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A SENSITIVITY STUDY OF BUILDING PERFORMANCE USING 30-YEAR ACTUAL WEATHER DATA

Tianzhen Hong[1,*], Wen-Kuei Chang[2], Hung-Wen Lin[2]
[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
[2]Green Energy and Environment Laboratories, Industrial Technology Research Institute, Taiwan, R.O.C.

ABSTRACT

Traditional energy performance calculated using building simulation with the typical meteorological year (TMY) weather data represents the energy performance in a typical year but not necessarily the average or typical energy performance of a building in long term. Furthermore, the simulated results do not provide the range of variations due to the change of weather, which is important in building energy management and risk assessment of energy efficiency investment. This study analyzes the weather impact on peak electric demand and energy use by building simulation using 30-year actual meteorological year (AMY) weather data for three types of office buildings at two design efficiency levels across all 17 climate zones. The simulated results from the AMY are compared to those from TMY3 to determine and analyze the differences. It was found that yearly weather variation has significant impact on building performance especially peak electric demand. Energy savings of building technologies should be evaluated using simulations with multi-decade actual weather data to fully consider investment risk and the long term performance.

Keywords: Actual meteorological year, building simulation, energy use, peak demand, weather data

INTRODUCTION

Buildings consume more than 40% of the world's total primary energy. The IEA Annex 53 identified and studied six influencing factors on building energy performance, including climate, building envelope, building equipment, operation and maintenance, occupant behavior, and indoor environmental conditions. Among these influencing factors, climate plays a unique and significant role. Weather contributes directly and significantly to the variations of thermal loads and energy use of heating, ventilation, and air conditioning (HVAC) systems, lighting (for buildings with daylighting controls. It is important to understand and estimate the weather impact on the long-term performance of buildings in order to support policy makers, building operators and owners to better respond to climate changes in terms of energy supply and demand in buildings.

Various methods to generate annual hourly weather data have been developed in the past. Such weather data include the typical metrological year (TMY), the test reference year (TRY), the weather year for energy calculation (WYEC), the design reference year (DRY), as well as synthetically modeled meteorological year (SMY). However, the lack of long-term weather records usually limits the generation of typical annual weather data files in any format (Ai-Mofeez et al., 2012).

The use of inappropriate weather data can result in large discrepancies between predicted and measured performance of buildings. The influence of the various weather data sets on simulated annual energy use and cost are compared in (Crawley, 1998). The variations of the annual energy consumption and costs can be significant from the simulation results using different weather data sets. The results show that the TMY and the WYEC data sets represent the closest typical weather patterns. Simulated results using the TMY weather data provides the average/typical energy use for buildings, but the peak electric demand predictions and uncertainty analyses based on TMY are often not reliable because a single year cannot capture the full variability of the long-term climate change (Barnaby, 2011). In view of the long-term climate change, the year period assigned for TMY selection should include the most recent meteorological data and should be reasonably long to reflect the weather variations (Chow, 2006).

The energy use in buildings calculated using the TMY weather data aims to represent the average or typical values, but not necessarily so because different types of buildings with different energy service systems and operations have different responses to weather. Furthermore, a single set of energy use results from the TMY simulation does not provide the range of variations due to the change of weather from year to year. The typical life of a building is more than 50 years, therefore the assessment of long-term building performance becomes very important. Although some related studies have been done, there are limited ones focusing on the weather effect on peak electric demand and energy use of buildings by using actual weather data in a timeframe of multiple decades across a complete coverage of climate zones for typical commercial buildings.

This study focuses on providing insights to the following important questions: 1) how significant is the weather impact on both the peak electric demand and energy use of buildings? 2) does the simulated energy use using the TMY3 weather data represent the average or typical energy use of buildings across a 30-year period? 3) what climates are subject to more weather impact on building performance? 4) what types of office buildings are subject to the greatest weather impact? and 5) what is the risk of using the TMY3 weather data in simulations to evaluate the energy savings and electric demand reduction of energy efficiency technologies? The results of this study can support building designers, owners, operators, and policy makers make better decisions on energy efficiency to reduce peak electric demand and energy use of buildings. Additionally, considering the weather impact year-over-year can improve the evaluation of investment risks of energy conservation measures (ECMs) for new and existing buildings.

METHODOLOGY

These energy models are simulated using EnergyPlus 7.1. There is a total of 3162 simulation runs: 3 Office Building Types X 2 Design Efficiency Levels X 17 Climates X 31 Weather Files. The performance metrics of each AMY run are compared with those of the corresponding TMY3 (Wilcox and Marion 2008) run to calculate the percentage changes.

To investigate the weather impact on energy savings and demand reduction of building technologies, two sets of these prototypical office models representing two design efficiency levels: ASHRAE standard 90.1-2004 and 90.1-2010 are further simulated using the TMY3 and 30-year AMY weather files. The energy savings and demand reductions of the 90.1-2010 models over the corresponding 90.1-2004 models using the same TMY3 or AMY weather files are calculated to determine their variation ranges. The 90.1-2010 models represent high efficient designs, with better insulation and windows, more efficient lighting and HVAC systems, which exceed the performance of the 90.1-2004 models by about 30% reduction in site energy use. The source energy is used in this study because it considers the energy loss during energy generation, transmission, and distribution. The weather data for the 17 climate zones, including the 30 years' AMY weather files covering 1980 to 2009 from Weather Analytics and the TMY3 (compiled from meteorological data in 12 typical months selected from years 1976 to 2005) are used in the simulations to investigate the weather impact on building performance. Most cities investigated in this study are in U. S. except Riyadh in Saudi Arabia and Vancouver in Canada.

Office buildings represent the most typical commercial buildings in the United States in terms of buildings numbers and total floor area (USEIA, 2012). Three types of office buildings (USDOE, 2012) with different sizes, small, medium and large, are chosen for this study. Detailed methodology and modeling strategy used to develop these prototype models and the energy and cost saving analysis is presented in (Thornton, 2011). The EnergyPlus models for the three office buildings in 17 climates based on ASHRAE Standard 90.1-2004 and 90.1-2010 were downloaded and converted to EnergyPlus version 7.1 which are then used for the study.

RESULTS AND DISCUSION

Variations of weather data

Variations of weather data and climate zone classification for each of the 17 cities based on the annual heating degree day (HDD) and cooling degree day (CDD) of the AMYs from 1980 to 2009 are illustrated in figure 1. It can be seen that most cities do not belong to only one climate zone. For the 30-year period, the climates of some cities vary across two zones and some even across three or more zones. For example, Fairbanks varies across the very cold Climate Zone 7 and the subarctic Climate Zone 8; while Helena varies across five climate zones, including the cool-humid 5A, the cool-dry 5B, the cool-marine 5C, the cold-humid 6A, and the cold-dry 6B. The spread of climate zones for a city based on 30-year AMY weather data is a good indicator of weather change year-over-year, which cannot be represented by a single-year TMY3 weather data. Therefore, running simulation with multi-decade AMY weather data is necessary to fully evaluate the weather effect on energy performance of buildings. In summary, the variations of weather data year-over-year are significant especially for cold climates, which should not be ignored and such variations cannot be represented by a single-year weather data, either a historical year or a synthetic year such as TMY.

The TMY3 data sets (Wilcox and Marion 2008) cover weather data from 1976 to 2005 for most locations, while the AMYs used in the current study cover weather data from 1980 to 2009. Weather data from different sources and different periods will be different, sometimes significantly. To investigate such differences, the statistics of annual average outdoor air dry-bulb temperature and global horizontal solar radiation are calculated from the AMYs and TMY3, and their differences are further calculated.

Table 1 summarizes the highest, lowest, and average of the annual average outdoor air dry-bulb temperature of the 17 cities from the 30-year AMYs. The annual average outdoor air dry-bulb temperature from TMY3 is listed for each city, as well as the difference between the average AMYs and TMY3. The variations are more significant for cold climates. For example, Fairbanks, Helena and Duluth all have variations greater than 3.7°C. In general, the differences between the TMY3 values and the average AMY are small, except the TMY3 values have a higher average temperature by 0.6°C for Fairbanks and a lower temperature by 0.8°C for Vancouver.

Table 2 summarizes the annual average global horizontal solar radiation for the 17 cities from the 30-year AMYs. Generally, the AMYs have higher solar radiation than the TMY3. This can be due to two reasons: 1) the solar data of the AMYs and TMY3 are from different sources that calculate solar radiation differently, and 2) the AMYs and TMY3 cover different time periods. The higher solar radiation in the AMYs will contribute to the higher cooling loads and lower heating loads than those from TMY3. Future work is recommended to use the new TMY3 created from the 30-year AMYs rather than NREL's TMY3, or use the NREL's TMY3 and the AMYs that were used to create NREL's TMY3.

Weather impact on HVAC source energy use

HVAC energy use are directly affected by weather as cooling and heating loads of buildings are dependent upon weather conditions such as outdoor air temperature and humidity, wind speed, and solar radiation. The variations of percentage changes of HVAC source energy use intensity (EUI, kWh/m^2), for the three types of office buildings with ASHRAE 90.1-2004 efficiency level in the 17 cities are shown in figure 2. The cities on the vertical axis of the figures from the top to the bottom are arranged by climate zone from the very hot and humid climate zone 1A to the subarctic climate zone 8. The simulation results from using the TMY3 weather data are used as the baseline and are represented as 0% in these figures. The red bars represent the variations of the percentage changes across the 30-year period (1980 to 2009). The green bars show same results but excluding the top three largest and the bottom three smallest values to filter out the extreme AMY cases. The left side bars with negative values indicate TMY3 results are over-estimating the AMY results while the right side bars with positive values indicate TMY3 results are under-estimating the AMY results.

In general, the AMY results show large differences from those of the TMY3. The TMY3 results can over-estimate AMY results as much as 15% and under-predict as much as 28%. The comparisons are made to analyze the relative weather impact by climate zone and building type. First, it can be seen that most large changes occur in colder climates, regardless of the building type (large-, medium-, or small-size office). Usually the largest under-estimates occur in Boise, followed by Helena and then San Francisco; while the largest over-estimates occur in Fairbanks, followed by Chicago and then Duluth. Secondly, the larger changes occur for the medium-size office building, followed by the large-size and then the small-size. The medium office building has larger perimeter areas than the large office, and has air-side economizers while the small office does not. Thirdly, the differences between the red and the green bars for each case are compared. The largest differences occur in Boise regardless of building size, followed by Helena, Fairbanks, and Miami. In general, the differences in the hotter and colder climates are larger than those in the mixed climates. In summary, the weather impacts on the HVAC source energy use are significant, especially for the medium-size office building and for all office buildings in cold climates. The impacts are the least for the small-size office among the three office types. Meanwhile, large differences between the simulated results using TMY3 weather data and the AMYs are observed across the 30-year period, and the TMY3 results often under-estimate those of the AMYs.

It should be noted that the systematic under-estimate from the use of TMY3 weather data is mainly due to the AMY data sources have higher solar radiation than the TMY3 as discussed before.

Weather impact on total source energy use

The building total source energy use intensity (EUI, kWh/m^2) for the three types of office buildings with ASHRAE 90.1-2004 efficiency level in the 17 cities are shown in figure 3. As HVAC source energy use is roughly one-third of the building total source energy use, the variations of the percentage changes of the building total source EUI are about one-third of those of the HVAC source EUI, because weather changes only affect the HVAC source energy use. The percentage changes of the building total source energy, although much smaller, represent significant amount of absolute differences in the building total source energy use. Similar but slightly different patterns are observed for the building total source EUI. In general, the AMY results show noticeable differences from those of the TMY3. The TMY3 results can over-estimate AMY results as much as 6.2% and under-estimate as much as 9%. First, it can be seen that most large changes occur in colder climates, regardless of the building. Usually the largest under-estimates occur in four climates: Riyadh, Boise, Helena and Fairbanks; while the largest over-estimates occur in four climates: Miami, Chicago, Duluth and Fairbanks. Secondly, the larger changes occur for the medium-size office, followed by the large-size and then the small-size. Thirdly, the differences between the red and the green bars for each case are compared. The largest differences occur in five climates: Miami, Chicago, Boise, Helena, and Fairbanks. This implies that these climates tend to have more severe weather impacts.

Weather impact on peak electric demand

The variations of the percentage changes of the building peak electric demand are displayed in figure 4. The peak demands of the medium office from using the TMY3 weather data can over-estimate by up to 15% and under-estimate that of the AMYs by up to 28%. Unlike the variations of the HVAC source energy use mentioned before, there is no clear correlation between the changes of peak demand and the climate/city, except for the medium office, the mixed climates show larger percentage differences. The variations for the medium office, as shown in figure 4(b) is much larger than those of the large and small offices. Additionally, the percentage changes for the small office are mostly within ±6% except for a few cases as shown in figure 4(c). For a particular city, if only one green bar can be seen, it is because the red bar is almost the same as the green bar but overlapped by the red bar and thus cannot be seen. This implies that for the small office building in this city, the peak demand is not so sensitive to extreme weather conditions (the top three and bottom three years). On the other hand, if only one red bar can be seen, it is because the green bar is too small to be seen. This implies that the peak demand is sensitive to extreme weather conditions; when the top three and the bottom three years are eliminated, peak demands from the remaining 24-year AMYs and the TMY3 are very close or equal, thus the differences cannot be seen. In summary, the weather impact on the peak electric demand is significant, even greater than the impact on building energy use. The simulated peak demands from TMY3 can significantly under- or over- estimate those of the AMYs. It is necessary to run simulations using multi-decade of AMYs to accurately assess demand response strategies.

Weather impact on peak electric demand reduction and energy savings

The peak demand reduction (in %) and the HVAC and building total source energy savings (in %) are calculated by comparing the peak demand and source energy use of the building with high efficiency level to those of the same building with low efficiency level, using the TMY3 and the 30-year AMY weather data for the three building types across the 17 climates. Such results are respectively shown in figures 5(a)-5(c), where the green bars representing the variation ranges of the demand reduction and source energy savings using the 30-year AMY weather data, while the red marks representing corresponding results using the TMY3. A few key points can be seen from the results in figures 5(a)-5(c). First, the weather impact on the peak demand reduction is generally much greater than on the HVAC source energy savings. Secondly, larger weather impacts on HVAC source energy savings occur for the mixed to cold climates. The savings based on the TMY3 are usually within the ranges of savings based on the AMYs, except for over-estimates in San Francisco, Albuquerque, Boise, Vancouver, and Helena, where the red marks are usually at the very right end or outside of the green bars. Thirdly, the peak demand reduction can vary significantly year-over-year for most climates. The differences of demand reduction can be as high as 15% for Chicago and Fairbanks across the 30-year period for the large office. Finally, the peak demand reductions based on the TMY3 are generally within the ranges of reductions based on the AMYs, but a few cases show the TMY3 results (the red marks) are at the high or low end of or even outside the AMY results (the green bars).

It should be noted that the calculated peak demand reduction and source energy savings come from a combination of energy efficiency improvements from ASHRAE standard 90.1-2004 to 90.1-2010. Whether similar trends apply to an individual energy efficiency improvement, such as better wall or roof insulation, better windows, high efficient lighting system, or high efficient HVAC system, is an open question worth further studies.

CONCLUSION

Nowadays with the availability of long term AMY weather data and sufficient computational power of personal computers. It is feasible and necessary to run simulations with AMY weather data covering multiple decades to fully assess the impact of weather on long-term building performance and to evaluate energy saving potentials of energy conservation measures for new and existing buildings from a life cycle perspective. Main findings from the study include:

- Weather has significant impact on both the peak electric demand and energy use of office buildings, but the impact on the peak demand is even greater.
- The simulated energy use using the TMY3 weather data is not necessarily representing the average energy use using the AMYs across the 30-year period, and the TMY3 results can be significantly higher or lower than those of the AMYs.
- The weather impact is greater for buildings in the cold climate than others.
- The weather has the greatest impact on the medium-size office buildings, followed by the large office and then the small office.
- Simulated energy savings and peak demand reduction by energy conservation measures using the TMY3 weather data can be significantly underestimated or overestimated compared to the results using AMYs.

These findings can serve as better understanding and quantifying the weather impacts on the performance of building, which can support energy policy making, energy code development, building technologies evaluation, and utility incentive programs planning.

A limitation of the current study is the AMY and the TMY3 weather data are from two different sources, this contributes to the discrepancies in simulated energy performance, especially the solar radiation data tend to deviate more than the outdoor air temperature between the two sources.

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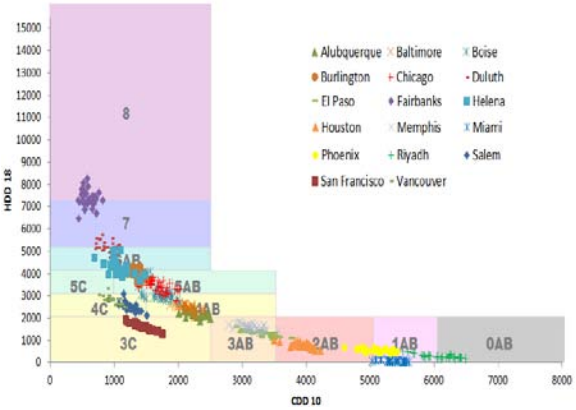

Figure 1. Variations of climate zone based on annual HDD and CDD for 17 cities using AMY weather data from year 1980 to 2009.

Table 1 Statistics of the annual average dry-bulb temperature of the 17 cities from year 1980 to 2009

City	**Annual average dry-bulb temperature (°C)**				**Diff =**
	Highest	**Lowest**	**Average AMY**	**TMY3**	**TMY3 – AMY**
Miami	25.3	23.8	24.7	24.5	-0.2
Riyadh	27.8	25.0	26.6	26.2	-0.4
Houston	21.4	19.0	20.5	20.4	-0.1
Phoenix	24.8	22.5	23.9	23.8	-0.1
Memphis	18.5	16.2	17.2	17	-0.2
El Paso	19.8	16.7	18.3	18	-0.3
San Francisco	14.7	12.8	13.8	13.8	0.0
Baltimore	14.4	12.2	13.2	13.2	0.0
Albuquerque	15.0	13.0	14.0	13.7	-0.3
Salem	12.9	10.0	11.6	11.7	0.1
Chicago	12.1	8.7	10.0	10	0.0
Boise	12.7	8.1	11.1	11.2	0.1
Vancouver	11.6	9.1	10.5	9.7	-0.8
Burlington	9.2	7.0	7.9	7.9	0.0
Helena	9.1	4.8	7.1	7.2	0.1
Duluth	6.3	2.6	4.3	4.0	-0.3
Fairbanks	0.3	-4.4	-2.0	-1.4	0.6

Table 2 The annual average global horizontal solar radiation of the 17 cities from year 1980 to 2009

City	**Annual average global horizontal solar radiation (Wh/m^2)**		
	Average AMY	**TMY3**	**%Diff = (TMY3 – AMY) / AMY**
Miami	5612	4803	-14.4
Riyadh	6318	6114	-3.2
Houston	4750	4459	-6.1
Phoenix	5832	5738	-1.6
Memphis	4564	4493	-1.6
El Paso	5758	5657	-1.8
San Francisco	5322	4703	-11.6
Baltimore	4223	4078	-3.4
Albuquerque	5881	5426	-7.7
Salem	3881	3701	-4.6
Chicago	4100	3854	-6.0
Boise	4926	4429	-10.1
Vancouver	3674	3369	-8.3
Burlington	3699	3675	-0.6
Helena	4377	3997	-8.7
Duluth	3744	3678	-1.8
Fairbanks	2868	2591	-9.7

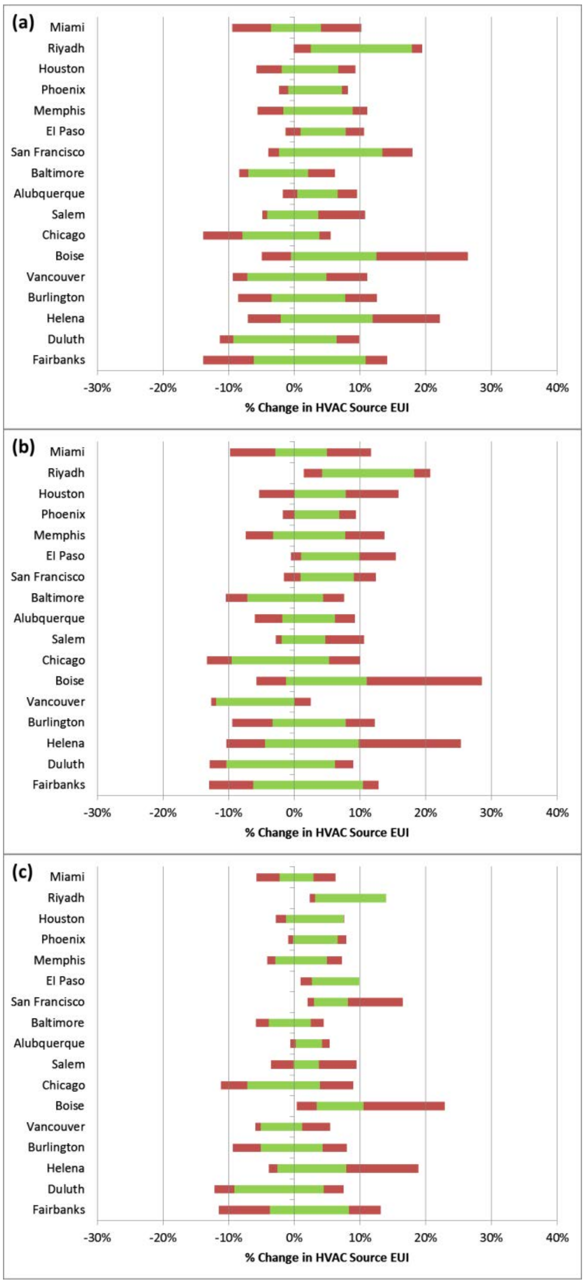

Figure 2. Variations of percentage changes of HVAC source EUI between AMY and TMY3. (a) large office; (b) medium office; (c) small office. The red bars represent the variations across the 30-year while the green bars excluding the six percentage changes from the top three and the bottom three extreme weather years.

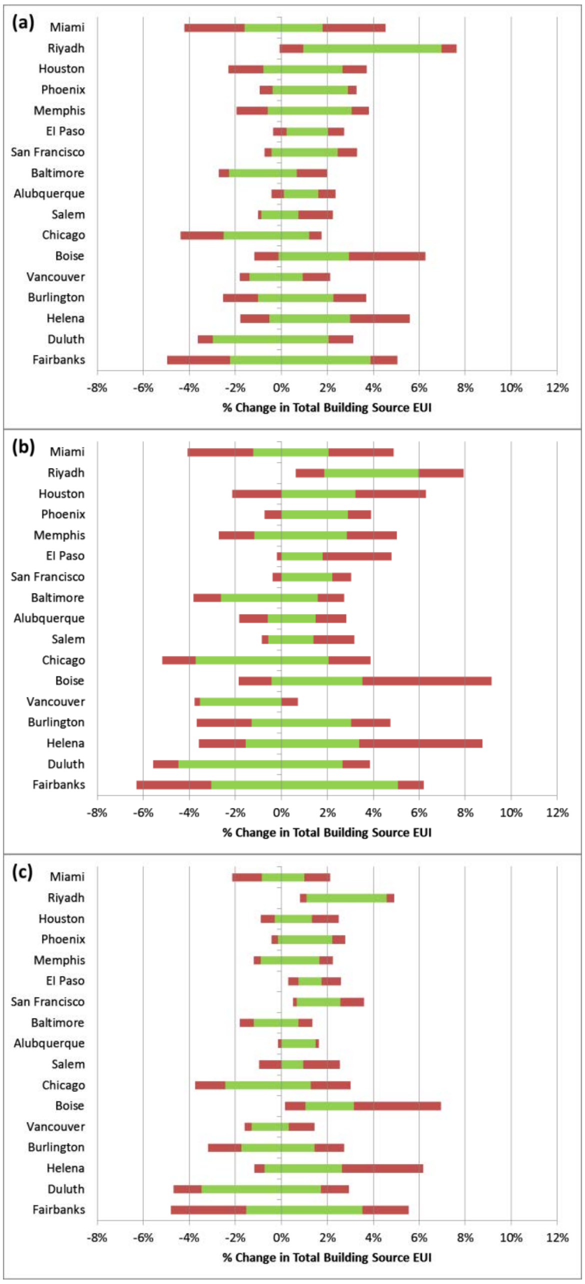

Figure 3. Variations of percentage changes of total building source EUI. (a) large office; (b) medium office; (c) small office. The red bars represent the variations across the 30-year while the green bars excluding the six percentage changes from the top three and the bottom three extreme weather years.

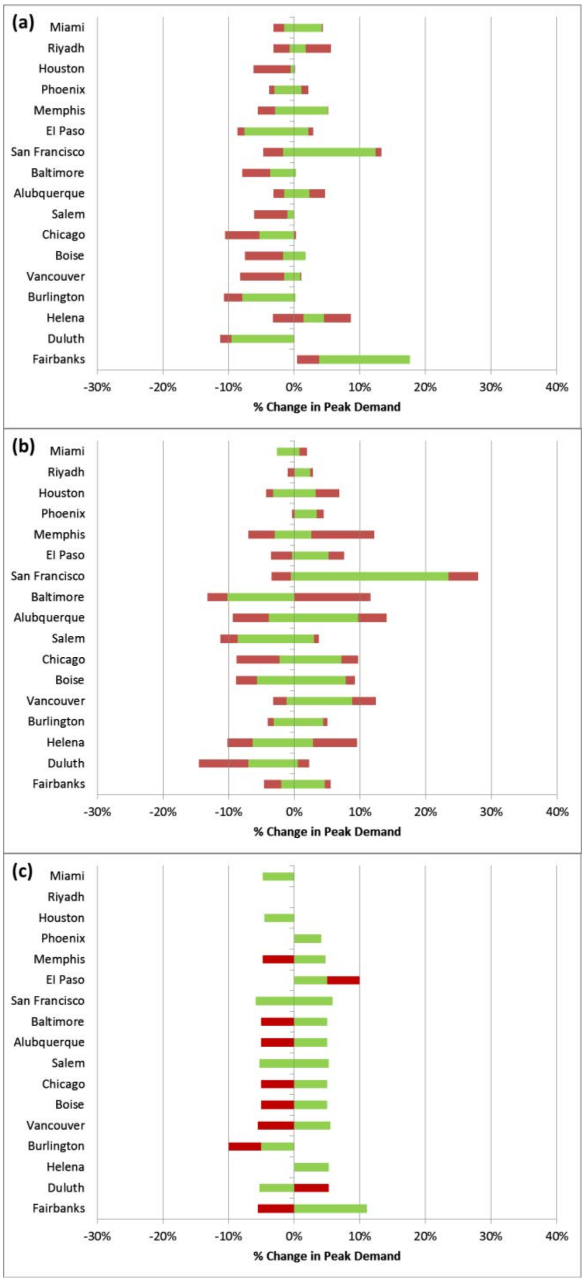

Figure 4. Variations of percentage changes of peak electricity demand. (a) large office; (b) medium office; (c) small office. The red bars represent the variations across the 30-year while the green bars excluding the six percentage changes from the top three and the bottom three extreme weather years.

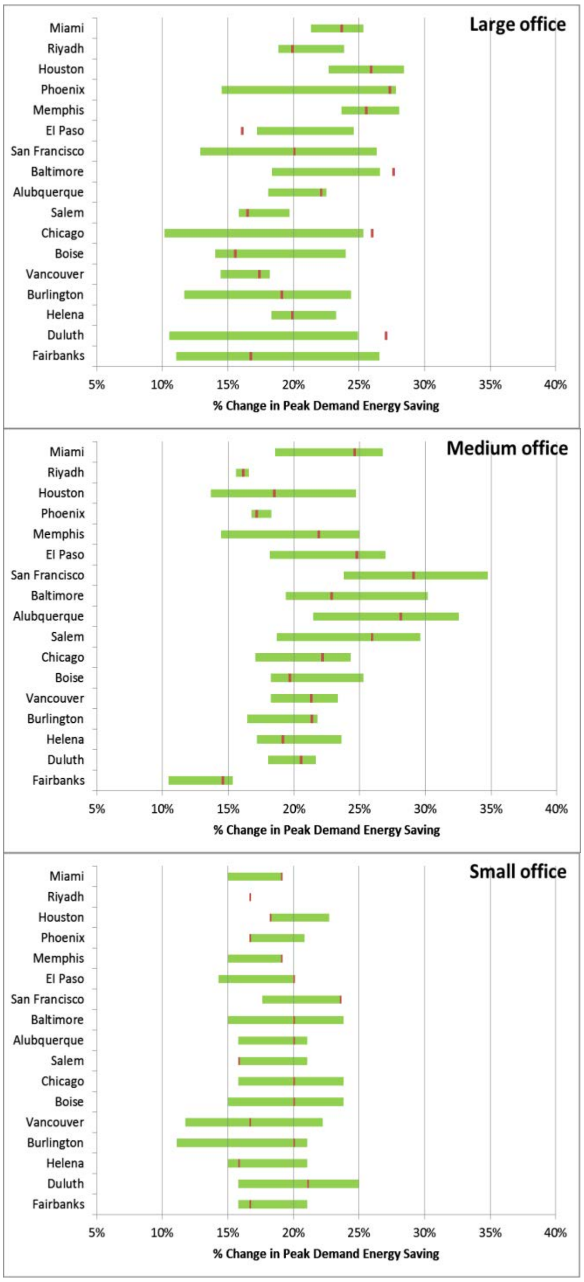

Figure 5(a). Variations of percentage reduction of peak electricity demand of the 90.1-2010 models over the 90.1-2004 models for three different size offices.

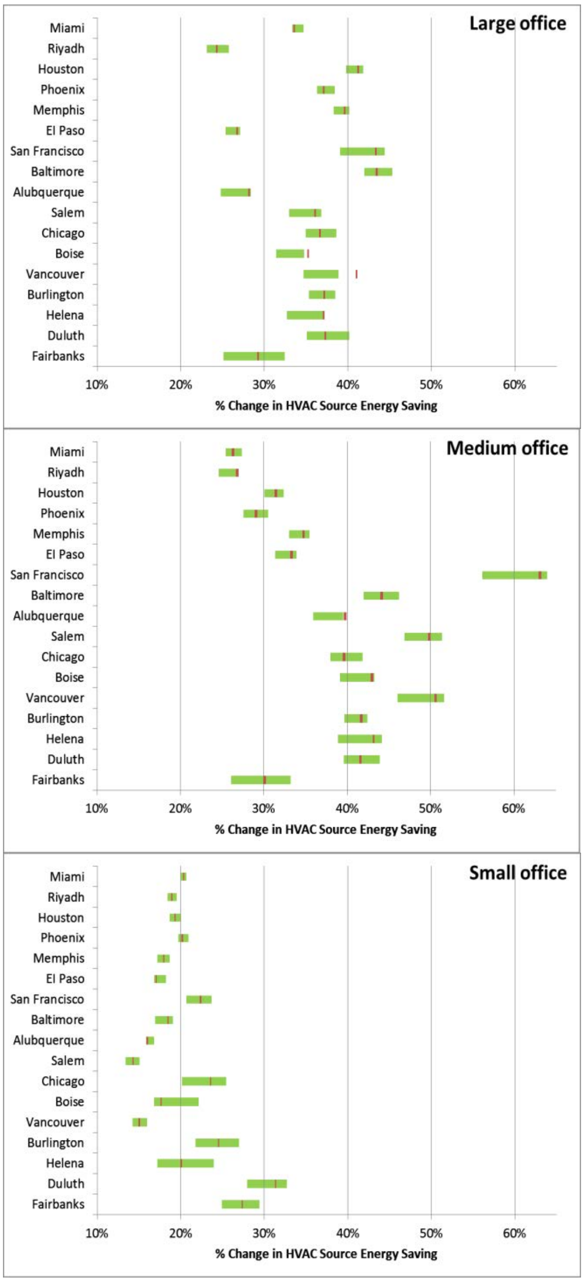

Figure 5(b). Variations of percentage savings of HVAC source energy of the 90.1-2010 models over the 90.1-2004 models for three different size offices.

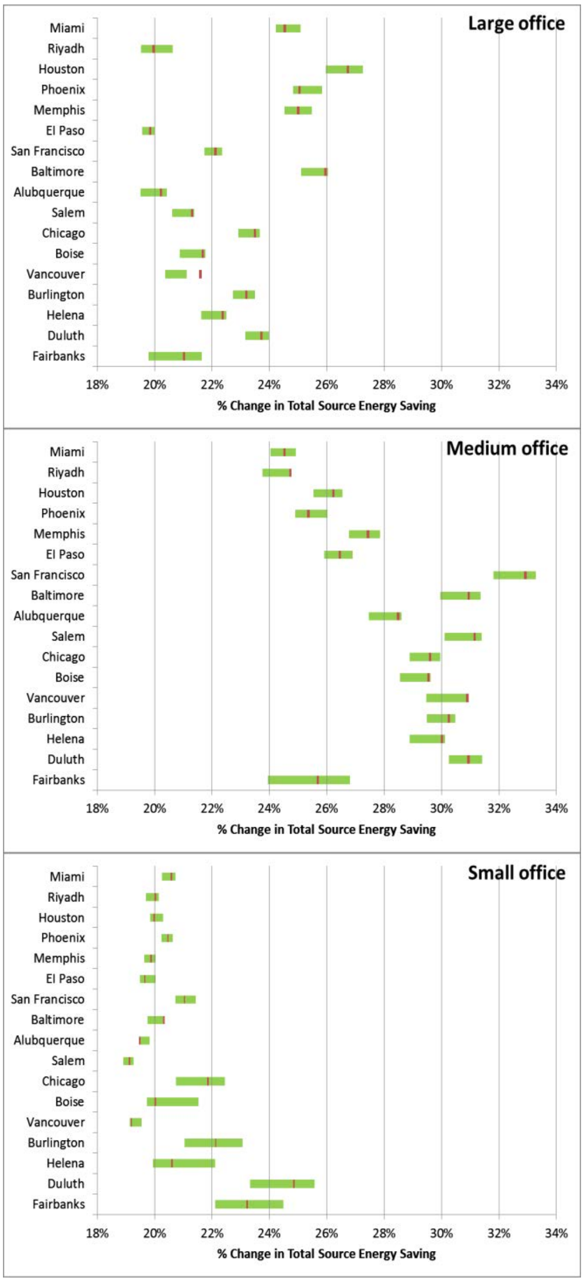

Figure 5(c). Variations of total source energy of the 90.1-2010 models over the 90.1-2004 models for three different size offices