely Use Patterns
  - Stay-at-home family vs. working adults
  - Preference, frugal or smart thermostat setting

Status Quo: Continuously Improved Performance Metrics

- THEN
  - Absolute Cooling Capacity (tons) → Comparative Energy Efficiency (COP) → Seasonal Energy Efficiency (SEER) = Btu/Wh if in reference climate
- NOW
  - Refined to Less Generalized Climate: SEER = Btu/Wh
- NEXT
  - Location-specific calculation of refrigerant, embodied, and energy greenhouse gas emissions weighted by time-of-day carbon intensity of supplied electricity

    LCCP = tons carbon/year = carbon footprint
  - Continuous improvement, including consideration of evolving carbon intensity of electricity as wind and solar come on line and electric car charging is smartly managed to minimize additional grid carbon production

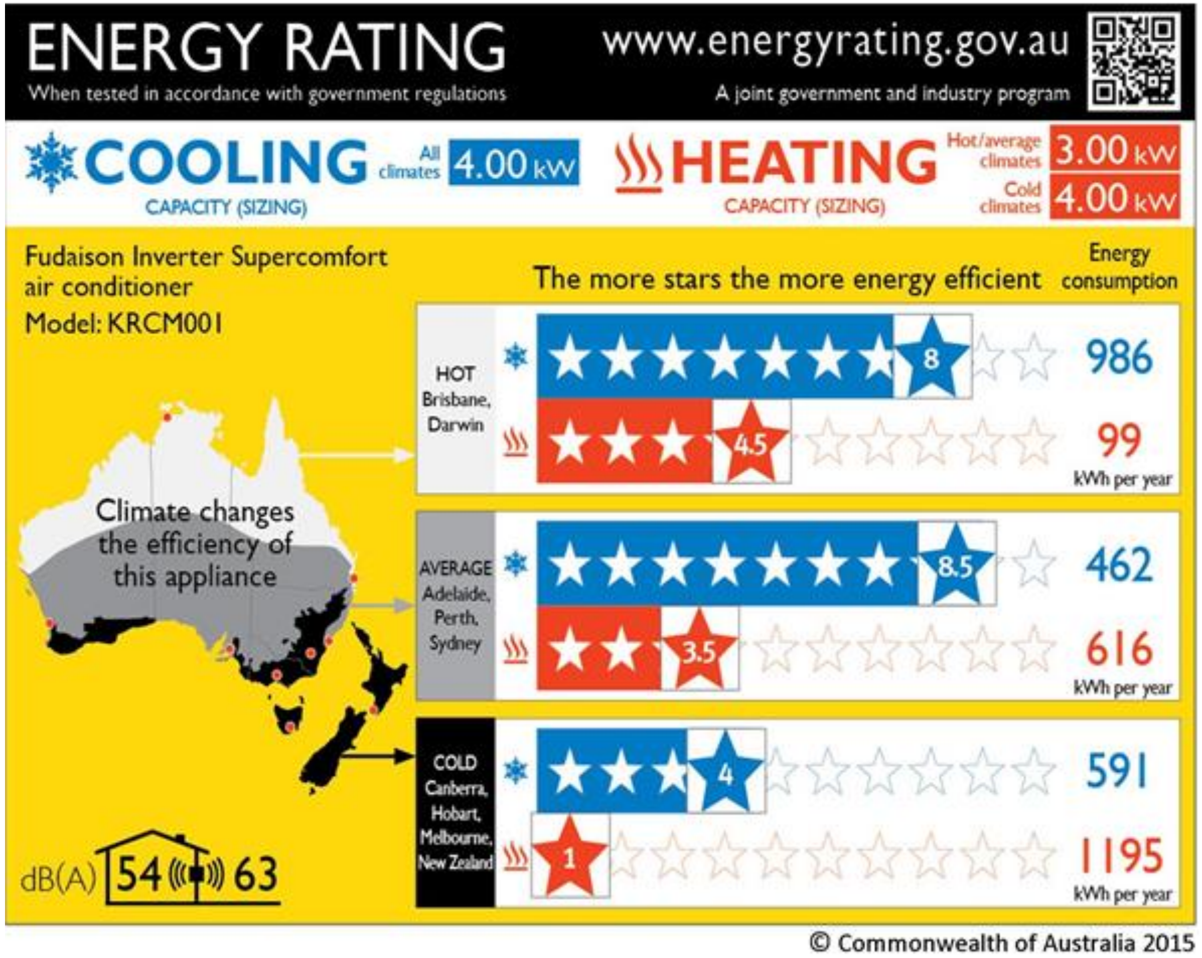
Now: Poor Balance of Simplicity & Accuracy

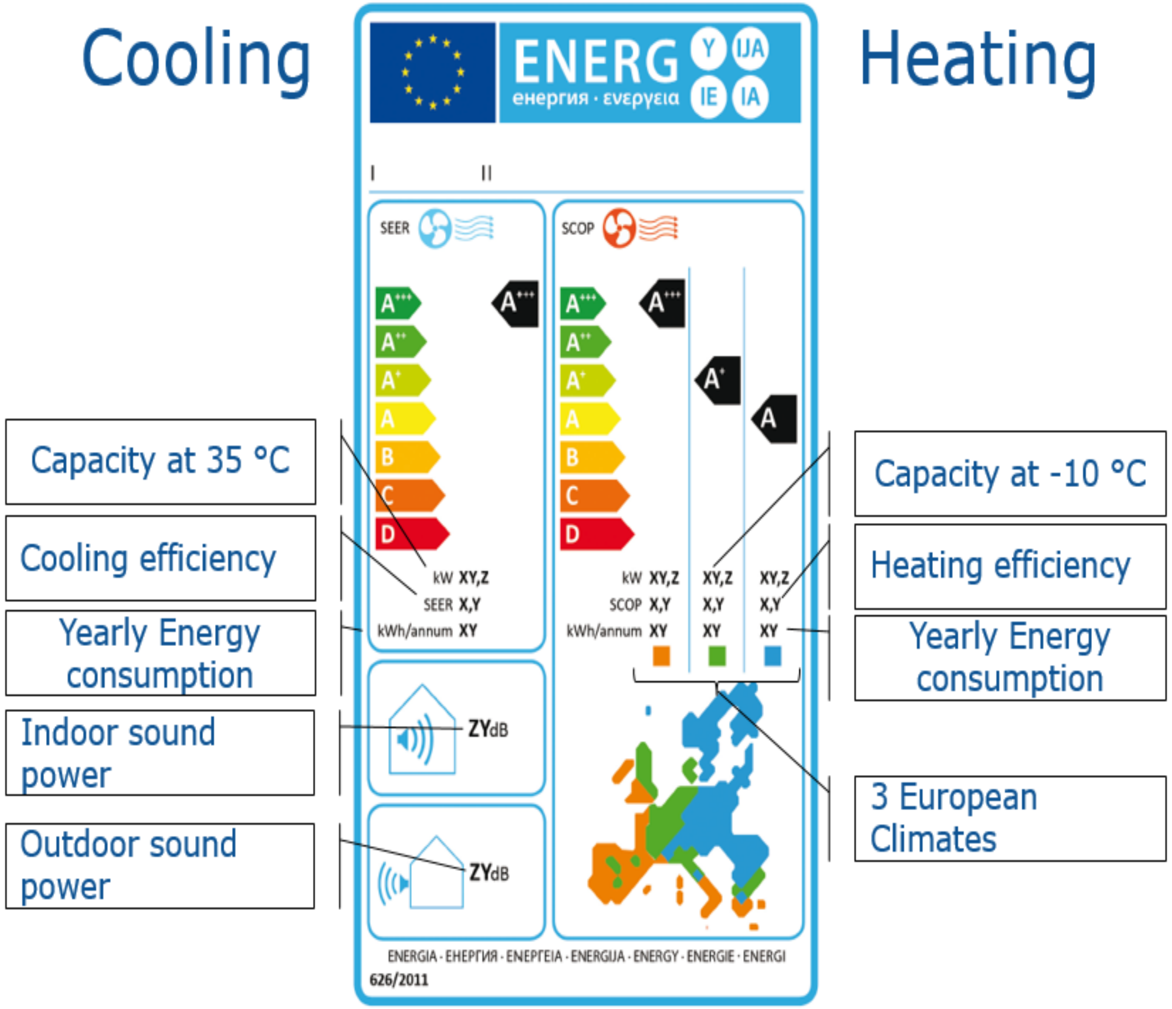


Sample Label 7 – Split-system Central Air Conditioner

"Federal law prohibits installation…in other states"

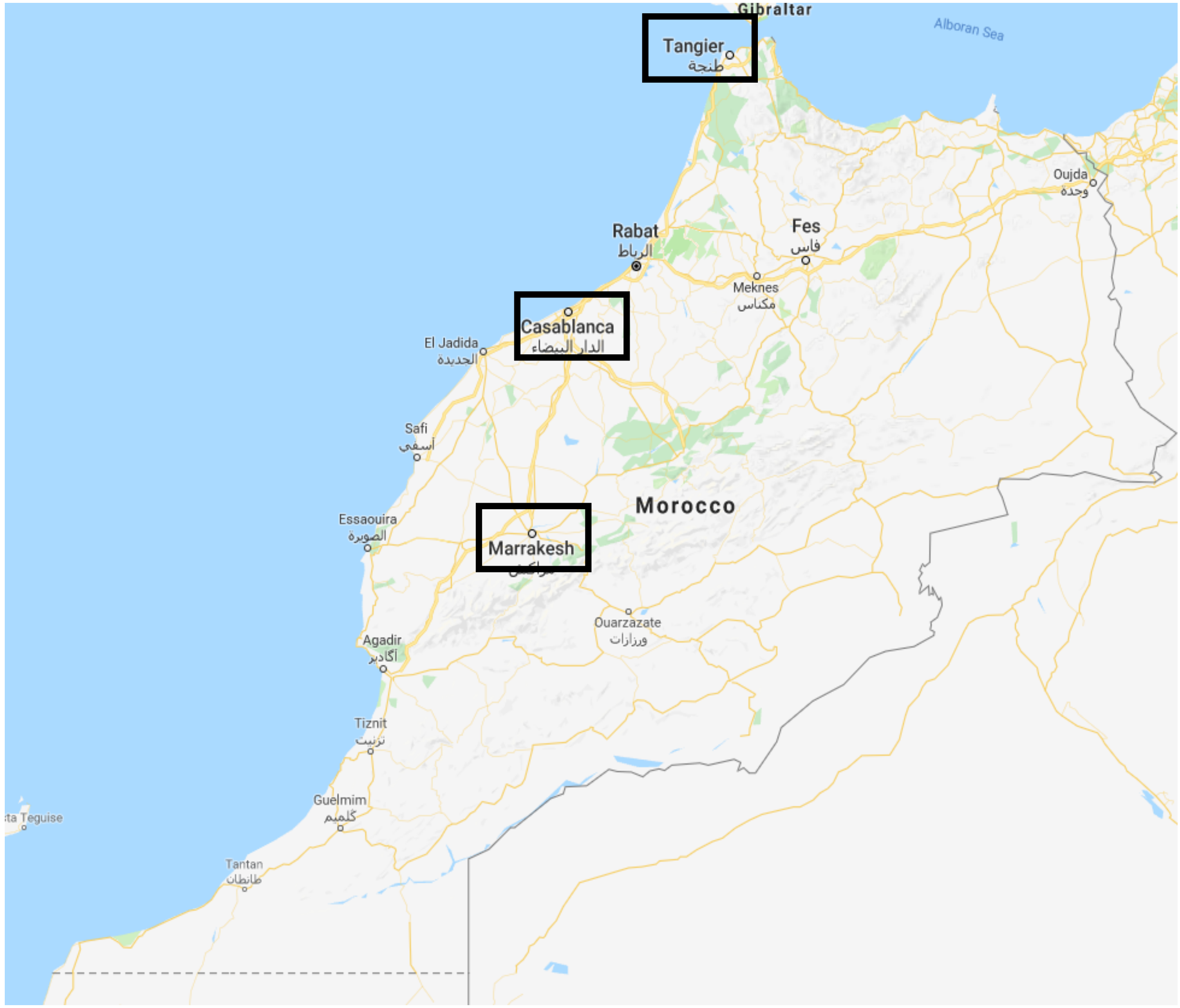
Now: Less-Poor Balance of Simplicity & Accuracy





Three Selected Moroccan Cities

- Marrakech (Marrakesh)
  - Population: 928,850
  - Coordinates: 31°37’N; 8°0’W
- Tangier
  - Population: 947,952
  - Coordinates: 35°46’N; 5°48’W
- Casablanca
  - Population: 3,359,818
  - Coordinates: 33°32’N; 7°35’W



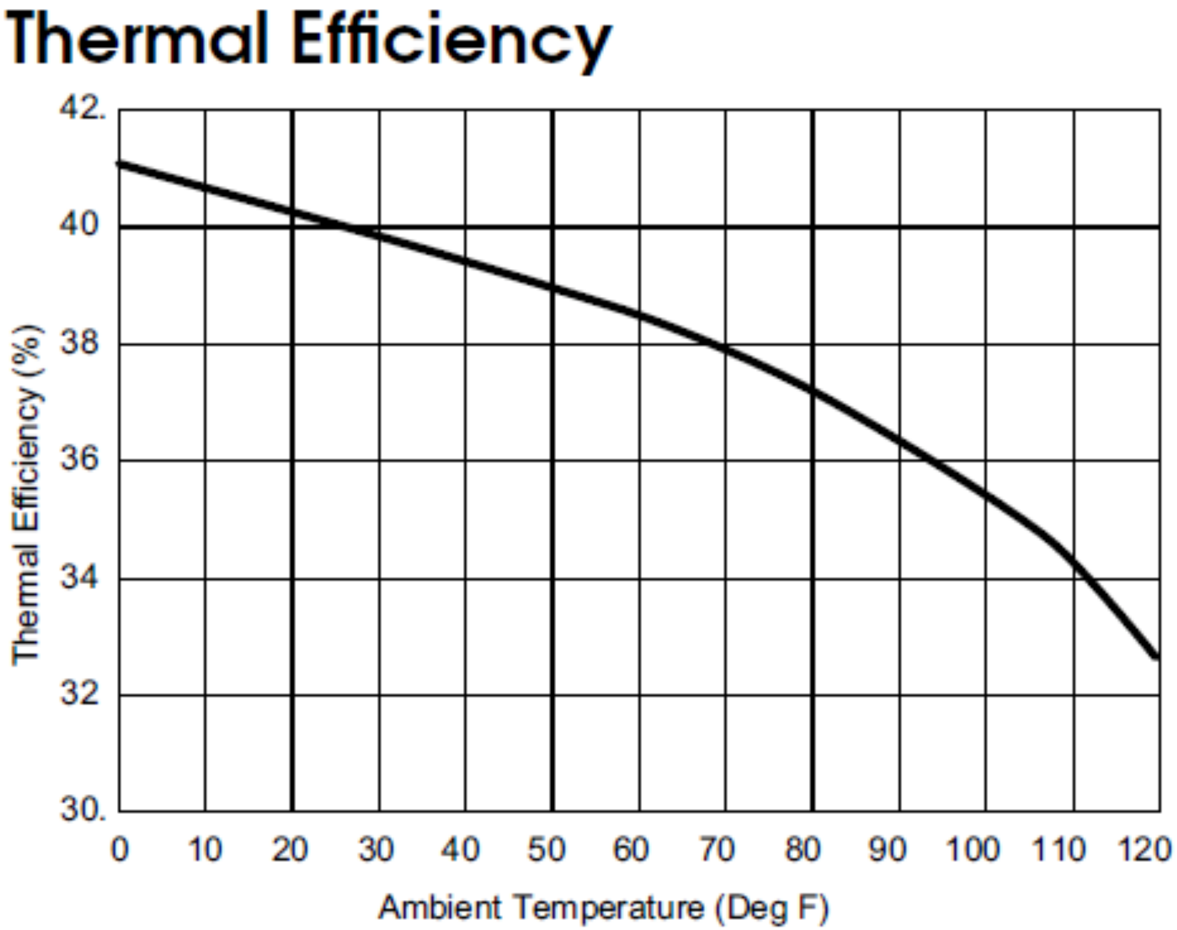
Temperature Bins

		Marrakech	Tangier	Casablanca
Bin Number	Temperature Bins [°C]	Bin Hours	Bin Hours	Bin Hours
1	18.3-21.1	1,213	1,388	1,862
2	21.1-23.8	811	953	1,645
3	23.9–26.6	887	867	688
4	26.7-29.3	650	366	116
5	29.4–32.1	501	150	16
6	32.2-34.9	298	43	0
7	35–37.7	207	14	0
8	37.8-40	161	1	0
ASHRAE 1% Design Temperature [°C]		40	32	27.6

More Practical Factors to be Considered

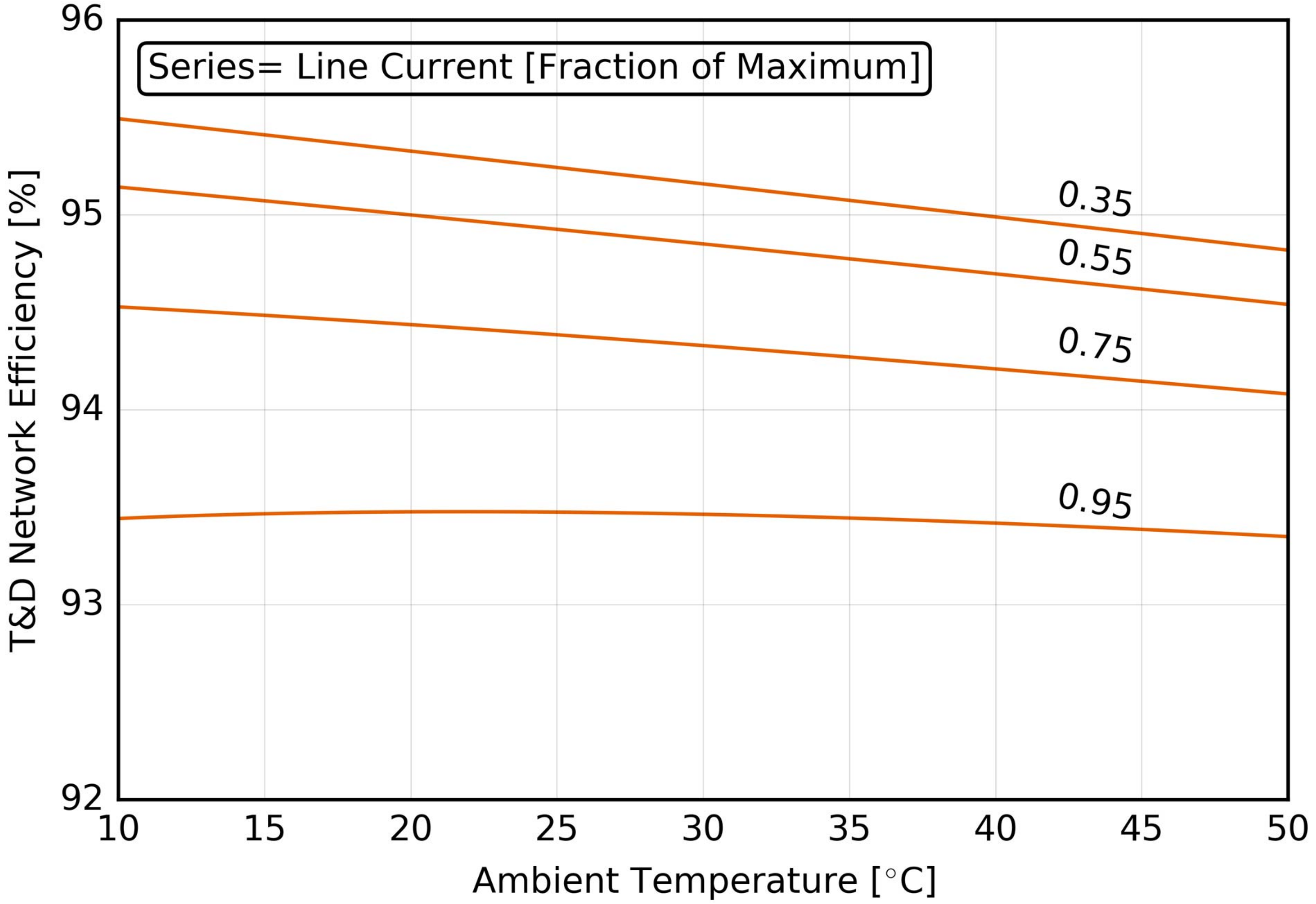
- Electricity generation
  - Time-of-day carbon intensity
    - Most carbon intense at peak annual demand
    - Lower efficiency at highest temperatures (Carnot)
    - Adjusted if CO_2 is captured or coal ash offsets concrete GHG emissions
    - Black carbon (highest with least efficient coal, oil, biomass, and waste combustion)
- Transmission and distribution (T&D) loss
  - Highest at peak demand (system less efficient, electricity moved further)
- Use of Voltage Stabilizer for poor quality power (additional 5% loss)
- System install / operating circumstances (hotter than at isolated weather stations)
  - Condenser stacked and clustered and/or without heat dissipation/ sometimes in direct sun
    - Less efficient condenser heat rejection plus heated wall increases building load
  - Urban heat island and global warming

Ambient Temp. Effect on Power Plant Efficiency



http://turbotrain.net/en/cingl.htm

Ambient Temp. Effect on Transmission & Distribution Efficiency



Thomas A Deetjen et al., Can storage reduce electricity consumption? A general equation for the grid-wide efficiency impact of using cooling thermal energy storage for load shifting, 2018 *Environ. Res. Lett.* **13** 024013

Voltage Stabilizer Losses

- AC voltage stabilizers condition "poor quality power" significantly and continuously deviating from rated voltage.
- The voltage stabilizers used in some countries like India to clean "poor quality power" and avoid appliance damage.
- Loss is about 5%.
- Types:
  - Relay type: conditions input voltage variations of ±15% to ±6%
  - Servo controlled: conditions input voltage variations of ±50% to ±1%
  - Static: uses power electronics for accurate conditioning of ±1%

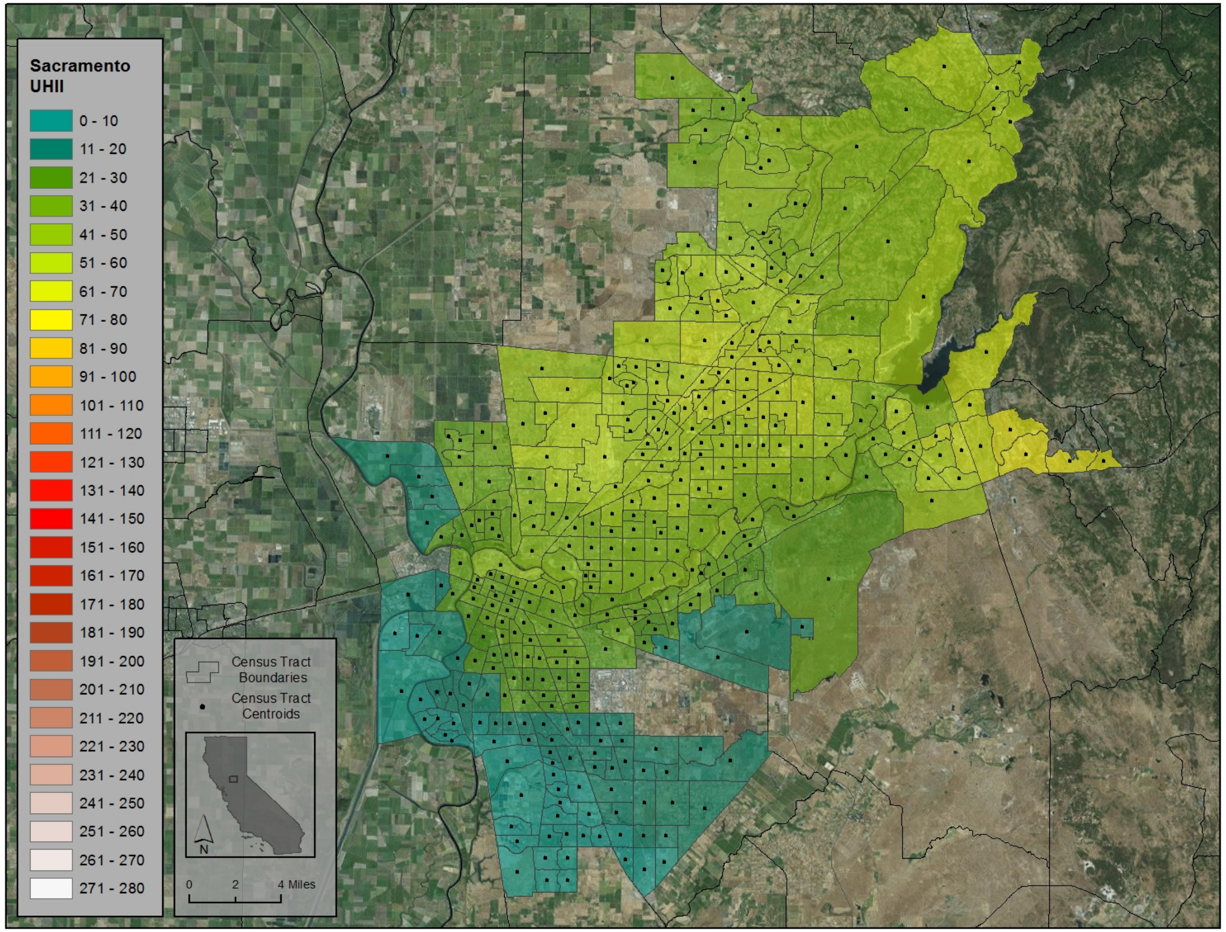
https://www.electricaltechnology.org/2016/11/what-is-voltage-stabilizer-how-it-works.html

Stevenson Screen Instrument Shelter

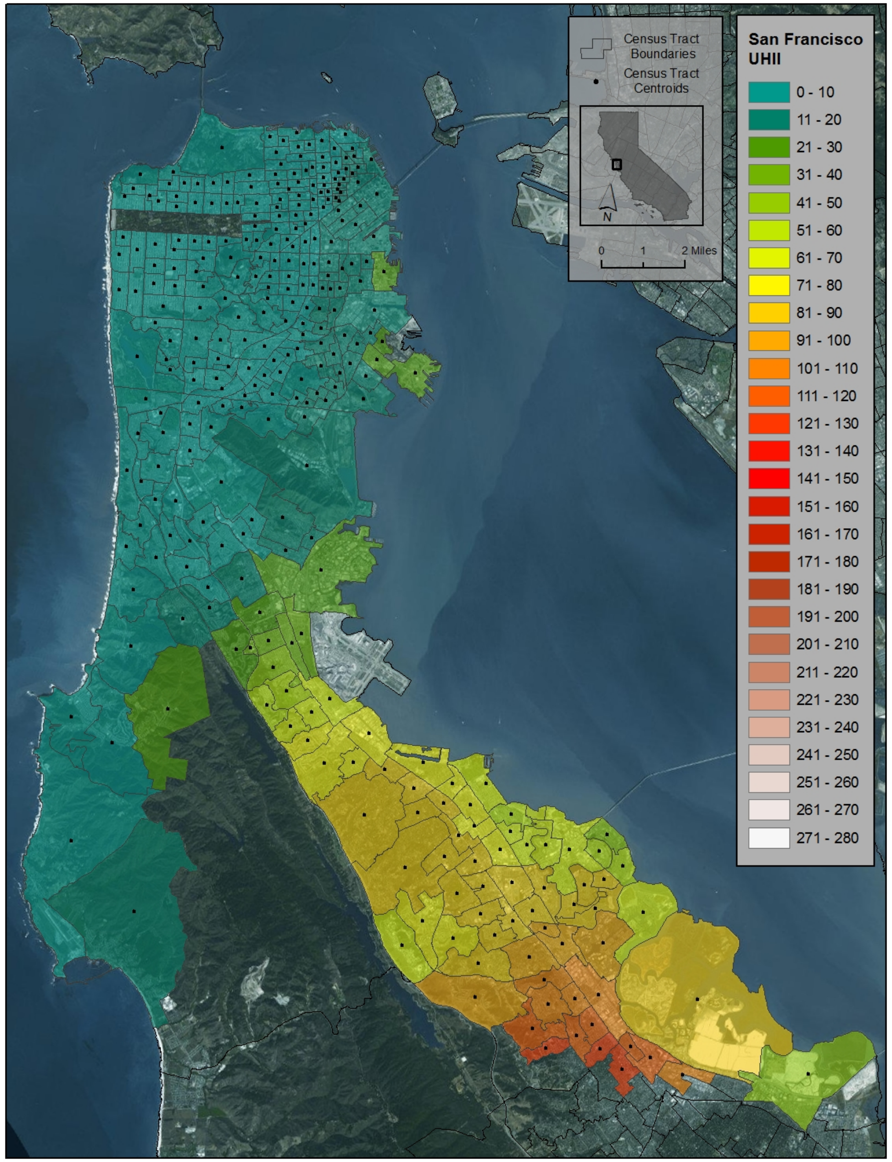
- A WMO-certified white wooden box with louvers to shelter meteorological instruments from solar and local heat and to allow air circulation
- Sited above lawn and soil in locations that avoid data degradation by the effects of buildings and pavement
- Understating the higher ambient temperatures of AC condensers adjacent to buildings

World Meteorological Organization, Instruments and Methods of Observation: http://www.wmo.int/pages/prog/www/IMOP/IMOP-home.html

Urban Heat Island Effects



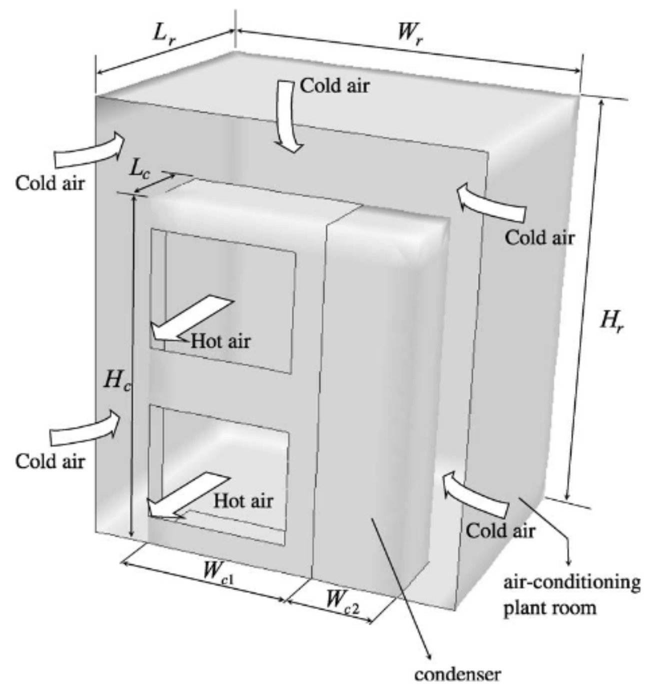
Sacramento Urban Heat Island Index

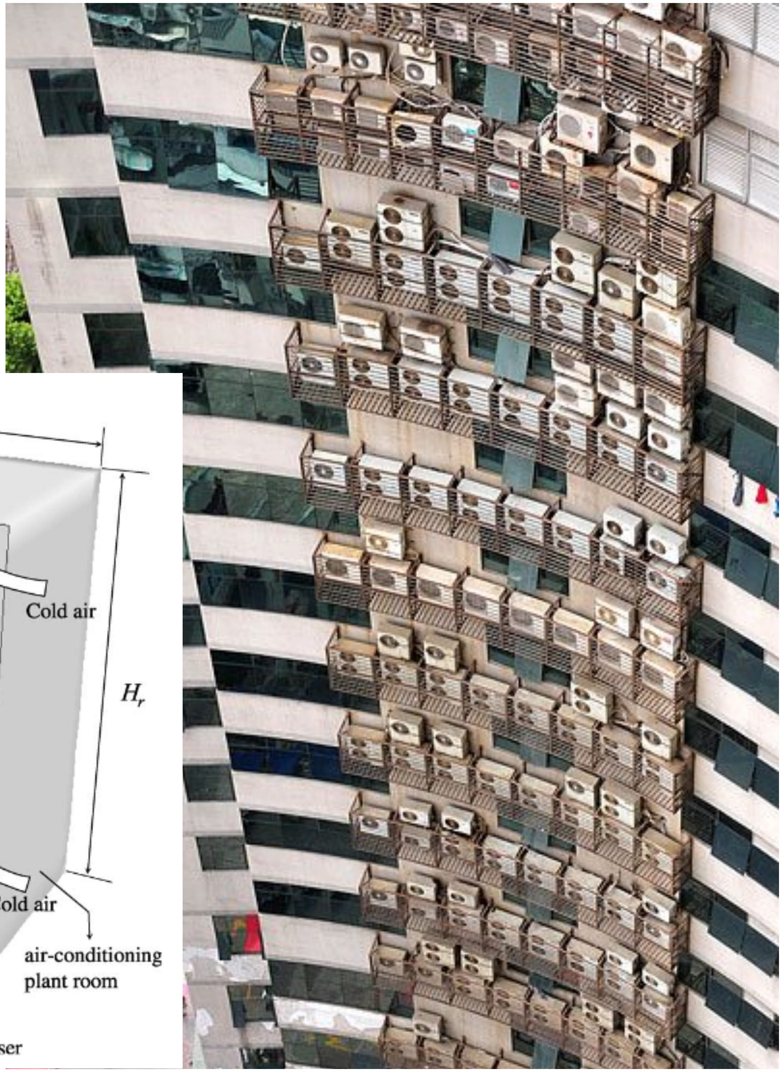


San Francisco Urban Heat Island Index

Source: CalEPA
https://calepa.ca.gov/climate/urban-heat-island-index-for-california/urban-heat-island-interactive-maps/

Stacked AC Outdoor Units in High-rises

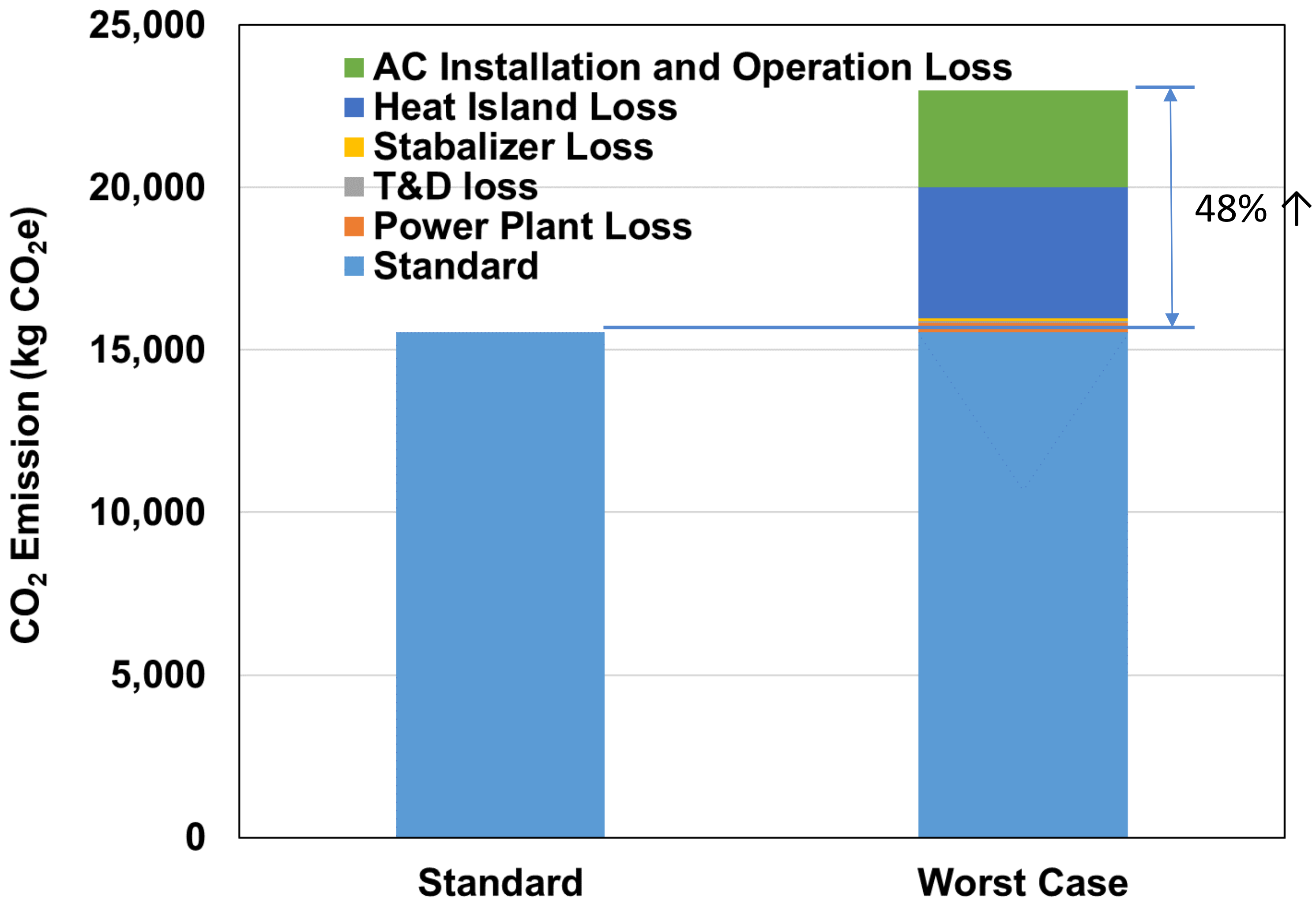




Seok-Ho Choi, Kwan-Soo Lee, Byung-Soon Kim, Effects of stacked condensers in a high-rise apartment building, Energy, Volume 30, Issue 7, 2005, Pages 968-981

Effects of Power Quality and Installation on LCCP

- Standard Case:
  - Power plant standard emission
  - T&D losses: 5%
  - Ambient temperature
- Worst Case:
  - Amb. temp. degrades power plant emission by 2%
  - T&D losses: 5.5%
  - Vol. stabilizer loss: 5%
  - AC COP degrades by 47% due to Stacked ACs (27%) and Heat Island Impact (20%)



Where Next Metrics Project?

- Vision and Illustration
  - Contrasting HFC-32, HC-290 and HFC-410A RACs in specific locations
  - Estimating the Margin of Energy Efficiency to Overcome Higher GWP
  - Isoquants of GWP and SEER Translated to Carbon Footprint
- Global Model Trusted and Continuously Improved
  - Available as web-based tool
  - Certified results, where desirable, including reasonable assumptions and appropriate sensitivity analysis
- Ideally Becoming a Consensus Standards (AHRI develops test standard adopted by ASHRAE in building standards)

Backup Sides Follow

LCCP Equation

$$LCCP = \text{Direct Emissions} + \text{Indirect Emissions}$$

$$\text{Direct Emissions} = C * (L * ALR + EOL) * (GWP + Adp.\ GWP)$$

$$\text{Indirect Emissions} = L * AEC * EM + \sum(m * MM) + \sum(mr * RM) + C * (1 + L * ALR) * RFM + C * (1\text{-}EOL) * RFD$$

C = Refrigerant Charge (kg)
L=Average Lifetime of Equipment (yr)
ALR = Annual Leakage Rate (% of Refrigerant Charge)
EOL = End of Life Refrigerant Leakage (% of Refrigerant Charge)
GWP = Global Warming Potential (kg CO_{2e}/kg)
Adp. GWP = GWP of Atmospheric Degradation Product of the Refrigerant (kg CO_{2e}/kg)

AEC = Annual Energy Consumption (kWh)
EM = CO_2 Produced/kWh (kg CO_{2e}/kWh)
m = Mass of Unit (kg)
MM = CO_{2e} Produced/Material (kg CO_{2e}/kg)
mr = Mass of Recycled Material (kg)
RM = CO_{2e} Produced/Recycled Material (kg CO_{2e}/kg)
RFM = Refrigerant Manufacturing Emissions (kg CO_{2e}/kg)
RFD = Refrigerant Disposal Emissions (kg CO_{2e}/kg)

Invention and Evolution of LCCP

YEAR	DRIVERS	ELABORATION
1999	Andersen Chairs TEAP Task Force HFCs and PFCs	Andersen invents LCCP to account for HFC-23 emissions in HCFC-22 production (adding ~20% to GWP) and to account for energy in aqueous cleaning
2005	IPCC/TEAP Special Report on HFC & PFC Ozone & Climate Impacts	IPCC/TEAP endorses LCCP framework but notes that detailed modelling and application is not yet available
2010	Hill, Papasavva & Andersen chair Society of Automotive Engineers (SAE) committee to perfect for MACS	"Green MAC LCCP" becomes an SAE standard and is used by global industry to select HFO-1234yf to replace HFC-134a in response to EU MAC F-gas rule
2012-16	Hwang chairs International Institute of Refrigeration (IIR) committee to perfect for stationary ACs and chillers	IIR model developed, elaborated and accepted, but IIR has no standards activity
2015-17	Andersen, Wolf, Hwang, et al. form Tiger Team to tailor LCCP to inform HFC phase-down	Ambition is to quantify the carbon advantage of combined refrigerant and incremental energy efficiency improvements

Application to EESL Bulk Procurement Outcome

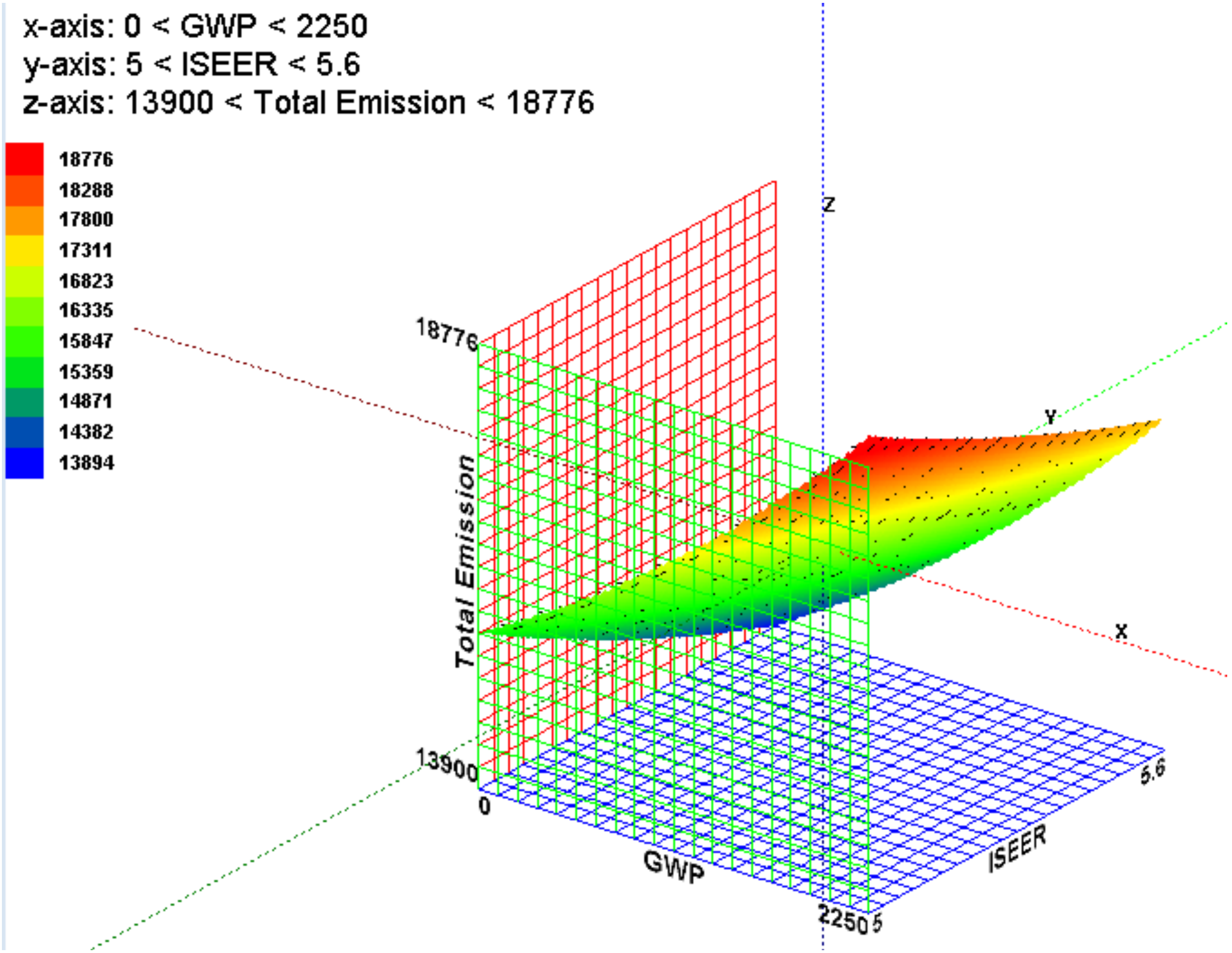
- Three Bids in First Round
  - Godrej HC-290 (GWP~3) ISEER 5.2
  - Panasonic HFC-410A (GWP=1924) ISEER 5.2
  - Daikin HFC-32 (677) ISEER 5.4
- EESL disregarded the advantage of +0.2 ISEER and lower-GWP of HC-290 and HFC-32
  - Godrej matched Panasonic low bid and Daikin dropped out
- How could the LCCP Carbon Metric have informed bid crafting and selection if modelling had been available?

LCCP of EESL Contender (High Ambient)

Refrigerant	R410A	R32	R-290	R410A Improved	R-32 Improved	R-32 Improved
ISEER	5.2	5.2	5.2	6.6	5.4	5.6
Total Lifetime Emission (kg CO_2e)	19,093.4	16,133.3	15,450.3	15,927.3	15,906.1	15,455.7
Total Direct Emission (kg CO_2e)	3,601.8	961.9	1.1	3,601.8	961.9	961.9
Annual Refrigerant Leakage (kg CO_2e)	2,881.4	769.5	0.9	2,881.4	769.5	769.5
EOL Refrigerant Leakage (kg CO_2e)	720.4	192.4	0.2	720.4	192.4	192.4
Total Indirect Emission (kg CO_2e)	15,491.6	15,472.6	15,449.2	12,325.5	14,944.2	14,493. 1
Energy Consumption (kg CO_2e)	15,076.4	15057.4	15034	11,910.4	14,529.1	14,078.7
Equipment Mfg. (kg CO_2e)	408.7	408.7	408.7	408.7	408.7	408.7
Equipment EOL (kg CO_2e)	6.5	6.5	6.5	6.5	6.5	6.5
Refrigerant Mfg. (kg CO_2e)	39.4	21.9	0.0	39.4	21.9	21.9

15% EOL Scenario

Balancing between GWP and Efficiency: Split ACs



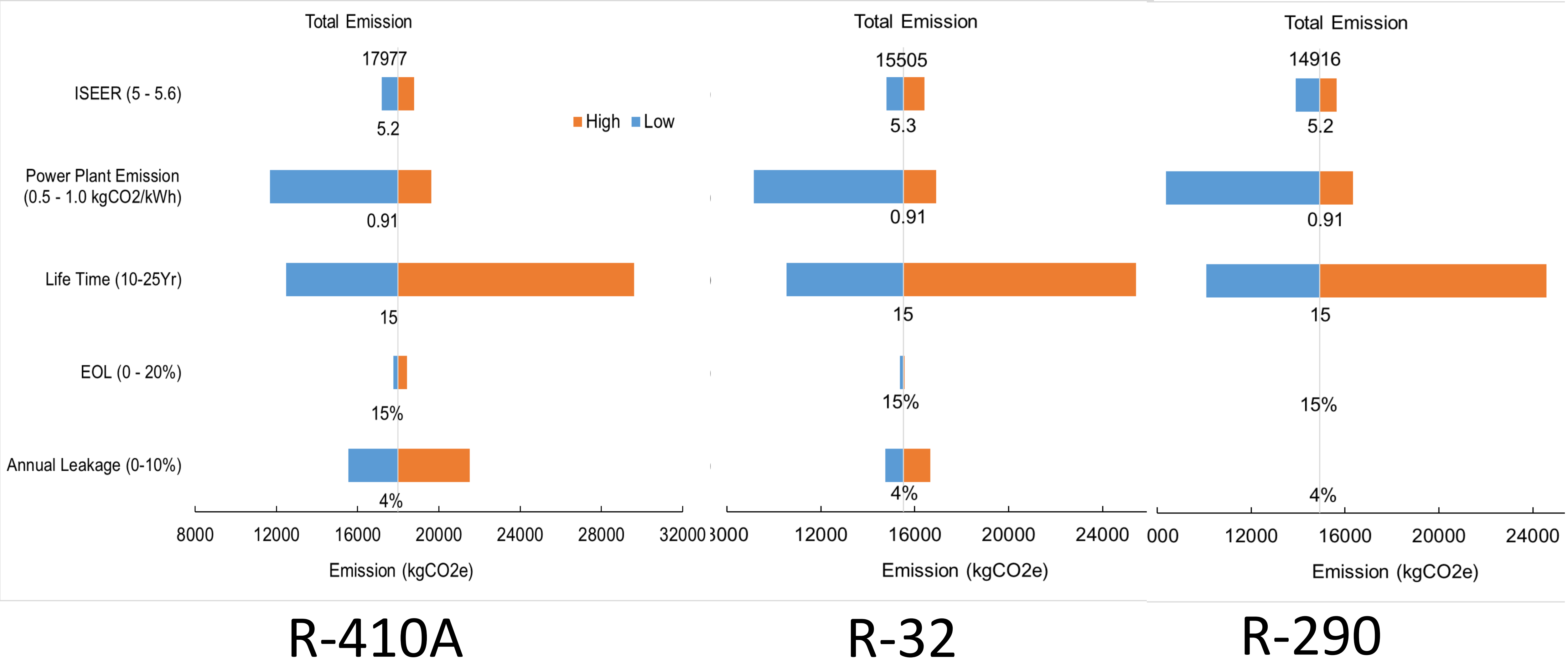
When ISEER increases from 5 to 5.6

- R290 systems reduce LCCP by **11%**
- R410A systems reduce LCCP by **8%**

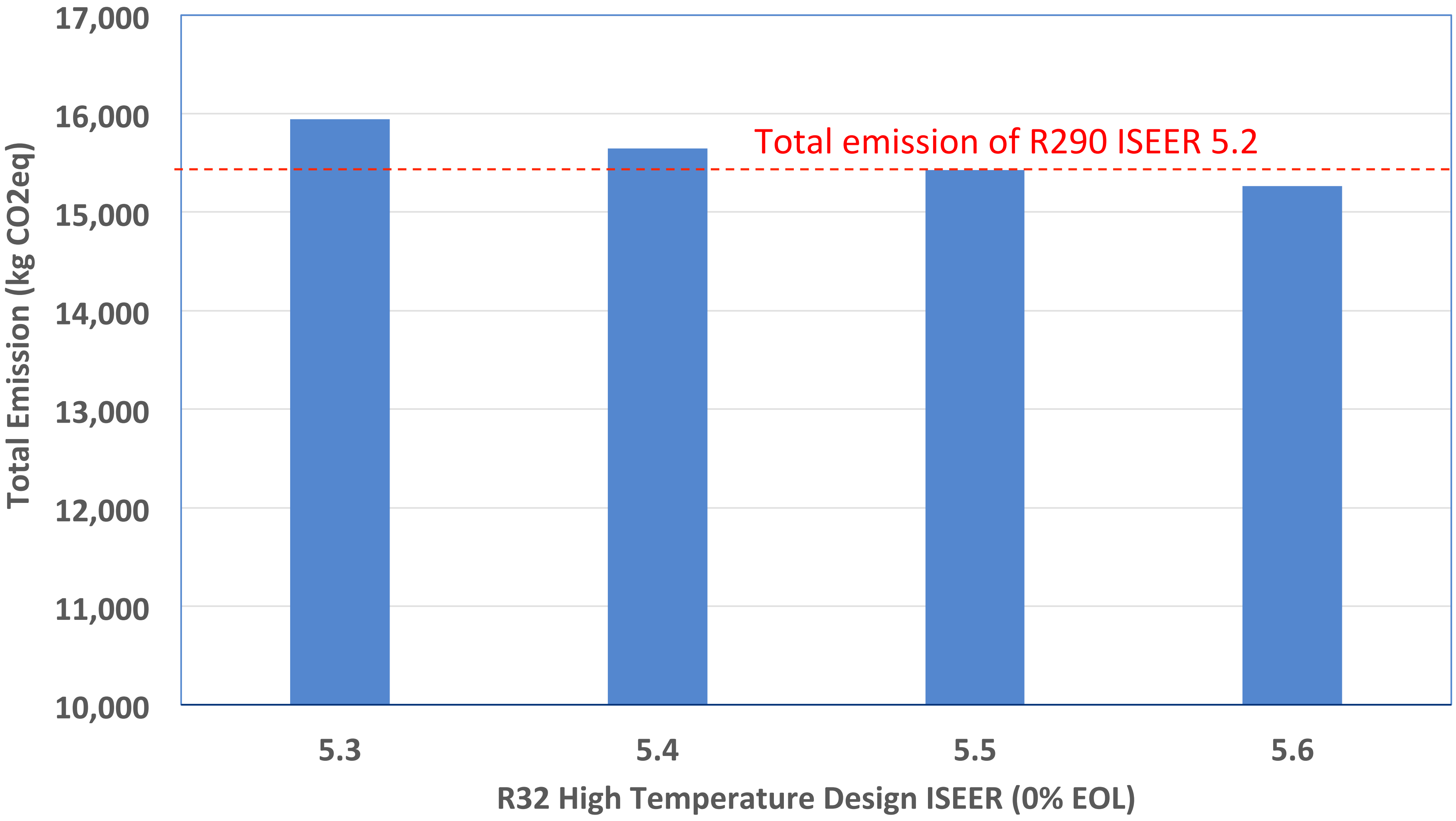
When GWP decreases from 2088 to 3

- Highest efficient systems (5.6) reduce LCCP by **19%**
- Lowest efficient systems (5.0) reduce LCCP by **17%**

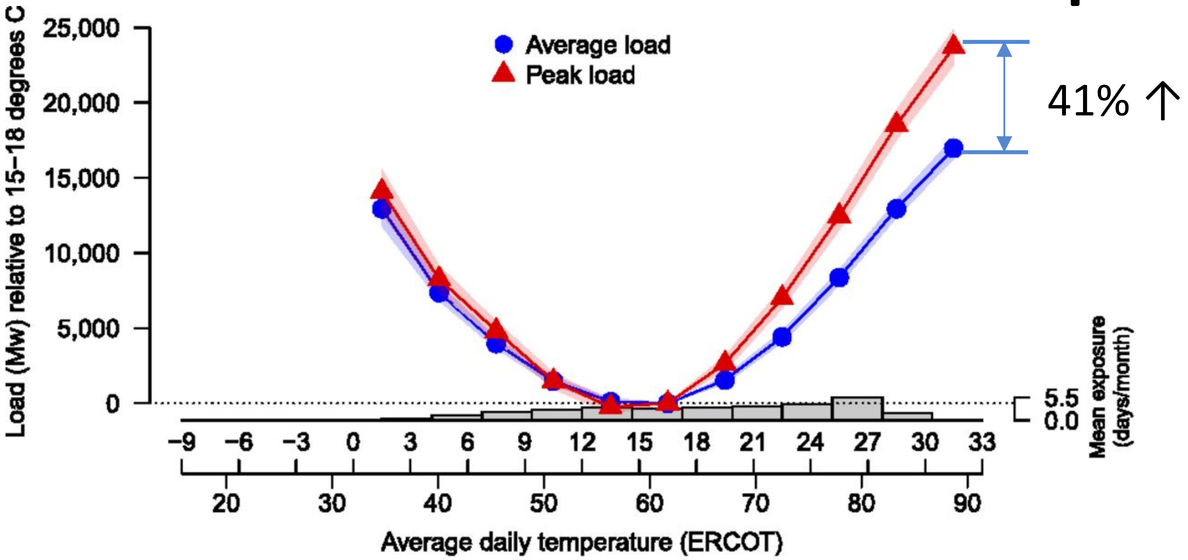
LCCP Comparison



LCCP of EESL Contender (High Ambient)



Effects of Ambient Temp. on Peak Load



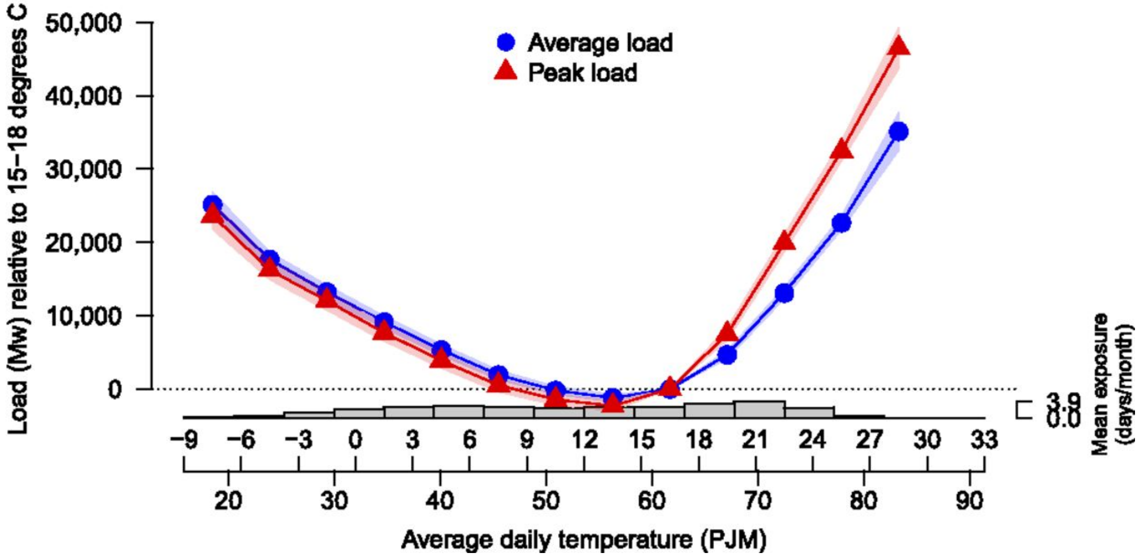


Table 1. Increases in peak demand dwarf increases in average demand by end of century

Simulation type	%Δ average hourly load Intensity	%Δ peak daily load Intensity	%Δ 95th percentile daily peak load Intensity	%Δ frequency days w. peak load > current 95th percentile Frequency	%Δ frequency days w. peak load > current 99th percentile Frequency
			RCP 4.5		
FERC	2.8	3.5	6.8	158	382
ERCOT	3.7	4.3	6.2	150	460
ISONE	1.6	2	7.1	103	260
NYISO	2.7	3.3	8.5	128	312
PJM	2.3	3.1	8	133	329
Total	2.8	3.5	7	152	374
			RCP 8.5		
FERC	8	9.7	17.2	407	1, 532
ERCOT	10.1	11.5	15.2	406	1, 634
ISONE	5	6	17.7	281	1, 024
NYISO	8	9.2	21.2	334	1, 230
PJM	7	8.9	20.5	354	1, 347
Total	7.9	9.6	17.6	395	1, 492

Column 1 is the projected percent change in hourly generation, column 2 is the projected percent change in daily peak load, column 3 is the projected percent change in the 95th percentile of daily peak load, and columns 4 and 5 are the projected percent change in the number of days with peak load greater than the present-day 95th and 99th percentiles, respectively. Each projection is based on the average projected change in temperature for 19 independent climate models. The five rows display results across five geographic regions of the United States.

Climate change impacts on US electricity demand, Maximilian Auffhammer, Patrick Baylis, Catherine H. Hausman, Proceedings of the National Academy of Sciences Feb 2017, 114 (8) 1886-1891

Stacked AC Outdoor Units

https://motherboard.vice.com/en_us/article/nz73xg/what-air-conditioning-can-teach-us-about-innovation-and-laziness

Stacked AC Outdoor Units in High-rises

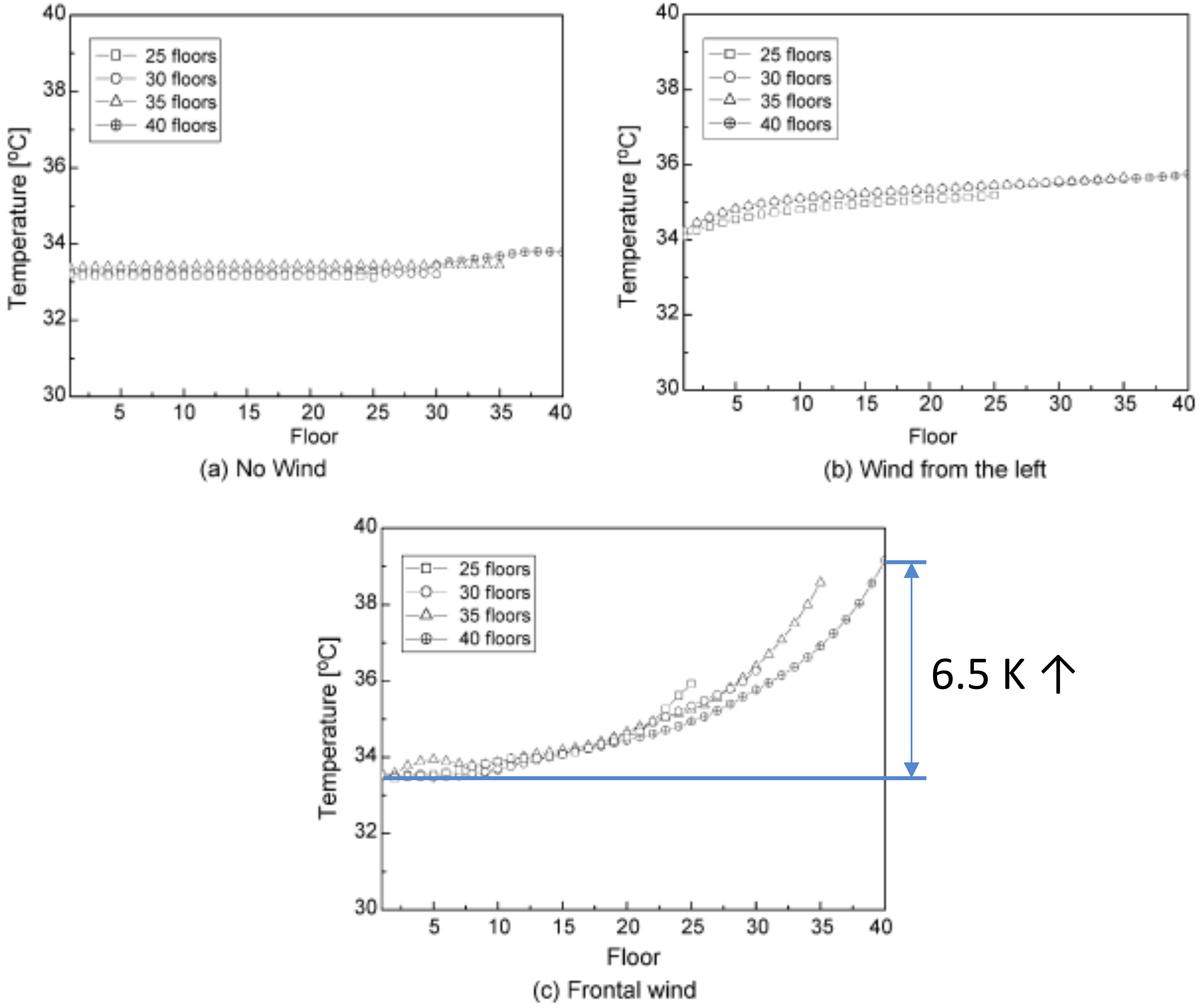


Fig. 4. Condenser on-coil temperature for different floor levels. (a) No wind, (b) wind from the left, and (c) frontal wind.

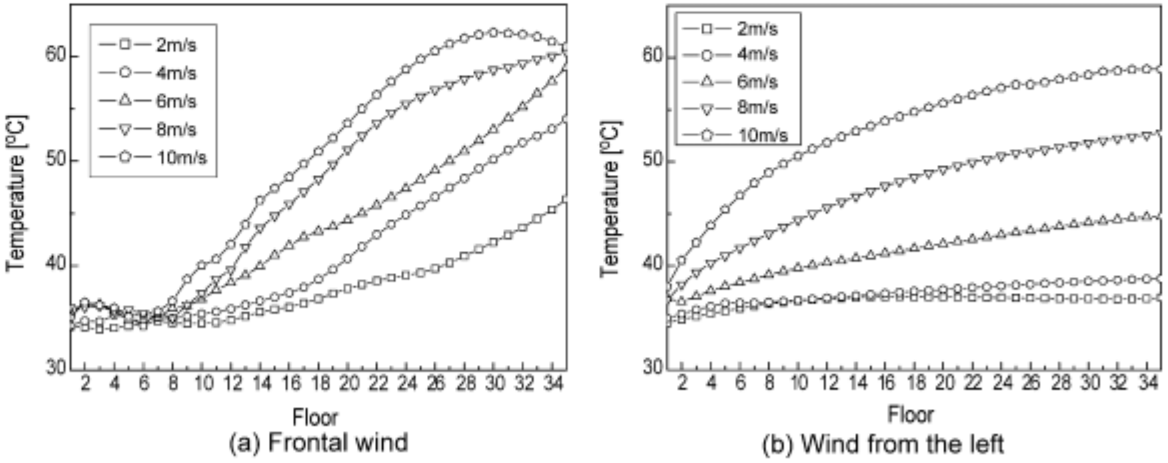
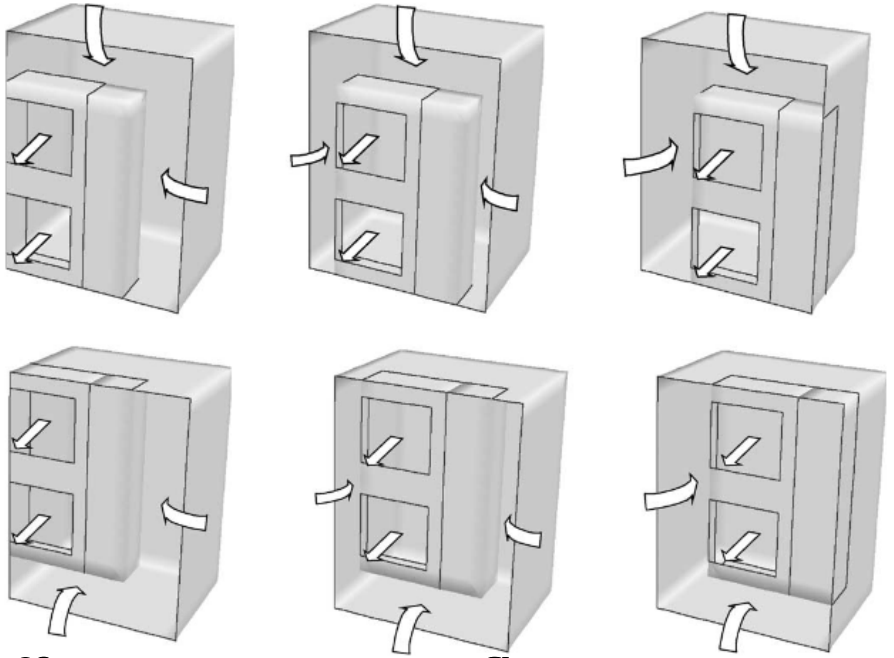


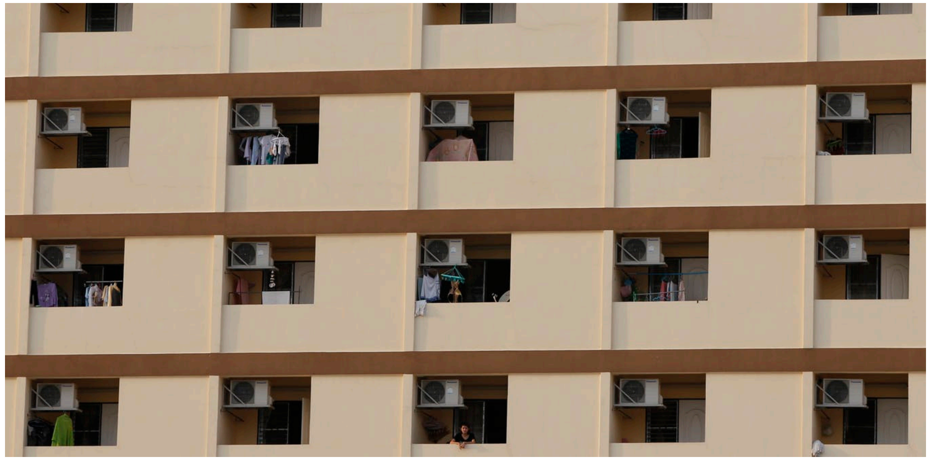
Fig. 5. Condenser on-coil temperature for various wind speeds. (a) Frontal wind, and (b) wind from the left.

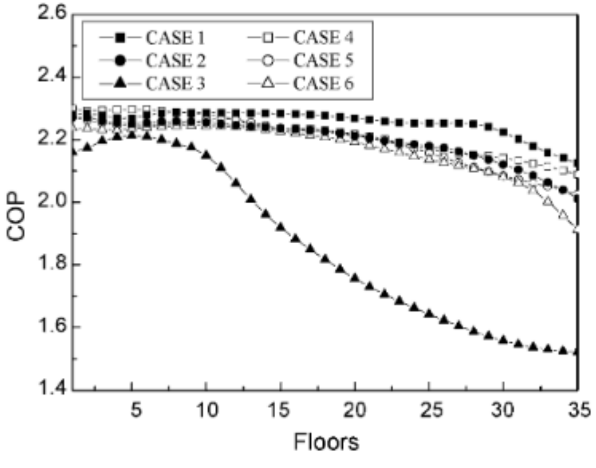
Seok-Ho Choi, Kwan-Soo Lee, Byung-Soon Kim, Effects of stacked condensers in a high-rise apartment building, Energy, Volume 30, Issue 7, 2005, Pages 968-981

Stacked AC Outdoor Units in High-rises

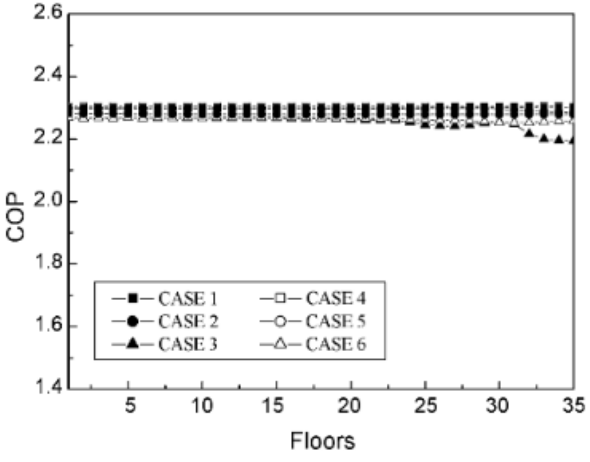


Different AC OU air flow arrangement

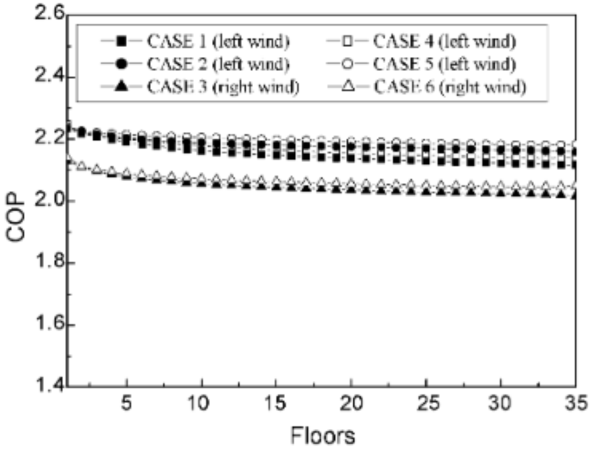




(a) No wind



(b) Frontal wind



(c) Side wind

COP degradation for different AC OU arrangement