Is it Getting Hot in Here? How Climate Change Will Impact Energy Efficiency Choices

Scott Schuetter, Seventhwave
Saranya Gunasingh, Seventhwave
Doug Ahl, Seventhwave

ABSTRACT

We design, construct and operate buildings in a world affected by climate change, but the potential to curb greenhouse gas emissions by implementing energy efficiency in the built environment is substantial. Our paper will show how energy efficiency recommendations change when climate variability is considered, and how future buildings should be designed with respect to energy use.

We studied the impacts of future climate variability on energy consumption and operating costs at NASA's John C. Stennis Space Center in Mississippi. By coupling a representative set of energy models with low and high impact climate change scenarios, we were able to identify adaptation approaches with the most energy savings potential, through simulation. Our analysis of the Stennis Center indicates an increase of up to 11% and 36% for electricity and natural gas respectively, resulting in 9-17% annual utility cost increase in the next fifty years. We were able to identify the top three mitigation strategies for this geography with the most climate resilience. We demonstrated that this method could be replicated with other building types and geography with two other case-studies. For large facilities that spend millions on utility bills, this operating cost increase implies a large energy cost investment. Building owners, designers and decision makers will find the paper useful in informing climate mitigation and resiliency through building design. This process will help utilities reward measures that allow greater flexibility in future extreme degree days, and respond better to regulatory environments that are growing more climate-conscious.

Introduction

The International Energy Agency reports that globally, buildings consume one-third of the total primary energy generated and are also responsible for one-third of energy related greenhouse gas emissions (International Energy Agency., 2013). This large ecological footprint of buildings continues to rise and if current trends continue, energy demand in buildings is projected to increase by 50% by 2050.

Discussions on mitigating adverse climate impacts typically involve curbing CO_2 emissions from fossil fuel consumption. How existing infrastructure will perform under changing climate scenarios, or a climate profile that is significantly different from the one it was designed for, is often overlooked. Much of the building infrastructure that will exist in 2035 is currently being built. About three-fourths of U.S. floor space will be new or renovated in the next two decades (Guttman, 2013). This presents an immediate opportunity and an urgent need for designers and utilities to address future climate resilience in new construction and major retrofits.

This paper discusses three case studies in three U.S geographic regions examining the impact of climate variability on energy use and operating costs.. We developed a building energy modeling approach that incorporated future climate variability and allowed us to quantify expected impacts and uncertainties in future energy consumption, peak demand and operating costs. The approach allowed us to identify new construction and retrofit design strategies that offer the most climate resilience.

Method

The general method we used, whether applied to existing buildings or new construction, followed the same basic steps. For our three cases, we applied the methodology to one existing set of buildings, the Stennis Space Center (Case 1, ASHRAE climate zone 2A) and two new construction projects, the Chicago (Case 2, ASHRAE climate zone 5A) and Fort Collins (Case 3, ASHRAE climate zone 5B) multifamily buildings.

Gather Building Data

For new construction buildings, we acquired design documents such as building drawings and specifications. For existing buildings, we collected the same documentation where available and performed level 1 building audits to fill in any information gaps and obtain a better understanding of the facilities' use type and operation schedule. In addition, we obtained monthly historical energy consumption data.

Develop Building Models

We built energy models in DOE2 (DOE2, 2013) using eQUEST as a graphical user interface. The first case for which we developed our models was for a subset of existing buildings at the Stennis Space Center (SSC).

Building geometry (footprint, number of floors) for the SSC models was based on remote sensing imagery and building square footage provided by facility staff. Interior zoning was predominately set to perimeter-core with specific zoning only occurring for areas with loads significantly different than the building as a whole (i.e. warehouse adjacent to an office). Windows were modeled as approximated window to wall ratios taken from site photos. Because of the age of many of the buildings, we could not determine precise assembly properties for roofs, walls, and windows. For these cases, we assumed the roof had R-10 insulation. We assumed the walls to be 12" medium weight concrete with minimal insulation, and the windows to be single-paned with clear glazing. For the handful of newer buildings, we assumed code required minimum values of insulation and window properties from ASHRAE 90.1-2004. Occupancy density was provided by facility staff. The buildings were predominately occupied between 6:00 am and 6:00 pm as corroborated by facility staff. We preliminarily set lighting to code required values from ASHRAE 90.1-2004 for the building's predominant use type (i.e. 1.0 W/ft^2 for buildings that were mostly office). No daylighting controls were reported for the modeled buildings. We initially set miscellaneous loads to default values outlined in COMNET's Commercial Buildings Energy Modeling Guidelines and Procedures (COMNET, 2013) for a given building's predominant use type. Infiltration flow rates were approximated according to guidelines published by Pacific Northwest National Laboratory (PNNL, 2009). We modeled HVAC system types according to input from facility staff. The majority of primary HVAC systems for the existing buildings were variable air volume with hot water reheat. Cooling was provided by water-cooled chillers, while heating was provided by atmospheric boilers. The HVAC system capacities were autosized in the energy models and the analysis is based on the assumption that the current HVAC system is sufficiently oversized to meet increased heating and cooling loads under future climate scenarios. The efficiencies for the HVAC equipment were preliminarily set to code required minimum values as outlined in ASHRAE 90.1-2004. No demand control ventilation controls were found in the modeled buildings, and only one instance of energy recovery ventilation was found.

These models were calibrated to reflect the buildings' actual energy consumption by comparing the initial modeling results to the actual monitored energy usage. We used Actual Meteorological Year weather data in our models corresponding to the same period as the measured energy usage. Discrepancies between the modeled and actual performance were assumed to be the result of uncertainty in model inputs such as envelope properties, lighting power, plug load equipment power, infiltration flow rates, outdoor air flow rates and HVAC equipment efficiencies.

We then used the Nelder-Mead simplex optimization algorithm (Nelder and Mead, 1965) to calibrate each of the models to actual monthly energy use data. The algorithm searches for the energy model input parameter set that minimizes an objective function comparing modeled energy use to actual energy use. Our choice for objective function follows ASHRAE Research Project 1051 and Guideline 14 for energy model calibration and evaluation. We used Goodness of Fit (GOF) as our objective function, which is based on the coefficient of variation of the root mean squared error between modeled and measured monthly energy consumption, weighted by the annual cost of each fuel type. The convergence criteria for the objective function was set to 15 percent for each model (i.e. GOF <15 percent for each building model). We inspected all calibrated model parameters to ensure values fell within acceptable ranges based on our understanding of the building and our engineering experience. Quality checks were also performed on model results. Cooling load, economizer operation, and reheat controls were each rigorously explored to determine proper performance.

After the calibration algorithm had been applied to each building energy model, we had a set of models that represented energy use for the existing buildings under current climate conditions.

Once the calibration was finalized, we input Typical Meteorological Year (TMY) weather data representing years 1997 to 2012 into our models such that our existing models represent buildings operating under the current climate scenario.

The modeling approach was similar for the new construction buildings (Case 2, 3) except that models were developed using the design documents to reflect an ASHRAE 90.1-2010 Appendix G baseline and they were not calibrated to reflect actual energy consumption. The next step was to select the future climate scenarios for analysis.

Analyze Climate Scenarios and Impacts

We screened 11 future climate model data sets provided by the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2007). Each of these data sets contained projected climate data on a 30 mile (50 km) grid encompassing all of the U.S. We selected the grid point closest to the particular building under analysis. Each data set contains a variety of climate variables on 3 hour intervals for the years 2041 to 2070. Due to the computationally intensive nature of simulating all future climate scenarios, we instead chose data sets representing low and high impact scenarios. In this manner, our results would bracket the potential range of climate impacts without taking an inordinate amount of computational time. Our selection method for specific climate datasets is discussed in more detail subsequently.

We had planned to use the full set of climate variables in our energy models. However, some climate variables produce only secondary effects on building energy consumption. In order to minimize the impact of those variables, we used NARCCAP data pertaining only to drybulb temperature, wetbulb temperature, atmospheric pressure and corresponding atmospheric variables that could be calculated directly from these primary variables (e.g. enthalpy). All other variables were held constant between current and future scenarios.

We used the future climate data in our models to estimate the impact of climate change on annual electric consumption, annual natural gas consumption, peak electricity demand, and annual utility cost. Variation in peak cooling and peak heating demand were also observed, but this study did not include an in-depth analysis of peak loads. This aspect will be addressed in future work.

Develop Mitigation Strategies

Once we quantified the expected range of impacts, we developed mitigation strategies to offset them. For all three cases, we analyzed a range of standard energy conservation measures (ECM) affecting building envelope, lighting, and HVAC systems. The impact of each ECM was individually quantified and ranked based on its effectiveness at saving energy for the specific building type in the specific future climate.

Results

Case1: Southern Mississippi Space Center

NASA's John C. Stennis Space Center (SSC) in southern Mississippi is a campus with 142 buildings encompassing a variety of usage types (Schuetter et al., 2014). We developed and calibrated thirty-two models representing buildings consuming over 80% of SSC's annual energy consumption under current climate conditions. Modeled total energy use was within 5.5 percent and 2.1 percent of measured annual data for electricity and natural gas, respectively. The coefficient of determination between measured and modeled energy use improved noticeably from uncalibrated models (0.86) to calibrated models (0.98) as seen in Figure 1.

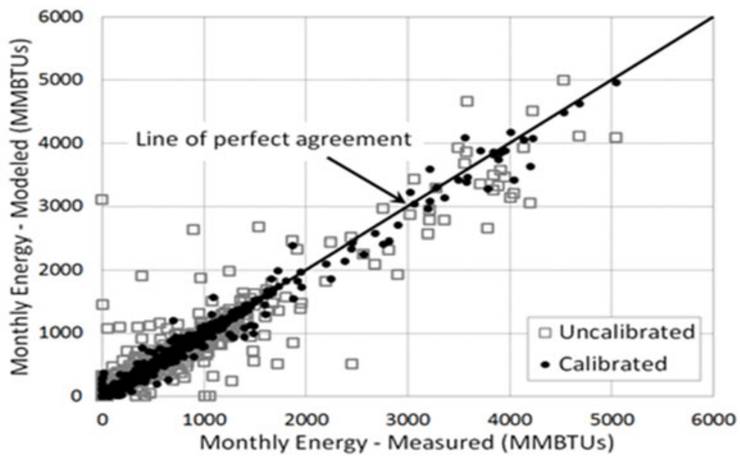

Figure 1: Monthly modeled versus measured energy usage for all existing models before and after calibration.

Our two climate change scenarios (low and high impact) were selected as the year with the average annual drybulb temperature closest to the median of all years from the future climate model data sets with the smallest and biggest impacts, respectively. Our analysis for the SSC site shows a general cooling trend for the low impact scenario that does not align with the warming trend of the larger region. The low impact future climate indicates average annual temperatures that are 4 °F (2 °C) lower compared to the current climate, and a maximum annual temperature 7 °F (4 °C) higher. The high impact future climate scenario shows no change in annual average temperature but an increase of 19 °F (11 °C) for the maximum annual temperature. Additionally, both scenarios project colder winters and a corresponding increase in heating degree days.

Table 1 compares temperature metrics between climate scenarios: TMY (represents the present climate 1997-2012); Low Impact (future); and High Impact (future).

Table 1: Drybulb temperature summary for TMY, and future climate scenarios at SSC.

	TMY	Low impact	High impact
Average Tdb (°F)	71	67	71
Maximum Tdb (°F)	102	109	121
Minimum Tdb (°F)	26	25	26
Heating degree days – base 65°F	1248	1842	1859
Cooling degree days – base 65°F	3322	2498	4269

Using these different climate scenarios, we quantified the impact of climate change on SSC building performance. Figure 2 illustrates this impact, with each bar graph representing the range of impacts bracketed by the low and high impact future climate scenarios.

Total site energy consumption increased over current climate conditions for each climate scenario we examined, as shown in Figure 2. Our models showed an increase of between 4.3% and 11.3% in annual electricity consumption for the low and high impact future scenarios, respectively.

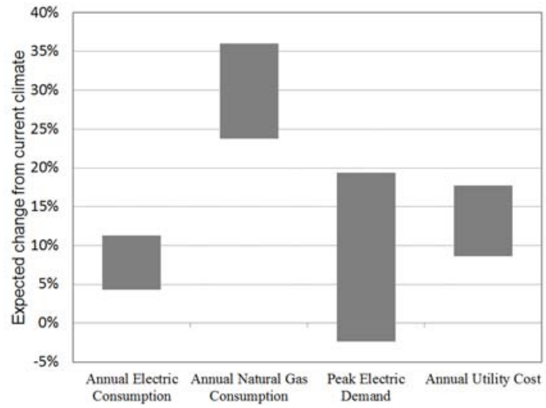

Figure 2: Expected change in building performance for each climate scenario at SSC.

The low impact peak electric demand decreases 2.4% and the high impact scenario projects an increase of 19.4%. This reflects the significantly higher drybulb and wetbulb temperatures projected under this scenario. Total gas consumption increased 23.8% and 36.0% percent for the low and high impact scenario respectively. This follows the generally lower and more variable wintertime temperatures projected under both climate scenarios. The total projected annual energy cost is expected to increase 8.6% and 17.7% for the low and high impact scenarios, respectively. For a facility of this size, this translates to around $1 million dollars.

We then ran a number of typical ECMs and ranked their effectiveness at mitigating climate change impacts into two groups; primary strategies were the most effective, secondary strategies had a smaller, but sizable mitigation effect. Table 2 outlines the most effective climate change mitigation strategies at SSC.

The three primary strategies include improving roof insulation, upgrading the water-cooled chillers and installing ventilation energy recovery wheels. Additional roof insulation reduces the cooling and heating loads at SSC during the more extreme summers and winters by reducing the amount of energy used by the heating and cooling equipment.

Table 2: Climate change mitigation strategies at SSC.

Primary strategies	Description
Roof insulation	Add additional roof insulation, minimum R-20
Cooling equipment	Upgrade to high-efficiency centrifugal chillers; minimum 0.639 kW/ton, 0.45 kW/ ton-IPLV
Energy recovery ventilation	Install enthalpy wheel energy recovery systems on exhaust with bypass and modulation control; 70%+ latent effectiveness, ~0.7” ΔP
Secondary strategies	
Wall insulation	Add additional wall insulation, 2” continuous insulation
High performance windows	Replace existing windows with low conductivity glass and thermally-broken frames; maximum Assembly U-Value of 0.35
Tighter envelope	Install continuous air-vapor barrier using spray on air barrier or spray foam to seal all roof penetrations (piping, ductwork, electrical) at both the top and the deck level
Heating equipment	Upgrade to condensing gas-fired boilers; 90%+ thermal efficiency

Upgrading to more efficient chillers directly reduces the amount of cooling energy needed to offset the increased need for cooling during hotter summers. The energy recovery ventilation will recover energy from the exhaust air stream, reducing the wasted energy already used to condition the hotter or colder outside air.

We also identified four secondary strategies. The first three strategies—increasing wall insulation, installing high performance windows, and sealing air leaks—indirectly reduce energy use by isolating the conditioned indoor environment from the outdoor climate. The fourth strategy—upgrading to condensing boilers—directly reduces the amount of heating energy needed to offset the increased need for heating during the colder winters. A number of additional strategies were analyzed, but found not to be particularly effective at offsetting the impact of climate change. These were predominantly strategies that affected internal loads, such as more efficient lighting.

Case 2: Chicago Multifamily Building

We explored the energy impacts of future climate variability in a 428,000 square foot multifamily development in Chicago, Illinois. We applied the method developed for the SSC study to understand the energy use, quantify the impacts of climate change on building performance and understand the resilience to climate change from each design upgrade. However, we did not have actual building energy consumption data to use for calibration. The model therefore reflected a theoretical baseline in line with the applicable building energy code.

For this case, we selected the two future climate datasets (low and high) based on the year with the lowest and highest average annual drybulb temperature. The low impact climate data for the Chicago site shows average annual temperatures that are 1 °F (0.5 °C) lower compared to the current climate, and a maximum annual temperature 1 °F (0.5 °C) higher. The high impact future climate scenario shows average annual temperatures that are 4 °F (2.2 °C) higher compared to the current climate, and a maximum annual temperature 21 °F (11.7 °C) higher.

Using these different climate scenarios, we quantified the impact of climate change on the Chicago multifamily building's performance. Figure 3 illustrates this impact, with each bar graph representing the range of impacts bracketed by the low and high impact future climate scenarios.

Total site energy consumption increased over current climate conditions for each climate scenario we examined. For the project's baseline, our models showed an increase of between 3.9% and 16.9% in annual electricity consumption for the low and high impact future scenarios, respectively. The low impact peak electric demand decreases 1.1%, and the high impact scenario projects an increase of 10.8%. This reflects the significantly higher drybulb and wetbulb temperatures projected under this scenario. Total gas consumption decreased 11.4% and increases 7.6% percent for the low and high impact scenario respectively. This follows the generally more variable wintertime temperatures projected under future climate scenarios. The total projected annual energy cost is expected to increase 3.7% and 14.7% for the low and high impact scenarios, respectively. For a facility of this type, this translates to an increase of between $0.04 and $0.13 per square foot ($17,000 to $56,000).

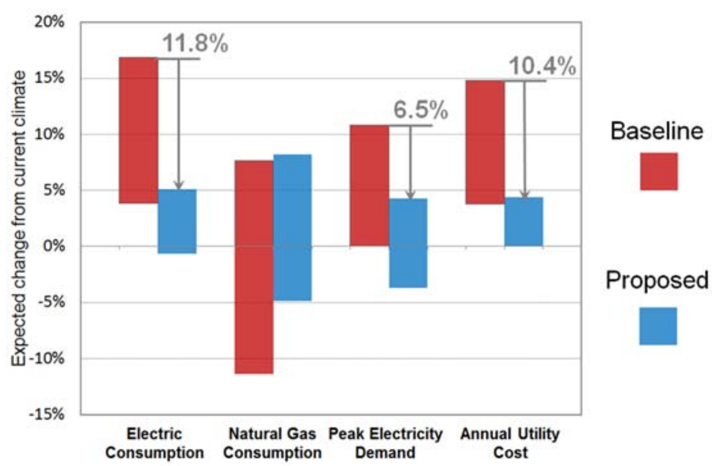

Figure 3: Expected change in building performance for each climate scenario for the Chicago multifamily building

We then individually simulated the actual energy conservation measures pursued for this project — partition insulation, wall insulation, high performance windows, efficient interior lighting, efficient exterior and garage lighting, demand control ventilation, efficient fans, garage, ventilation controls, efficient water heating, efficient HVAC, infiltration reduction, ERV type and effectiveness.

It should be noted that since the building is a 3 story multifamily building, the baseline envelope properties were modeled in compliance with the residential code provisions. These provisions result in a very stringent set of code-required baseline envelope properties. There therefore wasn't significant room for improvement on this project. We expect building envelopes to have a large impact on building performance both in current and future climate scenarios.

However, in this case study, this effect was not observed since the baseline and proposed designs are almost identical.

The most difference between current and future climate performance was observed from the HVAC ECMs, specifically the fan power reduction and efficient HVAC. Figure 4 illustrates the energy impact from fan power reduction and from installing higher efficiency split units, RTU’s and Make-up Air Units. Since the climate models predict an average increase in temperature, most savings are seen from high efficiency cooling equipment.

Increased electricity savings are also realized from high efficiency fans, which save even more energy due to the increase in cooling loads and resulting higher supply airflow rates. Although natural gas usage increase from fan power reductions due to less motor waste heat being available in the air stream, a net savings in energy cost was observed.

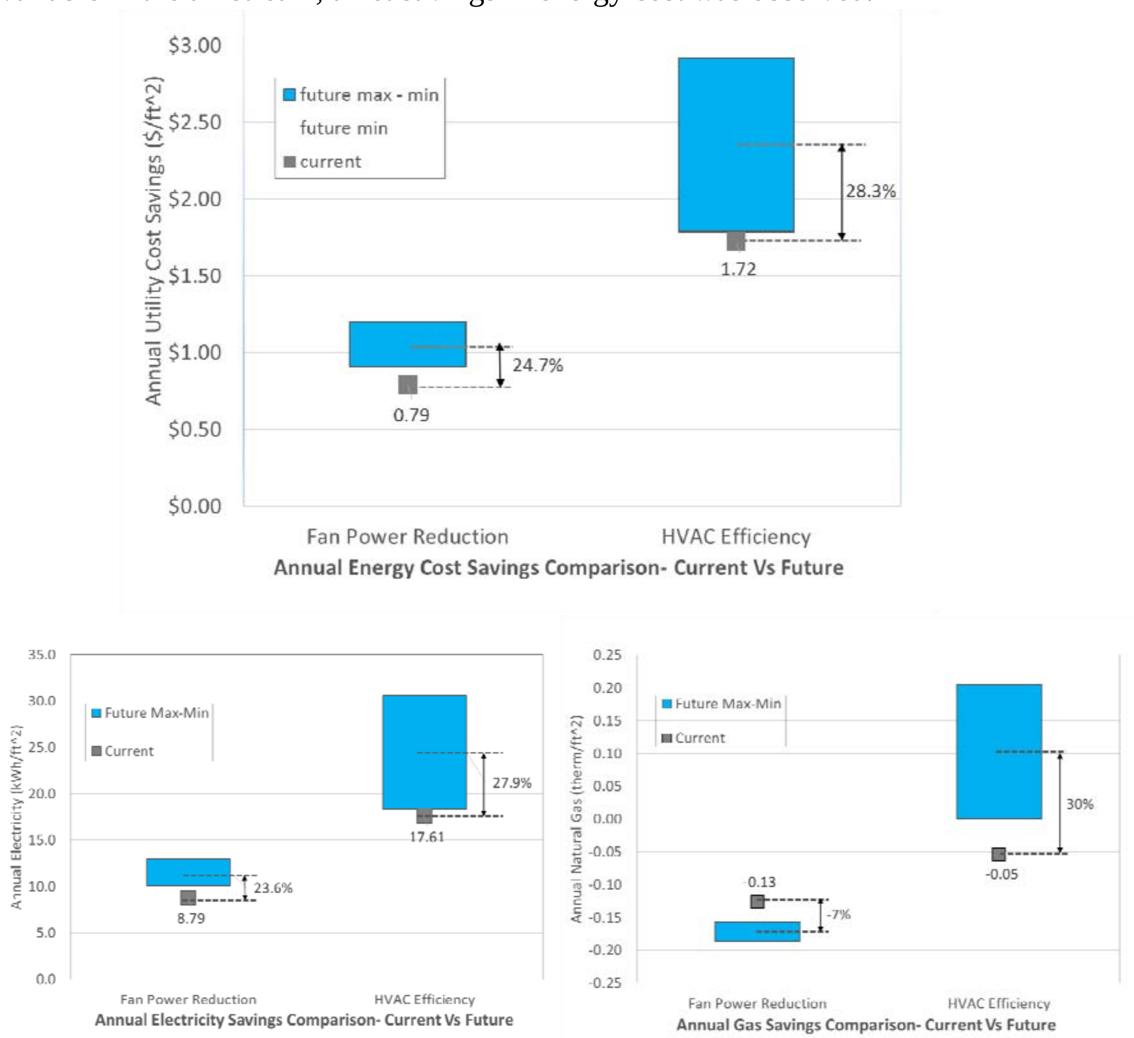

Figure 4: Annual cost and energy savings potential comparison under current and future climate scenarios for HVAC upgrades.

Case 3: Fort Collins Multifamily Building

In order to help us understand how geographic location might influence our results, we repeated the analysis done for Chicago using climate data from Fort Collins, Colorado. We chose

Fort Collins because of the community's progressive policies toward sustainability practices and we were asked by a local power producer to examine these potential effects.

We used the CCSM/CGSM3 model data from the NARCCAP project (Mearns et al. 2007) to represent both current and future conditions for building energy modeling and comparison purposes. We chose the CCSM model data because summary data suggested a high impact (high temperature change) for the region. We did not analyze other scenarios.

Data compiled from one local weather station indicated that average temperature at that station had increased at a rate of 0.15 °F (0.08 °C) per year and 0.13 °F (0.07 °C) per year for the past 30 years for the months of July and January respectively.

The future climate model data for model year 2050 shows an average monthly increase in winter temperatures from 20 to 40% over a current modeled climate year, whereas average summer temperature change is almost 10% (Figure 5).

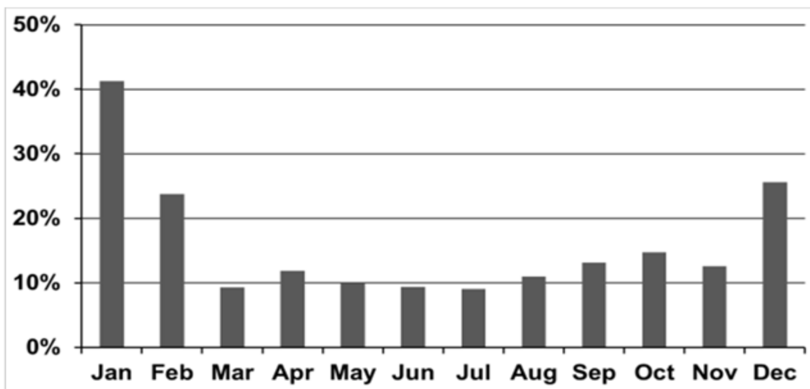

Figure 5: Modeled 2050 average monthly air temperature change from current climate.

We used the building energy model from the Chicago multifamily case study to examine Fort Collins climate impacts. We simulated the same 12 ECMs under both climate scenarios with a baseline case simulated without any energy efficiency upgrades.

Baseline annual electricity consumption for the building increased 2%, peak demand increased 6% and natural gas consumption decreased 18%

Table 3 shows almost 80% of the energy savings under current climate conditions came from efficient fans (37%), efficient lighting (16%), infiltration reduction (15%) and demand control ventilation (11%). In the future climate scenario almost 80% of the energy savings comes from efficient fans (39%), efficient lighting (20%), demand control ventilation (11%), and high performance windows and doors (8%).

Table 3: Comparison of top four energy conservation strategies and their expected energy savings under current and future climate scenario.

Current	Future
Efficient fans 37%	Efficient fans 39%
Efficient lighting 16%	Efficient lighting 20%
Infiltration reduction 15%	Demand control ventilation 11%
Demand control ventilation 11%	High performance windows, doors 8%

Discussion

The results of these three cases are generally consistent with several previous studies that show the expected change in building energy consumption follows the same trend as the projected change in temperature. However, building designers, energy managers, and program planners need more detailed information in order to make sound decisions related to addressing climate resiliency in buildings. We attempted to quantify the effects of climate change on the energy efficiency choices that need to be made when constructing a new commercial building, or retrofitting an existing one. Alongside energy savings, building owners and design teams must consider budget constraints, payback expectations, and design and scheduling concerns when deciding whether to include an energy efficiency upgrade as part of their design. In our cases we showed how simple rank ordering of energy efficiency measures using simulation modeling and climate change data would likely affect how energy efficiency is implemented or even perceived by a building owner. This method makes the energy efficiency component more rigorous from climate resilience perspective than current standard practices, potentially increasing its weight relative to other decision criteria. For example, in the Fort Collins case, where infiltration reduction accounted for almost 15% of the expected energy savings under a current climate, it only accounted for 4% of the expected savings under a future climate. Determining the reasons for this unexpected change were beyond the scope of our work, but also represents an area of new research needed to understand how simulation modeling with future climate data can be used to help develop design criteria for constructing and operating climate resilient buildings. Coley et al. (2012) provide another useful starting point in this regard. They suggest modeling with the 50th percentile of climate change data and examining ‘hard’ mitigation measures to reduce expected climate risk and using ‘soft’ approaches for greater than expected changes.

Future work on this topic could include addressing Lifecycle Cost Analysis benefits from using this method. Additionally, future work could include analysis of the impacts on equipment sizing, as well as the feasibility of utilizing peak shaving technologies such as chilled water storage.

The method developed for this analysis can be implemented in any geographical location and building type. The three case studies outlined illustrate this by analyzing office and lab buildings in southern Mississippi, and multifamily buildings in Chicago, IL and Fort Collins, CO. However, more development is necessary surrounding the criteria for selecting future climate scenarios.

Conclusion

While we apply efficient building technology to new construction and existing buildings, it also contributes to lessening future energy impacts from climate change. By using the approaches of previous studies with the one we developed for this study, we can target mitigation strategies that are most effective for a given region and building type. While results of this study are specific to southern Mississippi, Chicago and Fort Collins, the method could be replicated with other building types and geographic locations. For large organizations that spend millions of dollars on utility bills, changing climate patterns represent a potentially significant risk to facility investments. This study infers that standard energy efficiency approaches are effective strategies to adapt to projected energy use changes and imparts knowledge to industry practitioners on ways to identify and implement climate mitigation resiliency strategies in building design.

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