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Impacts of climate change on U.S. building energy use by using downscaled hourly future weather data

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ABSTRACT

With the growing concern of global climate change in the future, how building energy use pattern would change in response is of great interest and importance in drafting future building performance regulations and codes. In this paper, the outputs from global climate model (GCM) are integrated to typical meteorological year weather file to downscale and predict local hourly weather data in the context of U.S. climate regions using a "morphing" methodology. The "morphed" future hourly weather data is then used by EnergyPlus to predict future energy use pattern for residential building in the United States.

Case studies in four representative cities in the U.S. show that climate change is to have great impacts on residential and office building energy use during the year of 2040–2069. The change of annual energy use is predicted to range from −1.64% to 14.07% for residential building and from −3.27% to −0.12% for office building under A2 scenario (a carbon emission scenarios defined by IPCC) in different regions. The research results suggest that the climate change will narrow the gap of energy use for residential buildings located in cold and hot climate regions in the U.S. and generally reduce office building energy use in the future. It is also found that the energy use of lightings and fans will slightly decrease in the future. Moreover, the growing peak electricity load during cooling seasons is going to exert greater pressure for the future grid.

1. Introduction

With the growing concern that the earth is now undergoing accumulation of greenhouse gas (GHG), the problem of climate change is drawing attention from the academia world-widely. As shown in Fig. 1, the level of GHG in different scenarios projected by Intergovernmental Panel on Climate Change (IPCC) demonstrated dramatic rise in the coming future.

On the other hand, energy use in building is important considering its large proportion in U.S. total energy use. In the U.S., commercial and residential buildings consume about 40% of the primary energy [2]. Moreover, Commercial and residential buildings account for 15.3% of global GHG emissions, including 9.9% for commercial buildings and 5.4% for residential [3].

Several researches had been conducted on the impact of climate change on building energy use world widely. Xu et al. from Tongji University conducted a research together with Lawrence Berkeley National Laboratory (LBNL), studying the impacts of climate change on building heating and cooling energy patterns in California [4]. The results shows that cooling electricity usage will increase by about 25% and the aggregated energy use of all buildings including both heating and cooling will only increase slightly. In UK, Jenkins et al. conducted the research on the climatic factors affecting future UK office heating and cooling energy use [5], and found out that the warmer 2030 climates will increase the annual cooling energy uses by 2–4 kWh/m^2, and those southern office are facing more concern in their cooling energy growth. In Australia, Wang et al. evaluated the heating and cooling energy requirements and the corresponding carbon emissions of residential houses under different future climatic conditions [6]. It was found that the carbon emission of a 5-star house was projected to have an average increase of 30% in Darwin, 15% in Alice Springs and 19% in Sydney. Hassan Radhi evaluated the potential impact of climate change on the United Arab Emirates residential buildings regarding with CO_2 emissions [7]. In this research, the design of building envelope and fenestrations in the future is highlighted in combating the increase of and building energy use as well as CO_2 emission. Shen and Lukes estimated that the climate change will bring down the energy efficiency of GSHP system which has high energy efficiency in the present days for residential building applications in the U.S. by using TRNSYS and eQuest building energy modeling tool because the warmer ground in the future will cause an average rise of about 2–3 °C in the inlet

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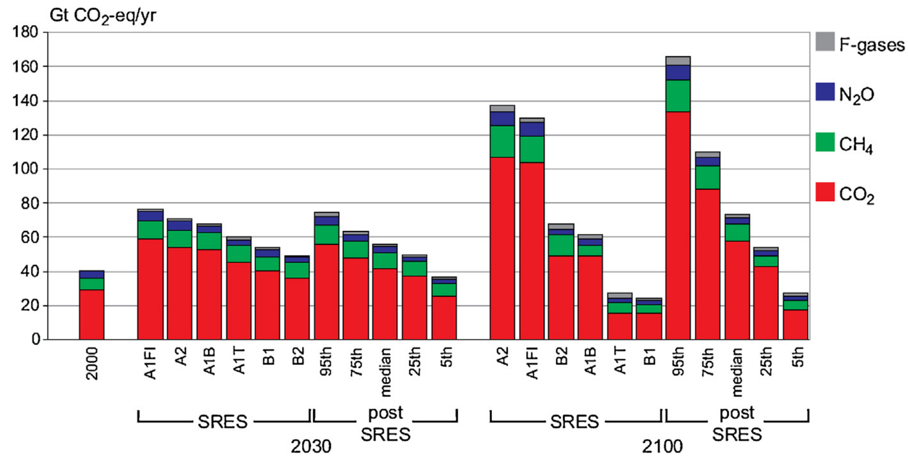

Fig. 1. Global GHG emissions for 2000 and projected baseline emissions for 2030 and 2100 [1].
(*Notes:* A1FI, scenario of very rapid economic growth that is fossil intensive; A1B, scenario of very rapid economic growth that is balanced across all sources; A1T, scenario of very rapid economic growth that is non-fossil energy sources; A2, scenario of self-reliance and preservation of local identities; B1, scenario of reductions in material intensity and the introduction of clean and resource-efficient technologies; B2, local solutions to economic, social and environmental sustainability).

and outlet water temperatures of GSHP during the cooling season [8]. Chan developed future hourly weather files for studying the impact of climate change on building energy performance in Hong Kong [9] and found that there would be substantial increase in air conditioning energy use in the future, ranging from 2.6% to 14.3% and from 3.7% to 24% for office building and residential building, respectively. The building heating and cooling energy use change in the U.S. is studied by Wang and Chen [10] and it is found that there would be a net increase in source energy use in heating and cooling by the 2080 s for hot humid, warm humid, and mixed humid climate zones and net decrease in cold and very cold climate zones based on the HadCM3 weather projection. Wan et al. studies climate change's impacts on office in five cities in China using MIROC3.2-H for weather projection and found that there will be 11–20% increase in cooling energy and 13–55% decrease in heating energy [11]. There is also research being conducted on evaluating impacts of climate change on the durability of wall assemblies retrofit to residential building in Canada [12] and it is found that upgrading wall assemblies to residential building would increase the frost damage risk of bricks, however, this risk would decrease under 2080 climatic conditions. Under the influences of climate change on design of zero energy building, Robert and Kummert developed hourly future climate data to evaluate if the existing zero energy buildings in Canada will function as it is expected to be in the future [13], concluding that climate-sensitive buildings such as net zero energy buildings should always be designed using multi-year simulations with weather data that take climate change into account. Recently, a research which aims to find the future design of energy efficient residential building envelopes conducted by Karimpour et al. concluded that with climate change, heating becomes significantly less important in better insulated buildings and therefore measures which reduce cooling load are more critical [14].

Nonetheless, the detailed research on influence of future climate change on the energy use pattern of building sector was not enough explored in the U.S. With the great potential of future climate change, the surface temperature in most places in the US will be raised. The building cooling and heating energy use are greatly dependent on the outdoor temperature and relative humidity (in this paper, if not specifically stated, building cooling energy refers to the electricity use of building cooling, and heating energy refers to the gas use of building heating). The temperature rise may decrease the building heating energy use while raising the cooling energy use. Considering the US is a huge country having vast territory, how the change in building energy demand in various regions would be, and how much the approximate magnitude of change would be are questions still remained to be answered. Without a comprehensive and insightful understanding of the future building energy demand pattern, it would be rather unclear for the governments or participators concerned with green building design to further put forward niche targeting and effective future low energy building code.

The goal of this research is to draw a big picture and better understand building energy use pattern to the year of 2050 in United States by means of projecting future hourly weather data for building simulation tools. The representative climate regions in the United States and their corresponding local cities would be selected for further detailed analysis in building energy use. Recommendations on future building design code or building retrofit trend in the U.S. will be mentioned and more importantly, the end of this research is to let people be aware of the potential problem that our current building standard and design should always be progressive with the ticking clock.

2. Developing future local hourly weather data

2.1. Climate model

How climate change will impact the building energy performance in future? To answer this question, we should first reflect on the question on how future climate will be, not in a qualitative way, but in a quantitative way with different scenario possibilities as put forward by IPCC. To realize this goal, the Global Climate Model (GCM), which is originally created by Syukuro Manabe and Kirk Bryan at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, is first invented to answer the question. It is a mathematical model of the general circulation of a planetary atmosphere or ocean and based on the Navier–Stokes equations on a rotating sphere with thermodynamic terms for various energy sources [15]. There exists groups of GCM with different grid resolution, like BCM2 (Norway), CSIRO:MK3 (Australia), INM:CM3 (Russia), NASA:GISS-AOM (U.S.A.), MIROC3 2-HI (Japan). In this paper, one of the most well know GCM–- HadCM3, developed at the Hadley Center in the United Kingdom, is adopted to generate future weather file. HadCM3, like other GCMs, is a grid point model with large grid cells (2.5° in latitude and 3.75° in longitude over land areas). The HadCM3 is comparatively high in resolution compared with some other GCMs and more importantly, HadCM3 has high temperature sensitivity, which is vital for building energy performance. With each GCM, a set of carbon emission scenario are assigned according to IPCC, namely A1FI, A2, B1 and etc. These scenarios are described in the IPCC's Third Assessment Report (TAR) and Fourth Assessment Report (AR4). In this paper, the A1FI scenario and A2 scenario are selected to predict future weather data, and the projection period of 2040–2069 is chosen. The A2 scenario is characterized by a heterogeneous world with independently operating, self-reliant nations; continuously increasing population; regionally oriented economic development; and slower and more fragmented technological changes, while A1FI is the worst carbon scenario, and it is characterized by rapid economic growth and an emphasis on fossil fuels [16]. Since the current carbon emission scenario is not too optimistic considering the ongoing climate change trend, B2, the best carbon emission scenario which relies on reductions in material intensity and the introduction of clean and resource efficient technologies, is not taken into account in this research. The selection of projection period (2040–2069) depends on the premise that an existing building possesses the life period of fifty years from now on according to some reviewed literatures on life-cycle carbon emission research of building [17,18].

2.2. Downscaling of global climate model

GCM runs on a coarse model based on the numerical methodology of Navier-Stokes equations because of the due computational resources and expense. Merely studying the broad change fetched by the result of Global Climate Model (GCM) is far from enough to evaluate precisely the impact of climate change on building industry since hourly building energy use data and its implication can only be obtained by running simulation tools, like EnergyPlus, DOE 2 or TRNSYS, which are based on hourly weather data information. Moreover, for renewable energy systems relying greatly on natural resources and greatly impacted by climate conditions, like PV (for solar irradiation) or wind turbine (wind speed), it is still necessary and exigent to perceive the influence of future climate condition on the energy efficiency of these systems. The method of obtaining future climate data based on simplified analysis of adding monthly mean change in climate variables to existing weather file will be inaccurate and insufficient to precisely quantify the climate change impacts on building energy performance.

Among all the existing downscaling methodologies before 1997, Wilby and Wigley divided them into four categories: regression methods, weather pattern-based approaches, stochastic weather generators, which are all statistical downscaling methods, and limited-area modeling [19]. Among them, the statistical regression method is widely used. Xu et al. used the statistical method to generate future hourly weather data, which is based on the application of third-to-fifth-order linear equations with coefficients trained using historical observations [4]. However, this technique entails great amount of statistical data of the local weather condition and dynamic procedure, which makes it difficult to implement in places where historical weather file is barely available. The stochastic method is computationally cheap, but it does require large data sets to 'train' the model to give appropriate statistics and fix unknown model coefficients, and the weather series it produces may not always be meteorologically consistent [20]. While the limited-area modeling is quite expensive in computational expense, a methodology put forward by Belcher et al. which adjust present day design weather data by the changes to climate forecast by GCMs and regional climate models based on methodology of time series, is adopted here to downscale the future hourly weather data [20]. This method is called "morphing". By applying morphing method to the outcome of HadCM3, we are able to predict future hourly weather data from GCM which gives changes to monthly mean value of weather variables.

2.2.1. Selection of representative cities for U.S. climate zones

Fig. 2 shows a simplified zoning of major climate zones in United States [21]. They are Cold and very cold climate zone, Hot-dry and mixed dry climate zone, Hot and humid climate zone, Marine climate zone, Mixed-humid climate zone, respectively. In order to find the implication of climate change on future building energy performance, certain specific places should be chosen to locate the grid cell in which the morphing method will be carried out and further building performance simulation will be implemented. For this purpose, four representative cities, Philadelphia (mixed-humid), Chicago (cold), Phoenix (hot-dry) and Miami (hot-humid), are chosen for the further downscaling of GCM. The marine climate zone is not considered because of its relatively low proportion in the total area of the U.S. Furthermore, a comparatively comprehensive research on the impact of climate change on building energy performance in California was conducted by Xu et al. recently [4], and this research almost covered all regions in California, whose representative climate pattern is classified as marine climate.

For the four selected cities, their latitudes and longitudes are 39.86N and 75.23W for Philadelphia, 41.78°N and 87.75°W for Chicago, 33.4500°N, 112.0667°W for Phoenix, and 25.81°N and 80.3°W for Miami, respectively. Then their outputs from HadCM3 including monthly mean changes in values of different climate variables, including temperature, wind speed, RH, precipitation for each month in a year are searched and used.

2.2.2. Typical Meteorological Year (TMY) data

In the morphing method, certain "baseline climate" is entailed, which is defined as the present-day weather sequence averaged over a number of years. The World Meteorological Organization recommends using an averaging period of 30 years to define a climate baseline, and using the period 1961-/1990 to define the 'normal' baseline for climate reference [22]. The averaging period for the baseline climate should be the same period as the baseline used for the climate change scenarios. Thanks to the U.S. National Solar Radiation Data Base archives, the typical meteorological year data for the U.S. can be found in the TMY3 dataset, which contains 1020 locations in the United States and its territories [23]. The TMY2 andTMY3 data were created based on the procedures developed by Sandia National Laboratories [24] to create the original TMYs from the 1952 to 1975 SOLMET/ERSATZ data. Modifications to the Sandia method were made to better optimize the weighting of the indices, to provide preferential selection for months with measured solar radiation data, and to account for missing data [23].

2.2.3. Morphing method

In this research, the morphing method proposed by Belcher et al. is introduced [20]. The first step of this method is to calculate the mean value for each climate variable of each month m for the baseline scenario (here refers to TMY3), the baseline climate value of x_0 for month m is defined to be:

$$\langle X_0 \rangle_m = \frac{1}{24 \times d_m} \sum\nolimits_{\text{month m}} X_0 \quad (1)$$

where, dm is the number of days in month m and the 24 comes from averaging the hourly measurements over the 24 h of each day.

The morphing method adopted here includes three operations, which is rhetorically described as: 1) a shift; 2) a linear stretch (scaling factor); 3) a shift and a stretch, the following equations demonstrates the three operations

$$X = X_0 + \Delta X_m \quad (2)$$

$$X = \alpha_m X_0 \quad (3)$$

$$X = X_0 + \Delta X_m + \alpha_m \times (X_0 - \langle X_0 \rangle_m) \quad (4)$$

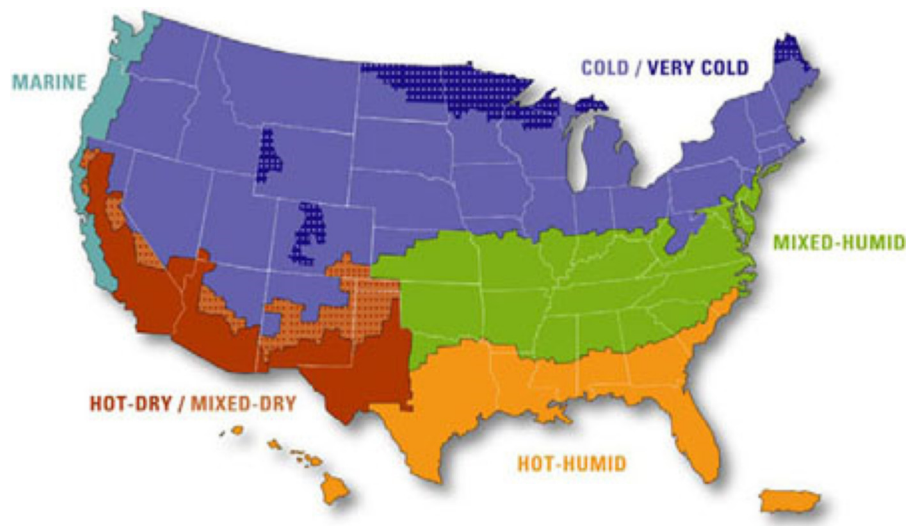

Fig. 2. Major climate zones in the US [16].

where x_o is the existing hourly climate variable, Δx_m is the absolute change in monthly mean climate variable for month m (which is obtained from GCM outcome), α_m is the fractional change in monthly mean climate variable for month m, and x_{0m} is the climate variable x_o average over month m.

The adding of absolute change in monthly mean climate variable for certain month is called shift. It indicates the mean value in baseline scenario has an absolute change, like the change in atmospheric pressure. A stretch is used when the change of certain variable is embodied as fractional change rather than absolute increment, like solar radiation which can never be a positive number at night. The combination of stretch and shift can be applied to those variables like dry-bulb temperature, where both fractional diurnal change and absolute increment take place, especially when taking into account the changes in both maximum and minimum daily temperatures. After applying the stretch and/or shift changes to specific climate variables, the future hourly weather data can be morphed on the basis of current TMY hourly weather data. The following equations manifest the different application of stretch and shift to different variables:

2.3. Results of morphing

The baseline climate data of the four selected cities is available on website of National Solar Radiation Data Base (NSRDB). The four cities are located in the grid cells of HadCM3 and the TMY3 data of them are obtained. After applying morphing method to the current TMY3 data, the projection results of future climate data in the year 2050 (period 2040–2069) are calculated. Table 1 shows the annual value of climate variables in the four cities in 2050.

The future temperature of the four cities will mostly experience increase, and this is quite consistent with our understanding of climate change that the earth surface temperature will be on the rise. As per Table 1, the level of dry-bulb temperature change for different cities located in different climate zones is different. For cities located in cold climate zones (Philadelphia and Chicago), the annual temperature change in 2050 is slightly higher than cities located in hot climate zones. The change in solar irradiance for the four cities is very little in proportion compared with the baseline. But the general trend for growing solar irradiance in future climate is expected. The trend of relative humidity value for future climate is declining, but less significant for cities which are having a dry climate (Phoenix and Chicago compared with Miami). The change in wind speed is rather complicated and a simple pattern cannot be drawn from the results.

Table 1
Annual average value of climate variables in the four cities in 2050.

	TMY	A2	A1FI
Philadelphia			
Dry-bulb Temperature (°C)	12.68	15.28	16.59
Solar Irradiance (W/m^2)	167.43	171.71	172.11
RH (%)	65.95	62.82	62.10
Wind Speed (m/s)	4.17	4.20	4.17
Chicago			
Dry-bulb Temperature (°C)	11.32	14.08	15.55
Solar Irradiance (W/m^2)	156.90	161.05	162.55
RH (%)	65.71	62.70	61.41
Wind Speed (m/s)	4.54	4.54	4.58
Phoenix			
Dry-bulb Temperature (°C)	23.12	24.59	25.40
Solar Irradiance (W/m^2)	178.16	175.90	181.49
RH (%)	42.32	41.21	41.69
Wind Speed (m/s)	3.46	3.75	3.83
Miami			
Dry-bulb Temperature (°C)	24.49	27.01	27.92
Solar Irradiance (W/m^2)	200.01	200.25	204.27
RH (%)	72.57	69.61	67.10
Wind Speed (m/s)	4.13	4.03	4.04

The impacts of global warming on the cooling and heating energy in U.S. climate zones are vital. Heating degree day (HDD) and cooling degree day (CDD) are measurements designed to reflect the demand for energy needed to heat or cool a building. In this paper, the base temperature for CDD and HDD are 26 °C and 18 °C. Figs. 3 and 4 show the heating and cooling degree days in Phoenix and Chicago under different SRES scenarios. The major trend is that HDD is going to fall and the CDD is going to raise. The different level of change is the key to understand future building cooling and heating energy demand pattern. For a more detailed and precise insight of how much change in energy use for future building will have, we shall turn to building performance simulation.

3. Results and Discussions

To understand the impacts of climate change on building energy use by making use of projected local weather data file, building simulation is run on the established residential building model. EnergyPlus 7.2, which is developed by U.S. Department of Energy

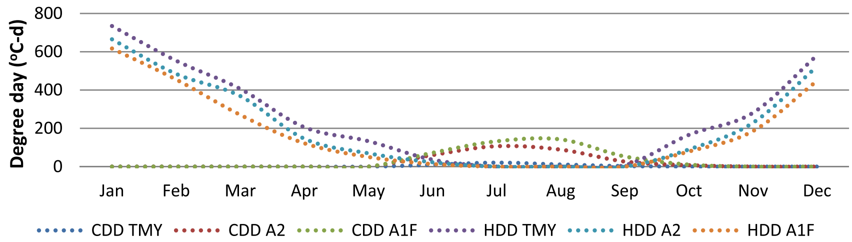

Fig. 3. Heating and cooling degree days for Chicago under different SRES scenarios.

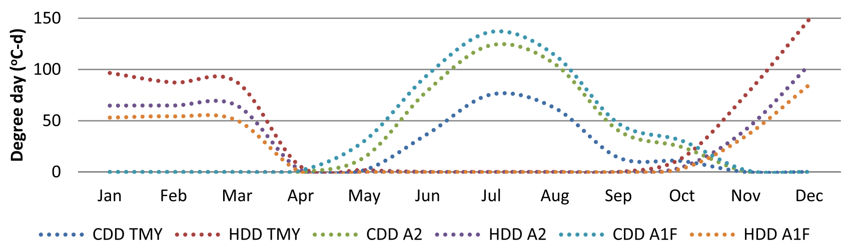

Fig. 4. Heating and cooling degree days for Phoenix under different SRES scenarios.

[25], is used as the building simulation tool in this research. The future hourly weather data is compiled and formatted into .epw file, which is used as weather data input for EnergyPlus.

3.1. Building description

A typical low-rise residential building model, which is common in the U.S., is used as the building model in EnergyPlus. The building is three-storey high, 14 m in length and 8 m in width. The total area of the house is 336 m^2. The cooling system for the house is packaged terminal air conditioner, and the heating source is a boiler fueled by natural gas.

When it comes to office building, a typical 6-storey high office building is considered for building energy simulation in EnergyPlus. It is 40 m in length and 20 m in width. The building faces south and also possesses one core zone and four perimeter zones. The HVAC system for the office building is air handling units plus variable air volume (VAV) box with reheating. The heating and cooling source is chillers driven by electricity and boilers driven by natural gas. Constant speed cooling towers are equipped as heat sink for the chiller.

For the existing building in the U.S., the average residential building lifetime in the U.S. is currently 61 years and has a linearly increasing trend according to the research conducted by Aktas and Bilec [26]. For commercial buildings, the Energy Information Administration in the U.S. (EIA) estimates that the median value for the lifetime of commercial buildings, based on the analysis of data from Commercial Building Energy Consumption Survey (CBECS) ranges from 65 to 80 years, depending on the type of building [27]. The building is assumed to last about 50 years to the end of 2060s.

The aim of this research is to investigate the global climate change's impact on future building energy use under the assumption that no technological advances are going to take place for the existing building. The reason for that is if technological advances are included, then building retrofit will be introduced here to implement these advances to the building, which will incur financial investment to the building characteristics influencing cooling, heating, and equipment electricity use, and that will be another more complicated topic which needs further discussion and research. Moreover, excluding technological advances here to the existing building gives us a purer scenario of how existing building itself will react to the climate change, which would be of interest to study what kind of technological advances should be developed in the future.

3.2. Simulation results for four cities

In this section, results of the building simulation are presented. Though some cooling or heating systems or device may vary from region to region, the end of this paper is to examine and quantify the relative change of different SRES scenarios brought by impacts of climate change based on a "controlled" baseline model. The simulation results are shown in Figs. 5 and 6 and Table 2.

3.3. Results discussion

3.3.1. Heating and cooling energy use

As per the simulation results regarding heating and cooling energy use shown in Figs. 5 and 6, rises in the monthly cooling energy use and decrease in heating energy use in both residential and office buildings are found for all the cities due to the outdoor dry-bulb temperature rise brought by the climate change, but the magnitude of the change varies for different regions and building types. For both heating and cooling energy use, A1FI scenario has greater heating energy decrease and cooling energy increase than A2 scenario, indicating the extreme energy use change occurs in A1FI.

3.3.1.1. Residential building. For residential building, the increase in cooling energy use in four cities is different. For Chicago and Philadelphia, the cooling energy change is more dramatic in proportion than that in Phoenix, and this may be attributed to their lower cooling energy use in present days. Nonetheless, in Miami, the increase in cooling energy use in extreme hot month including July and August undergoes increase in future possible climate conditions, indicating the availability of cooling energy use in the hot and humid regions may be greatly challenged, especially the summer peak load electricity demand. For monthly heating energy use, drops can be found in all the three cities having heating degree days. The heating energy use in Chicago and Philadelphia is similar in their pattern, except that the average heating demand in Chicago is much higher than that in Philadelphia. In Phoenix, the building heating energy use will become more insignificant in comparison to cooling energy use, and the climate change is turning the winter

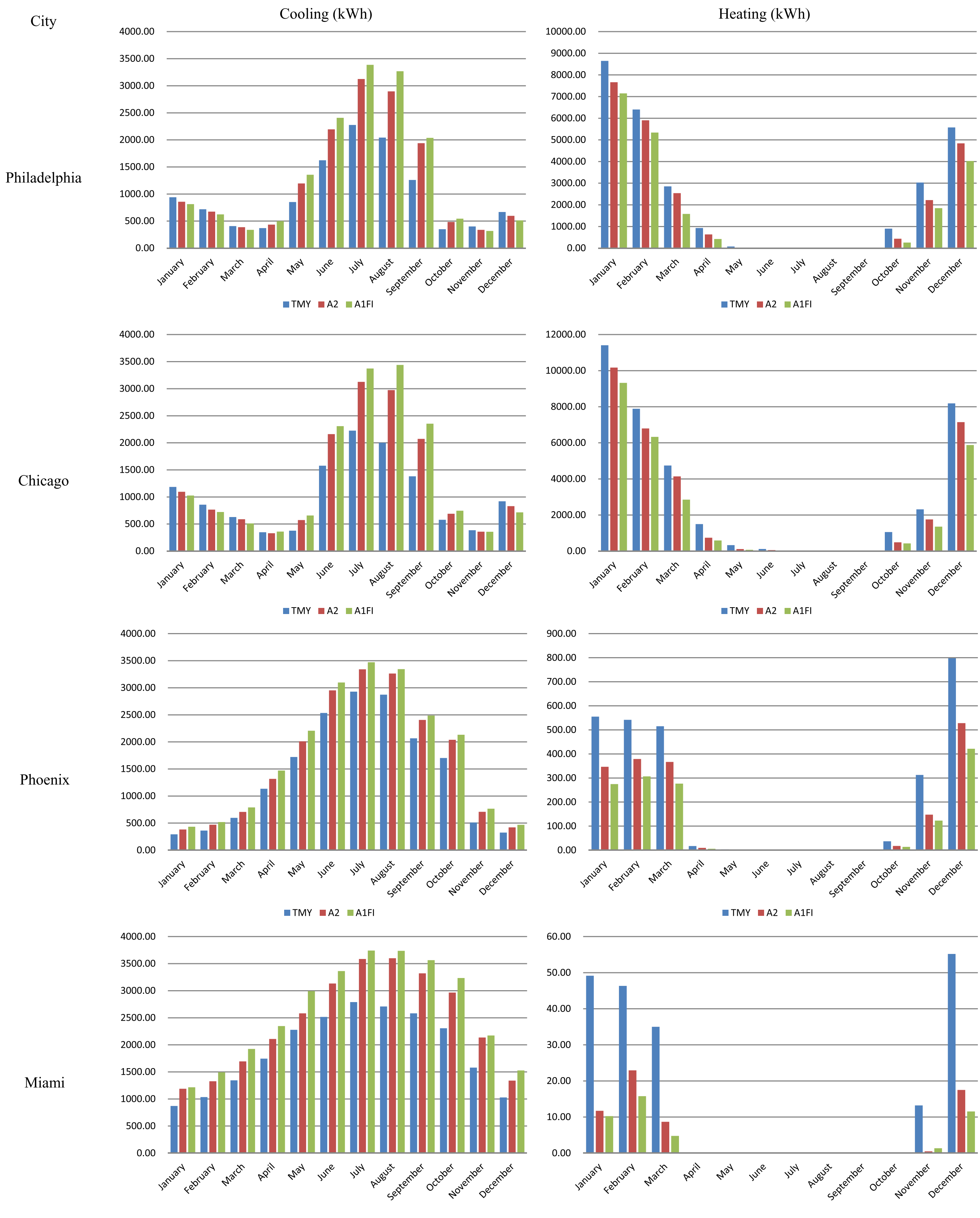

Fig. 5. Cooling and heating energy use in four cities under different SRE Scenarios (Residential).

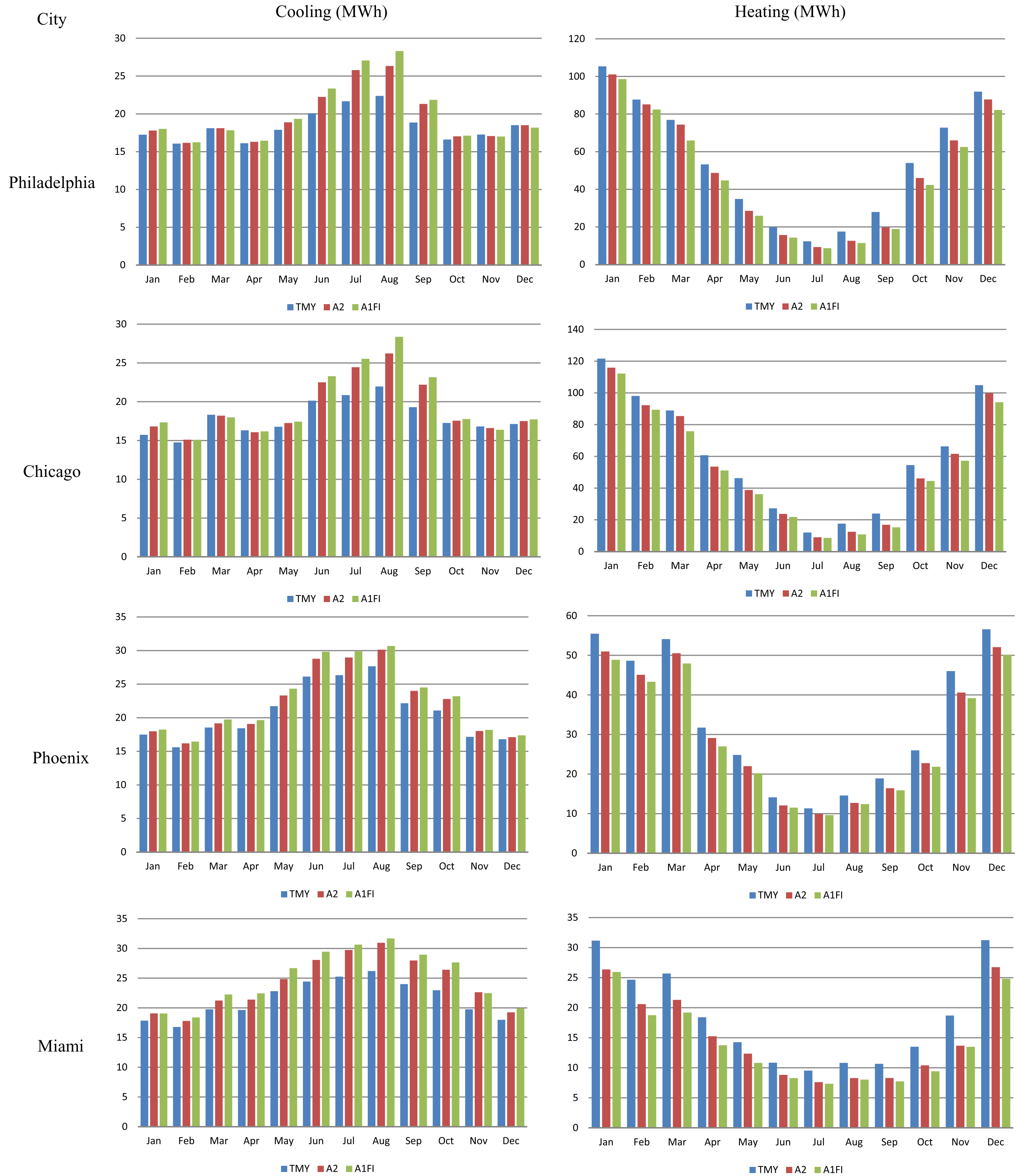

Fig. 6. Cooling and heating energy use in four cities under different SRE Scenarios (Office).

weather in Phoenix (which is already fairly mild) into a hotter one which scarcely needs heating for residential building.

Table 3 shows the annual heating and cooling energy use for the residential buildings in four cities (the heating energy in Miami is so insignificant that it is not shown in the table). As per the results, the heating and cooling energy use in residential building are found to be very sensitive to climate change. Phoenix has the lowest change in cooling energy increase meanwhile showcases the largest change in heating energy decrease. The dramatic decrease in heating energy in Phoenix is due to the comparatively low total

Table 2
Energy end use breakdown in four cities under different SRES scenarios (Residential & Office).

End Use	Residential			Office		
	TMY	A2	A1FI	TMY	A2	A1FI
Philadelphia						
Heating	46.45%	40.29%	35.86%	49.42%	46.44%	44.70%
Cooling	11.96%	17.44%	20.34%	16.67%	18.39%	19.29%
Lighting	9.31%	9.45%	9.89%	5.93%	6.13%	6.30%
Other Appliances	20.43%	20.77%	21.74%	12.96%	13.40%	13.75%
Fans	7.50%	7.68%	7.65%	8.65%	8.99%	9.14%
Cooling Tower	N/A	N/A	N/A	2.36%	2.49%	2.59%
Pumps	0.39%	0.35%	0.31%	3.82%	3.97%	4.04%
Domestic Hot Water	3.96%	4.02%	4.21%	0.18%	0.19%	0.19%
Chicago						
Heating	52.73%	46.11%	41.61%	51.84%	48.85%	47.15%
Cooling	9.76%	14.97%	17.81%	15.47%	17.17%	18.06%
Lighting	8.37%	8.74%	9.22%	5.70%	5.92%	6.07%
Other Appliances	17.57%	18.37%	19.39%	12.32%	12.79%	13.12%
Fans	7.76%	7.88%	7.88%	8.59%	8.92%	9.08%
Cooling Tower	N/A	N/A	N/A	2.20%	2.32%	2.41%
Pumps	0.41%	0.37%	0.34%	3.71%	3.85%	3.92%
Domestic Hot Water	3.40%	3.56%	3.75%	0.17%	0.18%	0.19%
Phoenix						
Heating	6.92%	4.26%	3.31%	36.77%	33.91%	32.67%
Cooling	35.58%	40.30%	42.02%	22.76%	24.72%	25.54%
Lighting	13.38%	12.74%	12.50%	7.05%	7.18%	7.25%
Other Appliances	31.14%	29.70%	29.15%	15.68%	15.97%	16.11%
Fans	6.87%	7.21%	7.33%	10.71%	11.00%	11.13%
Cooling Tower	N/A	N/A	N/A	2.69%	2.74%	2.77%
Pumps	0.08%	0.05%	0.04%	4.11%	4.24%	4.30%
Domestic Hot Water	6.03%	5.75%	5.64%	0.22%	0.23%	0.23%
Miami						
Heating	0.47%	0.12%	0.09%	24.19%	19.83%	18.48%
Cooling	45.40%	50.87%	52.56%	28.36%	31.92%	33.02%
Lighting	11.70%	10.23%	9.76%	8.42%	8.43%	8.43%
Other Appliances	29.13%	25.54%	24.39%	18.91%	18.93%	18.92%
Fans	7.65%	8.30%	8.48%	11.86%	12.39%	12.60%
Cooling Tower	N/A	N/A	N/A	3.17%	3.21%	3.23%
Pumps	0.01%	0.00%	0.00%	4.82%	5.01%	5.06%
Domestic Hot Water	5.64%	4.94%	4.72%	0.27%	0.27%	0.27%

Table 3
Annual heating and cooling energy use under different SRE scenarios and their changes compared with TMY scenario (Residential) (Unit: kWh/m^2).

Cities	Cooling					Heating				
	TMY	A2	Change	A1FI	Change	TMY	A2	Change	A1FI	Change
Philadelphia	35.5	45.0	27.0%	47.9	35.2%	84.6	72.2	−14.7%	61.4	−27.4%
Chicago	37.1	46.3	24.8%	49.3	32.9%	111.8	93.5	−16.4%	79.9	−28.5%
Phoenix	50.7	59.6	17.4%	63.0	24.2%	8.3	5.3	−35.4%	4.2	−48.9%
Miami	59.1	74.8	26.6%	80.6	36.4%	/	/	/	/	/

heating energy use amount, which makes the building energy use more sensitive to climate change. Other cities show almost same magnitude in change of cooling and heating energy use.

3.3.1.2. Office building. The pattern of cooling and heating energy change in the office building is different from residential buildings. For office building, the current cooling and heating energy use in the four cities are closer to each other than that of residential building due to the fact that office building is more dominated by internal load rather than by climate.

Table 4 shows the annual heating and cooling energy use of office building. When compared with residential building, the energy use intensity (EUI) for office building is much more than residential building. The magnitude of change in heating and cooling in office building is less than residential building. The largest change for residential cooling and heating energy use is 36.4% (A1FI, Miami, cooling) and −48.9% (A1FI, Phoenix, heating), respectively, while that for office is 16.4% (A1FI, Miami, cooling) and −23.7% (A1FI, Miami, heating), respectively. The change in heating energy is also proportional to the change in cooling energy in the four cities.

3.3.1.3. Discussion of heating and cooling energy use. In this research, the heating and cooling energy use is projected to the time period of year 2040–2069 considering the aforementioned building life time assumption. Nonetheless, for residential building, it is anticipated from this report that in the future, cities that have mild winter climate no longer needs building heating, but after considering the shift of more heating energy to cooling energy, the electricity energy demand will be at great stake in summer, which is a warning sign to the grid in those regions considering the dramatic soar in both the total amount of electricity use and peak load demand in summer. For the residential building sector, it is imperative for the local government to modify the allocation in primary energy use in the coming future. However, for larger building types, like office building or commercial building, the simulation results in this research corresponds to the research conducted by Xu et al., whose conclusion stated that the heating load of large buildings

Table 4
Annual heating and cooling energy use under different SRE scenarios and their changes compared with TMY scenario (Office) (Unit: kWh/m^2).

Cities	Cooling					Heating				
	TMY	A2	Change	A1FI	Change	TMY	A2	Change	A1FI	Change
Philadelphia	61.3	65.4	6.7%	66.9	9.0%	181.8	165.3	−9.1%	155.0	−14.8%
Chicago	59.8	64.0	7.0%	65.6	9.7%	200.6	182.1	−9.2%	171.4	−14.6%
Phoenix	69.2	73.8	6.6%	75.6	9.2%	111.8	101.2	−9.5%	96.7	−13.5%
Miami	71.5	80.4	12.4%	83.2	16.4%	61.0	49.9	−18.1%	46.6	−23.7%

Table 5
Annual total energy use per unit area under different SRE scenarios and their changes compared with TMY scenario (Residential) (Unit: kWh/m^2).

	Baseline: TMY	A2	Change	A1FI	Change
Philadelphia	182.22	179.23	−1.64%	171.27	−6.01%
Chicago	211.94	202.71	−4.35%	192.05	−9.39%
Phoenix	119.56	125.40	4.88%	127.74	6.85%
Miami	127.82	145.81	14.07%	152.69	19.46%

Table 6
Annual total energy use per unit area under different SRE scenarios and their change compared with TMY scenario (Office) (Unit: kWh/m^2).

	Baseline: TMY	A2	Change	A1FI	Change
Philadelphia	367.90	355.87	−3.27%	346.72	−5.76%
Chicago	386.88	372.82	−3.64%	363.40	−6.07%
Phoenix	304.00	298.43	−1.83%	295.88	−2.67%
Miami	252.10	251.81	−0.12%	252.01	−0.04%

is not as sensitive to weather changes as that of small buildings because the envelope heat gain (loss) of small buildings is a larger portion of their cooling (heating) load than that of large buildings [4]. However, the major trend of future primary energy use in building sector shows propensity to electricity instead of natural gas unless future replacement of building energy system with energy efficient gas fueled cooling plants for both heating and cooling are cost competitive and welcomed in the market.

3.3.2. Building end use breakdown

In Table 2, the results of energy end use break down for office and residential building are shown. It can be concluded that the energy use on HVAC systems in both office and residential buildings is a preeminent factor. Thus, the decrease in winter outdoor temperature is good news to cities like Philadelphia and Chicago where heating energy use is more dominant in their annual energy use composition. Moreover, it is interesting to notice the lighting energy use will have a small decrease in all the four cities under different SRES scenarios. This is mainly due to the change in solar irradiation value in future hourly weather data input of the simulation produced by climate change, which leads to a higher day lighting illuminance for the indoor environment of the residential house. The fan energy for air conditioning system all rises in the four cities due to the climate change as well as to higher need for air exchange rate of building occupants.

For residential building, the absolute change for heating and cooling energy use proportion for Philadelphia and Chicago is negative, which leads to the rise of the proportion of other energy end uses. This trend is reversed in cities where cooling energy is dominant. The proportion in other categories except the fan energy is decreasing in Miami and Phoenix because of the squeezing effect from rises in energy use on heating, ventilation, and air conditioning (HVAC) system.

For office building, the change in building heating and cooling energy use is comparatively smaller because of the thermal inertia in office building is much larger than that in residential building. It is interesting to notice that the proportion of energy use of fans, pumps, and cooling towers in office building are all on the rise in future climate, which infers that more advanced future technologies in transporting systems and heat sinks are of great potential for energy saving in future office buildings in the United States.

3.3.3. Annual energy use

3.3.3.1. Residential building. As shown in Table 5, the four selected cities have shown differences in the magnitude of change in annual total energy use in residential sector. For Philadelphia and Chicago, the annual total energy use is decreasing under both A2 and A1FI scenarios due to that the saved heating energy use offsets the cooling energy use in summer. Cities located in colder climate manifests higher annual energy use per unit area than those located in a milder or hotter climate. According to the results, the more heating energy the building consumes in winter, the more potential it has in magnitude of decrease in annual energy use. Chicago has more annual heating energy use (111.8 kWh/m^2) compared with Philadelphia (84.6 kWh/m^2) in present days, making it able to save more energy in future climate. The same pattern is also found in cities where annual total energy use is increasing, but just manifested in a reverse way. For Phoenix and Miami, those having more cooling energy use nowadays will have more increase in future annual energy use. As indicated in Table 5, the magnitude of annual energy use rise in Miami is more significant than Phoenix. Though this pattern still requires more strict critical assessment when taking into account the a better cooling strategy, better building passive design, it can still be considered as an important results in future annual energy use pattern for residential buildings as their energy use in hot climate is so predominated by cooling energy use. According to the results in Table 5, in the future, the climate change is dragging closer the “pinch point” of energy use in residential buildings located in cold and hot climate regions in the U.S.

3.3.3.2. Office building. As per the compiled annual energy use data in Table 6, the EUI in office building is much higher than EUI in residential buildings. The VAV box provides dehumidification and reheating to indoor environment, making the heating energy use in office building more significant than that in residential building. The results in Table 5 also indicate that climate change is actually reducing total energy use in office building in the future climate condition for cold climate regions. In this research, the total annual energy use reduction ranges from 3.27% to 0.12% for office building under A2 scenario. Large office building located in nowadays cold climate regions in the United States will save more energy than these located in hot climate regions. However, the peak electricity load during cooling seasons is still a vital issue for future power plants and grid. To conclude, the global climate change reduces future office building energy use and making it more reliable on electricity.

4. Conclusions

In this research, the impacts of climate change on residential and office building energy using pattern in the U.S. climate condition are evaluated. The morphing method described in Belcher et al.’s research [20] is used in downscaling the HadCM3 model output into local hourly weather information during the year of

2040–2069. Four cities in representative climate regions of United States are chosen for the residential building simulation. The morphing results show that the four cities located in different climate zones are going to experience rise in dry-bulb temperature and more extreme weather conditions in the future. The accompanied results of temperature rise are changing heating and cooling degree days which will further influence the heating and cooling energy use in residential buildings.

To quantify and better present the impacts of climate change on office and residential buildings, building energy simulation is conducted under the help of projected future hourly weather data. The building model is constructed and simulated by EnergyPlus. The morphed weather data deals well with the building simulation program and can be of great help in similar research in future. The simulation results show that there is rise in the monthly cooling energy use and decrease in heating energy use during heating and cooling seasons in both office and residential buildings for all the climate zones. The largest change for residential cooling and heating is 36.4% (A1FI, Miami) and −48.9% (A1FI, Phoenix), respectively, while that for office cooling and heating is 16.4% (A1FI, Miami) and −23.7% (A1FI, Miami). When it comes to the wording "heating and cooling seasons", one should be aware of that climate change is extending the duration of cooling seasons while shortening heating season. The potential rise in summer cooling electricity demand and peak load will serve as a warning sign to local government and power plants. Though it is conclusive but not inclusive, the future primary energy use for buildings is showing great inclination on electricity use rather than natural gas or oil. In addition, the energy use on lighting is expected to drop as discussed on previous section and fan energy use is going to rise due to the growing demand on building cooling and ventilation in future residential buildings. The proportion of energy use of fans, pumps, and cooling towers in office building will be rising in future climate.

On the aspect of annual energy use, the annual energy use is predicted to change from −1.64% to 14.07% for residential building and from −3.27% to −0.12% for office building under A2 scenario in different regions. The change for office building heating and cooling energy use is smaller to residential building because office building is more internal load dominant. It is concluded for the residential building that, the place where more heating energy the building consumes in winter, the more potential it has in the decrease of annual energy use, and the more cooling energy it uses in summer, the more increase it will have in future annual energy use. That is to say, the climate change is narrowing the gap of energy use in residential buildings located in cold and hot climate regions in the U.S. given that the climate change trend is not restrained. For office building, climate change will actually reduce total energy use in office building in the future. Large office building located in present cold climate regions in the United States will save more energy than these located in hot climate regions.

The findings in this research proposes possible and potentially energy saving advances in future building codes and technologies, providing clues for the question how the current building heating and cooling systems, and lighting systems would play their roles in future climate conditions. In the future, the method can be applied to more research studying various types of building in each respective climate zones in detail to predict the future energy use for each type of building and provide local building design and energy use guidelines.

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