Building performance analysis considering climate change

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ABSTRACT: Climate change will significantly influence building performance in the future both through differences in energy consumption (perhaps drastically in certain climate zones) and by changing the thermal level of comfort that occupants experience. A building that meets the current energy consumption standard has the potential to become energy inefficient in the future, and well-meaning designers might be applying passive strategies for current conditions without understanding what impact their choices have under different climate change scenarios for their location. By analyzing a case study building's thermal performance, specifically lifecycle energy use, for multiple climate change scenarios and in different climate zones, it is possible to inspect the resilience of passive design strategies over time. Varying the solar heat gain coefficient (SGHC) was the first strategy tested. To estimate the building's future performance, three projected future climate conditions were created (for low, moderate, and severe climate change) in three climate zones for three different time periods (2020s, 2050s, and 2080s). The first step was to create new projected weather files. They were calculated from a world climate change weather file generation tool that was developed at the University of Southampton. Then the weather files were used in EnergyPlus to determine the energy consumption. Aggregated multiple runs provided lifecycle energy use for each of the three locations. Then the SHGC values were varied to determine which initial values provided the best long-term result. Although currently only SHGC was tested, this research provides a methodology for architects and engineers during the early stage of design that they can use to avoid the detrimental consequences that might be caused by climate change over the lifecycle of the building. Another result of the study was a better understanding of the shifting of the ASHRAE climate zones.

KEYWORDS: Climate Change, Climate Zones, Energy Performance, Passive Strategies, Weather Files

INTRODUCTION

Sustainable design requires that architects and engineers fully understand the interaction between climate, as encoded in a weather file, and the predicted building performance. However, it is easy for designers when running computer simulations to overlook that climate is a dynamic system. Research into building life-cycle energy use considering non-static weather conditions can provide designers valuable recommendations that they can use during the conceptual design stage to help the decision making process. This type of integrated design process can better ensure the building performance is not just for code compliance or even for lessening current energy consumption, but takes into account future climate conditions.

1.0 RELATIONSHIP BETWEEN BUILDING PERFORMANCE AND CLIMATE

It is estimated that buildings are responsible for 40% of total energy consumption (SBCI, 2009) and 72% of the total electricity use in the world, which makes structures one of the main causes of world energy depletion (Action Energy, 2003). Building performance relies on two main factors: the building's properties and the weather conditions. Either of these two factors will affect the performance analysis results. Predicting future building performance requires the use of simulated, "future" weather files, and assuming the building stays the same throughout its life, the influence of building's properties alone can be tested, and recommendations to avoid negative effects can be provided.

1.1. Building energy simulation overview

Building energy simulation is used to predict and analyze building energy use before the building is constructed. Energy modeling is based on a virtual description of the geometry and building physics (properties); it relies on a simulation engine (such as DOE 2) and often a second software program that provides a user interface. Building energy simulation is widely used in the architecture industry. It is one of the two paths that help designers evaluate their projects and achieve code requirements or purse a sustainability certificate. One path is *prescriptive design*, where specific requirements have to be met (e.g. a specific R-value of insulation in the walls) to achieve the code requirements and building energy efficiency. The other path is *whole building energy simulation*, which allows designers to rely on software results to evaluate building energy performance. In the latter method, there is more freedom in the choices, but there is still an energy allowance that has to be met depending on state and local codes. In either case, the critical point is that for both prescriptive methods and energy simulation, predicted performance is based on current climate conditions (in the weather file) and not future climate conditions. Buildings that appear to meet or exceed base building performance now may not in the future.

1.2. Climate change

Many phenomena have been observed by researchers that support the theory of climate change (http://www.epa.gov/climatechange/, http://climate.nasa.gov/, http://www.ipcc.ch/). Building performance will be influenced by climate change, since buildings are sensitive to their local microclimate. For example, some buildings in Europe has already experienced overheating issue in the last several years due to increasing temperatures (Hulme et al., 2002). Climate should not be considered as a static value when analyzing building performance as buildings are in use over decades, sometimes even centuries. Instead, climate is a critical variable that should be considered for reducing the risk of poor building performance in the future (e.g. high energy consumption) and to make the building more resilient over its lifetime.

1.3. Weather file and its role in energy simulation

A weather file is a record from a weather station that contains very detailed data for a specific location. There are many different types of weather files serving different purposes. A TMY (Typical Meteorological Year) file contains the monthly weather (with hourly values recorded) selected from different years to represent a "typical" weather condition throughout a year; it is not the representation of any one specific year. A TMY3 weather file's data is not derived to represent the weather extremes and is not suitable for building system design. Other weather file types are more suitable for system design as the extremes have not been "averaged out." However, a TMY 3 weather file does have diurnal and seasonal variations that represent a typical year's climate condition for that location. (Wilcox and Marion, 2008). It represents a typical weather condition over a long period of time, such as 30 years (Marion and Urban 1995). There are three different types of TMY weather files: TMY3 = 1976 -2005, TMY2 = 1961-1990, TMY = 1952-1975 (Holmes and Ap 2011).

Based on the future weather variables projection considering the IPCC climate change scenario, the UK Climate Impacts Programme in 2002 (UKCIP02) proposed that the 15 weather variables will be different in the future including maximum, minimum, and mean temperature; specific and relative humidity; 10 mile wind speed; net surface longwave and shortwave flux and total downward surface shortwave flux; soil moisture content; mean sea level pressure; surface latent heat flux; total precipitation and snowfall rate; and total cloud in longwave radiation (Belcher, Hacker, and Powell 2005).

1.4. Life-cycle energy use

Life-cycle energy use will be used as to evaluate the building energy use. It reflects the building energy consumption during its entire life cycle. Energy Use Intensity (EUI) is not applicable in this case since the climate change is going to result in a different EUI year by year, and it is necessary to take the total energy use for a building's entire life cycle to determine if the building is consuming more or less energy over time (EUI_{LC}).

2.0 FUTURE WEATHER FILES

Current TMY files will be used as the basis for creating the "future" weather files using the HadCM3 climate model and pattern scaling.

2.1. HadCM3 and pattern scaling

Many climate change models have been developed to represent the changed patterns and predict the future possible climate conditions. The HadCM3 model has been used to explore climate change's impact on different building types (Wang and Chen, 2014). The model was developed at the Hadley Centre in the United Kingdom (Collins, Tett, and Cooper, 2001). Two advantages with this model make it appropriate for building energy use: it has a relatively smaller grid spacing than some others, which means the simulation resolution is higher than other models and results in higher precision, and it has also adopted in IPCC for future global warming trend projection. The model was used by the IPCC to represent recent temperature from a 1961 – 1990 average.(Hulme et al., 2002)

Based on the HadCM3 climate change model, it is possible to project the future climate weather from TMY weather files. The weather data generated from existing tool developed at the University of Southampton is used only for one scenario, which is "medium high emission" (A1) (Hulme et al., 2002). It is important to determine more scenarios (such a low, medium, and high emissions) so that the impact of climate change can be studied more comprehensively. To derive climate data for the other three scenarios, pattern-scaling is used, which uses factors that are associated with the magnitude of each scenario. Uncertainties are unavoidable, but assessments of the pattern-scaling technique have concluded that it is reasonable to make these assumptions for the present generation of General Circulation Models (GCMs) (Hulme et al., 2002).

2.2. Creating the weather files

The core of climate change building energy simulation is the weather file, since every calculation and the simulation is based on this file. A convenient representation of this data is the spreadsheet. However, the file initially generated from the spreadsheet is not a usable weather file; it is necessary to convert the file to other format which can be read by energy simulation software, the EPW format. The tools that were used for conversion are "CC world weather generator" and the EnergyPlus weather file convertor. After generating the new weather file, the heating degree day (HDD) and cooling degree day (CDD) values were calculated.

The first step was to create a weather file for every emission scenario. According to the IPCC climate change model HadCM3, the future climate condition is simulated based on four different emission scenarios, which are B1-Low Emission, B2-Medium Low Emission, A2-Medium High Emission, and A1F1-High Emission (Barker 2007). However, the "CC world weather generator" developed at the University of Southampton is only able to calculate the future weather condition for scenario A2(Jentsch, Bahaj, & James, 2008). Several projections of future climate for 2020s, 2050s, 2080s can be made (each with low, medium, and high emissions) (Belcher, Hacker, & Powell, 2005). Four additional emission scenarios were calculated using pattern scaling. Pattern scaling is based on a series of factors that provide a magnitude for the change (Table 1). Although derived for the UK, the method is appropriate even if new factors are determined later either due to more accurate predictions or better location sensitive values.

Table 1: Pattern scaling factors (Hulme et al., 2002)

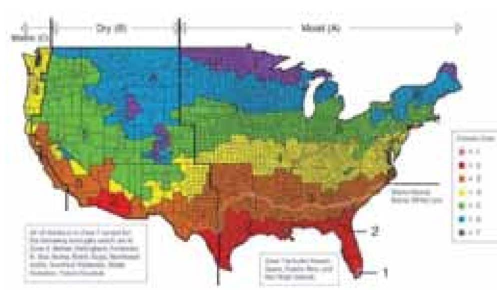
Time-Slice	Low Emission	Medium-Low Emission	Medium-High Emission	High Emission
2020s	0.24	0.27	0.27	0.29
2050s	0.43	0.5	0.57	0.68
2080s	0.61	0.71	1	1.18

By using the pattern scaling factors, it was possible to generate weather files for the other three scenarios for each time-slice in the weather file by calculating the magnitude of change for each weather parameter.

2.3. Climate zone map example

An additional use of the "future" weather files (when completed for thousands of locations) will be to create a new climate zone map of the United States. The climate map is used for building performance analysis, since the determination of some characteristics of the building are selected based on the climate zone that it is located in. For example, the determination of solar heat gain coefficient (SHGC) is based on the climate zone designation.

The most commonly used climate map for United States is ASHRAE (or IECC) climate map, in which the entire U.S is divided into seven climate zones based on the temperature difference, the numeral letters in a climate zone name represent the heating degree day and cooling degree day, which are used to determine the temperature division of a place (Fig. 1). Climate zones are not the best characterization of the variety of climates that exist in the U. S. (for example, there are only 7 zones in the US plus an indicator for marine conditions), but these climate zones are referred to in ASHRAE 90.1 to provide guidance for architects and engineers design decision making and also play a role for projects pursing LEED certification.



Zone	Thermal Criteria CDD 50*	HDD 65**
1	> 9000	–
2	6,300–9,000	–
3	4,500–6,300	–
4	< 4,500	< 5,400
5	–	5,400–7,200
6	–	7,200–9,000
7	–	9,000–12,600
8	–	> 12,600

* Cooling Degree Days over 50°F
** Heating Degree Days under 65°F

Figure 1: The ASHRAE (or IECC) climate zone map for United States (DOE, 2010)

Since the designation of climate zone is based on the CDD and HDD, it is possible use the "CC world weather generator," "Emission scenario generator," EnergyPlus weather file convertor, and the definition of climate zones 1 – 7 to create a new climate map for a specific future time. A test was done using seven counties in California at different latitudes. Generally, each county shifted from current climate zone to the next level (Fig. 2). Eventually the sequencing will be automated so that a climate zone is determined for each county in the U. S., and a map will be created.

Year	County	Average Temp	CDD	HDD	Precipitation	Climate zone(Calculated)	Climate zone(ASHRAE)
2014	Iyon	58	3684	4052	2.067	4B	4B
2050		63	5150	3063	0	3B	
2014	Imperial	74	8852	842	2.262	2	2
2050		79	10517	428	0	1	
2014	Sacramento	60	4553	2586	0.546	3B	3B
2050		67	6148	1795	0	3B	
2014	Shasta	62	4873	2694	72.3	3B	3B
2050		69	6896	1871	0	2	
2014	Siskiyou	54	2589	5498	6.9	5	5
2050		59	4228	3927	0	4	
2014	Tulare	63	4924	2464	11.8	3B	3B
2050		59	7103	1525	0	2	
2014	LA	63	4724	1186	0	3B	3B
2050		68	6662	459	0	2	

Figure 2: Highlighted counties have new climate zones (left) and their locations in California (right)

3.0 METHODOLOGY DEMONSTRATION

A climate zone map is a useful graphic for envisioning climate change, but was not part of the methodology for testing future climate on the long-term effectiveness of passive strategies. The workflow for the building lifecycle energy use study was as follows: create many new weather files and baseline buildings (one for seven ASHRAE climate zones) and then run simulations for the applicable variables (Fig. 3).

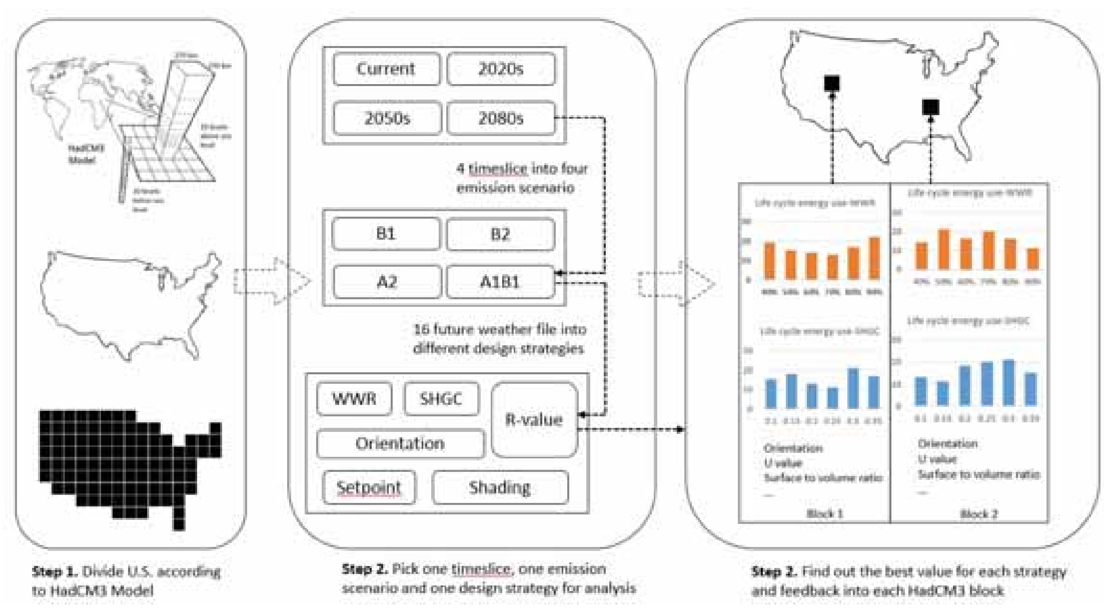


Figure 3: Workflow of building life cycle energy use calculation

3.1. Baseline building

Several baseline buildings were considered. For example, if the study only focused on California, Title 24 should be the best reference since it has prescriptive design requirements that can be used as the default model information. However, since the analysis is across the U.S. and seven climate zones, the reference selected was ASHRAE 90.1 because it includes detailed requirements for each climate zone. ASHRAE 90.1

Appendix G specifically addresses the development of a baseline model, which will be used to compare against the proposed model simulation result (ASHRAE, 2007). A medium office building was chosen (a three storey office building with 33% window-to-wall ratio; the total floor area is 53,600 square feet). It is included in the prototype baseline model package downloaded from the DOE website (http://www.energycodes.gov/commercial-prototype-building-models).

This model was used for the initial testing and will be used for the continuing study of different passive strategies for each climate zone and each U. S. county. The geometry will stay the same throughout the entire process. However, the building variables will be different for each climate zone to create another baseline model that meets the AHRAE 90.1 standards and has specific requirements for the building in different climate zones. For example, the wall construction, fenestration, system type, and others will be changed. The demonstration of the methodology used the solar heat gain coefficient (SHGC) as the variable.

3.2. Creating climate change scenarios

"CC world weather generator" is a spreadsheet based software that allow users to generate future weather for a known current weather file. In the interface of the software, users are required to complete three steps in order to generate future weather file:

1. Select a weather file
2. Select a time slice among 2020s, 2050s, and 2080s
3. Generate weather file

This software is only able to generate one emission scenario for each time period, which is A2 (medium high emission scenario). Therefore, with the pattern scaling method provided from IPCC report, it is possible to develop a spreadsheet that can further convert the A2 scenario based weather file to future weather files based on other emission scenarios (B1, B2 and A1F1) (Hulme et al., 2002).

3.3. Sensitivity testing

Before the analysis, it is necessary to find out the sensitivity of the variables to make sure that there will be a noticeable change in the results. The first variable is the weather file, since the weather file plays a key role in studying the future climate condition. For each specific location, 16 sensitivity tests were done to provide a more comprehensive understanding of the climate change's impact in the future; this ranged from the lowest impact (B1 scenario in 2020s) to the highest impact (A1F1 scenario in 2080s). Since the influence of climate change is different from place to place, the sensitivity of climate change should be different. Therefore, it is necessary to test more locations. Two locations were selected: Los Angeles and Boston. The two cities are representative of two very distinct sets of climate characteristics, which are hot-dry, hot-humid and cold- dry. Each time-slice will have four emission scenarios, and in total, there are three future time-slices plus the current year. Even though only two cities will be address at this moment, the third city will be added to take account of the cities in those hot and humid climate condition.

In addition, the sensitivity for each weather variable will help to decide which variables have more influence, since it is not necessary to analyze the parameters that have no any impact on building energy use when the climate changes. The internal factors can be excluded from the climate change related study since the internal load does not respond to the outdoor environment. For example, there is no need to analyze the occupant schedule's response to climate change, since the building occupant profile is determined by the building type rather than climate condition.

The building façade features are sensitive variables to climate change because different weather conditions will generate different loads based on the building façade. For the initial demonstration, solar heat gain coefficient (SHGC) were chosen to test the methodology.

3.4. Energy use analysis

3.4.1 Baseline building analysis

The selected baseline building is the ASHRAE office prototype building. The building is three stories tall, the total floor area is 53,600 ft^2 with 33% window to wall ratio. The default zoning method was to separate the each floor into two parts, the perimeter zone and core.

To generally understand the climate change's impact on building future energy use, seven California counties, from low to high latitude, were used first to test the methodology for the 2020s, 2050s, and 2080s, so that a general trend of the future building energy use could be seen. For each time slice, the selected emission scenario was A1F1, which was the worse case. Because heating and cooling energy account for a large portion of the building total energy consumption, the results show the change for cooling, heating, and combined. For the counties at low latitudes, the building energy use will increase, and the 2080s scenario has the highest heating and cooling energy use. The highest increase will happen in Los Angeles at 2080s (40% increase). However, for the counties at high latitude, the heating and cooling energy use is actually decreasing in the future and most significant decrease is 15% for office in Siskiyou in 2080s (Fig. 4).

Figure 4: Future heating and cooling energy for office building in selected counties

3.4.1 Solar heat gain coefficient and future building energy use

The selection of solar heat gain coefficient (SHGC) depends on the location of the building. SHGC is a value that reflect glazing's capability to transmit solar radiation from the exterior environment to indoor space (Bhandari and Bansal, 1994). The higher the value of SHGC, the better the glass can transmit the solar radiation, and the indoor space will experience a higher cooling load. Generally, a high SGHC is desired in cold locations where the extra heat is needed during the winter, and a lower SHGC is desired in hot areas to block radiation in the summer could increase the cooling load and building energy use. Since the SHGC reflects the glazing's capability to transmit solar radiation, it is closely related with application of passive strategies. One passive strategy that is highly relevant to this coefficient is passive heating in the winter. By increasing the SHGC value, the glazing's ability to transmit solar radiation is improved, which will allow radiation transmitted to the indoor environment, and the heating load during the winter can be reduced. (Bhandari and Bansal, 1994)

The selection of SHGC impacts the building life cycle energy use. The question is for each location, is it a beneficial or detrimental in the long term to have a higher or lower SHGC for the initial condition assuming that it cannot be changed over time?

Unlike the selection of seven counties to understand the climate change's overall impact, the selected two cities were Los Angeles and Boston for testing SHGC. Not only do they have very distinct climate conditions, but the long-term goal is to use this methodology for many cities to test several passive strategies. Los Angeles is hot and dry throughout the year, while Boston is cold and dry during the winter. The selection of SHGC and the lifecycle energy use should be very different for these cities.

The lifecycle energy use is calculated based on the total energy use from the current year to 2080 using the Medium-High Emission scenario. Intermediate values were calculated for 2020 and 2050 with the energy used between each pair of time-slices assumed linear (this will be further refined later). The total energy for a building's life cycle is the shaded area (Fig. 5).

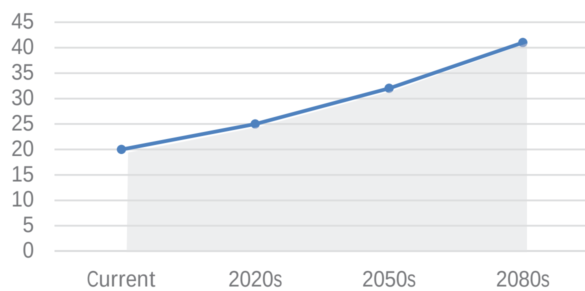
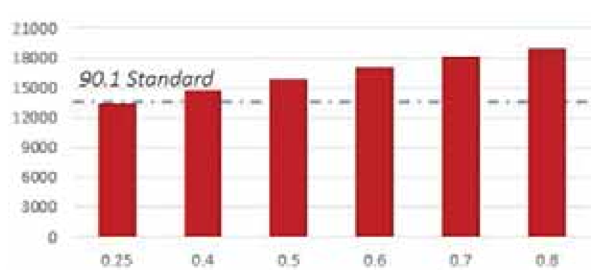


Figure 6: Calculation method for lifecycle energy (shaded area under curve)

For Los Angeles (climate zone 3, hot-dry) and Boston (climate zone 5, cold-dry) the values of SHGC were based on ASHRAE 90.1, which provides the maximum value of SHGC for climate zones 3 and 5. For Boston it is 0.4, and for Los Angeles, the value is 0.25. The study selected different values for comparison and an "optimized" SHGC value was found that had the lowest building life cycle energy use. For Los Angles, the lower SHGC is always better for building energy efficiency; however, for Boston, the best value 0.7, which will has a 15% decrease of heating and cooling life cycle energy use compared against ASHRAE 90.1 standard (Fig. 6, Fig. 7).



igure 6: Life cycle heating and cooling energy use for different values of SHGC, Los Angeles

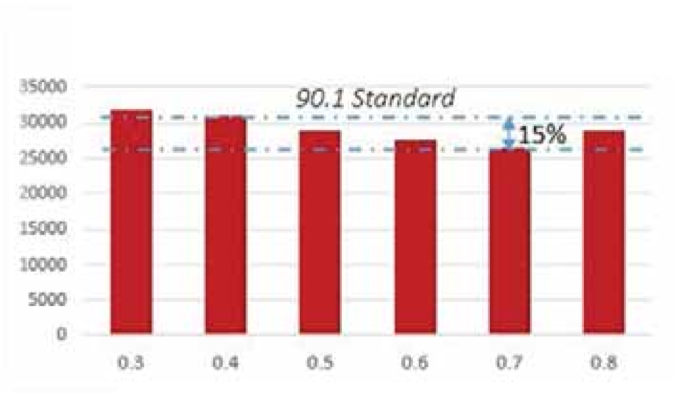


Figure 7: Life cycle heating and cooling energy use for different values of SHGC, Boston

3.4. Conclusion

Two methodologies have been presented. Both use the HadCM3 climate change model. The first was to demonstrate how to create a new climate zone map for the U.S. Several counties in California were used as case studies to show that changing climate will effect climate zone designations, which also effect the building performance predictions. The second was an initial demonstration of determining what passive strategies chosen by the designer now will have the best payoff in the future under different climate change scenarios. SHGC was tested for Los Angeles and Boston; it was determined that the lower SHGC, the better for Los Angeles, and a value of 0.7 for Boston is best for life cycle energy savings (heating and cooling). This methodology will be applied to a half dozen different variables that reflect passive strategies across multiple climate zones. The final analysis will determine which strategies are most suitable for long term benefit (low life-cycle energy use) for different climate zones considering climate change.

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