Future Climate Impacts On Building Design

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The climate is changing as evidenced by ASHRAE Research Project 1453, which recently updated the climate zones and design conditions in ANSI/ASHRAE Standard 169-2013, *Climate Data for Building Design Standards.*[1] How will the changing climate impact building design and operation? For instance, is more cooling or heating capacity needed? What energy conservation technologies will be most effective in the future? At present, there are no standardized methods for estimating future climate impacts to building systems.

In this article, we discuss an initial effort that uses a building energy modeling framework to examine the impacts of future climate variability on the energy consumption, peak energy demand and energy costs at NASA's John C. Stennis Space Center (SSC) in southern Mississippi. We additionally look at adaptation strategies to mitigate the effects of climate change on building energy performance.

Facility Characteristics

We began by collecting building and energy data from SSC for 2011. We found that the building stock at SSC is very diverse in size, age, and function, reflecting the unique scientific nature of the facility and the range of both public and private tenants. The total SSC campus includes 2.9 million gross ft^2 (275 697 gross m^2) of facilities.

In 2011, the SSC campus consumed 99 million kWh of electricity and 1.5 million therms of natural gas. In terms of source energy, natural gas represents 7.5% of campus energy consumption. Generally speaking, the SSC campus consumes just over double the national building average consumption per unit floor area. This reflects the industrial and research nature of the space center and the presence of a number of large data centers. *Table 1* compares SSC campus energy to national averages.

We also collected one-hour electric interval data for the SSC campus from the local electric utility for calendar year 2011. Similar interval data for natural gas consumption was not available. *Figure 1* illustrates that below approximately 60°F (16°C), the electric demand is fairly constant, showing little climate dependence. This confirms that the majority of SSC's heating comes from natural gas. Above approximately 60°F (16°C), the electric demand increases rapidly as the cooling equipment and associated pumps and fans come online to cool the spaces.

Figure 1 also shows that while the electric load profile

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TABLE 1 2011 SSC Campus Energy Consumption

	ELECTRICITY KWH/FT²	NATURAL GAS KBTU/FT²	SITE ENERGY USE INTENSITY KBTU/FT²
SSC Campus	33.3	48.9	162.4
National Average[1]	14.9	40.3	91.0

[1]Energy Information Administration, 2003 Commercial Buildings Energy Consumption Survey: Energy End-Use Consumption Tables E4A and E2A.

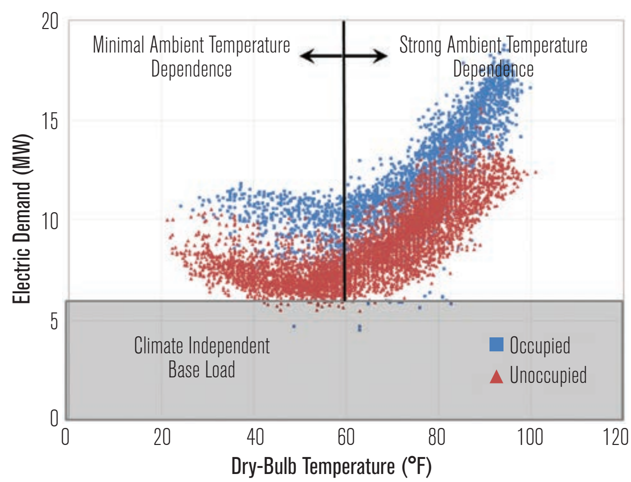

FIGURE 1: SSC hourly electric demand versus outdoor dry-bulb temperature, occupied and unoccupied times.

displays some temperature dependence, there is a substantial amount of consumption that is unaffected by outdoor temperature. This climate-independent energy consumption is primarily due to campus loads such as data center computer consumption and research and industrial process loads.

Climate and Weather Data

We obtained Actual Meteorological Year (AMY) weather data for calendar year 2011 developed from data gathered at the Slidell, La., airport. The Slidell Airport is approximately 10 miles west of SSC with little intervening geography to alter climate. We then used this weather file to calibrate the energy models for each building to calendar year 2011 measured energy data, as outlined below.

Typical Meteorological Year (TMY) data files contain one-hour measured interval data for a given site, and are commonly used in building energy models. The measured data over a range of years is collated into a single typical year. Different periods of each year are selected for the typical year such that the final data set contains diurnal and seasonal variability while giving the same annual averages as the full range of represented years. We obtained TMY data representing the years 1997–2012 developed from data gathered at the Slidell Airport (KASD). This climate file was chosen to represent "present" conditions and was used as the baseline climate file when comparing to future conditions.

We screened 11 different future climate model data sets provided by the North American Regional Climate Change Assessment Program (NARCCAP)[2] and chose two data sets representing low and high impact scenarios. The two scenarios reflected the lowest and highest seasonal dry-bulb temperature increases above current conditions from the 11 climate scenarios surveyed. Each of these data sets contained projected climate data for the 30 mile (50 km) grid encompassing SSC for the years 2041 to 2070. Within each data set, we selected the year with the average annual dry-bulb temperature closest to the median of all years.

TABLE 2 Dry-bulb and wet-bulb temperature summary for AMY, TMY, and future climate scenarios.

	AMY	TMY	LOW IMPACT	HIGH IMPACT
AVERAGE ANNUAL TDB °F	68	71	67	71
AVERAGE SUMMER TDB °F	84	83	79	91
MAXIMUM TDB °F	101	102	109	121
MINIMUM TDB °F	21	26	25	26
HEATING DEGREE DAYS BASE 65°F	1,941	1,248	1,842	1859
COOLING DEGREE DAYS BASE 65°F	3,133	3,322	2,498	4,269
AVERAGE ANNUAL TWB °F	61	64	62	65
MAXIMUM TWB °F	82	84	79	93
MINIMUM TWB °F	19	23	20	26

The low impact climate data for the SSC site shows a general cooling trend 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, a phenomenon that was consistent across most of the climate models for this location. A more sophisticated approach would be to use all of the climate models, as well as each

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of the 30 years of predictions within each. This would yield a range of potential impacts. However, due to budget constraints, we chose the low and high impact approach, which allowed us to approximately bracket the potential range of climate impacts to building performance.

Table 2 (Page 37) compares temperature metrics among the four climate files: AMY (for model calibration); TMY (represents the present climate 1997–2012); Low Impact (future); and High Impact (future).

Originally, we were planning to use the full set of climate variables in our energy models. However, we had less confidence in some climate variables that produce only secondary effects on building energy consumption. One exception to this was solar radiation, which has a sizable influence on building energy performance, but for which the diffuse and direct components needed for building energy modeling were not available. We therefore determined that in order to minimize the impact of secondary climate variables, we would only use NARCCAP data pertaining to dry-bulb temperature, wet-bulb 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.

Energy Models

Energy Model Prototypes

Developing an energy model to represent a campus of buildings can be a complex undertaking. Generally, it is not cost-effective to develop an energy model of every building. Typically, some method of representing, or prototyping, groups of buildings with a single model is developed to reduce the number of models. We attempted to use both group prototyping techniques[3] and a space-type method[4]—but were hindered by the highly heterogeneous building stock at SSC.

While energy consumption of buildings in large campuses varies greatly, it is often the case that a minority of the buildings consume a majority portion of the energy. SSC is no exception to this general rule. As illustrated in *Figure 2,* 31 buildings (of 142) consume 80% of the SSC source energy.

We decided to use this characteristic of campus energy consumption as a building energy model prototyping approach. We constructed energy models of the 31 buildings that consume 80% of the SSC source energy—assuming that these buildings so thoroughly dominate campus energy consumption that their aggregate energy behavior is an appropriate substitute for modeling the entire collection of buildings. Finally, after a site visit to verify building conditions and adding buildings to the list due to shared heating and cooling systems between groups of buildings, a total of 39 buildings were prototyped using 24 separate energy models. The additional eight buildings in the modeled group increased the percentage of source energy represented to a final 85%.

Descriptions of the Models

We built each of the 24 building energy models (representing 39 buildings) in DOE2[5] using eQuest as a graphical user interface. Building geometry, such as footprint and number of floors, was created based on satellite imagery of SSC and building square footage provided by SSC 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 to initially have R-10 insulation. We assumed the walls to be 12 in. (300 mm) medium weight concrete with minimal insulation, and the windows to be single-paned with clear glazing. For the handful of newer buildings in our study, we assumed code required minimum values of insulation and window properties from ASHRAE Standard 90.1-2004, as required under federal regulations near the time of construction. Occupancy density was provided by SSC facility staff. The buildings were predominately considered occupied between 6:00 am and 6:00 pm as corroborated by facility staff and the electric interval data. We preliminarily set lighting to code required values from Standard 90.1-2004 for the building's predominant use type (i.e., 1.0 W/ft^2 [11 W/m^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[6] for a given building's predominant use type. Infiltration flow rates were approximated according to guidelines published by Pacific Northwest National Laboratory.[7]

We modeled HVAC system types according to input from SSC facility staff. The majority of primary HVAC systems for the modeled buildings were variable air volume with hot water reheat. Cooling was provided by water-cooled chillers, while heating was provided by atmospheric boilers. The efficiencies for the HVAC equipment were preliminarily set to code-required minimum values as outlined in Standard 90.1-2004. No demand control ventilation controls were found in the modeled buildings, and only one instance of energy recovery ventilation was found.

Model Calibration and Uncertainty

We then compared initial results from the 24 energy models to the actual monitored energy usage. Discrepancies between the two were assumed to be the result of uncertainty in model inputs such as envelope properties, lighting power, plug load equipment power,

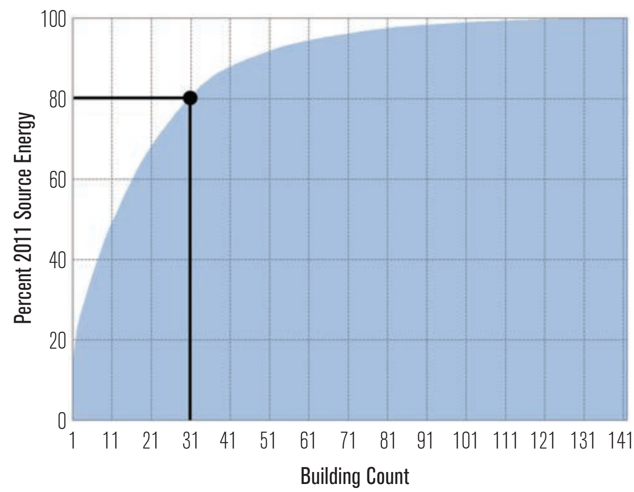

FIGURE 2: SSC cumulative source energy consumption by number of buildings largest energy users first.

infiltration flow rates, outdoor air flow rates and HVAC equipment efficiencies.

We used the Nelder-Mead simplex optimization algorithm[8] to calibrate each of the 24 energy 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 Standard 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, and weighted by the annual cost of each fuel type.

The convergence criteria for the objective function was set to 15% for each model (i.e., GOF <15% 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.

Once the calibration algorithm had been applied to each building energy model, we had a set of models that represented SSC energy use under current climate conditions. Modeled total annual energy use was within 5.5 % and 2.1 % of measured 2011 data for electricity and natural gas, respectively. The coefficient of determination (R^2) between measured and modeled energy use improved noticeably from uncalibrated models (0.86) to calibrated models (0.98) as seen in *Figure 3*.

Figure 3 shows measured and modeled electricity and natural gas consumption both plotted in the same units of energy. The models' monthly predictions are plotted one for one against the monthly measured values. If the model were predicting the measured consumption perfectly, then the points would each lie on a straight line with a slope of one. However, for any given month and model, the predicted value varies from the measured value by some over-prediction or under-prediction. For the uncalibrated data, it is apparent that many of the monthly predictions deviate far from the measured energy usage. Through our calibration effort, we were able to improve the models' agreement, thereby moving each point closer to the line of perfect agreement.

Energy Projections

We then inserted the future climate data into the calibrated energy models to estimate the energy impacts for each climate scenario. Total site energy consumption increased over current climate conditions for each climate scenario we examined. The total projected annual energy cost is expected to increase 8.6% and 17.7% for the low and high impact scenarios, respectively.

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. Interestingly, they project that peak cooling demand will decrease 4.7% under the low impact scenario, due to lower projected summer humidity levels (even though peak dry-bulb temperatures are expected to increase). The low impact peak electric demand decreases 2.4%, following the reduction in peak cooling. Conversely, the high impact scenario projects a cooling peak demand increase of 36.8% and an electrical peak demand increase of 19.4%. This reflects the significantly higher dry-bulb and wet-bulb temperatures projected under this scenario.

Total gas consumption increased 23.8% and 36.0% for the low and high impact scenario respectively, with a corresponding increase in peak heating demand of 37.9% and 43.1%. This follows the generally lower and more variable wintertime temperatures projected under both climate scenarios. *Figure 4* illustrates the results.

Climate Change Adaptation

We identified the energy-efficiency measures needed to offset climate change impacts. *Table 3* outlines each in more detail. The three primary strategies include improving roof insulation, upgrading the water-cooled chillers and installing ventilation energy recovery wheels. Additional roof insulation indirectly 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. Upgrading to more efficient chillers directly reduces the amount of electricity 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

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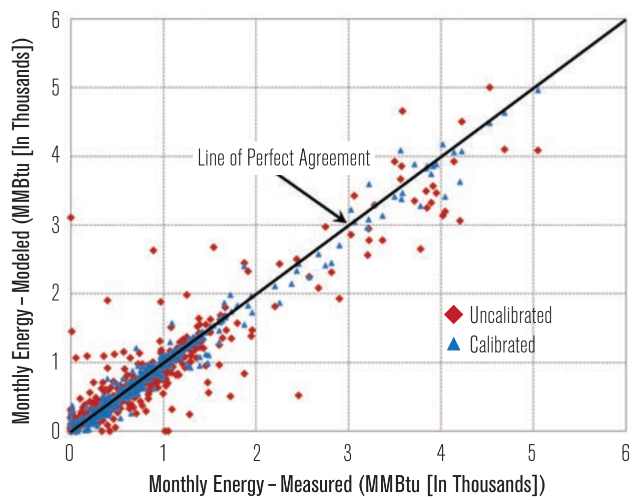

FIGURE 3 Monthly modeled versus measured energy use for all energy models before and after calibration.

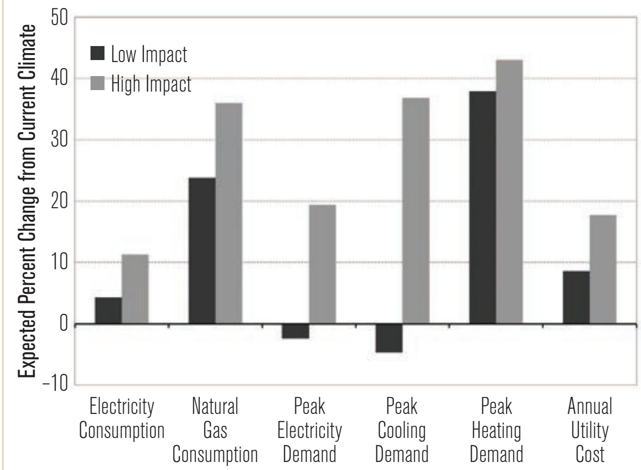

FIGURE 4 Expected change in building performance for each climate scenario.

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.

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Conclusions

Most of the projected energy impacts under the low impact scenario are moderate and do not present a great risk to facilities operations over a timespan of decades. These impacts are moderate due to small projected changes in climate at SSC and by the large percentage of climate-independent energy consumption. Both high and low impact scenarios project increases in natural gas consumption and peak heating demand. From an SSC facilities standpoint, care should be taken in applying traditional methods in the design of heating systems, as results indicate increased capacity may be needed in the future. Or, alternately, care should be taken to decrease heating loads through energy efficient design and retrofit.

The high impact scenario projects potentially disruptive increases in cooling peak demand and resulting peak electric demand. This is due to sizable projected increases in both peak dry-bulb and wet-bulb temperatures. Thermal storage technologies may offer increased value by providing methods to ride-through longer and more frequent peak demand events. Specifying larger capacities for these systems, in particular for campus distribution systems, should be considered during upgrades and new construction (when smaller incremental costs are incurred). Alternately, this study also found that applying conventional energy efficiency technologies, as evidenced by the primary and secondary strategies outlined in *Table 3,* are potentially effective countermeasures to the projected impacts, particularly in building retrofits. Specifically, increasing roof insulation, upgrading to more efficient cooling equipment, and using energy recovery ventilation were particularly effective for SSC. Thus, continuing to apply standard energy efficiency technologies to existing buildings and new construction, while already required for meeting federal energy reduction mandates, will also lessen the impacts from projected climate variability.

We believe that the approach developed in this study is a viable framework that could be used at other sites. However, additional investigation and analysis is needed in the following areas:

- New quantitative and graphical methods should be developed, similar to the work of Shamash[9], to communicate the probability of particular future climate scenarios, or range of scenarios, to facilities personnel so they can properly evaluate risks to facility infrastructure and weigh the costs of adaptation.
- Future climate data is not available in a format readily usable in building energy modeling and a standardized approach has yet to emerge for the selection of appropriate future or baseline climate data.
- More research is needed on applicability of climate model data to site-specific effects. The limits and sensitivity to using downscaled climate model data at a specific site are not fully known.

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TABLE 3 Climate change adaptation strategies at Stennis.

PRIMARY STRATEGIES	DESCRIPTION
ROOF INSULATION	Additional above deck roof insulation, minimum R-20 continuous (R-3.5).
COOLING EQUIPMENT	Upgrade to high-efficiency centrifugal chillers; minimum 0.639 kW/ton (5.5 COP), 0.45 kW/ton-IPLV (7.8 COP-IPLV).
ENERGY RECOVERY VENTILATION	Install enthalpy wheel energy recovery systems on exhaust with bypass and modulation control; 70%+ latent effectiveness, ~0.7 in. ΔP.

SECONDARY STRATEGIES	DESCRIPTION
WALL INSULATION	Add additional wall insulation, 2.0 in. continuous insulation.
HIGH PERFORMANCE WINDOWS	Replace existing windows with low conductivity glass and thermally broken frames; maximum assembly U-Value of 0.35 (0.20).
TIGHTER ENVELOPE	Install continuous air-vapor barrier using spray on air barrier or spray foam to seal the building envelope, 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.

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