Global Cooling Prize

Global Cooling Prize: **Solving the Cooling Dilemma**

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A report by

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About RMI
RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

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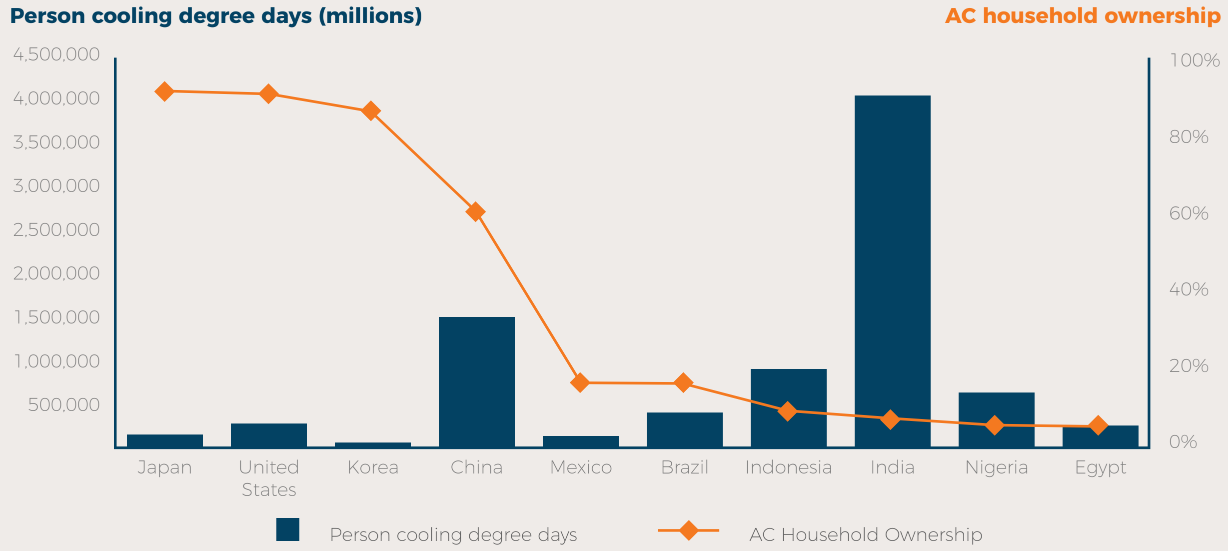
01 THE COOLING DILEMMA

In many parts of the world, access to affordable cooling is increasingly viewed as a necessity. Cooling supports positive health outcomes, higher productivity, and accelerated economic development. It is the source of thermal comfort in our homes and offices, it preserves our food and medicines, and it provides suitable conditions for learning in schools. However, over 3 billion people in the world today are at some risk to their health and safety due to lack of access to cooling.[1]

Access to cooling is not only critical to provide respite from extreme heat, but it is also an important climate justice and equity issue. Unfortunately, people living in developing countries in tropical and subtropical regions where the need is the greatest have dramatically lower access to cooling today (Exhibit 1).

Exhibit 1:
Cooling demand versus current AC ownership in different parts of the world



Note: The cooling demand, represented by "person cooling degree days," is a function of a country's average annual cooling degree days multiplied by the respective population.

However, increasing population and rapid urbanization, coupled with a warming planet, are expected to drive exponential growth in demand for cooling over the next three decades. Under a business-as-usual trajectory, the number of residential/room air conditioners (RACs) in service is estimated to increase from 1.2 billion units today to 4.5 billion units by 2050. RAC demand in developing countries is expected to increase fivefold over this same period.

The resulting increase in power demand would place a massive new burden on electricity grids that are already straining at their limits. Air conditioning accounts for 40%–60% of peak electricity consumption in many major

cities with high levels of penetration. Under a business-as-usual trajectory, these air conditioners would consume an additional 5,400 terawatt-hours (TWh), requiring an estimated 2,000 gigawatts (GW) of new electrical generation capacity, by 2050.

The electricity consumption associated with residential air conditioning, combined with the atmospheric impact of the refrigerants used in these systems, represents one of the single largest end-use risks to global climate goals. RACs alone will add about 132 Gt of carbon dioxide equivalent (CO_2e) emissions cumulatively between now and 2050, making it nearly impossible to meet the Paris Agreement goal of limiting global warming to well below 2°C as compared with preindustrial levels.

Herein lies the cooling dilemma. Although increased access to cooling positively impacts the health, well-being, and productivity of people around the world, it comes at an environmental cost that we simply cannot afford.

The Kigali Amendment to the Montreal Protocol, which aims to phase down the use of hydrofluorocarbon (HFC) refrigerants, is a step in the right direction. HFCs have high global warming potential (GWP), meaning that these gases can trap much more heat than an equivalent mass of CO_2 does. But refrigerants only account for one-fifth of the climate impact associated with RACs—the rest results from electricity consumption.

Therefore, a transformative cooling solution is needed—a solution that not only uses low-GWP refrigerants but also consumes dramatically less energy. Such a solution could be a step toward solving the cooling dilemma—keeping both people and the planet cool.

02 THE GLOBAL COOLING PRIZE

To spur the development of a super-efficient, climate-friendly, and affordable cooling solution that meets the world's booming demand for cooling without contributing to runaway climate change, an international coalition launched the Global Cooling Prize in November 2018. The coalition was led by RMI; the Department of Science & Technology (DST), Government of India; and Mission Innovation. The Prize was administered by RMI, Conservation X Labs, Alliance for an Energy Efficient Economy (AEEE), and CEPT University.

The Prize called on innovators across sectors and around the world to design a residential cooling solution for an existing apartment home in a mid- or high-rise building in a dense urban environment. Within that context, innovators had to meet clear, performance-based requirements—the Prize technical criteria.[2] The two primary criteria were:

1. The solution's climate impact had to be at least 5X lower than the standard AC units sold in the market today. Why 5X? This threshold was identified by considering both the need to neutralize the environmental impact of the inevitable growth in cooling over the next three to four decades and what science was indicating as the theoretical maximum efficiency of the cooling cycle.

2. The solution's installed cost to consumers could not be more than 2X that of the baseline AC unit when manufactured at a scale of 100,000 units per year.

A secondary set of criteria—supplementary criteria—required the winning solution to also perform within predefined boundary conditions on indoor temperature and humidity levels, refrigerants, materials, water consumption, maximum power consumption, volumetric size, and on-site emissions.

Over the past two and a half years, the Prize received global interest and an overwhelming response. Over 2,100 teams from 96 countries registered for the Prize. A diverse group of innovators—from large AC manufacturers and universities to startups and individuals—presented cooling solutions and ideas covering a wide variety of technologies. Of these, 139 teams from 31 countries submitted detailed technical applications. In November 2019, following review by the Technical Review Committee of the Prize, the coalition announced eight Finalist teams.

03 FINALISTS OF THE GLOBAL COOLING PRIZE

The Finalist teams included some of the world's largest air conditioner manufacturers, as well as some very promising corporations and startups from India, China, Japan, the United States, and the United Kingdom.

The teams were awarded $200,000 each to support the development and delivery of two working prototypes to the Prize's testing locations in India. The Finalists showcased a diversity of innovative residential cooling technology innovations, including smart hybrid vapor compression cooling, evaporative cooling, and solid-state cooling technology designs.

In August 2020, amid the global pandemic, six of the eight Finalist teams successfully developed and delivered two prototypes of their technology to the designated test locations in India. These prototypes were to be evaluated with reference to three test methodologies:

THE FINALIST TEAMS (IN ALPHABETICAL ORDER) WERE:

- Barocal Ltd.
- Daikin and partner Nikken Sekkei Ltd.
- Godrej and Boyce Manufacturing Company Ltd. and partner A.T.E. Enterprises Pvt. Ltd.
- Gree Electric Appliances Inc. of Zhuhai and partner Tsinghua University
- Kraton and partners Infosys, IIT Bombay, and Porus Laboratories
- M^2 Thermal Solutions
- S&S Design Startup Solution Pvt. Ltd.
- Transaera and partner Haier

The field test:
One prototype from each team was installed and tested in a real-world setting in an apartment building at the Tata New Haven Bahadurgarh site near New Delhi.

The lab simulated year-round performance test (lab test):
The second prototype was tested in a sequential manner under controlled conditions at CEPT University in Ahmedabad, India.

The Indian Seasonal Energy Efficiency Ratio test (ISEER test):
The prototypes from the field test were sent to Danfoss' lab in Chennai, India, for an ISEER test. The lab is accredited by the National Accreditation Board for Testing and Calibration Laboratories (NABL).

A brief description of the journey of each Finalist team, presented in alphabetical order, is provided below, including their progress and achievements throughout the Prize process:

Barocal Ltd.: Although they were not able to deliver working prototypes to the designated test facilities in India in accordance with the Prize timeline, we are very encouraged that they have continued in their work and have subsequently developed a working prototype. We remain excited about their innovative cooling technology.

Daikin and partner Nikken Sekkei Ltd.: We successfully tested their prototypes and are extremely pleased to report that they exceeded the 5X lower climate impact reduction target, the primary criteria of the Prize. In addition, we were also excited to see a successful demonstration of the use of ultralow-GWP refrigerant HFO 1234ze (GWP of less than 1 in the room air conditioner product category.

Godrej and Boyce Manufacturing Company Ltd. and partner A.T.E. Enterprises Pvt. Ltd.: We successfully tested their prototypes and were pleased to see a successful demonstration of their AC unit under simulated real-world conditions.

Gree Electric Appliances Inc. of Zhuhai and partner Tsinghua University: We successfully tested their prototypes and are extremely pleased to report that they exceeded the 5X lower climate impact reduction target, the primary criteria of the Prize. In addition, we were also excited to see a successful demonstration of the use of low-GWP refrigerant HFC-152a (GWP of 138) in the room air conditioner product category.

Kraton and partners Infosys, IIT Bombay, and Porus Laboratories: Although they successfully delivered prototypes to the designated test facilities in India, they encountered some operational problems and decided that they would not continue with the testing process. We are pleased that they are continuing their cooling journey, and we remain excited about their innovative cooling technology.

M² Thermal Solutions: Although they were not able to deliver prototypes to the designated test facilities in India in accordance with the Prize timeline, we are very encouraged that they have continued in their work and have subsequently developed a working prototype. We remain excited about their innovative cooling technology.

S&S Design Startup Solution Pvt. Ltd.: Although we tested their prototype as part of the field test, they were unable to continue their participation in the Prize beyond this phase due to nontechnical considerations.

Transaera and partner Haier: We successfully tested their prototypes in both the field and lab testing phase; however, their prototype was not tested under the ISEER test. We were pleased to see the real-world demonstration of their discrete approach to handling latent loads in the room air conditioner product category.

04 DEMONSTRATING PERFORMANCE THROUGH TESTING

Testing Methodology

The testing protocol consisted of three test methodologies to evaluate the performance of the prototypes that were successfully delivered by the Finalists:

Field test: To demonstrate the performance and scalability of these breakthrough technologies, one prototype from each of the teams, along with two baseline units, were installed on separate floors of the 14-story apartment building at the Tata New Haven Bahadurgarh site in India.

Before the test, we used measures such as blower door tests, thermal imaging, and floor insulation to ensure the apartment units were materially identical. This also ensured that all the cooling systems were subject to similar cooling loads to the extent possible within an acceptable uncertainty range. We operated the prototypes concurrently and monitored them for the full month of October under real-world conditions. Five of the Finalist prototypes completed this phase of testing.

Lab test: The Finalists' second prototype was tested for 10 days at the state-of-the-art testing facility at CEPT University in Ahmedabad, India, to determine full-year simulation-based performance. The laboratory comprises an internal and an external chamber and has the capability to simulate real-world conditions for temperature and humidity, heat gains from occupants, air exchange rates between indoor and outdoor environments, heat gains from appliances, and heat gains from the building envelope.

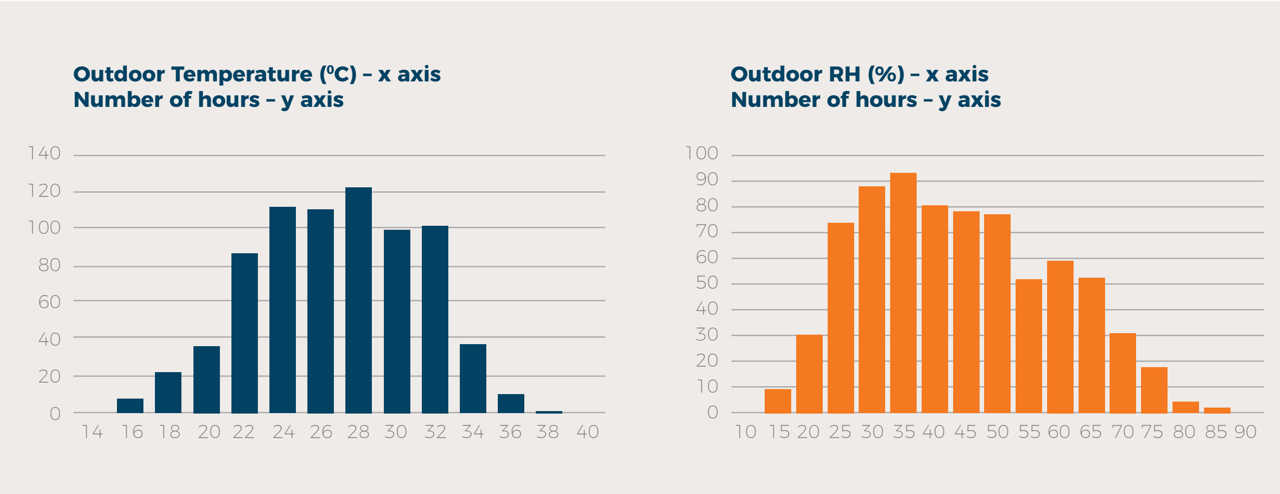
For each of the 10 test days, we simulated a unique weather profile, which represented a full year of operation when aggregated with appropriate weighting factors. Four of the Finalist prototypes completed this phase of the testing.

Indian Seasonal Energy Efficiency Ratio (ISEER) test: The ISEER test measures the rated cooling capacity and power consumption of the air conditioners to provide an ISEER rating for the appliances. The cooling capacity and associated power consumption tests are carried out in accordance with IS 1391(Part 1): 2017 and IS 1391 (Part 2): 2018, whichever is applicable. However, the current IS 1391 standards are only applicable to room air conditioners based on traditional vapor compression technology. Therefore, we made some minor adaptations to the current IS standard to include as many of the specific attributes of the Finalists' prototypes as possible.

Weather Conditions

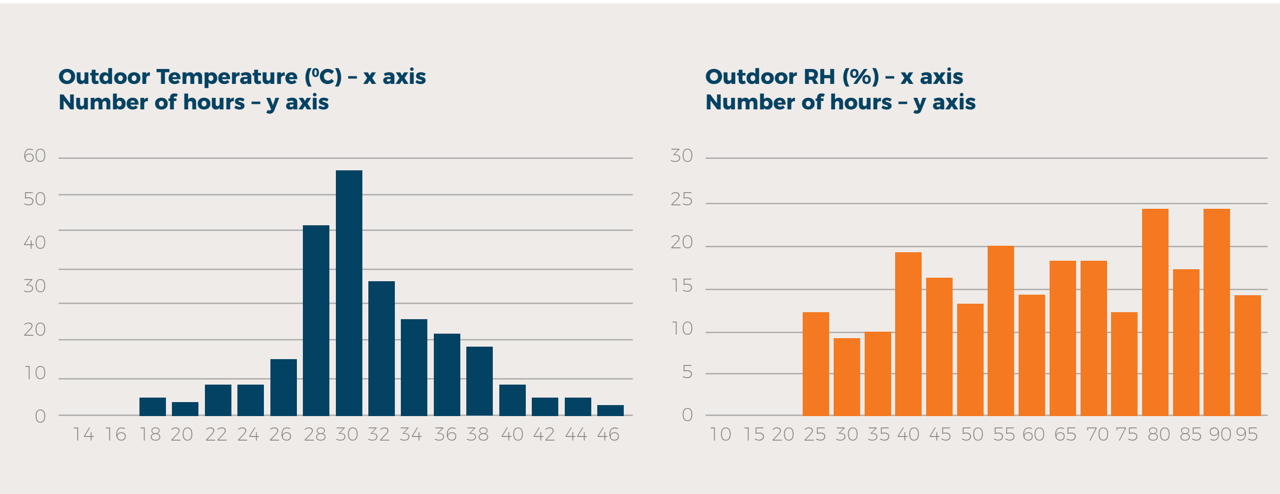
During **field testing**, mild outdoor weather conditions prevailed throughout the testing period. Temperatures reached a high of 36.2˚C, with an average of 25.6˚C. We observed a wide range of relative humidity levels, with a high of 80.1%. A histogram showing the breakdown of temperature and relative humidity is below in Exhibit 2.

Exhibit 2:
Outdoor weather conditions during field testing



During **lab testing,** simulated outdoor weather conditions covered a much wider range to account for extreme temperature and humidity conditions observed in a tropical country like India. Temperatures reached a high of 44.3˚C, with an average of 30.2˚C. We simulated a wide range of relative humidity levels, with a high of 93.3%. A histogram showing the breakdown of temperature and relative humidity is below in Exhibit 3.

Exhibit 3:
Simulated outdoor weather conditions during lab testing



Testing Results

Baseline Unit
We compared the performance of all the prototypes against the baseline unit, which was a fixed-speed, mini-split type RAC unit with an ISEER rating of 3.5 W/W that used R22 refrigerant. The baseline unit was representative of the most commonly sold RACs in the Indian market in 2017.

During both the field and the lab tests, we operated the baseline unit to ensure that the indoor conditions were always below 27˚C and 60% relative humidity in order to meet the operations criteria of the Prize.

Finalist Prototypes
All the Finalist teams that underwent the Prize testing process successfully demonstrated the operation of their prototypes in a real-world environment. For the purpose of this report, however, we only discuss the performance of the breakthrough technologies of the winning teams in the aggregate.

Both the winning teams—Daikin and partner Nikken Sekkei Ltd., and Gree Electric Appliances Inc. of Zhuhai and partner Tsinghua University—successfully completed testing under the three test methodologies. We weighted the results of the field and lab tests to account for the fact that the field test had higher uncertainties and covered a limited weather profile, as opposed to the much more tightly controlled lab test that spanned the full season of cooling operation.

Overall, the field test results received a weighting of 18.35% relative to the 81.65% weighting received by the lab test results.

The ISEER test, though important from the point of view of offering an air conditioning product in India, was not considered in the final evaluation because the ISEER test protocol does not fully align with the overall Prize performance criteria.

Performance of Winning Technologies against the Prize Technical Criteria
Throughout the testing period, the prototypes from the winning teams demonstrated that their breakthrough technologies were able to handle sensible and latent cooling loads much more effectively and efficiently as compared with the baseline unit and other competing prototypes. Sensible cooling loads refer to the loads that result from the difference in temperature between the indoor and outdoor environment; latent cooling loads are the loads that result from change in moisture (or humidity) in the space.

Electricity consumption:
The technologies of the winning teams achieved a **dramatically lower electricity consumption, over 75%** as compared with the baseline unit (depending on the day), while maintaining the indoor temperature below 27˚C and indoor relative humidity below 60%. But the energy savings weren't just achieved through part-load performance: even **on the extreme days** when ambient temperatures exceeded 44˚C, these technologies **delivered a reduction of over 60% in electricity consumption.**

Refrigerant: The refrigerant gases used by the winning technologies have a significantly lower global warming potential (GWP) as compared with the traditional HFC refrigerants used on the market today. Through the testing phase, **the winning teams demonstrated that** it is possible to shift away from today's high-GWP refrigerant gases and instead use **low- or ultralow-GWP refrigerants that are safe to deploy with regards to flammability and toxicity and do not negatively impact performance.**

Climate impact:
The technologies of the winning teams achieved **a reduction of more than 80% in climate impact compared with the baseline unit,** exceeding the Prize's

climate impact criteria of 5X lower climate impact. When compared with representative best-in-class RAC technology available in India today, the climate impact reduction of the winning technologies is more than 65%. We determined the climate impact of a prototype by combining electricity reduction (kWh) and refrigerant GWP reduction using a weighting of 80 to 20, respectively, relative to the baseline unit.

Power draw: Air conditioners are energy intensive and drive peak demand on the grid, particularly during hot days. This results in expensive power purchases, as well as blackouts or brownouts by the utilities. Additionally, this demand leads governments to construct new power infrastructure.

The breakthrough technology of the winning teams demonstrated that the peak power draw of ACs can be reduced by over 60% compared with the peak power draw of the baseline unit. Even **on the extreme days** when ambient temperatures exceeded 44˚C, the **peak power draw was 10% lower than the Prize criteria limit of 700 watts.**

Water use: The breakthrough technology of the winning teams used water to improve the efficiency, and consequently reduce the energy consumption, of the system. Under the water criteria of the Prize, a cooling technology must not use more water than it saves at the utility level through reduced energy consumption (i.e., the daily water use must not exceed 28 liters).

The **average daily water consumption** of the breakthrough technology from the winning teams **was 6 liters per day,** with a maximum consumption of just over 15 liters. To put this in perspective, 6 liters is **less than 2% and 0.7%** of the typical daily household water consumption in India and the United States, respectively.

Affordability: The installed cost to consumers of the winning technologies at an industrial scale of 100,000 units per year was assessed to be two to three times the baseline unit's installed cost to consumers. Although higher than the original Prize affordability criteria, taken together with the energy performance of the prototypes, this would equate to a simple payback of about three years to consumers on the incremental first cost. From a life-cycle cost perspective, the total cost of ownership of these technologies (i.e., cost to own and operate them over a 10-year period) would be about half that of the baseline AC unit.

We note that it is a challenging exercise to assess the comparative affordability of prototypes, which have varying degrees of vertical integration along with proprietary components and methods.

Key Attributes of the Winning Technologies

The Prize demonstrated that achieving a 5X lower climate impact requires combining one or more elements of vapor compression cooling, evaporative cooling, dehumidification strategies, advanced control strategies, free cooling, radiative cooling, and integrated solar PV, along with low-GWP refrigerants. The winning technologies of the Prize combined several such attributes, as noted below:

Variable-speed compressor that can modulate to very low cooling capacities: ACs with fixed-speed compressors are typically designed for peak load performance and usually run at a higher capacity than is required for normal everyday usage. These units turn on and off frequently, which causes broad temperature swings and poor humidity control, as well as decreasing aggregate efficiency and overall reliability.

The winning technologies used variable-speed compressors that are designed to specifically adjust capacity under varying ambient conditions, and thus can better handle part-load conditions. This change reduces compressor cycling, achieves higher part-load efficiency, and provides enhanced humidity control at lower loads, where the fixed-speed baseline unit was observed to struggle.

Improved evaporator design and advanced controls to enhance dehumidification capabilities: Humidity removal, which is typically a by-product of reducing the temperature of the air leaving the evaporator coil, depends on the sensible heat ratio of the air conditioner. Fixed-capacity units (like the baseline unit), along with units that lack an optimized dehumidification cycle, must overcool the air to achieve the desired relative humidity, which is both energy intensive and uncomfortable.

The winning technologies had improved evaporator design to provide high humidity removal capabilities and used advanced controls to separately sense the sensible and latent loads in the space. They were able to optimize the evaporator coil operation to the specific conditions required under the Prize criteria (i.e., at or below 27˚C and 60% relative humidity). As a result of their enhanced dehumidification capabilities, the winning technologies achieved the temperature and humidity requirements with very little overcooling and much higher energy efficiency as compared with the baseline unit.

Direct evaporative cooling at condenser: The performance of a typical room air conditioner is significantly impacted under extremely hot conditions. The compressor has to work much harder to reject the heat to the ambient environment, resulting in poor efficiency and higher energy use.

The winning technologies used a direct evaporative cooling approach to cool the outdoor air around the condensing unit during high ambient conditions, which increased the energy efficiency and thus lowered energy consumption.

Integrated solar PV and use of direct current components: Integrating solar PV to the AC is an effective way to offset a portion of the grid power demand, particularly during hot summer afternoons when the electricity grid is facing peak demand.

One of the winning technologies successfully demonstrated a low-cost PV integration. The addition of solar PV—combined with advanced controls, the use of high voltage, and high-efficiency direct current electrical componentry—further reduced energy consumption and peak demand on the grid.

Low-GWP refrigerant: The winning technologies used HFC-152a and HFO 1234ze refrigerant, which have dramatically lower GWP, are safe to deploy, and did not have a negative impact on performance under high-temperature and high-humidity conditions.

05 KEY TAKEAWAYS AND LEARNINGS

The testing of winning prototypes under simulated real-world conditions as per the Prize's testing protocol has allowed us to understand and identify gaps in the testing standards adopted for assessing the performance of room air conditioners today. Our preliminary analysis indicates that the **current test standards recognize only 69% or just over two-thirds of the weighted energy reduction** achieved by the winning technologies compared with the baseline unit when operating under simulated real-world conditions.

We believe that the remaining unrecognized gap of 31% weighted energy reduction can be identified. Below are our key takeaways:

- **Air conditioners with separate temperature and humidity sensors combined with optimized design and operation to address both provide better comfort and higher energy savings:** The test standards adopted today assess the performance of air conditioners at standard outdoor and indoor temperatures without much consideration for humidity conditions. However, in a real-world scenario, we know that humidity is an important factor and that efficient removal of moisture from the air has a major effect on occupant comfort.

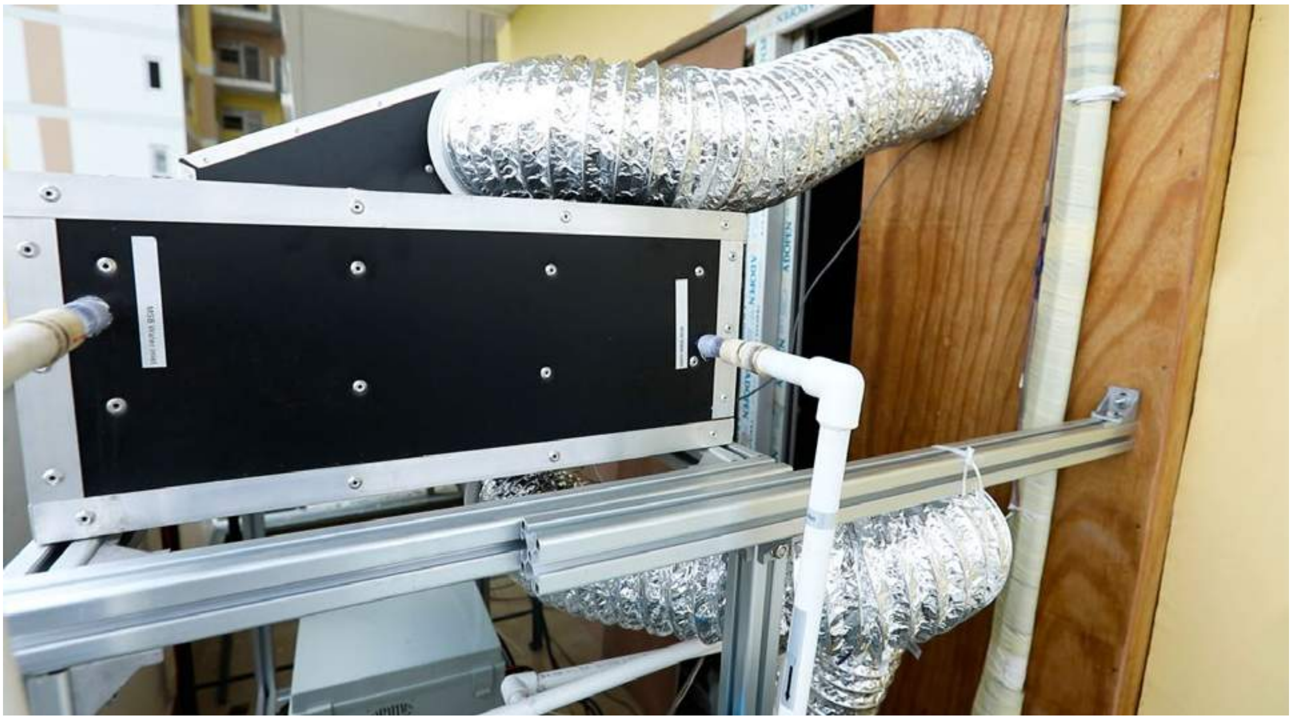
  Unfortunately, room air conditioners sold on the market today do not have a fully optimized dehumidification solution or cycle and will typically overcool to meet the desired humidity levels. This results in significantly more energy consumption to achieve thermal comfort than what is measured under the testing standards.

  Our preliminary analysis would indicate that 22%–24% of weighted energy reduction achieved by the winning prototypes is due to not having to overcool the space to meet the desired thermal comfort conditions of no more than 27˚C and 60% relative humidity as set under the Prize criteria. Simply put, air conditioners that overcool to meet the temperature and humidity conditions will consume much more energy than what is recognized under today's test standards.

- **Air conditioners with fully variable speed compressors deliver higher savings than recognized by current test standards due to operating at much lower levels of rated capacity:** Through the lab test that simulated weather conditions representing a full year of operation, we observed that the aggregate cooling load to be met in a hot and humid country like India is only about 20%–30% of full capacity typically sized for the hottest days of the year. In contrast, the testing standards adopted by the market today suggest an aggregate cooling load of about 50% of the standard cooling full capacity.

  Due to the lower aggregate cooling seasonal loads, ACs with variable speed compressors that can modulate to very low frequencies can deliver significantly higher energy savings than recognized by today's test standards. Our preliminary analysis would indicate that 7%–9% of weighted energy reduction achieved by the winning prototypes is due to using best-in-class variable speed compressor technology, recognizing the increased efficiency of operation at low load conditions.

These two areas reveal the likely "ghost" kWh consumption that is not able to be predicted by today's testing standards but that can be expected in real-world operation. This is especially true in the high humidity conditions of the Global South. It is important that these gaps in today's testing standards are understood and ultimately addressed with updated methods and protocols that can simulate the conditions sufficiently to predict true performance in the real world. This will give manufacturers a more complete target to design to and consumers better information to inform their purchase decisions. We do recognize that care must be taken to not add undue complexity or cost to the testing process, training procedures for labs, or compliance for manufacturers.



06 THE IMPACT

What is the impact of scaling 5X lower climate impact RACs, as demonstrated through the Prize testing protocol? Specifically, what impact will these RACs have if brought to market by AC manufacturers as early as 2025?[3]
To evaluate this question, we revisited the Growth and Impact Assessment model developed as part of our *Solving the Global Cooling Challenge* report.[4]

The adoption of RACs with 5X lower climate impact would mean an electricity consumption of about 1,800 terawatt-hours in 2050 (5X scenario). That consumption is approximately 75% less than the total global demand under the business-as-usual scenario, despite a growth in RAC stock from 1.2 billion to 4.5 billion over the same period. The analysis also suggests that the additional 2,000 GW of power generation capacity required to meet the peak demand from RACs in 2050 under the business-as-usual trajectory can be effectively neutralized by adoption of RACs with 5X lower climate impact.

In India, one of the fastest-growing markets for RACs, the scaling and adoption of RACs with 5X lower climate impact could reduce India's estimated peak loads by around 400 GW in 2050. In the year 2050, it would also result in the curtailment of about 1,300 TWh required to operate RAC units—an amount that is almost equivalent to India's total electricity consumption today. In countries such as China and Indonesia, adoption of RACs with 5X lower climate impact could reduce the total cooling-related electricity consumption by up to 80% as compared with the business-as-usual scenario. This will bring significant benefits to governments, power utilities, and consumers alike.

Finally, when scaled globally, the 5X lower climate impact RACs have the potential to mitigate up to 0.5˚C of warming by 2100.

07 WHAT'S NEXT?

Over the past two and a half years, the Global Cooling Prize has shown the world that the cooling dilemma can be solved in its entirety—and the solution lies in breakthrough cooling technologies with 5X lower climate impact. The Prize has identified, tested, and demonstrated the next generation of breakthrough cooling technologies. These technologies have dramatically lower energy consumption and use low-GWP refrigerants—achieving 5X lower climate impact—thus shattering the performance ceiling of what was previously believed to be possible.

But although the Prize has been successful in identifying the cooling solutions with 5X lower climate impact, the pace of commercialization and scaling of these solutions will define how quickly they can reach consumers. Achieving the desired pace will require a strong collaboration among multiple actors including innovators, manufacturers, investors, policymakers, and consumers.

We need manufacturers to develop and bring these solutions to market. We need policymakers to undertake targeted policy actions to raise the bar of minimum energy performance standards and stretch the performance rating systems to the level of these new RACs to better inform consumers. And finally, we need consumers to use their purchasing power to drive the market transformation and buy these 5X lower climate impact RACs for their homes.

We call on all actors in the cooling sector to come together and demonstrate their leadership in this decisive decade of action. It's possible to provide access to cooling for all, without further warming the planet.

08 ENDNOTES

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