
Nari Yoon\textsuperscript{1,2}, Sang Hoon Lee\textsuperscript{2}, Edward Arens\textsuperscript{3}, Hui Zhang\textsuperscript{3}, Ronnen Levinson\textsuperscript{2}  
\textsuperscript{1}Korea University, Seoul, Republic of Korea  
\textsuperscript{2}Lawrence Berkeley National Laboratory, Berkeley, CA, USA  
\textsuperscript{3}University of California, Berkeley, Berkeley, CA, USA

Abstract

Our research evaluated a comprehensive set of key performance indicators (KPIs) for passive or low-energy building technologies (hereinafter, “strategies”) for pre-1980 medium office buildings in Phoenix (AZ) and Chicago (IL). The strategies included cool roofs and cool walls to reduce solar heat gain, natural ventilation to remove excessive indoor heat, and ceiling fans to allow the cooling set point to be increased.

Using EnergyPlus and Python scripts, we assessed major KPIs for buildings with and without mechanical cooling. The analysis offered how each strategy can save energy in cooled buildings and help occupants of uncooled or inadequately cooled buildings adapt to increasingly frequent extreme heat events.

Key Innovations

- Four passive or low-energy cooling strategies are accessed, and KPIs for each cooled and uncooled buildings are identified.
- We assessed how each strategy reduced HVAC energy use in cooled buildings.
- Also assessed is how such strategies decreased discomfort-weighted exceedance hours in uncooled buildings.
- The workflow can be easily expanded to different building usages, vintages, and climates to better understand the passive or low-energy cooling strategies.

Practical Implications

When buildings are uncooled, cool roofs, cool walls, natural ventilation, and ceiling fans can help prevent overheating due to the extreme heat events.

In climates like Chicago, natural ventilation and ceiling fans are very effective cooling strategies, both in cooled and uncooled buildings.

Introduction

The U.S. Environmental Protection Agency & Centers for Disease Control and Prevention (2016) reported that the extreme heat events projected 2041–2070 would occur more frequently and more severely, while lasting longer than those observed 1980–2000. A building that solely depends on mechanical systems to maintain the habitable indoor environment may endanger its occupants if the cooling equipment cannot meet load or loses power.

To examine the ability of medium office buildings in the U.S. to sustain the habitability under such events, it is important to quantify the effect of potential measures a building can employ. The U.S. Department of Energy (DOE) provides detailed descriptions and simulation prototypes for reference buildings in various climates, categories, and vintages (U.S. Department of Energy, n.d.), which are widely used by many researchers to evaluate the different aspects of building performance.

Such research includes airflow and indoor air quality of commercial buildings (Ng et al., 2012), cool walls on residential and non-residential buildings (Rosado & Levinson, 2019), natural ventilation of single-family house (Yoon et al., 2020), air quality for natural ventilation in small commercial buildings (Chen et al., 2019), and HVAC optimization for medium office buildings (Papadopoulos & Azar, 2016). There are many studies examining passive and low-energy design strategies based on buildings other than the reference buildings—e.g., glazing systems (Gomes et al., 2014), night-time ventilation (Rouch et al., 2013), cool envelopes (Hernández-Pérez et al., 2014), and ceiling fans (Zhai et al., 2015). However, as we focus on cooling strategies generalizable to pre-1980 U.S. medium office buildings, starting with two climates, the evaluation based on DOE’s reference buildings will offer comprehensive information about the opportunity to save energy and improve thermal comfort in the existing U.S. building stock.

With the intention to extend the selection to further passive and low-energy technologies, we assessed KPIs to gauge the abilities of four selected strategies: cool roofs and walls to reduce solar heat gain, natural ventilation to remove excessive indoor heat, and ceiling fans to allow the cooling set point to be increased. These strategies are easy to implement to the existing buildings, thus suitable for retrofit.

The strategies may further reduce cooling loads from the electric grid, helping to prevent grid failure that could result from extraordinary demand for air conditioning under hot weather. They could also reduce illness and death related to heat exposure in disadvantaged communities where residents lack air conditioning (Guo...
Yuming et al., 2017) and could benefit any community subject to scheduled or unscheduled power outages.

**Methodology**

**The prototype building**

We examined a three-story medium office prototype building, built prior to 1980, in Chicago, Illinois (ASHRAE climate zone 5A) and Phoenix, Arizona (2B). The geometry and its property were based on DOE’s commercial reference building models (Figure 1). This three-story building has a core thermal zone and four perimeter thermal zones on each floor. The building has gas furnace heating systems and two-speed direct expansion (DX) cooling systems serving each zone.

Figure 1: The prototypical medium office building defined by U.S. Department of Energy (2020), visualized in SketchUp software.

Table 1 shows the exterior envelope properties and heating and cooling system efficiency values of the prototype pre-1980 medium office building. Table 2 summarizes its geometry. The energy simulation input files were downloaded from the website of the U.S. DOE.

<table>
<thead>
<tr>
<th>Location</th>
<th>Phoenix</th>
<th>Chicago</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof assembly thermal resistance [m² K/W]</td>
<td>1.79</td>
<td>2.53</td>
</tr>
<tr>
<td>Exterior wall assembly thermal resistance [m² K/W]</td>
<td>0.62</td>
<td>0.98</td>
</tr>
<tr>
<td>Exterior window solar heat gain coefficient (SHGC), visible transmittance (VT) and U-factor [W/m²·K]</td>
<td>SHGC 0.54, VT 0.81, U-5.35</td>
<td>SHGC 0.54, VT 0.81, U-5.35</td>
</tr>
<tr>
<td>Infiltration rate per exterior surface area [m³/s·m²]</td>
<td>0.001133</td>
<td>0.001133</td>
</tr>
<tr>
<td>Heating COP [-]</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>Cooling COP [-]</td>
<td>3.33</td>
<td>3.33</td>
</tr>
</tbody>
</table>

Table 2: Geometry of prototype pre-1980 medium office building. Adapted from Table ESM B-5 of Rosado & Levinson (2019).

| Number of floors | 3 |
| Conditioned floor area [m²] | 4,980 |
| Footprint area [m²] | 1,660 |
| Roof area [m²] | 1,660 |
| Net wall area a [m²] | 1,320 |
| Window area [m²] | 653 |
| Window-to-wall ratio b [-] | 0.330 |
| Roof-to-wall ratio c [-] | 1.25 |
| Floor-to-wall ratio d [-] | 3.77 |

a Net wall area excludes windows and doors.
b Ratio of window area to gross wall area (area of entire wall, including openings).
c Ratio of roof area to net wall area.
d Ratio of conditioned floor area to net wall area.

We also tested the building with and without mechanical cooling availability (hereinafter, “cooled” and “uncooled” buildings). For cooled buildings, we applied cooling setpoint temperature values of 24.9 °C during the occupied hours and 30.5 °C during the unoccupied hours. In both cooled and uncooled buildings, the heating setpoint temperature was 21.0 °C during the occupied hours and 15.6 °C during the unoccupied hours.

**Key performance indicators (KPIs)**

To access each strategy and understand the influence of different variables, we computed various KPIs for cooled buildings, including the following seven annual metrics:

- Heating gas site energy use per unit floor area [therm/m²]
- Fan and cooling site energy uses per unit floor area [KWh/m²]

Heating gas, fan, cooling, and HVAC (heating + fan + cooling) source energy uses per unit floor area [MJ/m²]. We calculated savings and penalties in energy use from the base case, where penalty refers to the increase in energy use from the base case due to the strategy applied. For example, cool roofs may reduce cooling energy use but may increase heating energy use, leading to cooling savings and a heating penalty.

Thermal sensation scale unit (TSSU) is used to express change in predicted mean vote (PMV). For example, raising PMV from +1 to +2 is an increase of 1 TSSU. For uncooled buildings, the following annual thermal comfort KPIs [TSSU-h] were calculated:

- Discomfort-weighted warm exceedance hours
- Discomfort-weighted cool exceedance hours
- Discomfort-weighted very-hot exceedance hours
- Discomfort-weighted very-cold exceedance hours

Exceedance hours is the number of occupied hours in which the indoor operative temperature lies outside the comfort zone (ASHRAE, 2017). Warm, cool, very-hot, and very-cold exceedance hours are the numbers of hours in which occupants are uncomfortably warm (PMV > 0.7), cool (PMV < -0.7), very hot (PMV > 3), and very cold (PMV < -3). Simulations can yield PMV values < -3 and > 3.

Discomfort-weighted exceedance hours is the sum of the positive values of PMV exceedance during occupied hours, where PMV exceedance = (PMV – threshold) for warm or very-hot conditions, and PMV exceedance = (threshold - PMV) for cool or very-cold conditions. For example, discomfort-weighted warm exceedance hours is the sum of the positive values of (PMV - 0.7) during occupied hours, where PMV is capped at +4, while discomfort-weighted cool exceedance hours is the sum of the positive values of (-0.7 - PMV) during occupied hours, where PMV is capped at -4. Discomfort-weighted very-hot and very-cold exceedance hours are calculated analogously, using thresholds of 3 and -3, respectively.
For our test cases, we calculated the increase or decrease of these discomfort-weighted exceedance hours from the base case.

**Strategies**
The strategies included cool envelope materials to reduce solar heat gain, natural ventilation to remove excessive indoor heat, and ceiling fans to allow the cooling set point to be increased. We evaluated the following strategies:

- Cool roof
- Cool wall
- Natural ventilation opening area
- Ceiling fan

The parameters for each case are shown in Table 3.

**Cool envelope materials** such as solar-reflective roofs and walls reduce solar heat gain at the building surfaces by increasing roof or wall solar reflectance (albedo). In our tests, all roofs and walls were assumed to have aged thermal emittance 0.90.

**Natural ventilation** removes excess indoor heat gains by bringing cooler outside air indoors and exhausting warmer air from the occupied space. We explored various fractions of openable window area ranged from 0% to 50% (Table 3). Windows were closed when the outdoor air temperature was equal to or lower than the heating set point. In cooled buildings, windows are also closed when the outdoor air temperature is equal to or higher than the cooling set point.

A **ceiling fan** makes a higher cooling set point acceptable to occupants (Hoyt et al., 2015). In our EnergyPlus settings, it is not possible to physically model a ceiling fan and its effect on the local air speed near the human body. Therefore, we assumed that a certain near-occupant air speed was achieved and the cooling setpoint temperature was raised accordingly (Table 3). The relationship between the air speed around occupants and cooling setpoint temperature was obtained from Figure 5.3.3A of ASHRAE Std. 55-2017 (ASHRAE, 2017). One can also explore them interactively through the CBE Thermal Comfort Tool (Tartarini et al., 2020).

**Diagnostics of the base case**
To ensure that the simulation results of base-case models in different climate regions were reasonable, we compared the heating, cooling, and ventilation fan annual site energy uses per unit floor area yielded by our simulations to the site energy use microdata provided by the U.S. Commercial Buildings Energy Consumption Survey (CBECS) (U.S. EIA, 2015). We normalized microdata heating, cooling, and ventilation fan energy uses to heated, cooled, and gross floor areas, respectively. Of the 6,720 sample building cases in the microdata, we filtered the data by conditions described in Table 4 for Phoenix and Chicago. Note that the geographic regions used to represent Phoenix and Chicago were quite large even after filtering.

Each sample case has a replicate weight, which represents the estimated population of such case (U.S. EIA, 2016). Therefore, we used the replicate weight to compute the quartiles of each energy use.

### Table 4: CBECS microdata categories*

<table>
<thead>
<tr>
<th>Census division</th>
<th>Phoenix</th>
<th>Chicago</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate region</td>
<td>“Hot-dry/Mixed-dry”</td>
<td>“Very cold/Cold”</td>
</tr>
<tr>
<td>Building activity</td>
<td>“Office”</td>
<td></td>
</tr>
<tr>
<td>Building total floor area</td>
<td>465 to 18,580 m²</td>
<td></td>
</tr>
</tbody>
</table>

* Values in double quotes denote the categorical values used in 2012 CBECS microdata.

**Tools and programs**
Whole building simulations were conducted using EnergyPlus (v.9.2) (NREL, 2019). For parametric EnergyPlus simulations, we used jEPlus (v.1.7.2) which enabled consecutive runs with the parameter values listed in Table 3.

The PMV calculation implemented in the current EnergyPlus is not fully consistent with the ASHRAE 55 method. Therefore, we used the pythermalcomfort Python package (v. 1.3.1) to calculate PMV values. This package follows the ASHRAE 55-2017 method (Tartarini & Schiavo, 2020).

We used Python scripts to post-process the EnergyPlus output files, compute hourly PMVs, generate annual KPI databases, and visualize the results for each location and cooling status (cooled or uncooled).

**Results and discussion**
In most cases with the four strategies, the annual cooling energy savings in each climate far exceeded the annual heating penalty. Substantial heating penalties were found in the cool roof and cool wall strategies in Chicago. In Phoenix, the annual heating degree days base 18 °C (HDD18C) is only about one sixth that in Chicago (543...
vs. 3,430), so the heating penalty of cool materials in Phoenix was negligible. Note that in the two natural ventilation strategies, windows could be closed when heating was needed, and that in the ceiling-fan strategy, the fan could be turned off when heating was required; therefore, the heating penalties in those three strategies were negligible.

In general, the ceiling fan strategy showed the largest savings in HVAC and decrease in discomfort-weighted exceedance hours. The HVAC savings and the decrease in discomfort-weighted exceedance hours were greater in Phoenix than in Chicago.

**Base-case results and diagnostics**

Table 5 lists the base-case KPIs of both cooled and uncooled medium office buildings. When uncooled, the base-case building in Phoenix showed the annual discomfort-weighted warm and very-hot exceedance hours more than four times higher than the building in Chicago. This is understandable given the differences between the climates: the annual cooling degree days base 18 °C (CDD18C) of Phoenix is 2,611, while that of Chicago is only 506. The annual discomfort-weighted cool- or very-cold exceedance hours were nearly zero in both locations because each building was heated as needed to maintain its heating setpoint.

Figure 2 shows the annual site energy uses per unit floor area computed from CBECS and from our energy simulations of base cases of the cooled buildings. The darker region within each bar bounds the interquartile range of the CBECS data, while the circle marks the base-case EnergyPlus simulation results. The comparison to CBECS data ensured that the results of the base cases of

### Table 5: Base-case results derived from EnergyPlus simulations.

<table>
<thead>
<tr>
<th>KPI (cooled building)</th>
<th>Phoenix</th>
<th>Chicago</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual heating gas site energy use per unit floor area [therm/m²]</td>
<td>0.04</td>
<td>1.75</td>
</tr>
<tr>
<td>Annual fan site energy use per unit floor area [kWh/m²]</td>
<td>39.9</td>
<td>40.3</td>
</tr>
<tr>
<td>Annual cooling site energy use per unit floor area [kWh/m²]</td>
<td>61.3</td>
<td>16.6</td>
</tr>
<tr>
<td>Annual heating gas source energy use per unit floor area [MJ/m²]</td>
<td>5.0</td>
<td>202</td>
</tr>
<tr>
<td>Annual fan source energy use per unit floor area [MJ/m²]</td>
<td>454</td>
<td>515</td>
</tr>
<tr>
<td>Annual cooling source energy use per unit floor area [MJ/m²]</td>
<td>699</td>
<td>212</td>
</tr>
<tr>
<td>Annual HVAC source energy use per unit floor area [MJ/m²]</td>
<td>1,160</td>
<td>929</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>KPI (uncooled building)</th>
<th>Phoenix</th>
<th>Chicago</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual discomfort-weighted very-hot exceedance hours [TSSU-h]</td>
<td>2,130</td>
<td>457</td>
</tr>
<tr>
<td>Annual discomfort-weighted warm exceedance hours [TSSU-h]</td>
<td>9,760</td>
<td>3,980</td>
</tr>
<tr>
<td>Annual discomfort-weighted cool exceedance hours [TSSU-h]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Annual discomfort-weighted very-cold exceedance hours [TSSU-h]</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Phoenix and Chicago could be deemed reasonable. They also offered the starting point for the other test cases.

**Cool roof and cool wall**

Cool-roof and cool-wall savings and penalties scaled linearly with rise in roof or wall albedo. Increasing roof or wall albedo yielded positive annual HVAC source energy savings in both locations as shown in Figure 3(a-b) and Figure 4(a-b).

While there was little to no annual heating penalty in Phoenix, the annual heating source energy penalty was roughly the half the annual cooling source energy savings in Chicago. Variations in HVAC savings are driven by differences in climate—e.g., annual heating degree days, annual cooling degree days, mean winter global horizontal solar irradiance, and mean summer solar, roof assembly thermal resistance, and HVAC operating hours. The interplay between energy use, climate, and building characteristics is complex, depending on whether roof solar heat gain is conducted into the occupied space during hours in which the building requires heating, cooling, or neither. However, simple ratios in the climate and envelope parameters are informative.

Reductions in discomfort-weighted warm- and very-hot exceedance hours also scaled linearly with rise in roof or wall albedo in the uncooled medium office building (Figure 3(c-d) and Figure 4 (c-d)).

Note that while the savings and penalties in these two figures have been normalized to floor area for comparison with other strategies, they are actually proportional to roof
Figure 3: Influence of a cool roof on cooled and uncooled buildings in Phoenix and Chicago.

Figure 4: Influence of cool walls on cooled and uncooled buildings in Phoenix and Chicago.
area or net wall area (gross wall area minus the area of openings, such as windows and doors). The cool roof lowers the discomfort-weighted warm- and very-hot exceedance hours only on the top floor of the building, and the cool wall does so in perimeter zones. Since the whole-building reduction in discomfort-weighted exceedance hours was computed as the floor-area-weighted average of reductions over all building zones, one should consider the number of floors or the ratio of building volume to net wall area to interpret the influence of cool roofs and walls. For example, cooling energy savings per unit conditioned floor area for a single-story building would be double those for an otherwise-identical two-story building, and triple those for an otherwise-identical three-story building.

Natural ventilation

We tested the influence of the openable area for natural ventilation. Cooling savings from opening windows were evident even with the smallest opening area fraction of 2.5% (Figure 5(a-b)). The savings did not scale linearly with the increase in fraction of window area that can be opened. Cooling savings were about three to six times greater from 0% to 2.5% than from 2.5% to 5%. Similarly, the decrease in discomfort-weighted warm exceedance hours was about five to eight times greater from 0% to 2.5% than from 2.5% to 5% (Figure 5(c-d)). The airflow rates entering the windows do vary linearly with the increase of the opening area. However, this did not lead to the linear relationship between the opening area and our KPIs. One major reason is because the temperature of the air entering the windows is bound to the outdoor air temperature, meaning that the indoor air temperature can be lowered only to a certain extent. Another reason is related to the need for cooling. Once the indoor air temperature is below the cooling setpoint and above the heating setpoint with a certain window area opened, additional airflow is not needed for cooling; therefore, it does not save more cooling energy nor reduce the discomfort-weighted warm- or very-hot exceedance hours. As described in Table 3, the ceiling fan strategy allows the cooling setpoint to be raised when the local air speed near occupants is increased. Natural ventilation can also increase local air speed and the cooling setpoint could be adjusted accordingly. However, we did not consider this benefit for the natural ventilation strategies. To evaluate the increase in local air speeds provided by natural ventilation, one would have to obtain the local air speed near the occupants, which was not an output of our EnergyPlus simulations. Had we been able to include the cooling of natural ventilation-induced air speed over the human skin, the HVAC savings and the decrease in discomfort-weighted exceedance hours would have been greater than what is shown in Figure 5.

Ceiling fan

In cooled buildings, the HVAC savings were not linearly related to the average air speed around the occupants, but followed curves resembling those of the equal-comfort curves inASHRAE Standard 55. In these, the elevation of comfortable temperatures increases most rapidly at low air speeds, especially just above still air, and the rate of elevation diminishes as air speed increases to its highest practical levels. For example, 0.4 m/s air speed increases the comfortable temperature 2 °C over that at still air, while 1.6 m/s increases it 4 °C. These increases in comfortable temperatures should, in a responsive HVAC control system, be translated directly into increased cooling setpoints.

The setpoint increases would be based simply on the known indoor air speeds available to the occupants from the installed ceiling fans. HVAC savings can be simulated for the increased cooling setpoints. The HVAC savings can be seen to be about two times greater from 0.1 to 0.4 m/s than from 0.4 to 1.6 m/s. Analogous trends were also found in uncooled buildings (Figure 6(c-d)). In these, the increase in the discomfort-weighted warm- and very-hot exceedance hours from 0.1 to 0.4 m/s were more than twice those from 0.4 to 1.6 m/s.

Note that an air speed of 0.4 m/s is easy to attain with fans operating at low to middle speeds, making substantial HVAC savings practically achievable.

There was little-to-no heating energy penalty in cooled buildings or increase in cool- and very-cold exceedance hours in uncooled buildings because ceiling fans were not operated during the heating season.

Conclusion

We assessed for pre-1980 medium offices how each strategy could reduce annual HVAC energy use in cooled buildings and decrease discomfort-weighted exceedance hours in uncooled buildings. These strategies could boost comfort, health, and productivity; reduce illness and death in disadvantaged communities where residents lack air conditioning and benefit any community subject to scheduled or unscheduled power outages. Our analysis of the selected strategies can thus inform to what extent a building and occupants may resist the consequences, reduce the impact, and recover from extreme weather conditions.

More cases need to be investigated, including window shading systems and solar-control windows. It will also be worth exploring the combinatorial effect of multiple strategies, such as natural ventilation with a ceiling fan, or cool roof with cool wall. When expanded to a wide range of building types, vintages, sizes, and climates, our approach can identify strategies that provide high cooling resilience under given conditions.

Below is a summary of our key findings.

1. These low- to zero-energy cooling strategies reduce HVAC energy use and decrease warm- and very-hot discomfort hours.

2. The annual HVAC source energy savings are larger in Phoenix than in Chicago (Figure 3–Figure 6).
Figure 5: Influence of openable window area on cooled and uncooled buildings in Phoenix and Chicago.

Figure 6: Influence of a ceiling fan on cooled and uncooled buildings in Phoenix and Chicago.
3. HVAC savings and the decrease in the discomfort-weighted exceedance hours varied linearly with the increase in roof and wall albedo.

4. Natural ventilation can save HVAC energy and decrease the discomfort-weighted exceedance hours even with a small opening area.

5. Ceiling fans provided the most HVAC savings and the most substantial decrease in the discomfort-weighted warm- and very-hot exceedance hours.

The next step would be to expand the scope of the test buildings. The same analysis framework can be applied to other commercial building types or residential buildings and newer building vintages, under various climates of the U.S. with more cooling strategies such as shading technologies.

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