The potential for indoor fans to change air conditioning use while maintaining human thermal comfort during hot weather: an analysis of energy demand and associated greenhouse gas emissions

Arunima Malik, Coen Bongers, Bonnie McBain, Olivier Rey-Lescure, Richard de Dear, Anthony Capon, Manfred Lenzen, Ollie Jay**

Summary

Background Increasing air conditioner use for cooling indoor spaces has the potential to be a primary driver of global greenhouse gas emissions. Moving indoor air with residential fans can raise the temperature threshold at which air conditioning needs to be turned on to maintain the thermal comfort of building occupants. We investigate whether fans can be used to reduce air conditioner use and associated greenhouse gas emissions.

Methods We developed an integrated framework, featuring a dynamic adaptive thermal comfort model with a geographical information system-based spatially gridded map of Australia, further complemented with census data. We assessed the change in energy use and associated greenhouse gas emissions for five scenarios of air conditioner and fan use: an air conditioner-only scenario (no fans); and four fan-first scenarios with fans operating at speeds of 0·1 m/s, 0·3 m/s, 0·8 m/s, and 1·2 m/s, with air conditioning used only once the upper temperature threshold for thermal discomfort is exceeded. For each day of the selected case study year, we estimated the upper temperature limit for thermal comfort and the number of hours in which air conditioning would be switched on.

Findings The thermal comfort threshold was increased by the use of fans compared with air conditioner use alone. We found that widespread indoor fan use had the potential to reduce energy demand and greenhouse gas emissions attributable to air conditioner use, without compromising thermal comfort. Taking an annual perspective, the use of fans with air speeds of 1·2 m/s compared with air conditioner use alone resulted in a 76% reduction in energy use (from 5592 GWh to 1344 GWh) and associated greenhouse gas emissions (5091 kilotonnes to 1208 kilotonnes).

Interpretation A common strategy to cope with hot weather is the use of air conditioners, which feed a cycle of high electricity consumption, often delivered by fossil fuel power stations that in turn contribute to further increases in emissions. Moving air with electric fans could serve as a sustainable alternative, reducing air conditioner use and associated greenhouse gas emissions without sacrificing thermal comfort.

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*Co-senior authors

Integrated Sustainability Analysis, School of Physics (A Malik PhD, Prof M Lenzen PhD), **Discipline of Accounting, Sydney Business School** (A Malik), **Thermal Ergonomics Laboratory, Heat and Health Research Incubator, Faculty of Medicine and Health** (C Bongers PhD, Prof O Jay PhD), **Indoor Environmental Quality Laboratory, School of Architecture, Design and Planning** (Prof R de Dear PhD), **School of Public Health, Faculty of Medicine and Health** (Prof A Capon PhD, Prof O Jay), **and Charles Perkins Centre** (Prof O Jay), **The University of Sydney, Sydney, NSW, Australia; Radboud University Medical Center, Radboud Institute for Health Sciences, Department of Physiology, Nijmegen, Netherlands** (C Bongers); **School of Environmental and Life Sciences, The University of Newcastle, Newcastle, NSW, Australia** (B McBain PhD, O Rey-Lescure BSc); **Monash Sustainable Development Institute, Monash University, Melbourne, VIC, Australia** (Prof A Capon)

Correspondence to: Prof Ollie Jay, Thermal Ergonomics Laboratory, Heat and Health Research Incubator, Faculty of Medicine and Health, The University of Sydney, Sydney, NSW 2006, Australia **ollie.jay@sydney.edu.au**

Introduction

The global pervasiveness of cooling indoor spaces with air conditioners has been well documented.[1] The electricity required to support air conditioner use, even at present-day levels, leads to the emission of large volumes of greenhouse gases because fossil fuels still supply about 80% of the world's energy, despite a 5% per-year growth in renewables from 2009 to 2019.[2] As the world continues to warm for at least the rest of the 21st century,[3] and household incomes increase over the coming decades, air conditioner use and associated greenhouse gas emissions will soar.[4] In 2020, the International Energy Agency listed for the first time the moderation of air conditioner use as a strategy to reduce greenhouse gas emissions.[5] Yet, how this goal can be currently attained without sacrificing thermal comfort, the primary driver of air conditioner use,[6] remains unknown. A growing number of materials and methods are being designed to improve the efficiency of future cooling technologies.[7] However, in the meantime, simple existing technology that is accessible to millions of people every day can be combined with air conditioning to potentially provide a sustainable low-tech cooling solution.

Moving air with devices such as electric fans requires around 30 times less electricity (~55 W per person) to operate than a standard central air conditioning unit cooling a 90-m³ space.[8,9] Fans generate higher air velocities across the skin surface, which elevate the convective heat transfer coefficient and produce a similar rate of convective heat loss from the skin surface, and associated thermal sensation, at warmer air temperatures, as at the more still but cooler air temperatures achieved with air conditioning.[6]

Research in context

Evidence before this study

On March 31, 2021, we searched the Web of Science, Google Scholar, and PubMed databases, without any filters for publication date, for studies in English, using the key words "air conditioner use", "greenhouse gas emissions", "fan use", "thermal comfort", "geographical information system", "adaptive thermal comfort", "heat stress", and "indoor cooling". The search did not yield any studies focusing on the integration of a comprehensive geographical information system-based model with an adaptive thermal comfort model for quantification of reduction in energy demand and associated greenhouse gas emissions under fan-use scenarios. Previous studies indicate that electric fans require around 30 times less electricity than a standard air conditioner unit for operation but, until now, the full extent of energy and emissions savings from fan use has not been studied.

Added value of this study

We report a quantification of savings in energy use and associated greenhouse gas emissions under a range of combinations of air conditioner and fan use. We chose Australia as the case study country for demonstrating the methodology for quantifying savings at spatial scales, and further examined the findings in light of greenhouse gas abatement costs and reduction targets associated with Australia's Paris Agreement commitments. This study paves the way for future national-level and global-level assessments of the use of fans as a sustainable, low-tech cooling solution.

Implications of all the available evidence

The Paris Agreement urgently calls for action to keep the increase of global average temperatures below 2°C above pre-industrial levels, and to pursue efforts to further limit warming to 1·5°C. This study analyses the potential of electric fans in reducing greenhouse gas emissions, as a potential solution for progress towards Paris Agreement targets. Furthermore, an assessment of the abatement potential shows that the use of electric fans can provide net overall benefits for both the environment and the economy.

Accordingly, fan use can substantially elevate (by around 3–4°C) the upper temperature threshold at which air conditioning needs to be turned on and used alongside electric fans to maintain the same level of thermal comfort, and serve as a way of moderating air conditioner use and reducing associated greenhouse gas emissions during hot weather. However, the full extent of energy and emissions savings that could accrue are yet to be quantified.

To answer this question, we developed an approach for quantifying energy use and associated greenhouse gas emissions under five scenarios for combinations of air conditioning and fan use: an air conditioning-only scenario; and four so-called fan-first scenarios, with fans operating at various speeds, and air conditioning used only once the upper temperature threshold for thermal discomfort is exceeded. Experimental[9,10] and biophysical modelling[11] studies have indicated that fans should be used below around 40–42°C, depending on humidity. Instead of using this set upper threshold temperature, we integrated a dynamic adaptive thermal comfort model[6] for each of the five scenarios, with a geographical information system (GIS)-based spatially gridded map of Australia, which was further complemented by census data to determine home-occupied hours on weekdays and weekends, and data on power consumption and greenhouse gas emission factors. We demonstrated the capability of the model using Australia as a case example, owing to the following characteristics: a long and hot summer season, with the major cities generally experiencing longer summers than winters;[12,13] a growing demand for air conditioning;[14] and a heavy dependence on non-renewable resources for electricity generation, thus making air conditioner use carbon-intensive.[15] Finally, we quantified the savings in energy use and concomitant emissions that can be achieved, and contextualised these results in terms of greenhouse gas abatement costs and reduction targets associated with Australia's Paris Agreement commitments. Adaptive thermal comfort strategies can lead to energy savings in built environments.[16] Our work offers a novel integrated modelling framework featuring detailed economic datasets and a dynamic adaptive thermal comfort model to assess the effect of strategically using fans to reduce the need for air conditioning.

See Online for appendix

Methods

Study design

We assessed five scenarios for combinations of air conditioner and fan use: an air conditioner-only scenario (no fans); and four fan-first scenarios with fans operating at speeds of 0·1 m/s, 0·3 m/s, 0·8 m/s, and 1·2 m/s, with air conditioning used only once the upper temperature threshold for thermal discomfort is exceeded. These fan speeds are within the upper range for discomfort due to non-thermal related factors,[6] and approximately equivalent to the speed settings of a standard pedestal fan placed at a distance of around 2 m. We enumerated the effect of residential fans on the thermal comfort threshold, and in turn on air conditioning use and greenhouse gas emissions, through an hourly simulation on a spatially gridded map of Australia (figure 1). For each day in 2010, we determined the upper temperature limit for thermal comfort, using the adaptive thermal comfort model from ASHRAE standard 55-2017 (appendix pp 3–5).[6] Subsequently, we determined whether air conditioning would be switched on by verifying whether ambient temperature exceeded the thermal comfort limit. Proceeding in hourly increments through the entire year, we then accumulated the total hours of air conditioning usage and determined the associated greenhouse gas emissions in the period between Jan 1 and Dec 31, 2010, using scope 2 and scope 3 emission factors for consumption of purchased electricity by end users for all Australian states (emissions resulting from purchase and production of electricity, including extraction, production, and transport of fuels): 0·95 kg CO_2 equivalent (CO_2e) per kWh in New South Wales and the Australian Capital Territory, 1·18 kg CO_2e per kWh in Victoria, 0·92 kg CO_2e per kWh in Queensland, 0·58 kg CO_2e per kWh in South Australia, 0·76 kg CO_2e per kWh in Western Australia, 0·17 kg CO_2e per kWh in Tasmania, and 0·73 kg CO_2e per kWh in the Northern Territory.[17]

Estimates of energy consumption

The following variables were defined as matrices for $N \times M$ GIS-gridded spatial points: p is population, h is average household size, P_{ac} is air conditioner power (W per household), g is the greenhouse gas emissions factor for electricity generation (specific to state and territory; kg/kWh), u is unemployment rate (%), a_5 is the proportion of the population aged under 5 years (%), and a_{65} is the proportion of the population aged over 65 years (%). We defined the following variable for $N \times M$ spatial points and for $T=8760$ h of the year: T_{amb} is ambient temperature (°C).

Using ASHRAE standard 55-2017,[6] we modelled the thermal comfort threshold as

$$\theta(i,j,t,v)=K_1\,\overline{T_{amb}}(i,j,t)+K_2+K_3(v), \tag{1}$$

where $i=1,\ldots,N$ and $j=1,\ldots,M$ are spatial GIS coordinates, t is the hour of the year, K_1, K_2, and $K_3(v)$ are constants, and T_{amb} i is the running mean ambient temperature defined by the recursive scheme:

$$\overline{T_{amb}}(i,j,t)=(1-\alpha)\,T_{amb}(i,j,t)+\alpha\,\overline{T_{amb}}(i,j,t-1), \tag{2}$$

where $\alpha=0\cdot8$ determined the sensitivity of thermal comfort to ambient temperature history. Equation 2 required seeding at $t=0$ with

$$\overline{T_{amb}}(i,j,0)=T_{amb}(i,j,0). \tag{3}$$

The constants were $K_1=0\cdot31$ and $K_2=20\cdot3$ for the 90% upper limit for thermal comfort (operative temperature that is comfortable for 90% of the population).[6,18] The constant K_3 was dependent on air velocity v, with $K_3(v)=[-1\cdot33, 0, 1\cdot94, 2\cdot47]$ for $v=[0\cdot1, 0\cdot3, 0\cdot8, 1\cdot2]$ m/s, respectively. Data for K_3 were derived from ASHRAE 55-2017.[6]

The number of degree-hours above the thermal comfort threshold was calculated as max (0, $T_{amb}-\theta$). To determine the number of degree-hours spent by the Australian population above the thermal comfort threshold, we estimated hourly home occupancy using two assumptions. The home is occupied: always between 1730 h and 0830 h (t_{night}); and by unemployed people and by people younger than 5 years or older than 65 years between 0830 h and 1730 h (t_{day}).

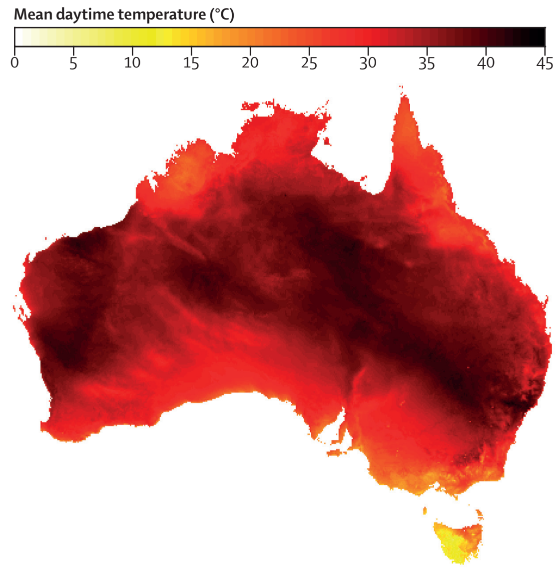

***Figure 1:* Spatial resolution of the geographical information system-based model**

This study uses weather data at a resolution of a 390 × 479 raster grid (8·9-km grid boxes). The colours in the figure show mean daytime temperature (°C) for a selected hot summer day in Australia (Jan 23, 2010).

Accordingly, we determined the hourly probability of daytime non-occupancy as

$$v(i,j,t_{day})=[1-u(i,j)]\,[1-a_5(i,j)]\,[1-a_{65}(i,j)], \tag{4}$$

and the hourly probability of daytime occupancy as

$$\pi(i,j,t_{day})=1-v(i,j,t_{day}). \tag{5}$$

We calculated the number of Australian households occupied during daytime as

$$H(i,j,t_{day})=\frac{p(i,j)}{h(i,j)}\,\pi(i,j,t_{day}) \tag{6}$$

and during night-time as

$$H(i,j,t_{night})=\frac{p(i,j)}{h(i,j)}. \tag{7}$$

Finally, the number of degree-hours spent by the Australian population above the thermal comfort threshold (the number of occupied degree-hours) was

$$H(i,j,t_{day})\max[0,T_{amb}(i,j,t_{day})-\theta(i,j,t_{day},v)] + H(i,j,t_{night})\max[0,T_{amb}(i,j,t_{night})-\theta(i,j,t_{night},v)]. \tag{8}$$

We assumed that air conditioning was switched on during these hours, and the electricity consumption across Australia was

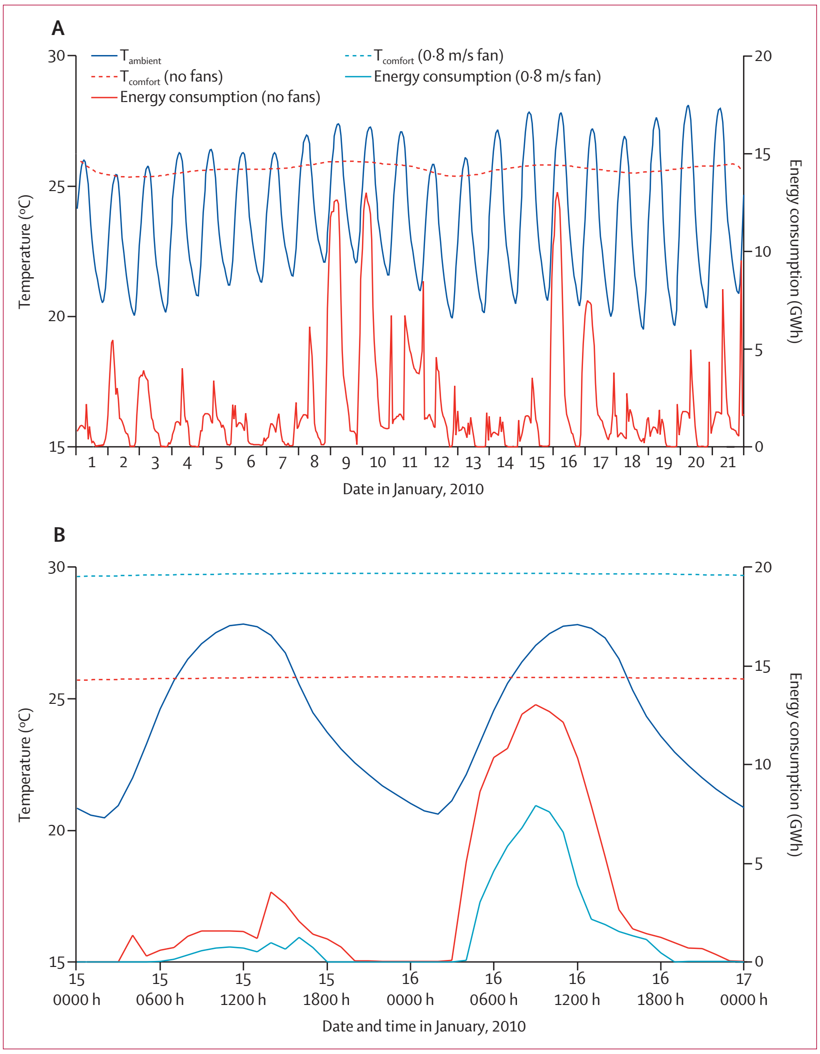

***Figure 2:* An example of the relationship between $T_{ambient}$, $T_{comfort}$, and energy consumption**

(A) Mean ambient temperature across Australia (dark blue lines) in January, 2010. $T_{comfort}$ is shown as a moving mean for the air conditioner-only scenario (red dashed line). The associated energy consumption is shown as a red solid line. (B) Comparison of $T_{comfort}$ for the air conditioner-only scenario (red dashed line) and the air conditioner with 0·8 m/s fan scenario (light blue dashed line) for Jan 15–17, 2010. Times are shown in Australian Eastern Daylight Time. Total hourly energy consumption across Australia is shown by solid red and light blue lines. $T_{ambient}$=ambient temperature. $T_{comfort}$=thermal comfort threshold.

$$E(i,j,t)=P_{ac}(ij)\ \{H(i,j,t_{day})\ \delta[T_{amb}(i,j,t_{day})-\theta(i,j,t_{day},\nu)] + \delta[T_{amb}(i,j,t_{night})-\theta(i,j,t_{night},\nu)]\}, \quad (9)$$

where δ is a Kronecker-like function with $\delta(x)=1$ if $x>0$ and $\delta(x)=0$ if $x\leq0$. Lastly, greenhouse gas emissions associated with this electricity use were calculated as

$$G(i,j,t)=E(i,j,t)\ g(i,j). \quad (10)$$

Equations 9 and 10 showed that energy consumption and greenhouse gas emissions from residential air conditioner and fan use were dependent on fan use through indoor air velocity ν, which, together with the ambient temperature history (T_{amb}), determined the thermal comfort threshold θ.

Data for populating the ambient temperature array T_{amb} with dimensions $N=390$ and $M=476$ were sourced from a solar energy resource assessment.[19] Equations 1–9 were enumerated using a 32-core 2·4 TB RAM high-performance server. A detailed explanation of the data sources and methodology is provided in the appendix (pp 3–5). We also analysed emissions resulting from air conditioner use under various scenarios, stratified by season.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

The relationship between the temperature threshold for thermal discomfort and the mean ambient temperature across Australia, and the implications for energy consumption, were estimated by initially modelling the first three weeks of January, 2010, for the air conditioner-only scenario (figure 2A). We used the GIS-based model to compare, in each hour, the local ambient temperature to the local upper limit for thermal comfort in each geographical grid point across the whole of Australia and translated this information into peaks and dips of hourly energy consumption.

Figure 2B focuses on 2 days within the 3-week period to show a comparison between the thermal comfort threshold and associated energy consumption between the air conditioner-only scenario and the air conditioner with 0·8 m/s fan scenario. The thermal comfort threshold for the air conditioner with 0·8 m/s fan scenario is higher than that for the air conditioner-only scenario, emphasising the potential of electric fans to expand the thermal comfort zone for humans and reduce the energy consumption required to maintain the same thermal comfort levels. On Jan 16 (a Saturday), the energy consumption peak is substantially higher than on Jan 15 (a Friday), despite a similar ambient temperature, due to homes being more occupied at the weekend. Note that both panels in figure 2 report mean temperatures across Australia, and local temperature in some grid points still exceeded the thermal comfort threshold in the air conditioner with 0·8 m/s fan scenario; therefore, considerable air conditioner use and associated energy consumption remains in some locations.

To calculate the variable of occupied hours above comfort threshold, the hourly probability of occupancy and non-occupancy was used to determine the number of hours that air conditioners would be turned on under the air conditioner-only scenario and the air conditioner with fan scenarios for four fan speeds. Subsequently, based on the usage of air conditioning, we determined the associated hourly emissions under all five scenarios (figure 3). Taking an annual perspective, the number of occupied hours above the comfort threshold decreases as fans are introduced at low speeds due to an elevation in

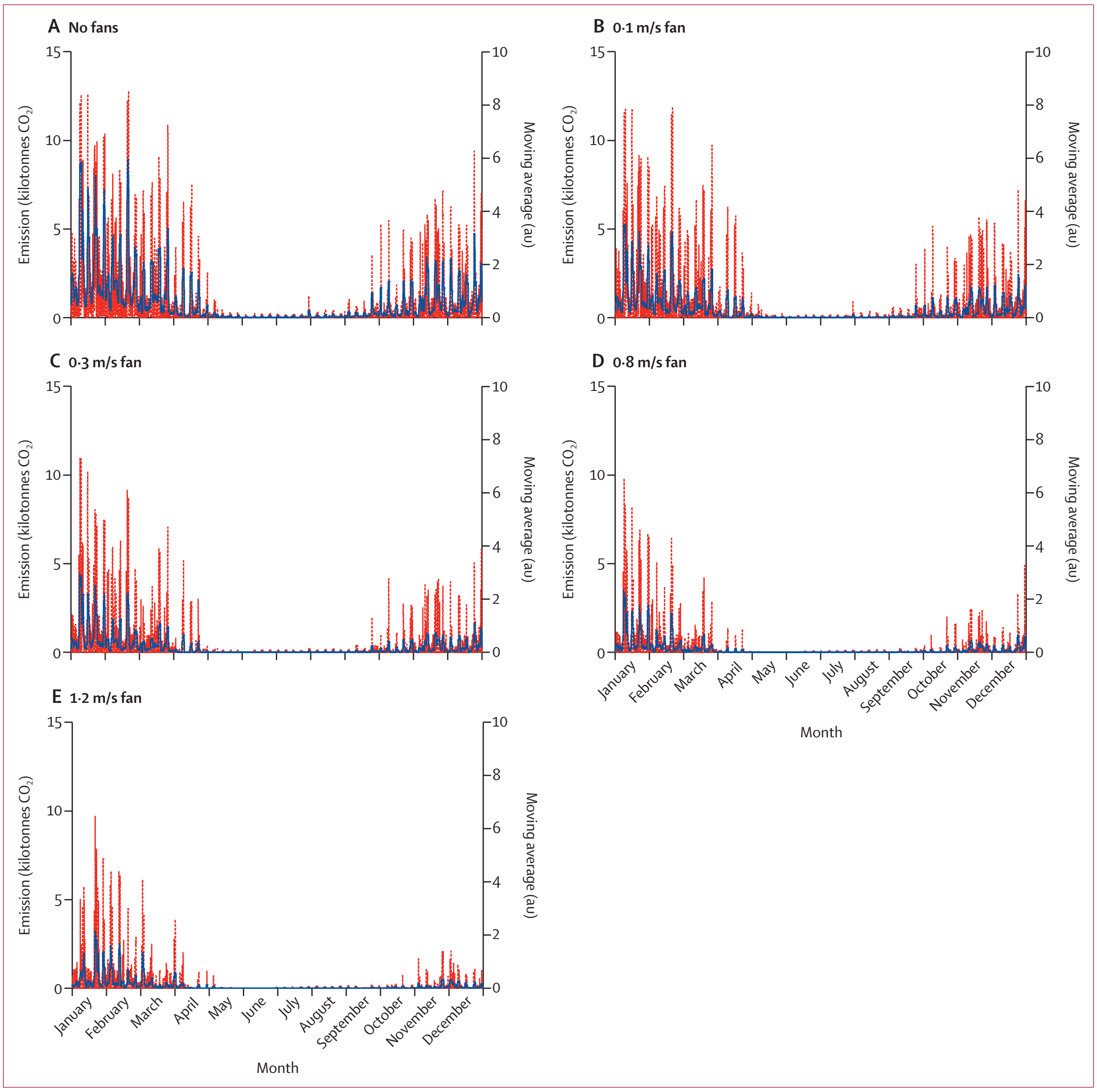

Figure 3: **Annual hourly emissions resulting from air conditioner use under various scenarios**
The scenarios shown are air conditioner only (A) and air conditioner with fan speed of 0·1 m/s (B), 0·3 m/s (C), 0·8 m/s (D), and 1·2 m/s (E). Hourly emissions in kilotonnes CO_2 equivalent are shown as red lines, and the moving average as overlaid blue lines. au=arbitrary unit.

the temperature threshold at which warm thermal discomfort occurs; and decreases further with increasing fan speeds, resulting in a reduction in energy use and greenhouse gas emissions. Progressing from the air conditioner-only scenario (figure 3A) to the air conditioner with 1·2 m/s fan scenario (figure 3E), we found a 76% reduction in energy use (from 5592 GWh to 1344 GWh) and associated greenhouse gas emissions (from 5091 kilotonnes to 1208 kilotonnes). This result shows that the use of fans in combination with air conditioners provides a way of maintaining thermal comfort while reducing greenhouse gas emissions and their associated environmental impacts.

As a further breakdown of energy use and emissions, we quantified the number of occupied hours above the comfort threshold during Australia's summer (December to February), autumn (March to May), winter (June to August) and spring (September to November; figure 4). Temperatures vary across the four seasons, as do the number of occupied hours above the comfort threshold. Although it is not surprising that under all scenarios the sequence of energy use and emissions for the four seasons of Australia (in descending order) is summer, autumn, spring, and winter (figure 4), it does support concerns about future emissions, given that summers are becoming longer and hotter,[12,20] with an increase in demand for air

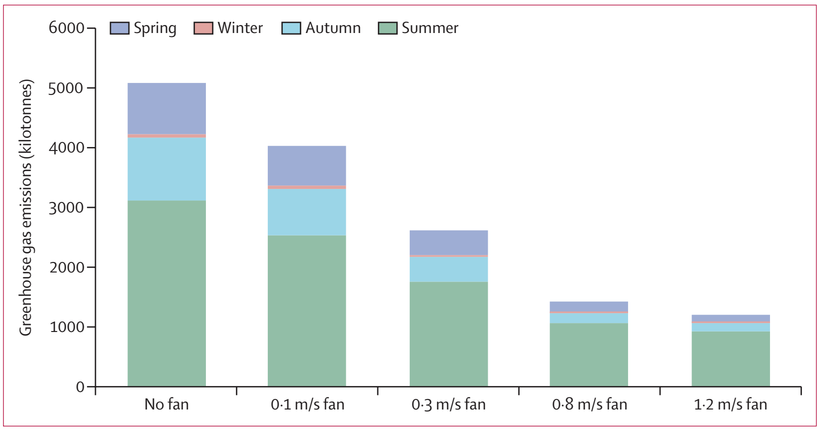

Figure 4: **Annual emissions resulting from air conditioner use under various scenarios, stratified by season**
The scenarios shown are air conditioner only and air conditioner with fan speed of 0·1 m/s, 0·3 m/s, 0·8 m/s, and 1·2 m/s.

conditioners.[1] Compared with the air conditioner-only (no fans) scenario, a 0·1 m/s fan results in a 21% reduction, a 0·3 m/s fan results in a 49% reduction, a 0·8 m/s fan results in a 72% reduction, and a 1·2 m/s fan results in a 76% reduction in greenhouse gas emissions (figure 4).

Discussion

We found that increasing indoor air movement with fans can decrease annual air conditioner use (captured in the variable of occupied hours above the comfort threshold) and associated electricity demand by up to around 76% with a fan speed of 1·2 m/s. However, additional reductions were small with increases in fan speed from 0·8 m/s (around 72%) to 1·2 m/s. Given that a fan speed of 0·8 m/s is better for ensuring comfort associated with other non-thermal factors (eg, draughts, disturbance of objects),[21] this speed is considered optimal. The upper temperature threshold at which warm thermal discomfort occurs was elevated by around 3–4°C with fan speeds of 0·8 to 1·2 m/s compared with no fans. The absolute temperature of this upper threshold changed dynamically based on the preceding temperature history within each 8·9-km grid box across the whole of Australia in accordance with the adaptive thermal comfort model from ASHRAE standard 55-2017.[6]

In 2010, electricity consumption in Australia resulted in 287 megatonnes of greenhouse gas emissions.[22] Based on our assumption that every household uses one or two pedestal fans per air conditioner unit (considering an energy consumption of 0·075 kWh for fans), we estimate that residential fans moving air at a speed of 0·8 m/s can reduce greenhouse gas emissions from electricity consumption by 2·1 megatonnes (0·7%). This amount is equivalent to a total reduction in Australian greenhouse gas emissions of 0·4%. According to the Paris Agreement signed in 2016, Australia's 2030 climate change target is a greenhouse gas emission reduction of 26–28% on 2005 levels (612 Mt CO_2 in 2005 to the target of 441–53 Mt CO_2 in 2030).[23] Using residential fans in combination with air conditioners to reduce the time and duration that air conditioning is operated, while maintaining the same level of thermal comfort of house occupants, could therefore accomplish around 1·2% of Australia's Paris Agreement target.

We used Australia as an example in the present study. If our methodology were to be applied across more densely populated and tropical regions (eg, India, China, or Indonesia), in which the non-fan upper temperature limit for thermal comfort will be exceeded daily throughout the year, the reductions in energy requirements and associated greenhouse gas emissions from air conditioner with parallel fan use would presumably be much greater. In the present analysis, the majority (around 56%) of reductions in electricity demand and greenhouse gas emissions from air conditioner use with fan use were attained in the three summer months of December to February, whereas in tropical regions warm temperatures occur year-round. Indeed, fan use could serve as a simple but effective climate change mitigation strategy for many countries to help meet their emission reduction targets. Moreover, augmenting convective heat loss to elevate the thermostat set-point temperature of an air conditioner unit could have a substantial effect on operating costs throughout the year, which, for many of the most vulnerable to extreme heat, can be unaffordable.[24]

It is important to raise awareness of the social and environmental benefits of fan use, particularly in developing countries with high within-country inequalities. Global air conditioner sales are expected to increase with growing incomes, particularly in developing countries where the pattern of air conditioner uptake is largely concentrated in high-income households.[25] Increasing affluence has been shown to be a key driver of global greenhouse gas emissions;[26] therefore, behaviour change is vital for realising the effectiveness of fans in reducing environmental impacts.

In Australia, 26% of residential homes do not currently use air conditioning. However, based on observations from other countries,[27] Australia could reach complete air conditioner saturation by 2100. An expected population growth for Australia to 53·6 million by 2100 will further increase air conditioner use and peak electricity demand.[28] Elsewhere, climate change and income growth, particularly in Asia, will collectively drive a dramatic increase in air conditioner use and therefore electricity demand.[4,29,30] Meeting these demands, especially at peak times, will not be possible without greatly expanding the capacity of electricity grids, which is costly[30] and, in many countries, will probably require the construction of new coal-fired power plants. However, our results indicate that peak electricity demand during the hottest times of the day could be substantially lowered if air conditioner use is complemented with convective flow from residential fan use. Secondary societal benefits could also include a reduced risk of power disruptions or outages with existing electrical infrastructure.

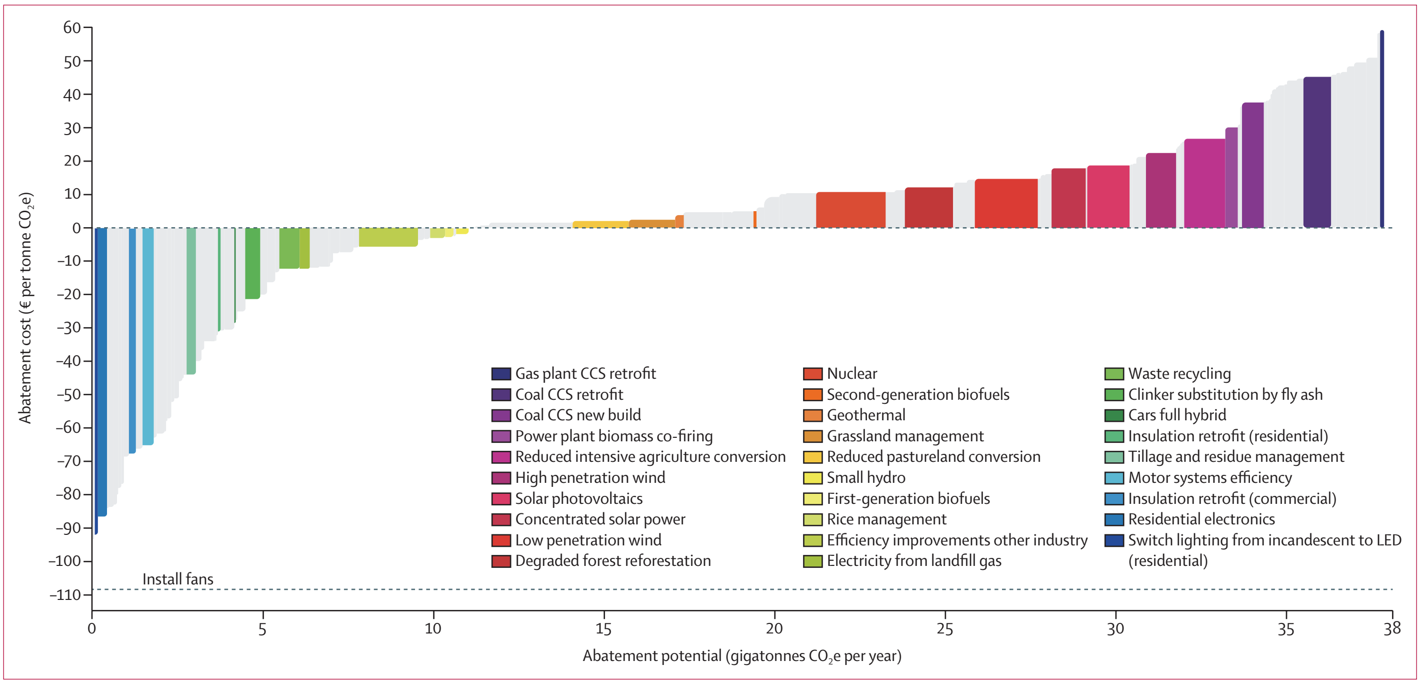

Figure 5: **Fans as a potential greenhouse gas abatement strategy**
The figure shows the abatement cost and abatement potential of a range of approaches (in grey, with some approaches highlighted in various colours). The global greenhouse gas abatement cost curve is presented in detail elsewhere.[32] The dashed line highlights the potential of installing fans as a possible greenhouse gas abatement strategy. CCS=carbon capture and sequestration. CO_2e=CO_2 equivalent.

The Paris Agreement urgently calls for keeping global average temperatures below 2°C above pre-industrial levels, and to pursue efforts to further limit warming to 1·5°C.[31] The agreement therefore requires the implementation of ambitious mitigation goals across major sectors of economies, including power, buildings, transport, and waste. Here, we undertook a cost-curve analysis to assess the abatement potential of the use of fans for meeting emission reduction commitments. Overall, our results point to total possible savings of 4248 GWh (from 5592 GWh to 1344 GWh) in energy consumption and 3882 kilotonnes (from 5091 kilotonnes to 1208 kilotonnes) of emissions per year, by simply transitioning from using air conditioners only in hot weather to air conditioners with 1·2 m/s of indoor air movement with a residential fan. We overlaid the abatement potential of fans on the global greenhouse gas emissions abatement cost curve produced by McKinsey (figure 5).[32] Assuming an electricity price of €0·10 per kWh of electricity, the savings for 4248 GWh of electricity would be €424·8 million, which translates to an abatement cost of €109 per tonne CO_2e. As such, fan use to raise the operating temperature of air conditioner units offers net financial benefits because the abatement cost falls far below the x axis. Indeed, our analysis indicates a potential abatement cost superior to switching from incandescent to LED home lighting.

Additional context of the potential emission reductions attained by reducing overall air conditioner use via fan use can be provided by calculating CO_2 equivalencies. According to the US Environmental Protection Agency,[33] the predicted annual 3882-kilotonne reduction in CO_2 emissions from using air conditioners with 1·2 m/s of indoor air movement with a residential fan compared with air conditioner use only is equivalent to 844 257 passenger vehicles driven for 1 year, 472 216 753 557 smartphones charged, and 4 756 139 acres of US forest. In a specifically Australian context, these reductions are also equivalent to the annual average per-capita footprint of 228 352 Australians.[34]

This study has some limitations and strengths. In our model, we used weather data for 2010 to show the impact of using residential fans to moderate air conditioner use and, by extension, greenhouse gas emissions.[19] The very high-resolution weather data required for our analysis was only available for this specific year, but the top five warmest years on Australia's record occurred after 2010 (2014–18).[35] Therefore, the analysis presented here is conservative, and probably underestimates the environmental burden likely to occur in future.

A strength of this predictive study is that we have used high-resolution historical temperature data on a spatial gridded map of Australia (8·9-km grid boxes, previously shown to be suitable for GIS assessments, such as in stimulating low-carbon electricity supply for Australia).[36] However, a limitation is that indoor temperatures are assumed to be equal to outdoor temperatures before air conditioning is employed, and this does not account for the many factors affecting building thermal performance, such as insulation, thermal mass, reflectivity of roofing material, window-to-wall ratio, glazing transmissivity, and air-change rates. In hotter climate zones, particularly at the hottest time of day, most buildings will passively maintain cooler temperatures indoors compared with outdoors, but they will be offset by warmer nocturnal temperatures indoors. Additionally, the number of hours when a home was occupied and the air conditioner was switched on was not measured, but was instead estimated using data from the Australian Bureau of Statistics on the household size, number of households, age distribution per household, unemployment rate, air conditioner availability, type of air conditioner, and number of air conditioner units per household. However, the assumptions used were conservative to reduce the risk of overestimating the effects of fan use.

In a national-scale analysis, it was also not feasible to account for all of the complex thermal behaviours of diverse occupants in their homes. It is well recognised in the thermal comfort literature that the insulation level of clothing worn indoors is weather-sensitive,[37] but to date the statistical models of that relationship have been derived exclusively from observations of occupants in office environments, and are probably not generalisable to residential settings. Therefore, in the current analysis we have assumed a fixed clothing insulation of 0·5 clo (0·08 $K \cdot m^2 \cdot W^{-1}$) which corresponds to a light summertime outfit. It was also not possible to account for all non-thermal factors that might affect fan-use behaviour. When used as the only mode of cooling, fans are often used alongside open windows to allow fresh air ventilation, but when air conditioning is turned on, windows are usually shut,[38] which could lead to decrements in air quality, even when used alongside fans. Increased indoor air movement may also disturb household items (especially paper). However, most of the benefit in terms of energy savings observed in the present study was attained with only a moderate fan air speed of 0·8 m/s and, as a large proportion of documentation transitions from paper to digital format, this impact is likely to become progressively smaller in the future.

The air speeds used in this study are considered spatial and temporal averages throughout the lowest 2 m of room volume. However, for ceiling fans, air speeds are highest in the core of the fan's downward jet, followed by a zone of lateral spreading at floor level and horizontal surfaces,[39] whereas for pedestal fans, different patterns of air flow would be produced within a room. Because the type and orientation of the fan used, its location within the room, and other factors such as furniture, would vary between households, the actual air speed across the skin surface for a given fan setting would not be identical.

A key assumption of the present analysis is that the thermostat set-point is altered according to the predicted change in the upper temperature threshold for warm thermal discomfort, both with fan use, and based on the adaptive thermal comfort model that accounts for recent temperature history.[6] To sustainably realise the electricity and greenhouse gas emission savings modelled in this study, automated thermostat control according to these variables would be essential.

The present analysis focuses on the maintenance of thermal comfort, and therefore the role of thermoregulatory impairments in groups that are typically considered more vulnerable to extreme heat are less relevant. In fact, older people have been reported to require warmer ambient temperatures to achieve thermal comfort compared with younger adults wearing similar levels of clothing insulation, mainly because of the reduced average activity level and therefore metabolic heat production of older people.[40] Due to the physiological equivalence of indoor climates in which fan-driven indoor air movement has been substituted for refrigerated air cooling, no negative consequences are expected for the older population group from a thermal comfort perspective. If anything, the warmer indoor temperatures accompanying the use of fans might even enhance the overall thermal comfort of older building occupants.

In conclusion, the world is experiencing a climate emergency, with global temperatures continually rising due to anthropogenic greenhouse gas emissions. A widespread strategy to cope with hot weather is the use of air conditioning. However, this causes a positive feedback loop in which air conditioner use leads to high electricity consumption, often delivered by fossil fuel power stations, which contribute to further increases in emissions, which, in turn, warm the climate. Moving indoor air with electric fans can raise the temperature threshold of heat discomfort that is the predominant driver of air conditioner use. Fans could therefore offer an effective strategy to reduce emissions attributable to air conditioner use in hot weather, and consequently serve as a possible abatement option. In this study, using Australia as a proof-of-principle model, we found that the widespread adoption of fans to elevate the temperature at which air conditioner units are turned on has the potential to reduce energy demand and emissions attributable to air conditioner use by up to 70–75%, making them an attractive mitigation option for meeting Paris Agreement commitments.

Contributors

ML, OJ, AM, and CB conceptualised and planned the study. CB, BM, OR-L, AM, ML, and OJ collected and processed underlying data. CB, ML, AM, and OJ reviewed the underlying data. AM, ML, CB, and OJ analysed data and produced the figures. AM, CB, OJ, ML, BM, OR-L, AC, and RdD wrote the manuscript. All authors contributed to the editing of the manuscript, had full access to all data in the study, and had final responsibility for the decision to submit for publication. OJ and AM accessed and verified the data.

Declaration of interests

We declare no competing interests.

Data sharing

Data underlying the figures are available upon request. Requests should be made to the corresponding author.

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