ENERGY CENTER
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Energy Center of Wisconsin

Impact of Climate Variability on the Energy Use and Economics of NASA Facilities

NASA Research Opportunities in Space and Earth Sciences 2011 – Grant NNX12AG01G

December 2013

ECW Report Number – 271-1

Impacts of Climate Variability on the Energy Use and Economics of NASA Facilities

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Acknowledgements

The Energy Center would like to acknowledge Rodney Mckellip, Agreement Coordinator at the John C. Stennis Space Center for his assistance in coordinating and gathering large amounts of on-site project data, arranging and scheduling site meetings and providing wide-ranging advice on the general research approach. We would also like to thank the numerous Stennis personnel for contributing their time and data to this project.

The Energy Center also acknowledges the contributions of interns Alexandra Newman and Alisa Petersen for their work in data processing, energy calculations and energy model development. Also, Jim Reichling's literature review was helpful in understanding existing and related research in this field.

This report is based upon work supported by NASA under grant number NNX12AG01G.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

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EXECUTIVE SUMMARY

Energy use in buildings accounts for about 40 percent of the entire U.S. annual energy consumption at a total cost of over $400 billion (U.S. DOE 2011). In FY09, NASA paid $179 million for facility energy and water consumption (NASA 2010). The potential to trim energy use from the built environment, and thereby help curb greenhouse gas emissions, is substantial. However, energy efficiency potential studies often lack consideration of the impacts of potential climate variability on future building energy use and costs. The expected changes in climate variability could have a significant effect on facility energy management planning.

For several decades, federal facilities have been under a series of congressional mandates and executive orders to reduce energy consumption. The most recent legislative requirement is the 2007 Energy Independence and Security Act (EISA 2007) that dictates a 30 percent reduction in energy intensity in federal facilities by FY15. Other recent requirements call for the reduction of water consumption (EO 13514), increases in renewable electricity consumption (EO 13423 and EPACT 2005), climate preparedness and resilience (EO 13653), and various sustainability and greenhouse gas reduction goals (NASA 2010). To meet these on-going and ever-increasing requirements, it is imperative to engage in both short-term and long-term energy planning. Evaluation tools are needed to support the energy planning process through the evaluation of future scenarios; including energy efficiency retrofits, renewable energy production, facility and utility master planning, and the effects of future climate variability.

The goal of this project was to establish a building energy modeling framework to examine the impacts of climate variability on the energy use and operating costs at NASA's John C. Stennis Space Center (SSC). The objectives of our work were to:

1) Quantify expected impacts and uncertainty in future energy consumption, peak energy demand, and energy costs due to climate variability at the SSC facility.
2) Evaluate potential adaptation approaches through the application of energy efficiency technologies.
3) Determine the viability of the proposed energy modeling approach as a long-term energy and utility planning tool to meet energy reduction mandates.
4) Foster collaboration and information sharing by participating in agency-wide meetings and outreach efforts.

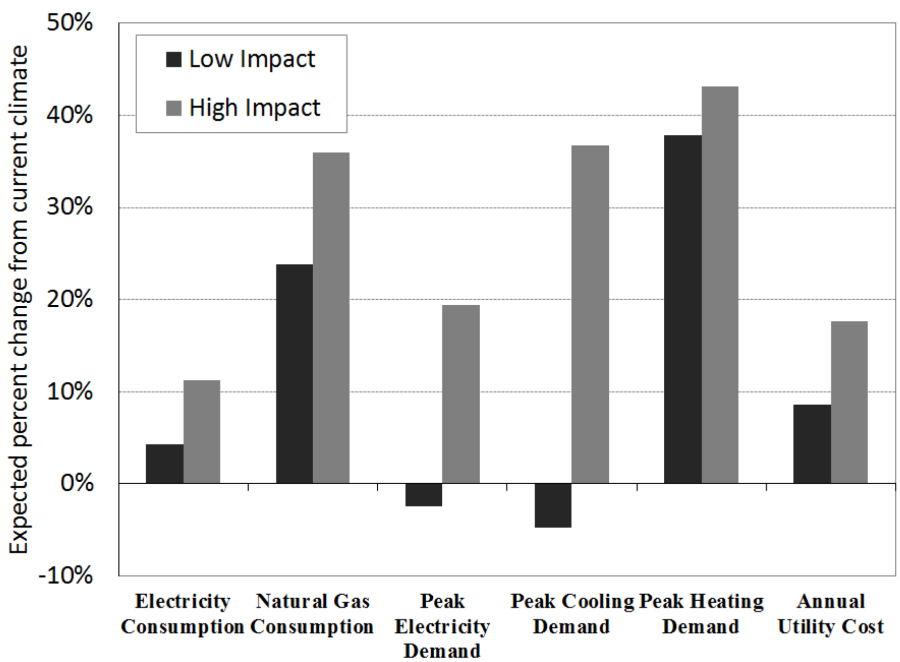
Our project team collected building characteristics and energy consumption data from SSC for 2011. We developed and calibrated building energy models for buildings representing 85 percent of the total SSC source energy consumption. Source energy consumed at SSC was 2,229,548 MMBtus in 2011 with 92.5 percent of that from electricity and the remainder from natural gas. The site has 4.58 million square feet of building area giving it an Energy Use Intensity (EUI) nearly twice the national average. The high EUI is a result of data centers and industrial processes at the site. The average electric demand at SSC was 21 MW in 2011 with 11 MW coming from one data center alone. A baseline energy consumption profile was established using current climate data.

We screened 11 different future climate model data sets provided by the North American Regional Climate Change Assessment Program (NARCCAP) and chose two data sets and two future climate years within each for a total of four future climate scenarios. The two future climate data sets represented low and high impact scenarios, respectively. The two future climate years within each data set represented the year with the median annual temperature and the year with the hottest summer temperatures. Downscaled hourly future dry bulb and wet bulb temperature were substituted into the energy models to estimate future energy consumption. Due to data quality concerns we held solar radiation, wind, and precipitation to current climate levels.

The low impact future climate data we used show that SSC could have average annual temperatures that are 4 °F lower compared to the current climate and cooler minimum annual temperatures. In this case only maximum annual temperatures were higher than current conditions, with an increase of 11 °F. The high impact future climate scenarios show only a slight increase in annual average temperature but an increase of as much as 22 °F for maximum summer temperature. Additionally, winters are expected to become cooler with an increase in heating degree days.

Future climate data were inserted into calibrated energy models to estimate energy use for each climate scenario. Total energy consumption increased over current climate conditions for each climate scenario we examined. Total electricity consumption increased 4.3 percent and 11.3 percent for the low and high impact future scenarios, respectively. Total gas consumption increased 23.8 percent for the low impact scenario and 36.0 percent for the high impact scenario. Annual cost is expected to increase 8.6 percent and 17.7 percent for the low and high impact scenarios, respectively. While peak electricity and cooling demand are expected to increase under the high impact scenario, they are expected to decrease under the low impact scenario. Figure 1 illustrates the expected future percent change relative to current climate conditions at SSC.

Figure 1. Expected change in building performance for each climate scenario.



To examine climate change adaptation, we calibrated our models using an optimization algorithm to identify the energy efficiency measures needed to mitigate climate change effects. The three primary strategies we identified included improving the roof insulation, upgrading the water-cooled chillers and installing ventilation energy recovery wheels. Additional roof insulation would indirectly reduce the cooling and heating loads at SSC during the more extreme summers and winters because it would minimize the amount of energy the heating and cooling equipment would be using under the future scenario. Upgrading to more efficient chillers would directly reduce the amount of cooling energy needed to offset the increased need for cooling during the hotter summers. The energy recovery ventilation would recover energy from the exhaust air stream, minimizing the wasted energy that had already gone in to conditioning the hotter or colder outside air.

We also identified four secondary strategies. The first three of these strategies, increasing wall insulation, installing high performance windows, and minimizing air leaks, indirectly reduce energy use by isolating the conditioned indoor environment from the outdoors. Additional wall insulation decreases the amount of heat that escapes the building through the walls. Better windows decrease the amount of heat that pass through the windows. Tighter envelopes allow less outside air to directly infiltrate into the building. By further isolating the building from the outdoors, these measures would help to improve SSC's climate resiliency. The fourth strategy, upgrading to condensing boilers, would directly reduce the amount of heating energy needed to offset the increased need for heating during the colder winters.

Table 1. Strategies for mitigating climate change effects on energy use 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	**Description**
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 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

Most of the projected energy impacts in this study are moderate and do not present a great risk to facilities operations over a timespan of decades. One possible exception is the consistent projected increase in natural gas consumption and peak heating demand. Care should be taken in applying traditional decision-making for the design of heating systems, as results indicate increased capacity may be needed in the future. There is an outside chance of large increases in all peak demands: electricity, heating and cooling. Specifying larger capacities for these systems should be considered in all long-term facilities planning decisions, especially during upgrades and new construction when smaller incremental costs are incurred. Also, this study indicates that conventional energy efficiency technologies may be an effective method of mitigating climate change impacts. Thus, continuing to apply standard energy efficiency technologies to existing buildings and new construction, while already required for meeting energy reduction mandates, will also contribute to lessening the energy impacts from climate change.

Key observations from this study include:

- Annual electricity and natural gas consumption increase at SSC under each climate scenario tested. Consequently annual cost would be expected to increase.
- Adaptation to projected energy impacts at SSC can likely be attained using standard energy efficiency approaches.
- The approach developed in this study could be replicated at other sites around the nation.
- Additional analysis is needed to assess the limits and applicability of utilizing downscaled future climate data in building energy models.

OVERVIEW OF APPROACH

We characterized the building stock and energy consumption at SSC by collecting a variety of facility data, such as: building types, building areas, building vintages, building-level energy consumption and campus-level utility data. We used this data to evaluate approaches to modeling campus energy consumption—with the final approach involving the construction of building energy models that represent 85 percent of the total SSC source energy consumption. For this study, SSC source energy consumption is defined as the 2011 total source energy consumption of all buildings at SSC, not including the buildings in area 9 (i.e., none of the 9000 buildings, including the large NCCIPS data center). The area 9 buildings are not historically considered part of the SSC campus. Additionally, source energy, as opposed to site energy, was used for determining the 85 percent criteria. Source energy involves converting any electrical consumption into the energy content of the generation fuels, accounting for electric transmission and distribution losses and accounting for small losses in the production and distribution of natural gas.

We conducted a site survey to verify existing building conditions and to meet with facilities managers. The information gathered during the site survey was combined with the facilities data to create building energy models for each of the buildings comprising the 85 percent set. We then calibrated the energy models to 2011 measured energy consumption using an iterative algorithm.

We developed future hourly annual weather data through the modification of NARCCAP climate model data sets. This data was then input into the calibrated building energy models to estimate future climate impacts on annual electric and natural gas consumption, peak electric demand, peak heating demand, peak cooling demand and annual energy cost.

Finally, we used the energy models to explore and develop adaptation strategies to the projected climate impacts.

FACILITY DATA

Several databases of building information were provided from NASA Headquarters Office of Strategic Infrastructure for all facilities located at SSC. One database contained building numbers, names, gross building areas and construction dates for each building. From this database the general purpose, size and age of the buildings was determined. Another database listed the building number, name, total net floor area and individual floor area of the various space types contained within each building (e.g., office, conference, training, laboratory. etc.). This database helped to further refine the general purpose of each building.

BUILDING TYPES, AREA AND AGE

We found that the building stock at SSC is diverse, ranging from typical office buildings to research laboratories, from military training centers to high-tech fabrication plants, from large data centers to enormous rocket engine test stands. These administrative, industrial, testing, training and research functions are housed in buildings ranging from 53 square feet up to 700,000 square feet. All buildings were constructed after 1960, with a relatively large group originating during the space programs of the 1960’s and a variety of other buildings constructed throughout the remaining decades. See Table 7 for an indication of the wide range of building functions at SSC.

CAMPUS-LEVEL ENERGY DATA

Based on building-level metered energy data, the SSC campus consumed the following energy in calendar year 2011:

Table 2. 2011 SSC energy consumption.

	Electricity [kWh]	Natural Gas [therms]	Site Energy [Million Btu]	Source Energy[1] [Million Btu]	Source Energy from Natural Gas
SSC Campus	98,726,614	1,451,800	481,973	1,341,841	7.5 %
SSC Campus + Area9	172,057,399	1,531,200	740,179	2,229,548	7.5 %

Calendar year 2011 energy statistics on a per-square-foot of gross building area basis include the following:

Table 3. 2011 SSC energy consumption on a per-square-foot of gross building area basis.

	Gross Building Area [square feet]	SSC Electric Consumption [kWh/GSF]	U.S. Average Electric Consumption[2] [kWh/GSF]	SSC Natural Gas Consumption [Btu/GSF]	U.S. Average Natural Gas Consumption[2] [Btu/GSF]	SSC Site Energy Consumption [Btu/GSF]	U.S. Average Site Energy Consumption[2] [Btu/GSF]
SSC Campus	2,967,576	33.3	14.9	48,922	40,300	162,413	91,000
SSC Campus + Area9	4,578,429	37.6	14.9	33,444	40,300	161,667	91,000

These statistics lead to the following observations:

- The SSC campus consumes a lot of electricity—just over double the national building average consumption per square foot. This is not surprising considering the industrial and research nature of the space center.
- Electricity consumption dominates total energy consumption. Natural gas consumption is a mere 7.5 percent of total source energy—the rest is electricity.

We collected detailed campus-level electric consumption data from Mississippi Power Company, the local electric utility. One-hour interval data from three main metering points were obtained for calendar year 2011 (Figure 2). Similar interval data for natural gas consumption was not available.

The 2011 hourly electric interval data yield the following statistics for electric consumption at SSC (these numbers include area 9):

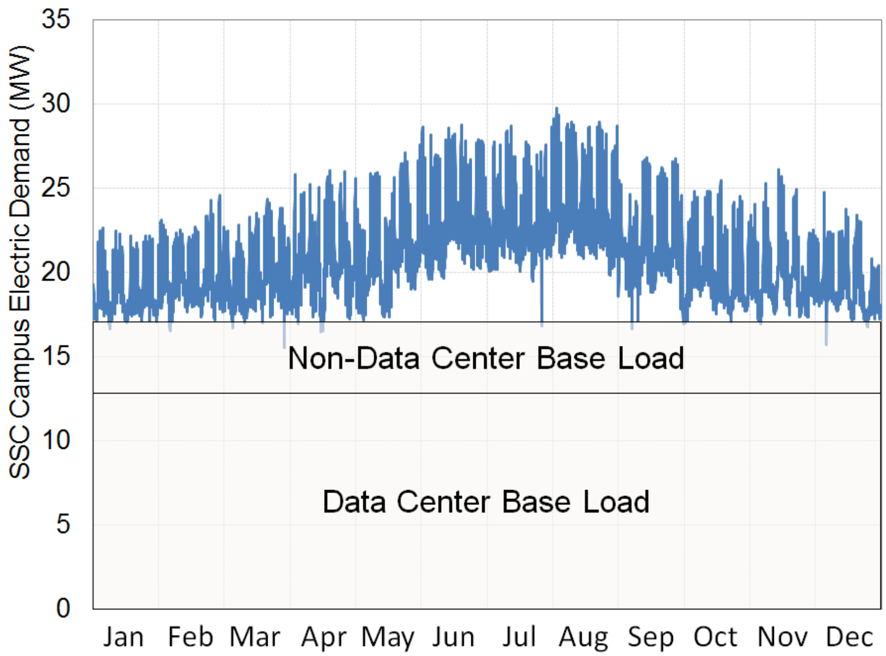
- Peak Demand: 29.7 MW
- Minimum Demand: 15.5 MW
- Average Demand: 20.9 MW
- Load Factor: 70 percent

[1] Source energy conversions were obtain from "Source Energy and Emissions Factors for Energy Use in Buildings" NREL Technical Report NREL/TP-550-38617 June 2007. An electric conversion factor of 3.513 (Table B-9 Mississippi Total Precombustion Source Energy Factor) and a natural gas factor of 1.092 (Table 5 Source Energy Factors for Fuel Delivered to Buildings) were utilized.

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

The annual 2011 electric consumption as measured at the utility delivery points was 183,434,911 kWh, or 6.6 percent more than measured at the building-level. This discrepancy reflects losses in transformers, the local distribution system and consumption by unmetered end-uses such as street and parking lot lighting.

Figure 2. SSC 2011 campus electric demand profile (including area 9).



Variations in electric demand from morning to night, from weekday to weekend, and from winter to summer are clearly visible. There is a constant 24×7 demand of 17 MW year-round. From informal discussions with SSC facilities staff, it is likely that roughly 13 MW of this demand is due to large, relatively consistent data center consumption.

Figure 3 displays the variation in electric demand imposed by workday building occupancy, with increased electric demand occurring around 6:00 am, peaking around midday, and then declining to a base value around 7:00 pm.

Figure 3. SSC Average campus daily electric load profile – by day type (includes area 9).

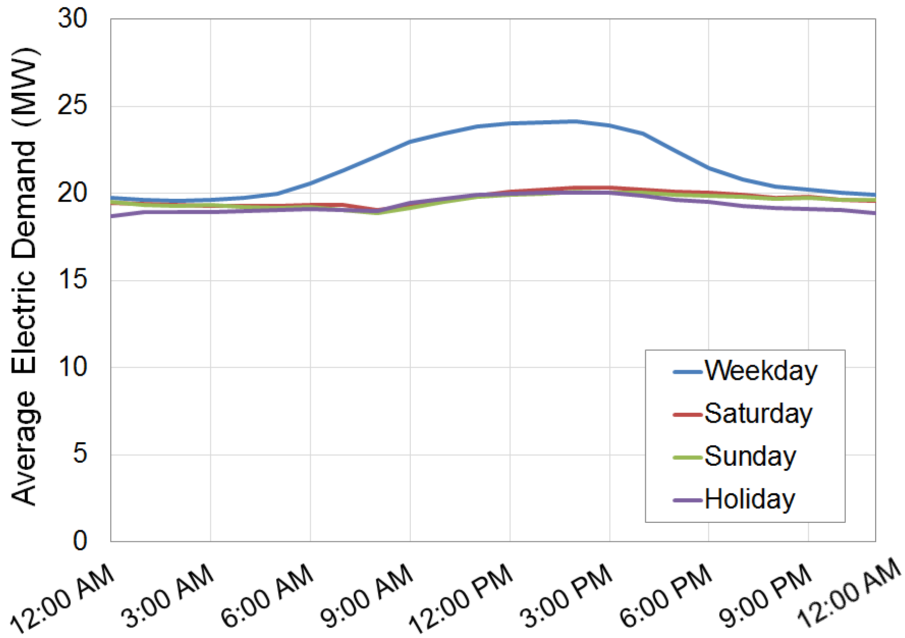


Figure 4 illustrates that below approximately 60 °F, the electric demand is fairly constant, showing little climate dependence. This confirms the fact that the majority of SSC's heating comes from natural gas, although there is a slight increase with decreasing temperatures, displaying some evidence of electric heating. Above approximately 60 °F, the electric demand increases rapidly as the cooling equipment and associated pumps and fans come online to cool the spaces. The data are further divided between occupied (7am-7pm weekdays) and all other times, again displaying the influence of workday occupancy times. Occupancy tends to increase electric demand by approximately 4 MW.

Figure 4. SSC Campus hourly electric demand versus outdoor drybulb temperature – occupied and unoccupied times (includes area 9).

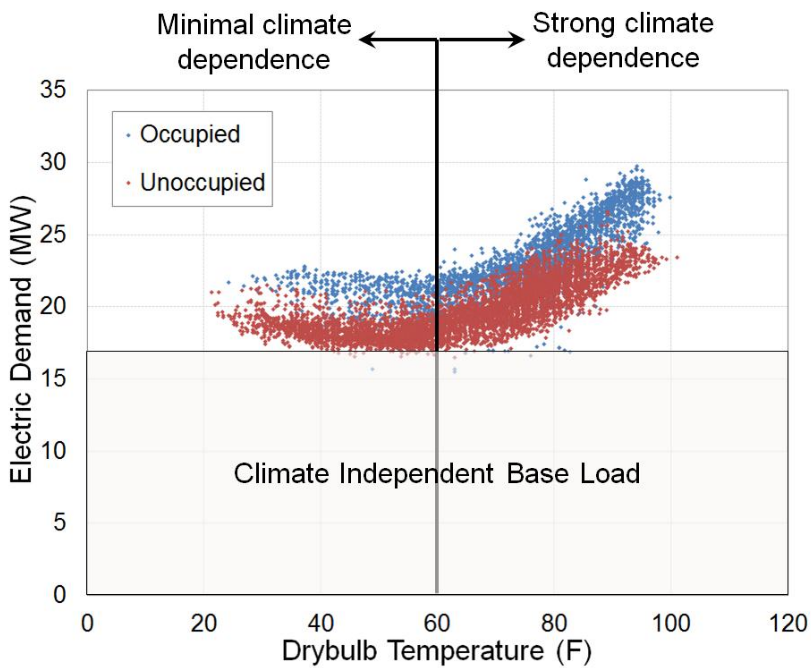


Figure 4 also shows that while the electric load profile displays some temperature dependence, there is a large amount of consumption that is unaffected by outdoor temperature. This climate-independent energy consumption is primarily due to campus loads such as data center computer consumption and research and industrial process loads. Therefore large portions of campus energy consumption will be unaffected by climate variations.

BUILDING-LEVEL ENERGY DATA

The SSC energy manager provided building-level monthly energy consumption data for fiscal years 2011 and 2012. Data for every campus building, for both electricity and natural gas were available. The data did not contain monthly peak demand values for electricity. These data were combined with the database containing building areas and building types.

BUILDING PROTOTYPING FOR ENERGY MODELING

Developing an energy model of 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. Four approaches were considered for this study.

MODEL ALL BUILDINGS

Using this approach, about 140 individual energy models would need to be developed to directly represent the building stock at SSC. We estimated this effort would inflate the project budget by nearly ten times, and was therefore discarded.

GROUP PROTOTYPE METHOD

Under this approach, facility property and energy consumption data are used to classify groups of similar buildings (Beasley 1996). Within each group, a prototype building is selected that is most representative with respect to size, age, occupancy patterns, and energy systems. A building energy model is then constructed to represent that prototype, and all other buildings in the group.

We attempted to utilize this approach; however the diversity of building types and functions at SSC made it difficult to group buildings that maintained similar characteristics. For example, one of the most homogeneous building groups is typically offices. However, within the SSC office group, on average each building only contained 48 percent office space, and there was wide variation in energy consumption. This trend became worse with more diverse building groups such as laboratory and storage. We ultimately determined there were no suitable prototype buildings in the groups to represent such diverse characteristics.

BUILDING SPACE-TYPE METHOD

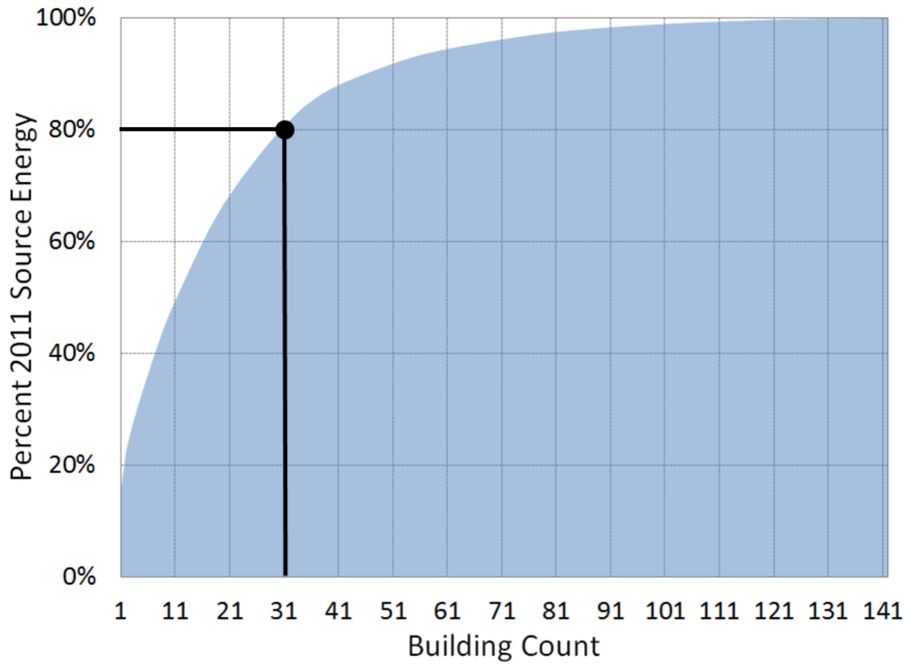
We attempted to address the problem of diverse building types by considering the development of energy models that solely represent single space types within buildings, such as office, shop, training, warehouse, and conference. The energy consumption determined by these models (per space type, per square foot) could then be scaled up to represent each building's unique mix of space types. This would dramatically reduce the number of required energy models, and potentially account for the individuality of each building. A similar approach was investigated by Brugman et al. (2012).

We rejected this approach after learning that the allocation of space types within the space type database likely was not consistent across or within NASA facilities. For example, the exact definition of a "technical" space versus a "laboratory" space may differ among facilities.

EIGHTY PERCENT METHOD

The energy consumption of buildings in large campuses varies greatly. However, 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 5, 31 buildings (of 142) consume 80 percent of the SSC source energy.

Figure 5. SSC cumulative source energy consumption by number of buildings—largest energy users first.



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 percent 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 and accounting for shared heating and cooling systems between groups of buildings, a total of 39 buildings were prototyped using 24 separate energy models. The additional 8 buildings in the modeled group increased the percentage of source energy represented to a final 85 percent.

ON-SITE BUILDING SURVEY

We conducted a two day on-site survey to collect detailed information on the 39 buildings of interest. A great deal of coordination took place with SSC staff to arrange and schedule security access and meetings with individual building managers.

SURVEY APPROACH

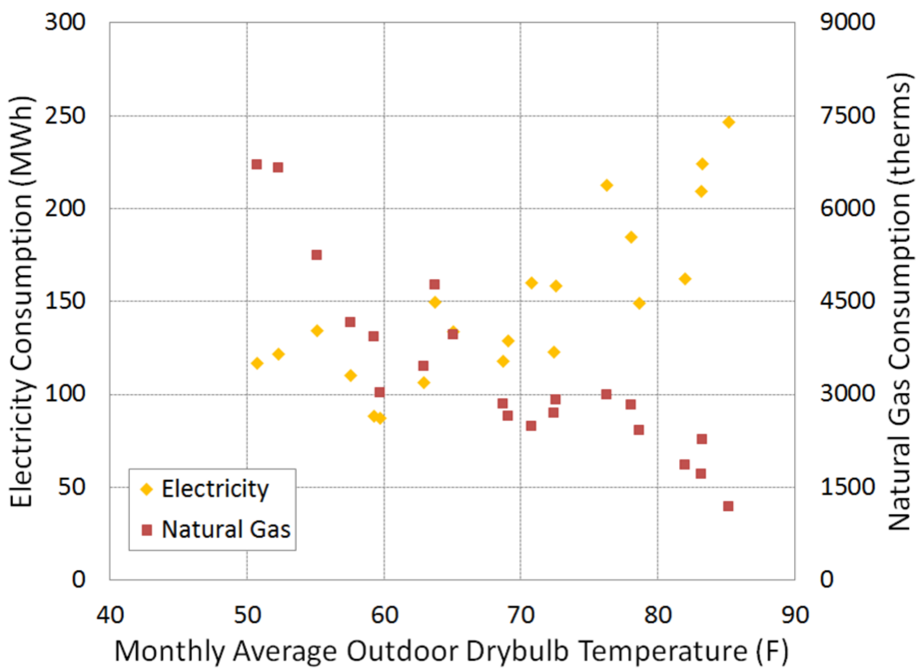
We requested the following information for each building before arriving for the site survey:

Table 4. Building information collected prior to site survey.

Year Built or Last Major Renovation	**Building Type**	**Occupied Times**	**Number of Floors**	**Total Floor Area**
Number of Occupants	Heating Fuel Source	Roof Type & Insulation	Wall Type & Insulation	Glazing Type & Number of Panels
Window-to-Wall Ratio	Exterior Shading Devices	Air-Side System	Cooling Type	Heating Type
Heating Setpoint	Cooling Setpoint	Temperature Setbacks?	Relative Humidity Setpoint	Economizer?
Energy Recovery Ventilation?	Demand Control Ventilation?	Lighting Description	Daylighting Controls?	

We developed building summary forms for the site visit that included graphs of monthly electric and gas consumption versus monthly average outdoor temperature. These graphs provided insight into the energy consumption behavior of individual buildings and allowed for site visits to focus mainly on missing details and verification of confusing data. The graphs also provided insight into the climate-dependent energy characteristics of each building before it was inspected. For example, some buildings displayed little correlation between electric consumption and outdoor temperature. They either had no cooling or were receiving cooling in the form of chilled water from another building. This was helpful to know before inspection. The graphs also helped isolate which buildings had little to no climate dependence, allowing us to confirm constant energy loads. Figure 6 is an example set of electricity and natural gas consumption data for building 1022.

Figure 6. Building 1022 monthly electricity and natural gas versus monthly average outdoor drybulb temperature.



From this graph, it was evident that building 1022 had strong climate dependence for both electricity and natural gas. For example, electricity consumption is relatively constant below 60 °F. However, above 60 °F, its electricity consumption increases rapidly. The inverse is true for natural gas consumption. As the monthly average outdoor drybulb temperature increases, the building’s natural gas consumption decreases

CLIMATE AND WEATHER DATA

Selecting the appropriate weather data for our calibration effort and future climate scenarios was an important and complex part of this project. We therefore spent much of our time understanding a variety of datasets and their strengths and weaknesses. The following section summarizes each as well as compares the ones we used in our modeling effort.

ACTUAL YEAR WEATHER DATA

Actual Meteorological Year (AMY) weather data contain one-hour measured interval data for a given site. AMY data for SSC was acquired from Weather Analytics Inc., a company specializing in providing weather files in a variety of formats. Their AMY data for a given site are interpolated from surrounding ground stations. Remote sensing data are used to fill in gaps and update historical data. The AMY files are available for a given year or 12 month range between 1980 and 2012. We purchased an AMY weather file from Weather Analytics for calendar year 2011, which was developed from data gathered at the Slidell Airport (KASD). The Slidell Airport is approximately 20 miles west of SSC and approximately as far from the Gulf of Mexico as SSC. This weather file was then used to calibrate the energy models for each building to the 2011 measured energy usage data.

TMY3 WEATHER DATA

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. Standard TMY3 climate files were created by the National Renewable Energy Laboratory from 1,020 monitoring locations throughout the US and represent 1976 to 2005, the most recent range to date (Wilcox 2008). We purchased a TMY3 climate file from Weather Analytics 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 in the building energy models.

FUTURE CLIMATE DATA

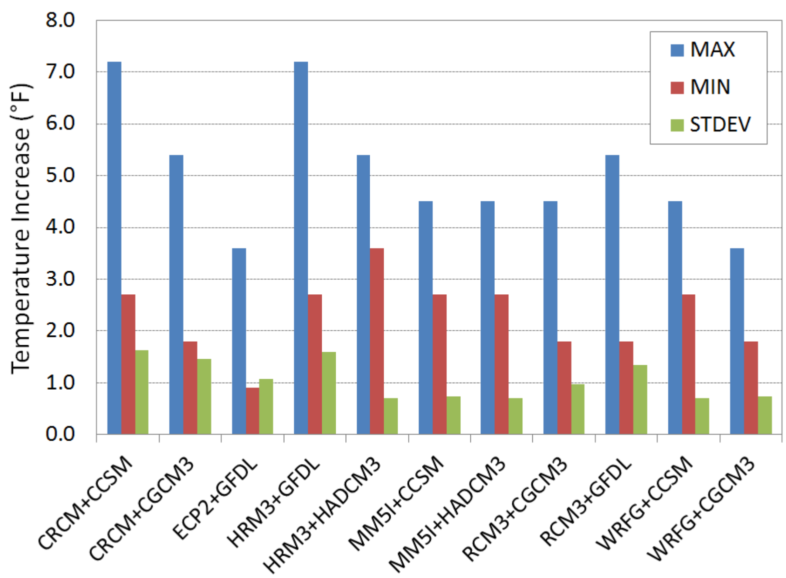
We acquired a future climate data set from Harkey and Holloway (2013), which was derived from the National Center for Atmospheric Research (NCAR) North American Regional Climate Change Assessment Program (NARCCAP) data. The three-hour interval data contained several variables including shortwave downwelling radiation, cloud fraction, drybulb temperature, dewpoint temperature, relative humidity, atmospheric pressure, wind speed, wind direction, snow accumulation, and precipitable water.

The climate simulations included in NARCCAP represent estimates of possible regional climate scenarios from research groups in the U.S., Canada, and the United Kingdom. NARCCAP has imposed a number of guidelines for contributing model simulations. These guidelines require that all NARCCAP simulations represent future weather on a 50 km × 50 km horizontal grid across North America. Also, all future simulations are based on the same assumptions about future economic growth, energy use and emissions as represented by the A2 scenario in the *Special Report on Emissions Scenarios*, an Intergovernmental Panel on Climate Change report. All NARCCAP participant models combine information from a global climate model (GCM) with a higher resolution regional climate model (RCM), and all NARCCAP participants define the future as 2041-2070. All complete model submissions provide 30 years of future weather across North America, every three hours of every day.

Harkey and Holloway (2013) found that the GCM that most reasonably reflected the historic summertime temperatures over the eastern U.S. was the Weather Research and Forecasting Model as driven by the Community Climate System Model (WRFG+CCSM). They also identified the average coolest and warmest future years from the 30-year data set and provided us with the corresponding downscaled weather variables for SSC.

We decided to expand our future climate analysis beyond the coolest and warmest years of only one GCM scenario. In order to get a sense of the range of predicted future temperature increases, we examined the data published by NARCCAP for a series of 11 combinations of RCMs and GCMs (NARCCAP, 2013). By visual inspection of the temperature contour maps, we determined the seasonal temperature increases over current conditions for each combination near SSC (Figure 7).

Figure 7. Predicted temperature increase for 11 future climate scenarios. Max and min represent the range of the contour band as determined by visual inspection of online published data. Note that the baseline temperature used in this comparison represents the climate model (RCM+GCM) run under current conditions.



From this preliminary analysis, we determined that the CRCM+CCSM combination represented the largest increase, particularly in the summer months, of the future climate scenarios (Figure 8). We also determined that the WRFG+CCSM combination represented a median increase when compared to the other future climate scenarios. From each 30-year future data set, we chose an extreme year and a median year to use in our energy models.

Figure 8. Monthly average temperature for each of the 30 years for the CRCM+CCSM and WRFG+CCSM future climate scenarios.

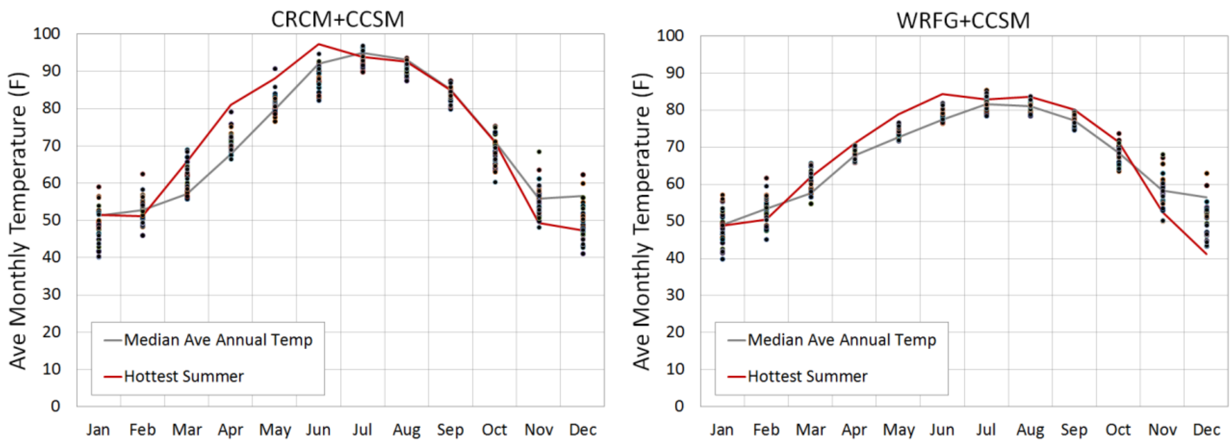


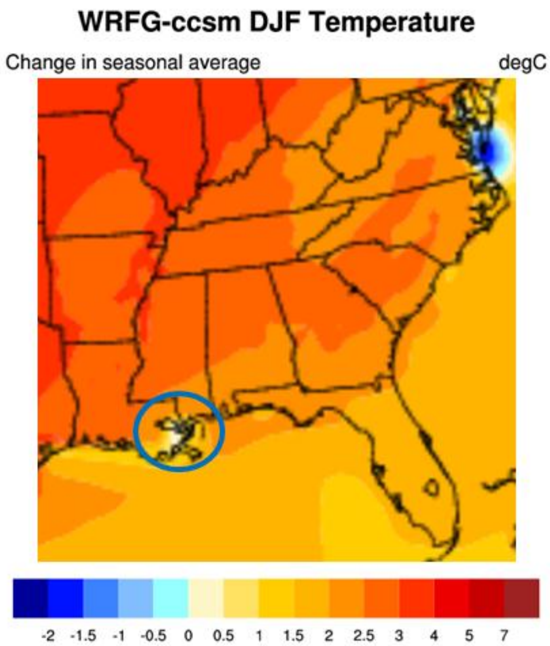
Figure 8 shows each of the 30 years of data as black circles, with the years we selected for further study called out as lines. From this analysis, we were able to find the year with the median average annual temperature and the year with the hottest average summer temperature. Note that the year with the hottest summer did not necessarily contain the highest hourly temperature of the entire 30 years. Another interesting observation is that the year with the hottest summer tended to have a cooler winter than the median year. In this way, we were able to identify four future climate years that bookended the range of predicted temperature increases. Those four scenarios were Future Middle – Average Annual (WRFG+CCSM 2052), Future Middle – Maximum Summer (WRFG+CCSM 2069), Future High – Average Annual (CRCM+CCSM 2052), and Future High – Maximum Summer (CRCM+CCSM 2069). A more comprehensive analysis would include building energy models run against each of the 30 years in all of the future climate combinations and a statistical range of results. In this way, the study would capture the full range of possible future climate impacts. However, due to time and budgetary constraints, we chose this bookending method as a means to minimize computational time while allowing nearly the full range of outcomes.

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. We therefore determined that in order to minimize the impact of secondary climate variables, we would only use NARCCAP data pertaining to drybulb temperature, wetbulb temperature, atmospheric pressure and corresponding atmospheric variables that could be calculated directly from these primary variables (i.e. enthalpy). We did not use any solar radiation, wind, or precipitation inputs from NARCCAP, but rather kept them consistent on an hour-by-hour basis with the current climate file being compared against TMY3. The three-hour data were linearly interpolated to a one-hour time interval required by our building energy models. As the future climate variables were processed from their raw NARCCAP format to a format usable by building energy models, they were each checked for consistency between file types. Additionally, each climate input's variation across the entire year was checked such that it was within an expected range.

Characteristics of Future Climate Data near Stennis Space Center

The future climate scenarios near SSC warrant closer inspection. The regional predictions for the Southeast show a statistically significant increase in annual mean temperature for both low emission and high emission scenarios (Kunkel 2013). The region is predicted to experience an increase in the number of days above 95 °F, a decrease in the number of days below 10 °F to near zero, and an increase in the number of wet days. However, the climate change impact at SSC varies somewhat from the regional trends. It is apparent that SSC does not have the same magnitude of temperature increase as the rest of the region either for the WRFG+CCSM or for the other scenarios (Figure 9). ***It should be stressed therefore that, due to the local nature of our future climate data, future climate impacts within this report should not be extrapolated to the U.S. Southeast region as a whole.***

Figure 9. Seasonal temperature increase for the southeast region.



Comparison of AMY, TMY3 and Future Climate Data

The average annual temperature increased for only one (Future High – Maximum Summer) of our future climate scenarios over current typical values. Table 5 compares the four climate scenarios' drybulb temperatures to actual and TMY3 climate data sets.

Table 5. Drybulb temperature summary for the AMY, TMY3, and Future climate scenarios.

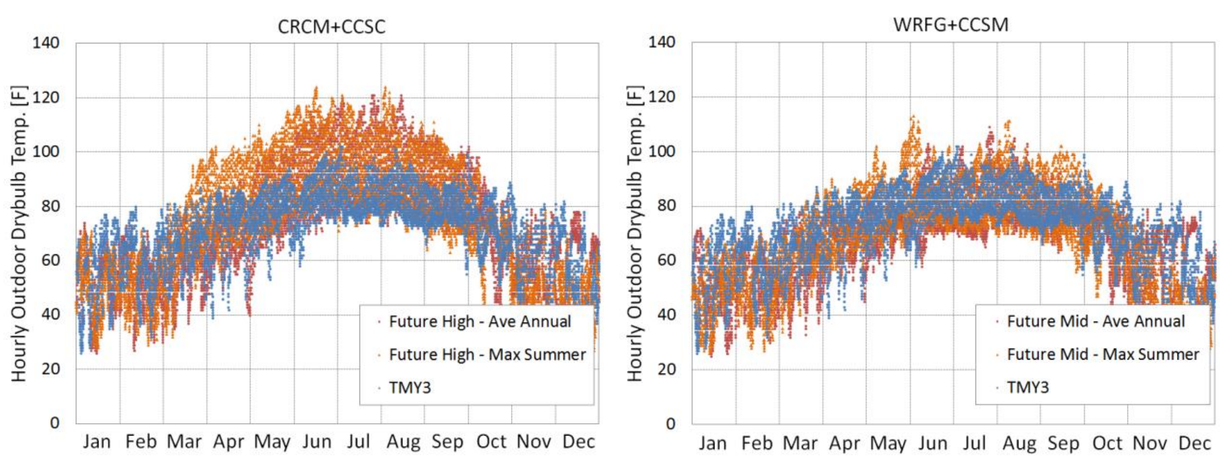
	AMY	TMY3	Future Mid. – Ave. Ann.	Future Mid. – Max. Summer	Future High – Ave. Ann.	Future High – Max. Summer
Ave. Ann. DB Temp. [F]	68	71	67	67	71	73
Ave. Summer DB Temp. [F]	84	83	79	83	91	92
Min. Ann. DB Temp. [F]	21	26	25	23	26	24
Max. Ann. DB Temp. [F]	101	102	109	113	121	124
Heating Degree Days	1941	1248	1842	2312	1859	2048
Cooling Degree Days	7192	7780	6534	7057	8293	8916

As described previously, the AMY climate file was used for calibrating the models to actual 2011 energy usage. However, the TMY3 climate file was used when comparing current energy usage to the four future climate energy usages. It is useful therefore to note the differences between the TMY3 and future climate scenarios. As we already mentioned, only one of the future climate scenarios has a higher average annual temperature than the TMY3 file.

Both of the Future Middle scenarios have 4 °F lower average annual temperatures. They also have cooler minimum annual temperatures. They both have lower or equivalent average summer temperatures as well. Only their maximum annual temperatures are higher, showing a 7 and 11 °F increase, respectively. These trends are reflected in the cooling degree days and heating degree days.[3] For both Future Middle scenarios, the cooling degree days decrease and the heating degree days increase, meaning that from the perspective of these simple climate metrics the climate is colder.

Both of the Future High scenarios showed increased temperatures with marginally higher annual average temperatures, but on average 8 and 9 °F higher summer temperatures. The maximum annual temperatures show the largest increase of 19 and 22 °F. The cooling degree days for both Future High scenarios increase. Counter to intuition, the heating degree days for these two scenarios actually increase. This means that both the cooling and heating systems for these scenarios will likely have to work harder. Figure 10 illustrates the hourly drybulb temperature profiles for the Future High and Future Middle climate scenarios as compared to the TMY3 dataset.

Figure 10. Hourly drybulb temperature profiles for the Future High and Future Middle scenarios as compared to TMY3.



Note that both of the Future High scenarios showed a marked elevation in temperatures, in particular during the summer months. The Future Middle scenarios each were more in line with the TMY3 dataset, with short periods of extreme temperatures during the summer months.

Table 6 compares the four future climate scenarios' wetbulb temperatures to actual and TMY3 climate data sets.

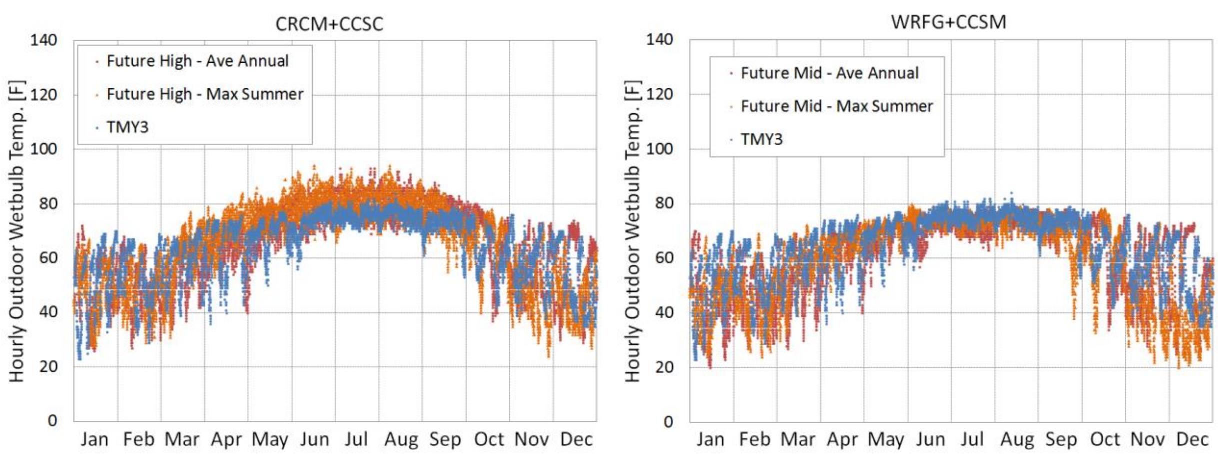
[3] Cooling degree days are a measure of the length of the cooling season and are defined as the difference between the hourly temperature and 50 °F, aggregated across the entire year. Heating degree days are a measure of the length of the heating season and are defined as the difference between 65 °F and the hourly temperature, aggregated across the entire year. Negative differences are not counted.

Table 6. Wetbulb temperature summary for the AMY, TMY3, and Future climate scenarios.

	AMY	TMY3	Future Mid. – Ave. Ann.	Future Mid. – Max. Summer	Future High – Ave. Ann.	Future High – Max. Summer
Ave. Ann. WB Temp. [F]	61	64	62	60	65	65
Ave. Summer WB Temp. [F]	73	74	73	72	78	77
Min. Ann. WB Temp. [F]	19	23	20	20	26	24
Max. Ann. WB Temp. [F]	82	84	79	80	93	94

As compared to the TMY3 dataset, the two Future Middle scenarios show lower wetbulb temperatures across the board. Conversely, the two Future High scenarios show higher wetbulb temperatures for all four metrics. Figure 11 illustrates the hourly wetbulb temperature profiles for the Future High and Future Middle climate scenarios as compared to the TMY3 dataset.

Figure 11. Hourly wetbulb temperature profiles for the Future High and Future Middle scenarios as compared to TMY3.



Note that the Future High scenarios show a marked increase in wetbulb temperatures, particularly in the summer months, while the Future Middle scenarios are comparable or slightly lower than typical conditions at SSC. Taken together, the Future High scenarios show much higher drybulb and wetbulb temperatures than the current typical climate scenario, particularly in the summer months. The Future Middle scenarios are much more similar to the typical climate scenario.

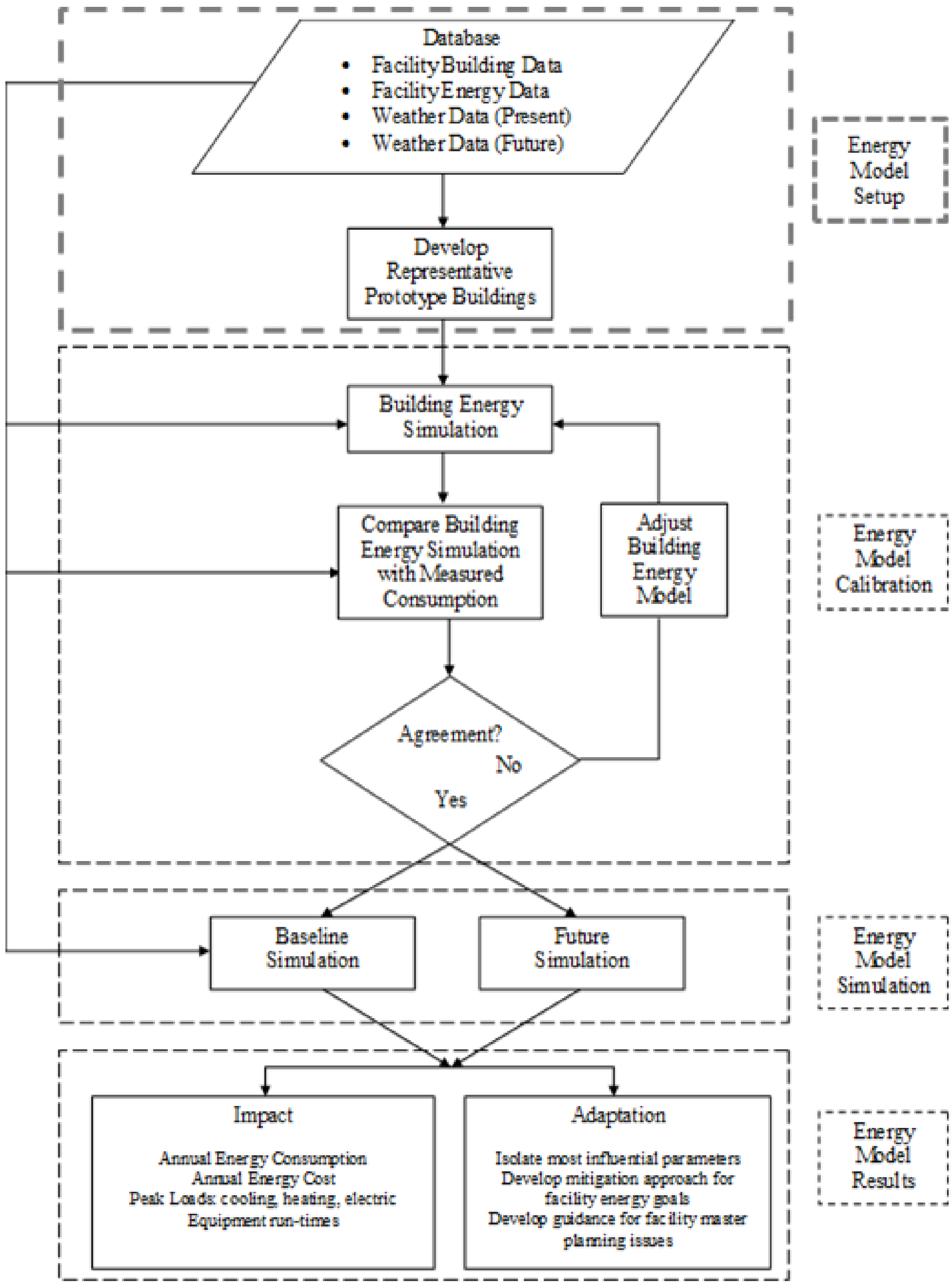
ENERGY PROJECTIONS: CALIBRATED BUILDING ENERGY MODELS

MODEL PROCESS FLOWCHART

Our energy modeling process followed four basic steps (Figure 12):

1. Energy model setup
2. Energy model calibration
3. Energy model simulation
4. Energy model results

Figure 12. Modeling process flowchart.

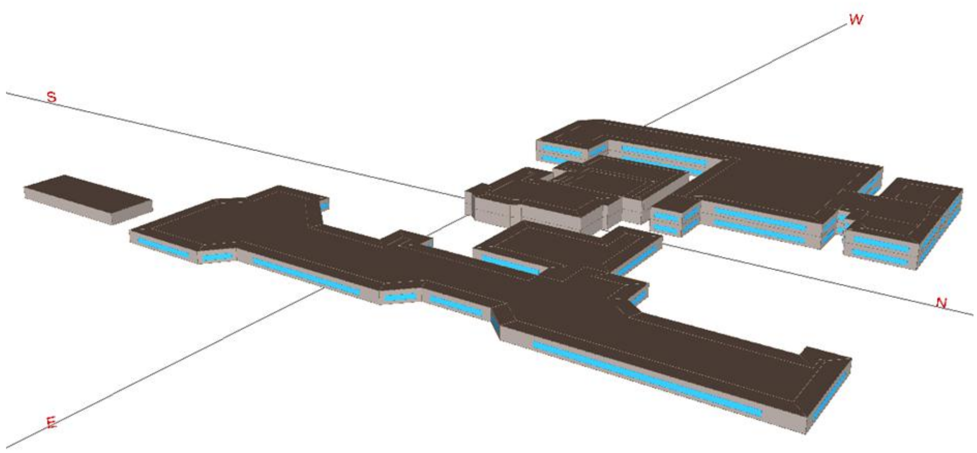


DESCRIPTIONS OF THE MODELS

During energy model setup, we gathered a considerable amount of data on each of the buildings modeled using the 80 percent method. This data included each building's age, square footage, number of floors, use type, occupant density and schedule, envelope characteristics, lighting, and HVAC type and controls. Table 4 outlines the main information used to set up each building group's model. We also used information from our site visit to identify which buildings to group together based on shared hot water and chilled water loops.

Each of the 24 building energy models (representing 39 buildings) was built in DOE2 (DOE2 2013) using eQuest as a front end. 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. Figure 13 illustrates the energy model created for the 1000, 1002, 1003, and 1011 building group.

Figure 13. Building energy model for the 1000, 1002, 1003, and 1011 building group.



Because of the age of many of the buildings, precise assembly properties for roofs, walls, and windows could not be determined. For these cases, the roof was initially assumed to have R-10 insulation. The walls were assumed to be 12" medium weight concrete with minimal insulation, and the windows were assumed 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 90.1-2004. 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 daily electrical load profile shown in Figure 3. Lighting was preliminarily set 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. Miscellaneous and plug loads were initially set to default values outlined in COMNET's Commercial Buildings Energy Modeling Guidelines and Procedures (COMNET) for a given building's predominant use type. Infiltration flow rates were approximated according to guidelines published by Pacific Northwest National Laboratory (PNNL 2009). HVAC system types were modeled according to input from SSC facility staff. The overwhelming 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. Out of the 39 buildings, only one building had air-source heat pumps as the primary HVAC system, another had electric reheat instead of hot water, and another had air-cooled chillers instead of water-cooled. 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. Enthalpy economizers were specified based on feedback from SSC facility staff. The Mississippi Large General Service LGS-HV-5 utility rate structure was then applied to the energy consumption and electricity demand results to determine the annual utility cost.

Table 7 summarizes the 24 different energy models representing the 39 different buildings that comprised 85 percent of SSC's total energy usage. This table emphasizes that the modeled buildings range in size from large office buildings to small facilities whose large energy usage comes from data centers or exterior testing facilities.

Table 7. Summary of energy models and buildings representing 85% of SSC energy usage.

Energy Model	Buildings in Group	Building Functions	Total Square Footage
1	1000, 1002, 1003, 1011	Data Centers/Office/Control Centers	250,837
2	1005	Science Laboratory	65,313
3	1009	Research Laboratory	52,378
4	1022	Marine Science	17,301
5	1032	Ocean Sciences Laboratory	171,587
6	1100, 1104	Office/Central Plant	285,442
7	1103	Business Incubator/Visual Lab	55,853
8	1105, 1110	Office/Laboratory/Data Center	100,159
9	1111	Office	107,927
10	1200, 1201	Restaurant/Auditorium/Museum/Telecom	63,810
11	2102, 2105, 2204	Engineering/Logistics/Warehouse	219,338
12	2201, 2205	Maintenance/Repair/Fabrication	111,190
13	2603	Office/Military Training	39,308
14	2606	Office/Military Training	41,273
15	3202	Office/Data	57,861
16	3203	Office/Data	77,221
17	3305	High Pressure Gas Facility	10,175
18	4010, 4050	Test Control Center/	28,341
19	4110, 4120, 4122, 4995	Rocket Test Stands/Control Center/Data	60,541
20	4210, 4220	Rocket Test Stands/Control Center	26,329
21	5008	Turbine Testing/Controls	5,561
22	5100	Space Vehicle Fabrication/Data	305,000
23	8000	Fire Dept/Security/Medical/Central Controls	75,557
24	8100, 8110	Facilities Support/Measurement/Calibration	100,394
	Total		***2,328,696***

Note that the total modeled building area was over 2.3 million square feet. The facility energy usage, in terms of monthly electricity and natural gas consumption was also compiled during this step. Finally, the current and future weather data, outlined previously, was formatted for use in the building energy models.

MODEL CALIBRATION AND UNCERTAINTY

Initial results from the 24 energy models were compared to the actual monitored energy usage. Discrepancies between the two were assumed to be the result of model inputs such as envelope properties, lighting power, plug load equipment power, infiltration flow rates, outdoor air flow rates and HVAC equipment efficiencies.

We used the Nelder-Mead simplex optimization algorithm (Nelder and Mead, 1965) to calibrate each of the 24 energy models to actual 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. APPENDIX A contains the initial and calibrated input parameters for each of the building energy models.

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 (CV) of the root mean squared error (RSME). The RSME for both fuel types was calculated by:

$$RSME = \sqrt{\sum_{i=1}^{12} \left(E_{measured,i} - E_{modeled,i}\right)^2 / 12}$$

where $E_{measured,i}$ is the measured energy usage for a given fuel type for month, i, and $E_{modeled,i}$ is the modeled energy usage for the same fuel type for the same month. We used a monthly timeframe for calibration because it was the only timeframe provided for each individual building. The CV was then calculated by:

$$CV = \frac{RSME}{\sum_{i=1}^{12} \left(E_{measured,i}\right) / 12}$$

The *GOF* was then calculated by:

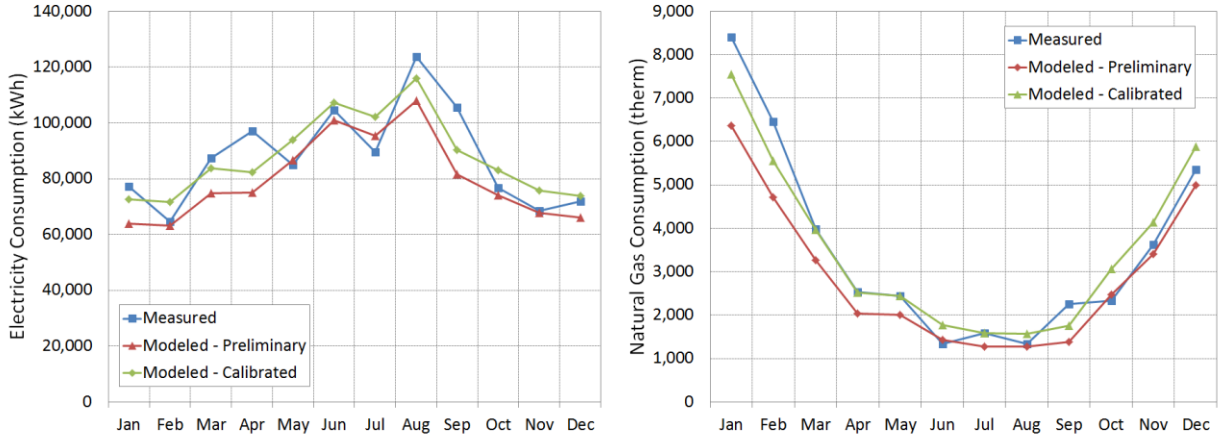
$$GOF^2 = \frac{w_{kWh}^2 CV_{kWh}^2 + w_{kW}^2 CV_{kW}^2 + w_{therms}^2 CV_{therms}^2}{w_{kWh}^2 + w_{kW}^2 + w_{therms}^2}$$

Weighting factors for electricity consumption, electricity demand, and natural gas consumption, w_{kWh}, w_{kW}, and w_{therms}, respectively, were calculated as the ratio of the cost of the fuel type energy use divided by the total annual utility cost. The electricity demand weight factor for this study was zero.

The convergence criteria for the objective function was set to 15 percent for each model (i.e. GOF <15 percent for each building model). All calibrated model parameters were inspected 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. The results were also compared against both percent increases in relevant climate metrics as well as published results in the relevant literature.

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. Figure 14 illustrates the modeled results both before and after the calibration process as compared to the measured energy usage for building 3202.

Figure 14. Monthly electricity and natural gas consumption for building 3202 both before and after model calibration.



Note that the calibrated model results are more in line with the measured results than the preliminary model results. For this model, the calibration process improved the GOF from just above 15 percent to 11 percent.

Modeled total energy use was within 5.5 percent and 2.1 percent of measured 2011 data for electricity and natural gas respectively (Table 8). 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 15.

Table 8. Measured and modeled 2011 electric and natural gas consumption for SSC (80% method).

	2011 Electric Consumption (kWH)	2011 Natural Gas Consumption (therms)
Measured	79,576,860	1,227,706
Modeled	83,950,556	1,253,386
% Difference	5.5%	2.1%

Figure 15. Monthly modeled versus measured energy usage for all 24 energy models both before and after model calibration.

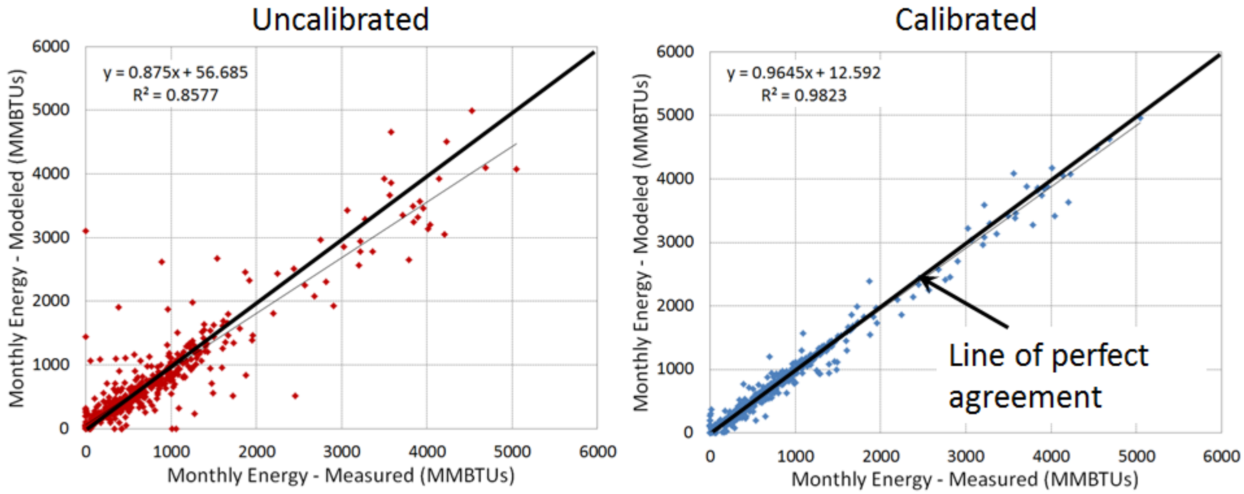
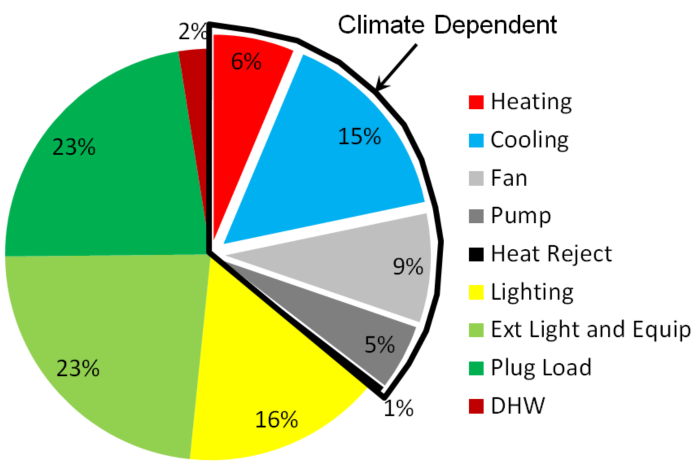


Figure 15 shows measured and modeled electricity and natural gas consumption in MMBTUs. The models' monthly predictions are plotted one for one against the monthly measured values. If the model were predicting the measured consumption perfectly, then the points would each lie on a straight line with 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 plot on the left of Figure 15, 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.

One interesting aspect of the calibrated energy models is that they may be used to disaggregate the SSC's energy usage into its component end uses. Figure 16 illustrates the percent contribution of each end use on a cost basis.

Figure 16. End use percent contribution to energy cost for SSC.



The largest contributors to energy cost at SSC are exterior lighting, exterior equipment and interior plug loads. This is not surprising as SSC is a highly equipment intensive facility with multiple large data centers and exterior test facilities. Interior lighting is the next largest end use at 16 percent and domestic hot water is relatively small at 2 percent. The remaining end uses (heating, cooling, fan, pump and heat rejection equipment) all are connected to climate, and could be affected by climate change. Taken together, they account for 36 percent of SSC's utility cost.

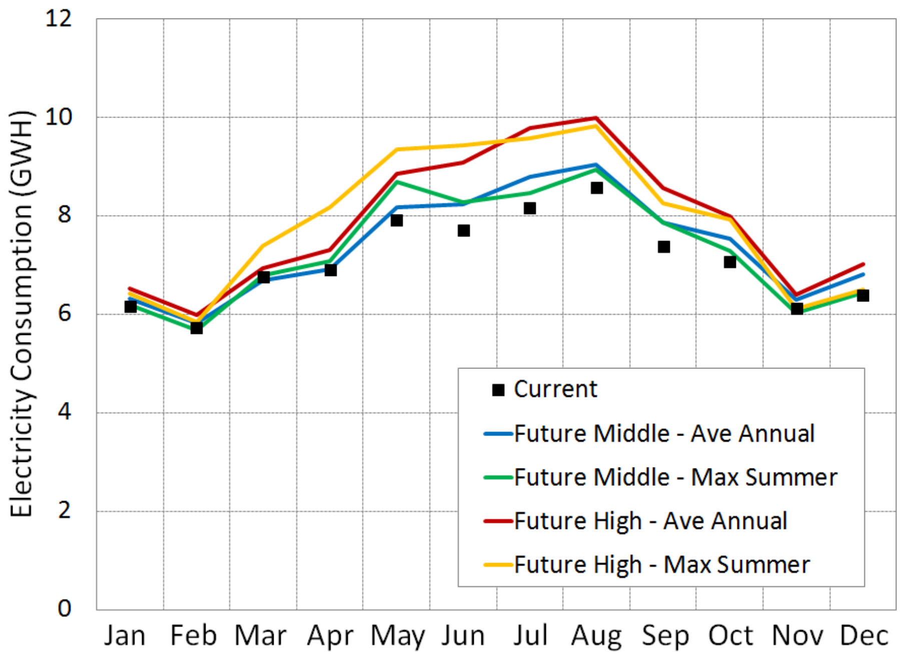
IMPACTS AND ADAPTATIONS

IMPACTS

During the energy model simulation step, we ran our calibrated energy models under five separate climate scenarios; Current (TMY3), Future Middle – Average Annual (WRFG+CCSM 2052), Future Middle – Maximum Summer (WRFG+CCSM 2069), Future High – Average Annual (CRCM+CCSM 2052), and Future High – Maximum Summer (CRCM+CCSM 2069). Each of the four future scenarios was then compared against the current scenario. The difference in results was taken as the impact of climate change on SSC's energy consumption and demand. Specifically, we calculated the impact on SSC's electricity consumption, natural gas consumption, peak electric demand, peak cooling demand, peak heating demand, and annual utility cost.

Electricity consumption at SSC increases under all future climate scenarios examined (Figure 17). Both the Future Middle and Future High scenarios show relatively similar increases between their Average Annual and Maximum Summer sub-scenarios.

Figure 17. Monthly electricity consumption at SSC under current and future climate scenarios.



Also, the two Future High scenarios show a greater increase than the two Future Middle scenarios. The increase for all scenarios is most pronounced during the summer months, when cooling (and associated pumps, fans and heat rejection) equipment is required to work harder under increased cooling loads. Table 9 summarizes the range of potential impacts on annual electricity consumption at SSC.

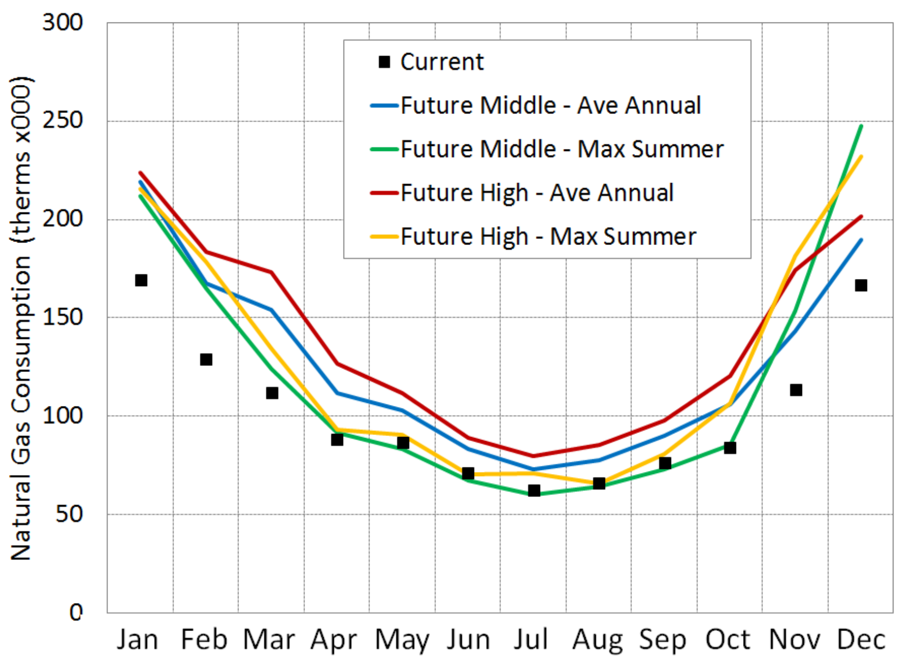
Table 9. Annual electricity consumption at SSC under current and future climate scenarios.

Scenario	Annual Electricity Consumption (GWh)	Percent Increase (relative to current)
Current	84.8	-
Future Middle – Ave Annual	88.4	4.3%
Future Middle – Max Summer	87.6	3.3%
Future High – Ave Annual	94.4	11.3%
Future High – Max Summer	94.8	11.7%

Under the scenarios tested electricity consumption increased between 3.3 percent and 11.7 percent.

Natural gas consumption at SSC increases under all future climate scenarios examined (Figure 18). The increase is most pronounced during the winter months when cooler outdoor air temperatures require the heating equipment to work harder. However, the natural gas increase during the summer is counterintuitive. Since all four scenarios show hotter outdoor air temperatures in the summer, one would expect natural gas usage during these months to decrease.

Figure 18. Monthly natural gas consumption at SSC under current and future climate scenarios.



However, the climate-dependent natural gas usage during these months is not due to heating, but rather it is due to reheat energy. In this humid region, considerable reheat energy is used to deal with large latent loads in the variable air volume systems. Under the future climate scenarios, these reheat loads increase, causing increased natural gas usage in the summer. Table 10 summarizes the range of potential impacts on annual natural gas consumption at SSC.

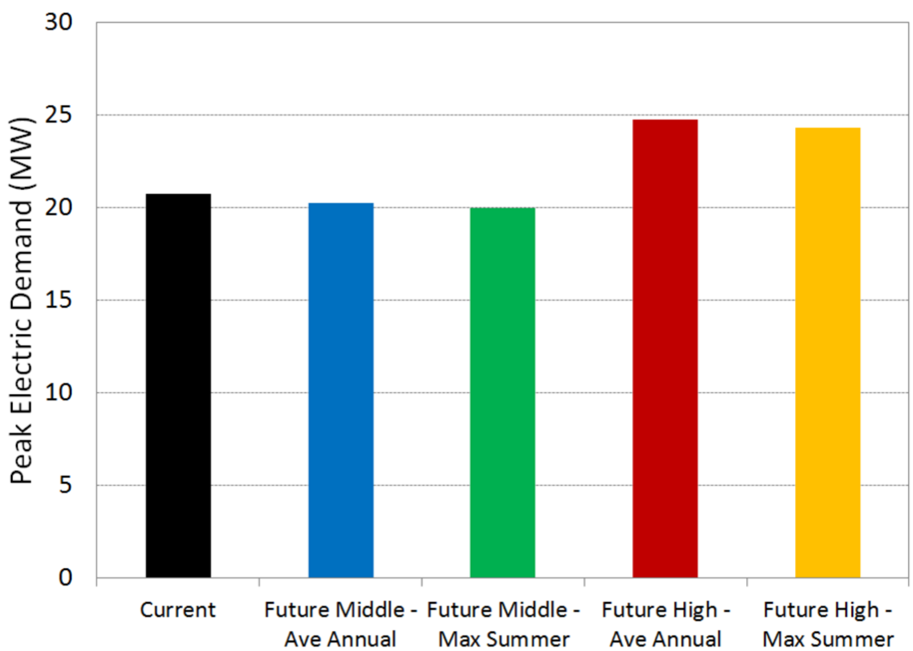
Table 10. Annual natural gas consumption at SSC under current and future climate scenarios.

Scenario	Annual Natural Gas Consumption (therms ×000)	Percent Increase (relative to current)
Current	1227	-
Future Middle – Ave Annual	1518	23.8%
Future Middle – Max Summer	1427	16.4%
Future High – Ave Annual	1668	36.0%
Future High – Max Summer	1520	23.9%

Under the scenarios tested annual natural gas consumption increases between 16.4 percent and 36.0 percent. It should be noted that the calibration exercise involved monthly electricity and natural gas consumption information at the building level. The models also predict peak electric demand, peak cooling demand and peak heating demand. However, since we did not have hourly measured data to compare against, results pertaining to these demand metrics are less grounded by measured data than results pertaining to consumption.

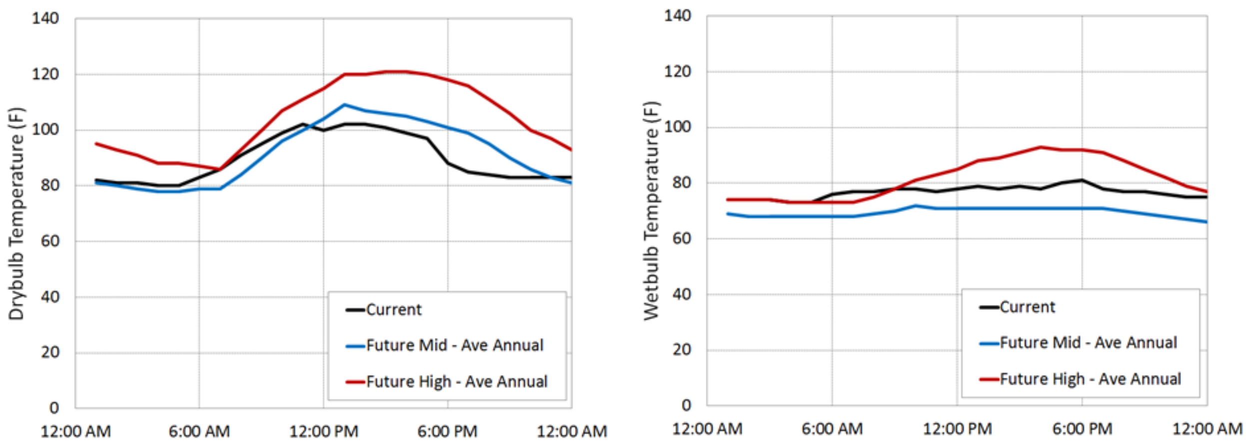
Peak electric demand increases for the two Future High scenarios (Figure 19). This is due to the hotter maximum summer drybulb temperatures causing the cooling (and associated pumps, fans, and heat rejection) equipment to work harder on the hottest day of the year.

Figure 19. Peak electric demand at SSC under current and future climate scenarios.



However, the two Future Middle scenarios show a decrease in peak electric demand. This is counterintuitive, as one would expect the higher maximum drybulb temperatures would cause the peak electric demand to increase in much the same way as the Future High scenarios. However, the peak demand is related to both the drybulb and wetbulb temperatures. For the Future High scenarios, both the drybulb and wetbulb temperature increase during the hottest day of the year. However, for the Future Middle scenarios, the wetbulb temperature actually decreases during this most extreme day. This means the hottest day of the year for the Future Middle scenarios is hotter, but drier, than the Current scenario, resulting in a net decrease in cooling electric demand. This phenomenon is illustrated by Figure 20.

Figure 20. Drybulb and wetbulb temperature over the course of the hottest day in the Current, Future Middle - Average Annual, and Future High - Average Annual scenarios.



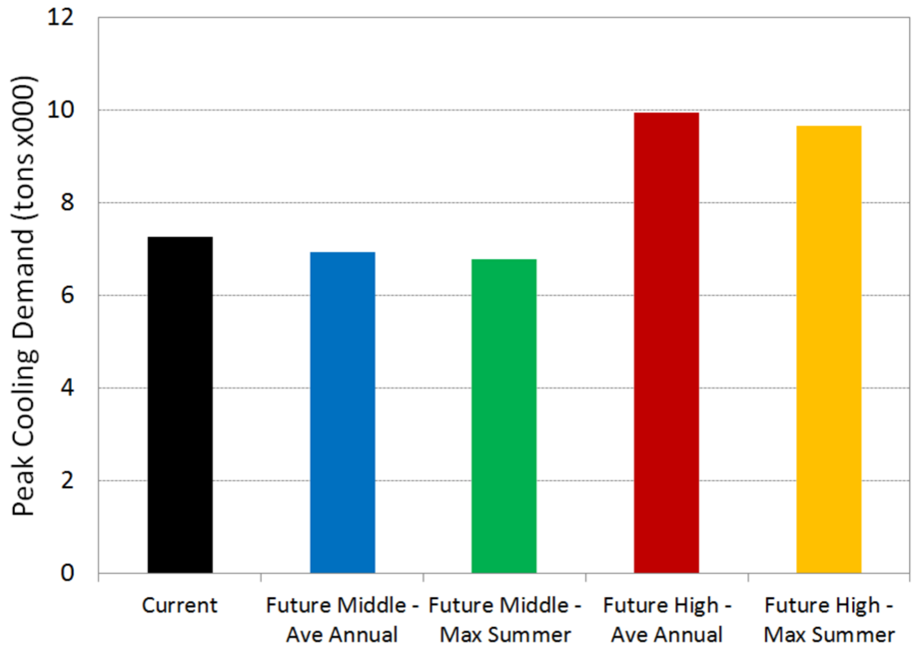
The left side of Figure 20 shows the drybulb temperature for the three climate scenarios. Each tends to increase over the course of the day, reaching its maximum sometime in the afternoon. Both the Future Middle and Future High scenarios have higher maximum drybulb temperatures than the Current scenario. The same is not true for the wetbulb temperatures. The right side of Figure 20 shows that the Future Middle scenario actually has a markedly lower wetbulb temperature then the Current scenario, resulting in lower overall peak electric demands. This reinforces the strength of the energy modeling approach. As opposed to a simple degree day proration or other simple empirical approaches, the energy modeling approach we used is able to differentiate at what times the extreme loads occur. It can account for both sensible and latent loads, and whether those loads occur during occupied or unoccupied times. This strong secondary impact of building energy consumption and demand was also found by Nik et al. (2012). Under the scenarios tested peak electric demand decreased by up to -3.7 or increased by 19.4 percent (Table 11).

Table 11. Peak electric demand at SSC under current and future climate scenarios.

Scenario	Peak Electric Demand (MW)	Percent Increase (relative to current)
Current	20.8	-
Future Middle – Ave Annual	20.3	-2.4%
Future Middle – Max Summer	20.0	-3.7%
Future High – Ave Annual	24.8	19.4%
Future High – Max Summer	24.3	17.2%

For the Future Middle scenarios the peak cooling decreases slightly, while for the two Future High scenarios it increases substantially (Figure 21).

Figure 21. Peak cooling demand at SSC under current and future climate scenarios.



These trends mirror the peak electric demand results for the same reasons as discussed above. Table 12 summarizes the range of potential impacts on peak cooling demand at SSC.

Table 12. Peak cooling demand at SSC under current and future climate scenarios.

Scenario	Peak Cooling Demand (tons ×000)	Percent Increase (relative to current)
Current	7.3	-
Future Middle – Ave Annual	6.9	-4.7%
Future Middle – Max Summer	6.8	-6.8%
Future High – Ave Annual	10.0	36.8%
Future High – Max Summer	9.7	32.9%

Under the scenarios tested peak cooling demand decreased by up to -6.8 percent or increased by up to 36.8 percent. For all four future scenarios, the peak heating demand at SSC increases due to the cooler minimum winter temperatures requiring increased heating capacities (Figure 22). Table 13 summarizes the range of potential impacts on peak heating demand at SSC.

Figure 22. Peak heating demand at SSC under current and future climate scenarios.

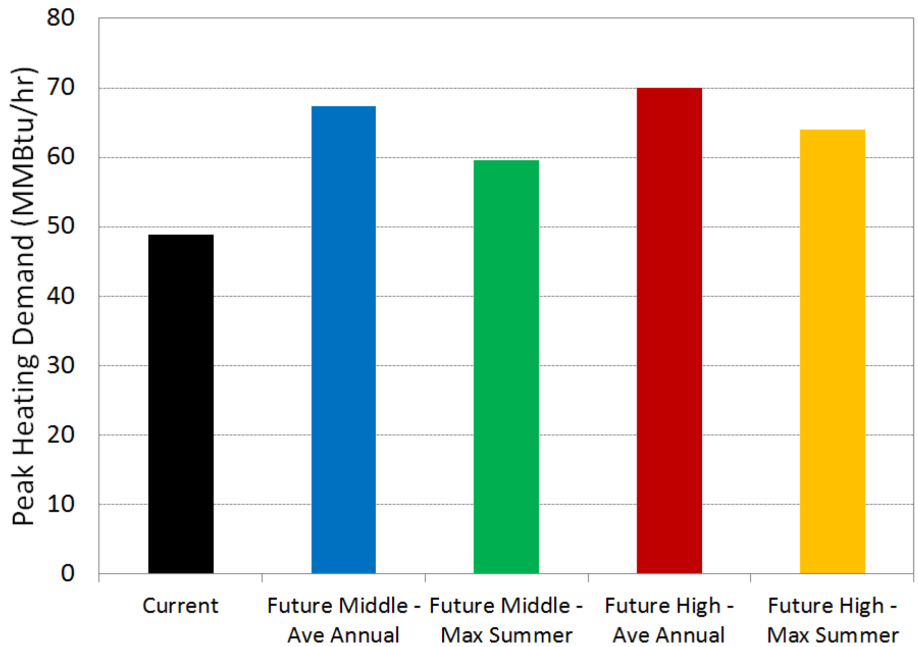
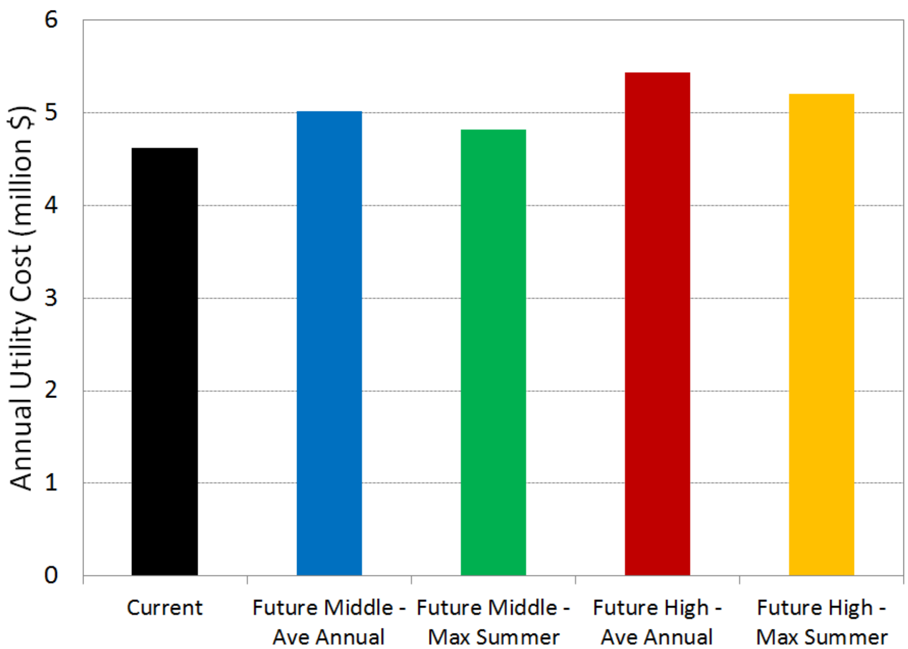


Table 13. Peak heating demand at SSC under current and future climate scenarios.

Scenario	Peak Heating Demand (MMBtu/hr)	Percent Increase (relative to current)
Current	48.9	-
Future Middle – Ave Annual	67.4	37.9%
Future Middle – Max Summer	59.5	21.9%
Future High – Ave Annual	69.9	43.1%
Future High – Max Summer	64.0	31.0%

Under the scenarios tested peak heating demand increased between 21.9 percent and 43.1 percent. Annual utility cost at SSC increases under all climate
scenarios examined due to the increased electricity and natural gas consumption (Figure 23).

Figure 23. Annual utility cost at SSC under current and future climate scenarios.



For the two Future Middle scenarios, the decreased peak demand charges were offset by the consumption increases. Table 14 summarizes the range of potential impacts on annual utility cost at SSC.

Table 14. Annual utility cost at SSC under current and future climate scenarios.

Scenario	Annual Utility Cost (million $)	Percent Increase (relative to current)
Current	$4.62	-
Future Middle – Ave Annual	$5.01	8.6%
Future Middle – Max Summer	$4.82	4.4%
Future High – Ave Annual	$5.43	17.7%
Future High – Max Summer	$5.21	12.8%

Our modeling found that annual utility costs at SSC may increase between 4.4 percent and 17.7 percent, corresponding to a net increase of between $200,000 and $810,000 ($0.08 to $0.34 per square foot) due to climate change alone. Note that this increase does not account for inflation, change of use of the facilities, or higher penetration of cooling equipment.

Summary of Impact Results

Table 15 summarizes the potential impacts on electricity consumption, natural gas consumption, peak electricity demand, peak cooling demand, peak heating demand and annual utility cost.

Table 15. Summary of energy impacts at SSC.

Scenario	Percent Increase (relative to current)					
	Electricity Consumption	Natural Gas Consumption	Peak Electricity Demand	Peak Cooling Demand	Peak Heating Demand	Annual Utility Cost
Future Middle – Ave Annual	4.3%	23.8%	-2.4%	-4.7%	37.9%	8.6%
Future Middle – Max Summer	3.3%	16.4%	-3.7%	-6.8%	21.9%	4.4%
Future High – Ave Annual	11.3%	36.0%	19.4%	36.8%	43.1%	17.7%
Future Middle – Max Summer	11.7%	23.9%	17.2%	32.9%	31.0%	12.8%

ADAPTATION TO CLIMATE VARIABILITY

We developed adaptation strategies to reduce or eliminate the impacts due to climate change. We started with a list of potential adaptation strategies from which a specific set of strategies for SSC would be developed. The initial set of potential strategies is outlined in Table 16.

Table 16. List of potential adaptation strategies.

Strategy	Description
Roof Insulation	Add additional roof insulation
Wall Insulation	Add additional wall insulation
High Performance Windows	Replace existing windows with low conductivity glass and thermally-broken frames
Efficient Lighting	Reduce interior lighting power through the use of high efficiency T8 fixtures, LED down lights, and task lighting
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
Cooling Equipment	Upgrade to high-efficiency centrifugal chillers
Domestic Hot Water Equipment	Upgrade to condensing gas-fired domestic hot water heaters
Energy Recovery Ventilation	Install enthalpy wheel energy recovery systems on exhaust with bypass and modulation control

The energy models were recalibrated with the goal of maintaining current energy consumption under a future climate scenario. Due to time constraints, we selected the Future Middle – Max Summer scenario for analysis. The algorithm ran our calibrated models under this future climate scenario and then found the set of model inputs that adjusted the future energy consumption to current usage. We only allowed the model inputs associated with our list of potential adaptation strategies to change. We performed the recalibration across all our energy models, and then calculated the area-weighted average percent changes of the adaptation strategies. The strategies that showed a significant impact towards climate adaptation were selected as the primary strategies to consider when making long-term facility planning decisions

(Table 17). A second set of strategies were identified as having a less significant impact towards climate adaptation, but still worth consideration. The remaining mitigation strategies had minimal impact on climate adaptation and were not included in our final set of recommendations. In this way, we developed a single set of specific adaptation strategies that would minimize the impact of climate change on energy use at SSC.

Table 17. Primary and secondary climate adaption strategies for 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	**Description**
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 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

The three primary strategies we identified were improving the roof insulation, upgrading the water-cooled chillers and installing energy recovery wheels. The first primary strategy, additional roof insulation, is a passive strategy. It would reduce the cooling and heating loads at SSC during the more extreme future summers and winters. This would then minimize the additional energy the heating and cooling equipment would be using under the future scenario. Upgrading to more efficient chillers would directly reduce the amount of cooling energy needed to offset the increased need for cooling during the hotter summers. The energy recovery ventilation would recover energy from the exhaust air stream, minimizing the wasted energy that had already gone in to conditioning the hotter or colder outside air.

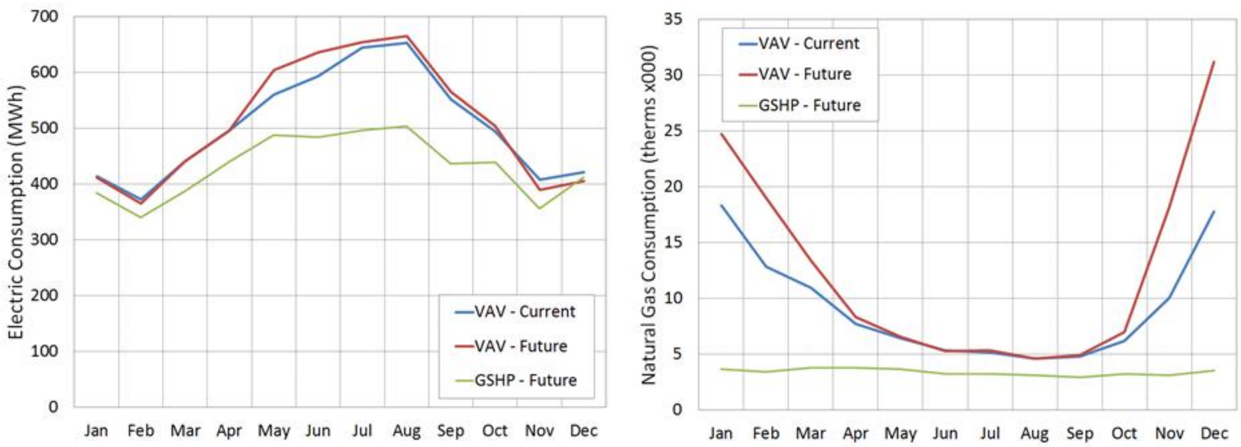
The first three secondary strategies are also passive. Increasing wall insulation, installing high performance windows, and minimizing air leaks all help to isolate the conditioned indoor environment from the outdoors. Additional wall insulation decreases the amount of heat that escapes the building through the walls. In much the same way, better windows decrease the amount of heat that passes through the windows. Tighter envelopes allow less outside air to directly infiltrate into the building. By further isolating the building from the outdoors, these measures would help to improve SSC’s climate adaptation. The final strategy, upgrading to condensing boilers, would directly reduce the amount of heating energy needed to offset the increased need for heating during the colder winters.

Ground Source Heat Pumps

The SSC facilities manager asked us to examine the effect of switching from the current HVAC system to a high performance ground source heat pump (GSHP) system on two sets of buildings at SSC. For this analysis we considered buildings 1100 and 1104 to be one building since they are served by the same HVAC system. We also performed this analysis for building 1103. These buildings are currently served by variable air volume systems with hot water reheat. Cooling is provided by water-cooled chillers and heating is provided by atmospheric boilers. The GSHP system analyzed for these buildings provided more efficient cooling and heating. However, the key to the GSHP system’s efficiency is that ventilation air is handled by a dedicated outdoor air system with an integral energy recovery wheel. This separation of conditioning and ventilation loads significantly reduces the need for reheat, which is such a large portion of energy usage, especially under the future climate scenarios. Combined with the energy recovery, switching to a GSHP system has the potential to significantly reduce SSC's energy usage. GSHPs are also an attractive technology for climate adaptation because they use the consistent temperature of the ground as their heat rejection medium, instead of the atmosphere.

Figure 24 illustrates the results of our GSHP analysis. It shows the combined monthly electricity and natural gas consumption for the buildings analyzed.

Figure 24. Combined monthly electricity and natural gas consumption for VAV and GSHP under current and future climates for buildings 1100, 1104 and 1103.



Energy consumption for the traditional VAV system under both current and future climates, as well as the GSHP system under a future climate scenario, is shown. Note that, for both electricity and natural gas, the energy consumption for the VAV system increases between current and future climates. However, the GSHP system not only makes up for this increase, but dramatically reduces the buildings' energy consumption for both fuel sources. This reduction is accomplished despite operating in the more extreme future climate. The relatively flat natural gas consumption for the GSHP case is due to gas-fired domestic hot water heaters, as GSHPs use electricity for heating instead of natural gas. This means that GSHPs are able to dramatically reduce electric consumption, despite having to additionally heat the building using electricity (Table 18).

Table 18. Annual electricity and natural gas consumption for VAV and GSHP under current and future climates for buildings 1100, 1104 and 1103.

Scenario	Annual Electricity Consumption (MWh)	Annual Natural Gas Consumption (therms ×000)
VAV - Current	6051	110
VAV - Future	6137	149
GSHP - Future	5170	41
Percent Decrease (VAV – Current to GSHP - Future)	15%	63%

We found that for the buildings analyzed, GSHPs were able to reduce annual electricity and natural gas consumption by 15 percent and 63 percent, respectively.

Moving from traditional HVAC systems to GSHPs is a significant undertaking. However, given the large potential benefit, this option may be worth investigating, particularly in light of its ability to minimize the impact that climate change will have on SSC's energy consumption, demand and cost.

CONCLUSIONS

We have estimated impacts to energy consumption, energy peak demand, and energy costs resulting from future climate variability for NASA's Stennis Space Center. A variety of challenges were surmounted in gathering the necessary data, prototyping buildings, calibrating energy models, selecting future weather data and evaluating adaptation approaches. However, the proposed research approach has been successfully executed through all stages and could be replicated at other NASA facilities.

The majority of energy consumption at SSC is not climate-dependent and the "average" or low impact future climate scenarios are not dramatically different than present climate conditions. As a result, most projected energy impacts at SSC are moderate, with the exception of significant relative increases in peak heating demand and natural gas consumption. Results for a more extreme, high impact scenario still provide moderate increases in electric consumption and total energy cost, however peak demand for electricity, cooling and heating increase dramatically—as does natural gas consumption.

The results of the study generally indicate that energy impacts due to future climate change do not warrant the status of a critical facilities planning issue at SSC. However, the following items are noted for consideration:

- An increase in heating fuel consumption and a significant increase in peak heating demand were projected under all future scenarios. It is advisable that facilities personnel raise awareness for long-term heating system design decisions. In particular, consider oversizing long-life systems such as underground steam or hot water piping, or the peak heating capacity of new or renovated building heating systems.
- The study has shown that adaptation to projected energy impacts at SSC can likely be attained using standard energy efficiency approaches. Efforts should continue to improve the energy efficiency of existing and new buildings, both to meet energy reduction mandates and to provide a buffer against future climate impacts. The selection of particular HVAC system types, such as ground source heat pump systems, also displays adaptation potential.
- Increased variability is a frequent characteristic of future climate scenarios. Heating and cooling systems that require significant switch-over time (such as some two-pipe systems) should generally be avoided. Thermal storage systems, along with their other inherent advantages, will likely be an asset towards smoothing out spikes in demand for heating or cooling. For example, chilled water thermal storage or earth-moderated ground-source heat pumps provide the ability to "ride" a building through periods of unusually high or low temperatures.
- There is an outside chance that peak demands for heating, cooling, and electricity will be significant. When facilities personnel are making decisions regarding long-life infrastructure for heating, cooling and electrical capacity, in particular distribution systems—care should be taken to size capacities liberally, especially when the incremental cost of upsizing capacity is a relatively small portion of total project costs.

The diversity of building types at SSC presented an initial challenge to constructing appropriate energy models. However, representing the majority of energy consumption through modeling a minority of buildings has proven to be a useful approach.

Furthermore, the energy models developed in the process can be utilized as a planning tool for future energy scenarios—either climate impacts, energy efficiency strategies or the viability of innovative heating and cooling systems.

We have found that there are a number of areas that warrant further investigation:

- Future climate data is not available in a format readily usable in building energy modeling.
- More research is needed on applicability of climate model data to site-specific effects. The limits and sensitivity to utilizing downscaled climate model data at a specific site are not fully known.
- TMY3 data does not properly express climate extremes. A better approach is needed to represent the present climate conditions.
- New quantitative and graphical methods should be developed 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.

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APPENDIX A: INITIAL AND FINAL MODEL INPUTS AFTER CALIBRATION

Table 19. Initial and final model inputs for buildings 1000, 1002, 1003, and 1011.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	2800	2176
Roof U-Value	hr-ft^2-F/BTU	0.093	0.1082
Wall U-Value	hr-ft^2-F/BTU	0.4	0.08339
Window U-Value	hr-ft^2-F/BTU	0.76	0.6396
Window Solar Heat Gain Coefficient	-	0.76	0.7921
Lighting Power Density	W/ft^2	1.0	1.767
Equipment Power Density	W/ft^2	0.75	0.8262
Infiltration Flowrate	air changes/hr	1.0	1.1076
Outside Air Flowrate	cfm/person	44	34.14
VAV Minimum	-	0.7	0.9897
Heating Efficiency[4]	-	1.429	1.217
Cooling Efficiency[5]	-	0.2164	0.2068
Domestic Hot Water Efficiency[4]	-	1.429	1.402

Table 20. Initial and final model inputs for building 1005.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	700	622.1
Roof U-Value	hr-ft^2-F/BTU	0.093	0.07282
Wall U-Value	hr-ft^2-F/BTU	0.4	0.4270
Window U-Value	hr-ft^2-F/BTU	0.76	0.3829
Window Solar Heat Gain Coefficient	-	0.76	0.8223
Lighting Power Density	W/ft^2	1.5	1.786
Equipment Power Density	W/ft^2	1.25	1.537
Infiltration Flowrate	air changes/hr	0.65	0.8465
Outside Air Flowrate	cfm/person	117	133.9
VAV Minimum	-	0.7	0.6279
Heating Efficiency	-	1.429	1.309
Cooling Efficiency	-	0.4180	0.5175
Domestic Hot Water Efficiency	-	1.429	1.318

Table 21. Initial and final model inputs for building 1009.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	175	174.5
Roof U-Value	hr-ft^2-F/BTU	0.048	0.048
Wall U-Value	hr-ft^2-F/BTU	0.057	0.057
Window U-Value	hr-ft^2-F/BTU	0.76	0.6501
Window Solar Heat Gain Coefficient	-	0.76	0.9467
Lighting Power Density	W/ft^2	1.5	1.280
Equipment Power Density	W/ft^2	3.5	4.973
Infiltration Flowrate	air changes/hr	0.65	0.5537
Outside Air Flowrate	cfm/person	117	89.88
VAV Minimum	-	0.6	0.9521

[4] Heating and domestic hot water efficiencies are expressed as their DOE-2 input, the Heating Input Ratio. This is defined as the inverse of the heating efficiency.
[5] Cooling efficiency is expressed as its DOE-2 input, the Electric Input Ratio. This is defined as the inverse of the cooling coefficient of performance.

Model Input Name	Units	Initial Value	Final Value
Heating Efficiency	-	1.429	1.126
Cooling Efficiency	-	0.4640	0.3761
Domestic Hot Water Efficiency	-	1.429	1.3582

Table 22. Initial and final model inputs for building 1022.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	3500	3507
Roof U-Value	hr-ft^2-F/BTU	0.093	0.1100
Wall U-Value	hr-ft^2-F/BTU	0.4	0.4460
Window U-Value	hr-ft^2-F/BTU	0.76	0.7022
Window Solar Heat Gain Coefficient	-	0.76	0.4855
Lighting Power Density	W/ft^2	2.5	2.740
Equipment Power Density	W/ft^2	6.0	7.283
Infiltration Flowrate	air changes/hr	1.0	0.9216
Outside Air Flowrate	cfm/person	280	292.2
VAV Minimum	-	0.7	0.6527
Heating Efficiency	-	1.429	1.416
Cooling Efficiency	-	0.4640	0.4357
Domestic Hot Water Efficiency	-	1.429	1.385

Table 23. Initial and final model inputs for building 1032.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	350	372.3
Roof U-Value	hr-ft^2-F/BTU	0.093	0.07554
Wall U-Value	hr-ft^2-F/BTU	0.0625	0.0625
Window U-Value	hr-ft^2-F/BTU	0.76	0.6464
Window Solar Heat Gain Coefficient	-	0.76	0.6459
Lighting Power Density	W/ft^2	1.0	0.8898
Equipment Power Density	W/ft^2	1.25	1.536
Infiltration Flowrate	air changes/hr	0.65	0.6317
Outside Air Flowrate	cfm/person	118	145.7
VAV Minimum	-	0.6	0.6664
Heating Efficiency	-	1.190	1.190
Cooling Efficiency	-	0.1803	0.2056
Domestic Hot Water Efficiency[6]	-	1.0	1.0

Table 24. Initial and final model inputs for buildings 1100 and 1104.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	780	805.3
Roof U-Value	hr-ft^2-F/BTU	0.048	0.04740
Wall U-Value	hr-ft^2-F/BTU	0.124	0.1230
Window U-Value	hr-ft^2-F/BTU	0.75	0.7118
Window Solar Heat Gain Coefficient	-	0.25	0.2441
Lighting Power Density	W/ft^2	1.0	1.076
Equipment Power Density	W/ft^2	0.75	0.6090
Infiltration Flowrate	air changes/hr	0.65	0.6337
Outside Air Flowrate	cfm/person	74	79.26
VAV Minimum	-	0.45	0.5498

[6] Heating Input Ratios of 1.0 delineate electric resistance heating.

Model Input Name	Units	Initial Value	Final Value
Heating Efficiency	-	1.429	1.395
Cooling Efficiency	-	0.1803	0.2246
Domestic Hot Water Efficiency	-	1.429	1.440

Table 25. Initial and final model inputs for building 1103.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	175	189.6
Roof U-Value	hr-ft^2-F/BTU	0.096	0.09475
Wall U-Value	hr-ft^2-F/BTU	0.4	0.3396
Window U-Value	hr-ft^2-F/BTU	0.76	0.7583
Window Solar Heat Gain Coefficient	-	0.76	0.8000
Lighting Power Density	W/ft^2	2.1	2.1
Equipment Power Density	W/ft^2	1.25	1.269
Infiltration Flowrate	air changes/hr	1.0	0.9876
Outside Air Flowrate	cfm/person	148	150.7
VAV Minimum	-	0.3	0.2923
Heating Efficiency	-	1.429	1.4481
Cooling Efficiency	-	0.2344	0.2394
Domestic Hot Water Efficiency	-	1.0	1.0

Table 26. Initial and final model inputs for buildings 1105 and 1110.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	1050	1013
Roof U-Value	hr-ft^2-F/BTU	0.093	0.09313
Wall U-Value	hr-ft^2-F/BTU	0.4	0.3602
Window U-Value	hr-ft^2-F/BTU	0.76	0.8564
Window Solar Heat Gain Coefficient	-	0.76	0.7747
Lighting Power Density	W/ft^2	1.9	1.9
Equipment Power Density	W/ft^2	2.5	3.428
Infiltration Flowrate	air changes/hr	1.0	0.8854
Outside Air Flowrate	cfm/person	83	74.90
VAV Minimum	-	0.7	0.7344
Heating Efficiency	-	1.429	1.349
Cooling Efficiency	-	0.2344	0.2225
Domestic Hot Water Efficiency	-	1.429	1.516

Table 27. Initial and final model inputs for building 1111.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	350	296.3
Roof U-Value	hr-ft^2-F/BTU	0.048	0.03711
Wall U-Value	hr-ft^2-F/BTU	0.151	0.2809
Window U-Value	hr-ft^2-F/BTU	0.75	0.5005
Window Solar Heat Gain Coefficient	-	0.25	0.2584
Lighting Power Density	W/ft^2	1.2	1.581
Equipment Power Density	W/ft^2	1.5	2.449
Infiltration Flowrate	air changes/hr	0.8	0.1049
Outside Air Flowrate	cfm/person	35	30.05
VAV Minimum	-	0.6	0.5970
Heating Efficiency	-	1.0	1.0
Cooling Efficiency	-	0.2164	0.2583

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Efficiency	-	1.0	1.0

Table 28. Initial and final model inputs for buildings 1200 and 1201.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person		179.5
Roof U-Value	hr-ft^2-F/BTU		0.08059
Wall U-Value	hr-ft^2-F/BTU		0.5260
Window U-Value	hr-ft^2-F/BTU		0.9277
Window Solar Heat Gain Coefficient	-		0.7550
Lighting Power Density	W/ft^2		2.754
Equipment Power Density	W/ft^2		2.261
Infiltration Flowrate	air changes/hr		0.4703
Outside Air Flowrate	cfm/person		27.16
VAV Minimum	-		0.9865
Heating Efficiency	-		1.613
Cooling Efficiency	-		0.03040
Domestic Hot Water Efficiency	-		1.25

Table 29. Initial and final model inputs for buildings 2102, 2105, and 2204.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	800	823.5
Roof U-Value	hr-ft^2-F/BTU	0.093	0.08627
Wall U-Value	hr-ft^2-F/BTU	0.4	0.4199
Window U-Value	hr-ft^2-F/BTU	N/A	N/A
Window Solar Heat Gain Coefficient	-	N/A	N/A
Lighting Power Density	W/ft^2	0.4	0.6765
Equipment Power Density	W/ft^2	0.2	0.2175
Infiltration Flowrate	air changes/hr	0.65	0.7346
Outside Air Flowrate	cfm/person	39	16.07
VAV Minimum	-	0.6	0.6607
Heating Efficiency	-	1.429	1.362
Cooling Efficiency	-	0.1803	0.1573
Domestic Hot Water Efficiency	-	1.429	1.426

Table 30. Initial and final model inputs for buildings 2201 and 2205.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	2400	2810
Roof U-Value	hr-ft^2-F/BTU	0.093	0.09428
Wall U-Value	hr-ft^2-F/BTU	0.4	0.4201
Window U-Value	hr-ft^2-F/BTU	N/A	N/A
Window Solar Heat Gain Coefficient	-	N/A	N/A
Lighting Power Density	W/ft^2	1.2	1.006
Equipment Power Density	W/ft^2	1.6	1.915
Infiltration Flowrate	air changes/hr	0.65	0.5848
Outside Air Flowrate	cfm/person	133	88.18
VAV Minimum	-	0.7	0.8378
Heating Efficiency	-	1.429	1.762
Cooling Efficiency	-	0.1803	0.2603
Domestic Hot Water Efficiency	-	1.429	1.379

Table 31. Initial and final model inputs for building 2603.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	2170	1235
Roof U-Value	hr-ft^2-F/BTU	0.048	0.048
Wall U-Value	hr-ft^2-F/BTU	0.133	0.133
Window U-Value	hr-ft^2-F/BTU	0.76	1.054
Window Solar Heat Gain Coefficient	-	0.76	0.6676
Lighting Power Density	W/ft^2	1.2	1.6
Equipment Power Density	W/ft^2	1.5	2.080
Infiltration Flowrate	air changes/hr	0.65	0.6140
Outside Air Flowrate	cfm/person	88.8	69.37
VAV Minimum	-	0.6	0.8904
Heating Efficiency	-	1.429	1.409
Cooling Efficiency	-	0.3569	0.3252
Domestic Hot Water Efficiency	-	1.429	1.216

Table 32. Initial and final model inputs for building 2606.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	175	102.2
Roof U-Value	hr-ft^2-F/BTU	0.048	0.048
Wall U-Value	hr-ft^2-F/BTU	0.133	0.133
Window U-Value	hr-ft^2-F/BTU	0.76	1.444
Window Solar Heat Gain Coefficient	-	0.76	0.5639
Lighting Power Density	W/ft^2	1.4	1.889
Equipment Power Density	W/ft^2	2.0	2.717
Infiltration Flowrate	air changes/hr	0.65	0.6106
Outside Air Flowrate	cfm/person	48	21.54
VAV Minimum	-	N/A	N/A
Heating Efficiency	-	1.25	1.207
Cooling Efficiency	-	0.2855	0.2913
Domestic Hot Water Efficiency	-	1.25	1.186

Table 33. Initial and final model inputs for building 3202.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	6000	7260
Roof U-Value	hr-ft^2-F/BTU	0.093	0.1029
Wall U-Value	hr-ft^2-F/BTU	0.4	0.4258
Window U-Value	hr-ft^2-F/BTU	N/A	N/A
Window Solar Heat Gain Coefficient	-	N/A	N/A
Lighting Power Density	W/ft^2	1.1	1.199
Equipment Power Density	W/ft^2	1.1	1.167
Infiltration Flowrate	air changes/hr	0.65	0.07440
Outside Air Flowrate	cfm/person	200	185.6
VAV Minimum	-	0.8	0.9015
Heating Efficiency	-	1.429	1.572
Cooling Efficiency	-	0.2855	0.2868
Domestic Hot Water Efficiency	-	1.429	1.366

Table 34. Initial and final model inputs for building 3203.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	200	165.6
Roof U-Value	hr-ft^2-F/BTU	0.093	0.03771
Wall U-Value	hr-ft^2-F/BTU	0.4	0.4541
Window U-Value	hr-ft^2-F/BTU	N/A	N/A
Window Solar Heat Gain Coefficient	-	N/A	N/A
Lighting Power Density	W/ft^2	1.2	2.158
Equipment Power Density	W/ft^2	1.4	1.442
Infiltration Flowrate	air changes/hr	1.0	0.8079
Outside Air Flowrate	cfm/person	162	281.7
VAV Minimum	-	1.0	0.9878
Heating Efficiency	-	1.429	1.720
Cooling Efficiency	-	0.1803	0.1339
Domestic Hot Water Efficiency	-	1.0	1.0

Table 35. Initial and final model inputs for building 3305.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	1000	1229
Roof U-Value	hr-ft^2-F/BTU	0.2	0.2905
Wall U-Value	hr-ft^2-F/BTU	1.0	1.285
Window U-Value	hr-ft^2-F/BTU	N/A	N/A
Window Solar Heat Gain Coefficient	-	N/A	N/A
Lighting Power Density	W/ft^2	1.0	1.105
Equipment Power Density	W/ft^2	5.0	11.07
Infiltration Flowrate	air changes/hr	0.65	0.6121
Outside Air Flowrate	cfm/person	86	64.54
VAV Minimum	-	N/A	N/A
Heating Efficiency	-	1.667	1.440
Cooling Efficiency	-	0.3103	0.03117
Domestic Hot Water Efficiency	-	1.429	1.211

Table 36. Initial and final model inputs for buildings 4010 and 4050.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	200	198.0
Roof U-Value	hr-ft^2-F/BTU	0.093	0.1115
Wall U-Value	hr-ft^2-F/BTU	0.4	0.2791
Window U-Value	hr-ft^2-F/BTU	0.76	0.8804
Window Solar Heat Gain Coefficient	-	0.76	0.6590
Lighting Power Density	W/ft^2	1.0	0.7442
Equipment Power Density	W/ft^2	1.25	1.517
Infiltration Flowrate	air changes/hr	0.65	0.6778
Outside Air Flowrate	cfm/person	73	73.79
VAV Minimum	-	0.3	0.07911
Heating Efficiency	-	1.0	1.0
Cooling Efficiency	-	0.4283	0.6948
Domestic Hot Water Efficiency	-	1.0	1.0

Table 37. Initial and final model inputs for buildings 4110, 4120, 4122, and 4995.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	175	164.8
Roof U-Value	hr-ft^2-F/BTU	0.093	0.1048
Wall U-Value	hr-ft^2-F/BTU	0.4	0.3914
Window U-Value	hr-ft^2-F/BTU	N/A	N/A
Window Solar Heat Gain Coefficient	-	N/A	N/A
Lighting Power Density	W/ft^2	1.0	1.040
Equipment Power Density	W/ft^2	2.0	1.980
Infiltration Flowrate	air changes/hr	0.65	0.6660
Outside Air Flowrate	cfm/person	850	895.3
VAV Minimum	-	0.6	0.4758
Heating Efficiency	-	1.429	1.3856
Cooling Efficiency	-	0.2164	0.2578
Domestic Hot Water Efficiency	-	1.429	1.409

Table 38. Initial and final model inputs for buildings 4210 and 4220.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	175	185.8
Roof U-Value	hr-ft^2-F/BTU	0.093	0.07339
Wall U-Value	hr-ft^2-F/BTU	0.4	0.4077
Window U-Value	hr-ft^2-F/BTU	N/A	N/A
Window Solar Heat Gain Coefficient	-	N/A	N/A
Lighting Power Density	W/ft^2	1.0	0.8235
Equipment Power Density	W/ft^2	2.0	2.199
Infiltration Flowrate	air changes/hr	0.65	0.6967
Outside Air Flowrate	cfm/person	34	63.59
VAV Minimum	-	0.6	0.3567
Heating Efficiency	-	1.25	1.25
Cooling Efficiency	-	0.2344	0.2167
Domestic Hot Water Efficiency	-	1.0	1.0

Table 39. Initial and final model inputs for building 5008.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	175	149.7
Roof U-Value	hr-ft^2-F/BTU	0.093	0.06661
Wall U-Value	hr-ft^2-F/BTU	0.4	0.7431
Window U-Value	hr-ft^2-F/BTU	N/A	N/A
Window Solar Heat Gain Coefficient	-	N/A	N/A
Lighting Power Density	W/ft^2	1.0	1.312
Equipment Power Density	W/ft^2	2.0	3.534
Infiltration Flowrate	air changes/hr	0.65	0.6521
Outside Air Flowrate	cfm/person	75	40.70
VAV Minimum	-	N/A	N/A
Heating Efficiency	-	0.3616	0.3953
Cooling Efficiency	-	0.3724	0.4370
Domestic Hot Water Efficiency	-	1.0	1.0

Table 40. Initial and final model inputs for building 5100.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	200	161.5
Roof U-Value	hr-ft^2-F/BTU	0.048	0.05147
Wall U-Value	hr-ft^2-F/BTU	0.124	0.1165
Window U-Value	hr-ft^2-F/BTU	0.76	0.5726
Window Solar Heat Gain Coefficient	-	0.76	0.9690
Lighting Power Density	W/ft^2	1.15	1.657
Equipment Power Density	W/ft^2	2.0	1.594
Infiltration Flowrate	air changes/hr	0.65	1.022
Outside Air Flowrate	cfm/person	196	208.8
VAV Minimum	-	0.3	0.2526
Heating Efficiency	-	1.25	1.415
Cooling Efficiency	-	0.1966	0.1910
Domestic Hot Water Efficiency	-	1.25	1.170

Table 41. Initial and final model inputs for building 8000.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person		2591
Roof U-Value	hr-ft^2-F/BTU		0.06048
Wall U-Value	hr-ft^2-F/BTU		0.09657
Window U-Value	hr-ft^2-F/BTU		0.9596
Window Solar Heat Gain Coefficient	-		0.1228
Lighting Power Density	W/ft^2		1.212
Equipment Power Density	W/ft^2		1.066
Infiltration Flowrate	air changes/hr		0.7409
Outside Air Flowrate	cfm/person		83.11
VAV Minimum	-		0.5000
Heating Efficiency	-		1.845
Cooling Efficiency	-		0.2407
Domestic Hot Water Efficiency	-		1.326

Table 42. Initial and final model inputs for buildings 8100 and 8110.

Model Input Name	Units	Initial Value	Final Value
Domestic Hot Water Load	BTU/hr-person	2450	2444
Roof U-Value	hr-ft^2-F/BTU	0.093	0.08765
Wall U-Value	hr-ft^2-F/BTU	0.4	0.4142
Window U-Value	hr-ft^2-F/BTU	1.21	1.385
Window Solar Heat Gain Coefficient	-	0.86	0.7197
Lighting Power Density	W/ft^2	2.5	2.937
Equipment Power Density	W/ft^2	2.0	2.599
Infiltration Flowrate	air changes/hr	1.0	1.008
Outside Air Flowrate	cfm/person	172	183.1
VAV Minimum	-	0.6	0.5869
Heating Efficiency	-	1.429	1.256
Cooling Efficiency	-	0.2344	0.1602
Domestic Hot Water Efficiency	-	1.429	1.424

APPENDIX B: LITERATURE REVIEW

Modeling future energy use is a key aspect of determining the operating cost and carbon emissions associated with a given building. This work is difficult in that it is comprised of two components, building modeling and climate modeling, that both involve complicated analysis and considerable uncertainty. Significant work has been done to improve the quality of this modeling and to account for the impact that global climate change will have on building energy use in a given region. Factors including construction, ventilation strategies, air-conditioning penetration, accuracy of climate models, and even behavior of occupants have been examined to try to predict the future performance of buildings in various climates, and highlights of these studies are described in the following review.

Hekkenberg et al. (Hekkenberg 2009) used a generalized climate model to study the accuracy of the temperature dependence patterns for energy consumption developed by different methods and the resulting building energy consumption predictions. Results indicated that degree day methods can fail to accurately characterize socio-economic factors and, therefore, often underestimate future energy demand.

Several studies focused on the generation and use of future climate data, such as a recent study by Nik, et al (Nik 2012). This study demonstrated the use of global climate models as inputs to regional climate models to provide future climate data with fine spatial and temporal resolution. It is argued based on differences resulting from different spatial resolutions that building modeling is sensitive to spatial resolution of models for some applications. It is also noted that temperature is not the only significant variable of importance in climate models as applied to building performance: humidity and its effects on integrity of building materials as well as wind loading may have significant and changing impacts on overall building performance in future climates. This paper also noted inaccuracies that can result from so-called morphed data sets, climate data that adjusts for changing average temperatures but that do not characterize changing frequency of extreme weather events. Further analysis of morphed weather data was conducted by Eames, et al (Eames 2012), who demonstrated that morphed data sets did in fact underestimate average maximum temperatures and overestimate average minimum temperatures. Error regarding maximum temperatures was found, in some cases, to exceed eight degrees Celsius. This morphed data was compared to more representative predictions which resulted from the UK Climate Projections (UKCP09) climate models. These models allowed generation of values for nine weather variables including, among others, daily precipitation, maximum and minimum temperatures, and direct and diffuse solar radiation.

Two recent studies investigated the impact of climate change on building energy consumption in particular regions of the United States. Ruth, et al (Ruth 2006), noted that overall per-capita electricity use is very geographically sensitive, and noted that Sailor (Sailor 2001) had found that neighboring states display significantly different sensitivities to factors influencing electricity demand. Ruth used a degree day method for determining monthly energy demand, noting that care has been taken to address non-uniform changes in temperatures during different seasons. Modeling of future climate change was done with data from the United Kingdom Hadley Centre climate models (HadCM2). This study generally determined that regional population changes and energy prices will have more significant impacts on energy consumption than climate change, and that climate change effects on electricity consumption were likely to be small, with changes of less than three percent appearing even for months with the most significant impacts. A more general study was conducted for a different US regional system, the electricity sector in California (Vine 2012). Vine identified three main impacts of climate change on the California electricity sector: increased demand (primarily due to increased use and penetration of air-conditioning), negative impact on current generating capacity (such as climate impacts on hydropower and potential water shortage concerns for thermoelectric plants) and risk to infrastructure (due to increased coastal storms and increased frequency of heat waves). Vine notes that climate change is not likely to cause significant increases in electricity cost, but peak demand could rise to problematic levels.

Vine references Miller (Miller 2008) to note that one model predicts an increase of extreme heat events for Los Angeles from a present-day value of 12 to as many as 96 by 2100, causing substantial increases in air-conditioning loads. Several strategies are recommended for decreasing peak demand, such as use of building codes, high efficiency air-conditioning systems, use of natural cooling and use of reflective roofing to reduce heat island effects. Energy conservation programs are also discussed, along with methods to better manage existing generators, such as data-driven management of hydroelectric reservoirs, increased water efficiency, and promotion of small distributed generators such as solar and wind arrays.

Significant attention has been given to climate change impacts on buildings in other countries, particularly in Australia and the UK. Guan (Guan 2012) conducted an analysis of increased energy use in Australian office buildings in eight different cities under several climate change projections. Building modeling was done using DOE2.1E. Key findings were that no existing buildings were able to meet cooling demand when analyzed for high degrees of climate change. Overall building energy use was expected to increase 0.4 to 15 percent depending on which climate models were implemented. Additional analysis explored the financial impact of increased electricity consumption in the context of the implementation of an Australian 2012 $23/tonne carbon tax and examined the impact of mitigation strategies such as varying window to wall ratios. Ren, et al (Ren 2011) analyzed performance of residential buildings in eight Australian cities, ranging from heating dominated to cooling dominated climates. Findings demonstrated that in heating dominated regions building envelope improvements were often sufficient to adapt existing buildings to changing climate but that additional measures were needed in cooling dominated regions. Economic analysis of building modifications for new and existing construction was also examined to determine the most cost-effective modifications for each climate region

Work in the UK has studied building performance in future climates with an emphasis on adapting buildings without adding air-conditioning. Holmes and Hacker (Holmes 2007) studied energy use in buildings in the UK using UK Climate Impacts Programme data (UKCIP02). They applied a building simulation model using a design summer year to analyze risk of overheating with overall performance analyzed using a separate test reference year, with the design summer year based on medium-high UKCIP02 climate change predictions. The analysis focused on different building operation strategies with reduced energy consumption a goal. Variable cooling set temperatures were analyzed, with occupant control of some systems analyzed as a potential energy saving strategy, and natural ventilation was also examined. In a later study Lomas and Giridharan (Lomas 2012) analyzed adaptation strategies for hospital wards in a UK hospital, predicting temperatures for extreme weather years and testing different cooling strategies using a building dynamic thermal model for future weather conditions. UKCP09 climate predictions were used, and thermal comfort was compared to applicable standards. In an additional study, Day, et al (Day 2009), used a cooling degree day method to examine energy use and CO2 emissions attributed to cooling in London. Results of this study predict a possible doubling of emissions by 2030 due to a combination of added building space, greater air conditioning penetration, and climate change. Kolokotroni, et al (Kolokotroni 2012), studied the effect of the London urban heat island on overheating in office buildings and reduction in energy for heating. Results indicated that climate change will cause significant increases in hours of overheating in buildings without cooling systems, especially in central London. As in other studies, this was found to increase air-conditioning penetration, likely with relatively inefficient retrofits, greatly increasing the CO2 emissions from the operation of these buildings. At the same time, new buildings that might not have installed cooling systems will in fact include them. A variety of mitigation strategies was investigated, including various methods of night ventilation to reduce building temperatures.

A different type of analysis was conducted by Coley, et al (Coley 2012), who studied the comparative impact of hard (physical building modifications) and soft (behavior and operation) changes with regard to their ability to limit hours of overheating in both a school and residence. The study found that a building with only hard modifications modeled at climate change in the 50th percentile had similar hours of overheating as a building with hard and soft modifications modeled at climate change in the 90th percentile. This finding suggests that both hard and soft modifications are significant in designing and retrofitting buildings for future climates. Climate data for this study was taken from the UKCP09 models.[7]

Finally, Pike, et al (Pike 2012), investigated the impact of LEED-NC criteria on building performance with regard to future climate change. Two new metrics were developed: the Climate Sensitivity Index and the Climate Adaptation Opportunity Index. These indices measure, respectively, whether design standards and assessments for buildings rely on climate conditions that are likely to change and if certain green building credits are more significant in providing building adaptability to future climates. The authors describe these metrics as ways to prioritize particular design areas as building performance in the context of future climates is considered.

[7] UK climate Projections (http://ukclimateprojections.defra.gov.uk/ accessed 12/2013).