TECHNICAL FEATURE

Life-Cycle Climate Performance Metrics and Room AC Carbon Footprint

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CFC and HCFC refrigerants are being phased out by The Montreal Protocol on Substances that Deplete the Ozone Layer. Today, 99% of emissive ozone-depleting substances (ODS) uses have been halted, with critical use exemptions for methyl bromide in quarantine and pre-shipment uses and continuing essential use exemptions for laboratory, analytical, and other minor uses.[1]

About 85% of ODSs phased out so far were replaced with not-in-kind (non-fluorocarbon),[2] or handled through containment or recovery/recycle, or, in cases of frivolous or meritless uses, by doing without.[3,4] The other 15% of uses that would otherwise depend on ODSs are today accomplished by hydrofluorocarbons (HFCs) with global warming potentials (GWPs) considered high in climate forcing, but typically far lower than the GWP of the CFCs and HCFCs they replace.

The replacement of CFC-12 (GWP=10,200) with HFC-134a (GWP=1,300) and next HFO-1234yf (GWP<1) is a conspicuous example of ozone safe and climate safer. The replacement of HCFC-22 (GWP=1,760) with HFC-410A (GWP=1,924) is a conspicuous example of an increase in GWP that was necessary to rapidly phase out ODSs. It should be noted that all GWP values used here are from IPCC AR5 report.[5]

The United Nations Framework Convention on Climate Change (UNFCCC), with its Kyoto Protocol and Paris Agreement address HFC emissions, while the Kigali HFC Amendment to the Montreal Protocol phases down HFC production and consumption. The UNFCCC Paris Agreement sets a target limit of a global warming increase of 2°C (3.6°F) and seeks to achieve 1.5°C (2.7°F).

The phasedown of HFCs under the Kigali Amendment will avoid 80 billion tons of CO_2e[6] and avert up to 0.5°C (0.8°F) of warming by 2100.[7] Significantly improving the energy efficiency of refrigeration and air conditioning equipment together with the refrigerant transitions could double the benefit by avoiding on the order of 60 billion tons of CO_2e by 2050.[8]

A technology is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input. For the last several

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TABLE 1 Underlying assumptions used in the current LCCP analysis.

PARAMETER	ASSUMPTION
Power Plant Emission	0.91 kgCO_2e/kWh (refer IEA, EPA e-Grid)
Transmission and Distribution (T&D) Loss	5%
Refrigerant	R-410A
Lifetime (L)	15 Years
End of Life Refrigerant Leakage (EOL)	15%
ISEER	5.2
Annual Leakage Rate (ALR)	4%
Location	India
Weather Data	IWEC (2013), TMY3 (2015)

Note: For other parameters, refer to IIR LCCP guidelines.[14]

decades, energy experts have continuously improved the metrics for measuring air conditioning systems' performance, and each metric approach is useful in guiding product engineering and policy.[9] These measures of air-conditioning performance include cooling capacity, energy efficiency (ratio of cooling output to electrical power input), and seasonal energy efficiency in regionalized weather conditions, expressed as Seasonal Energy Efficiency Ratio (SEER).

A typical SEER calculation is for cooling occupied space to 27°C (80°F) over a range of outside temperatures from 18°C to 40°C (64°F to 104°F), with a specified percentage of time in each of eight "bins" spanning 2.8°C (5°F).[10] A refinement of SEER tailors the estimate to the weather at a specific location and allows the choice of cooling temperature at any time of day.

The translation of direct refrigerant greenhouse gas (GHG) emissions, indirect fossil fuel GHG emissions as well as the emissions embodied in equipment to carbon footprint requires accounting of the carbon intensity of electricity as delivered to the AC under circumstances of real-world operation. Total Equivalent Warming Impact (TEWI) is the summation of carbon-equivalent direct refrigerant and indirect power plant GHG emissions,[11,12] while the more comprehensive Life-Cycle Climate Performance (LCCP) adds carbon-equivalent embodied emissions to the TEWI figure. Embodied emissions include materials, manufacture, transport, installation, service and recycle at the end of a product's life as shown in the sidebar "Life-Cycle Climate Performance."[3,5,13,14] Both TEWI and LCCP calculations are often made using "average" values for carbon intensity to estimate total warming impacts on national scales.

Life-Cycle Climate Performance

LCCP = Direct Emissions + Indirect Emissions

Direct Emissions = C × (L × ALR + EOL) × (GWP + Adp. GWP)

C = Refrigerant Charge (kg)
L = Average Lifetime of Equipment (yr)
ALR = Annual Leakage Rate (Percent of Refrigerant Charge)
EOL = End of Life Refrigerant Leakage (Percent 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)

Indirect Emissions = L × AEC × EM+∑(m × MM) + ∑(mr × RM) + C × (1+L × ALR) × RFM +C × (1-EOL) × RFD

L = Average Lifetime of Equipment (yr)
AEC = Annual Energy Consumption (kWh)
EM = CO_2 Produced/kWh (kg CO_2e/kWh)
m = Mass of Unit (kg)
MM = CO_2 Produced/Material (kg CO_2e/kg)
mr = Mass of Recycled Material (kg)
RM = CO_2 Produced/Recycled Material (kg CO_2e/kg)
C = Refrigerant Charge (kg)
L = Average Lifetime of Equipment (yr)
ALR = Annual Leakage Rate (Percent of Refrigerant Charge)
RFM = Refrigerant Manufacturing Emissions (kg CO_2e/kg)
EOL = End of Life Refrigerant Leakage (Percent of Refrigerant Charge)
RFD = Refrigerant Disposal Emissions (kg CO_2e/kg)

If refrigerants have near-zero GWP and/or are fully contained with near-zero emissions, then direct refrigerant emissions are relatively unimportant to LCCP calculations. If electricity is supplied by near-zero carbon electricity from nuclear, hydro, solar and wind, then indirect emissions are relatively unimportant to LCCP calculations. If the refrigerant is recovered and reused or destroyed and all materials are recycled into future uses, then the embodied emissions are relatively unimportant to LCCP calculations. *Table 1* shows underlying assumptions used in the current LCCP analysis.

With no barriers of data, computation, or programming, Enhanced and Localized LCCP (EL-LCCP) will ultimately account for: 1) local climate conditions, including high temperature and humidity; 2) local seasonal and time-of-day carbon intensity of electricity sources, including backup electricity generation; 3) electricity transmission and distribution losses, including through the application of any voltage stabilizers; 4) energy embodied in water used for power plant cooling; 5) black and brown carbon power plant emissions; 6) more realistic assumptions about the actual air temperature entering AC condensers (many open, located in urban heat islands, often stacked and clustered, arranged with poor ventilation, and placed in direct sunlight); and 7) realistic assumptions about matching AC capacity to cooling load and servicing to maintain efficiency over the lifetime of the installation.

How AC Energy-Efficiency Metrics Are Inappropriate to Predict Actual Field Performance

Among the reasons that current AC energy-efficiency metrics are inappropriate to predict actual field performance is that they:

- Do not necessarily require measurement of energy performance at high ambient temperatures and the actual temperature of condensers located in urban heat islands that are stacked and clustered on buildings;
- Are based on tests conducted at fixed humidity or in dry air, which neglect the substantial energy consumption of dehumidification during actual AC operation in humid locations;
- Assume customers of air conditioning would choose the same constant indoor temperature and would cool the space whether occupied or not, 24 hours a day, seven days a week;
- Assume part-load operation based on building load target and over-sizing factor rather than the actual operating conditions, where equipment is often much over-sized and operates at lower part-load conditions;
- Assume constant energy efficiency over the life of the equipment as if the charge were maintained at an optimum quantity, servicing kept heat exchangers at top performance and there were no degradation in efficiency from wear and tear. and
- Do not incorporate the carbon intensity of electricity generation and thus measure cooling output per kilowatt hour (kWh) but not per ton equivalent carbon emissions, or use simplified calculations of carbon intensity rather than time-of-day marginal values that would accurately reflect how many power plants are avoided or reduced in output by higher energy efficiency.

In addition, current metrics fail to include some of the most important options for energy efficiency, which discourages innovation. Examples of disregarded features include:

- Mono- or multi-split room ACs have one outside condenser unit and several inside evaporator units in separate rooms that, with appropriate sensors, could each detect occupancy and operate only when people need cooling, but the test procedure disregards this feature as if the whole house needed cooling at all times;
- Smart room ACs with infrared detectors to direct the flow of cool air to place(s) in the room where people are located and thereby avoid cooling unoccupied spaces;
- Outside condenser units painted with reflective coatings or shaded, which reduces heating in direct sunlight and increases the efficiency of cooling; and
- Integration of water heating and air-conditioning loads to reduce the combined GHG emissions.

The consequences of incomplete metrics are that the energy-efficiency label is not always an accurate indication of real-world product performance in specific locations, the benefits of the disregarded design features are invisible on the label, and manufacturers have little incentive to incorporate options not accounted for in the metric. Furthermore, existing metrics can distort refrigerant choice because refrigerants with comparable energy efficiency when tested at low ambient temperatures will not necessarily have comparable energy efficiency at the higher ambient temperatures typical of developing countries, which have the fastest growth in AC sales.

Identifying and Implementing Corrections to "Average" Assumptions Made in Previous Energy-Efficiency Metrics

The team of experts that developed the comprehensive metric identified and resolved three challenges when applying current energy-efficiency metrics for field performance prediction.

ACs Operate in Far Hotter Conditions Than Indicated by Weather Data and Test Procedures

SEER is the weighted average of efficiency at a prescribed range of outdoor temperatures. For the United States, the method for calculating SEER is elaborated by AHRI Standard 210/240-2017, *Performance Rating of Unitary Air-Conditioning and Air-Source Heat Pump Equipment*.[15] In the European Union, the European Ecodesign Directive and Energy Labelling Regulation define SEER (EU

Regulations 206, 2012 and 626, 2011). The Indian SEER assumptions are established by the Bureau of Indian Standards (BIS) decided by the Indian Bureau of Energy Efficiency (BEE). ISO 16358-1[10] specifies the test conditions and the corresponding test procedures for determining the seasonal performance factor of equipment. The outdoor temperature ranges used for weighting the energy performance are almost identical with the exception that India's system includes a hotter temperature bin than the others.

Local weather data is collected worldwide using a standardized monitoring station called a Stevenson Screen Instrument Shelter (Stevenson Shelter). The Stevenson Shelter is a World Meteorological Organization-certified white wooden box with louvers to shelter meteorological instruments from solar and local heat and to allow air circulation.[16] WMO specifies that the weather station be sited above lawn and soil in locations that avoid data degradation by the effects of buildings and pavement. The problems are: 1) the ambient temperature around buildings where ACs operate is often hotter than the temperatures measured in local Stevenson weather stations, and 2) AC condensers that disburse the heat removed from buildings by the AC are within urban heat islands may be stacked and clustered, located in direct sun, and/or with poor air circulation, so hot air discharged from one condenser heats another.

The urban heat island effect results from human activities, including modification of land surfaces and generation of heat through energy usage.[17] On a hot sunny day, dry exposed urban surfaces, such as roofs and pavement, can be 27°C to 50°C (81°F to 122°F), hotter than the air measured at the closest standardized weather stations located on grass or soil.[18] The annual mean air temperature of a city with a population of one million or more can be 1°C to 3°C (2°F to 6°F) warmer than its surroundings.[19] The energy impact of stacked and clustered condensers depends on the equipment design (cooling air intake and exhaust), spatial configuration, air exchange (including from wind and thermo-siphoning), and the amount of cumulative heat generated by the condensers.[20,21] The consequences of urban heat islands and stacked and clustered condensers are: 1) ACs that are designed to be efficient at standard test condition temperatures are less efficient at actual temperatures and 2) buyers choose equipment with lower efficiency than is in their self-interest or in the interest of community clean air and global climate protection.

The typical SEER test range assumes that a building will be air conditioned to 26.7°C (80°F) when the outside temperature is as low as 18°C (64°F) rather than naturally cooling by opening windows or using powered ventilation, such as a ventilation fan. The choice of 18°C as the lowest temperature bin for SEER calculations and the baseline for cooling degree days is premised on western architecture, where indoor temperature becomes uncomfortably hot at about 18°C ambient temperature due to solar loads, internal building energy use, and poor natural ventilation.

Transmission and Distribution Losses May Be Underestimated in Estimating Electricity Use and Emissions

AC carbon footprint is properly calculated at the point of use to take into consideration transmission and distribution (T&D) losses of the grid or sub-grid where the equipment is installed. The calculation should also include energy losses from any voltage stabilizing device at the point of use, which can add 5% loss. Electricity power transmission and distribution losses are significant, with a current global average of about 8% and losses ranging from 1% or less for countries with small grids and/or modern grids (e.g., Singapore 0%, Iceland 2%, Germany 4%, Bahrain 5%, and China 6%) to as high as 87% for large countries with a dispersed, obsolete grid and/or old infrastructure (e.g., Togo 87%, Haiti 55%, Republic of Congo 44%, Iraq 33%, and Honduras 31%).[22] Of course, the portion of electricity stolen from the grid is not included in the carbon intensity measurement of electricity for AC.

The Carbon Intensity of Electricity is Calculated at Average Rather Than Marginal Values of the Electricity Generation

In most hot climates, peak annual energy consumption occurs as a consequence of air conditioning on the hottest days during the hours between mid-day and evening. Electric utilities build their generation systems to satisfy this peak demand, with capacity to spare in case of unusually hot weather or power plant outages. Electric utilities with significant hydroelectric, wind and solar generation can add capacity as well as variability to power output. The strategy of managing electricity generation is to select the combination of power plants or purchased power that provides the electricity needed at the overall lowest cost, while satisfying renewable energy requirements and other environmental criteria. Most nuclear and fossil fuel plants produce electricity at the lowest cost at a specific output, but they can be controlled to produce more electricity at higher cost. Photovoltaic output depends on solar radiation and temperature (less output for any given radiation at higher temperatures), while wind energy depends on wind speed and not temperature. Hydroelectric power depends on the height of water above the generators, which can be drawn down during peak hours and allowed to recover during off-peak hours. The challenge is to continuously plan for the combination of generation that balances financial and environmental concerns and to continuously manage the supply from available sources in order to minimize financial and environmental costs.

Improving the energy efficiency of air conditioning reduces electricity consumption while the air conditioner is operating, including during peak hours. As demand for air conditioning grows, improving the energy efficiency of air conditioners can reduce the need to build new power plants.[23] A shift of investment from new power plants to higher energy efficiency saves money, reduces air pollution, and fights climate change.[24]

At high ambient temperatures, when AC cooling load is peaking, the carbon intensity of electricity increases as a consequence of decreasing volume and increasing temperature of water for cooling thermal power plants and increased air temperature for cooling gas turbine power plants, which lowers generation capacity and efficiency.[25–27] This impact can be considered by the new metric of marginal carbon intensity in particular circumstances, if the energy sources and performance of power plants are known. Another problem facing thermal power generation in many regions is the decreasing volume of available water for condenser cooling.

Table 2 shows additional losses not accounted for in the current LCCP analysis. *Figure 1* shows a comparison of carbon emissions with and without considering the above-mentioned assumptions. A worst case considers all additional losses listed in *Table 2* and may lead to an extra 2% power plant efficiency decrease; 0.5% more transmission and distribution losses; 5% loss from the voltage stabilizer; and a total of 47% air conditioner coefficient of performance (COP) degradation. As an accumulated result, the worst-case scenario demonstrates a 48% carbon emission increase!

FIGURE 1 Extra carbon emissions due to various losses.

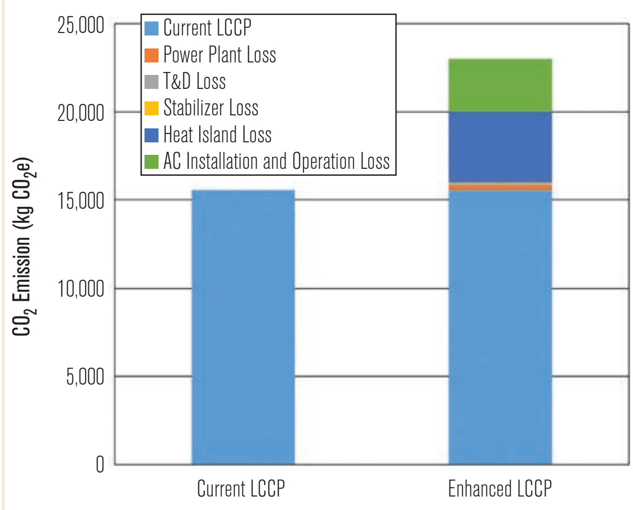

TABLE 2 Additional losses not accounted for in the current LCCP analysis.

ADDITIONAL DEGRADATION FACTORS	IMPACT
Power Plant Efficiency by Ambient Temperature	Power Plant Efficiency Reduced by 2% (36% to 34%)
T&D Loss by Ambient Temperature	Loss Increases by 0.5% (5% to 5.5%)
T&D Loss by Infrastructure	<5% Modern Grids; >50% Obsolete Grids
Voltage Stabilizer	Adds Additional 5% Loss
Heat Island Impact	Reduces AC COP by 27%
Stacked Condenser Impact	Reduces AC COP by 20%

Conclusions and Policy Implications

The comprehensive carbon metric described in this article accounts for the fact that AC electricity use and the integrated carbon intensity of that electricity can be both significantly higher in many cases by up to 48% than estimated using national "average" assumptions. Taking real-world operating conditions and the actual carbon intensity of electricity generation, transmission, and distribution at the end-use into consideration provides for a more accurate assessment of the significant climate and economic benefits from energy efficiency and power grid investment. Underestimating the carbon intensity of electricity generated in fossil fuel power plants located far from cities also short-changes the economics of solar or wind power, which can be located very near the point of use. In the future, this approach will be easily expanded to have more features. Consumer choice could be improved, for example, by users being able to input their own home occupancy hours and customized setpoint. As a result, users with higher usage could better understand the benefits of more efficient equipment or change of behavior. The ability to make adjustments related to deviations in the condenser inlet air temperature from ambient temperature can also be added to reflect the microenvironment of the unit, which may be associated with the installation situation. For example, discharge heat from nearby outdoor units can elevate an AC's incoming air temperature, which deteriorates the SEER and affects the LCCP.

There are several policy implications associated with underestimation of electricity at point-of-use and the consequently significantly higher carbon footprint of ACs:

- Higher energy efficiency is more effective at protecting climate than has been previously calculated because for every kWh saved through energy efficiency, much more than a kWh of electricity in generation is avoided.
- The higher carbon intensity of electricity at peak summer load indicates that electricity may be underpriced more than previously calculated, which implies that smart metering and time-of-day pricing would be more effective than current practices in reducing carbon emissions.
- Underestimating the carbon intensity of electricity generated in fossil fuel power plants located far from cities also short-changes the economics of solar or wind power, which can be located very near the point of use. The high level of electricity transmission and distribution losses makes locally sited wind and solar electricity generation more economically and environmentally valuable than previously understood.
- The Montreal Protocol strategy of HFC phasedown with energy-efficiency improvements delivers greater combined climate and clean air benefits than were expected when the Kigali Amendment and Kigali Decision on Energy Efficiency were agreed to by the parties. The comprehensive carbon metric underscores that major energy-efficiency gains are possible when the equipment is first purchased and properly installed. Proper maintenance is needed to fully realize these benefits, but they yield financial savings over the life of the equipment and also yield climate protection benefits for future generations.

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