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Perspective

Humidity's impact on greenhouse gas emissions from air conditioning

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SUMMARY

The increasing need to cool the air in our built environment is both a *cause* and an *effect* of climate change. Air conditioning accounts for a large portion of global greenhouse gas emissions today, which we estimate at 3.9%; however, the role that humidity plays in these emissions is often overlooked. Here, we show that the emissions associated with reducing air humidity (i.e., removing water vapor from air) are larger than emissions associated with reducing air temperature (i.e., cooling air). We calculate these emissions for today and 2050 and show how dramatically humidity-related emissions will increase with rising cooling demand around the world. We also calculate the minimum separation energy for removing water vapor from air and find that this is at least an order of magnitude less than the processes used today.

Context & scale

Cooling accounts for 10% of the global electricity use and nearly 4% of the annual greenhouse gas emissions. With a warming climate and growing prosperity in developing nations, this number is set to rise. This causes a self-reinforcing pattern that must be addressed through improved cooling, both for the health of humankind and the stabilization of the climate.

For more than a century, cooling solutions have focused on fans and heat pumps, with good strides toward optimization and little room left for disruptive efficiency gains. However, these solutions look only through the lens of temperature reduction, ignoring how humidity affects human comfort and safety. Humidity management can enable this comfort and safety at higher temperatures and can be approached with different and as-yet unoptimized technologies. This perspective quantifies humidity's impact and is a call-to-arms for the research community to view this challenge of human comfort and safety through a new lens with lower hanging fruit.

INTRODUCTION

Air conditioning offers significant benefits to humankind, including comfort, improved productivity, healthy indoor air quality, and safety from extreme heat. Air conditioners also drive significant energy use around the world, comprising 10% of global electricity use (2,000 TWh), which is 20% of the global electricity used in buildings.[1] However, this electricity consumption is growing. By 2050, air conditioning is conservatively projected to use 6,200 TWh globally.[1] This massive electricity use, in addition to refrigerant leakage, leads to greenhouse gas (GHG) emissions that make air conditioning a key driver of climate change.

Recent studies have investigated the expected growth in air conditioning in hot climates,[2,3] indicating significant increases in both energy use and refrigerant emissions[4] as air conditioner ownership grows. This has spurred research on improving thermodynamic cycles to increase cooling energy efficiency[5] and research on natural and low global warming potential (GWP) refrigerants to lower the direct emissions from refrigerant leakage.[6]

Although air conditioning energy use clearly impacts our greenhouse gas emissions, the portion used for humidity control is often overlooked, with the more familiar effects of temperature control receiving outsized attention. In hot-humid climates, removing water vapor could even be a more efficient and/or cheaper alternative to cooling the air and could contribute to saving lives by reducing the heat index with humidity management alone.

Removing water vapor from the air is required to keep people comfortable and is often a byproduct of temperature control, regardless of whether humidity is actively controlled or not: colder air can hold less moisture. This means that as the air is cooled, an energy-intensive phase change of the water vapor also occurs. Today's approach for removing water vapor from air is to condense it onto a cold surface created by a heat pump, the same approach used more than 100 years ago. However, this water vapor-to-liquid phase change is an inefficient way to remove humidity. For example, nearly 2,500 J of energy is released by condensing just one gram of water vapor out of the air.

Determining the greenhouse gas emissions associated with controlling humidity in our built environments is important for quantifying its significance in climate change yet has not been done to date. Several studies have estimated how air conditioning energy use may change in the future,[2,7] often using cooling degree days. However, this method looks only at ambient air temperatures and inherently ignores humidity. Other studies have looked at how much building energy use for heating and cooling could theoretically be reduced by improved technologies but again ignore the impacts of humidity.[8]

Here, we address three key shortcomings in the literature related to humidity. First, we calculate the global greenhouse gas emissions from managing humidity in our built environment and show that they are as large as the emissions from managing temperature and that they are growing. Second, we show the impact that changes to building efficiency and ventilation will likely have in the future, increasing the fraction of emissions from the humidity load even further. Finally, we calculate the theoretical minimum energy for separating water vapor from air, which shows an order of magnitude potential for improvement over today's state-of-the-art air conditioners. Our objective with this study is to highlight the direction and magnitude of humidity's impact on global greenhouse gas emissions and the large potential for improvement. Where possible, we make conservative, simplifying assumptions to prove this point.

HUMIDITY'S ROLE IN GLOBAL COOLING EMISSIONS

Air conditioning emissions comprise emissions from (1) operational energy use or "cooling energy" (the emissions associated with the electricity that powers air conditioners), (2) embodied emissions (emissions released during manufacturing), and (3) refrigerant leakage (direct emissions released during operations and end of life). This amounts to 1,950 million tonnes of CO_2 equivalent ($MtCO_2eq$) emissions annually or 3.94% of global greenhouse gas emissions, which we estimate based on existing literature[1,9,10] (see experimental procedures).

In this paper, we determine the fraction of the cooling energy emissions to manage both temperature (the "temperature load") and humidity (the "humidity load"). As described in experimental procedures, we estimate this with a granular approach for each 1° latitude by 1° longitude cell across the globe. Each cell is assigned a population,[11] gross domestic product (GDP),[12] an hourly weather file,[13] number of cooling degree days (which comes from the weather file), and the carbon intensity of the electric grid.[14–16] These data are used to estimate air conditioner ownership per capita, based on a correlation with cooling degree days and GDP, and are also inputs for a detailed building simulation. We ran 26,990 building simulations for representative commercial and residential buildings located in each cell with non-zero population.

The building simulations provide estimates for the temperature load and humidity load per installed air conditioner, and they enable the calculation of temperature

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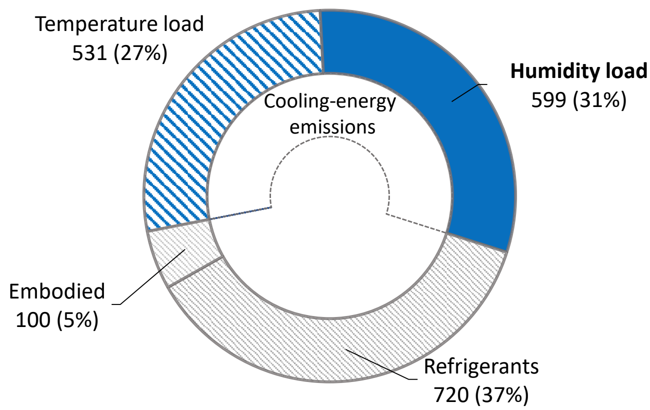

Figure 1. Greenhouse gas emissions from air conditioning (2016)
At nearly 600 $MtCO_2eq$ annual emissions, humidity loads comprise nearly a third of the total annual emissions from air conditioning (1,950 $MtCO_2eq$ per year). Air conditioning represents 3.9% of global greenhouse gas emissions, with the energy used for the humidity load representing more than 1% of global emissions.

and humidity load unlike previous approaches that use cooling degree days. We then multiply the humidity and temperature loads by the number of air conditioners per person in that cell, the cell's population, an effective air conditioner efficiency, and the electric grid carbon intensity to give the total emissions for that cell. The supplemental information includes global contour maps for the fraction of the cooling load due to humidity for residential and commercial buildings (Figures S1 and S2), as well as our estimate for the cooling-energy greenhouse gas emissions for each cell (Figure S3).

We aggregate these cells into the ten regions used by the International Energy Agency (IEA).[1] Our global estimate for the cooling-energy emissions was within 12% of the IEA global estimate, although larger differences were seen for certain regions (for details, see Note S1). For consistency, we scale our cooling-energy emissions to the IEA estimates for each region. This gives the breakdown of emissions due to the temperature load and those due to the humidity load for each region, which we then sum to get the global emissions.

From this method, we estimate that energy-related greenhouse gas emissions for the humidity load equals 599 $MtCO_2eq$ or 31% of total air conditioning emissions and 53% of cooling energy emissions (Figure 1). Said another way, removing water vapor from the air amounts to more than 1% of global GHG emissions, which is equivalent to half of the emissions from aviation.[8] This counterintuitive result shows that managing humidity with air conditioners contributes more to climate change than controlling temperature.

As the adoption of air conditioners expands around the world, total emissions from air conditioners are projected to increase significantly.[9] Here, we focus on the cooling-energy-related emissions and not on the embodied or refrigerant emissions. We estimate the expected cooling-energy emissions in 2050 for both humidity and temperature management by using estimated growth rates for each of the IEA regions.[1] These growth rates assume current policies and official targets from various governments. We did not consider the increase in ambient temperature expected by 2050 due to climate change nor the expected increase in the absolute humidity that will occur along with warming temperatures.[17] This makes our estimate conservative,

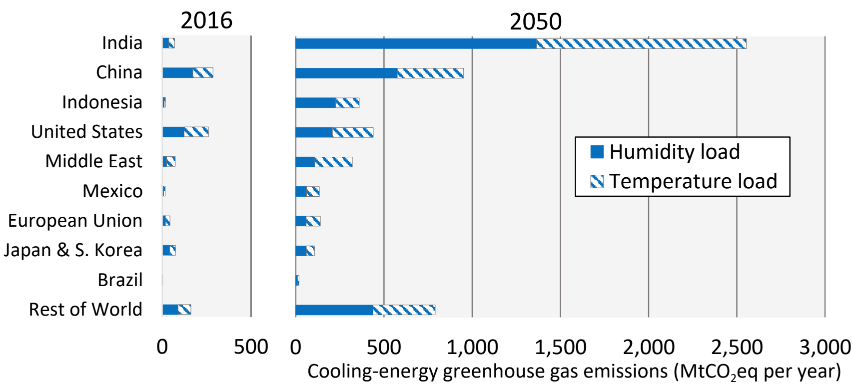

Figure 2. Annual emissions from cooling energy

Emissions due to humidity loads are expected to be 5 times larger by 2050 (assuming the same emissions intensity, static air conditioning efficiency, and building efficiency level), with India and China responsible for the largest increases.

with total emissions likely underpredicted. In contrast, we also assumed that the electric grid carbon intensities stay constant from today to 2050, which will overpredict emissions.

Climate change will impact not only the total emissions by 2050 but also the fraction of the emissions due to the humidity load. We explored how this will impact our results for four diverse locations across the globe using projected 2050 weather (see experimental procedures). The total air conditioning load increases by between 14% in the hottest climate (Chennai, India) to 41% in the mildest climate (Milan, Italy). The humidity load is expected to increase due to the projected higher absolute humidity, and the temperature load is expected to increase due to the projected higher temperatures. However, the humidity load increases more, raising the fraction of emissions due to the humidity load by 2%–3% in each climate (see also Note S4).

Our analysis shows that greenhouse gas emissions for both temperature and humidity loads are expected to be five times larger by 2050 (Figure 2). The growth varies by country, with much of the growth coming from India, China, and Indonesia. This is driven primarily by rising GDPs in these countries. There is also substantial growth in the "rest of world" category, which is primarily driven by Southeast Asia, South America, and Africa.

BUILDING EFFICIENCY, VENTILATION, AND HUMIDITY

The above analysis assumes that we continue to use today's air conditioners in buildings that have similar efficiency levels as today. There are two reasons these assumptions will underpredict the relative importance of emissions from humidity management: buildings are becoming more efficient, and ventilation requirements are increasing as societies recognize the importance of indoor air quality for human health.

Improving the efficiency of buildings means we are using improved insulation, better windows, and more efficient lighting.[18] As we move from incandescent and fluorescent lights to light-emitting diodes (LEDs), the heat generated by lighting indoors is reduced. Improved insulation will reduce the heat gain from the ambient air through the walls and ceiling, and low-emissivity coatings can reduce the solar heat gain through windows. Each of these improvements will lower the building's temperature

Table 1. Building-model assumptions for each residential-building (mid-rise apartment) scenario

		Baseline	High efficiency	Increased ventilation	High efficiency with increased ventilation
Lighting (W ft^{-2})	office	2.04	1.02	2.04	1.02
	apartment	0.92	0.46	0.92	0.46
	corridor	0.36	0.18	0.36	0.18
Wall insulation[a]		R-11	R-22	R-11	R-22
Roof insulation[a]		R-17	R-34	R-17	R-34
Window U value[b]		0.59	0.295	0.59	0.295
Window SHGC[c]		0.36	0.18	0.36	0.18
Ventilation rate (ft^3 min^{-1} $person^{-1}$)	office	21.2	21.2	42.4	21.2
	apartment	8.36	8.36	16.72	8.36

[a]R value has units ft^2-°F-h/BTU.
[b]U value has units BTU/(ft^2-°F-h).
[c]SHGC, solar heat gain coefficient.

load and its associated emissions but will do nothing to reduce the humidity load.[19] This increases the fraction of a building's cooling load that is due to humidity management, and it will continue to increase as our buildings improve further.

Ventilation is one of the largest contributors to the humidity load in buildings because it brings in water vapor with the outdoor air (especially in humid climates). Ventilation replaces exhausted air with fresh air, which is required to keep pollutant levels low and has been shown to improve health and mental acuity.[20–23] More recently, ventilation has been an important consideration to limit the spread of airborne viruses,[24,25] which is supported by a recent study showing a 39% reduction in respiratory virus transmission in schools that increased their ventilation.[26] In the building simulations above, we assumed code minimum levels of ventilation.

To understand the potential impacts of changes to building efficiency or ventilation, we calculate how the temperature load and humidity load will change the 2050 baseline performance (Figure 2) under three additional scenarios (see Tables 1 and 2). The first scenario assumes a more efficient building, whether that's a newly constructed building or a retrofitted building. We use a lighting energy density that is 50% lower than the baseline building, which aligns with some improvement in daylighting and switching to LEDs, and a 50% reduction in both the U-factor (more insulating windows) and the solar heat gain through windows (improved low-emissivity coatings). We also roughly doubled the ceiling and wall insulation levels. The second scenario assumes ventilation rates will double, which is still conservative compared with some recommendations today for improving public health.[24,25,27] The third scenario assumes both more efficient buildings and higher ventilation rates.

These simulations show that the relative impact of the humidity load fraction increases from 54% to 60%, 61%, and 67% for these three scenarios (Figure 3). Although none of the scenarios exactly matches what buildings will look like in 2050, the effect is clear and consistent toward an increase in the importance of humidity loads now and in the future.

THE POTENTIAL FOR NEW HUMIDITY CONTROL TECHNOLOGIES

The growth in greenhouse gas emissions due to managing humidity with air conditioners could be reduced, and even reversed, by removing water vapor from the air

Table 2. Building-model assumptions for each commercial-building (medium office) scenario

	Baseline	High efficiency	Increased ventilation	High efficiency with increased ventilation
Lighting (W ft^{-2})	1.569	0.785	1.569	0.785
Wall insulation[a]	R-11	R-22	R-11	R-22
Roof insulation[a]	R-17	R-34	R-17	R-34
Window U value[b]	0.59	0.295	0.59	0.295
Window SHGC[c]	0.36	0.18	0.36	0.18
Ventilation rate (ft^3 min^{-1} $person^{-1}$)	26.5	26.5	53	53

[a]R value has units ft^2-°F-h/BTU.
[b]U value has units BTU/(ft^2-°F-h).
[c]SHGC, solar heat gain coefficient.

more efficiently. However, this requires a new approach than simply using today's vapor compression air conditioners that condense water onto a cold surface. Thermodynamics dictates a relationship between cooling and humidity removal for a vapor compression air conditioner. This relationship generally results in water vapor condensing out of the air during cooling (the condensate often seen dripping from an air conditioning unit), and it makes it impossible to remove water vapor from the air without cooling it. The efficiency of vapor compression air conditioners depends heavily on the temperature lift or the difference between the refrigerant temperatures in the evaporator (where cooling is done) and the condenser (where heat is rejected). The condenser temperature depends on the ambient temperature, whereas the evaporator needs to be colder than the desired supply dewpoint temperature.

As described in experimental procedures, we calculate the moisture removal efficiency (Figure 4) for the current approach (vapor compression air conditioning) as well as the Carnot limit, which is for any type of heat pump using the cold surface condensation technique. We then compare that with the minimum separation energy.

The Carnot limit is calculated, assuming an ideal heat pump, with the low-side temperature set to the supply dewpoint temperature and the high-side temperature set to the ambient air temperature (25°C in this case). We also assume an ideal vapor compression cycle, which deviates from a Carnot cycle, and a realistic vapor compression cycle with reasonable compressor efficiencies and heat exchanger approach temperatures.

The minimum energy line is calculated using thermodynamic minimum work theory, in which water vapor is separated from an incoming air stream at constant temperature and pressure and then rejected to the same state as the incoming air. This line represents the energy required if it were possible to simply pull water vapor molecules from the air and into an infinite pool of ambient air. This approach relies on calculating energies for inlet and outlet airstreams and calculating the thermodynamic least work. See experimental procedures for details.

From Figure 4, we see that an ideal vapor compression cycle is already very near the Carnot limit. Improvements from new heat pump cycles (e.g., those using new caloric materials) can also not exceed the Carnot limit and therefore offer very limited efficiency gains compared with the vapor compression cycle. Actual vapor compression systems are even further below the limit than the ideal cycle, due primarily to realistic constraints of vapor compressors and the temperature

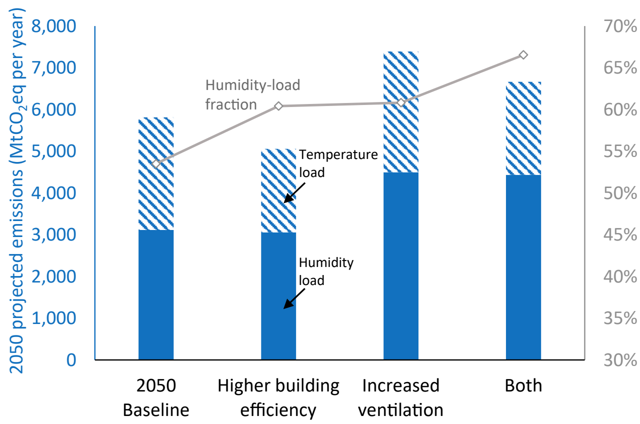

Figure 3. The fraction of cooling-related emissions from humidity (right y axis) are likely to increase to 67% in 2050 due to trends in building efficiency and ventilation requirements

The baseline case shown here is the same as the case shown in Figure 2, whereas the other three cases are for (1) a more efficient building with improved insulation, lighting energy density, and windows; (2) a doubling of ventilation rates; and (3) a more efficient building with a doubling of ventilation rates.

gradients required to keep heat exchanger sizes finite. Although the moisture removal efficiency of vapor compression air conditioners has moved closer to the ideal since its invention in 1902,[28] there are limited improvements that can still be made.

In contrast, the potential for moisture removal using other separation processes (i.e., not condensing water onto a cold surface) is immense—with an order-of-magnitude potential for improvement—yet still immature. The results show that significant improvements can be made toward this minimum separation energy if we consider moving away from condensing water vapor onto cold surfaces as our main method for dehumidification.

One possible alternative to vapor compression is to use a liquid desiccant that can pull water vapor from the air on its own without additional energy. However, for practical applications, additional energy is still required to keep the temperature constant and to regenerate the desiccant for continued use. One such implementation utilizes a heat pump in combination with the liquid desiccant; the heat pump removes heat from the desiccant that is absorbing water vapor and adds heat to the desiccant that is being regenerated.

This process has two advantages over cold surface condensation. First, the temperature lift is less than the process for cold surface condensation. Second, the amount of cooling (and in some cases, reheating) required is also reduced, as the air does not need to be cooled to its dewpoint. Assuming an ideal process, this method would use twice the amount of the minimum separation energy. Real devices will certainly deviate from the ideal, but they will approach this much higher limit instead of the Carnot limit (see Figure 4).

Other technologies that move away from cold surface condensation include membrane-based water vapor compressors,[29] which pull water vapor across a semipermeable membrane and then reject that vapor back to ambient across a second membrane. This achieves a limit just above the desiccant described above, as shown in Figure 4. Similar membranes can also be used to reduce the humidity load from ventilation air by

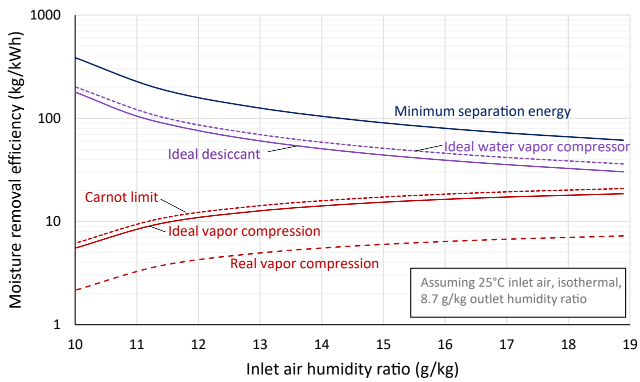

Figure 4. Moisture removal efficiency for existing technologies compared with the minimum separation energy

The vapor compression cycle is used in most air conditioning units on the market today. When condensing water vapor onto a cold surface, the ideal vapor compression cycle is close to the theoretical (Carnot) limit for moisture removal efficiency. However, there is great potential for efficiency gains in moisture removal using other separation processes. The limits for two such technologies are shown just below the minimum separation energy line.

exchanging moisture from the incoming ventilation air with the outgoing exhaust air.[29] There is also the potential to use thermo-responsive desiccants that reject water in liquid phase, which avoids the energy required for evaporation,[30] or to regenerate desiccants using electrodialysis, which separates the ions from the desiccant rather than evaporating water.[31] Finally, newer technologies such as electrochemical or electric field-driven moisture removal act directly on the water vapor molecules in the air.[32]

There are still technical challenges to these approaches. For example, liquid desiccant systems are often more complex, and dehumidification with a membrane-based compressor system requires better water-vapor compressors. However, these are addressable challenges that give a path to much lower emissions since their efficiencies are not limited by the Carnot limit in Figure 4 for a condensing-surface heat pump.

Another advantage of these alternative water-vapor separation techniques is that they allow for more efficient sensible cooling than the current approach. For example, if we first dehumidify the air, a heat pump can cool the air with a much higher low-side temperature. This was recently explored by Gluesenkamp and Nawaz,[33] who found that handling the humidity and temperature load separately can increase the overall efficiency by 1.5–3 times for an ambient temperature of 30°C. This also makes possible more efficient strategies to cool the air, including indirect evaporative[34] or low temperature-lift radiant cooling.[35,36] Of course, one needs to consider how these alternative technologies may also affect fan and pump power as well as the cost and embodied emissions of new or upsized equipment.

To benchmark the potential impact of using more efficient moisture removal technologies, we can estimate 2050 greenhouse gas emissions assuming a technology that can achieve a doubling of the moisture removal efficiency, which is moving roughly halfway from the current real vapor compression line toward the minimum separation energy line in Figure 4. We can also assume a 50% increase in the sensible cooling efficiency, which is at the low end of the estimates from the study above. This hypothetical improvement would reduce cooling-energy emissions by 42% in 2050.

This neglects any reduction in reheating the air, which is often required for the cold-condensation technique in mild-humid conditions, or any sensible heat added from the dehumidification technique. This also neglects any potential change in embodied emissions or refrigerant leakage emissions, but it will be important to pay attention to these other factors when considering new technologies (see Note S4 for more details). If the embodied and refrigerant emissions remain the same, this theoretical technology would avoid 2,460 $MtCO_2eq$ of greenhouse gas emissions annually.

CONCLUSIONS

We have analyzed the impact of humidity on air conditioning energy use and greenhouse gas emissions across the globe today as well as its expected impact in 2050. The results show that managing humidity in the building environment is as important as controlling temperature, and the trends indicate that the importance of humidity relative to temperature is increasing. As air conditioner adoption grows, this humidity impact will be five times larger by 2050 without additional technologies or policy interventions to slow or reverse their emission growth.

Our findings also highlight the importance of research and development in humidity-management technologies—humidity is a key contributor to greenhouse gas emissions, and there's an order of magnitude potential for improvement between currently used technologies and the theoretical separation energy. This will likely require multidisciplinary research teams, with experts not just in thermal sciences and mechanical engineering but also experts in separation technologies, materials science, and chemistry. Such teams must be empowered to develop the needed materials and systems that approach the theoretical energy limit for separating water vapor from air.

Harnessing more efficient ways to manage humidity would benefit more than just abated greenhouse gas emissions; each advance could bring second-order effects. For example, a more energy efficient process could limit the amount of refrigerant needed, thereby reducing direct emissions from refrigerant leakage, and it could reduce the burden on energy systems during peak demand. It could also render air conditioning more affordable for those who need it. As extreme heat events become more common, improved humidity management could help reduce the indoor environment's heat index, which governs the limits of human survivability. In fact, removing humidity alone could be the low cost and energy efficient solution to preventing deaths from extreme heat and humidity.[37] A new approach to manage humidity is critically needed, for the health of the climate and humankind.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and materials should be directed to and will be fulfilled by the lead contact, Jason Woods (Jason.woods@nrel.gov).

Materials availability

This study did not generate new materials.

Data and code availability

All data generated or analyzed during this study are included in the published article, its supplemental information, or available at https://github.com/NREL/HumidityImpacts. The building energy simulation files are available at https://github.com/NREL/HumidityImpacts.

Greenhouse gas emissions from air conditioning

Greenhouse gas emissions from air conditioning consist of operational energy emissions, embodied emissions, and refrigerant emissions. The focus of this study is to quantify the operational energy emissions from air conditioners removing humidity from the air. The fraction of emissions to address humidity, rather than to control temperature, is discussed in the next section. The total operational energy emissions, without distinguishing between humidity and temperature, were estimated by the IEA[1] at 1,130 $MtCO_2eq$ per year.

"Embodied" emissions, or the emissions released during manufacturing of air conditioners, are estimated to contribute 100 $MtCO_2eq$ annually. We estimated this by taking embodied carbon intensities for heating, ventilating, and air conditioning (HVAC) equipment (compiled from equipment Life Cycle Assessments for cradle-to-gate),[10] and multiplied by conditioned floor area. We then multiply this by the global floor area[38,39] and then the fraction of floor area that is conditioned.[1]

In addition, the leaking of refrigerants from an air conditioner, either during its lifetime or at the end of its life, lead to direct emissions. This is because most of the refrigerants used today are hydrofluorocarbons (HFCs), which are themselves greenhouse gases with a high GWP. Two common refrigerants for air conditioning, R134a and R410a, have a GWP of 1,430 and 2,088 respectively[40] (by comparison, CO_2 has a GWP of 1). The global greenhouse gas emissions from refrigerant leakage were recently estimated at 720 $MtCO_2eq$ annually.[9]

The above calculations give us 1,950 $MtCO_2eq$ per year for the total contribution of greenhouse gas emissions from air conditioning, as shown in Figure 1. We also calculate the fraction of total global emissions from air conditioning at 3.9% based on an estimate of 49,400 $MtCO_2eq$ per year of total global emissions.[41]

Estimating emissions due to humidity and temperature

We estimate the emissions due to humidity and temperature management with a bottom-up approach that is then scaled to the IEA estimate for emissions. We split the globe into 1° latitude by 1° longitude cells (~120 × 120 km) and use whole-building energy models to estimate the energy used per building floor area and to quantify the sensible cooling load ("temperature load") and the latent cooling load ("humidity load").

The following equations were used to estimate the emissions for each cell:

$$GHG\ emissions|_{humidity} = \frac{Elec.CO2\ intensity}{COP_{eff}}\left[Cooled\ Floor\ Area|_R \times \left(\frac{Latent\ cooling\ load}{Cooled\ Floor\ Area}\right)_R + Cooled\ Floor\ Area|_C \times \left(\frac{Latent\ cooling\ load}{Cooled\ Floor\ Area}\right)_C\right] \quad \text{(Equation 1)}$$

$$GHG\ emissions|_{temperature} = \frac{Elec.CO2\ intensity}{COP_{eff}}\left[Cooled\ Floor\ Area|_R \times \left(\frac{Sensible\ cooling\ load}{Cooled\ Floor\ Area}\right)_R + Cooled\ Floor\ Area|_C \times \left(\frac{Sensible\ cooling\ load}{Cooled\ Floor\ Area}\right)_C\right] \quad \text{(Equation 2)}$$

The first term converts the cooling load, whether from humidity or temperature, to the CO_2 emissions with the electricity carbon intensity of each cell and dividing it by the effective coefficient of performance (COP) of the air conditioner. The former is obtained from each IEA region and applied to each cell within that region. The grid carbon intensity for each cell are based on country- or region-level data.[14–16] For the "rest of world" category, we used the global average emissions intensity.[15]

A value of 3.8 is used for the effective COP, based on an estimate from the IEA.[1] We did not consider the changing efficiency of the cooling equipment with ambient conditions, and instead applied the same efficiency across the entire humidity and temperature load (see Note S2 for more details). A heat pump's efficiency will be less efficient when the ambient temperature is higher, which may correspond more with times when the temperature load is higher. On the other hand, there are also times with a high humidity load and low temperature load, and in these cases air conditioners often overcool the air to remove moisture and then reheat it to maintain the zone temperature. This added reheat energy associated with the humidity load is also not captured.

The terms in square brackets in Equations 1 and 2 are the latent or sensible cooling loads for buildings within each cell, for both residential (subscript "R") and commercial (subscript "C") buildings. The loads per cooled floor area are estimated with building energy simulations, while the cooled floor area is estimated with several correlations based on GDP, cooling degree days, and population in each cell.

We recognize many limitations in our method to predicting the overall cooling-related emissions across the globe, although the 12% difference between our method and the IEA estimates adds some credibility to this method. Nevertheless, we still group the latent and sensible loads for each of the cells into the ten IEA regions,[1] and scale each of these fractions with the total CO_2 emissions reported by the IEA for those regions (see Note S1).

Latent and sensible cooling loads from building energy simulations

The latent and sensible cooling energy on a per building area basis was determined using two of the "post-1980" U.S. Department of Energy's (DOE) commercial reference building models. The "post-1980" models meet the minimum requirements of ASHRAE/IESNA Standard 90.1-1989.[42,43] We assume these "post-1980" models represent an average building across different locations and climates. Two models were used: one to represent residential buildings (the midrise apartment model) and one to represent commercial buildings (the medium office model). Although the full building stock would comprise many more different types of buildings, the intent was to capture general differences between commercial and residential buildings. We are inherently assuming that the selected commercial and residential buildings represent all buildings across the globe; the lack of data on building types and characteristics for different countries requires this simplifying assumption. See Note S3 for more details and a sensitivity analysis on our assumed building vintage.

The climate zone 4A model for the midrise apartment and medium office served as starting points for the building energy modeling analysis. First, the models were transitioned to EnergyPlus version 9.5.[44] The models were stripped of their native HVAC systems and replaced with an idealized model that mixes return air and the specified amount of outdoor air and then adds or removes heat and humidity at 100% efficiency to produce supply air at the specified conditions. The default temperature setpoints were preserved in the models and a humidistat was added to keep zone relative humidity at or below 60%.

The simulation uses 1 h weather data from typical meteorological year files, with each "TMYX" weather file downloaded from http://climate.onebuilding.org/.[13] For each cell with non-zero population, we assigned the weather file with the minimum great-circle distance (calculated using the haversine formula) to the cell center point. The average and maximum distance of the weather file location from the center of each cell was 85 and 766 km, respectively.

Finally, the two seed energy models were simulated for each weather file that was assigned to a population grid. EnergyPlus Version 9.5, a free and open-source building energy simulation engine, was used for all building energy simulations. EnergyPlus is a detailed analysis tool that computes building energy use based on the interactions between the building and ambient factoring the ambient air conditions, solar radiation, radiation to the surroundings, and building form and fabric. It also considers internal sensible and latent heat gains and heating and cooling from HVAC systems. Custom EnergyPlus energy management system code was developed to provide a whole-building total from the per-zone sensible and latent energy for cooling both the space and incoming ventilation air. The values of interest were logged as the simulation executed and totaled when the simulation completed.

Estimating cooled floor area for each cell

We estimated the cooled floor area for each 1° × 1° cell by using cell-level data for cooling degree days, population, and GDP. Cooling degree days were obtained from the aforementioned weather data. Gridded 1° × 1° population was obtained from the Gridded Population of the World dataset,[11] while GDP values were obtained for the year 2010,[12] and scaled to today using country level data from the World Bank.[45]

The cooled floor area used in Equations 1 and 2 are estimated with:

$$Cooled\ Floor\ Area_R = Population.\cdot AC\ Penetration\cdot Floor\ Area_R \qquad \text{(Equation 3)}$$

$$Cooled\ Floor\ Area_C = Population\cdot AC\ Penetration\cdot Floor\ Area_C \qquad \text{(Equation 4)}$$

Correlations predicting floor area per capita were obtained for residential buildings[46] and commercial buildings[47]:

$$Floor\ Area_R = 6.33\cdot ln\left(\frac{GDP_{\$PPP1995}}{Pop.}\right) - 28.95 \qquad \text{(Equation 5)}$$

$$Floor\ Area_C = 0.005\cdot\left(\frac{GDP_{\$PPP2010}}{Pop.}\right) - 0.004847 \qquad \text{(Equation 6)}$$

To use these relations, GDP estimates for 2020 were adjusted for inflation to the respective years needed in the correlations. Next, air-conditioning penetration was estimated for each 1° × 1° cell with correlations for air conditioner penetration[46,48]:

$$AC\ Penetration = AC\ Penetration_{climate}\cdot AC\ Penetration_{economic} \qquad \text{(Equation 7)}$$

$$AC\ Penetration_{climate} = 1 - 0.949\cdot e^{(-0.00187\cdot CDD)} \qquad \text{(Equation 8)}$$

$$AC\ Penetration_{economic} = \frac{1}{1 + e^{4.152}\cdot e^{\left(-0.237\cdot\frac{GDP_{\$PPP1995}}{1000\cdot Pop.}\right)}} \qquad \text{(Equation 9)}$$

Emissions from temperature and humidity loads in 2050

We extrapolate the emissions estimates for today to 2050 using the growth estimates by region from the IEA.[1] To create Figure 2, we assume that the energy use per floor area, as well as the fraction of emissions due to humidity and temperature, remains the same for each cell, and that the cooled floor area increases such that we match the growth rate from the IEA. See Note S4 for more discussion on these assumptions.

We used today's weather files for each 2050 simulation, but we also investigated the sensitivity of this assumption. For this, we modified the EnergyPlus weather files for four climates using WeatherShift.[49,50] This gives updated hourly temperature, humidity, and radiation based on predicted climate data from the Intergovernmental Panel on Climate Change (IPCC). We selected an intermediate scenario, using the 4.5 representative concentration pathway (RCP 4.5), which gives an additional 4.5 W m^{-2} of heating by 2100, and selected the median temperature projection from the ensemble of IPCC projections. We used four climates covering different hemispheres, cooling degree days, and humidity: Chennai, India; Rio de Janeiro, Brazil; Atlanta, USA; and Milan, Italy.

For Figure 3, we re-calculate the latent and sensible cooling loads per floor area by running the building simulations for each cell three times to include efficiency upgrades, increased ventilation, or both. The assumed parameters for the baseline simulations and the three alternative scenarios are shown for the residential and commercial building in Tables 1 and 2, respectively.

Moisture removal efficiency and minimum separation energy comparison

We estimated the performance of the hypothetical dehumidification systems in Figure 4 using physics-based equations. The equations were developed in the engineering equation solver (EES) software,[51] which solves each cycle's equations. We utilized the software's internal material properties for moist air, water vapor, and R410A refrigerant.

Minimum separation energy

This model assumes a machine that removes water vapor from the air by separating water vapor molecules from the supply air stream down to the desired humidity ratio and rejecting the separated water vapor to the ambient air at the same vapor pressure as the ambient air. This uses the thermodynamic minimum work theory[52,53] whereby water vapor is separated from an inlet process stream isothermally and adiabatically (constant temperature and pressure). The dead state in the calculation is assumed to be the incoming air stream, which for simplicity is assumed equal to the ambient air.

Carnot limit

This model assumes a process operating as an ideal Carnot refrigeration cycle that removes water vapor from air by condensing it in a cold heat exchanger operating at the delivered air dewpoint temperature (which corresponds to the specified supply air humidity ratio on the x axis in Figure 4). This process then collects the sensible and latent heat from the cold heat exchanger and rejects it to ambient using a second heat exchanger operating at the ambient temperature.

Ideal vapor compression

This model assumes an ideal vapor compression machine that removes water vapor from air by condensing water vapor in a cold direct-expansion heat exchanger operating with the saturation refrigerant temperature (dew point) equal to the supply air dewpoint (which corresponds to the specified supply air humidity ratio on the x axis in Figure 4). The condensed water is discarded at its condensed temperature. It then collects the sensible and latent heat from the cold heat exchanger and uses a vapor compression cycle operating with refrigerant R410A and a compressor with 100% isentropic efficiency. This cycle rejects the heat to the ambient air with a refrigerant-to-air heat exchanger, with the refrigerant condensing temperature (bubble point) equal to the ambient air temperature. The system operates with no refrigerant line pressure or heat losses, and no condenser-side subcooling or evaporator-side superheat.

Real vapor compression

This model assumes a real vapor compression machine, like the ideal vapor compression machine, but with more realistic heat exchanger effectiveness values and compressor efficiencies. The water vapor again condenses in a cold direct expansion heat exchanger, but with the refrigerant dewpoint temperature at a constant 2°C below the air dewpoint corresponding to the delivered supply air humidity ratio. The condensed water is discarded at its condensed temperature. The sensible and latent heat is collected from the cold heat exchanger and uses a vapor compression cycle operating with refrigerant R410A and a compressor with constant 75% isentropic efficiency. The cycle rejects the heat to the ambient with a refrigerant-to-air heat exchanger, with the refrigerant condensing temperature (bubble point) 8°C above the ambient air temperature. The condenser also subcools the refrigerant to 3°C below the condensing bubble point temperature, and we assume 5°C of superheat in the evaporator. The system operates with no refrigerant line pressure or heat losses.

Ideal desiccant

Our model for an ideal desiccant separation process assumes the desiccant absorbs water vapor into the desiccant at 25°C and rejects that water vapor at a higher temperature. We assume properties for LiCl from Conde,[54] but similar results will be achieved for other desiccants since most follow a near-constant relative humidity line at a constant mass concentration. For the required outlet humidity ratio of 8.7 g kg^{-1}, the desiccant is ~30 wt % concentration, which is in equilibrium with air of 45% relative humidity. The desiccant is assumed to be regenerated by evaporating water from it, which requires bringing the desiccant into contact with air below the 45% relative humidity, such that vapor moves from the desiccant back into the air. This requires heating the 25°C air by an amount dependent on the assumed humidity on the x axis in Figure 4. We then assume a Carnot heat pump collects the enthalpy of absorption of the desiccant (enthalpy of condensation + enthalpy of dilution), and rejects that heat at the higher temperature required for regeneration.

Ideal water vapor compressor

Our model for an ideal membrane-based water vapor compressor assumes two membrane exchangers, one each on the low- and high-pressure sides of the compressor. On the low-pressure side, water vapor is pulled across an air-impermeable membrane, dehumidifying the air. We assume an isothermal process and the same outlet humidity ratio of 8.7 g kg^{-1}, which sets the low-side pressure equal to the vapor pressure corresponding to air at 25°C and 8.7 g kg^{-1}. Assuming the ambient air is equal to the inlet condition (25°C and the x axis in Figure 4), the compressor must increase the pressure of the water vapor to the same vapor pressure as this ambient air. The resulting delta pressure is used to calculate the compressor work, assuming 100% isentropic efficiency.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2022.02.013.

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AUTHOR CONTRIBUTIONS

Conceptualization, J.W. and J.R.; methodology, J.W., N.J., E.K., E.B., and K.B.; formal analysis, J.W., N.J., E.K., E.B., K.B., and L.V.; software, E.B.; writing – original draft, J.W.; writing – review & editing, J.W., N.J., E.K., E.B., K.B., L.V., and J.R.; supervision, J.W.

DECLARATION OF INTERESTS

K.B., L.V., and J.R. are employed by Xerox PARC. Xerox has publicly stated an intention to develop clean technologies, including those making commercial cooling more efficient. All other authors declare no competing interests.

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