CLIMATE CHANGE IMPACTS ON OFFICE BUILDINGS PERFORMANCE: A CASE STUDY OF PHILADELPHIA, USA

Abstract

Global warming and its impact on human activity, especially in buildings, has become a major concern in recent years. To study the impact of climate change on the built environment, the use of building simulation techniques together with forecast weather data are necessary. However, current building designs are dependent on reference year databases that are a representative of past weather observations and are not appropriate for modeling future weather conditions. In addition, the changing climate complicates building energy consumption projections. Therefore, it is necessary to develop analytical methods to model building performance under future climate scenarios. This study evaluates the energy performance of three vintages of large, medium, and small Department of Energy (DOE) reference office buildings under current and future weather conditions for Philadelphia. The Intergovernmental Panel on Climate Change (IPCC) fourth assessment report climate scenarios are used, and the results are compared to typical weather data. The impacts of climate change on energy consumption are presented, and potential mitigation strategies are discussed. The practical outcome of this investigation is not only to provide guidance for the development of standards addressing new building design, but also to promote improved adaptation and mitigation strategies in the current building stock.

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Keywords

Global warming, building energy performance, mitigation strategies

Introduction

The importance of minimizing energy consumption in buildings is well understood. However, the climate is changing and this would exacerbate the probability that energy consumed by a building exceeds its original design. Many simulation tools exist to analyze building energy performance and they depend on input data such as weather files (Fiocchi et al., 2014). Using average historical weather data, known as Typical Meteorological Year (TMY), is a commonly used method in building energy assessment tools. However, the TMY weather data does not represent future weather conditions and given the current trend of global warming, the use of typical weather files might not be appropriate. Therefore, the development of typical weather data that would consider future climate changes for building energy assessment is necessary.

A common way of producing future weather data is the use of synthetic future weather generators that apply possible future climate scenarios (Herrera et al., 2017). Scenarios are used to better understand the future climate and its uncertainties. The Intergovernmental Panel on Climate Change (IPCC) presents several climate scenarios based on carbon dioxide emissions to assess future climate research (IPCC, 2014). This study evaluates the energy performance of three vintages of large, medium, and small Department of Energy (DOE) reference office buildings under current and future weather conditions for Philadelphia. The weather generator Meteonorm was used to generate future TMY files for Philadelphia under three emission scenarios (B1-low emissions, A1B-mid emissions, A2-second highest emissions) from the 2007 IPCC fourth assessment report for nine future time slices (from 2020 to 2100). Meteonorm integrates a climate database, a spatial interpolation tool, and a stochastic weather generator. The output of the software contains essential weather parameters for building energy purposes. Figure 1 shows the historical annual average air temperature from 1880 to 2018 and trends of the different future scenarios, projected to 2100 for Philadelphia.

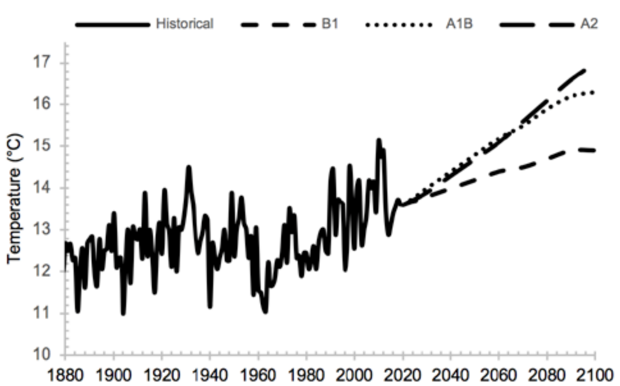

Figure 1: Annual mean temperatures for different scenarios.

The DOE developed 256 EnergyPlus models across 16 cities that covers 70% of the US commercial building stock (Field et al., 2010). EnergyPlus was used for the whole building energy simulation. EnergyPlus requires weather files and design days as input for the location where the building is being considered. Design days are required for the proper sizing of the HVAC systems and are based on annual percentiles of 0.4% for warm seasons to design cooling equipment and 99.6% for cold seasons to design heating equipment. EnergyPlus uses design day runs for sizing the equipment in the building for each location with a sizing factor of 1.2. These data allow the designer to consider various operational peak conditions (ASHRAE, 2014). The future weather files generated by the Meteonorm software are directly used in EnergyPlus as the EnergyPlus Weather (EPW) format. Four scenarios are used to comprehensively assess the impact of climate change on the building stock under different climate conditions (scenarios B1, A1B and A2, and base case). The scenarios are projected in three time periods: 2040, 2070, and 2100. The model is run for all office building types and vintages and results are compared. A sensitivity analysis is then conducted to understand the most important factors influencing energy consumption.

Summary of Input Data

The DOE divided office buildings into small, medium, and large based on the number of floors and total area which have typical floors (Figure 2). The typical floor consists of a core zone in the middle surrounded by four perimeter zones which define the thermal zones for each floor. The office reference building parameters such as floor area, floor-to-floor height (F-F) and floor-to-ceiling height (F-C) are listed in Table 1.

Type	Area (m^2)	No. floors	F-F (m)	F-C (m)
Small	511	1	3.05	3.05
Medium	4982	3	3.96	2.74
Large	46320	12+(basement)	3.96	2.74

Table 1: Reference building parameters.

For clarification of the different building categories, the word "type" is used for the three different building sizes (small, medium, and large); "period" is used for the different time slices (base, 2040, 2070, and 2100); "vintage" is used for the period of construction (new construction, post-1980, and pre-1980); and "scenario" is used for the three different emission scenarios used in the model (B1, A1B, and A2).

To develop a complete energy model for a building, it is necessary to consider floor area, plug loads, ventilation requirements, occupancy, schedules, windows fraction and orientation, fabric materials, infiltration rate, lighting density, HVAC system types, and control settings (Field et al., 2010). Below, a brief summary is given of the data used in the office buildings.

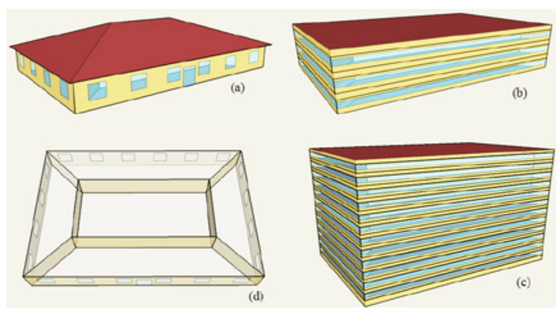

Figure 2: DOE office reference building benchmark.
A) Small office building. B) Medium office building. C) Large office building. D) Typical floor for all office buildings.

OCCUPANCY

Properly defining building occupancy and occupancy schedule is of great importance because many factors, such as HVAC utilization, plug loads, lighting, and ventilation requirements, depend on the occupancy schedule and density. The occupancy density for all office buildings is defined as 18.58 m²/ person. While the schedule is constant for the different periods for each building type, the schedules do differ depending on the size of the building.

VENTILATION

The amount of ventilation required varies depending on the purpose of the building and the type of activity occupants have within a space. For office buildings, the outside air requirement is set based on ASHRAE (1999) standard and is equal to 9.44 L/s/person. As such, for an occupancy density of 18.59 m²/person, the total outdoor air requirement would be 0.51 L/s/m².

FABRIC

Proper fabric selection of a building can provide considerable reduction in HVAC equipment sizing and maximize energy benefits. Table 2 shows the material construction used in walls and roofs for the reference office buildings. IEAD refers to Insulation Entirely Above Deck (Deru et al., 2011).

	Roof Construction			Wall Construction		
	New	Post	Pre	New	Post	Pre
Small	Attic	Attic	IEAD	Mass	Mass	Steel
Medium	IEAD	IEAD	IEAD	Steel	Steel	Steel
Large	IEAD	IEAD	IEAD	Mass	Mass	Mass

Table 2: Wall and roof construction.

The construction of the foundation for all types of buildings is a 101mm (4-inch) slab with an R-value of 0.54 m²K/W and partitions (if used) are steel frame with gypsum board. Table 3 shows the total wall and roof R-value (m²K/W) of the exterior fabric and total U-value (W/m²K) of the fenestration material used in all office buildings. In addition, the solar heat gain coefficient is 0.39 and 0.36 for new and post-constructed office buildings, respectively, and 0.54 for pre-constructed buildings.

	New			Post			Pre		
	L	M	S	L	M	S	L	M	S
Wall	1.2	1.4	1.2	1.5	2.0	1.5	1.0	1.0	1.0
Roof	2.8	2.8	5.2	3.0	3.0	3.0	2.0	2.0	2.0
Window	3.2	3.2	3.2	3.4	3.4	3.4	5.8	5.8	5.8

Table 3: R-values of wall and roof and U-value of windows.

Note that all building types of pre-1980 vintage have the same parameters. Table 4 shows the total area of walls, roof, fenestration and partitions.

	Small	Med	Large
Wall	281.5	1,978	11,590
Roof	598.8	1,661	3,563
South window	16.7	195.9	1,391
East window	11.2	130.6	927
North window	16.7	195.9	1,391
West window	11.2	130.6	927
Total window area	55.8	652.8	4,636
Partitions	0	1,424	8,524

Table 4: Total area of all sections of the building in m².

INFILTRATION

Due to lack of knowledge regarding the size and distribution of building cracks, the DOE uses a simple method of calculation to determine the infiltration rate inside the reference buildings. The infiltration is modeled as 0.36 air changes per hour (ACH) for core zones and 1 ACH for attics for all office buildings. Building perimeter infiltration is modeled as 0.059 cfm/ft² for new construction buildings and 0.223 cfm/ft² for post-1980 and pre-1980 office buildings (Field et al., 2010).

LIGHTING AND PLUG LOAD

Exterior lighting in the office building stock is included in the facade which operates from dusk until dawn. For new construction, the exterior Lighting Power Density (LPD) is set to 2.15 W/m² and for pre- and post-1980 stock, exterior LPD is 2.69 W/m² based on ASHRAE Standard 90.1-2004. The interior LPD differs for the new construction and pre- and post-1980 models. Table 5 provides details regarding the LPD, basement LPD (BLPD) and the Plug Load Density (PLD) of the office buildings in watts per square meter.

	New	Post			Pre		
W/m²	All	L	M	S	L	M	S
LPD	10.8	16.2	16.9	19.5	16.2	16.9	19.5
BLPD	10.8	7.5	16.9	19.5	7.5	16.9	19.5
PLD	10.8	10.8	10.8	10.8	10.8	10.8	8.1

Table 5: LPD and PLD of the office building stock.

Note that the LPD of the building is identical for all types of new construction at 10.8 W/m² and for post-1980 and pre-1980 vintages, the LPD is identical for all three building types.

HVAC

Table 6 shows a summary of the system equipment types for heating system and cooling systems while Table 7 shows their efficiency. The HVAC equipment type includes Single-Zone Constant Air Volume (SZ-CAV) and Multi-Zone Variable Air Volume (MZ-VAV). The heating systems are either gas boiler (B), gas furnace (F) or gas furnace with electric preheat (FR). Three different cooling systems are used: two-water cooled chillers (CH), Packaged-Air Conditioning Unit (PACU), and Direct Expansion (DX) cooling systems. Large office buildings use reheat VAV systems.

	New & Post			Pre		
	L	M	S	L	M	S
System	MZ-VAV	MZ-VAV	SZ-CAV	MZ-VAV	SZ-CAV	SZ-CAV
Heating	B	FR	F	B	F	F
Cooling	CH	PACU	DX	CH	PACU	DX

Table 6: HVAC equipment used in office buildings.

	New			Post			Pre		
	L	M	S	L	M	S	L	M	S
COP	5.5	3.2	3.7	5.2	2.8	3.1	5.1	3.5	3.4
(%)	78	80	80	70	80	80	76	78	78

Table 7: Heating (%) and cooling (COP) efficiency.

SCHEDULES

The lighting and equipment schedules are the same for all large and medium office buildings, regardless of their vintage. Small office buildings have measurable differences compared to large- and medium-size offices.

Results

In total, nine types of buildings were modeled using three future scenarios for three time slices and one base scenario. This is a total of 90 simulations for Philadelphia. EnergyPlus reports the energy consumption as source energy and site energy. Source energy is the total energy production minus losses in transmission and delivery. Site energy is the amount of energy consumed by the building as reflected in the utility bill. In this study, we focus on the site energy consumption since the objective is to understand how the energy consumption in office buildings will change over different climate scenarios. The energy sources in Philadelphia for office buildings are natural gas and electricity. As a result, the site energy consumption for heating and cooling are reported separately due to the difference in exergy of the energy sources. Electricity has higher energy than natural gas. To compare heating and cooling, a site-to-source conversion factor is required (Wang & Chen, 2014). Below are the results of the site energy consumption for large, medium, and small offices (Figure 3).

As it can be seen from Figure 3, pre-1980 buildings have higher heating and cooling consumption compared to new construction and post-1980 for all scenarios and periods for large and small office buildings. This changes for medium-size office buildings, where for heating, the post-1980 vintage shows higher heating consumption compared to pre-1980 buildings, which is in contrast to other types and vintages. The most likely reason behind the higher heating consumption (for medium-size post-1980 buildings) is the use of a mixed natural gas-electricity heating system. For cooling, as shown in Figure 3, the post-1980 and pre-1980 show a similar change in energy consumption for different scenarios and periods. Nevertheless, new construction shows lower heating and cooling consumption compared to the post-1980 and pre-1980 for all building types and climate scenarios.

For all building vintages and types, the base case climate scenario has the highest heating consumption and lowest cooling energy consumption which is accordance with climate change trends. In addition, for all building vintages and types, the changes in energy consumption for different emission scenarios for the 2040 period does not vary significantly. However, by shifting to the later time periods (2070 and 2100), the changes become more apparent. The reason for this is the inertia of GHG concentration, so the impact of climate change for each scenario becomes more significant after 2040. For each scenario and period, cooling and heating consumption of small office buildings show higher sensitivity to different vintages compared to medium and large office buildings. Table 8 is a summary of the heating and cooling energy consumption of the A2-2100 scenario for all building types and vintages.

	New		Post		Pre	
	Heat	Cool	Heat	Cool	Heat	Cool
L	2085	3045	3392	3614	5328	4321
M	318	556	457	706	311	687
S	26	34	38	51	99	72

Table 8: Heating and cooling energy consumption (MJ) for the A2-2100 scenario.

For the A2-2100 scenario and time period, new construction shows 110% less energy consumption compared to pre-1980 buildings for cooling, and 277% less energy consumption for heating. In addition, for this scenario, new large office buildings show a reduction of 41.8% in cooling and a 155% in heating compared to pre-1980 large office buildings. For small office buildings, new buildings show a 27% reduction in cooling and 43.6% reduction in heating compared to post-1980 medium office buildings. Note that for large and small building types, pre-1980 vintages have the highest heating and cooling energy consumption and for medium office types, the post-1980 vintage has the highest heating and cooling energy demand. Therefore, small office buildings have the highest variation in energy consumption and medium office buildings have the smallest variation between different vintages of their category. This is mainly because small office buildings have faced more changes between building vintages in factors influencing the energy performance of the building. A summary of the heating and cooling energy use intensity for large office (Table 9), medium office (Table 11), and small office (Table 10) is given below for all scenarios and vintages. Based on these results, a comparison between the base case and the worst case (A2-2100) is made for all building types and vintages. The highest heating intensity (dark shade), lowest heating intensity (light shade), highest cooling intensity (ellipsoid), and lowest cooling intensity (circle) are differentiated in the tables by shapes.

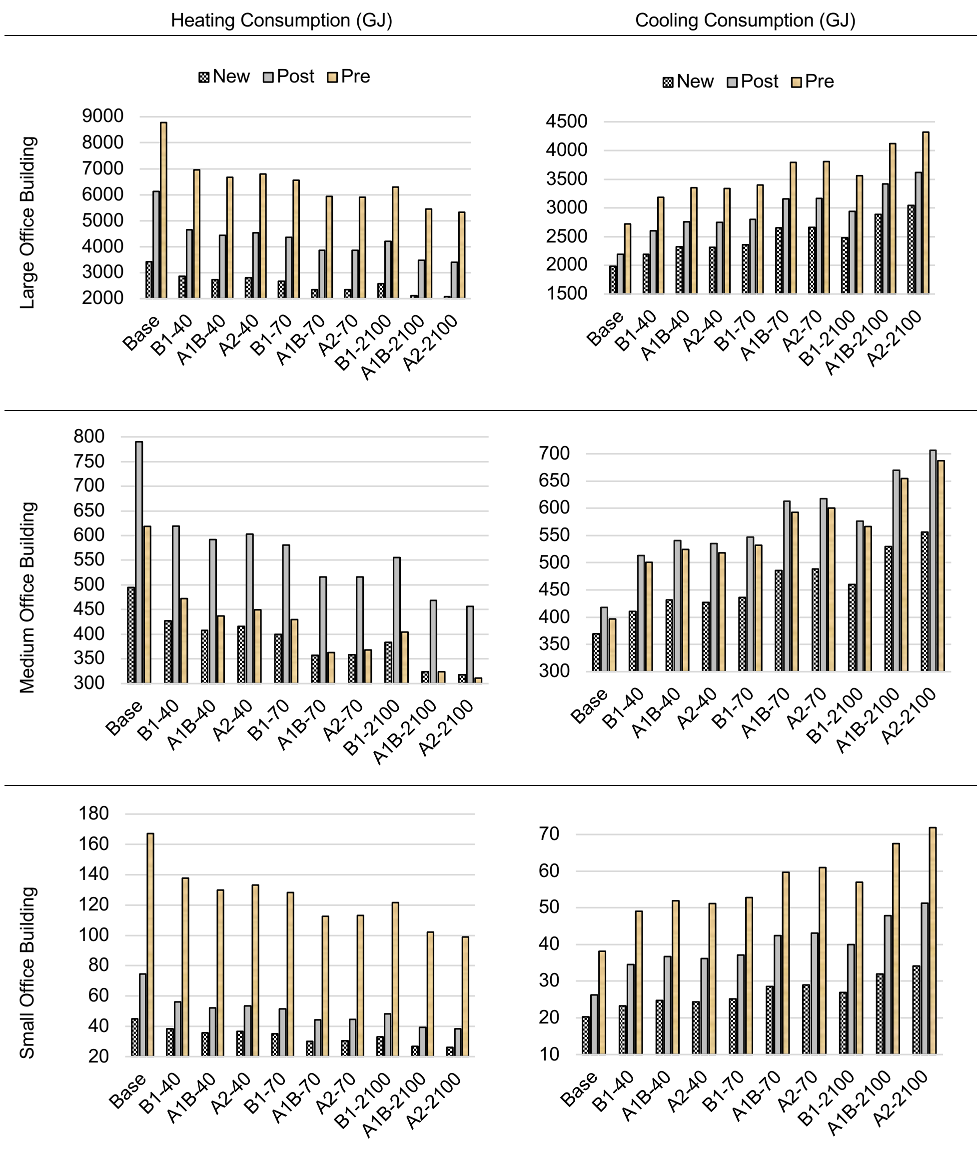

Figure 3: Office building heating and cooling energy consumption.

From Tables 9, 10, and 11, by 2100, for new vintages, large office buildings show a 28.84 MJ/m² heating intensity decrease and a 22.9 MJ/m² cooling intensity increase. Medium office buildings show a 35.5 MJ/m² heating intensity decrease and a 37.43 MJ/m² cooling intensity increase. And small office buildings show a 36.77 MJ/m² heating intensity decrease and a 27.1 MJ/m² cooling intensity increase.

For post-1980 vintages, large office buildings have a 59 MJ/m² decrease in heating intensity and a 30.61 MJ/m² increase in cooling intensity. Medium office buildings have a 66.86 MJ/m² decrease in heating intensity and a 57.86 MJ/m² increase in cooling intensity. And small office buildings show a 70.84 MJ/m² decrease in heating intensity and a 48.86 MJ/m² increase in cooling intensity.

For pre-1980 vintages, large office buildings show a 74.49MJ/m² decrease in heating intensity and a 34.54 MJ/m² increase in cooling intensity. Medium office buildings show a 61.68 MJ/m² decrease in heating intensity and a 58.32 MJ/m² increase in cooling intensity. And small office buildings show a 133.54 MJ/m² decrease in heating intensity and a 65.97 MJ/m² intensity increase in heating.

The net energy consumption for heating and cooling cannot be extracted from the values given because these values show the site energy consumption and are intended to report the energy use of the selected buildings. Table 12 shows the energy consumption changes in percentage for all buildings by 2100 reflecting the A2 emission scenario. As mentioned before, new buildings have the lowest heating and cooling consumption compared to other vintages. In addition, the new buildings, for all types, have the lowest changes in consumption by 2100 except for small buildings heating consumption which is 1% higher than the pre-1980 building vintage. This reveals that new construction has a lower energy consumption and are likely more resilient toward climate change compared to other vintages.

	Large Office Building					
	New		Post		Pre	
	Heat	Cool	Heat	Cool	Heat	Cool
Base	74	43	132	47	190	59
B1-40	62	47	101	56	150	69
A1B-40	59	50	96	60	144	72
A2-40	60	50	98	59	147	72
B1-70	57	51	94	61	142	73
A1B-70	51	57	83	68	128	82
A2-70	51	57	83	68	127	82
B1-2100	55	53	91	63	136	77
A1B-2100	46	62	75	74	118	89
A2-2100	45	66	73	78	115	93

Table 9: Summary of the heating and cooling energy use intensity (MJ/m²) of a large office building.

	Medium Office Building					
	New		Post		Pre	
	Heat	Cool	Heat	Cool	Heat	Cool
Base	99	74	159	84	124	80
B1-40	86	82	124	103	95	101
A1B-40	82	87	119	109	88	105
A2-40	83	86	121	107	90	104
B1-70	80	88	117	110	86	107
A1B-70	72	98	104	123	73	119
A2-70	72	98	104	124	74	121
B1-2100	77	92	111	116	81	114
A1B-2100	65	106	94	134	65	131
A2-2100	64	112	92	142	62	138

Table 10: Summary of the heating and cooling energy use intensity (MJ/m²) of a medium office building.

	Small Office Building					
	New		Post-1980		Pre-1980	
	Heat	Cool	Heat	Cool	Heat	Cool
Base	88	40	146	51	327	75
B1-40	75	46	110	68	270	96
A1B-40	70	49	102	72	254	102
A2-40	71	48	105	71	261	100
B1-70	68	49	101	73	251	103
A1B-70	59	56	87	83	220	117
A2-70	60	57	87	85	221	119
B1-2100	65	53	94	78	238	112
A1B-2100	53	63	77	94	200	132
A2-2100	51	67	75	100	194	141

Table 11: Summary of the heating and cooling energy use intensity (MJ/m²) of a small office building.

	New		Post-1980		Pre-1980	
	Heat	Cool	Heat	Cool	Heat	Cool
L	-39.0	53.4	-44.6	64.6	-39.3	58.8
M	-35.7	50.4	-42.2	68.9	-49.7	73.2
S	-41.8	68.2	-48.7	95.0	-40.8	88.3

Table 12: Energy consumption changes by 2100 in percentage.

SENSITIVITY ANALYSIS

The major factors that influence the building energy performance are LD, fabric R-value, window U-value, infiltration rate, COP of cooling equipment, and heating systems efficiency. However, boiler efficiency is independent of outdoor temperature, and improving the boiler's efficiency will result in a total heating consumption improvement but is unlikely to vary for future time periods. A sensitivity analysis is conducted to examine the impact of Lighting Density (LD), window U-value and infiltration rate of the buildings.

The values used in the new building vintages are applied to pre-1980 and post-1980 buildings for two scenarios, base and A2-2100 (most extreme) to better understand the effect of possible mitigation strategies on the existing building stock. The results are presented in Figure 8. An infiltration rate of 0.059 cfm/ft² was applied to the post-1980 and pre-1980 vintages which originally had an infiltration rate of 0.233 cfm/ft². This is a 277% decrease in infiltration rate. Although this value might seem far from reality, based on the DOE standards, new buildings must comply with this rate. A window U-factor of 3.24 W/m²K was applied to both post-1980 and pre-1980 buildings, which previously had 3.35 W/m²K and 5.84 W/m²K window U-factors, respectively. For interior LD, new buildings are designed with a lighting density of 10.76 W/m² and this value was used as the LD for the existing building stock. Table 13 summarizes the changes of LD in percentages.

	Post-1980			Pre-1980		
%	L	M	S	L	M	S
LD	-50	-57	-81	-50	-57	-81

Table 13: Summary of the changes in LD.

From Figure 4, reducing the window U-value decreases heating and cooling energy consumption for most of the building categories. Unsurprisingly, by modernizing the windows in the existing building stock to new building standards, significant reductions in energy consumption are expected. This impact is most notable for pre-1980 buildings compared to post-1980 vintages. In addition, large office building types show a sizable reduction in both heating and cooling requirements for the pre-1980 building vintage. However, window U-value reductions offer less improvements for the extreme scenarios compared to the base case. For instance, by replacing the windows with a higher performing U-factor in the large office building base case results in a 15.4% reduction in cooling requirements but only presents a 12.3% reduction for cooling purposes in the extreme climate scenario.

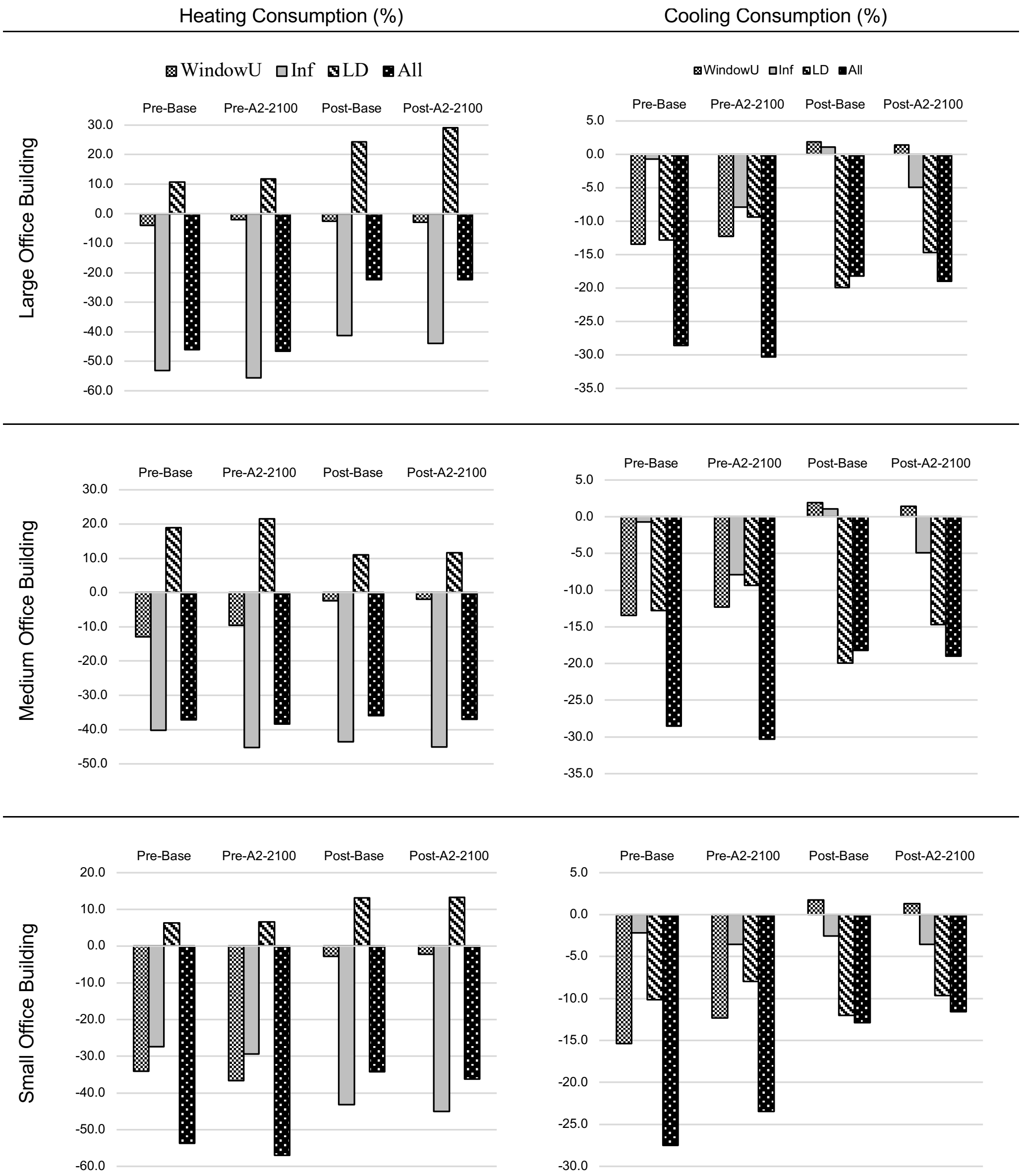

Figure 4: Percent change in energy consumption for the base case and A2-2100 scenario of the pre- and post-1980 building vintages with mitigation strategies.

Reducing the infiltration rate in the perimeter zones of all office buildings shows a reduction in both heating and cooling requirements and is most significant in reducing heating energy consumption. In contrast to the window U-value modernization strategy, the impact on heating and cooling energy consumption of a reduced infiltration rate increases for the extreme scenario compared to the base case for all existing office building stock. For instance, from Figure 8, heating requirements of the small office shows a 53% reduction in the base case and 55.6% reduction in the extreme scenario for pre-1980 buildings.

A reduction in the LD, as expected, increases the heating energy consumption and reduces the cooling energy requirements for all buildings. In addition, the reduction in cooling requirement is greater for the extreme scenario compared to the base case for all buildings.

A fourth strategy is also applied by taking all three factors (window U-value, infiltration rate, and LD) into consideration and is shown in Figure 4 as "All." From this figure, when considering all factors, complex behavior is observed. Even though a reduction in both heating and cooling requirements is observed for all buildings, when compared to each factor individually, the aggregate change is not summative. This suggests that applying all strategies at once might not be the best technique for all buildings. In general, applying all strategies shows a significant reduction in cooling requirements for all pre-1980 building types and scenarios. In addition, for large office buildings, a considerable reduction in both heating and cooling requirements for pre-1980 buildings is observed. For instance, a 57% reduction in heating and 23.5% reduction in cooling was calculated when applying all strategies to the extreme scenario of pre-1980 buildings. However, the impact decreases for heating requirements for most buildings compared to infiltration individually.

Conclusion

In this study, the impact of future weather scenarios on the DOE reference office buildings were examined under Philadelphia climate conditions. The IPCC SRES were used for the future scenarios, and weather files were created using the weather generator Meteonorm to assess building energy consumption. We found that new buildings perform better compared to existing buildings because they comply with contemporary energy standards that are more conservative. We applied the most extreme weather scenario (A2) on all buildings and found that new buildings show an increase in cooling requirements by 68.2% for small offices, 50.4% for medium offices, and 53.4% for large offices. They show a decrease in heating requirements by 41.8% for small offices, 35.7% for medium offices, and 39% for large offices when compared to the base weather scenario. In large and small building types, pre-1980 buildings have the highest heating and cooling energy consumption, and for medium office types, post-1980 buildings show the highest heating and cooling energy demand. Small office buildings have the highest variation in energy consumption, and medium office buildings have the smallest variation between different vintages. The major mitigating factors influencing the building energy consumption under climate change are found to be LD, window U-value (U), infiltration rate, fabric R-value, and COP of cooling equipment. A sensitivity analysis was conducted for the first three factors. Table 14 summarizes the first-best and the second-best mitigation strategy for all office buildings for the base case (B) and the extreme scenario (E) (A2-2100).

		Heating				Cooling			
		Pre-B	Pre-E	Post-B	Post-E	Pre-B	Pre-E	Post-B	Post-E
First	S	Inf	Inf	Inf	Inf	All	All	All	All
	M	Inf	Inf	Inf	Inf	All	All	LD	All
	L	All	All	Inf	Inf	All	All	All	All
Second	S	All	All	All	All	U	U	LD	LD
	M	U	U	Inf	Inf	U	U	All	LD
	L	U	U	All	All	U	U	LD	LD

Table 14: Summary of the first-best and second-best mitigation strategy for the office buildings.

We found that, in general, reducing LD increases heating requirements. Likewise, reducing infiltration rates reduces overall energy consumption for both heating and cooling but has a higher impact on decreasing heating requirements. We also found that applying all mitigation factors did not result in straightforward improvements/reductions in energy consumption, but rather the result was more complex and needs further study. This implies that in order to make a building resilient toward climate change, it is important to know the purpose of the building and a detailed sensitivity analysis of potential mitigation factors is necessary.

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