ABSTRACT

Title of Document: THE IMPACT OF COOL ROOFS IN DIFFERENT CLIMATIC REGIONS: A QUANTITATIVE EMPIRICAL ANALYSIS

Kimberly Johanna Petry, Doctor of Philosophy, 2014

Directed By: Professor Marla McIntosh, Plant Sciences

This research investigated regional climate differences and weather impacts on the effectiveness of cool roofs. In most US climate zones, cool roofs can reduce energy consumption because they reflect more sunlight and heat than standard roofs. Since temperatures are expected to increase in many regions, cool roofs may offer greater energy and cost savings than currently estimated. Energy consumption by Department of Energy (DOE) Research Laboratory buildings across the US with cool and standard roofs were assessed using metered energy datasets collected from 2003-2013. Statistical tests were conducted to compare differences in energy consumption of buildings between cool and standard roofs at sites in different climatic regions. In order to better understand the effectiveness of cool roof technologies in a future that is expected to become increasingly warmer, data collected from weather stations near each DOE site were used to interpret the potential influences of weather patterns on

cool roof energy savings. This research confirmed that cool roofs do reduce energy consumption, especially at sites with warmer summers and milder winters. Regression analyses of energy consumption and temperature data were conducted to identify associations between air temperatures and heating and cooling degree-days with seasonal energy consumption. While the energy consumption of buildings with cool roofs was generally less than buildings with standard roofs, the differences in energy consumption varied depending on building use and building size.

THE IMPACT OF COOL ROOFS IN DIFFERENT CLIMATIC REGIONS: A QUANTITATIVE EMPIRICAL ANALYSIS.

By

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Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

For Future Generations,

May they be wiser and more stalwart caretakers of our planet than us.

Acknowledgements

I will be forever indebted to my advisor, Marla McIntosh, whom has helped make this a most polished and scholarly work. I express my sincere appreciation of her exceptional guidance and constant encouragement over the past four years.

I would like to thank my committee members, Ralph Bennett, Jim Cohen, Pat Kangas, and David Lansing for their constructive comments and immense help in crafting this dissertation and Debbie Morrin-Nordlund, Diana Owen, Ken Paynter, and Powell Draper who assisted me throughout the graduate process.

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With the love and support of my family, especially Brandon, Savanna, and Lance, this endeavor was possible.

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Chapter 1: Introduction

A cool roof is a roofing application that reflects more sunlight and emits more heat than a standard or dark roof. A cool roof may be a white or a colored roof with a high solar reflectance. A building with a cool roof, see Figure 1, benefits from reduced gain and cooling loads, which will net an overall energy savings in most climates (Konopacki and Akbari 2001; Synnefa et al. 2007; Sailor et al. 2012). However, the energy savings depends on the type of cool roof, the climate, and many other conditions. *Studies have demonstrated the energy savings potential of cool roofs for various cities, but have not investigated how variations in temperature over the past decade have impacted cool roof energy savings.* Cool roof savings vary between regions in the United States (US) (Santamouris 2012). But how has climate change, especially increasing temperature, influenced the effectiveness of cool roofs in those regions? In a world where climate change is upon us, low-cost technologies are needed that are proven to be effective now, but also in the future. Thus using empirical methods to explore the relationship between cool roofs, seasonal weather patterns, and energy savings has become relevant.

Figure 1: Example of a cool roof on a government building in Washington D.C.

Rationale for the Study

This research was designed to determine whether and how regional climatic differences and variation in temperature impact the effectiveness of cool roof technologies. The analysis compared energy usage of buildings with cool and standard roofs based on metering datasets collected from selected Department of Energy (DOE) research laboratories in four different climate regions across the U.S. Building energy consumption and local weather records over the last eleven years were compiled and analyzed at DOE sites. Energy consumption, which is defined as the amount of energy used to power a building, was compared between matched pairs of buildings (a standard and a cool roof) in one geographic climate zone; while the energy consumption of buildings pre and post cool roof installation was compared in three other climate zones. Comparisons were based on several years of monthly and yearly energy utilization data in each climate zone. Temperature data from National Oceanic and Atmospheric Administration (NOAA) weather stations were used to explore the relationship between cool roof energy savings and temperature. An additional purpose of this study was to investigate whether increasing temperatures would create opportunities for greater energy savings and energy conservation benefits than the current cool roof data available indicates. Increasing temperatures may create a greater need for reduced energy consumption and may make cool roofs a more attractive and more mainstream roofing option.

Brief Review of the Literature

Cool Roofs Defined

Traditional roofs absorb solar radiation, which is then transferred to the interior of the building and the ambient air around the building (Synnefa et al. 2008; Garrison et al. 2012). A cool roof uses radiative forcing to reflect significant amounts of solar radiation back to space and absorbs less solar radiation, see Figure 2, (Akbari and Matthews 2012). Albedo (i.e., solar reflectance) is the fraction of the incident radiation that is reflected. For example in California, the average radiative forcing per 1% increase in albedo is -1.38 W/m^2 (VanCuren 2012). The results from another study show an average increase of approximately 50 W/m^2 of outgoing solar radiation (Salamanca et al. 2012). Campra et al. (2013) study showed a 22.8 W/m^2 annual average reduction of solar radiation using observed and modeled data in southeast Spain.

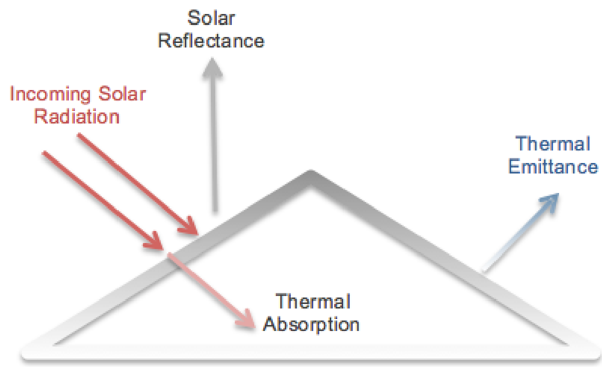


Figure 2: Schematic of the process of reflection, absorption and emittance on a roof surface

Since the high absorption of solar radiation directly correlates with a higher roof surface temperature, air-conditioning demand and heat gain in a building are reduced with a cool roof (Akbari 2008; Akbari et al. 2009; Ray 2010; Synnefa et al. 2012). This in turn increases the thermal comfort of the building in the summer for its occupants (Synnefa et al. 2007).

According to the California Energy Commission, a cool roof has a minimum Solar Reflective Index (SRI) rating of 64 for low-sloped roofs and 16 for steep-sloped roofs. The SRI, depicted in Figure 3, is calculated using the air temperature, thermal emittance and solar reflectance of a roofing surface (Akbari et al. 1996). A white roof with the highest solar reflectance has an SRI of 100. A standard dark colored roof with the lowest solar reflectance has an SRI of 0 (Urban and Roth 2010).

	White Surface	Cool Roof low sloped min	Cool Roof steep sloped min	Standard black roof
Albedo	**1.0**	**0.65**	**0.3**	**0**

SRI	**100**	**64**	**16**	**0**

Figure 3: The full range of albedo and SRI values are shown, from 1 to 0, and 100 to zero, respectively. The higher the SRI and albedo values are, the cooler the surface of the roof. Based on Levinson (2009).

The thermal emittance value, a measure of a surface's ability to emit thermal radiation efficiently, ranges between 0.80 and 0.95 for most roofing materials. Cool roofs have high thermal emittance values averaging 0.9 emittance (Urban and Roth 2010). Traditional roof surfaces can reach temperatures of up to 85°C during the summer, while the surface of a cool roof can be 28°C to 33°C cooler (Chin et al. 2008). High albedo surfaces present a lower sensible heat flux than low albedo surfaces which minimizes heat stress on the roofing (Kolokotsa et al. 2013). Sensible heat flux is defined as the transfer of energy by convection and conduction processes between the interface of the earth's surface and the atmosphere and is expressed by the quantity of heat transmitted per unit area of time (NOAA 2012). Cools roofs tend to minimize the latent heat flux impacts. The latent heat flux is defined as a rate of energy flow by time based on the transfer of heat between phases of a material at the same temperature (DOE 2013). It is derived as:

$$LE = \lambda \rho_{air} C_E u (q_{satTs} - q_a)$$

where λ is the latent heat of vaporization in MJ/kg, ρ_{air} is the density of moist air in kg/m^3, C_E is the bulk transfer coefficient for water vapor (dimensionless), u is wind speed in m/s, q_{satTs} is saturated specific humidity at surface temperature in kg/kg, and q_a is specific humidity at observation height in kg/kg (Maupin and Weakland 2009).

Energy Savings Benefit of Cool Roofs

Recent field and modeling studies have verified both energy savings and demand reduction from the installation of cool roofs. (Akbari et al. 2001; Konopacki and Akbari 2001; Akbari and Konopacki 2005; Akbari 2008; Ray 2010; Synnefa and Santamouris 2012; Zinzi and Agnoli 2012). Table 1 summarizes data from two studies, which illustrate the variable impacts of cool roofs in diverse locations using building energy simulations and actual field measured data (Konopacki and Akbari 2001; Levinson and Akbari 2010). In general, cool roofs yield the greatest benefit in energy and cost savings in areas where incoming solar radiation and temperatures are high. On average, Lawrence Berkeley National Laboratory studies show that in the U.S. there is an eight-fold cooling energy saving as compared to the heating energy penalty (Menon et al. 2011). Accordingly in 2010, the former Secretary of Energy Steven Chu required that all DOE building roofs, when replaced or constructed, use cool roofing technologies with a thermal resistance of at least R-30 (Chu 2010).

	Location	Measurement
Cooling energy savings		
	Alaska	3.30 kW/m^2
	Arizona	7.69 kW/m^2
	USA	5.02 kW/m^2
Heating energy penalty		
	Hawaii	0.003 $therm/m^2$
	Wyoming	0.14 $therm/m^2$
	USA	0.065 $therm/m^2$
Cost Savings		
	Texas	$0.77/$m^2$
	West Virginia	$0.13/$m^2$
	Arizona	$1.14/$m^2$
	USA	$0.36/ m^2

Table 1: Measurements of yearly average cooling energy savings, heating energy penalty and cost savings potentials for various states and the U.S. (Levinson and Akbari 2010) (Konopacki and Akbari 2001).

Roof insulation thickness is a component that can increase or decrease cool roof effectiveness. The effectiveness of a cool roof in winter is impaired by the combination of the low thermal storage capacity of a roofing material and insulation with a low R-value, where above average insulation is in the R-30 range. Therefore, cool roofs are less effective at higher elevations, during winter, and in generally cool climates (Oleson et al. 2010). In the northern latitudes of the United States low incoming solar radiation makes cool roofs less effective (Akbari and Konopacki 2005; Oleson et al. 2010). Also, only marginal energy savings are achieved when a cool roof is added to an already highly efficient building, where a highly efficient building is one with a very tight building envelope and above average insulation thickness (Urban and Roth 2010). The correct balance of insulation thickness combined with the appropriate cool roof solar reflectance is needed to net the greatest energy savings.

Proper plenum ventilation can positively impact the effectiveness of a cool roof. Modeling studies on next-generation roofing with above-sheathing ventilation predicted that with a larger airspace or cavity in the plenum, below the roofing material, increased energy savings and that using convective air flow as an insulator in above-sheathing ventilation is as effective as using a cool roof (Miller and Kosny 2008; Kriner and Desjarlais 2011). Thus, the combination of appropriately sized plenum ventilation, insulation thickness and a cool roof provide the best energy savings for a building.

Green Roofs

The term cool roof often encompasses the suite of roofing solutions using vegetation known as green roofs. Green roofs can achieve some of the same energy efficiency effects that white or light colored cool roofs achieve, but have additional aspects to their use that make them more appropriate for specific applications. Green roofs generally require a higher upfront capital investment than a cool or standard roof as the material costs for plant matter, specially designed water barriers, and soil tend to be higher and the installation is more labor intensive (Bell et al. 2008). However, green roofs when maintained properly can have a longer overall life span than standard and cool roofs (Garrison et al. 2012) and they provide similar energy savings benefits as reflective cool roofs using their natural metabolic processes of evapotranspiration, respiration, and photosynthesis (Zinzi and Agnoli 2012). Green roofs also have the aesthetic benefits for building users and wildlife, along with beneficial stormwater management properties (Garrison et al. 2012).

Climate Change

Due to increasing atmospheric concentrations of greenhouse gases (GHG), increased comprehension of the climate system by climate scientists, and observed warming trends there is clear evidence that anthropogenic influences are impacting the climate system. The most recent IPCC report uses more forceful language than previous versions and asserts higher confidence levels.

The planet functions due to numerous interdependent systems. Changing one of these systems can create cascading impacts on other systems. Some examples of cascading impacts of global warming include a warming and expanding ocean, which leads to sea level rise; an increase of CO_2 absorption in the ocean lowering the ocean's overall pH, which leads to an undersaturation of essential calcium carbonate minerals needed for marine life to build their shells and skeletons; and increasing global temperatures which reduce sea ice, causing sea level rise and reducing snow pack which is a primary feeder of water for communities across the globe. The IPCC report asserts a very high confidence that snow cover in the Northern Hemisphere has declined in the last 60 years (Stocker et al. 2013).

Reduced snow cover equates to fewer reflective areas in the Northern Hemisphere. This is one of the areas where cool roofs can play a positive role in mitigating climate change. Cool roofs can also reduce thermal radiation flow into the atmosphere (Ronnen Levinson 2009). The warming of the troposphere is a direct effect of the positive total radiative forcing that has caused the climate system to absorb this additional energy. Radiative forcing determines the magnitude and rate of climate change globally (Stocker et al. 2013).

Urban Heat Island Impacts

This dissertation evaluates buildings in both rural and urban areas, so it is worthwhile to mention the positive benefits that cool roofs provide to reduce the urban heat island (UHI) effect. An UHI is created when humans drastically alter the natural landscape and when trees and other plants are replaced with stone and concrete structures, roads and sidewalks. Both small and large cities have a UHI, but larger cities can have temperatures up to 12° C higher than their rural surroundings (Akbari et al. 2008). The UHI effect directly affects energy costs of a city. Akbari et al. (2001) quantify the impacts at several billion dollars a year. Up to 10% of the current electricity demand in urban areas have been attributed to cooling buildings to compensate for this UHI and the increased 0.5°C to 3°C in urban temperatures (Akbari et al. 2001). Cool roofs can reduce the ambient air temperature around a building and reduce the UHI impacts. UHI effects have been estimated to account for a 2%-4% component of gross global warming, which includes all warming factors that increase global temperatures over time (Jacobson and Ten Hoeve 2011).

Cool Roofs for Mitigation and Adaptation to Climate Change

Cool roofs have many environmental benefits and are being used to help mitigate and adapt to climate change. Cool roofs have been touted as a low-cost technology with the potential to reduce greenhouse gas emissions, lower ambient air temperatures, reduce smog formation, improve air quality, combat heat related mortality, and reduce global warming, see Figure 4, (Akbari 2008; Luber and McGeehin 2008; Ray 2010; Urban and Roth 2010; Stocker et al. 2013).

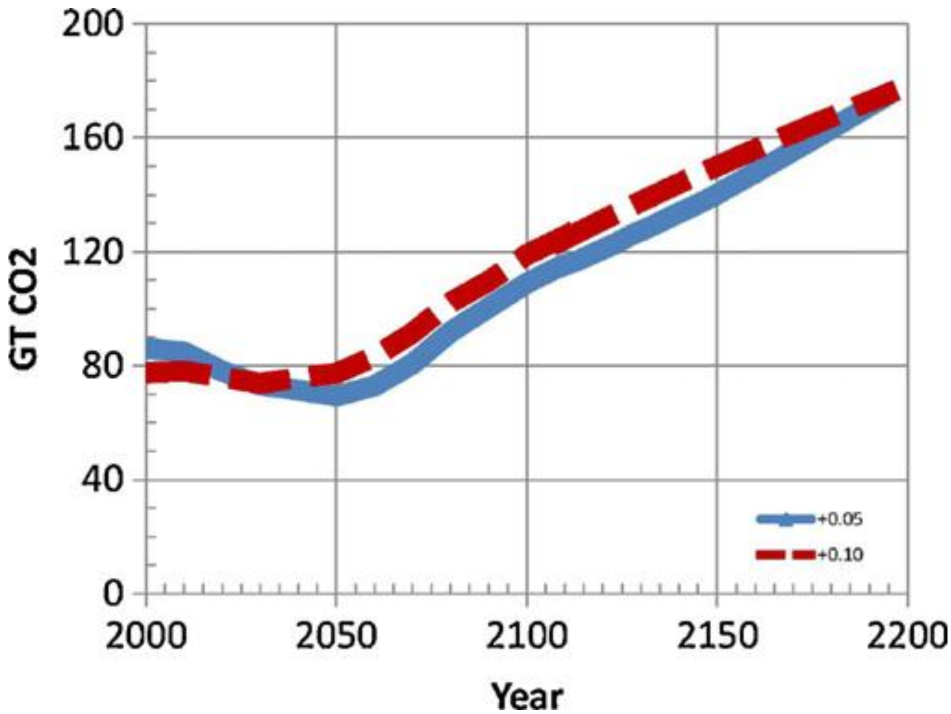


Figure 4 shows the potential offsets of CO_2 emissions if the albedo of urban surfaces is increased by 0.10 and 0.05 for urban areas. Note the significant increase in CO_2 offset equivalence of increasing albedo in urban areas, approximately 1% of land area, over the next two centuries. (Akbari and Matthews 2012)

According to the IPCC (2007), many of the impacts of climate change can be avoided, minimized or delayed by using mitigation strategies. Oreskes et al. (2010) posit that the less humans mitigate, the more deftly they will need to adapt. Decisions related to implement adaptation and mitigation strategies are often based on the related costs, and cool roofs should be a cost-effective strategy for both adaptation and mitigation (Oreskes et al. 2010). The material and installation costs are generally equivalent to a standard roof and in climates with over 1000 cooling degree-days. The simulations suggest that there is a long-term cooling effect of $3x10^{-15}$ K for each one square meter of cool roof installed (Akbari and Konopacki 2005; Akbari and Matthews 2012).

However, whether cool roofs can reduce overall global warming remains controversial. Using global climate modeling, Jacobson and Ten Hoeve (2011) stated that while cool roofs may reduce ambient air temperatures locally, they may or may not reduce global warming overall. Their simulation showed that if all roofs were white and despite the local cooling effects, the overall effect would be no reduction in global warming. Another study, using a global climate model suggests the greater space heating loads of cool roofs would outweigh the air-conditioning loads (Oleson et al. 2010). Menon et al. (2011) rebut the Jacobson and Ten Hoeve hypothesis based on the uncertainties in several of their assumptions and shows that a growing body of literature suggests that the targeted use of cool roofs can reduce warming of the Earth's surface. Additionally, another study by Millstein et al. (2011) also used modeled data, similar to Jacobson and Ten Hoeve, and found that an increase in outgoing radiation was found globally when there was in increase in albedo even though a regional impact of local warming was possible in some places.

Cool Roof Life Cycle and Life Span

Additional considerations for utilizing a cool roof should include its Life Cycle Analysis (LCA) and its effective lifespan as compared to other alternatives. An LCA is an important tool for evaluating resource inputs and environmental impacts of human dominated systems. An LCA was done for a cool roofing technology, a white elastomeric coating, which showed that there are ancillary impacts of manufacturing and transporting these materials. The impacts range from transportation such as fossil fuel usage, greenhouse gas emissions and air pollution, to weathering and debriding of the elastomeric coating over time, which contains toxic ingredients (Matt et al. 2012). Zhang et al. (2013) examined the weatherization process of elastomeric coatings and determined, based on laboratory tests mimicking the effect of natural weathering, that the decrease in solar reflectance over time was an approximate two percent reduction. However this reduction in solar reflectance was considered negligible in comparison with the experimental error (Zhang et al. 2013).

A 50-year life cycle cost analysis compared cool white roofs, green roofs and standard black roofs based on the following parameters: avoided costs for energy, stormwater management, installation, and maintenance. The study showed that the 50-year net savings when using a cool white roof over a black roof is $\$25/m^2$ and a

50-year net savings of $96/m^2 is gained when using a cool white roof over a green roof. The study concluded cool roofs offer the best financial benefit. However, a green roof may be the best choice when a building owner is more concerned with UHI impacts and aesthetic considerations (Sproul et al. 2014).

A leasing company in Baltimore found significant cost savings in using a cool roof elastomeric coating over the standard hot asphalt built-up roof used in many Baltimore row homes. In a cost comparison study of 92 row homes the leasing company found a savings of $77,280 in material and installation costs when using a cool roof elastomeric coating versus a conventional roof. Those savings do not include the energy savings from having a cool roof (Jacobson 2013). Other studies have shown that the monetary cost for using a cool roof over a standard roof is minimal and in many cases has no additional cost (Akbari et al. 2001).

Research Objectives

Energy Analysis

An analysis and comparison of the energy consumption of cool roof and standard roof buildings was completed to determine how cool roof technology effects vary between regions and years.

Weather Analysis

An analysis of weather data was completed to show the variations in temperature and Heating Degree-Days (HDD) and Cooling Degree-Days (CDD) between regions mirroring the years that energy data was collected at each of the sites. Data was analyzed by month, season and year.

Relationships Analysis

A combined analysis of regional weather and energy consumption was completed to show the relationships among increasing temperature and its influence on the effectiveness of cool roofs across the US.

Chapter 2: Energy Analysis

Introduction

Cool roofs have been shown to reduce energy consumption (Akbari 2008). This study investigates how over the past decade the energy consumption of cool roof buildings has been impacted by variations in temperature across different regions of the US. A study was conducted to analyze and compare the energy consumption patterns of cool roof and standard roof buildings within and between regions over several years. As a first step, a pilot study was conducted with building energy data at one location, the Idaho National Laboratory (INL), to determine the feasibility of the proposed study. After the feasibility study was assessed, data gathering from the various laboratory sites began, which was a seven-month process. The first part of this chapter explains the feasibility study and the management of identified problems with the data, such as building location issues and outliers. The second part of this chapter is devoted to the description, analysis, and comparison of the energy consumption at selected DOE buildings in California, Illinois, Nevada, and Tennessee with standard and cool roof buildings over 11 years.

Idaho Pilot Energy Analysis Study

In order to compare cool roofs and standard roofs it was important to determine the quality of the data and the feasibility of gathering the data. There were several goals of the feasibility study. They were to determine: 1) how to choose and pair the buildings; 2) if enough years of data were available; 3) how the data were formatted, and measured; and 4) if the data were reliable.

Study Description

The pilot study consisted of collecting data at the INL to compare cool roofs and standard roofs at one location over time. An example of a cool roof installed on an INL building is shown in Figure 6. It was known prior to the study that metered data might not be available for an extended number of years, but this was deemed sufficient for a preliminary study. The data gathered in the pilot were not included in the final analysis in this dissertation due to insufficient consecutive years of accurately metered energy data.

Figure 5: Idaho National Laboratory (INL) cool roof

The proposed experimental design for the study required energy data from buildings that met the criteria described in Table 3. The buildings had to be paired and matched, and the data had to be available for several consecutive years. Identifying buildings at the INL that met the criteria was more difficult than anticipated and could not have been accomplished without the assistance from the certified energy manager and real property managers at the site. First-hand knowledge of the buildings at the site was found to be imperative for assessing the data. Of major importance, site staff advised whether retrofits other than the installation of cool roofs were completed in a particular building. This information assisted in narrowing down the list of buildings under consideration. Another example, in one building pair selected at INL, a data center was housed in part of one of the buildings. Normally this would exclude the building from being selected because of the high-energy consumption required to run a data center. However, due to requirements for separate metering of data centers put into place several years ago, the energy usage of the data center was able to be measured and subtracted out of the total energy consumption of the building.

One of the major obstacles to locating buildings that met the study criteria was the inadequacy of electricity meters in non-urban laboratory areas. Some of the INL major facilities are located in the town of Idaho Falls but most are about 60 miles away in an isolated area where nuclear energy research and development is conducted. The meters at the non-urban site were installed in 2010 via an energy savings performance contract. Energy data were found to be limited and some meters were still not calibrated properly (meters showing negative electricity consumption).

Out of almost 1,000 buildings at the site only three suitable building pairs with only one to three consecutive years of metered energy data were identified. The certified energy manager suggested concentrating site selection on more urban laboratories where the local utility company requires a meter and are measured monthly. The INL pilot energy study results suggested that primarily focusing building selection on urban research laboratories, where energy meters have been in place for a decade or more, should provide a sufficient number of years of energy data for the proposed study.

Multi-Region Analyses

An analysis and comparison of the energy consumption of cool roof and standard roof buildings was conducted to determine how cool roof effects vary between regions and years.

Site Description

Study sites were located at DOE national research laboratories across the US, where the Department of Energy (DOE) Roof Asset Management Program has installed over 4 million square feet of cool roofs at DOE national research laboratories. Approximately 500,000 square feet of cool roofs have been installed each year since 2004. These cool roofs have been installed at mostly rural laboratory sites in many US states (Tennessee, Kansas, Texas, Illinois, New Mexico, Idaho, Nevada and California), and climate zones ranging from semiarid steppe to humid subtropical (Baechler et al. 2010).

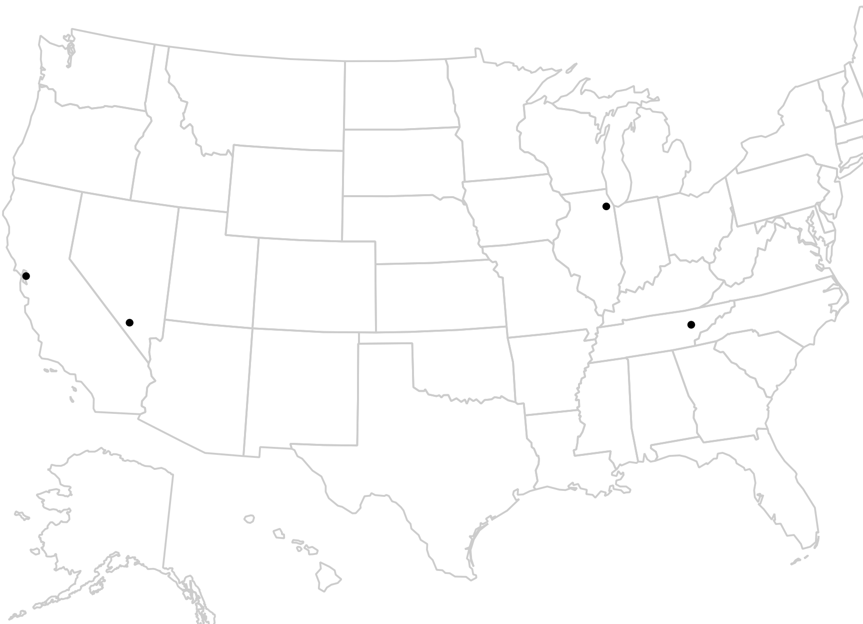


Figure 6: Site Locations

Study sites were chosen to represent four different geographic regions (Figure 6). Each site has extensive cool roofs that have been monitored for energy consumption between two and sixteen continuous years.

Data Description

Energy and associated building data were obtained from thirteen DOE national research laboratory sites. These datasets were evaluated for quality, adequate consecutive years of data, and adherence to the building pairing criteria. Data from only four sites, California, Illinois, Nevada, and Tennessee, were deemed sufficient to be used in this study. The nine remaining data sets were rejected because: 1) of incomplete and estimated data; 2) an insufficient number of consecutive years of data existed; and 3) data were missing. Energy data for each building was obtained for a range of years between 1997-2013 with a minimum of two to a maximum of 16 years of consecutively metered energy data for all buildings in California, Illinois, and

Tennessee and for each cool or standard roof building pairs in Nevada. Monthly electricity data were collected in kilowatts per hour (kWh) from each site's certified energy manager. Monthly natural gas data used to power the selected buildings were collected and converted from their original unit, therms, into kWh. Electricity and natural gas were used to heat and power buildings at the California and Illinois sites. Only electricity was used to power the buildings at the Nevada and Tennessee site. In Illinois, approximately 63% of the energy to the buildings was from natural gas, while electricity provided the other 37% of energy. In California, approximately 52% of energy to the buildings was from natural gas and 48% was from electricity. The kWh from all fuel sources for each building were combined and divided by the building's area, gross square meters, to calculate energy used per square meter, or the energy density, to allow comparing energy consumption between buildings of different sizes. Energy consumption and not energy cost or cost-effectiveness was used due to the fluctuating prices of energy. While costs could have been normalized for the dollar value in a given year, using energy consumption allowed for simple conversion of the current cost of energy, if energy cost was desired.

At the California, Illinois, and Tennessee sites subject buildings were selected which had metered energy consumption data available for several year before a cool roof was installed. Energy consumption in this study is defined as the total energy consumed by the building, which may include any combination of the following: electricity, natural gas, and steam (powered by natural gas). Monthly energy consumption data was also compiled for several years post cool roof installation.

At the Nevada site, subject-building pairs were chosen based on similar building types, e.g. office building, and size. Each pair of buildings consisted of metered energy data from a cool roofed building and a comparable standard roof building. There were a total of 19 paired energy data sets and 25 buildings overall across the US, as shown in Table 2. There were eleven offices, seven laboratories, and seven miscellaneous buildings among the 25 buildings. The miscellaneous building type includes specialty buildings such as storage facilities, communications buildings, housing facilities and others that could not be identified as a laboratory or an office.

Site	Region	Building Identifier	Years Monitored		Total Years Monitored
			Pre-Cool	Post-Cool	
IL	Midwest	Total Buildings	4	4	2002-2013
		1i	2004-2006	2006-2013	
		2i	2002-2010	2010-2013	
		3i	2002-2009	2009-2013	
		4i	2002-2004	2004-2013	
CA	West Coast	Total Buildings	7	7	2000-2013
		1c	2000-2008	2008-2013	
		2c	2000-2006	2006-2013	
		3c	2000-2008	2008-2013	
		4c	2000-2007	2007-2013	
		5c	2000-2007	2007-2013	
		6c	2002-2007	2007-2013	
		7c	2002-2007	2007-2013	
TN	Southeast	Total Buildings	2	2	2001-2013
		1t	2002-2006	2006-2013	
		2t	2001-2009	2009-2013	
NV	Southwest	Total Buildings	6 Standard Bldgs	6 Cool Roof Bldgs	1997-2013
		1n pair	2000-2013		
		2n pair	1998-2013		
		3n pair	2004-2013		
		4n pair	1999-2013		
		5n pair	1998-2013		
		6n pair	1997-2013		

Table 2: Location and region of DOE Research Laboratories studied and years buildings were monitored for energy consumption. Nevada had a total of 12 buildings, six were standard roofed and the six were cool roof buildings.

Building pairs in Nevada were of similar characteristics, which include age of the building, for area of the building in square meters, the number of floors, roof surface area, number of occupants in the building, use of the building, (e.g. laboratory, warehouse, or office use), building construction type (e.g. metal, concrete, or stick frame), Table 3. Discussions with the certified energy managers and facility representatives at each site yielded information about the process loads of the facilities, e.g. a data center would only be compared to another data center, or alternatively a maintenance facility would only be compared to another building on the same site with similar process loads.

Building Characteristic	Range	Permitted Variance
Age	1940-Current	+/- 20 years
Size Number of Floors	500 -500,000 ft^2 1-5	+/- 15%
Roof Surface Area	500-500,000 ft^2	+/- 15%
Number of Occupants	0-1,000	+/- 15%
Usage	N/A	Limited to similar process load type
Construction Type	Varies	Materials used for construction will be compared (e.g. concrete versus steel framing)

Table 3: Nevada building pairs permitted variances for selection.

Certain DOE national research laboratories have classified activities at their sites; therefore site and building names and certain characteristics of the structures are confidential. Buildings were coded by location, roof type, building type, size, and pair number, if applicable. Additionally, where confidential data could not be shown, summary data was given and explained.

Outliers and Model Construction

Outlier Analysis

After the site data were assembled it was evaluated for errors and outliers. Outliers that were greater than three standard deviations away from the mean were evaluated in the context of the data to determine the cause of the variation from the mean. The data were examined for error versus inherent variation in the data. All outliers were determined to have been caused by equipment malfunction and/or meter calibration issues, including negative electricity meter readings, and were excluded from the analysis. On average about 1% of the observations were outliers. For the Nevada site energy consumption values greater than 100 kWh/m^2 were excluded from the analysis because they were not realistic measurements. There were 11 readings out of over 2000 eliminated, which constituted 0.005% of the data. The NV outliers occurred in two standard roofed buildings.

In addition to eliminating energy consumption outliers greater than three standard deviations from the mean, a leverage plot analysis was run for each effect in the model using JMP Pro 11.1. This analysis showed which data points were exerting undue influence on the hypothesis test. For easier identification of multicollinearity issues, abnormal patterns and violations of the model assumptions a leverage plot analysis was used. Plots of the residual error, which are the unaccounted or error variation versus actual and predicted values, were also completed. Several energy consumption data points over 100kWh/m2 were eliminated, as they were all well above three standard deviations from the respective means. There were no discernible patterns to the remaining potential outliers and was likely an inherent part of the data variation. There was a strong central tendency about the mean for all data sets.

Model Construction

The purpose of the energy analysis was to determine how cool roof effects varied between regions and years. The statistical analysis investigated the effect of year (time effects), site (regional effects), and treatment effects (cool versus standard roof), and their interactions. Statistical analyses and visualization of patterns were conducted using JMP Pro 11.1.

The analysis of variance assumes that errors are homogeneous. In order to investigate this assumption, the correlation between the standard deviations and means was examined. In general, there was a significant increase in variance with an increase in mean. There was a significant correlation between standard deviation and mean for California (R=0,89). There was a significant correlation between standard deviation and mean for Illinois (R=0.85). There was a significant correlation between standard deviation and mean for Nevada (R=0.83). However, variances were not significantly different based on an F-test comparing the largest variance to the smallest variance ($p \leq 0.05$). Thus, the F-tests and T-tests did not violate this assumption. Regardless, these tests are robust.

Regression analysis, means analyses, boxplot analyses and ANOVA were conducted on the data. The boxplot analysis compared each building's energy consumption before installation of a cool roof and after installation of a cool roof. There was a great deal of building-to-building variation within and between each site. This will be explored with boxplot analyses site by site. Some of this variation could be due to a building changing its mission at a site, which may impact the use of a single building over time. For example, a building may have been completely operational and utilized one year, but the next year due to funding and mission changes, it may have become only partially utilized.

There was a great deal of variation in energy consumption over buildings by season. The overwhelming majority of the literature states that cool roofs reduce overall energy consumption, assuming all other factors remain consistent. Although every effort was made to control other factors by matching pairs or comparing the same buildings before and after cool roof installations, some factors may not have remained consistent. A great deal of effort was expended to ensure this type of error was eliminated from the data in this study. Despite thousands of buildings initially evaluated for inclusion into this study across the DOE complex and hundreds of different individuals responsible for these buildings over a 15 year period, there was likely some of this type of error inherent in the data.

Energy Consumption

This study evaluated 25 buildings in four regions. There was a great deal of building-to-building variation within and between each site. This is shown by table 4, which gives the annual mean energy consumption of each cool roof and standard roof building or pair. The range in cool roof energy consumption was 13.4±0.3 kWh/m^2 to 85.5±4.2 kWh/m^2 for California. The range in standard roof energy consumption was 15.5±0.4 kWh/m^2 to 105.0±5.7 kWh/m^2 for California. The range in cool roof energy consumption was 3.1±0.4 kWh/m^2 to 83.4±3.5 kWh/m^2 for Illinois. The range in standard roof energy consumption for Illinois was 3.7±0.1 kWh/m^2 to 96.8±9.1 kWh/m^2. The range in cool roof energy consumption for Nevada was 9.4±0.3 kWh/m^2 to 22.8±0.8 kWh/m^2. The range in standard roof energy consumption for Nevada was 6.3±0.5 kWh/m^2 to 45.5±1.2 kWh/m^2. The range in cool roof energy consumption in Tennessee was 12.1±0.5 kWh/m2 to 14.1±0.3 kWh/m^2. The range in standard roof energy consumption in Tennessee was 9.9±0.6 kWh/m2 to 14.6±0.9 kWh/m^2.

Bldg.	Bldg. Use	Bldg. Size	Energy Consumption (kWh/m^2) Cool Roof	Standard Roof
California				
1	Laboratory	Large	53.4 ±2.6	65.0 ±2.1
2	Laboratory	Small	85.2 ±3.0	91.3 ±5.9
3	Laboratory	Medium	46.5 ±2.2	56.4 ±1.7
4	Laboratory	Small	85.5 ±4.2	105.0 ±5.7
5	Office	Large	25.1 ±1.0	22.6 ±0.9
6	Office	Small	14.5 ±0.4	17.6 ±0.5
7	Office	Large	13.4 ±0.3	15.5 ±0.4
Total in CA			46.3 ±1.6	52.2 ±1.9
Illinois				
1	Miscellaneous	Small	4.1 ±0.3	4.7 ±0.4
2	Laboratory	Medium	3.1 ±0.4	3.7 ±0.1
3	Laboratory	Large	78.6 ±3.2	66.9 ±2.7
4	Laboratory	Large	83.4 ±3.5	96.8 ±9.1
Total in IL			46.5 ±2.7	38.9 ±2.9
Nevada				
1	Office/Misc.	Small	10.2 ±0.4	6.3 ±0.5
2	Misc./Misc.	Medium	22.8 ±0.8	28.6 ±1.6
3	Offices	Small	9.4 ±0.3	16.5 ±0.6
4	Offices	Small	18.8 ±0.6	13.2 ±0.4
5	Misc./Misc.	Small	20.2 ±1.3	45.5 ±1.2
6	Misc./Office	Small	11.3 ±0.3	12.5 ±0.3
Total in NV			15.9 ±0.3	20.9 ±0.6
Tennessee				
1	Office	Small	14.1 ±0.3	14.6 ±0.9
2	Office	Small	12.1 ±0.5	9.9 ±0.6
Total in TN			13.4 ±0.3	11.4 ±0.6
Over All Sites			28.0 ±0.7	29.2 ±0.7

Table 4: Annual means and standard errors for energy consumption for each building pre-cool roof and post-cool roof at each site and overall total for each site and all sites combined for years 2003-2013.

In a modeling study, differences in building uses had been previously found between offices and lodging, where building use had been shown to affect energy consumption differences between cool and standard roofs (Sailor et al. 2012). In figure 7, the mean energy consumption by building use and roof type is shown. Cool roof building types consumed less energy than their standard roof counterparts. Cool roof laboratories consumed 66.6±1.9 kWh/m^2 of energy and standard roof laboratories consumed 68.8±2.2 kWh/m^2 a 3.2% reduction. Cool roof buildings in the miscellaneous category consumed 13.6±0.5 kWh/m^2 of energy, while their standard roof counterparts consumed 27.0±1.2 kWh/m^2 a 49.6% reduction. Cool roof office buildings consumed 14.4±0.2 kWh/m^2 of energy and standard roof office buildings consumed 17.0±1.0 kWh/m^2 of energy, a 15.3% reduction.

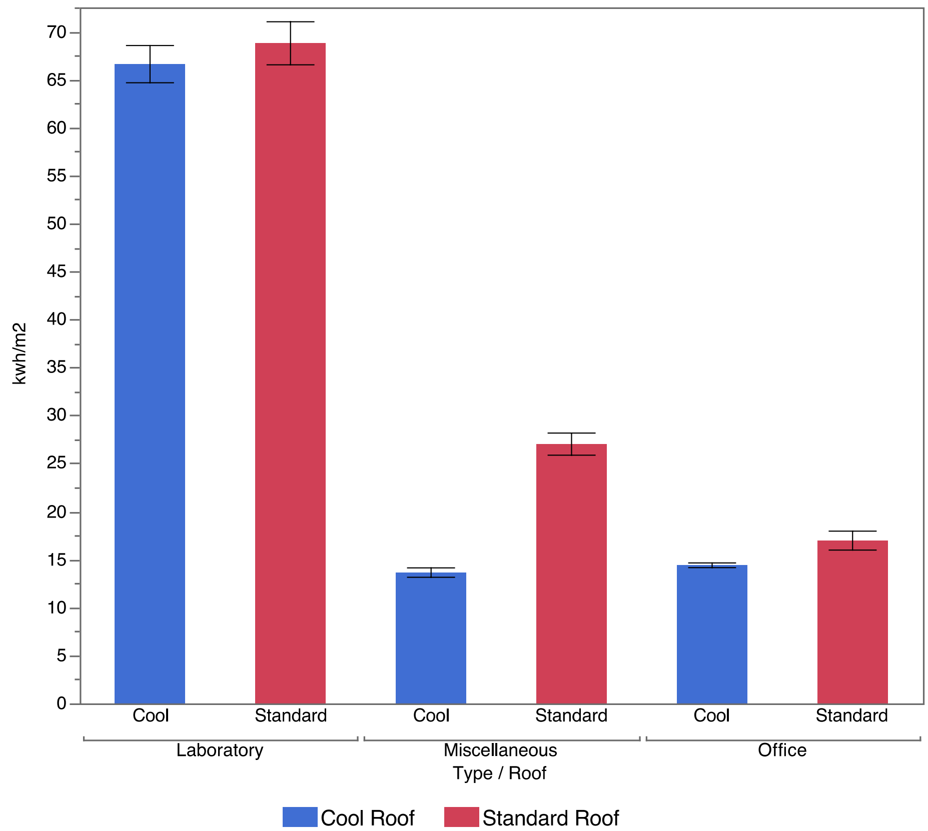
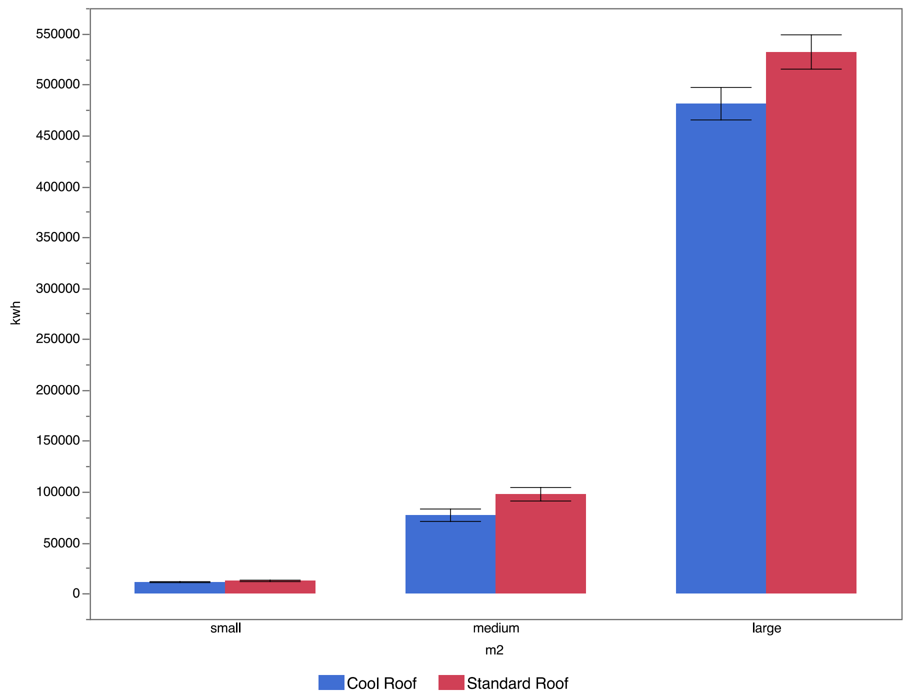


Figure 7: Energy consumption averaged over years 2003-2013 by building type and roof type.

To investigate the influence of building size, the buildings in the dataset were divided into three categories, where small buildings were less than 1,500 m^2, medium buildings were between 1,500 m^2 and 5,000 m^2, and large buildings were over 5,000 m^2. Small buildings in the dataset had less energy consumption (kwh) per square meter than medium and large buildings, as shown in Figure 8 (a). Large buildings had the most energy consumption per square meter. In Figure 8 (b) relativized energy consumption (kwh/m2) is shown, where the cool roof buildings use less energy than their standard roof counterpart. The percentage difference in energy consumption between cool and standard roofs is very similar over all size categories. However, retrofitting larger buildings presents a greater opportunity for saving money overall, because the quantity of energy consumption avoided is greater.

(a)



(b)

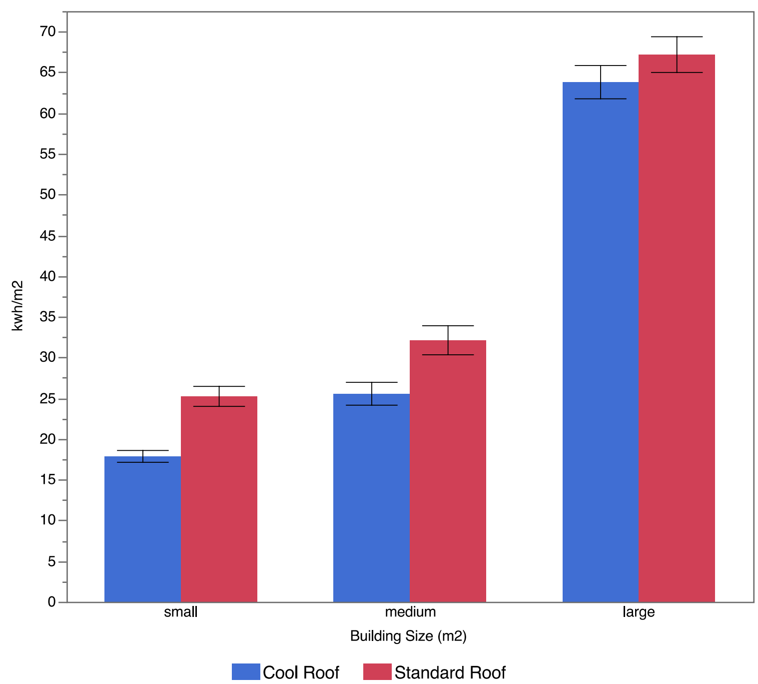


Figure 8: Energy consumption averaged over years 2003-2013 by building size, (a) energy use (kwh) by building size, (b) energy consumption (kwh/m2) by building size.

California

Energy consumption over seasons for cool roof buildings and standard roof buildings was shown in the California boxplot analysis (Figure 9). There were great variations in energy consumption for buildings 1, 2 and 4. For cool roof building 1, energy consumption ranged from 50.8±4.3 kWh/m^2 in the spring to 55.9±8.0 kWh/m^2 in the winter. For standard roof building 1, energy consumption ranged from 57.7±3.9 kWh/m^2 in the fall to 69.3±4.4 kWh/m^2 in the spring. For cool roof building 2, energy consumption ranged from 66.2±4.7 kWh/m^2 in the fall to 119.9±7.6 kWh/m^2 in the winter. For standard roof building 2, energy consumption ranged from 71.2±9.3 kWh/m^2 in the summer to 124.31±6.1 kWh/m^2 in the spring. For cool roof building 4, energy consumption ranged from 73.7±8.6 kWh/m^2 in the fall to 108.7±8.9 kWh/m^2 in the winter. For standard roof building 4, energy consumption ranged from 111.7±17.9 kWh/m^2 in the summer to 132.0±9.8 kWh/m^2 in the winter. Variation for buildings 3 and 5 were moderately minimal, ranging from 19.4±1.4 kWh/m^2 for standard roof building 5 in the fall to 62.4±3.4 kWh/m^2 for standard roof building 3 in the winter. Variation for buildings 6 and 7 were extremely minimal, ranging from 13.2±0.5 kWh/m^2 for cool roof building 7 in the fall and 18.8±1.5 kWh/m^2 for standard roof building 6 in the spring.

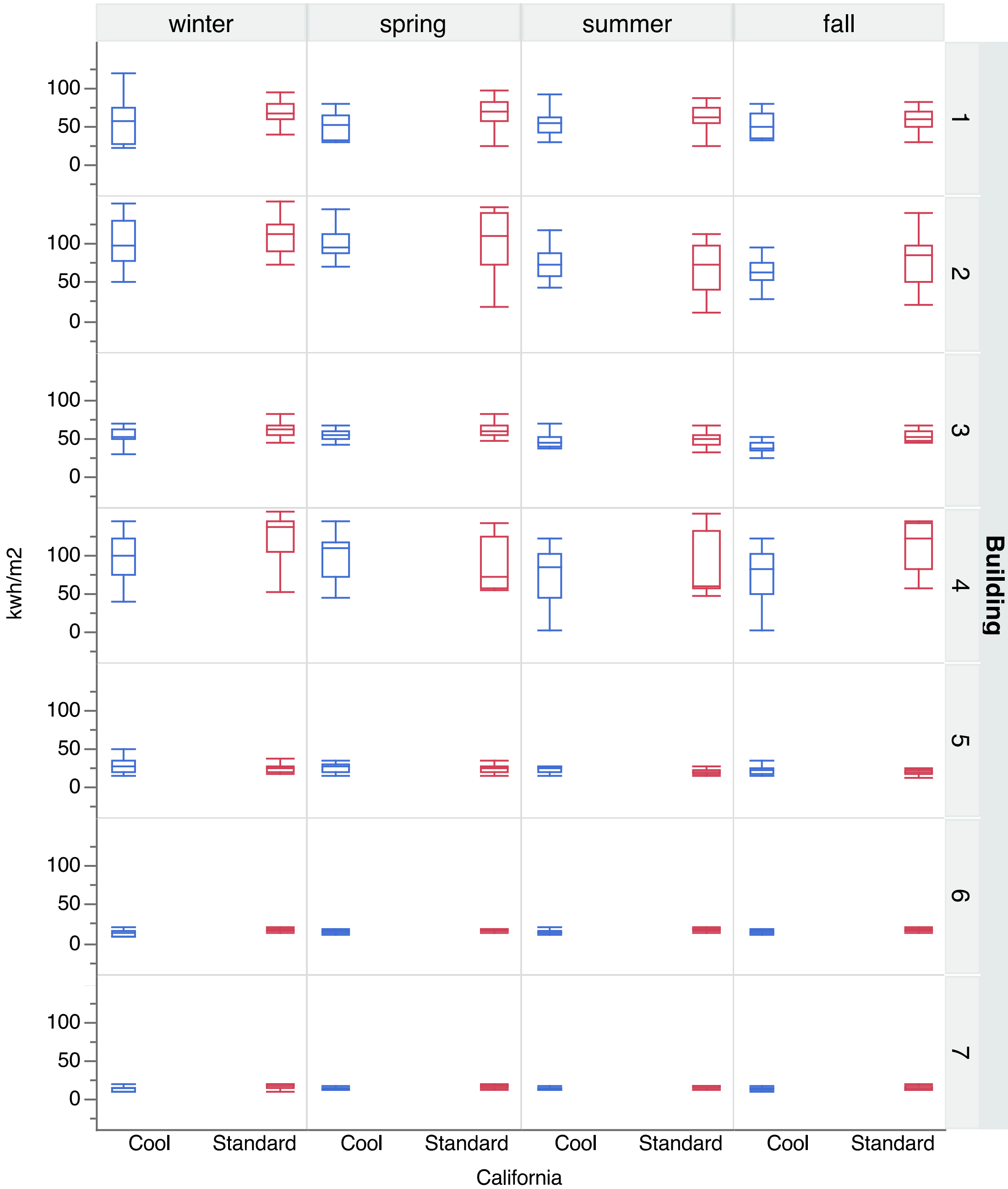


Figure 9: Boxplots of energy consumption over seasons for cool roof buildings and standard roof buildings in California.

The regression analysis, Figure 10, shows a strong relationship between the standard deviations of energy consumption for the California sites and the means of energy consumption, where the r-value is 0.89. Buildings that did not use much energy did not have great variances. There would be more variation in energy consumption in buildings that used a lot of energy than in buildings that did not.

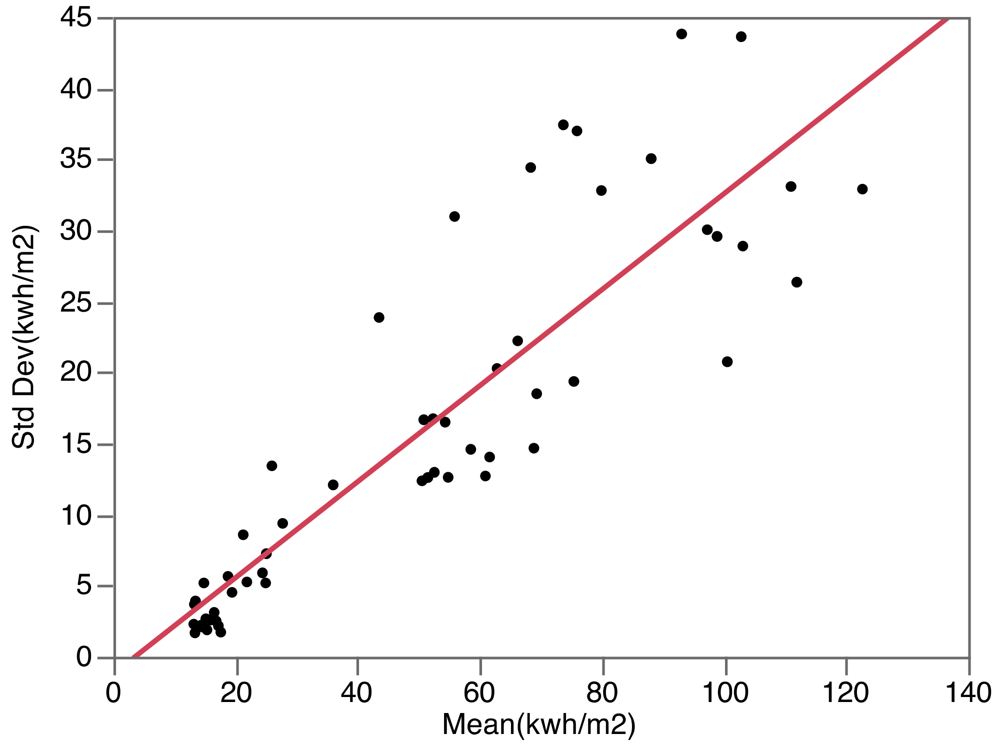


Figure 10: Bivariate fit of the standard deviation of energy consumption as plotted with the mean for the California site, where r=0.89.

For six out of seven buildings, cool roof buildings outperformed the standard roof buildings in energy consumption by at least five percent (Table 5). Five cool roof buildings outperformed the standard roof buildings in energy consumption by at least ten percent. Four cool roof buildings outperformed the standard roof buildings in energy consumption by fifteen percent or more. Building 5 had an energy increase after the cool roof was installed of 10%. The increase in energy consumption between the standard roof and post-cool roof installation showed no trends that could be attributed to the size of the building. However, the laboratories at this site, specifically buildings 1, 2, 3 and 4, had higher energy consumption than their office-building counterparts, buildings 5, 6, and 7.

Bldg.	Cool Roof Energy Consumption (kWh/m^2)	Standard Roof Energy Consumption (kWh/m^2)	Energy Reduction or Energy Increase
1	53.4±2.6	65.0±2.1	-18%
2	85.2±3.0	91.3±5.9	-7%
3	46.5±2.2	56.4±1.7	-18%
4	85.5±4.2	105.0±5.7	-19%
5	25.1±1.0	22.6±0.9	+10%
6	14.5±0.4	17.6±0.5	-18%
7	13.4±0.3	15.5±0.4	-14%
Total	46.3±1.6	52.2±1.9	-11%

Table 5: Mean energy consumption for cool and standard roof buildings at the California site averaged over years 2003-2013.

An in-depth look at the reduction in mean energy consumption of cool and standard roofs by season is given in Table 6. Building 4 has the greatest decrease in energy consumption after installation of the cool roof. A reduction in energy consumption in the summer and possibly spring and fall were expected, but there is a significant difference in energy consumption in all months. Therefore, it is likely that other factors are contributing to the energy reduction. It may be that other energy conservation retrofits were installed at the same time as the cool roof. This information was not readily available. The mean energy consumption for cool roof building 4 are significantly lower in winter, at 108.7±8.9 kWh/m^2, summer, at 83.3±10.9 kWh/m^2, fall, at 73.7±8.6 kWh/m^2, and spring, at 103.4±8.1 in California, totaling a 19% reduction in energy consumption from pre- to post-cool roof installation. The mean energy consumption for standard roof building 4 is higher in all months over its cool roof building counterpart. The mean energy consumption for standard roof building 4 was 130.1±15.9 kWh/m^2 in spring, 111.7±17.9 kWh/m^2 in summer, 128.7±18.9 kWh/m^2 in fall, and 132.0±9.8 kWh/m^{2}in winter.

		kwh/m2			
		Roof			
		Cool		Standard	
Building	Season	Mean	Std Err	Mean	Std Err
1	winter	55.9	8.0	69.0	3.7
	spring	50.8	4.3	69.3	4.4
	summer	54.3	4.0	62.8	5.1
	fall	52.4	4.2	57.7	3.9
2	winter	111.9	7.6	116.5	9.8
	spring	103.3	5.2	124.3	16.1
	summer	80.5	6.5	86.9	21.2
	fall	66.2	4.7	71.2	9.3
3	winter	52.6	3.3	62.4	3.4
	spring	54.8	3.3	60.9	3.0
	summer	43.5	5.8	50.5	3.1
	fall	36.0	3.0	51.6	3.4
4	winter	108.7	8.9	132.0	9.8
	spring	103.4	8.1	130.1	15.9
	summer	83.3	10.9	111.7	17.9
	fall	73.7	8.6	128.7	18.9
5	winter	27.7	2.2	24.4	1.6
	spring	24.9	1.2	25.1	1.9
	summer	26.0	3.0	21.3	2.4
	fall	21.9	1.2	19.4	1.4
6	winter	13.4	0.9	16.8	0.7
	spring	15.1	0.6	18.8	1.5
	summer	14.8	1.2	17.6	0.5
	fall	14.5	0.5	17.1	0.6
7	winter	13.3	0.9	16.6	1.2
	spring	13.4	0.4	15.9	0.9
	summer	14.0	0.5	15.3	0.6
	fall	13.2	0.5	14.1	0.5

Table 6: Energy consumption and standard error for pre- and post-cool roof in California.

There was an approximately equal or greater consumption of energy in every season for building 5 in California, which compares to the 10% increase in energy consumption for the building pre- versus post-cool roof installation. Seasonal variations impacting energy consumption in the building 5 was not what was expected. It was expected that summer energy consumption would be higher, but the cool roof consumed more energy in the summer than its standard roof counterpart. The overall energy consumption for this building, an office building, was relatively low compared to other buildings at this site. Therefore, the overall impact on energy consumption to the site was fairly low. The mean energy consumption for cool roof building 5 is significantly lower in fall, at 21.9±1.2 kWh/m^2, and higher in the summer, at 26.0±3.0 kWh/m^2, and spring, at 24.9±1.2 kWh/m^2, and winter, at 27.7±2.2 kWh/m^2. The mean energy consumption for standard roof building 5 is lower for fall, at 19.4±1.4 kWh/m^2, and summer, 21.3±2.4 at kWh/m^2, and higher for spring, at 25.1±1.9 kWh/m^2, and winter, at 24.4±1.6 kWh/m^2.

There are seven buildings in the California means chart analysis, where the error bars are constructed using one standard error from the mean, as shown in Figure 11. Building 4 has great seasonal variation from cool to standard roof, where spring is the only season where the cool roof building has higher energy consumption than the standard roof building. Buildings 1, 2, and 3 have moderate seasonal variation, while buildings 5, 6, and 7 have very minimal variation.

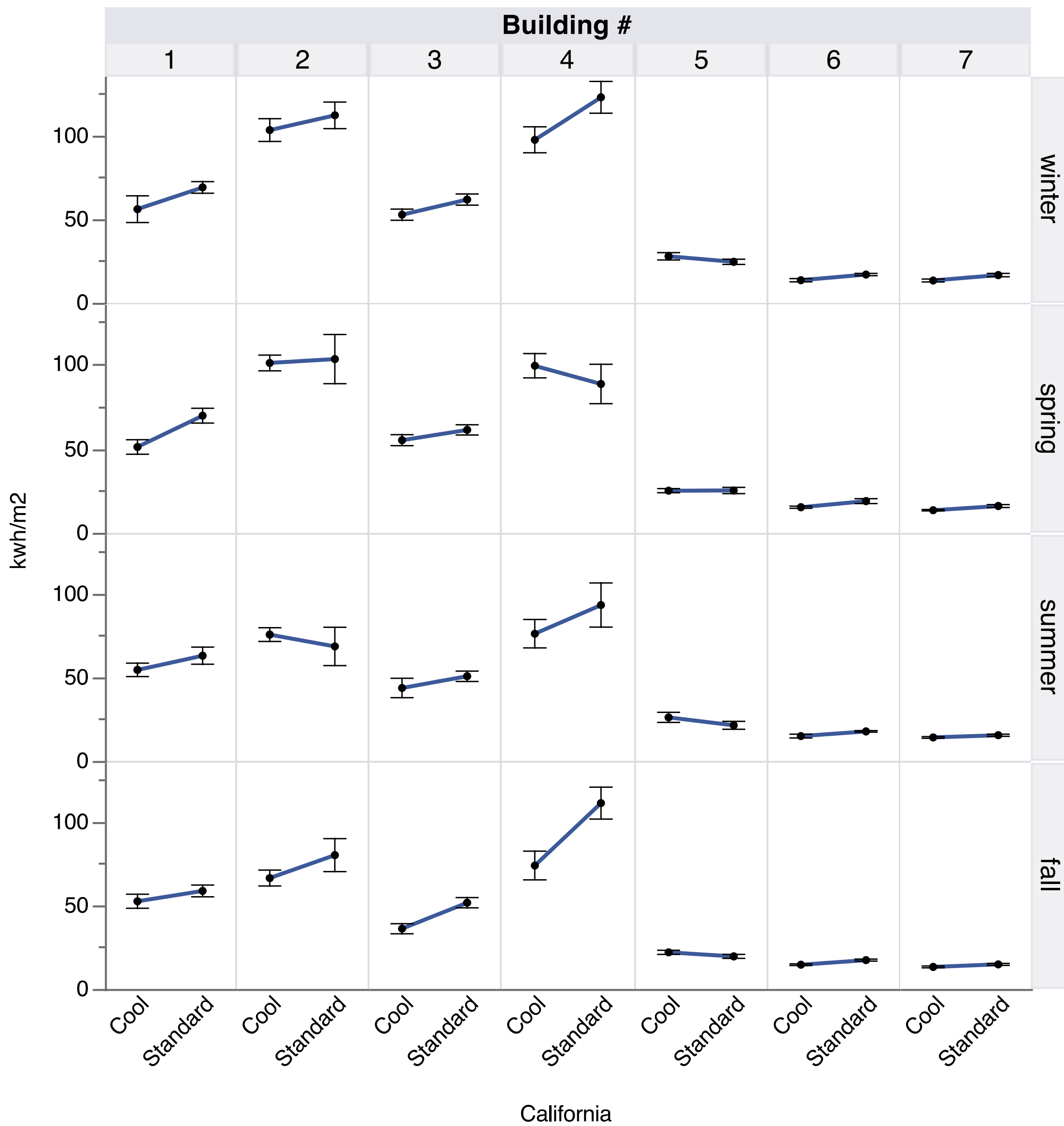


Figure 11: Means chart with error bars comparing the seasonal means in energy consumption between cool roof buildings and standard roof buildings in California averaged over years 2003-2013.

Illinois

Energy consumption over seasons for cool and standard roof buildings was shown in the Illinois boxplot analysis (Figure 12). There were great variations in energy consumption for buildings 3 and 4. For cool roof building 3, energy consumption ranged from 58.7±2.0 kWh/m^2 in the summer to 100.5±6.0 kWh/m^2 in the winter. For standard roof building 3, energy consumption ranged from 43.2±2.3 kWh/m^2 in the fall to 93.0±3.0 kWh/m^2 in the winter. For cool roof building 4, energy consumption ranged from 51.2±1.9 kWh/m^2 in the summer to 123.3±6.8 kWh/m^2 in the winter. For standard roof building 4, energy consumption ranged from 62.7±5.9 kWh/m^2 in the summer to 145.4±10.2 kWh/m^2 in the winter. Variation for buildings 1 and 2 were minimal, ranging from 2.1±0.3 kWh/m^2 for cool roof building 2 in the winter to 5.9±0.6 kWh/m^2 for standard roof building 1 in the winter.

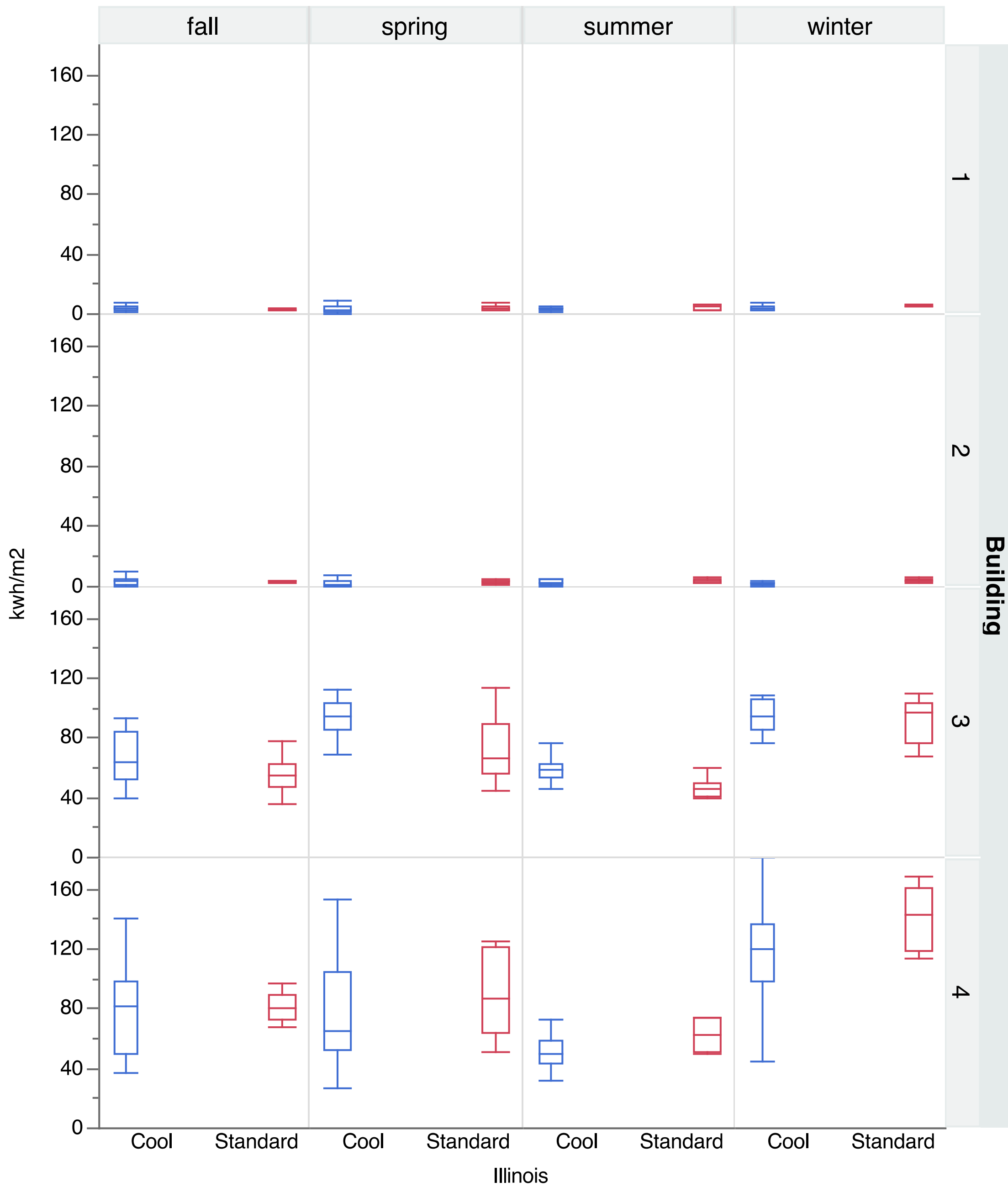


Figure 12: Boxplots of energy consumption for cool roof buildings and standard roof buildings in Illinois

The regression analysis, Figure 13, shows a strong relationship between the standard deviations of energy consumption for the Illinois sites and the means of energy consumption, where the r-value is 0.85. Buildings that did not use much energy did not have great variances. There would be more variation in energy consumption in buildings that use a lot of energy than in buildings that did not.

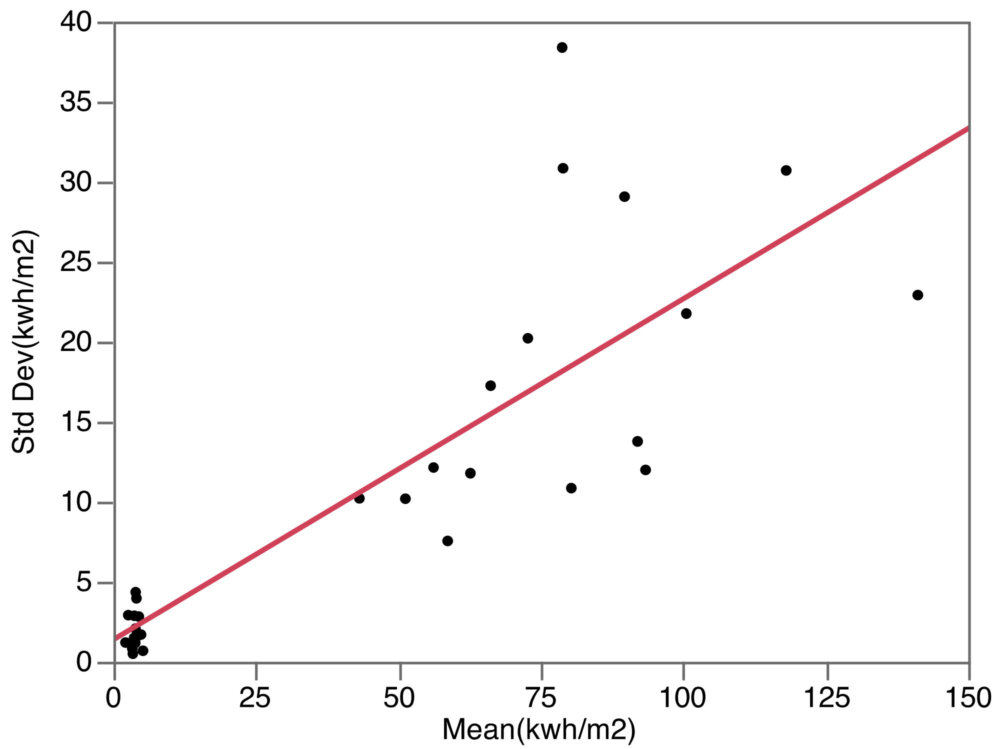


Figure 13: Bivariate fit of the standard deviation of energy consumption as plotted with the mean for the Illinois site, where r=0.85.

For three out of four buildings, cool roof buildings outperformed the standard roof buildings by 10% or more (Table 7). Building 3 had an energy increase after the cool roof was installed of 15%. Building 3's energy consumption increase overshadowed the results for the entire site. The sizes of buildings 1, 2, and 4, which had a reduction in energy consumption post-cool roof installation, ranged from small to large. Two were laboratories and one was a miscellaneous use building. Other factors, such as the number of occupants using the building or mission changes, were likely responsible for the increase in energy consumption by building 3 post-cool roof installation.

Bldg.	Cool Roof Energy Consumption (kWh/m^2)	Standard Roof Energy Consumption (kWh/m^2)	Energy Reduction or Energy Increase
1	4.1±0.3	4.7±0.4	-13%
2	3.1±0.4	3.7±0.1	-16%
3	78.6±3.2	66.9±2.7	+15%
4	83.4±3.5	96.8±9.1	-14%
Total	46.5±2.7	38.9±2.9	+16%

Table 7: Mean energy consumption for cool and standard roof buildings at the Illinois site averaged over years 2003-2013.

An in-depth look at the greatest reduction and increase in energy consumption is shown in Table 8. A higher consumption of energy is evident in every season for cool roof building 3 over standard roof building 3 in Illinois, totaling an 18% increase in energy consumption for the building pre- versus post-cool roof installation. The mean energy consumption for cool roof building 3 is significantly lower in summer, at 58.7±2.0 kWh/m^2, and higher in winter at 100.5±6.0 kWh/m^2. The mean energy consumption for standard roof building 3 is lower for summer, at 43.2±2.3 kWh/m^2, and higher for winter, at 93.0±3.0 kWh/m^2. If energy consumption was only higher in the winter for the cool roof building, it might have been attributed to a potential heating penalty, but because energy consumption was higher for all seasons there were other unknown contributing factors.

		kwh/m2			
		Roof			
		Cool		Standard	
Building	Season	Mean	Std Err	Mean	Std Err
1	winter	4.2	0.3	5.9	0.6
	spring	4.0	0.9	4.3	0.9
	summer	3.6	0.3	4.8	0.8
	fall	4.5	0.6	3.3	0.5
2	winter	2.1	0.3	3.8	0.3
	spring	2.6	0.8	3.6	0.3
	summer	3.9	1.3	3.8	0.3
	fall	3.7	0.8	3.5	0.1
3	winter	100.5	6.0	93.0	3.0
	spring	93.4	3.5	72.7	4.4
	summer	58.7	2.0	43.2	2.3
	fall	66.2	4.5	56.1	2.8
4	winter	123.3	6.8	145.4	10.2
	spring	81.7	7.8	89.7	11.9
	summer	51.2	1.9	62.7	5.9
	fall	78.9	5.6	75.8	4.3

Table 8: Energy consumption and standard error for pre- and post-cool roof in Illinois.

There is higher consumption of energy in every season for standard roof building 4 over cool roof building 4 in Illinois, totaling a 17% reduction in energy consumption for the building pre- versus post-cool roof installation, as shown in Figure 14. The mean energy consumption for cool roof building 4 is significantly lower in summer, at 51.2±1.9 kWh/m^2, and higher in winter at 123.3±6.8 kWh/m^2. The mean energy consumption for standard roof building 4 is lower for summer, at 62.7±5.9 kWh/m^2, and higher for winter, at 145.4±10.2 kWh/m^2.

There were four buildings in the Illinois means chart analysis, where each error bar was constructed using one standard error from the mean, as shown in Figure 18. Buildings 3 and 4 had some seasonal variation from cool to standard roof. Building 3 had less variation in winter between pre- and post-cool roof. Building 4 had less variation in the fall between pre- and post-cool roof. Buildings 1 and 2 had very minimal seasonal variation.

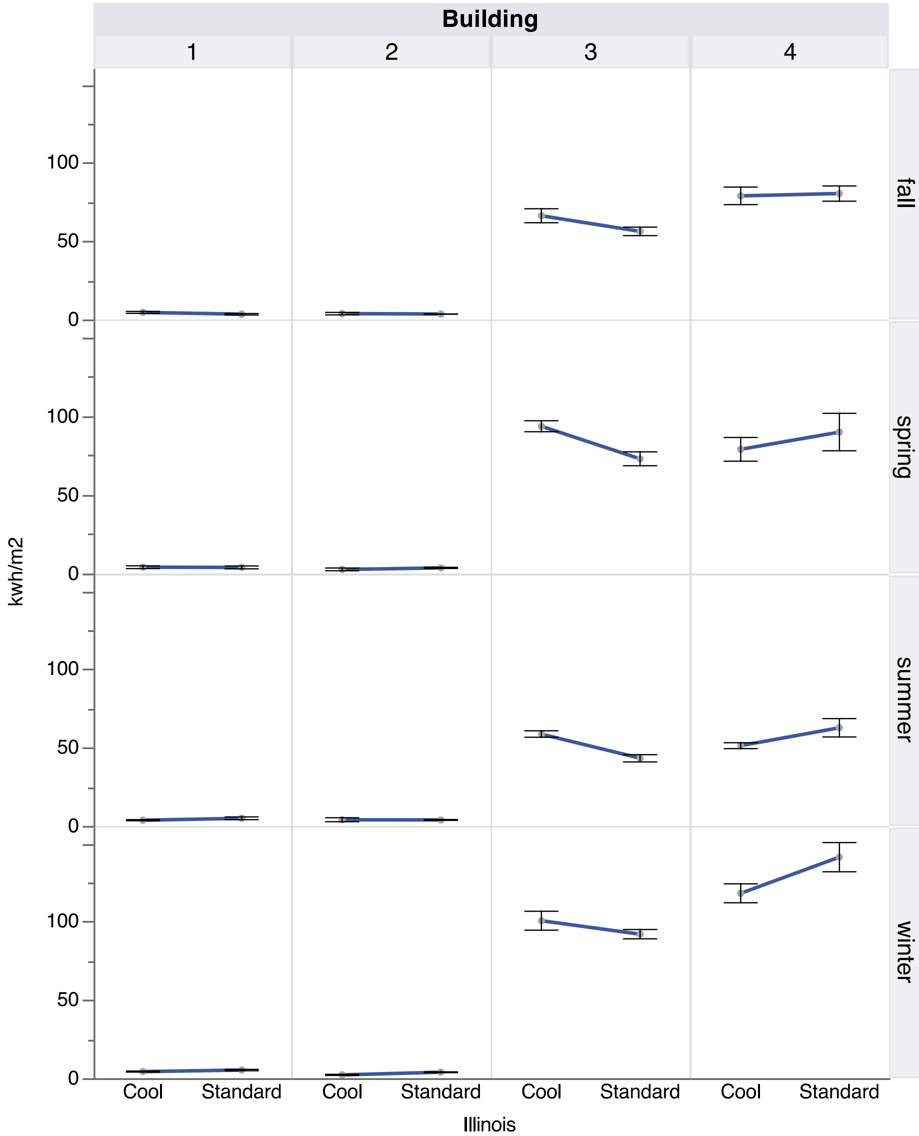


Figure 14: Means chart with error bars comparing the seasonal means in energy consumption between cool roof buildings and standard roof buildings in Illinois averaged over years 2003-2013.

Nevada

Energy consumption over seasons for cool roof and standard roof buildings was shown in the Nevada boxplot analysis (Figure 15). There were great variations in energy consumption for buildings 2 and 5. For cool roof building 2, energy consumption ranged from 15.2±1.2 kWh/m^2 in the fall to 28.4±1.7 kWh/m^2 in the winter. For standard roof building 2, energy consumption ranged from 12.0±0.8

kWh/m^2 in the summer to 59.3±4.0 kWh/m^2 in the winter. For cool roof building 5, energy consumption ranged from 11.9 kWh/m^2 in the spring to 20.9±3.3 kWh/m^2 in the winter. For standard roof building 5, energy consumption ranged from 39.9±2.2 kWh/m^2 in the spring to 51.1±2.8 kWh/m^2 in the summer. Variation for buildings 1, 3, 4, and 6 were moderate to minimal, ranging from 4.0±0.3 kWh/m^2 for standard roof building 1 in the fall to 39.9±13.2 kWh/m^2 for standard roof building 3 in the winter.

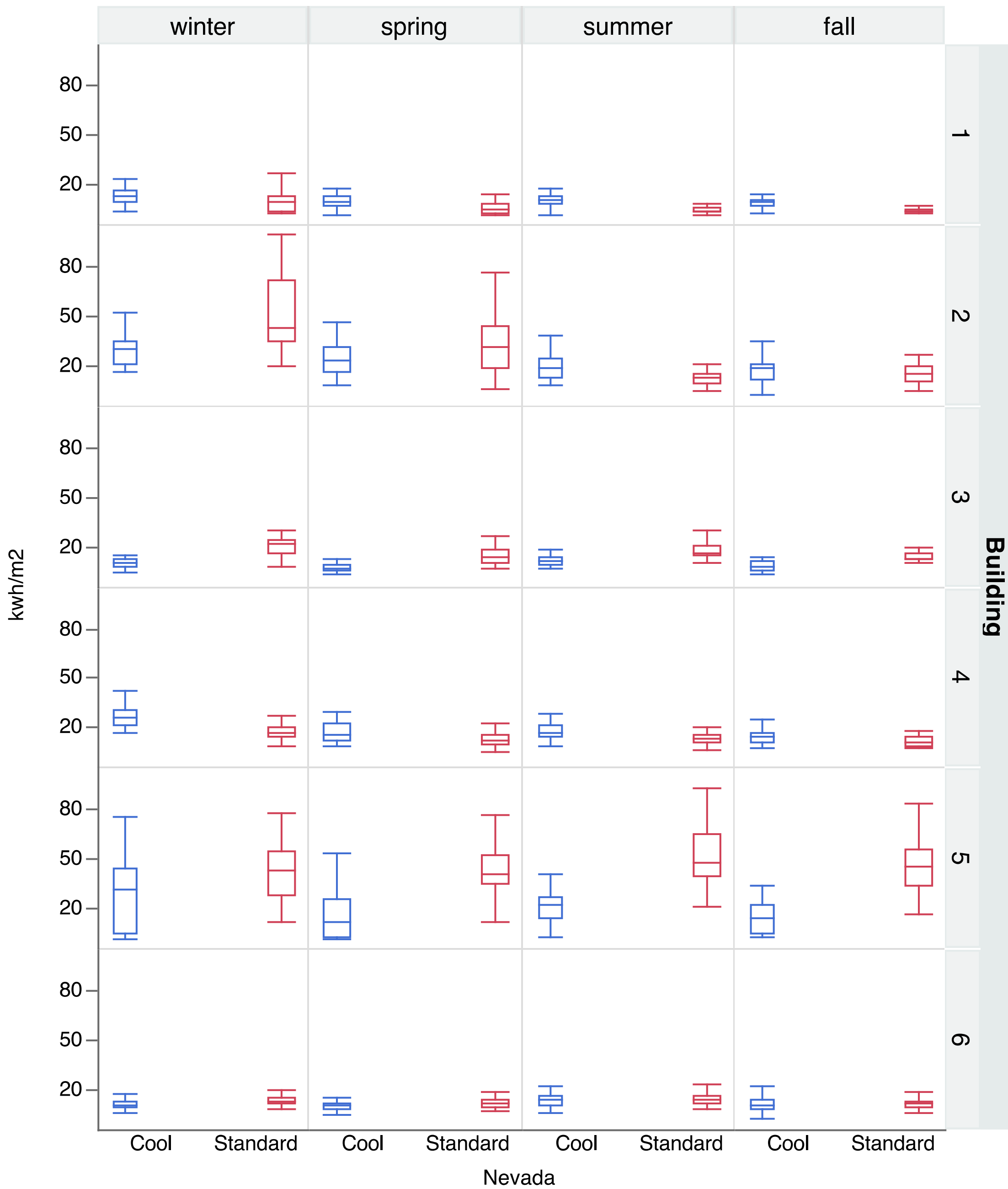


Figure 15: Boxplots of energy consumption for cool roof buildings and standard roof buildings in Nevada

The regression analysis, Figure 16, shows a strong relationship between the standard deviations of energy consumption for the Nevada site and the means of energy consumption, where the r-value is 0.83. Buildings that did not use much energy did not have great variances. There would be more variation in energy consumption in buildings that used a lot of energy than in buildings that did not.

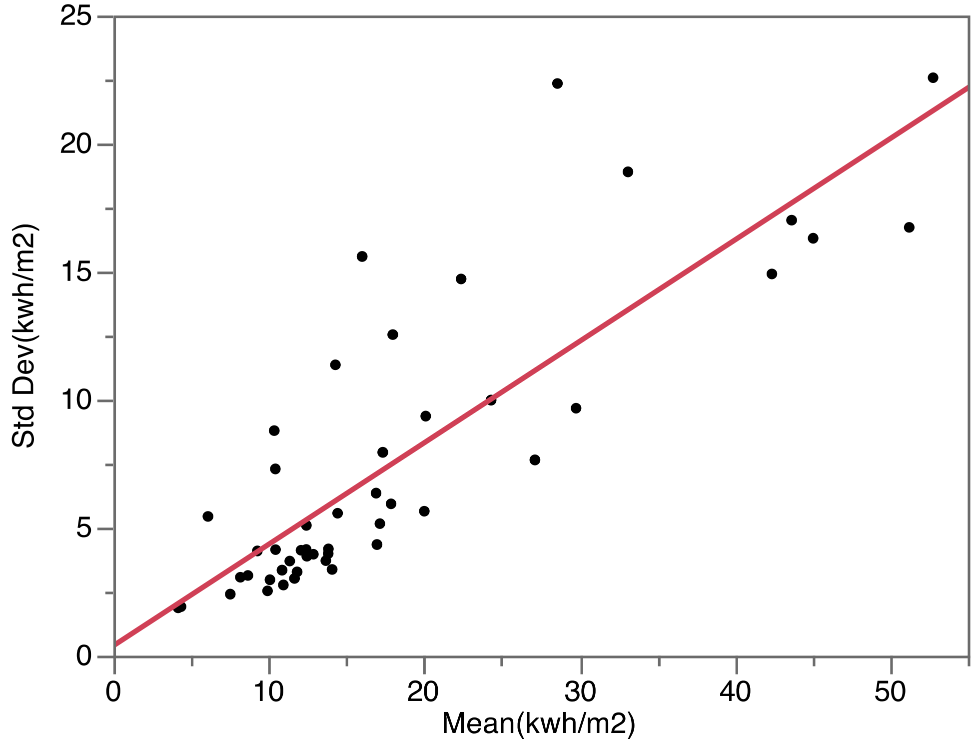


Figure 16: Bivariate fit of the standard deviation of energy consumption as plotted with the mean for the Nevada site, where r=0.83.

For four out of six buildings, cool roof buildings outperformed the standard roof buildings in energy consumption by at least ten percent (Table 9). Three cool roof buildings outperformed the standard roof buildings in energy consumption by at least twenty percent. Two cool roof buildings outperformed the standard roof buildings in energy consumption by forty percent or more. Two buildings, 1 and 4, had an energy increase after the cool roof was installed of 39% and 30%, respectively. Out of all the sites in this study, Nevada was the only one to have paired buildings and not use pre- and post-cool roof installation data. While the pairs met strict criteria for usage, size, number of occupants, number of floors, and construction materials, these buildings were not identical. This factor likely contributed in part to the large energy reductions and increases over the two types of roofs. Additionally, the Nevada site buildings were much smaller in size overall than their counterparts at other sites.

Bldg.	Cool Roof Energy Consumption (kWh/m^2)	Standard Roof Energy Consumption (kWh/m^2)	Energy Reduction or Energy Increase
1	10.2±0.4	6.3±0.5	+39%
2	22.8±0.8	28.6±1.6	-20%
3	9.4±0.3	16.5±0.6	-43%
4	18.8±0.6	13.2±0.4	+30%
5	20.2±1.3	45.5±1.2	-56%
6	11.3±0.3	12.5±0.3	-10%
Total	15.9±0.3	20.9±0.6	-24%

Table 9: Mean energy consumption for cool and standard roof buildings at the Nevada site averaged over years 2003-2013.

An in-depth look at the highest and lowest increases and reductions in energy consumption is shown in Table 10. Higher consumption of energy in every season was evident for building 1 in Nevada, totaling a 39% increase in energy consumption for the building pre- versus post-cool roof installation. The mean energy consumption for cool roof building 1 was significantly lower in fall, at 9.8±0.4 kWh/m^2, and higher in winter at 13.7±0.6 kWh/m^2. The mean energy consumption for standard roof building 1 is lower for fall, at 4.0±0.3 kWh/m^2, and higher for winter, at 12.3±1.6 kWh/m^2. Higher energy consumption would be expected in summer and winter, but for standard roof building 1, energy consumption in the winter was three times greater than the energy consumption in the summer. This only occurred in two other buildings in Nevada, both the cool and standard roof buildings from pair 2.

		kwh/m2			
		Roof			
		Cool		Standard	
Building	Season	Mean	Std Err	Mean	Std Err
1	winter	13.7	0.6	12.3	1.6
	spring	9.9	0.6	7.1	1.1
	summer	12.3	1.2	4.3	0.3
	fall	9.8	0.4	4.0	0.3
2	winter	28.4	1.7	59.3	4.0
	spring	22.4	1.7	36.9	3.6
	summer	17.9	1.4	12.0	0.8
	fall	15.2	1.2	18.9	2.5
3	winter	10.1	0.6	39.9	13.2
	spring	7.5	0.4	28.2	7.8
	summer	11.7	0.5	37.2	11.3
	fall	8.2	0.6	25.3	8.7
4	winter	25.2	1.0	16.8	0.7
	spring	16.2	1.1	12.9	0.9
	summer	15.9	0.8	13.7	0.5
	fall	12.5	0.6	12.0	0.5
5	winter	20.9	3.3	42.6	2.8
	spring	11.9	2.3	39.9	2.2
	summer	17.6	1.5	51.1	2.8
	fall	12.0	1.5	44.9	2.3
6	winter	10.6	0.5	12.0	0.7
	spring	9.4	0.5	11.3	0.5
	summer	13.4	0.7	13.5	0.6
	fall	9.8	0.8	11.3	0.7

Table 10: Energy consumption and standard error for pre- and post-cool roof in Nevada.

The mean energy consumption figures for the post-cool roof in building 5 in Nevada were significantly lower in all four seasons, totaling a 56% reduction in energy consumption from pre- to post-cool roof installation. The mean energy consumption for cool roof building 5 was significantly lower in spring, at 11.9±2.3 kWh/m^2, and higher in winter, at 20.9±3.3 kWh/m^2. The mean energy consumption for standard roof building 5 was lower for spring, at 39.9±2.2 kWh/m^2, and higher for summer, at 51.1±2.8 kWh/m^2. Seasonal variations, higher energy consumption in winter and summer, were as expected for this building pair.

There were six buildings in the Nevada means chart analysis, where each error bar is constructed using one standard error from the mean, as shown in Figure 17. Buildings 2 had great seasonal variation from cool to standard roof, where the cool roof building consumed less energy in winter and more in the summer. Building 3 had less variation in winter between pre- and post-cool roof. Buildings 3 and 5 had similar variation patterns, where the cool roof building consumed less energy in all season. Building 4 had the opposite pattern where more energy was consumed by the cool roof building than the standard roof building. Buildings 1 and 6 had very minimal seasonal variation.

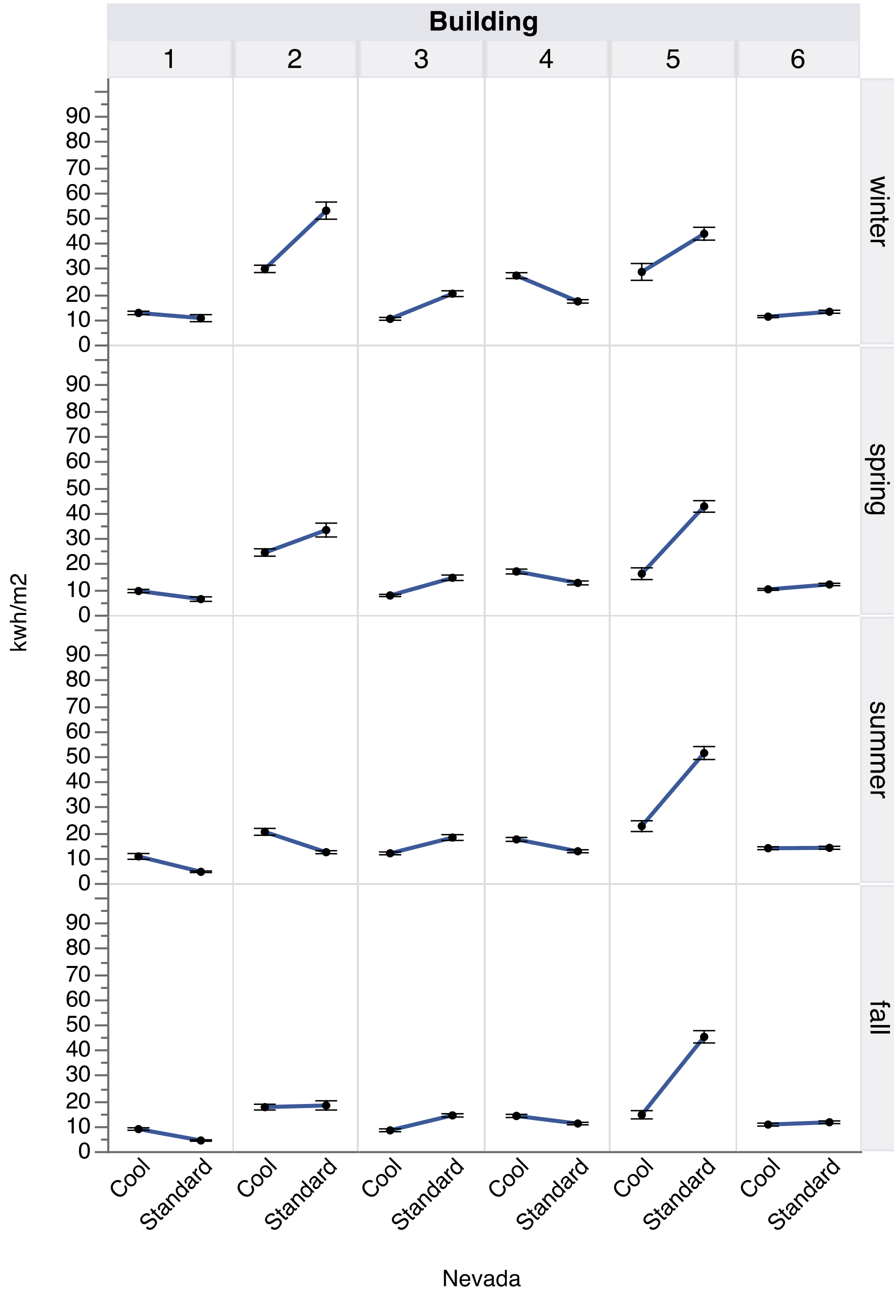


Figure 17: Means chart with error bars comparing the seasonal means in energy consumption between cool roof buildings and standard roof buildings in Nevada averaged over years 2003-2013.

Tennessee

Energy consumption over seasons for cool and standard roof buildings were shown in the Tennessee boxplot analysis (Figure 18) The variation for buildings 1 and 2 were minimal, ranging from 7.1±1.0 kWh/m^2 for standard roof building 2 in the summer to 17.4±1.6 kWh/m^2 for standard roof building 1 in the winter. Energy consumption for the winter months in both standard and cool roof buildings were much higher than other months, which was to be expected in a climate with a distinct cold winter season.

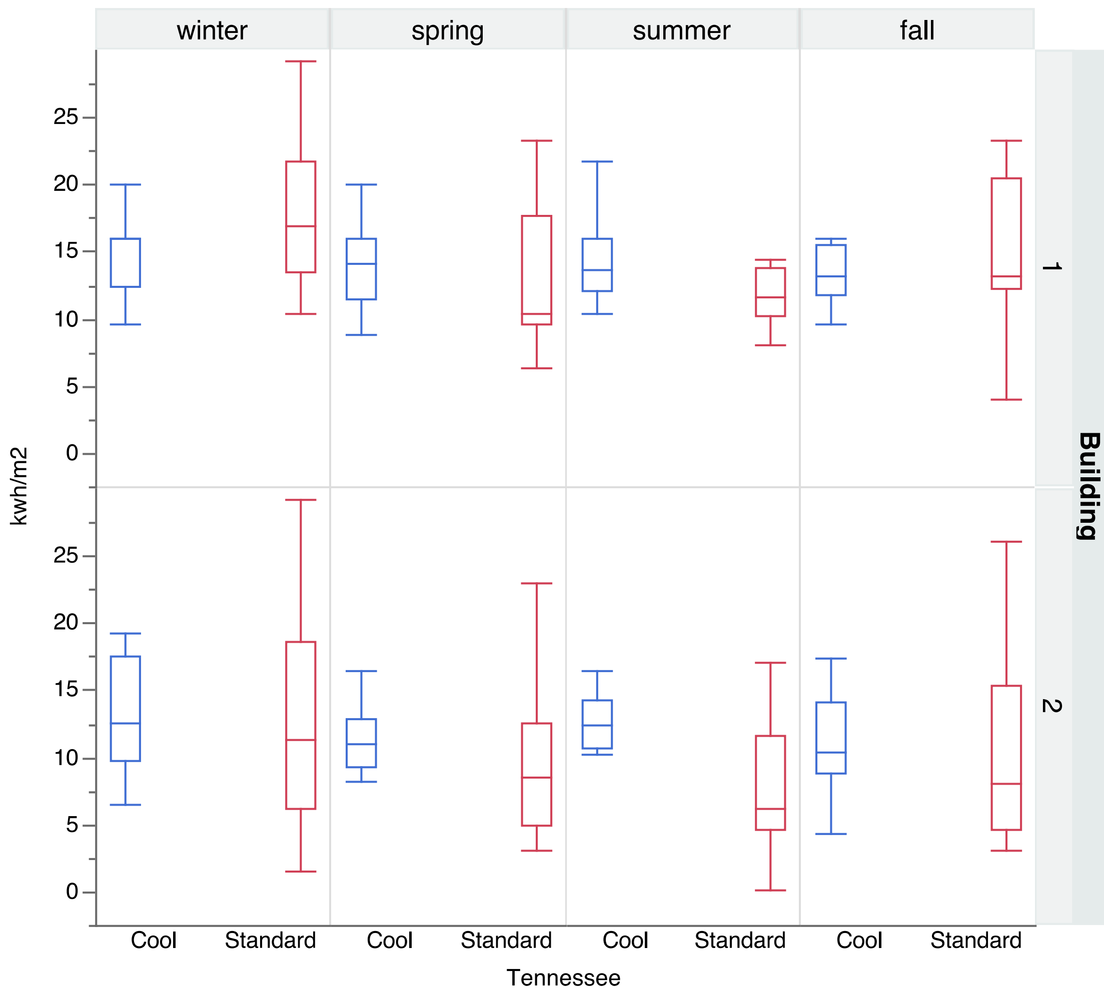


Figure 18: Boxplots of energy consumption for cool roof buildings and standard roof buildings in Tennessee

The regression analysis, Figure 19, shows that there was no relationship between the standard deviations for energy consumption for the Tennessee site and the means for energy consumption, with an r-value of 0.01. This was likely due in part to the small sample size for this site. Buildings that did not use much energy did not have great variances. More variation in energy consumption would be expected in buildings that used a lot of energy than in buildings that did not.

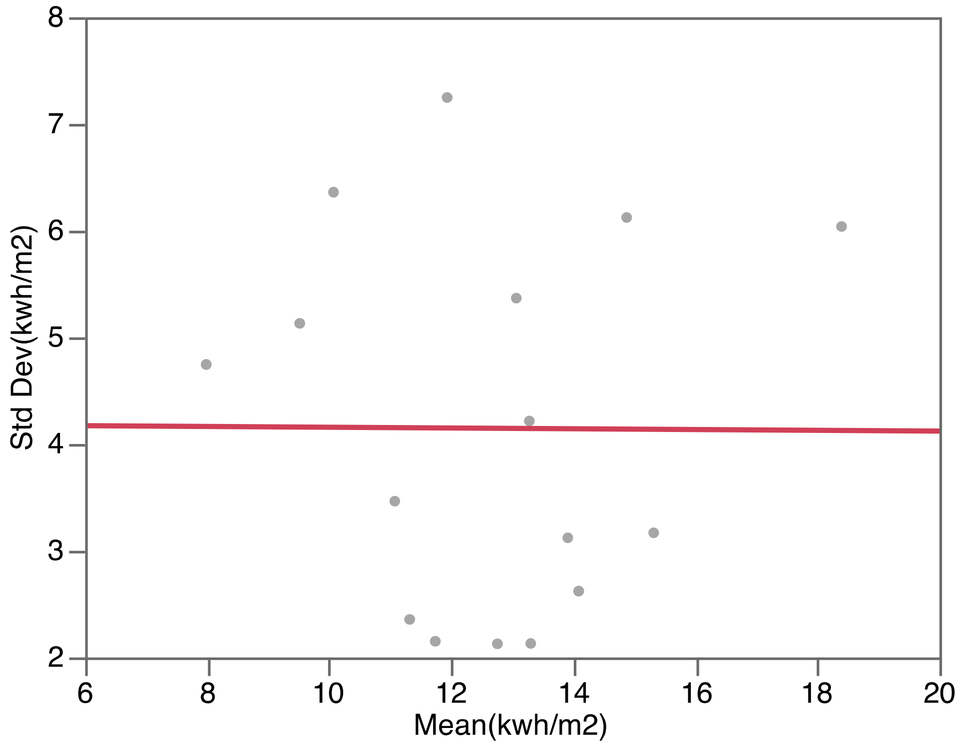


Figure 19: Bivariate fit of the standard deviation of energy consumption as plotted with the mean for the Tennessee site, where r=0.01.

For one out of two buildings, the cool roof building outperformed the standard roof building in energy consumption. This included building 1 with a three percent reduction in energy consumption. The other, building 2, had an energy increase after the cool roof was installed of 18%. Building 2’s energy consumption increase overshadowed the results for the entire site.

Bldg.	Cool Roof Energy Consumption (kWh/m^2)	Standard Roof Energy Consumption (kWh/m^2)	Energy Reduction or Energy Increase
1	14.1±0.3	14.6±0.9	-3%
2	12.1±0.5	9.9±0.6	+18%
Total	13.4±0.3	11.4±0.6	+15%

Table 11: Mean energy consumption for cool and standard roof buildings at the Tennessee site averaged over years 2003-2013.

An in-depth look at the highest and lowest increases and reductions in energy consumption is shown in Table 12. The mean energy consumption figures for the post-cool roof in building 1 in Tennessee are lower or equal in winter, spring, and fall, totaling a 3% reduction in energy consumption from pre- to post-cool roof installation. Summer was the only season where mean energy consumption was greater for the building post-cool roof install. The mean energy consumption for cool roof building 1 was lower in fall, at 13.3±0.5 kWh/m^2, and higher in winter at 15.7±0.8 kWh/m^2. The mean energy consumption for standard roof building 1 was lower for summer, at 11.7±0.7 kWh/m^2, and higher for winter, at 17.4±1.6 kWh/m^2.

		kwh/m2			
		Roof			
		Cool		Standard	
Building	Season	Mean	Std Err	Mean	Std Err
1	winter	15.7	0.8	17.4	1.6
	spring	14.4	0.8	13.1	1.5
	summer	14.1	0.5	11.7	0.7
	fall	13.3	0.5	14.9	2.2
2	winter	13.3	1.2	10.6	1.6
	spring	11.3	0.7	9.0	1.1
	summer	12.8	0.6	7.1	1.0
	fall	10.5	1.1	8.7	1.2

Table 12: Energy consumption and standard error for pre- and post-cool roof in Tennessee.

Higher consumption of energy was evident in every season for building 2 in Tennessee, totaling an 18% increase in energy consumption for the building pre- versus post-cool roof installation. The mean energy consumption for cool roof building 2 was lower in fall, at 10.5±1.1 kWh/m^2, and higher in winter at 13.3±1.2 kWh/m^2. The mean energy consumption for standard roof building 2 was lower for summer, at 7.1±1.0 kWh/m^2, and higher for winter, at 10.6±1.6 kWh/m^2. Both building 1 and 2 were the same size, small, and were both office buildings. Other factors, such as building usage over time, may have contributed to the higher energy consumption of the cool roof over the standard roof for building 2. Seasonal energy consumption usage was as expected, higher energy consumption in winter than in any other season.

There are two buildings in the Tennessee mean bar chart analysis, where each error bar was constructed using one standard error from the mean, as shown in Figure 21. Buildings 1and 2 had very minimal seasonal variation, where in spring the cool roof used more energy than the standard roof.

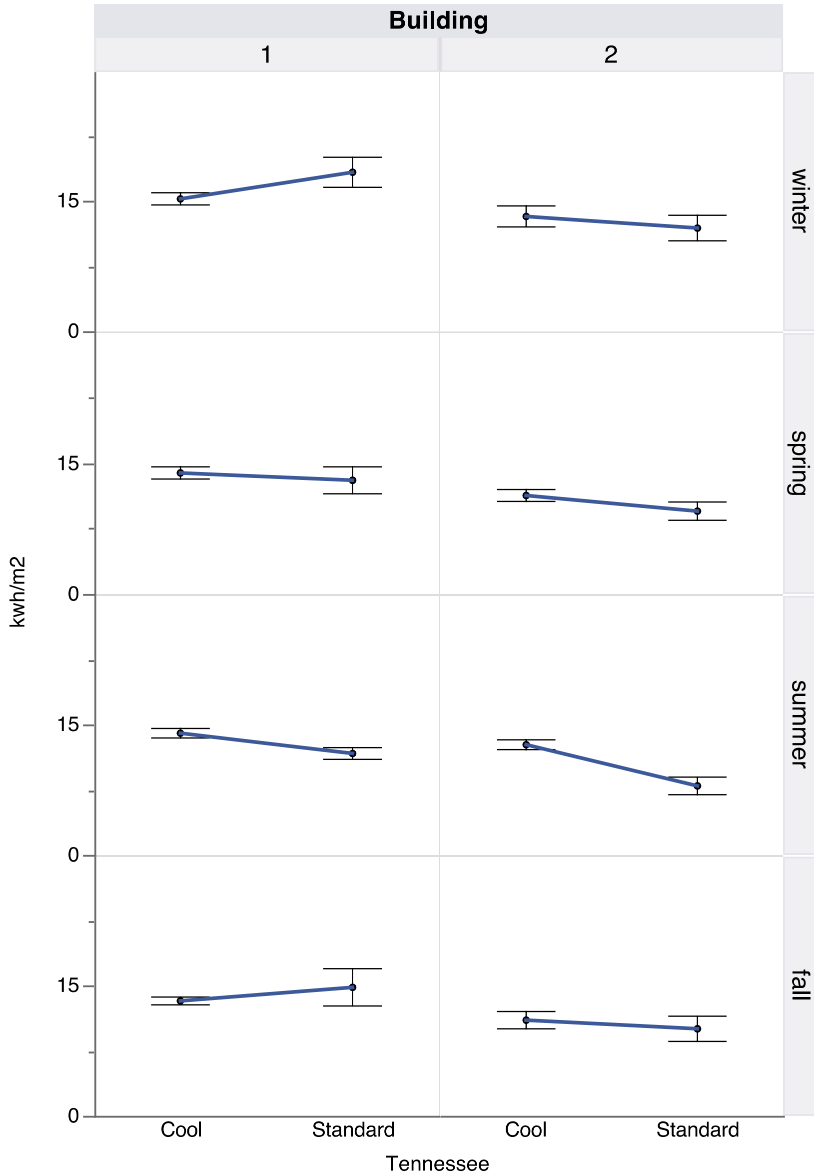


Figure 20: Means chart with error bars comparing the seasonal means in energy consumption between cool roof buildings and standard roof buildings in Tennessee averaged over years 2003-2013.

Site Comparisons

The energy consumption of cool roof buildings in California and Nevada was significantly lower than the energy consumption of standard roof buildings (Figure 21). The California and Nevada site had the largest sample sizes out of the four sites, seven and six buildings, respectively. Therefore statistical tests of those datasets were more powerful. Additionally, Nevada was the ideal location for the installation of cool roofs to reduce energy consumption because buildings located in areas with higher incoming solar radiation should reap the greatest benefits from the installation of cool roofs (Menon et al. 2010). This was corroborated with the Nevada dataset. Five out of seven of the Nevada cool roof buildings had lower energy consumption than their standard roof counterparts, an average 33% decrease in energy consumption for the five buildings. Six of the seven buildings in the California dataset demonstrated reduced energy consumption after cool roofs were installed, an average 15% decrease in energy consumption post cool roof installation for the six buildings.

Although the literature indicates that cool roof buildings reduce cooling loads (Synnefa et al. 2007), there were a few explanations for why cool roof building energy consumption in Illinois and Tennessee were on average higher than their standard roof counterparts. Illinois and Tennessee had the smallest sample sizes out of the four sites, four buildings and two buildings, respectively. Therefore they had the most potential for noticeable errors. Illinois also has very cold winters, which may have contributed to a heating penalty in the winter. At the Illinois site, the difference between the cool and standard roof building energy consumption was so great that it overshadowed any positive results from cool roof buildings 1, 2 and 4. In Illinois, building 3 had 15% greater mean energy consumption from 2009-2013, after the cool roof had been installed, than prior to cool roof installation from 2002-2009. The usage of the building had possibly changed after the cool roof installation. At DOE sites, this happens on a frequent basis, where buildings are repurposed. The usage of the building over time is sometimes difficult to accurately track in government real property databases, and institutional knowledge about specific buildings is sometimes lost when facility managers retire. During building selection this problem was avoided to the greatest extent possible, by questioning the site's energy managers and real property managers. In addition, studies with non-significant differences between cool roof standard roofs may not be published.

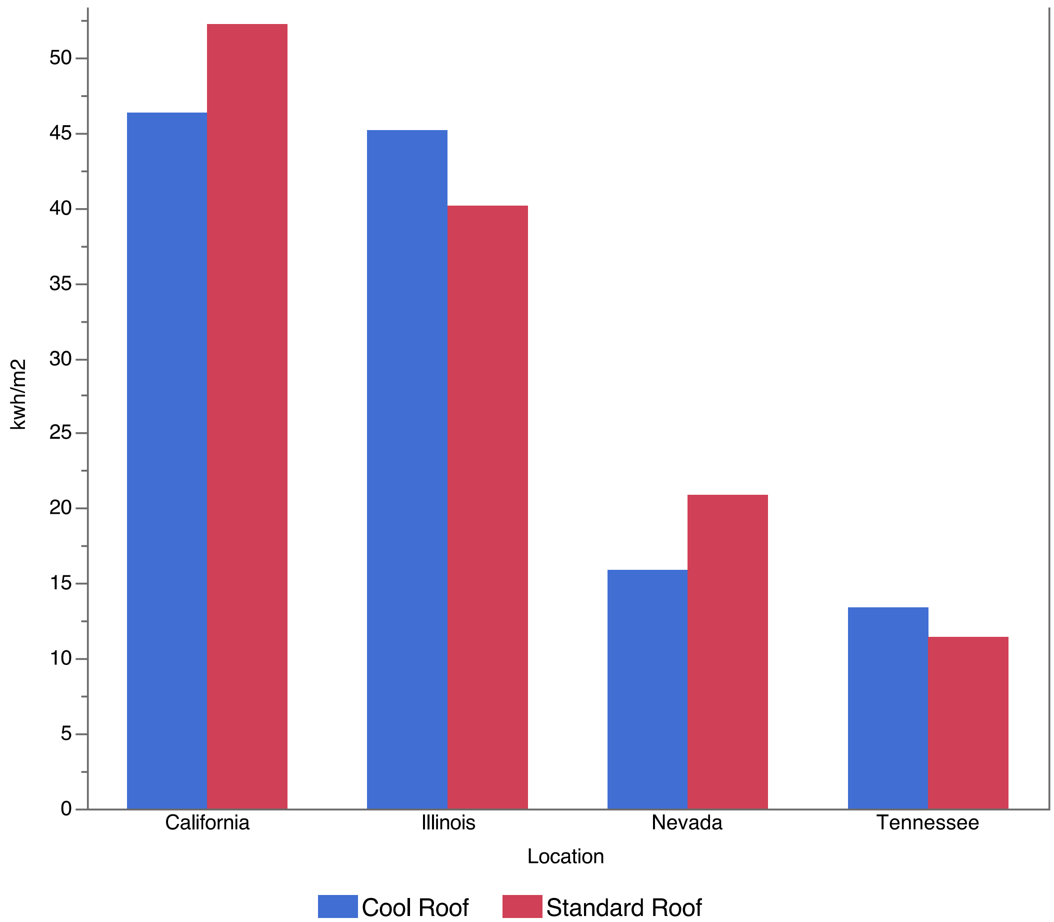


Figure 21: Mean energy consumption for cool and standard roof buildings at each site.

Chapter 3: Regional Weather Descriptions/Analysis

Introduction

Cool roofs reduce energy consumption, but the degree of reduction depends on many variables, including the type of roof and the climate. This study demonstrates how variations in temperature over the past decade have impacted cool roof energy savings over regions. This study seeks to determine how rising temperatures have influenced the effectiveness of cool roofs in certain regions of the US. In order to mitigate some of the impacts of climate change, specifically rising temperature, exploration of the relationship between seasonal weather patterns and energy savings was necessary.

The energy data were collected from different climatic zones to investigate how differences in temperatures over regions, i.e. different climates, have impacted cool roof energy savings, where energy savings is defined as the delta in energy consumption between a standard roof and a cool roof building. Temperature data were collected and analyzed for each region for the time period corresponding to the energy data analyzed. In this chapter, these temperature datasets were used to characterize regional variations in temperature patterns and heating and cooling demands. To do this an extensive evaluation of temperature patterns were required.

Cooling Degree-Days (CDD) and Heating Degree-Days (HDD) are calculated variables used to measure the impact of temperature on a building (Fraisse et al. 2011). CDD and HDD were used to estimate the number of degree-days a building needed to use heating or cooling systems to condition the ambient interior air temperature. Annual CDD and HDD values can range from 0 to several thousands. Examples of annual CDD and HDD values for states ranging from warm to cold climate zones are shown in Table 13.

State	Mean Temp. (°C)	Minimum Temp. (°C)	Maximum Temp. (°C)	CDD (Degree-days)	HDD (Degree-days)
Miami, FL	26	22	29	4992	59
Baltimore, MD	14	9	19	1558	4171
San Francisco, CA	14	10	18	115	2960
Fargo, ND	6	1	12	694	8594

Table 13: Annual mean, minimum, and maximum temperatures, and CDD, and HDD for selected US cities in 2011 (NOAA/NCDC 2014).

Cool roofs should reduce cooling demand in the summer. Thus the impact should be greater in a region with a higher CDD, because there will be more days where reflecting incoming solar radiation will lower energy consumption. On the other hand, in regions with a higher HDD there may be a minor negative effect, as stated in the literature review. Regardless, in most regions an eight-fold cooling energy saving from using a cool roof can be quantified when compared to the heating energy penalty (Menon et al. 2011).

The DOE Building America program, whose mission is to find ways to improve the efficiency of building construction and building retrofits in the US, created a useful tool to aid builders in constructing their buildings with the appropriate climate designation in mind. Figure 23, shows the various climate zone designations as defined in the *Guide to Determining Climate Regions by County (Baechler et al. 2010).* The climate zones delineated in this guide are based on the climate zone maps used by the International Energy Conservation Code (IECC) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

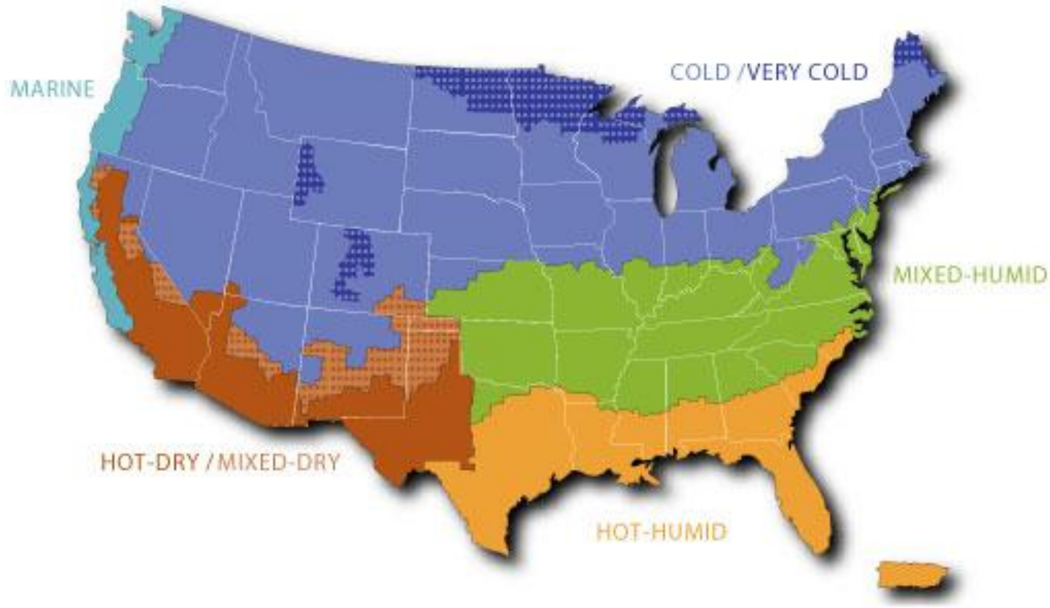


Figure 22: Climate zone designations identified by the DOE Building America Program (Baechler et al. 2010)

The California site is located in a mild climate zone, specifically in the *marin*e climate region (Baechler et al. 2010). The *marine* climate region is distinguished by: (NOAA 2002):

- Summer mean temperature lower than 22°C
- Winter mean temperature between -3°C and 18°C
- Average mean temperature of 14° C
- Mean annual temperature range of 10° C-18° C
- Mean temperatures higher than 10°C for at least four months
- Cold season months are October through March

The Illinois site is located in the *cold* climate region (Baechler et al. 2010). The *cold* climate region is distinguished by having a monthly HDD between 3,000 and 5,000. The *cold* climate region has the following attributes (NWS 2014):

- Mean annual temperature of 10° C
- Minimum annual temperature of 5° C
- Maximum annual temperature of 15° C

The Nevada site is located in the *hot-dry* climate region (Baechler et al. 2010). The *hot-dry* climate region is distinguished by (Gorelow and Skrbac 2005):

- Mean monthly temperature stays above 7°C

- Mean annual temperature of 20° C
- Minimum annual temperature of 14° C
- Maximum annual temperature of 27° C

The Tennessee site is located in a temperate climate zone, specifically in the *mixed-humid* climate region (Baechler et al. 2010). The *mixed-humid* climate region is distinguished by (NWS 2014):

- 3,000 HDD or fewer (18°C basis)
- Mean monthly winter temperature falls below 7°C
- Mean annual temperature of 15° C
- Mean temperature range of 9° C-21° C
- Cold season October through March

Weather Data Description

Weather data sets were obtained from the National Climatic Data Center (NCDC) a division of the National Oceanic and Atmospheric Administration using the Climate Data Online (CDO) database (NOAA/NCDC 2014) from the weather station closest to each national research laboratory site for the years (1997-2013) corresponding to the energy datasets. The Tennessee and California weather station locations were onsite, while the Nevada and Illinois weather stations were the closest NOAA stations with enough years of data available. All of the weather stations reported the minimum and maximum temperatures each day. The mean temperature for each day was calculated as the average of the minimum and maximum temperature. The mean temperature was used to calculate the Heating Degree Days (HDD) and Cooling Degree Days (CDD) for each day.

Daily temperature data were obtained for each site for the same time that the energy data sets were collected. The temperature data file was given in Celsius degrees to the tenths and the temperatures were converted to the standard format for both minimum and maximum temperature. The mean daily temperature was suitable for the purposes of this study since the expected error due to this calculation is inconsequential (Weiss and Hays 2004).

CDD and HDD were calculated assuming an average ambient interior building temperature of 18.3°C (65° F) as the heating and cooling degree base temperature. The base temperature used depends on the application and the building's function. In this case, 18.33° C was used for both CDD and HDD because it is the standard base temperature used in the US (NOAA/NCDC 2011). Other more unconventional situations, such as a swim center, may use a base temperature of 25° C (78° F) because the interior ambient temperature would need to be higher than normal.

The HDD and CDD are based on the difference between the base temperature and the mean daily temperature was estimated as the average temperature of maximum and minim. The mean daily temperature (T_d), which is the sum of the maximum temperature (T_{max}) and the minimum temperature (T_{min}) (Fraisse et al. 2011),

$$T_d = \frac{T_{max} + T_{min}}{2}$$

CDD was calculated as the degree-days that the daily mean temperature exceeded the base temperature, where the cooling degree-day base temperature constant (*BT)* was 18.3°C. Negative CDD values were set to zero.

$$CDD = T_d - BT$$

HDD was calculated as the degree-days that the heating degree-day base temperature exceeded the daily mean temperature, where the heating degree-day base temperature constant (*BT)* was 18.3°C. Negative HDD values were set to zero.

$$HDD = BT - T_d$$

For example, to determine the HDD for a 10°C (50°F) day, given that $BT = 18.3°\text{C}$

$$HDD = 18.3°\text{C} - 10°\text{C} = 8.3 \text{ degree-days}$$

Therefore for that day there are 8.3 heating degree-days. The CDD for the same day would be a negative value and set to zero.

Statistical analysis of the weather data for several combinations of variables was conducted. All statistical analyses were conducted using JMP Pro 11.1. The NCDC weather data for all four sites were analyzed for errors and outliers. There were no outliers and only a small number of missing values in three of the four weather station data sets (the exception being Tennessee), which constituted less than 0.02% of the data. The average minimum, maximum, and mean temperatures were calculated by season and month. HDD and CDD figures were calculated by season and month.

Regional Climates

California

As expected in a consistently mild climate, seasonal fluctuations in temperature were small, and seasonal shifts were generally gradual (Table 14 and Figure 24). The difference in the average minimum temperature between winter and summer was only 5° C, ranging from 6° C in the winter to 11° C in the summer. The difference in the average maximum temperature between winter and summer was 9° C, ranging from 15° C in the winter to 24° C in the summer. The difference in the average mean temperature between winter and summer was only 6° C, ranging from 11° C in the winter and 17° C in the summer.

	Minimum Temperature	Maximum Temperature	Mean Temperature
Winter	6° C	15° C	11° C
Spring	8° C	20° C	14° C
Summer	11° C	24° C	17° C
Fall	10° C	22° C	16° C
Annual	**9° C**	**20° C**	**15° C**

Table 14: Seasonal average minimum, maximum and mean temperatures at the California site averaged over years 2003-2013.

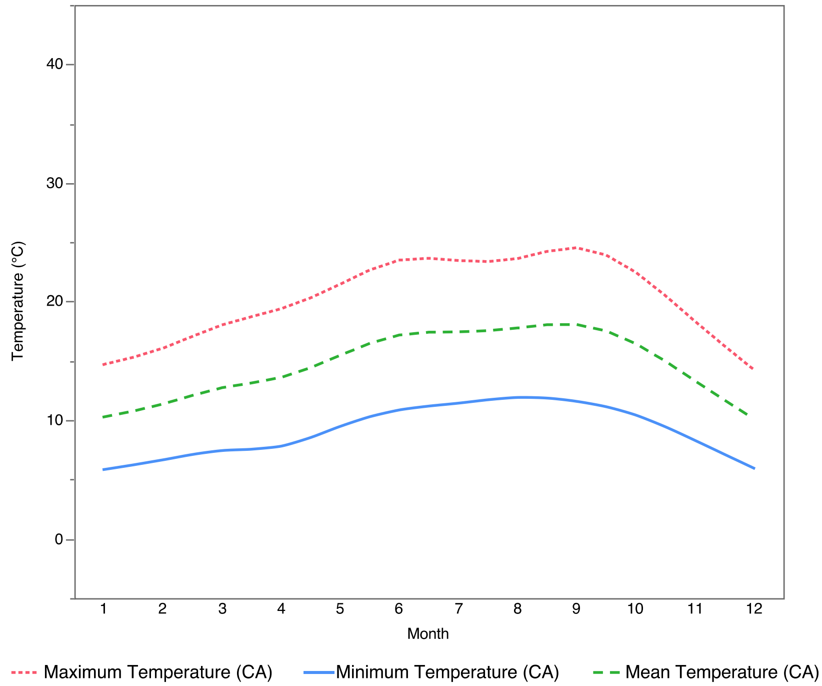


Figure 23: Monthly average minimum, maximum and mean temperatures for the California site averaged over years (2003-2013)

Annual cumulative HDDs averages were relatively minimal in the low 1400s, as shown in Table 15 and Figure 25. Monthly and annual CDD averages are very low with as shown by the cumulative average of 107. The summer cumulative CDD was 46 degree-days and the winter cumulative CDD was 0, only a 46-degree-day difference. The summer cumulative HDD was 123 degree-days and the winter cumulative HDD was 615, a 492-degree-day difference. In spring and fall there are relatively few cooling degree-days, but moderate heating degree-days. With an annual average temperature of approximately 15 °C (59 °F), days where a building heating system is operating are very few and focused in the winter months.

	CDD	HDD
Winter	0	615
Spring	14	417
Summer	46	123
Fall	47	262
Annual	**107**	**1417**

Table 15: Seasonal average cumulative CDD and HDD for the California site averaged over years 2003-2013, units in degree-days.

There is a very minimal peak in the CDD in Figure 32, due to the relatively stable maximum temperature of 20° C. HDD peaks in the winter months and is almost zero in the summer.

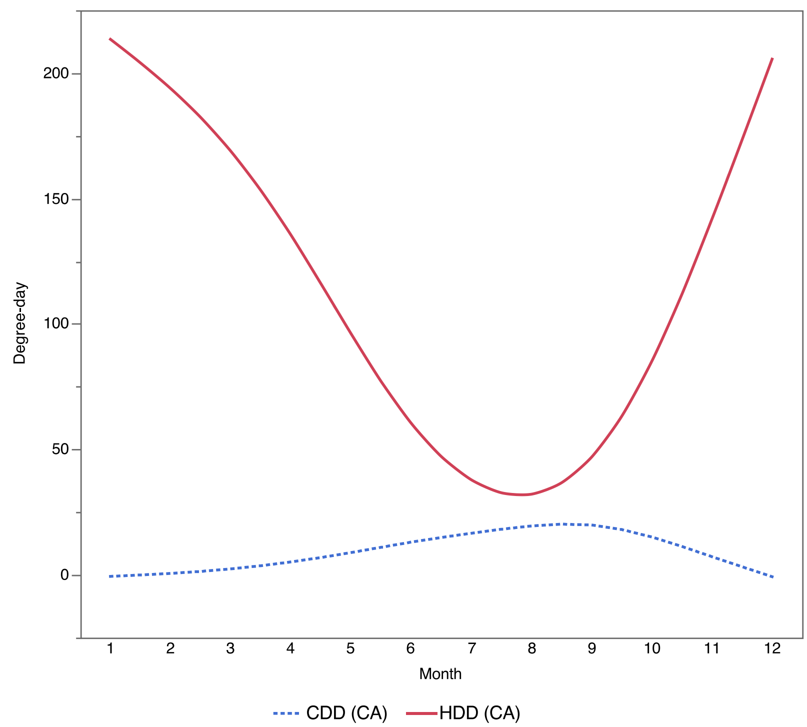


Figure 24: Monthly average cumulative CDD and HDD for the California site averaged over years 2003-2013, units in degree-days

Illinois

There were large swings in monthly and seasonal temperatures in this area near Lake Michigan. The difference in the average minimum temperature between winter and summer was 26° C, ranging from -9° C in the winter to 17° C in the summer, as shown in Table 16 and Figure 26. The difference in the average maximum temperature between winter and summer was 28° C, ranging from 0° C in the winter to 28° C in the summer. The difference in the average mean temperature between winter and summer was 26° C, ranging from -4° C in the winter to 22° C in the summer.

	Minimum Temperature	Maximum Temperature	Mean Temperature
Winter	-9° C	0° C	-4° C
Spring	5° C	17° C	11° C
Summer	17° C	28° C	22° C
Fall	5° C	17° C	11° C
Annual	**5° C**	**16° C**	**10° C**

Table 16: Seasonal average minimum, maximum and mean temperatures at the Illinois site averaged over years 2003-2013.

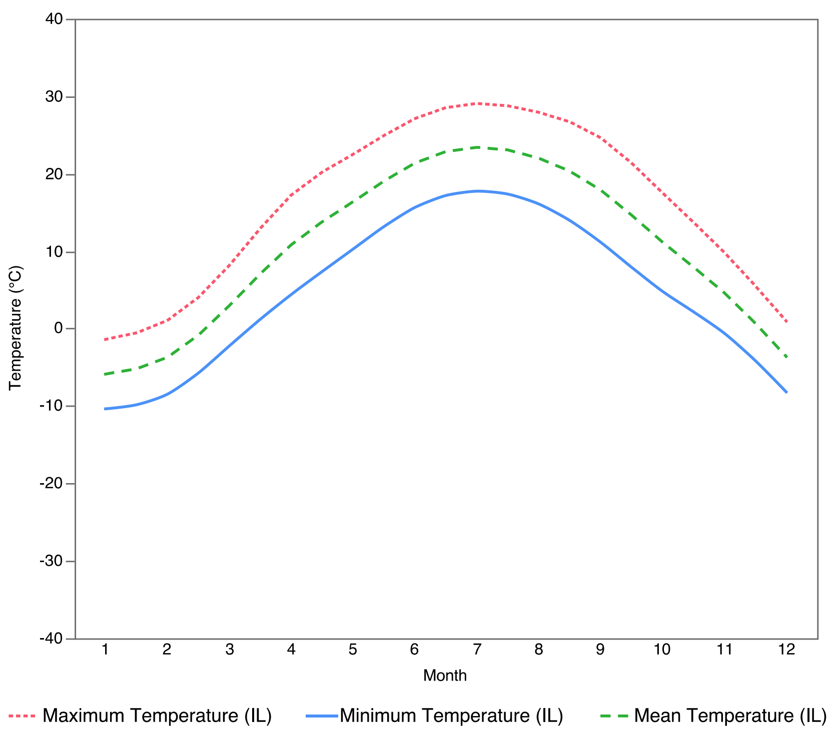


Figure 25: Monthly average minimum, maximum and mean temperatures for the Illinois site averaged over years (2003-2013)

The cumulative HDD average is 3288 due to the very cold temperatures in winter, spring, and fall, as shown in Table 17 and Figure 27. Monthly and annual CDD averages are low, only in the 400s, which mirrors the relatively mild summers. The summer cumulative CDD was 370 degree-days and the winter cumulative CDD was 0, a 370-degree-day difference. The summer cumulative HDD was 23 degree-days and the winter cumulative HDD was 1922, an1899 degree-day difference. In spring and fall there are relatively few cooling degree-days. In the summer there are few HDD and in the winter there are a great deal of HDD, due to the low mean winter temperature of -4° C. With an annual average temperature of approximately 10 °C, days where a building heating system is operating are fairly high.

	CDD	**HDD**
Winter	0	1922
Spring	42	654
Summer	370	23
Fall	56	689
Annual	**468**	**3288**

Table 17: Seasonal average cumulative CDD and HDD for the Illinois site averaged over years 2003-2013, units in degree-days.

There is a low peak in the CDD, as shown in Figure 27. As expected HDD has a large peak in the winter months and is almost zero in the summer.

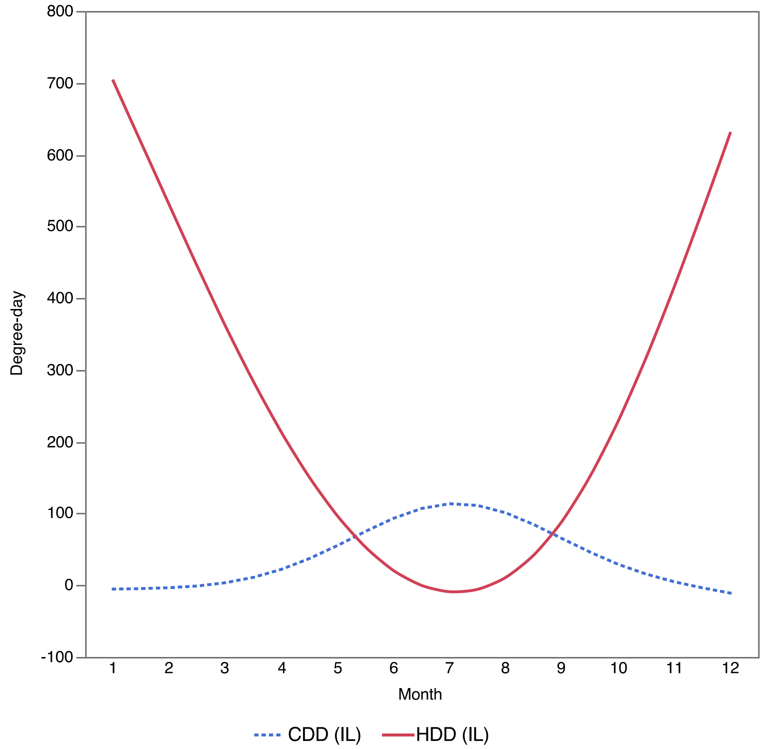


Figure 26: Monthly average cumulative CDD and HDD for the Illinois site averaged over years 2003-2013, units in degree-days.

Nevada

As expected in a desert climate, there are relatively large swings in monthly and seasonal temperatures, as shown in Table 18 and Figure 28. The difference in the average minimum temperature between winter and summer was 20° C, ranging from 3° C in the winter to 23° C in the summer. The difference in the average maximum temperature between winter and summer was 22° C, ranging from 11° C in the winter to 33° C in the summer. The difference in the average mean temperature between winter and summer was 21° C, ranging from 7° C in the winter and 28° C in the summer.

	Minimum Temperature	Maximum Temperature	Mean Temperature
Winter	3° C	11° C	7° C
Spring	10° C	21° C	15° C
Summer	23° C	33° C	28° C
Fall	13° C	23° C	18° C
Annual	**12° C**	**22° C**	**17° C**

Table 18: Seasonal average minimum, maximum and mean temperatures at the Nevada site averaged over years 2003-2013.

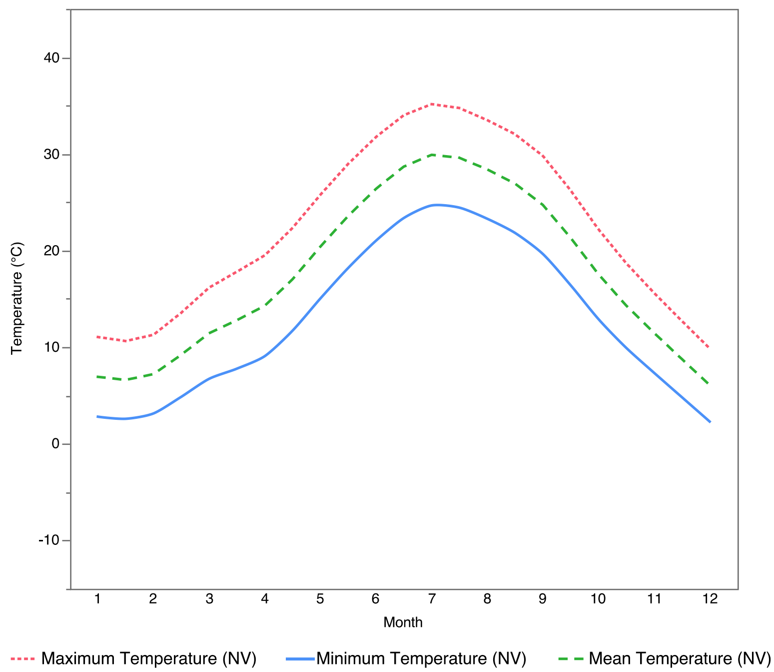


Figure 27: Monthly average minimum, maximum and mean temperatures for the Nevada site averaged over years (2003-2013)

The cumulative HDD average is 1736, as shown in Table 19 and Figure 29. Monthly and annual CDD averages are in the mid-range, at 1292. The summer cumulative CDD was 912 degree-days and the winter cumulative CDD was 0, a 912-degree-day difference. The summer cumulative HDD was 2 degree-days and the winter cumulative HDD was 1048, an1046 degree-day difference. In spring and fall there are a low to moderate number of cooling degree-days. In the summer there are very few HDD and in the winter there are a moderate number of HDD.

	CDD	**HDD**
Winter	0	1048
Spring	126	395
Summer	912	2
Fall	254	291
Annual	**1292**	**1736**

Table 19: Seasonal average cumulative CDD and HDD for the Nevada site averaged over years 2003-2013, units in degree-days.

There are converse peaks in the winter and summer months, as shown in Figure 29. A great deal of cooling is required in the summer and a great deal of heating is required in the winter. Spring and fall months have moderate HDD and CDD.

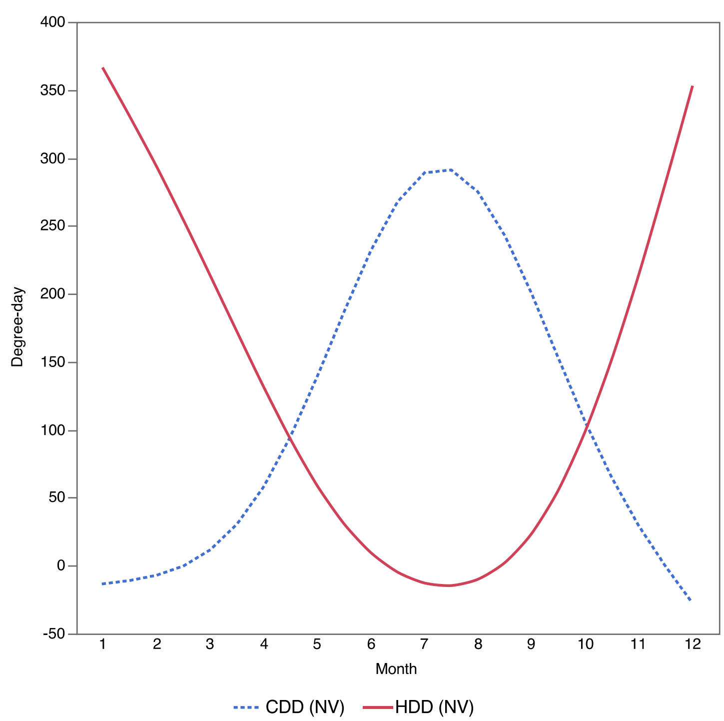


Figure 28: Monthly average cumulative CDD and HDD for the Nevada site averaged over years 2003-2013, units in degree-days

Tennessee

As expected in a temperate climate, there are swings in monthly and seasonal temperatures, as shown in Table 20 and Figure 30.

The difference in the average minimum temperature between winter and summer was 20° C, ranging from 0° C in the winter to 20° C in the summer. The difference in the average maximum temperature between winter and summer was 21° C, ranging from 10° C in the winter to 31° C in the summer. The difference in the average mean temperature between winter and summer was 20° C, ranging from 5° C in the winter and 25° C in the summer.

	Minimum Temperature	Maximum Temperature	Mean Temperature
Winter	0° C	10° C	5° C
Spring	9° C	22° C	15° C
Summer	20° C	31° C	25° C
Fall	10° C	22° C	16° C
Annual	**8° C**	**21° C**	**15° C**

Table 20: Seasonal average minimum, maximum and mean temperatures at the Tennessee site averaged over years 2003-2013.

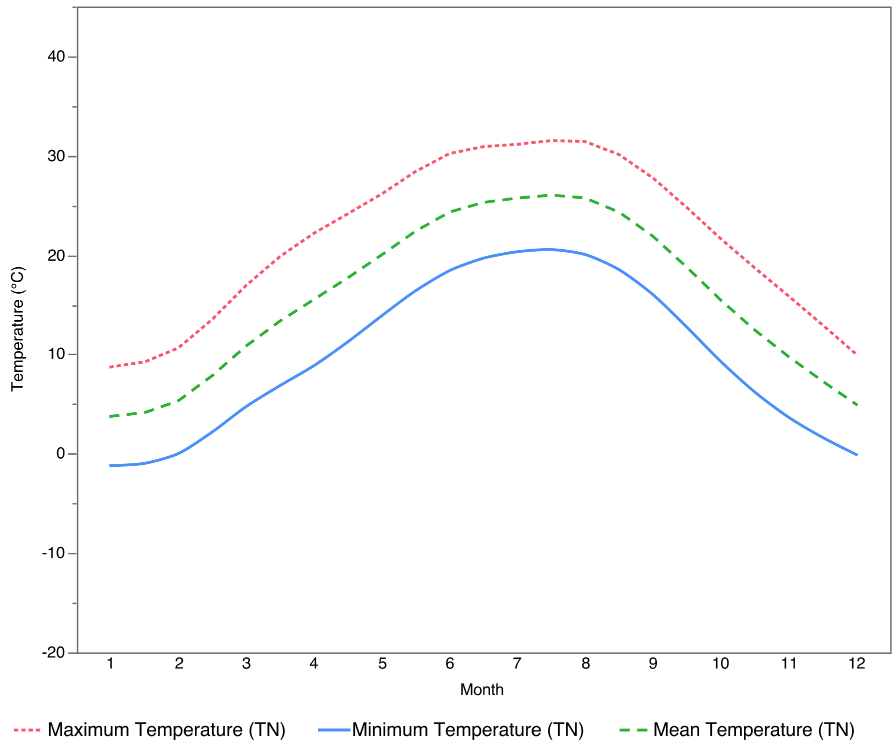


Figure 29: Monthly average minimum, maximum and mean temperatures for the Tennessee site averaged over years (2003-2013)

The cumulative HDD average is 1940, as shown in Table 21 and Figure 31. Monthly and annual CDD averages are in the mid-range, at 879. The summer cumulative CDD was 640 degree-days and the winter cumulative CDD was 0, a 640-degree-day difference. The summer cumulative HDD was 1 degree-day and the winter cumulative HDD was 1198, an1046 degree-day difference. In spring and fall there are a low to moderate number of cooling degree-days. In the summer there are practically zero heating degree-days and in the winter there are a moderate number of HDD.

	CDD	HDD
Winter	0	1198
Spring	105	368
Summer	640	1
Fall	134	373
Annual	**879**	**1940**

Table 21: Seasonal average cumulative CDD and HDD for the Tennessee site averaged over years 2003-2013, units in degree-days.

Monthly CDD averages are low to moderate in the summer months, in the 200 range, as shown in Figure 31. Winter HDD averages are moderate to high in the 300-500 range.

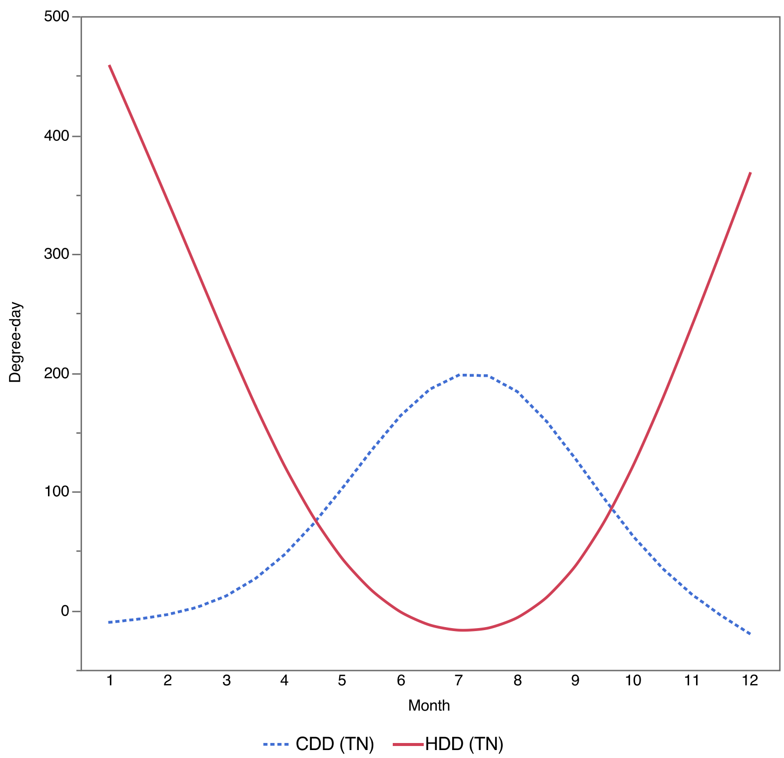


Figure 30: Monthly average cumulative CDD and HDD for the Tennessee site averaged over years 2003-2013, units in degree-days

Combined Regional Weather Analysis

All weather data is averaged over the 11-year period of 2003-2013.

Temperature

The minimum temperature over sites ranged from -9° C in the winter in Illinois to 20° C in the summer in Nevada with a 29° C difference between the two, as shown in Table 22. The maximum temperature ranged from 0° C in the winter in Illinois to 33° C in the summer in Nevada with a 33° C difference between the two. The variation between the winter and summer annual means ranged from -4° C in the winter in Illinois to 28°C in the summer in Nevada.

State	Minimum Temperature	Maximum Temperature	Mean Temperature
Winter			
California	6° C	15° C	11° C
Illinois	-9° C	0° C	-4° C
Nevada	3° C	11° C	7° C
Tennessee	0° C	10° C	5° C
Summer			
California	11° C	24° C	17° C
Illinois	17° C	28° C	22° C
Nevada	23° C	33° C	28° C
Tennessee	20° C	31° C	25° C

Table 22: Winter and summer averages of minimum, maximum and mean temperatures for all sites, averaged over years 2003-2013.

Over the 11-year timeframe of this study, there are some changes in overall temperatures, as shown in Figures 32-35. In Figure 32, increasing maximum summer temperatures are observed in Tennessee and Illinois. California shows a moderate decrease in the maximum summer temperature over the past decade, while Nevada shows a minor decrease.

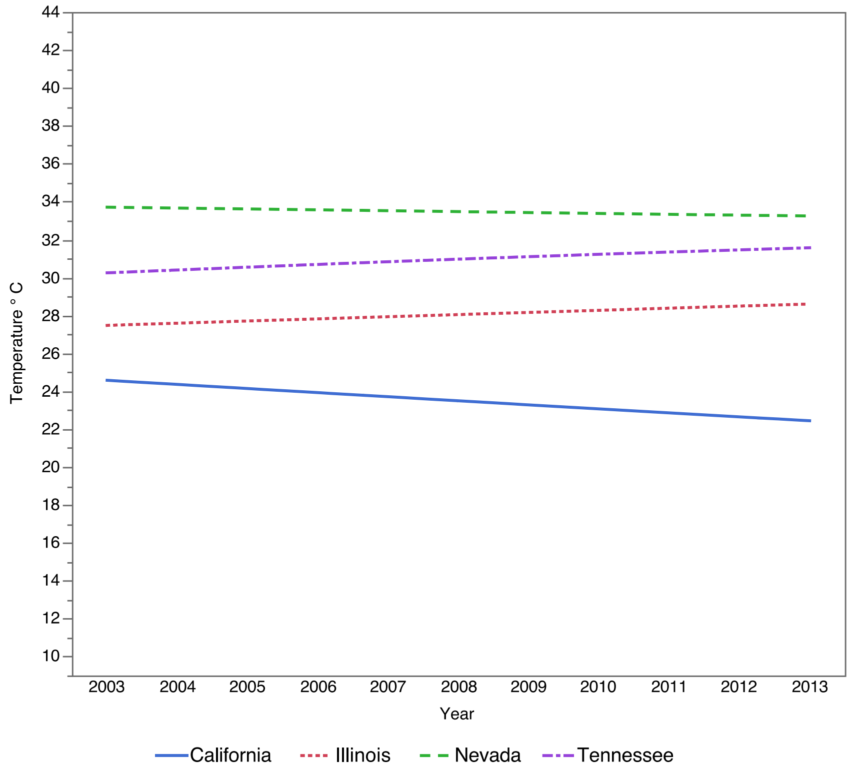


Figure 31: Mean maximum temperature in summer by site by year.

The mild temperatures and minimal seasonal temperature shifts experienced in California are starkly evident when displayed with the other sites, as shown in Figure 33. Nevada, Tennessee and Illinois share similar seasonal shifts in temperature, with Illinois being the coldest and Nevada being the hottest.

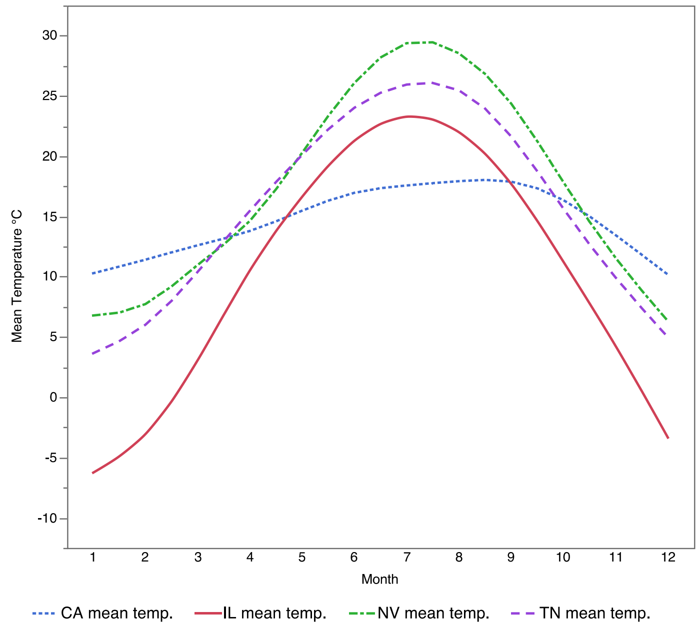


Figure 32: Mean monthly temperatures by site averaged over years 2003-2013.

In Figure 34, increasing maximum winter temperatures are observed in California and Tennessee. In Illinois and Nevada there are no obvious changes in maximum winter temperature over years. There were no evident changes in maximum spring or fall temperatures at any site.

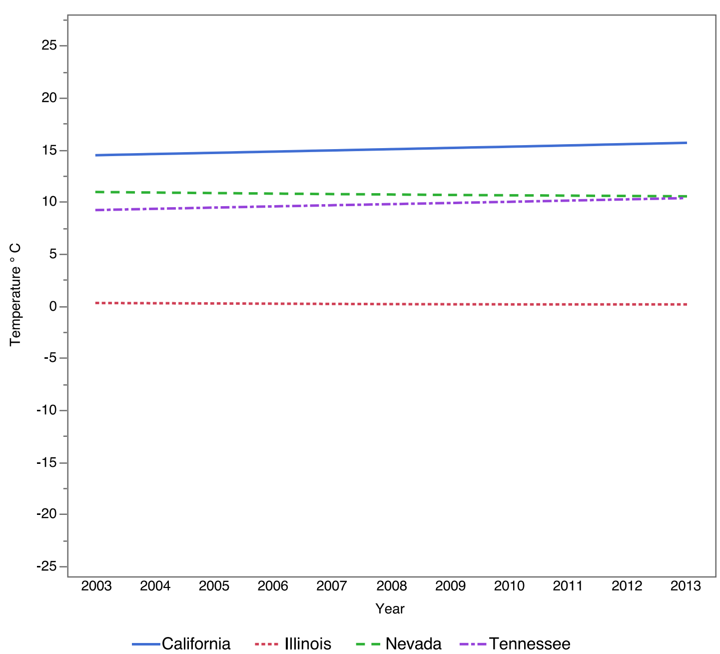


Figure 33: Mean maximum temperature in winter by site by year.

There are noticeable trends in mean maximum and minimum temperatures over sites over years. California mean and maximum temperatures are relatively unchanged with a minor decrease in minimum temperature. The minimum and maximum temperature in Nevada is stable over the eleven-year period. The minimum and maximum temperatures in Illinois and Tennessee increase over the years. Figure 35 does starkly show how much colder the maximum temperature is in Illinois.

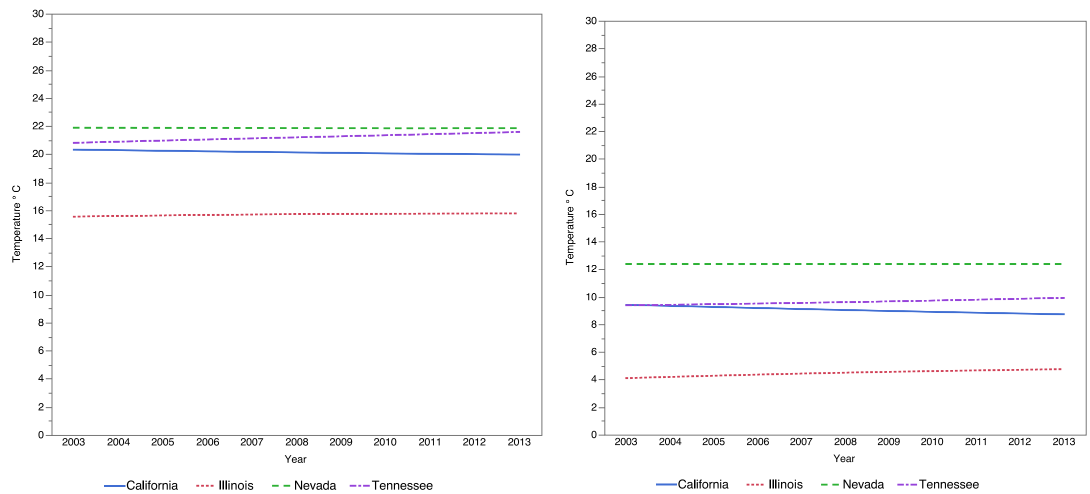


Figure 34: Mean maximum (left) and minimum (right) temperatures by site by year.

<u>*Cooling and Heating Degree-Days*</u>

California and Tennessee share very similar mean temperature profiles, but their climates are very dissimilar as evidenced by the widely contrasting CDD and HDD figures as shown in Table 23.

State	**CDD**	**HDD**
Winter		
California	0	615
Illinois	0	1922
Nevada	0	1048
Tennessee	0	1198
Summer		
California	46	123
Illinois	370	23
Nevada	912	2
Tennessee	640	1
Annual		
California	107	1417
Illinois	468	3288
Nevada	1292	1736
Tennessee	879	1940

Table 23: Cumulative annual and seasonal CDD and HDD for all sites, units in degree-days, averaged over years 2003-2013.

The minimum winter cumulative HDD was 615 degree-days in California, and the maximum winter cumulative HDD was 1922 in Nevada, a 1307 degree-day difference. The CDD for all sites in the winter was zero, as expected in non-tropical climates. The minimum summer cumulative CDD was 46 degree-days in Tennessee and the maximum summer cumulative CDD was 912 in California, an 866 degree-day difference.

Nevada, as the climate in this study with the highest mean temperature also has the CDD with the highest peak. In this type of hot desert climate, building cooling spans more months of the year and requires a higher energy load, i.e. higher CDDs, than the other sites, as shown in Figure 36. Also very noticeable is the very low CDD for California in comparison to the other sites, which is to be expected in a mild climate.

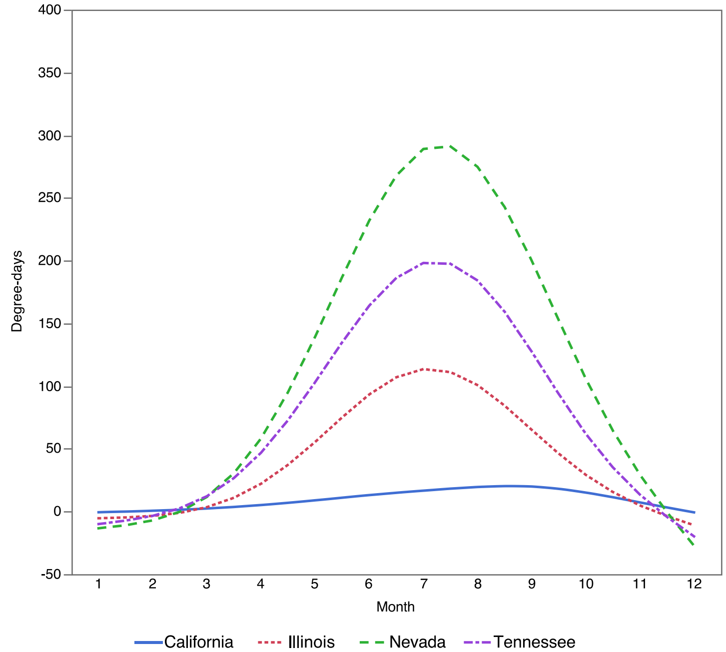


Figure 35: Mean CDDs by site by month from 2003-2013

Heating system use is much higher in Illinois than in California as evidenced by the fact that there are more than three times as many HDD in Illinois in the winter months, as shown in Figure 37. Nevada and Tennessee, at 1736 and 1940 respectively, have very similar HDD profiles.

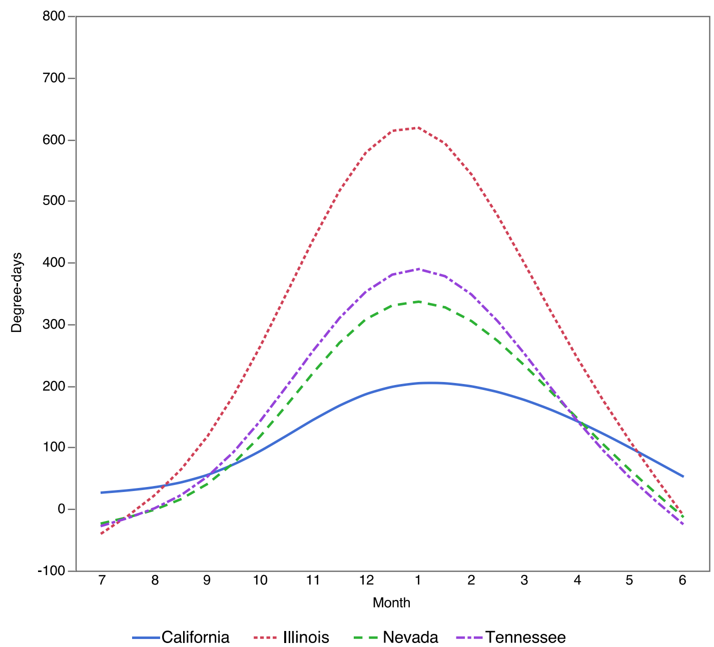


Figure 36: Mean HDDs by site by month from 2003-2013.

Chapter 4: Analysis of Weather and Energy Interactions

Introduction

This study investigates how the energy consumption of cool roof buildings over the past decade has been impacted by variations in temperature across different climatic regions of the US. This chapter examines and compares the influence of temperature on the energy consumption of the cool and standard roof buildings studied. The energy and temperature data analyzed in Chapters 2 and 3, respectively, were combined into one dataset to investigate the effect of temperature on energy consumption and determine whether the effect of temperature differed between cool and standard roofs and if these differences varied, between seasons, buildings, and/or sites.

The relationship between energy consumption and type of roof was expected to be different for each season, especially summer and winter. In the winter, cool roofs can have a negative effect, a "heating penalty", which was likely for cool roofs based on the existing literature, especially in climates with very cold and long winters. The heating penalty was low compared to an eight-fold cooling energy savings annually (Menon et al. 2011). In summer, a positive effect on energy consumption was expected due to the reflectance properties of cool roofs. Cool roofs yield the highest benefit to a reduction in energy consumption in areas where incoming solar radiation and temperatures are higher (Menon et al. 2011). At the California site, it was expected that the impact of cool roofs would be lower, due to their mild climate, compared to a climate with very hot summers. In Tennessee, Nevada, and Illinois, it was expected that the impact of cool roofs would be more significant, due to hot summers and high incoming solar radiation.

Data Description and Analysis

Data analyzed in the previous chapters were combined to investigate the relationships between energy consumption and temperature for cool and standard roof buildings in different climate zones. The relationship between each independent temperature variable (mean temperature, HDD, and CDD) and the dependent energy consumption variable was analyzed using a linear regression model. For each season and location, the slopes of the regression lines for cool roof and standard roof buildings were estimated and tested for significance using the Bivariate platform (JMP Pro 11.1).

California

At the California site, building-to-building variation accounted for a very significant proportion (61%) of the total variation in energy consumption. In order to examine this building-to-building variation, the relationship between energy consumption and temperature for the winter and summer seasons was separately plotted for each building (Figure 37). By plotting energy consumption with mean temperature for the winter and summer seasons for each building, the building-to-building variation was evident. The mean energy consumption was less than 19 kWh/m^2 for building 5, 6, and 7 as compared to 47 kWh/m^2 and 105 kWh/m^2 for buildings 1, 2, 3, and 4. As demonstrated in chapter 2, office buildings consumed much less energy than laboratories overall. Buildings 5, 6, and 7 were office buildings and had consistently low energy consumption. Building 1, 2, 3, and 4 were laboratories and had higher energy usage that was more variable. Additionally, the overall efficiency of the buildings may have been a contributing factor, such as having a tight building envelope or low-e glass tripled paned windows, for example. It is important to note that the energy consumption of each building was similar for summer and winter seasons. The mean energy consumption per building in California ranged from 14 kWh/m^2 to 113 kWh/m^2 in the winter and from 14 kWh/m^2 to 95 kWh/m^2 in the summer.

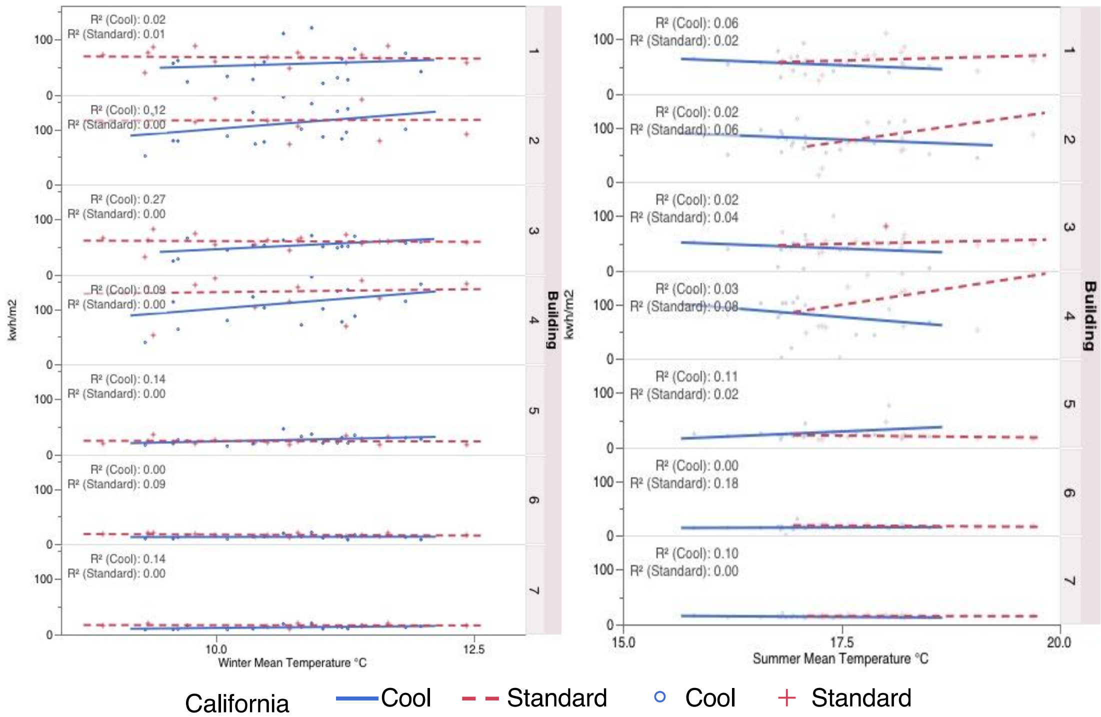


Figure 37: Energy consumption and mean temperature averaged over years 2003-2013 for each building in winter and summer in California.

One reason that energy consumption did not differ between seasons was that in California, there were not many cooling and heating degree-days. For the years studied there were an average of 107 CDD and 1417 HDD annually, and the average temperature (15 °C) was moderate over seasons. Therefore, few days required heating or cooling of buildings in this climate. Although there was a significant linear relationship ($p \leq 0.05$) between mean temperature and energy consumption for cool roof buildings 2, 3 and 4, and standard roof buildings 3 and 5, the cause is not evident and the slope was not different between cool and standard roofs (Figure 38). The mean temperature for California is not only very close to the base temperature for determining whether a building should be in heating or cooling mode (18 °C), but because the variation in temperature is minimal over the seasons the outside temperature at this site year round was nearer the optimal temperature where neither much heating or cooling was needed.

In California, for cool roof buildings 1, 5 and 6, the test was not significant because of the linear relationship between energy consumption and mean temperature, as evidenced in Figure 38 by the relatively flat lines of fit. The standard roof buildings, 1, 2, 4 and 6, had no variation in energy consumption with regards to temperature. However, energy consumption was lower overall for the cool roof buildings. Temperature had little to no effect on these buildings’ energy consumption.

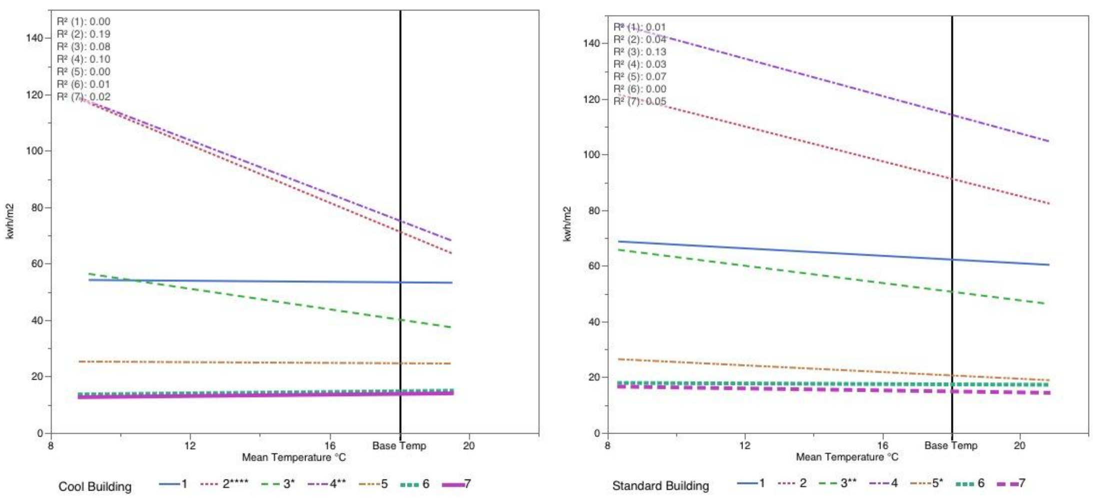


Figure 38: Mean annual temperature averaged over years 2003-2013 as compared with energy consumption for cool and standard roof buildings in California (significant slopes denoted by asterisks, $p \leq 0.05$).

Illinois

At the Illinois location, building-to-building variation accounted for a very significant proportion (60%) of the total variation in energy consumption. In order to examine this building-to-building variation, the relationship between energy consumption and temperature for the winter and summer seasons was separately plotted for each building (Figure 39). By plotting energy consumption with mean temperatures for the winter and summer seasons for each building, the building-to-building variation was evident. The mean energy consumption was less than 4 kWh/m^2 for buildings 1 and 2 compared to 67 kWh/m^2 and 97 kWh/m^2 for buildings 3 and 4. Laboratories, buildings 3 and 4, consumed the majority of energy at this site, while the one miscellaneous building did not consume much energy at all. Building 2 was a medium sized laboratory and should have consumed much more energy than it did. Building 2 was the lowest energy consuming building overall. Other factors besides size and building use may have contributed. Energy consumption profiles for buildings 1 and 2 were similar for summer and winter seasons. In winter, energy consumption was expected to be higher, and in all buildings this was the case except for building 2. In buildings 3 and 4, energy consumption increased as winter temperature decreased. Conversely, energy consumption increased as summer temperature increased. Energy consumption profiles for buildings 1 and 2 were similar for summer and winter seasons. The mean energy consumption for all buildings in Illinois ranged from 3 kWh/m^2 to 97 kWh/m^2.

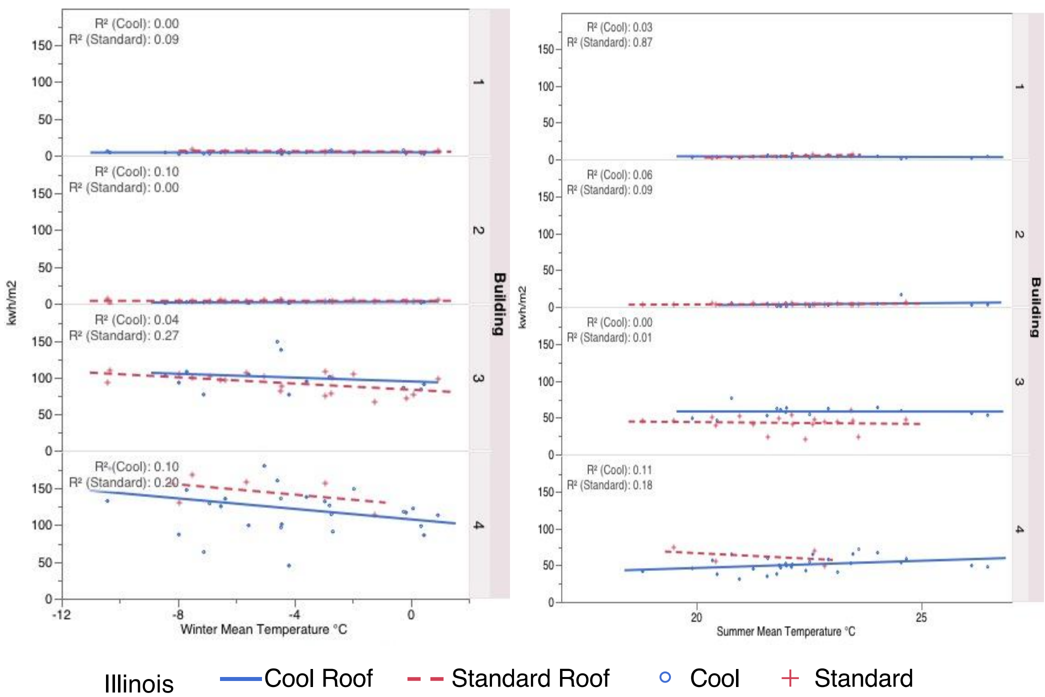


Figure 39: Energy consumption and mean temperature averaged over years 2003-2013 for each building in winter and summer in Illinois.

One reason that energy consumption differed between seasons was that, in Illinois, there were some cooling degree-days and a great deal of heating degree-days. For the years studied there were an average of 468 CDD and 3288 HDD annually. There were great variations in temperature over seasons, with an average temperature of 10 °C. Therefore, many days required heating and cooling of buildings in this climate. Although there was a significant linear relationship ($p \leq 0.05$) between mean temperature and energy consumption for cool roof buildings 3 and 4, and standard roof buildings 3 and 4, the cause is not evident and the slope was not different between cool and standard roofs (Figure 40). Other factors besides the roof type contributed must have contributed to the difference in energy consumption. These factors could have been changing mission or use for the building. As often as possible, DOE building are fully utilized, but often when there are mission changes, utilization percentage can drop or rise significantly in a short amount of time.

In Illinois, for cool roof buildings 1 and 2, the test was not significant because of the linear relationship between energy consumption and mean temperature. Standard roof buildings 1 and 2 had no variation either in energy consumption with regards to temperature. Temperature had little to no effect on these buildings' energy consumption.

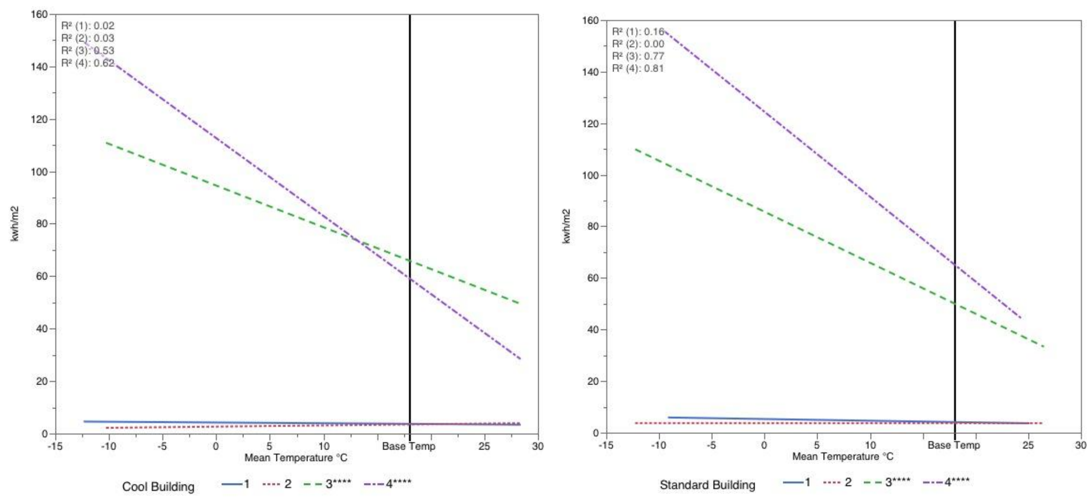


Figure 40: Mean annual temperature averaged over years 2003-2013 as compared with energy consumption for cool and standard roof buildings in Illinois (significant slopes denoted by asterisks, p≤0.05).

Nevada

At the Nevada site, building-to-building variation accounted for a small proportion (12%) of the total variation in energy consumption. In order to examine this building-to-building variation, the relationship between energy consumption and temperature for the winter and summer seasons was separately plotted for each building in Nevada (Figure 41). By plotting energy consumption with mean temperatures for the winter and summer seasons for each building, the building-to-building variation was evident. Mean energy consumption was less than 11 kWh/m^2

for buildings 1, 3, and 6 and between 19 kWh/m^2 and 46 kWh/m^2 for buildings 2, 4 and 5. In winter, in almost all buildings energy consumption increased when temperatures fell. Cool roof buildings 1, 2, 3, 5, and 6 consumed less energy than their standard roof building counterpart in winter. Only cool roof building 4 consumed more energy than the standard roof building 4. In summer, as the temperature rose, energy consumption rose for both standard and cool roof buildings. In buildings 3 and 5, as the temperature rose, the standard roof building consumed a great deal more energy than its cool roof counterpart. The mean energy consumption for all buildings in Nevada ranged from 6 kWh/m^2 to 46 kWh/m^2.

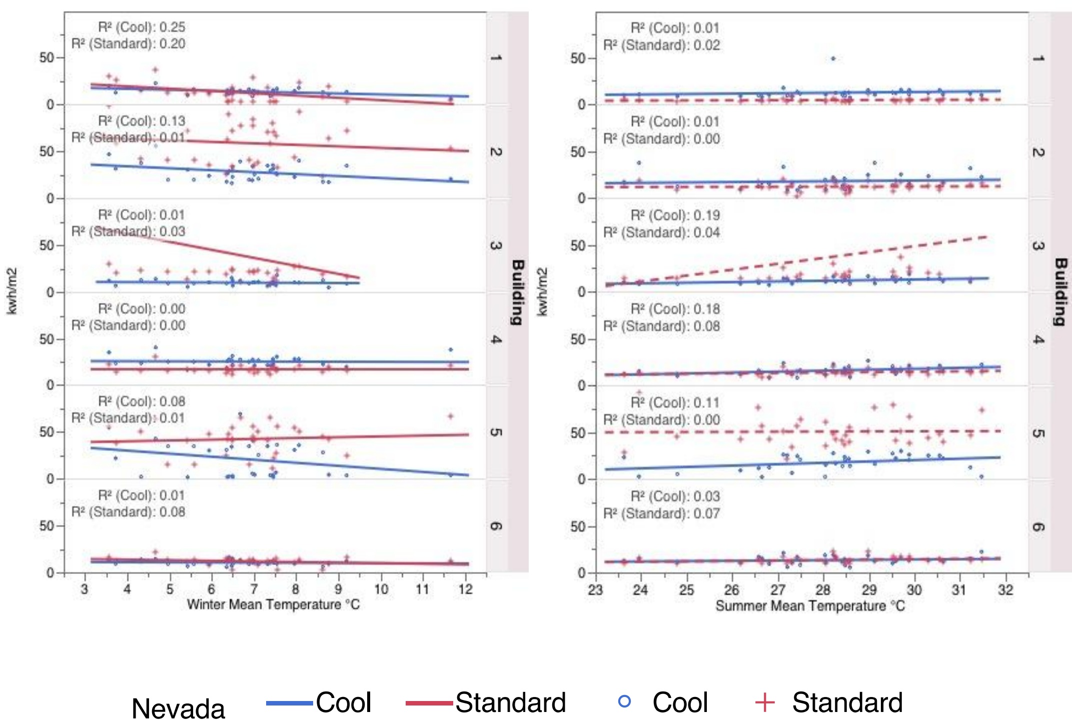


Figure 41: Energy consumption and mean temperature averaged over years 2003-2013 for each building in winter and summer in Nevada.

One reason that energy consumption differed between seasons was that, in Nevada, there were a relatively high number of cooling and heating degree-days. For the years studied there were an average of 1292 CDD and 1736 HDD annually. There were variations in temperature over seasons, with an average temperature of 17 °C. Therefore, many days required heating and cooling of buildings in this climate. Although there was a significant linear relationship ($p \leq 0.05$) between mean temperature and energy consumption for cool roof buildings 2, 3, 4 and 6, and standard roof buildings 1, 2, 4, 5 and 6 the cause is not evident (Figure 42). It may be inferred that other factors besides the roof type and temperature were impacting the energy consumption of these buildings.

In Nevada, for cool roof buildings 1 and 5, and standard roof building 3 the test was not significant because of the linear relationship between energy consumption and mean temperature. Temperature had little to no effect on these buildings' energy consumption.

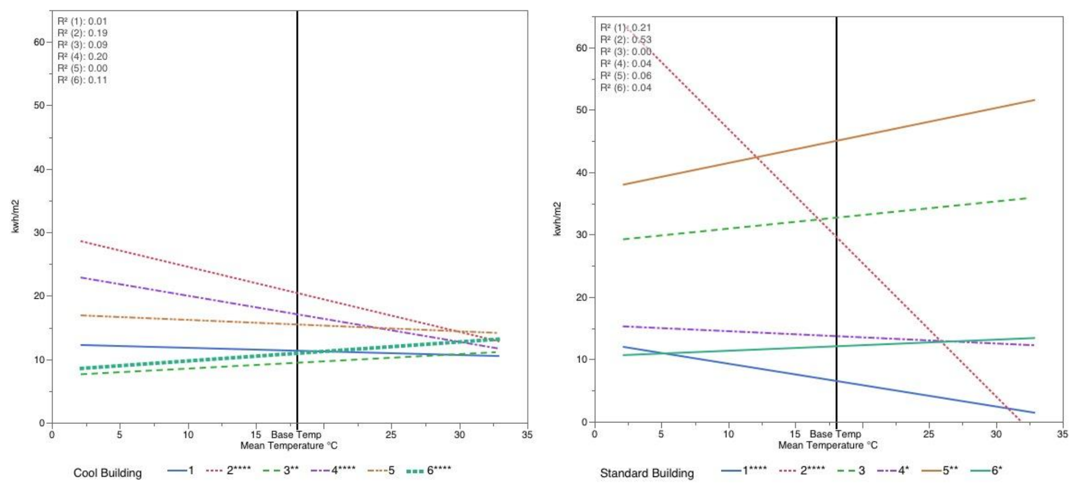


Figure 42: Mean annual temperature averaged over years 2003-2013 as compared with energy consumption for cool and standard roof buildings in Nevada (significant slopes denoted by asterisks, p≤0.05).

Tennessee

At the Tennessee location, building-to-building variation accounted for a small proportion (18%) of the total variation in energy consumption. In order to examine this building-to-building variation, the relationship between energy consumption and temperature for the winter and summer seasons was separately plotted for each building (Figure 43). By plotting energy consumption with mean temperatures for the winter and summer seasons for each building, the building-to-building variation was evident. Mean energy consumption for building 1 was 14 kWh/m^2 and for building 2 was 11 kWh/m^2. The mean energy consumption for all buildings in Tennessee ranged from 10 kWh/m^2 to 15 kWh/m^2. In winter, cool roof building 1 consumed less energy when temperatures fell than standard roof building 1, but cool roof building 2 consumed more energy when temperatures fell than standard roof building 2. Not many useful conclusions were drawn from the Tennessee data, in part because of the small sample size. Both Tennessee buildings were small office buildings that consumed very small amounts of energy in all seasons. Minor variations in energy consumption by these two buildings, caused by external factors other than the cool roof installation, may have skewed any significant results.

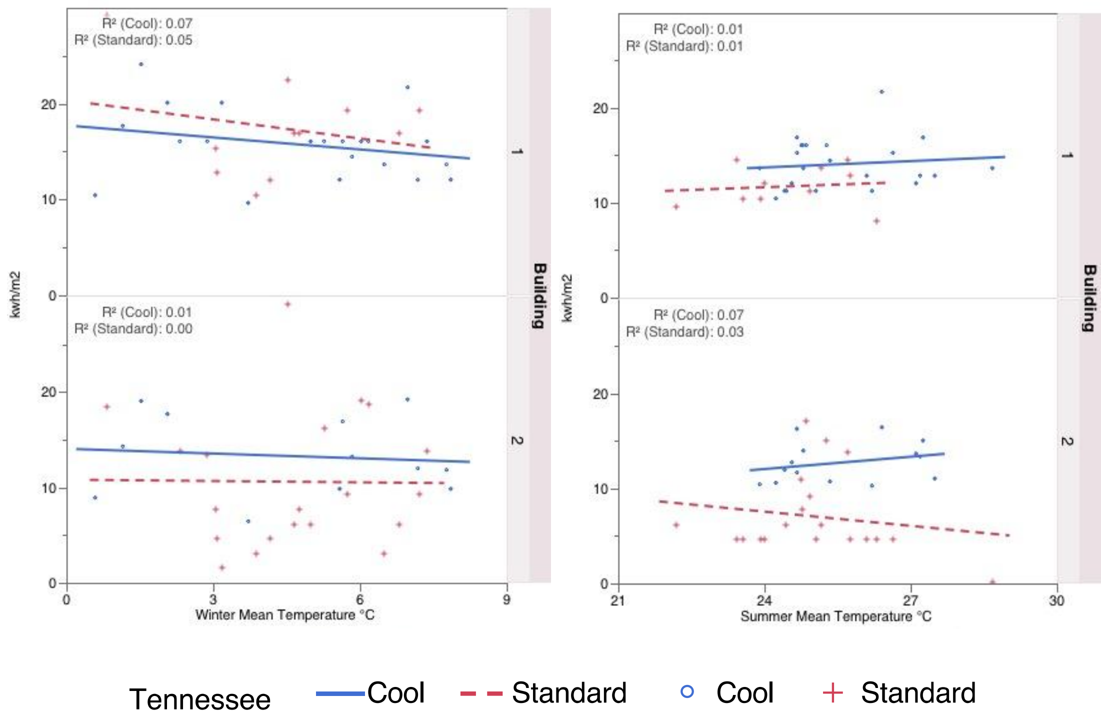


Figure 43: Energy consumption and mean temperature averaged over years 2003-2013 for each building in winter and summer in Tennessee.

One reason that energy consumption differed somewhat between seasons was that, in Tennessee, there were a moderate number of cooling degree-days and a moderate number of heating degree-days. For the years studied there were an average of 879 CDD and 1940 HDD annually. There were variations in temperature over seasons, with a mean annual temperature of 15 °C. Therefore, a moderate number of days required heating and cooling of buildings in this climate. Although there was a significant linear relationship ($p \leq 0.05$) between mean temperature and energy consumption for cool roof building 1, and standard roof buildings 1, and 2 the cause is not evident (Figure 44).

In Tennessee, for cool roof building 1, the test was not significant because of the linear relationship between energy consumption and mean temperature. Temperature had little to no effect on this building's energy consumption.

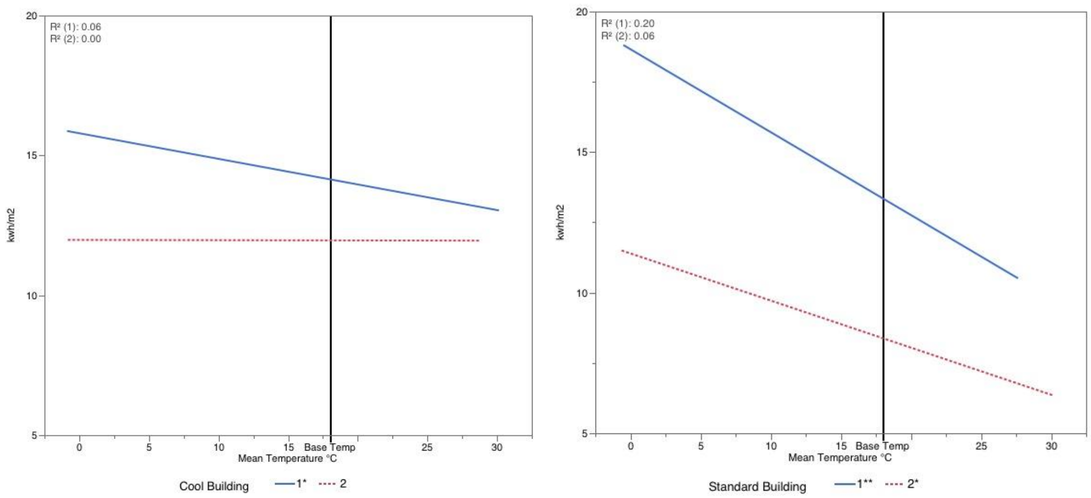


Figure 44: Mean annual temperature averaged over years 2003-2013 as compared with energy consumption for cool and standard roof buildings in Tennessee (significant slopes denoted by asterisks, $p \leq 0.05$).

Site Comparisons

The relationship between the independent temperature variables (mean temperature, HDD, and CDD) and the dependent energy consumption variable was analyzed using a linear regression model. For summer and winter at all sites combined, the slopes of the regression lines for cool roof and standard roof buildings were estimated and tested for significance using the JMP Pro 11.1 Bivariate platform.

In Figure 45, the relationship between mean temperatures was compared with the energy consumption of cool roofs for each site. In Illinois and Tennessee, there was lower energy consumption in the standard roof buildings as compared with the cool roof buildings in part because of their lower mean temperatures and distinct seasons, which results in a heating penalty in the winter months. The Illinois and Tennessee datasets also contained the smallest sample size. The cool roof buildings in California and Nevada consumed much less energy than their standard roof counterparts. The building-to building variation between standard roof buildings and cool roof buildings was prevalent in this study. Lower variability in energy consumption, much more common in cool roof buildings, enables site energy managers to predictably budget for energy costs.

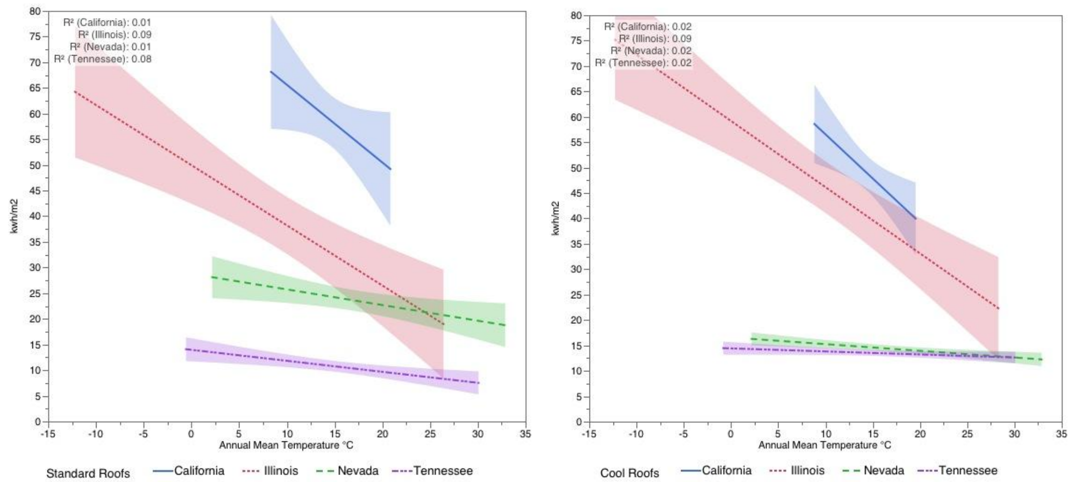


Figure 45: The relationship between mean temperature averaged over years 2003-2013 and energy consumption of standard roof buildings (left) and cool roof buildings (right) by site.

Chapter 5: Conclusions

Previous research has shown that depending on climatic zone, cool roofs can effectively reduce energy consumption during the summer. Although energy models have been developed to predict energy saving from cool roofs, there are few studies of the relationship between variations in temperature and the reduction in energy consumption due to cool roofs. The objectives of this research were to first gather the requisite building and weather datasets in different climatic regions in the US to analyze and compare the energy consumption of buildings with cool and standard roofs. The buildings in this study were located in California, Illinois, Nevada, and Tennessee. Weather data obtained from weather stations in each region was summarized and used to investigate monthly temperature and energy consumption of buildings with cool and standard roofs.

Ultimately, while cool roof energy consumption reductions were generally demonstrated over their standard roof counterparts, a relationship between cool and standard roof energy consumption and temperature was not evident.

In this study, cool roof buildings consumed less energy than standard roof buildings in climates with hot summer temperatures, such as Nevada. Cool roofs were less effective at reducing energy consumption in regions, such as Illinois and Tennessee, with colder temperatures in winter and cooler temperatures than Nevada in summer. Energy consumption data revealed that buildings in milder climate regions of the US, such as California, still obtain benefits from cool roofs, in part due to significant incoming radiation over all seasons.

Cool roof buildings consumed significantly less energy than their standard roof counterparts in two regions, Nevada and California. They were the locations with the most robust datasets and the greatest number of building subjects. Overall, across all regions, cool roof buildings consumed 4% less energy than standard roof buildings. Mean energy consumption was 30.2±0.8 kWh/m^2 for cool roofs compared to 33.6±1.0 kWh/m^2 for standard roofs (Figure 46). California cool roof buildings consumed 11% less energy than their standard roof counterparts. Illinois cool roof buildings consumed 16% more energy than their standard roof counterparts. Nevada cool roof buildings consumed 24% less energy than their standard roof counterparts. Tennessee cool roof buildings consumed 15% more than their standard roof counterparts.

The energy consumption of standard roof buildings had much greater variation than their cool roof counterparts. Cool roof buildings consumed a smaller range of energy in all seasons over standard roof buildings in all locations. In this study, laboratories in the DOE complex consumed much more energy than offices and other miscellaneous buildings. Larger buildings included in this study in the DOE complex consumed much more energy than smaller and medium sized buildings per square meter.

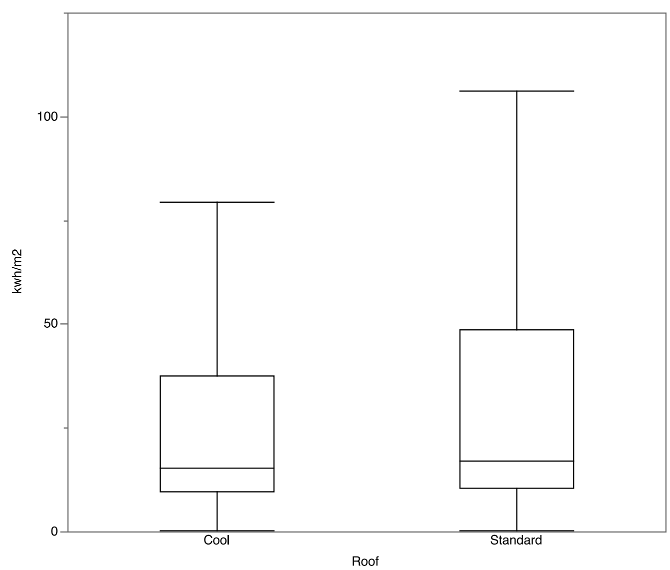


Figure 46: Energy consumption of cool and standard roof buildings over all sites averaged over years 2003-2013.

<u>*Future Research*</u>

The data used in this research were empirical not simulated data. They were actual verifiable observed data. Statistical modeling, specifically a general linear model and several different regression models, were used to test whether the effects of roof type, years, buildings, and regions were significant. The use of modeled and simulated data has its place, but conclusions drawn from empirical data are usually more robust.

Modeled and simulated data do not always consider real world challenges and influences on a system. Often assumptions must be made in order to set the parameters for modeled or simulated data analyses. In reality though there would be deviations from these assumptions. Using empirical data in this dissertation allowed for estimating variation based on actual observations with the technical details included. Additionally, using empirical data can assist in refining and gaining insight regarding the parameters in simulated mechanistic models, which often allow for assumptions to be made about the underlying causes of variability (Bolker 2008).

Many factors contribute to building energy consumption and not all of those factors could be held constant in this study. A controlled study based on observed energy consumption, where the activities and use of the building remains the same over time would improve this research. This would entail holding steady over time the process loads of the buildings, i.e. the energy intensive activities outside of minimal office equipment, lighting and heating and cooling the interior space.

In reviewing the literature, the lack of data on the energy and cost savings of residential cool roofs was evident. Installing a cool roof versus a standard roof on a residential application should be somewhat commensurate regarding energy consumption savings, but further research and analysis using metered data should be done.

In addition to mean, maximum and minimum temperature variables, other weather variables could be analyzed for their impact on cool roof effectiveness, such as relative humidity, precipitation, and the amount of incoming solar radiation.

Although certain facets of effective cool roof construction are known, additional research into how the R-value of insulation impacts cool roof effectiveness is worthy of further investigation.

There are several Presidential Executive Orders (EO) that influence Federal Agencies to focus on energy efficiency improvements and green house mitigation strategies, including EO 13423 *Strengthening Federal Environmental, Energy, and Transportation Management* (2007), EO 13514 *Federal Leadership in Environmental, Energy, and Economic Performance* (2009), and EO 13653 *Preparing the United States for the Impacts of Climate Change* (2013). As climate change impacts become more intrusive and self-evident, more focus will be put on mitigation techniques, such as cool roofs. Future research might include an analysis of best practices for successful adoption of mitigation strategies at government facilities.

The initial proposal for this dissertation research was to investigate whether variations in climate over the past decade had impacted cool roof energy consumption. Despite nine months of gathering and analyzing data from the 13 DOE laboratory sites, it was not possible to obtain metered datasets for five paired buildings for 10 years. Major obstacles in obtaining the requisite data included: not all energy data for a building was metered. In some buildings only natural gas was metered, in others only electricity was metered. This presented a problem when trying to evaluate total building energy use. All energy inputs had to be accounted for, therefore if a natural gas line was not metered, but the electricity was, the building data had to be rejected and excluded from the study. There were several other labs besides the four ultimately chosen with robust datasets, but some energy data was not metered and therefore those buildings had to be excluded.

Current metering conditions throughout the DOE complex are varied. Some sites, especially more urban sites, have standard electric meters installed. Other sites, especially rural sites, are in the process of installing meters via Energy Savings Performance Contracts (ESPCs) or with funding dedicated to sustainability. At present, most DOE sites do not have advanced meters that record data electronically in small temporal increments, e.g. seconds or minutes. Advanced meters allow for easy and efficient tracking of energy consumption and therefore give energy managers the ability to monitor and recalibrate energy usage at different facilities. Great effort, in part due to EO 13514, has been expended in the past few years to strategically install meters whenever possible. More advanced meters should be installed at DOE sites to allow this type of research to be redone with more complete energy consumption data in future years after the advanced metering has been put in place. Reducing energy consumption in government buildings not only saves taxpayer dollars, it reduces overall energy demand and greenhouse gas emissions. Finding ways to reduce energy consumption has become much more difficult as the easier energy efficiency solutions have already been adopted. Building and retrofitting government buildings in the most efficient manner possible, in part by installing cool roofs where appropriate, will assist in continued energy consumption reductions. These strategies can and should be applied to residential and general commercial buildings as well.

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