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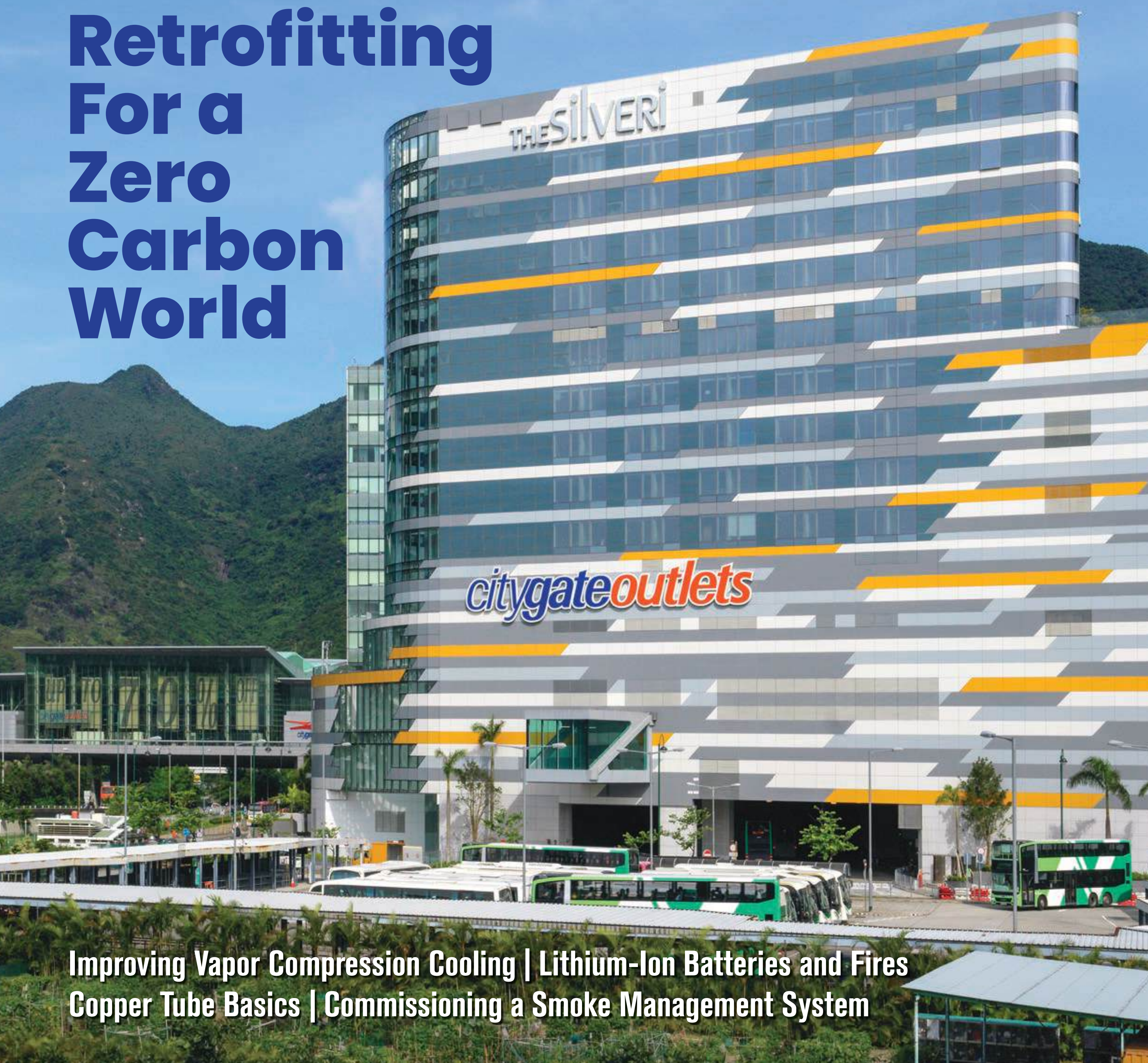

Improving Vapor Compression Cooling | Lithium-Ion Batteries and Fires
Copper Tube Basics | Commissioning a Smoke Management System

The Dehumidification Dilemma

Unlocking Efficiency in Vapor Compression Cooling

BY YASHKUMAR SHUKLA, PH.D., MEMBER ASHRAE; BILL MCQUADE P.E., CDP, PRESIDENTIAL/FELLOW/LIFE MEMBER ASHRAE; ANKIT KALANKI; IAN MCGAVISK

Room air conditioners (ACs) based on vapor compression technology are primarily designed to address sensible cooling loads, while latent load removal (dehumidification) is achieved as a by-product when the evaporator coil surface is held below the dew-point temperature of the entering air. In warm–humid climates, this approach to dehumidification often results in overcooled spaces, significant energy use and compromised thermal comfort (see "Thermal Comfort" sidebar). This article argues that while existing performance standards have been effective in driving efficiency improvements, they would benefit from clearer treatment of latent performance and operating conditions representative of warm–humid climates, particularly under real-world and part-load operating conditions commonly encountered in India and comparable regions. It focuses on typical residential room ACs—ductless split-type products operating in India and comparable warm–humid regions globally.

Impact of Rising Wet-Bulb Temperatures on Human Comfort: Why Next-Gen ACs Must Deal With It

A well-recognized limit exists to how much heat and humidity humans can handle comfortably, expressed through wet-bulb temperature. It's an important measure that provides an understanding of how uncomfortable and potentially dangerous the weather can "feel" to a person. As temperatures hit a wet-bulb of 30°C (86°F), people worldwide begin to experience significant discomfort, particularly when outdoors or without access to cooling methods. The situation becomes severe when the wet-bulb temperature rises to 35°C (95°F), marking the threshold where the human body struggles to effectively cool down

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through sweating. Such conditions create a high risk of heatstroke, dehydration, heat exhaustion and other critical health issues.

Recently, many regions have experienced alarming increases in wet-bulb temperatures, posing serious challenges to human comfort and safety. This can lead to increased risks of heat-related health conditions.[1] In the Middle East, wet-bulb temperatures have occasionally exceeded 30°C (86°F) during extreme heat waves. Similarly, parts of the southern U.S. and Southeast Asia have seen these temperatures rise to levels that impact the ability to conduct outdoor activities and heighten health risks. Cities such as Philadelphia, Washington and Baltimore recently saw record-breaking stretches of days with dew points above 24°C (75°F). These rising wet-bulb temperatures highlight the urgent need for communities to find effective ways to adapt and protect themselves.

These rising global temperatures—especially in terms of wet-bulb temperature, which reflects the combined effects of heat and humidity—are placing a new kind of strain on traditional cooling systems.

Exponential Growth in Air-Conditioning Use Demands a Shift Now

While most developed countries including Japan and the U.S. have significantly high AC penetration today, in many countries, particularly in India and parts of Southeast Asia, the household penetration of AC is below 10%. However, the sales of room ACs are expanding by around 10%–15% each year, driven by rising temperatures, urbanization, income levels and increased awareness of comfort. Global air conditioner stock has grown rapidly over the past decade, reaching approximately 1 to 1.6 billion units, and is projected to reach 5.6 billion units by 2050, reflecting a steep and sustained rise in cooling demand worldwide.[2,3] Single split ductless type room air-conditioning systems with a capacity of 1 ton to 2 tons (3.5 kW to 7 kW) of refrigeration are popular for residential and small commercial use in large parts of the world and are increasingly becoming popular in the U.S.

This rapid growth means more households will have air-conditioning systems than before. This creates significant challenges for electricity infrastructure and climate for many developing countries.[4] ACs often are a major contributor to peak demand, particularly during evenings, which can strain the power grid. For the same reason, power grids in many regions will need major upgrades and expansions to supply the extra electricity required. This installation and upgrade process will involve substantial investments and planning from governments and energy providers.[2]

The ductless split-type air conditioners (*Figure 2*) that

Thermal Comfort

Have you ever been in a hotel, office building or convention center in a hot and humid climate and noticed the rooms are too cold for comfort? You might have even had to wear a light coat or sweater. Most people think of thermal comfort in terms of what we see on the thermostat. However, ASHRAE Standard 55-2023 tells us many factors affect people's thermal perception. Thermal comfort is influenced by multiple factors beyond air temperature, including humidity, air speed, radiant temperature, clothing and activity level (*Figure 1*). We can all think back to a "thermal comfort experience" such as when we were hot on a summer day and sought relief in the shade. This is the power of radiant heat and why building envelope performance is so important. Another example: a light breeze on a hot and humid day providing just enough cooling to make us feel comfortable. This is the power of elevated air speeds.

Humidity is one of the most important factors, as it affects our body's ability to cool itself and regulate temperature. The higher the humidity at elevated temperatures the harder it is for our body to remove heat by evaporating sweat. In warm–humid climates, humidity plays a particularly important role because it limits the body's ability to dissipate heat through evaporation. ■

FIGURE 1 Factors affecting thermal comfort of occupants.

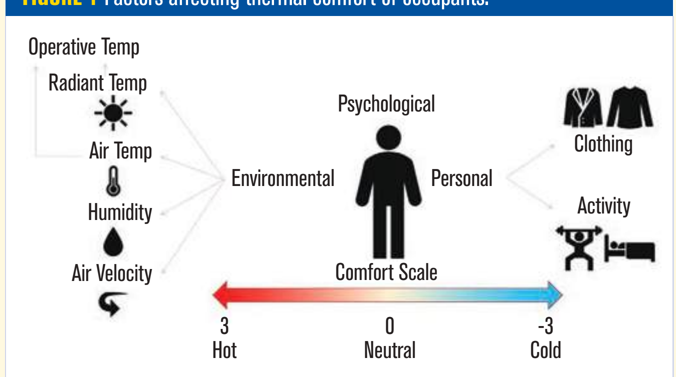
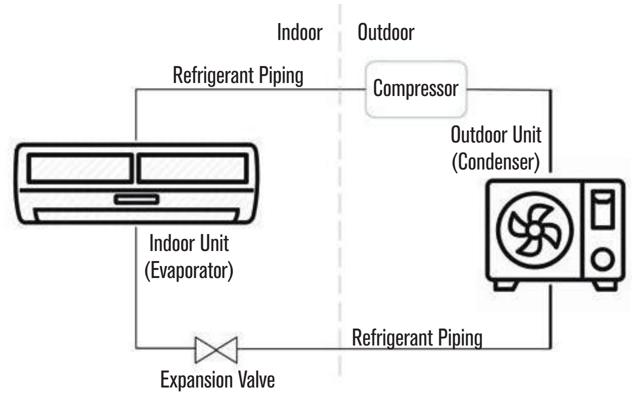


FIGURE 2 Typical room air-conditioning system (split) used in the residential and light commercial sector.



are the focus of this article consist of an indoor unit that cools the room and an outdoor unit that dissipates heat.

How Conventional Air Conditioners (ACs) Dehumidify: A Focus on Sensible Cooling and Its Limitations

In vapor compression systems, dehumidification occurs when the evaporator coil surface temperature falls below the dew point of the entering air, causing water vapor to condense on the coil. As a result, sensible and latent cooling are inherently coupled. This coupling can become inefficient when substantial moisture removal is required to achieve indoor thermal comfort.

Occupants frequently respond to high indoor humidity by lowering thermostat setpoints. Then, systems operate at lower coil temperatures and for longer than necessary to achieve the target humidity, increasing energy consumption and causing unintended overcooling. This effect is particularly pronounced at nighttime or warm and humid conditions, when sensible loads are lower but latent loads remain high, requiring extended operation primarily for moisture removal.

This limitation does not reflect a fundamental constraint of vapor compression technology, but the design and control strategies of conventional systems, which prioritize temperature regulation while treating humidity control as an indirect outcome. Although air conditioner efficiency has improved substantially over the past two decades, standardized rating methods such as ISO 5151, ISO 16358, AHRI 210/240 and national seasonal efficiency metrics—including the ISEER defined in IS 1391 (Part 2)— evaluate performance under fixed indoor and outdoor psychrometric conditions that may not fully represent real-world operation.

Next-Gen Air Conditioning System: What Design and Technology Features are Needed

A growing need exists to advance the design of air-conditioning systems, particularly room air conditioners, and to develop innovative cooling technologies that can maintain thermal comfort while reducing energy consumption and environmental impact. One promising direction involves improving thermal management by decoupling sensible and latent heat transfer processes, enabling more precise and efficient control of indoor conditions.

Meeting this need will require AC systems capable of independently and effectively regulating both sensible cooling and dehumidification. Technologies that enable such decoupled control can improve thermodynamic efficiency, reduce unnecessary energy use and enhance indoor environmental quality. These advancements have the potential to lower operating costs, reduce environmental impact and provide more consistent, physiologically appropriate indoor comfort.

Impacts of Energy Efficient Dehumidification

The need for a shared understanding of the real-world performance of ACs is becoming essential and is key to inform future performance standards, which in turn would give the industry the right design targets for product development.[5,6] Field studies can generate valuable data and evidence to uncover inefficiencies such as overcooling, poor latent load handling and energy waste that are often masked in today's performance ratings.

The field study, conducted in 2023–2024 by the Global Cooling Efficiency Accelerator[7] in partnership with one of India's largest real-estate developers represented a pivotal effort in assessing field performance of today's AC products and technologies that are optimized for real-world conditions. All systems were installed in materially equivalent apartments and operated under identical comfort targets of 27°C (81°F) and 60% RH. Continuous monitoring of indoor conditions, energy use and humidity ensured comparable and consistent performance assessment across systems. To ensure comparability across apartments, additional validation was conducted including envelope U-value comparison, baseline measurements without AC operation and CO_2 tracer gas tests to assess air leakage. These steps confirmed the apartments exhibited materially similar thermal and air exchange characteristics, enabling consistent comparison of sensible and latent load conditions across systems.

This nine-month scientific investigation, conducted in residential apartment homes within Palava, a city near Mumbai, India, aimed to provide real-world comparative performance data between commercially available ACs and "super-efficient" AC. Super-efficient air conditioners, in this context, refer to systems incorporating high-efficiency components, optimized heat exchanger design and improved control strategies capable of maintaining target temperature and humidity conditions with reduced overcooling and lower energy consumption (*Figure 3*).

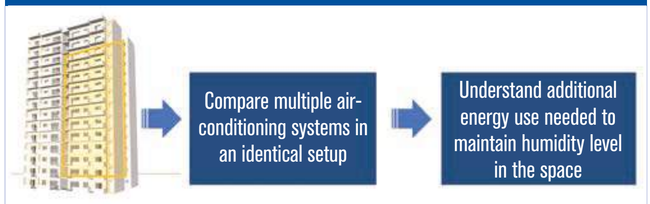
The 27°C (81°F) and 60% RH targets were derived based on establishing comfort parameters using the predicted mean vote (PMV) that indicates a neutral and comfortable environment for most people. For seated, quiet work (metabolic rate [met] of 1) and a clothing insulation of 0.61 clo (trousers with long-sleeve shirt), maintaining 27°C (81°F) and 60% RH at an air velocity of 0.17 m/s (0.56 ft/s) yields a PMV of approximately +0.5, at the upper limit of the acceptable comfort range ($-0.5 \leq PMV \leq +0.5$, $PPD \leq 10\%$) defined in ASHRAE Standard 55-2023.[8] Higher air speeds would require the elevated air speed method of the standard. This condition corresponds to a dew-point of approximately 18.6°C (65.5°F), which is critical for maintaining both thermal comfort and acceptable indoor humidity levels in warm–humid climates.

Additionally, these conditions are consistent with the India Model for Adaptive Thermal Comfort (IMAC), which is based on measurements from a large population across multiple climate zones of India.[9,10] The units were monitored continuously to gather data on energy use, peak demand and indoor conditions. The study showed that super-efficient air conditioners prototypes have many clear advantages.[11]

Key Findings from Real-World Study in India

The study found that super-efficient AC prototypes use much less energy compared to typical ACs on a typical warm and humid day. In India ACs are rated from 1 to 5 stars (least efficient to most efficient); the rating thresholds were revised in 2026, and all star ratings cited in this article are those in force in 2025. Under the 2025 rating, a 3-star AC is the most commonly sold average-efficiency unit, with an Indian Seasonal Energy Efficiency Ratio (ISEER) of 3.8 W/W, and the representative high-efficiency room AC used in this study is a 5-star unit, with an ISEER of 5.4 W/W. The Global Cooling Prize baseline unit is a fixed-speed unit with an ISEER of 3.5 W/W. The prototypes also maintained indoor humidity closer to target levels with minimal overcooling, indicating improved latent load management compared to conventional systems (*Figure 4*).

FIGURE 3 Concurrent testing of multiple room air conditioners under a warm and humid climate in India from October 2023 – June 2024 in newly built and materially equivalent apartments in a dense urban environment.



The study also found that these super-efficient AC prototypes draw less power during peak use, especially on hot and humid days. (*Figure 5*).

Key Findings from Laboratory Study in India

In addition to field testing, the room AC units were further examined in a controlled laboratory environment setup, under different weather and thermal load conditions, to better understand how much extra energy they use for overcooling when achieving the same target temperature and RH conditions of at or below 27°C (81°F) and 60% (target dew-point ≈18.6°C [65.5°F]). Laboratory testing was conducted under controlled load-based testing conditions using calibrated instrumentation to ensure consistent, comparable measurement of temperature, humidity and energy performance across different AC systems. The laboratory assesses the performance of ACs using a controlled, profile-based laboratory method aligned with the Global Cooling Prize lab-simulated year-round performance testing method.[12]

In this method, the indoor chamber emulates a typical bedroom with calibrated thermal mass, controlled heat and moisture inputs (heaters, humidifiers) and measured airflow paths. Outdoor temperature and humidity conditions are simulated in an outdoor climatic chamber. Units operate under their native control logic (thermostat settings, auto fan, adaptive features). Tests begin from defined preconditioned states, logging data at fine intervals (e.g., 15 minutes) to capture transient responses.

The results (*Figure 6)* showed that the overcooling to reduce moisture in the air (dew-point of approximately 18.6°C (65.5°F)—corresponding to

FIGURE 4 Average grid power profiles of typical AC and super-efficient AC prototype to meet indoor comfort conditions on a typical warm and humid day in India.[10]

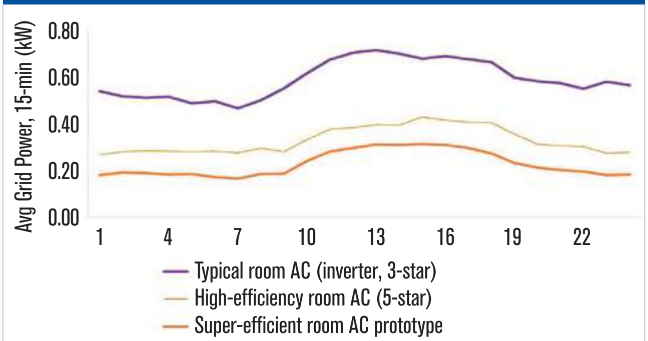


FIGURE 5 Power draw (peak) characteristics of air conditioners during field testing in Palava, India.[10]

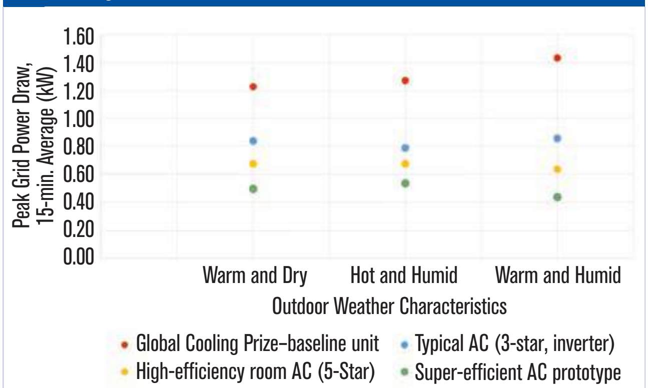
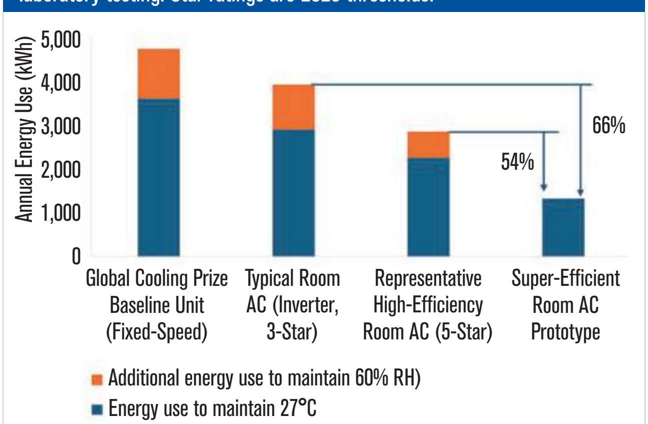


FIGURE 6 Annual energy use estimates of room air conditioners based on laboratory testing. Star ratings are 2025 thresholds.



27°C (81°F) and 60% RH can add around 20%–25% to the annual energy use of a given unit (in orange, *Figure 6*). Total annual energy use for the super-efficient prototype is 66% lower than that of the typical 3-star room AC and 54% lower than that of the representative high-efficiency 5-star room AC (both 2025 ratings). This extra energy use is not usually shown in current standards or regulations for AC performance because the standard test conditions do not represent real-world applications.

While this article focuses on key energy outcomes, detailed time-series performance data including temperature, RH and system runtime behavior will be presented in a forthcoming technical publication.

Implications and Recommendations: Charting the Path Forward

Optimized AC designs that improve the dehumidification process and are engineered for real-world conditions can maintain comfort while reducing energy consumption, costs and environmental impact. For example, the super-efficient AC prototypes, using vapor compression technology combined with optimized design and controls, were able to achieve the target indoor conditions with very little to no overcooling. These controls enable more precise management of humidity and temperature while minimizing energy use, providing a more efficient and comfortable indoor environment.

Achieving this requires coordinated action among policymakers, industry and consumers:

- Standards bodies should update performance standards to reflect real-world operation, including humidity control, temperature stability and part-load performance. Current standards primarily evaluate cooling under controlled conditions and do not fully represent actual use.
- Revised equipment performance standards should require improved control systems for both temperature and humidity. Vapor compression technology combined with advanced controls can improve efficiency, comfort and environmental performance.
- Large customers and HVAC distributors should promote super-efficient AC systems and support pilot deployments and field testing. This will help

validate performance under real-world conditions and accelerate adoption.

- Community organizations and civil society should educate consumers about the benefits of energy efficient AC systems with improved humidity control. Greater awareness will support wider adoption, reduce energy use and improve indoor comfort.

This article highlights the need to better align AC design and performance evaluation with real-world humidity-dominant conditions. Strengthening standards and advancing control strategies can enable more efficient cooling while maintaining comfort and reducing grid stress.

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