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The value of air conditioning

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The advent of global climate change and rising incomes, particularly in some developing countries such as Egypt, means that the use of air conditioning is poised for a dramatic increase over the next few decades. Although this anticipated increase appears inevitable, it is often associated with a negative connotation because of the increased energy demands and greenhouse gas emissions associated with expanded air conditioning use. Yet, the benefits of air conditioning are not often described in existing literature in conjunction with its associated negative externalities. For example, higher productivity in commercial buildings, and positive health benefits in all manner of buildings (residential, commercial, and industrial) could potentially offset the greater energy consumption and related disadvantages. A levelized cost of cooling (*LCOC*) analysis is presented to quantify under what circumstances building air conditioning provides benefits that exceed its costs, and *vice versa*. The *LCOC* is calculated for the application of air conditioning to a small office building located in either Phoenix, Arizona, United States, or in Cairo, Egypt. The electrical energy required for cooling is calculated with *EnergyPlus* software. The results indicate that the benefits of air conditioning far outweigh its disadvantages for the Phoenix location, largely because of the productivity benefits derived from maintaining the interior temperature at a comfortable setting. The results for Egypt are more nuanced, but still indicate the overall benefits of air conditioning in an office environment.

KEYWORDS

cooling, buildings, productivity, health, heat, levelized cost of cooling

1 Introduction

Air conditioning, i.e., the cooling of indoor air to maintain comfortable conditions, has become nearly ubiquitous around the world. Rising global temperatures (Change, 2024) indicate that the demand for air conditioning (AC) is not likely to decrease in the future, with especially large increases forecast for developing countries (India energy Outlook 2021 – analysis, 2024). In a developed nation like the United States, air-conditioning is the norm in most parts of the country for both residential and commercial buildings. A significant amount of energy in the United States is devoted to air conditioning, representing between 4% and 7% of the total annual primary energy consumption over the last 20 years (Figure 1). The annual data in Figure 1 were determined from the *Annual Energy Outlook*, with a one-year publication lag time for plotted annual values. Note that the values for commercial buildings include the energy required for both space cooling and for ventilation, while those for residential buildings are only for space cooling. The only discernible trend in the data appears to be a general increase around the year 2005, but it's possible that this is due to a change in model assumptions around that time.

Air conditioning is largely provided by vapor-compression cycles that require electrical energy input. Because of the cost of electrical energy and the desire to reduce associated greenhouse gas (GHG) emissions, building owners may be inclined to increase the AC

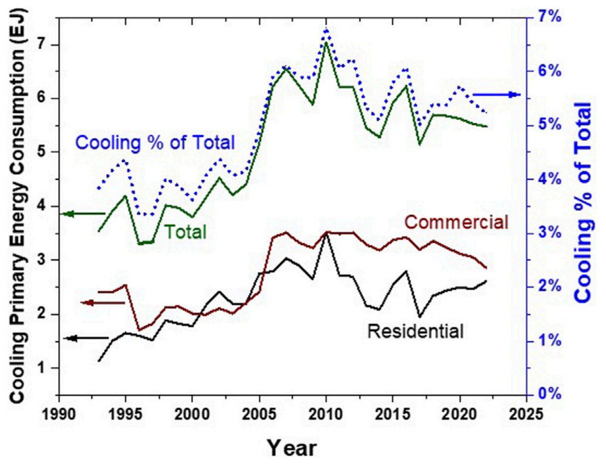

FIGURE 1
United States Air conditioning primary energy consumption.

temperature setpoint during operating hours so as to reduce the amount of time the AC has to operate, or even to turn off the AC altogether. Although energy savings and GHG reductions will be realized, this may result in deleterious productivity and health impacts that may well offset any energy and GHG reductions. Here we therefore investigate the trade-offs between reduced AC usage resulting from higher thermostat setpoint temperatures and decreased productivity and health outcomes through calculating the Levelized Cost of Cooling (*LCOC*) for a small office building. The office building is situated in either Phoenix, Arizona, United States, or in Cairo, Egypt, in order to represent both developed and developing country situations. We make use of *EnergyPlus* software (EnergyPlus, 2024) to determine the annual electrical energy required for cooling, as well as the cooling energy delivered to the building. The results indicate that in the United States, it is far more advantageous to maintain a comfortable setpoint (75°F, or 23.9°C) rather than to increase the indoor temperature during the summer cooling season.

2 Approach

2.1 Levelized cost of cooling

The levelized cost of cooling (*LCOC*) was previously introduced as a means to compare the cost effectiveness of various cooling technologies, similar to how the levelized cost of energy (*LCOE*) is utilized to compare electricity-generating systems. One of the earliest reports of *LCOC* compared a variety of solar cooling technologies (Gabbrielli et al., 2016), and indeed this was the objective of a number of later studies [see, e.g., (Bellos and Tzivanidis, 2017), (Shirazi et al., 2018), (Altun and Kilic, 2020), (Mortadi and El Fadar, 2022), (Teles et al., 2023)]. Still others have employed the general concept of levelized costs to evaluate and compare polygeneration systems [see, e.g., (Leiva-Illanes et al., 2018), (Askari et al., 2019)), while others have evaluated district cooling (see, e.g., (Novosel et al., 2021)] and solar-assisted systems with thermal energy storage [see, e.g., (Jarimi et al., 2024)]. But, to our knowledge we have not seen an *LCOC* calculation that includes ancillary costs and benefits of air conditioning, such as productivity and health impacts (a benefit), GHG emissions (a cost), etc., in addition to the cost of energy (typically electricity) and the provided cooling. Therefore here we start with the definition of *LCOC* ($/kWh$_c$) based on the definition of *LCOE* described by the Intergovernmental Panel on Climate Change (IPCC) (Krey, 2014):

$$\sum_{t=0}^{n}\frac{C_t LCOC}{(1+i)^t}=\sum_{t=0}^{n}\frac{Expenses_t - Benefits_t}{(1+i)^t} \tag{1}$$

where C_t is the cooling energy provided in year t (kWh$_c$), n the lifetime of the cooling system (years), i the discount rate, $Expenses_t$ the sum of all costs incurred by the cooling system in year t ($ or local currency), and $Benefits_t$ all the benefits incurred by the cooling system in year t ($ or local currency). Equation 1 can be solved for *LCOC*:

$$LCOC=\frac{\sum_{t=0}^{n}\frac{Expenses_t - Benefits_t}{(1+i)^t}}{\sum_{t=0}^{n}\frac{C_t}{(1+i)^t}}\left(\frac{\$}{\mathrm{kWh_c}}\right) \tag{2}$$

where the currency can be either US $ or a local currency. For the annual costs $Expenses_t$, here we consider the following:

$$Expenses_t=\begin{pmatrix}\text{Initial}\\ \text{Capital}\\ \text{Cost}\end{pmatrix}_0+\begin{pmatrix}\text{Energy}\\ \text{Cost}\end{pmatrix}_t+\begin{pmatrix}\text{O\&M}\\ \text{Cost}\end{pmatrix}_t+\begin{pmatrix}\text{CO}_2\\ \text{Cost}\end{pmatrix}_t \tag{3}$$

where the initial capital cost is applied only during year 0, and the costs of energy, operations and maintenance (O&M), and the social cost of carbon (CO_2 cost) are applied for all subsequent years $1 \le t \le n$. Note that here the CO_2 cost is equivalent only to the cost incurred due to energy (electricity) consumption; GHG emissions resulting from refrigerant leakage are neglected. The initial capital cost and O&M cost are taken from (Updated buildings sector appliance and equipment costs and efficiency, 2024) for *SEER* 14.0 AC units (*SEER* = Seasonable Energy Efficiency Ratio). Given the relatively small size of the modeled office building (explained in the next subsection), we assume AC values for "Residential Central Air Conditioners – South (Hot-Dry and Hot-Humid)," considered the 2022 "current standard."

The *social cost of carbon* is defined as "the economic cost caused by an additional ton of carbon dioxide emissions or its equivalent" (Nordhaus, 2017). Since most jurisdictions do not have a carbon tax or other "real" cost associated with GHG emissions, here we employ the social cost of carbon as the CO_2 cost, and take our initial value of $62/tonne CO_2 as developed by the US federal government from (Notice of availability and request, 2024). In the results discussed below we also consider a higher value.

Finally we have the annual benefits of AC, $Benefits_t$, which may be described as

$$Benefits_t=\begin{pmatrix}\text{Productivity}\\ \text{Gain}\end{pmatrix}_t+\begin{pmatrix}\text{Health}\\ \text{Gain}\end{pmatrix}_t \tag{4}$$

where Productivity Gain ($) refers to increased economic output due to maintaining interior temperatures at comfortable conditions, and likewise Health Gain ($) refers to reduced health costs due to

TABLE 1 Effect of indoor temperature on productivity in an office environment.

Optimal temperature (°C/°F)	Optimal relative humidity (%)	% Decline in productivity per °C	Notes	Ref.
15.6–21.1 / 60.1–70.0	—	—	Meta-review that established impacts with respect to the wet bulb globe temperature (WBGT); therefore not used in this study	Pilcher et al. (2002)
22.6 / 72.7	—	2.8%	Optimal temperature assumed; tested 2 temperatures at a call center	Niemelä et al. (2002)
21.6/70.9	—	1.2%	Also examined sick building syndrome and effect of ventilation rates	Seppänen and Fisk (2006)
23.3 / 73.9	40%	0.9%	"Optimal performance is achieved when people feel slightly cool"	Lan et al. (2011)
22.0 / 71.6	—	1.1%	Varied temperature in 2°C increments from 16°C to 28°C	Geng et al. (2017)
25.15 / 77.3		2.0%	". . . there is a trade-off relationship between the labor-productivity-enhancing perspective and the energy-saving perspective"	Kim and Hong (2020)

maintaining temperatures at comfortable conditions. As discussed later, since we found it difficult to quantify (i.e., monetize) health impacts due to interior temperatures we treat that qualitatively in this paper and instead focus on productivity impacts due to interior temperatures being higher than what are generally considered as comfortable conditions.

The role of ambient (i.e., exterior) temperatures on a society's general level of productivity are well known (see (Heal and Park, 2015) for an interesting discussion), but our focus here is on the interior, or indoor temperature. Note that we are *not* addressing the effects of ventilation rates, which received a great deal of attention because of COVID-19 [see, e.g., (McLeod et al., 2022)], nor in general "green" buildings [see, e.g., (Cedeño-Laurent et al., 2024)], but instead just the interior temperature setpoint of a building's AC system during the summer cooling season.

Table 1 provides a noncomprehensive summary of several studies that have examined how interior temperatures impact productivity, in an office setting. Most did not consider the effect of relative humidity, so here we choose to ignore that and instead focus on the dry-bulb temperature. Although there can be relatively large uncertainties in the data, and often the sample sizes are relatively small, as Table 1 indicates there is general agreement that as the temperature is increased above some optimum, typically 21–23°C (70–74°F) the measured productivity of the building occupants decreases at a rate as high as 2.8% per °C. Here, we choose to take the rate of productivity decrease as 1%/°C, and neglect any cultural or gender differences, noting how one study found that men are more productive at cooler temperatures, while women are more productive at warmer temperatures (Kawakubo et al., 2023).

Recognizing that most office buildings, at least in the United States, already have AC we consider here how the AC temperature setpoint affects productivity, and take as the maximum temperature setpoint T_{max} 28.0°C (82.4°F), and reduce the AC temperature setpoint T_{set} by 0.56°C (1°F) down to the assumed optimal $T_{set} = 23.89°\text{C}$ (75.0°F). At $T_{set} = T_{max} = 28.0°\text{C}$ we consider there to be no productivity gain because of temperature, but as T_{set} is reduced below 28.0°C productivity increases 1%/°C down to the optimal $T_{set} = 23.89°\text{C}$:

$$\begin{pmatrix}\text{Productivity}\\\text{Gain}\end{pmatrix}_t = (T_{max} - T_{set})\left(\frac{1\%}{°\text{C}}\right)\left(\frac{\text{GDP}}{\text{person}}\right)\begin{pmatrix}\text{Number}\\\text{of}\\\text{Occupants}\end{pmatrix} \tag{5}$$

where GDP/person is the gross domestic product *per capita*. Admittedly this is at best only a rough estimate of the productivity of the occupants inside the building, but it is a readily available number for countries around the world and thus enables easy inter-country comparisons. Finally, the Number of Occupants refers to the number of people occupying/working in the office building. For that we use the average number of occupants assumed by *EnergyPlus* in the building energy simulation, as described next.

2.2 Building energy simulation

We apply the above methodology to compute the *LCOC* for a small office building, for which we require the annual cooling energy delivered to the building by its AC system, C_t (kWh$_c$/yr), and the annual electrical energy consumed by the AC system, E_t (kWh/yr) on which both the annual energy cost ($/yr) and CO_2 cost ($/yr) depend. Here we use EnergyPlus software (EnergyPlus, 2024) with the OpenStudio interface (OpenStudio, 2024) to compute both, and take the "small office building" from the list of commercial reference building models developed by the US Department of Energy (DOE) (Commercial reference buildings, 2024) to represent a typical office building. There are several versions of the small office building model to choose from, representing different building energy codes. Here we assume that the ASHRAE 90.1-2019 code (Update of Standard 90.1 ashrae.org, 2019) applies, indicating *SEER* = 14.0 for the AC system as described above. The average number of people in the building during working hours is given as 19.28 in the EnergyPlus building model, and so we apply that number in

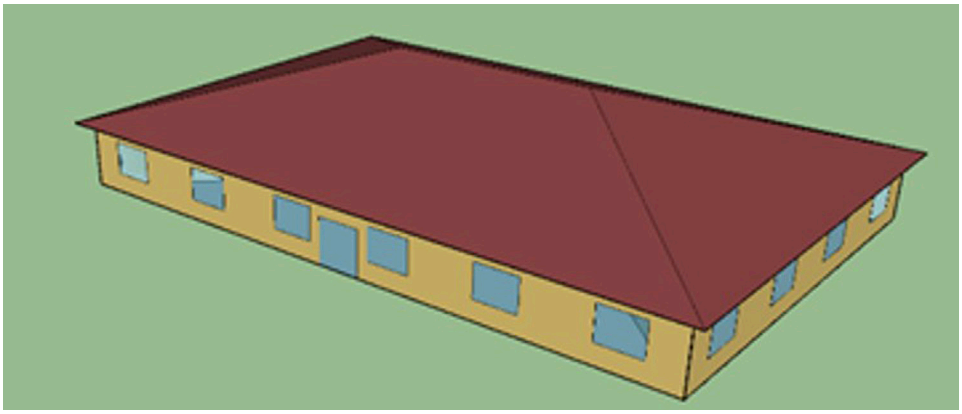

FIGURE 2
Small office building model in EnergyPlus used in this analysis.

TABLE 2 Key inputs and outputs for the calculations.

	Phoenix, Arizona, United States		Cairo, Egypt	
Inputs		Ref.		Ref.
Cost of Electricity	\$0.1177/kWh	(Electric power monthly - U.S. Energy information administration, 2024) (3/24, commercial customers)	E£1.36/kWh (\$0.0283/kWh)	Electricity prices increased (2024)
Grid Carbon Intensity	3.52×10^{-4} tonnes CO_2/kWh	(O. US EPA, 2024)	4.01×10^{-4} tonnes CO_2/kWh	(Egypt - countries and regions, 2024)
Discount Rate	5.33%	(Federal funds effective rate, 2024) (6/24)	27.75%	(Discount rates historical data, 2024) (6/3/24)
GDP per Capita	\$76,330	(World Bank open data, 2024)	E£90,097 (\$1,877)	(World Bank open data, 2024)
Social Cost of Carbon	\$62 or \$185/tonne CO_2	(Notice of availability and request, 2024), (Rennert et al., 2022)	E£1.29/tonne CO_2 (\$62/tonne CO_2)	(Notice of availability and request, 2024)
Exchange Rate	—		E£48 = \$1	Google (6/30/24)
Lifetime, *n* (years)	11	(Updated buildings sector appliance and equipment costs and efficiency, 2024)	11	(Updated buildings sector appliance and equipment costs and efficiency, 2024)
Outputs				
Total AC Capacity After Rounding Up (RT)	12.5		9	
Annual Cooling Energy (kWh_c/yr)	50,109		26,101	
Annual Electricity Required for Cooling (kWh/yr)	12,213		6,361	

Equation 5 to compute the Productivity Gain. We assume the building is located in either Phoenix, Arizona, United States, or in Cairo, Egypt, and input the corresponding weather and design day files accordingly.

Figure 2 shows the small office building assumed in this analysis. It is a one-story building with a total area of 511 m^2 (5,502 ft^2), with a total of 5 cooling zones (the core and 5 perimeter zones). This is a wood-framed building with an attic roof, and a window-to-wall ratio of 21.2%. Interested readers are encouraged to consult (Commercial reference buildings, 2024) for all details regarding the building construction.

EnergyPlus readily calculates the annual electricity required for cooling, E_t, and to calculate C_t we apply the definition of the *SEER* value:

$$SEER = \frac{\text{Cooling Output (Btu)}}{\text{Electricity Consumed (Wh)}} = \frac{C_t}{E_t} \tag{6}$$

which after appropriate unit conversions enables us to calculate C_t in kWh_c/yr. EnergyPlus also determines the cooling capacity required for each zone, which we round up to standard sizes to calculate the installed AC cost.

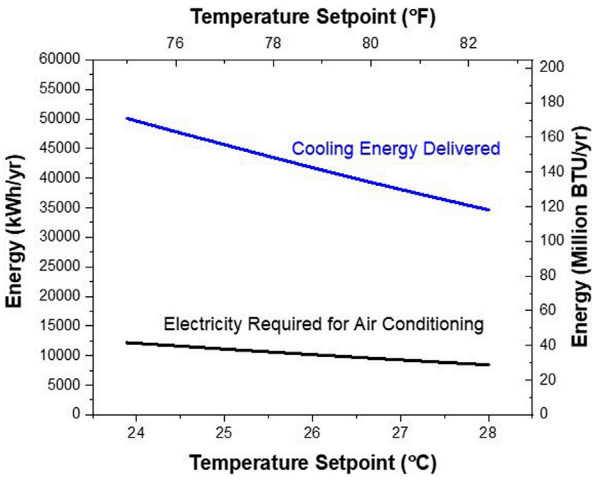

FIGURE 3
Annual electricity required for cooling, and cooling energy delivered, for a small office building in Phoenix, Arizona, United States

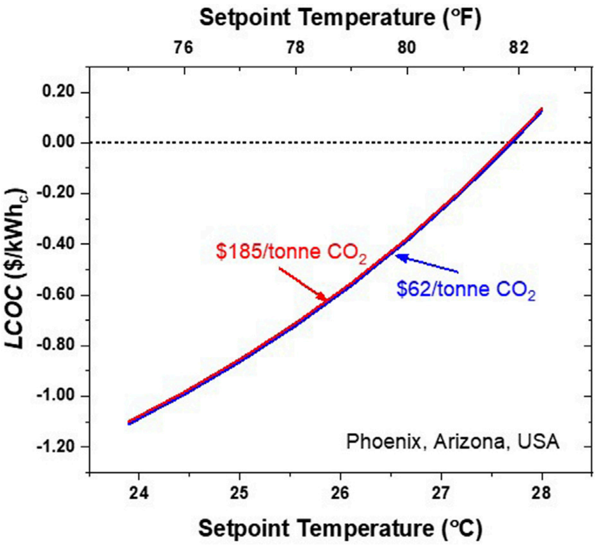

FIGURE 4
Levelized Cost of Cooling (*LCOC*) for a small office building in Phoenix, AZ as a function of temperature setpoint and the cost of carbon.

The small office building shown in Figure 2 is assumed to have occupancy Monday–Friday such that the thermostat is maintained at the desired setpoint, T_{set}, from 6:00 a.m. to 6:00 PM. At all other times thermostat setback is assumed such that T_{set} = 29.44°C (85.0°F), including weekends.

3 Results and discussion

As discussed above, simulations were carried out for a small office building located in either Phoenix, Arizona, United States, or in Cairo, Egypt. Some key inputs and outputs from the simulations for both locations are presented in Table 2, where the outputs were computed in EnergyPlus/OpenStudio. Note that it is necessary to carry out the calculations in local currency because of the nonlinear nature of Equation 2.

3.1 *LCOC* for an office building in Phoenix, Arizona, United States

An example of the EnergyPlus/OpenStudio simulation is provided in Figure 3 for the small office building located in Phoenix, Arizona, United States. The temperature setpoint T_{set} was varied between 23.89°C and 28.00°C (75.0°F–82.4°F), in increments of 1°F (0.56°C), and the annual electricity required for cooling the building E_t and the associated annual cooling energy delivered C_t were calculated for each setpoint. As expected, with increasing T_{set} both E_t and C_t decreased, with the ratio between the two fixed by $SEER = 14.0$ (Equation 6).

The levelized cost of cooling *LCOC* is presented in Figure 4 for the same building in Phoenix, Arizona, United States. Two curves for *LCOC* are presented: one for a social cost of carbon of $62/tonne CO$_2$, and another much higher cost of $185/tonne CO$_2$ as has been recently suggested (Rennert et al., 2022). Clearly, the social cost of carbon does not make much difference here, as those costs are overwhelmed by the increase in productivity predicted by Equation 5. For example, the net present value (*NPV*) of the total expenses (Equation 3) for T_{set} = 23.89°C (75.0°F) is $39,507, while the *NPV* of the total benefits Equation 4, with no health benefits taken into account) is $493,945! The expenses, by the way, include the purchase of the AC units. These results strongly suggest that any energy efficiency strategy which raises T_{set} above an optimal temperature is likely to lead to substantial productivity losses that will significantly outweigh any energy cost savings, even when the cost of CO$_2$ is taken into account. Note that this finding holds true for an office environment (i.e., a commercial building) as has been reported elsewhere (Shi et al., 2024), but at this time we are not able to conclude if the same holds true for an industrial (i.e., manufacturing) environment. We therefore leave that analysis for future work.

The negative values of *LCOC* for $T_{set} < 27.7$°C (81.9°F) indicate that the business is actually making money by keeping the temperature below 27.7°C, and losing money once T_{set} is increased above that point. This precise value of T_{set}, however, should be treated with caution since we arbitrarily assigned T_{max} = 28.0°C (82.4°F) as the maximum temperature condition where zero productivity benefits would be realized. Still, the lesson appears to be clear: any increases in indoor temperature above the comfortable range should be treated with caution. Similarly, although it is not treated by our analysis, reducing T_{set} below the comfortable range will also have negative impacts on productivity, as will lack of consideration for gender, cultural, and other differences.

3.2 *LCOC* for an office building in Cairo, Egypt

It is clear from Figure 4 that productivity gains can be much larger than energy and CO$_2$ costs, yet how much of that is because

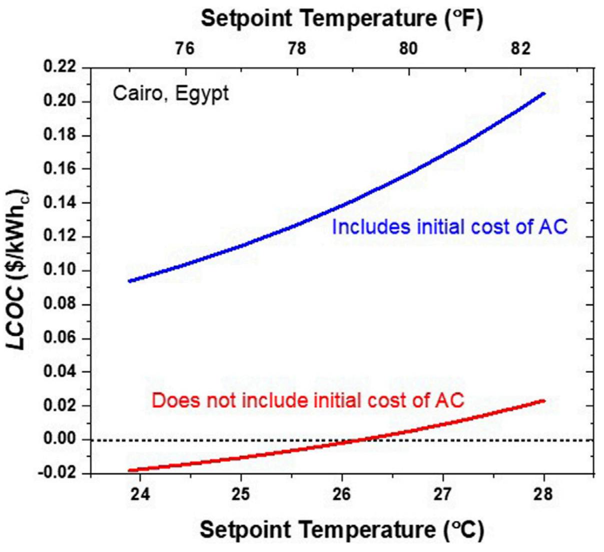

FIGURE 5
Levelized Cost of Cooling (*LCOC*) for a small office building in Cairo, Egypt, for a cost of carbon of \$62/tonne.

the *GDP per capita* in the United States is relatively large? We therefore conducted the same simulation, for the same building, but positioned in Cairo, Egypt. One of the key differences between the United States and Egypt, of course, is the *per capita GDP* (\$76,330 in the United States vs. \$1,877 in Egypt), as well as the cost of electricity (\$0.1177/kWh in Arizona vs. E£1.36/kWh or \$0.0283/kWh in Cairo) and the discount rate *i* (5.33% in the United States vs. 27.8% in Egypt). Note that the *LCOC* is not overly sensitive to *i*, since *i* appears in both the numerator and the denominator (Equation 2). But, in general as *i* increases the *LCOC* increases, albeit to a much greater extent in Egypt compared to the United States. For example, increasing *i* from 5.33% to 8.0% in the United States increased *LCOC* by less than 1%, whereas increasing *i* from 27.75% to 30.0% in Egypt increased *LCOC* by 8%.

Figure 5 shows two curves for the *LCOC* in Egypt: one in which the initial capital cost of the AC system is included, and the other where that initial capital cost is not included. We did this because the initial capital cost represents a large fraction of the *NPV* of the expenses, but it must be noted that we assumed the same AC capital cost in Egypt as we did for the United States. For T_{set} = 23.89°C (75.0°F), including those initial capital costs leads to expenses *NPV* = E£880,366, but neglecting those initial capital costs yields expenses *NPV* = E£115,726. Similar to the results in Figure 4 for Phoenix, Arizona, United States, the impact we're trying to observe is the net benefits/costs of maintaining the indoor temperature at a comfortable level. If the AC system is already in place then the initial AC costs are not relevant anyway, only the energy, O&M, and CO_2 costs. The lower curve in Figure 5 (where initial costs are neglected) suggests the break-even point in *LCOC* occurs around *Tset* = 26.2°C (79.2°F), but again this precise value is relatively uncertain. What appears to be certain is that, just like the building in the United States, it is advantageous to maintain a comfortable temperature inside an office building in Egypt, regardless of the expense of operating the AC. We reach this conclusion even without explicitly considering the detrimental health impacts of elevated temperatures, as discussed next.

3.3 Impact of elevated temperatures on health

Understanding the impact of high temperatures in outdoor and indoor environments is gaining attention from different scientific lenses such as healthcare, engineering, and environmental sciences. The rising concern of its impact is undeniable as recent severe temperature changes are manifested in life-changing experiences that present an unprecedented financial and economic burden both at the individual level and society at large. One may expect that these temperature changes and their associated costs will only increase in the future unless effective interventions are adopted.

As shown in Figure 6, there are three pathways to examine high temperatures impact: through health, occupational safety, and productivity (Morrissey et al., 2021). While these three pathways are interconnected, the intensity and trajectory of the overall impact, however, may differ depending on other confounding factors present (Vaidyanathan et al., 2024). These factors include the socio-economic characteristics of the individual, heat intensity, geographic location, acclimatization, and adaptive capacity, the latter being dependent heavily on availability of adaptation strategies such as adequate cooling infrastructure.

A review of findings from studies using meta-analysis of existing literature [e.g., (De Sario et al., 2023), (Wondmagegn et al., 2019)] suggest that health impact of high heat is manifested through the strain on either an individual's physical, physiological, psychological (mental health), or overall general health. The direct healthcare cost includes medical treatment, excess emergency department visits, excess hospital admissions, increased ambulance call outs, and mortality. In addition, when an individual experiences cognitive impairment, occupational safety is compromised. It could potentially lead to injuries, which could be monetized by increased occupational injury claims. Health deterioration and occupational injuries consequently result in a marginal cost in productivity changes through increased absenteeism, presenteeism, and potential labor supply-related issues due to heat-related workforce reductions.

Whether the topic of interest is specific to indoor or outdoor environment, according to a report published by the World Health Organization, "outside of regions where air conditioning is common, high indoor temperatures are associated with high outdoor temperatures. Studies of morbidity and mortality rates during periods of high outdoor temperatures can also be used to provide indirect evidence of the harmful health effects of high indoor temperatures in such regions" (WHO Housing and health guidelines, 2024).

Although not specifically measured for high indoor temperatures, a study by Yang estimated that for every 1°C increase above 29°C leads to about 3% more adult hospitalization (Yang et al., 2021). In the case of British Columbia, it was estimated that 30% of heat-stress claims in 2021 (when a heat wave was experienced) were primarily from workers who worked indoors compared to only 20% of indoor industry claims on average in 2020

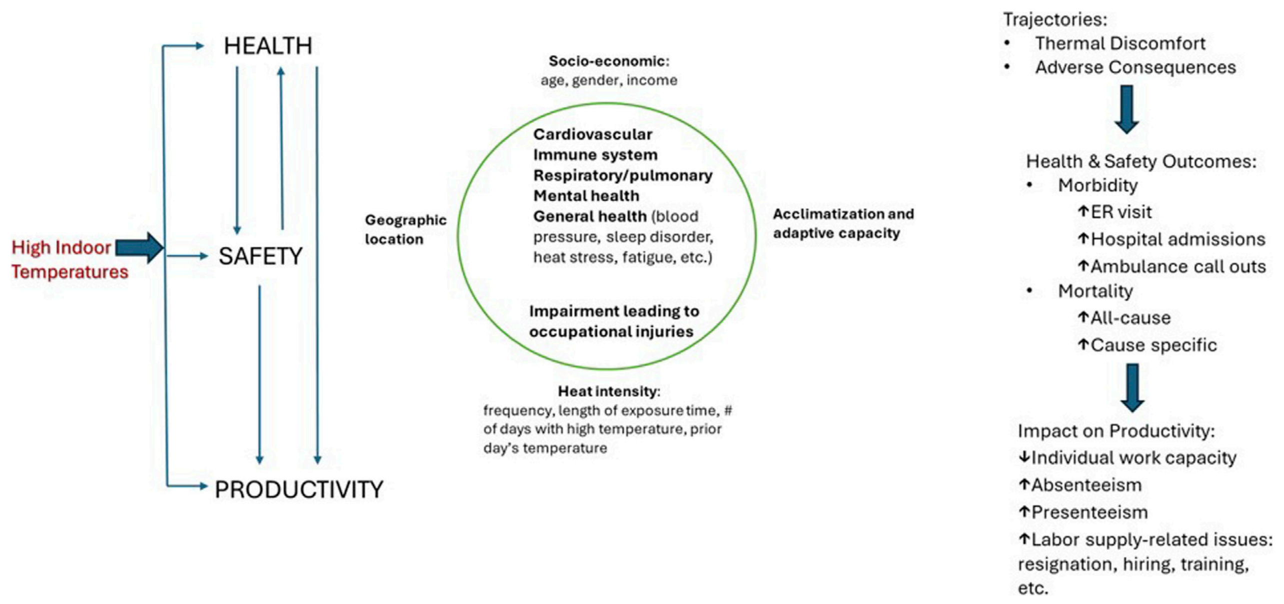

FIGURE 6
Relation of high indoor temperatures to health, occupational safety, and productivity.

(The case for adapting to extreme heat: costs of the 2021 BC heat wave, 2024).

These estimates only imply that the combined cost of high temperatures is substantial and not to be ignored. Studies isolating the high heat-specific cause impact in indoor work environments remain sparse. Extensive occupational research and monetization of the impact of high indoor temperatures, particularly in an office setting, is warranted. Most importantly, comparative studies that show variations in cost by controlling various confounding factors would be helpful in identifying and adopting appropriate mitigating strategies.

4 Conclusion

Air conditioning (AC) has benefits beyond simply human thermal comfort. Based upon previous literature, the impact of maintaining optimal dry-bulb temperature conditions (~75°F or 23.9°C) is profound, resulting in ~1% reduction in productivity for every 1°C increase above this optimum. Therefore, the impulse to increase thermostat setpoints above the optimum to reduce energy consumption and costs is misplaced. A levelized cost of cooling (*LCOC*) analysis for an office building in Phoenix, Arizona, suggests that in the United States, reductions in productivity far outweigh any cost savings from increased air conditioning energy consumption as the AC setpoint is increased, even when the social costs of CO_2 are taken into account. A similar analysis of the same office building in Cairo, Egypt presents the same trend, although the lower electricity cost and lower economic output per worker there relative to the United States reduces the impact. Future analysis will also include the impact of AC setpoint temperatures on health, which will only exacerbate the trends observed here. It is clear that establishing and maintaining optimal comfort conditions inside commercial buildings, whether through air conditioning, improved building design and construction, or a combination of both, has to be a priority for economic output even at the expense of additional energy consumption and associated greenhouse gas emissions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PP: Conceptualization, Formal Analysis, Methodology, Supervision, Writing–original draft, Writing–review and editing. BP: Conceptualization, Methodology, Writing–original draft, Writing–review and editing. AS: Formal Analysis, Writing–review and editing.

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Conflict of interest

Author BP was employed by Phelan International LLC.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Nomenclature

$\mathit{Benefits}_t$	Annual benefits derived from air conditioning in year *t* ($)
C_t	Cooling energy provided in year *t* (kWh$_c$)
$\mathit{Expenses}_t$	Annual costs derived from air conditioning in year *t* ($)
i	Discount rate (%)
LCOC	Levelized cost of cooling ($/kWh$_c$)
n	Air conditioning equipment lifetime (years)
NPV	Net Present Value ($)
SEER	Seasonable Energy Efficiency Ratio (BTU Wh^{-1})
t	Year
T_{set}	Air conditioning dry-bulb temperature setpoint (°C)
T_{max}	Maximum air conditioning dry-bulb temperature setpoint (°C)