THE IMPACT OF CLIMATE CHANGE: VULNERABILITY, ADAPTATION AND RISK ANALYSIS TWO BUILDINGS IN BOULDER, COLORADO

EXECUTIVE SUMMARY

INSTITUTE OF CLIMATE AND CIVIL SYSTEMS

AUGUST 2014

EAST BOULDER COMMUNITY RECREATION CENTER & WILDLAND FIRE STATION

ANALYSIS: IMPACT OF CLIMATE CHANGE THROUGH 2100

SUMMARY: CLIMATE CHANGE IMPACT ON SELECT BUILDINGS

The current study presents the potential risk of climate change to the East Boulder Community Center and Wildland Fire Station in Boulder, Colorado. The study utilized the IPSS system to determine the cost impacts through 2100 on the two structures. The study utilized 54 IPCC-approved climate scenarios together with historic weather information to determine projected impacts. The combination of these projections with engineering-based impact scenarios provided the cost implications outlined in the study.

In summary, the study found that all scenarios indicate potential impacts to the buildings under consideration. Differences exist in terms of the magnitude of the impact and the timeframe in which the impacts will occur. However, when considering the appropriateness of an adaptation policy or a no adaptation policy, the scenarios indicate that by 2060, changes in precipitation, humidity, and temperature elements will impact the performance of the buildings' HVAC systems, energy use, and potentially have impacts on building design by a change in ASHRAE Climate Zone Definition.

This summary report includes: Highlights of findings from the analysis, changes in local climate affecting the buildings analyzed, increase in energy use if no adaptation action is taken, and a timeline for both buildings that highlights key future dates related to climate impact and costs.

According to the City of Boulder Climate Action Plan, there are six community strategies designed to reduce greenhouse gas emissions and become a more climate resilient city. More than 75% of Boulder's emissions come from energy use in buildings. The Climate Action Plan, combined with the recent naming of Boulder as one of the Rockefeller Foundations "100 Resilient Cities", provides an opportunity and imperative to consider the impacts of climate change on the buildings considered in this analysis and throughout the City. By understanding the impacts that a changing future climate will have on energy and operations, as well as design considerations, Boulder can take advantage of the challenge presented by climate change and turn it into an opportunity to create a more resilient and sustainable future.

HIGHLIGHTS OF ANALYSIS FINDINGS:

- Adaptation of windows by 2020 reduces energy costs significantly

East Boulder Community Recreation Center:

- By 2050, energy cost increases between 3 – 18% above current costs, depending on model.
- By 2075, energy costs increasing by 6-26% above current costs, depending on model.
- Increases in humidity necessitate HVAC updating as early as 2040 for the Recreation Center

Wildland Fire Station:

- By 2050, energy cost increases between 2-16% above current costs, depending on model.
- By 2075, energy cost increases between 3-20% above current costs, depending on model.
- Increases in humidity necessitate HVAC updating as early as 2025 for the Fire Station

CHANGES IN CLIMATE (2050)

The General Circulation Models have the capability to predict monthly temperature and precipitation. The bar graphs below show the monthly projected climate data in 2050 for the two locations of study. Three values are graphed: the maximum and the minimum projected climates (among the 54 GCMs) and the base climate (the base is equivalent to the historic recorded data).

Temperature is predicted to increase a maximum of 20 degrees in every single month while the minimum predicted values are very similar to the historic data, meaning that no climate models predict lower temperature by 2050. Precipitation has much more variability. The models project maximum increase of 2 inches on rainy month and maximum decrease of 1.5 inches by 2050 respect historic data. However, the precipitation increases do not affect any aspects of the buildings analyzed in this report.

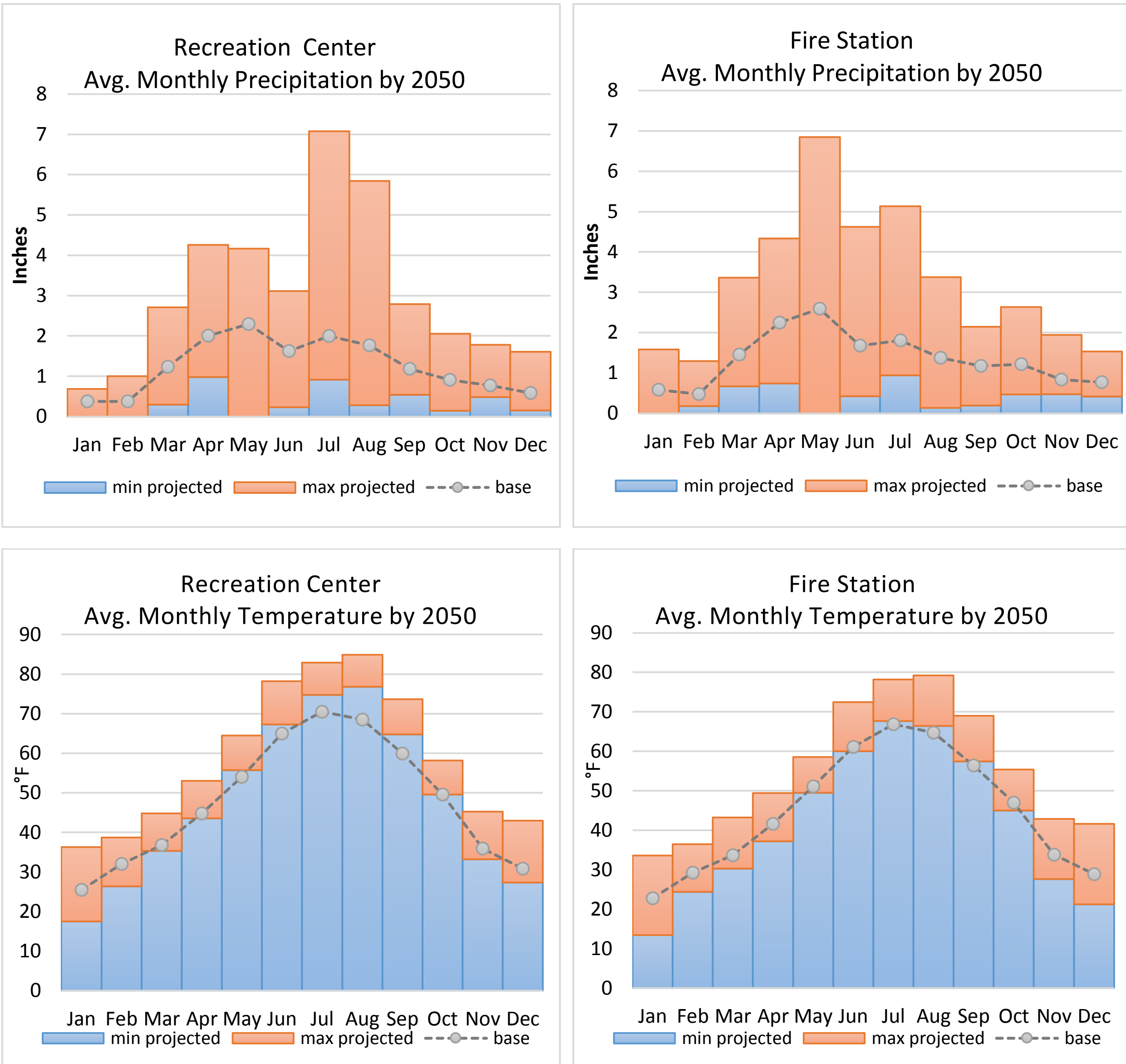


Figure 1: Average Projected Monthly Precipitation/Temperature by 2050. The GCMs have the capability to predict monthly temperature and precipitation through 2100. At the beginning of the report, the results of the climate projections are shown on a State-wide scale. The bar graphs above show the monthly projected climate data in 2050 for the two locations analyzed. Three values are graphed: the maximum and the minimum projected climate (among the 54 GCM) and the base climate (the base is equivalent to the historic recorded data). Temperature is predicted to increase a maximum of 10 degrees in every single month while the minimum predicted values are very similar to the historic data, with colder temperatures during winter season. No climate models predict lower temperature by 2050 during summer months. Precipitation has much more variability. The models project maximum increase of 2 inches in wetter months and a maximum decrease of 1.5 inches by 2050, as compared to historic data.

IMPACT ON ENERGY CONSUMPTION: NO ADAPTATION

The following figures show over time the annual energy cost of both buildings of study. The lines represent the energy consumption of three selected models representing the 95th, 50th and 5th percentiles of costs among the 54 GCMs studied. The values are compared to the baseline energy cost, based on historic recorded data. Values follow the assumption that in both building the same interior temperature is required over time.

The three climate models predict a peak on energy demand in 2045 and 2075. The rapid increase in maximum temperature will produce a high energy consumption due to A/C usage during summer season. The most severe climate model predicts increase of $ 2,000 of annual energy cost by 2050 for the Fire Station while predicts over $ 10,000 increase for the Recreation Center.

A key recommendation is to adapt the windows in both buildings to high-efficiency, double- or triple-paned windows with tint and Argon gas fill. While this incurs a construction cost, over time it significantly reduces energy use related to increases in temperature.

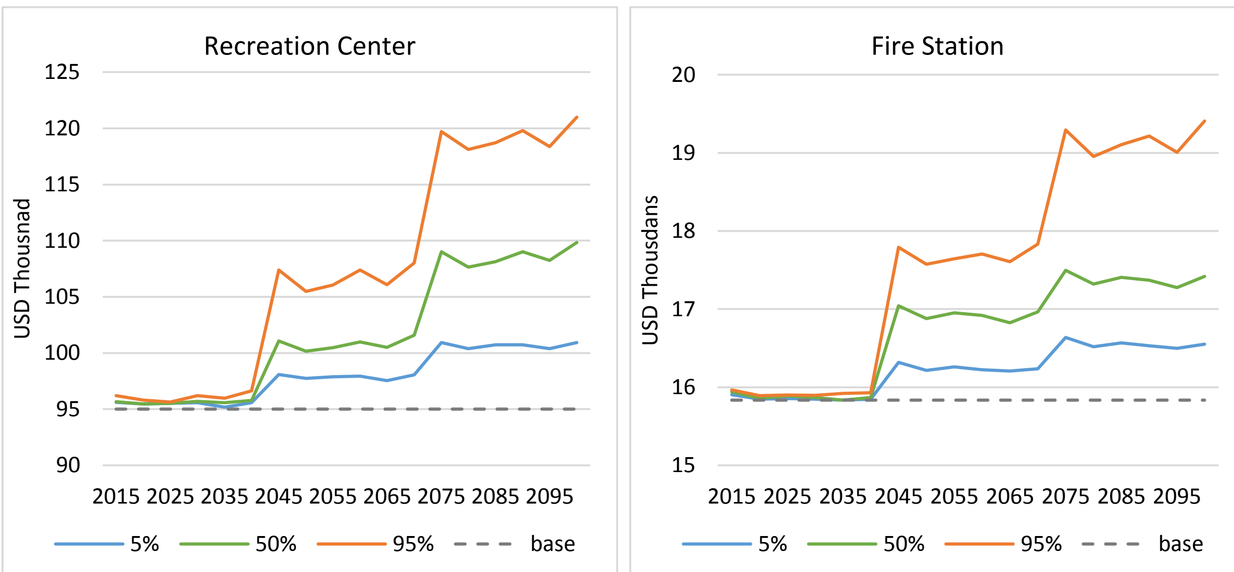
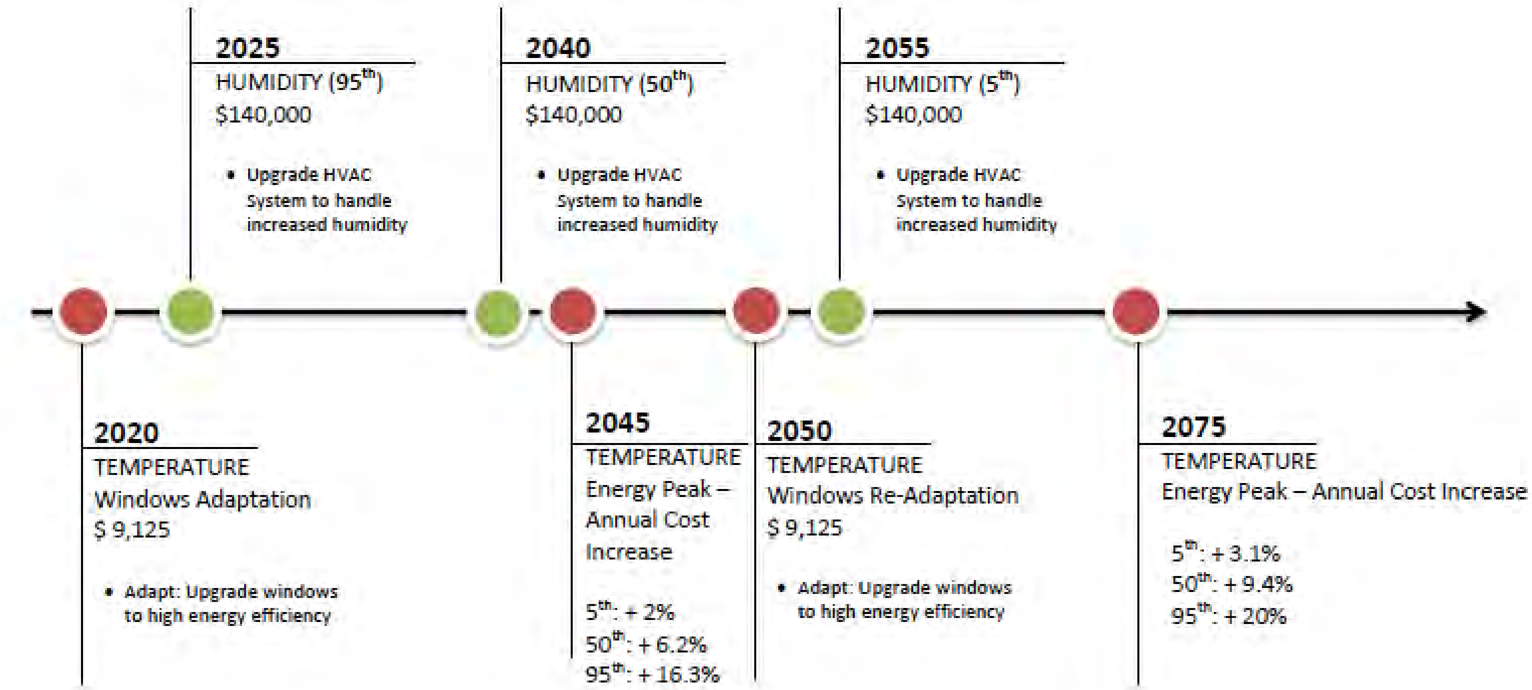


Figure 21: No Adaptation – Average Annual Energy Cost. The above figures show over time the annual energy cost of both buildings of study. The above line graph shows the projected energy consumption in each building for three different models, the 95%, 50% and 5% GCMs. The three projections are compared with the historic climate (dash line). Values follow the assumption that in both building the same interior temperature is required over time. The three climate models predict a peak on energy demand in 2045 and 2075. The rapid increase on maximum temperature will produce high energy consumption due to increased cooling needed during the summer season. The most severe climate model predicts increase of $ 2,000 of annual energy cost by 2050 for the Fire Station while predicts over $ 10,000 increase for the Recreation Center.

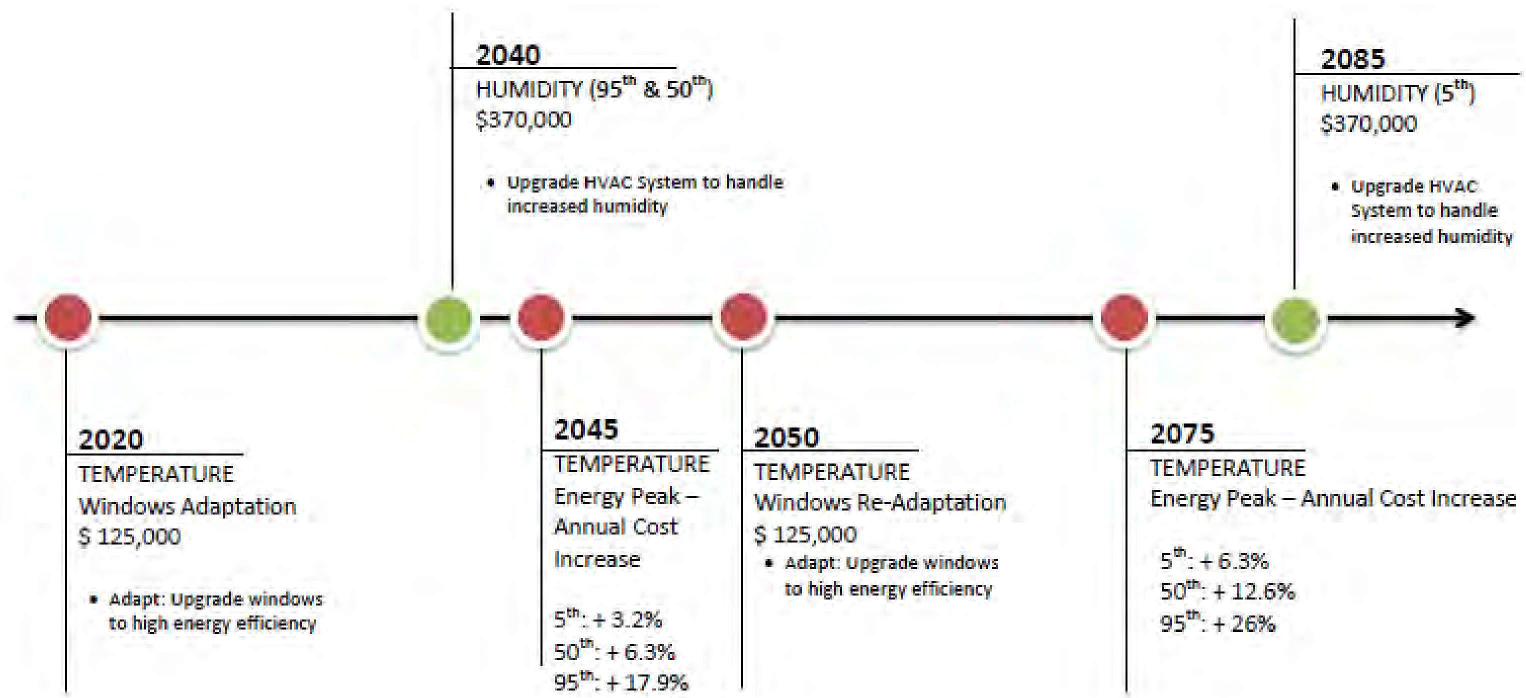
Wildland Fire Station

	2020 2030 2040 2050	2060 2070 2080	Life Time Energy Savings
Adapt	**2020 – Windows Adaptation Investment: $9,125** Life-Cycle Energy Savings (2015 – 2050) 5^{th}: $32,000 50^{th}: $32,000 95^{th}: $33,000	**2050 – Windows Adaptation Re-Investment: $9,125** Life-Cycle Energy Savings (2051 – 2100) 5^{th}: $ 41,000 50^{th}: $ 43,000 95^{th}: $ 42,000	5^{th}: $ 73,000 50^{th}: $ 75,000 95^{th}: $ 79,000 Base (no climate change): $ 71,000
No Adapt	Life-Cycle Energy Cost Increase (2015-2050): 5^{th}: $ 13,000 50^{th}: $ 14,000 95^{th}: $ 14,000	Life-Cycle Energy Cost Increase (2051 – 2100): 5^{th}: $ 42,000 50^{th}: $ 43,000 95^{th}: $ 47,000	



East Boulder Community Recreation Center

	2020 – 2050 (2020, 2030, 2040, 2050)	2050 – 2080 (2060, 2070, 2080)	Life Time Energy Savings
Adapt	**2020 – Windows Adaptation Investment: $125,000** **Life-Cycle Energy Savings (2015 – 2050)** 5^{th}: $ 384,000 50^{th}: $387,000 95^{th}: $395,000	**2050 – Windows Adaptation Re-Investment: $125,000** **Life-Cycle Energy Savings (2051 – 2100)** 5^{th}: $ 498,000 50^{th}: $ 528,000 95^{th}: $ 571,000	5^{th}: $ 882,000 50^{th}: $ 915,000 95^{th}: $ 966,000 Base (no climate change): $ 855,000
No Adapt	**Life-Cycle Energy Cost Increase (2015-2050):** 5^{th}: $ 136,000 50^{th}: $ 139,000 95^{th}: $ 146,000	**Life-Cycle Energy Cost Increase (2051 – 2100):** 5^{th}: $ 498,000 50^{th}: $ 528,000 95^{th}: $ 572,000	



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FULL REPORT

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EAST BOULDER COMMUNITY RECREATION CENTER & WILDLAND FIRE STATION

ANALYSIS: IMPACT OF CLIMATE CHANGE THROUGH 2100

INSTITUTE OF CLIMATE & CIVIL SYSTEMS

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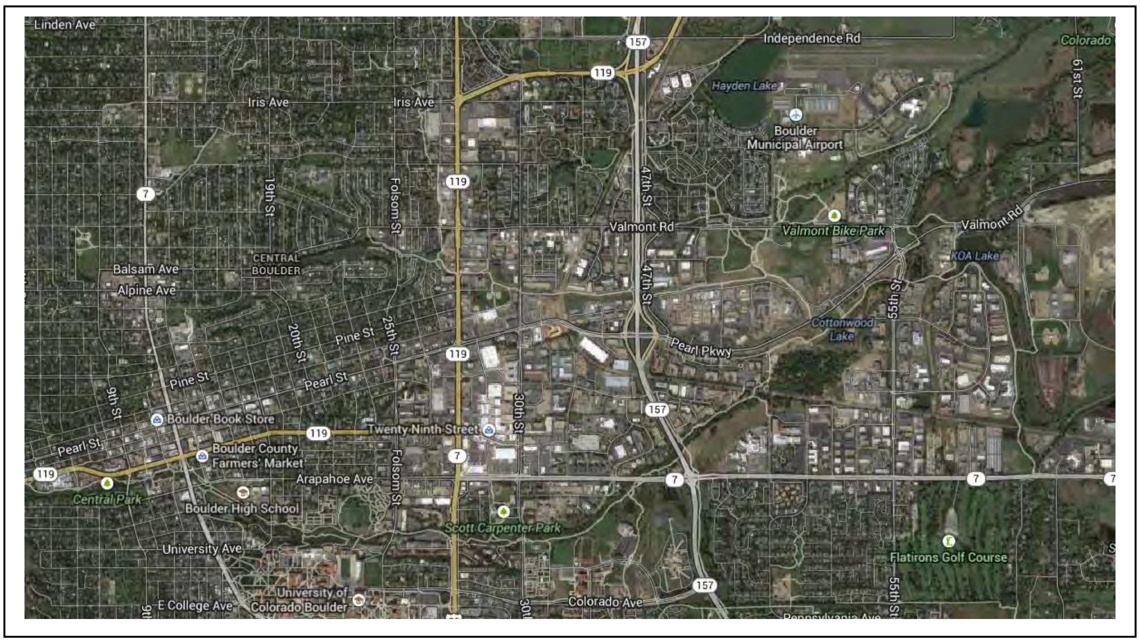
1 INTRODUCTION

Location: Boulder, CO

Project Type: Analysis of Two Buildings:

Wildland Fire Station & East Boulder Community Recreation Center

Customer: City of Boulder



1.1 IPSS Analysis Overview

The analysis presented here is based on an engineering analysis that evaluates potential climate impacts on existing and future infrastructure. Evaluation of cost is based on two distinct strategies, or policy approaches: reactive and proactive. The proactive strategy, *adapt*, is based on incorporating measures to make the infrastructure resilient to climate impacts by changing specific elements during design and construction. The adapt strategy incorporates design standard upgrades to increase resilience. The reactive approach, *no-adapt*, does not anticipate future climate change impacts. Rather, any climate impact is addressed through increased maintenance on a yearly basis. In both strategies, the calculated costs are based on the actions needed to maintain the original design-life of the infrastructure. Additionally, an *incurred* cost is applied when climate conditions indicate that an upgrade to the air ventilation system (HVAC) is necessary to maintain compliance to health codes relating to building air flow and operations. To develop the subsequent costs presented here, IPSS performs a three-step process.

First, the projected climate impact of the specific region is examined. IPSS has a flexible input allowing different climate models to be incorporated. The current study uses 54 AR4 General Circulation Models (GCMs) to obtain the predicted future values of climate stressors including temperature, precipitation, and humidity. These values are compared to historic climate data to obtain increments of change due to projected changes in climate. Analysis is computed by default at a 0.5 x 0.5 degree of latitude and longitude resolution.

Second, IPSS determines potential impacts on the specific infrastructure being evaluated, in this case two separate buildings in the City of Boulder limits. IPSS incorporates material-based analysis to determine specific impacts from individual climate stressors. These analyses are based on a combination of materials studies, case studies, and historical data. Impacts are calculated on a per-kilometer or per square-foot (meter) basis depending on the type of infrastructure being considered.

Finally, the potential cost of climate impacts are calculated based on projected maintenance and retrofit costs and/or changes in design costs. Results are presented in terms of potential climate risk, incurred costs, potential adaptation strategies, and no-adaptation impacts and costs.

The overall process described here is reflected in the diagram below. As illustrated, the same process is used for each infrastructure type and for each element in the provided inventory.

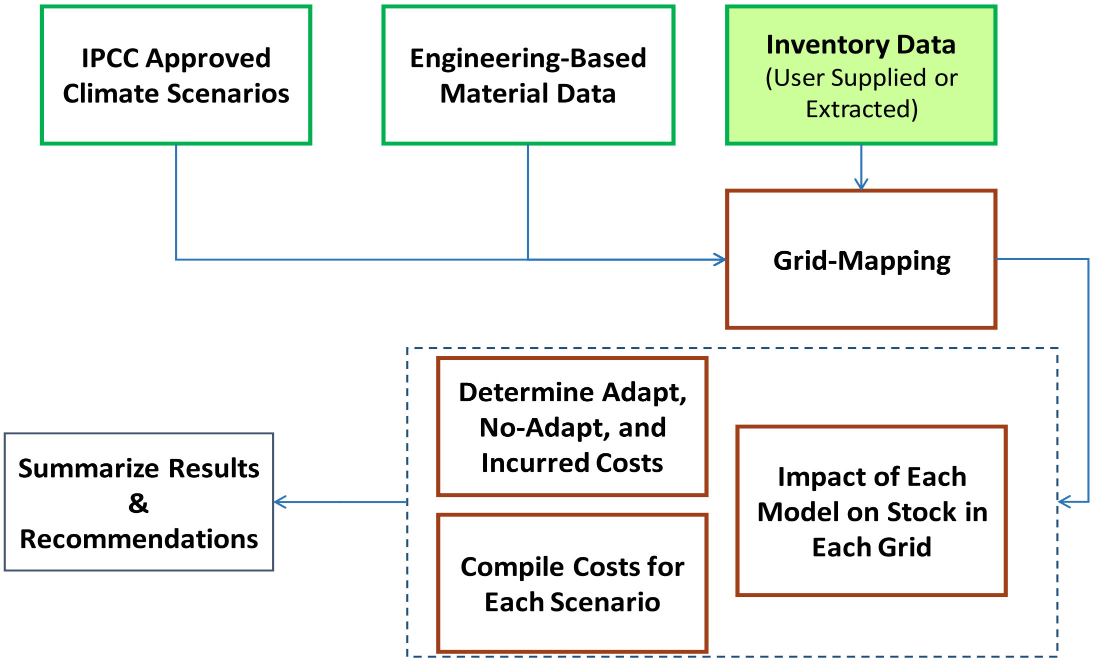


Figure 1: IPSS overall process diagram

1.2 REPORT STRUCTURE

The following sections of this report present the results of the climate analysis on five sections. The sections are described as follows:

- **Climate Analysis** – Section 2 provides an overview of the climate scenario projections for the region under study. Median and maximum scenarios are provided in map form while timelines illustrate the variance of the projections over the time of the study. This report includes information for the State of Colorado.
- **Vulnerability Analysis** – Section 3 provides a detailed vulnerability analysis based on the climate scenarios and specific infrastructure elements. A timeline illustrates when key vulnerabilities may be anticipated. This section also includes specific climate changes in the North and South Boulder regions that cause key vulnerabilities in the buildings under evaluation.
- **Adaptation Analysis** – Section 4 builds on the vulnerability analysis by projecting adaptation options on the infrastructure in anticipation of future climate variances. Variances in cost and timeframes are presented in relation to adaptation costs.
- **Risk Analysis** – Section 5 utilizes the results of the Adaptation Analysis to present multiple risk perspectives for informing adaptation or no adaptation policies. Cost of resiliency and regret or risk costs are used as the basis for the analysis.
- **Recommendations & Summary** – Section 6 summarizes the key findings from this evaluation and highlights specific areas where risks to the infrastructure are found. It also highlights additional risks and considerations that are outside the scope of this specific study but are important factors to consider current and future resilience of infrastructure in the study.

The report highlights key climate changes and the impacts on infrastructure under evaluation. When possible, adaptation options are suggested and the cost-benefit of implementation is compared with a no adaptation strategy.

All graphics are accompanied by explanatory text boxes with information on interpreting and using the data.

2 CLIMATE ANALYSIS

The climate change projections utilized in this study were analyzed using data from General Circulation Models (GCMs). The 22 GCMs are approved by the Intergovernmental Panel on Climate Change. They provide climatological data for future climate change scenarios through 2100. The data used in this analysis include the available A2, A1B and B1 scenarios for each GCM, which represent different scenarios of future development based on the accepted definitions of the Intergovernmental Panels Fourth Assessment Report[1]. To provide a robust analysis of possible climate change projections, all GCM data sets approved by the IPCC containing complete data projections for climate data on the region being studied were used in the current analysis. In total, 54 GCMs are used in the IPSS analysis. Each of these climate models contains predictions for precipitation, humidity, and temperatures. In an effort to get a broad picture of the potential effects of climate change, the results presented in this study focus on the variations in predictions presented by both specific models representing the 5th percentile, the median and 95th percentile of the total collection of GCMs and a comparative analysis of the models in aggregate.

The current analysis has been carried out using climate change projections analyzed by GCMs at the resolution of 0.5° grid squares, which are then applied to the specific study area. The GCMs selected are the models that have complete datasets appropriate for making temperature and precipitation projections through 2100. For each model, historical monthly climate data is used from the Climate Research Unit (CRU) for 1961–1990 to produce a baseline 'no climate change' scenario for each geographic region analyzed. The baseline scenario assumes that future weather patterns will retain the characteristics of historical climate variability. Taking the baseline scenario, monthly deviations in temperature and precipitation are used to establish deltas that are applied to the new projected baselines in each GCM. The application of these deltas to the baselines in each of the future decades provides the climate scenarios that are used as the basis for the specific impact analyses.

The analysis presented in this section will focus on the projections made by each of the selected climate scenarios at the CRU level on an annual basis. The maps and graphs presented are intended to illustrate the variances present in these models and the potential differences that may exist in each CRU grid.

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[1] IPCC (2007). "Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change," Pachauri, R.K. and Reisinger, A. (Eds.), IPCC, Geneva, Switzerland.

2.1 Historic Statewide Climate

The historic climate in Colorado varies depending on geographic location. The eastern half of the state is dry and warm on average. The central part of the state has an alpine climate with cooler and wetter patterns. While the southwest is notably wetter on a historic basis while still having an overall warm climate on an annual basis. This variance in climate patterns creates a need to examine future scenarios on a specific local level to determine infrastructure vulnerabilities.

Boulder, Colorado is located in the north central part of the State at the foot of the Rocky Mountains. It has an altitude of 5,400 feet and an average daily temperature of approximately 65 degrees F. Future climate projections vary considerably in some models from historic climate

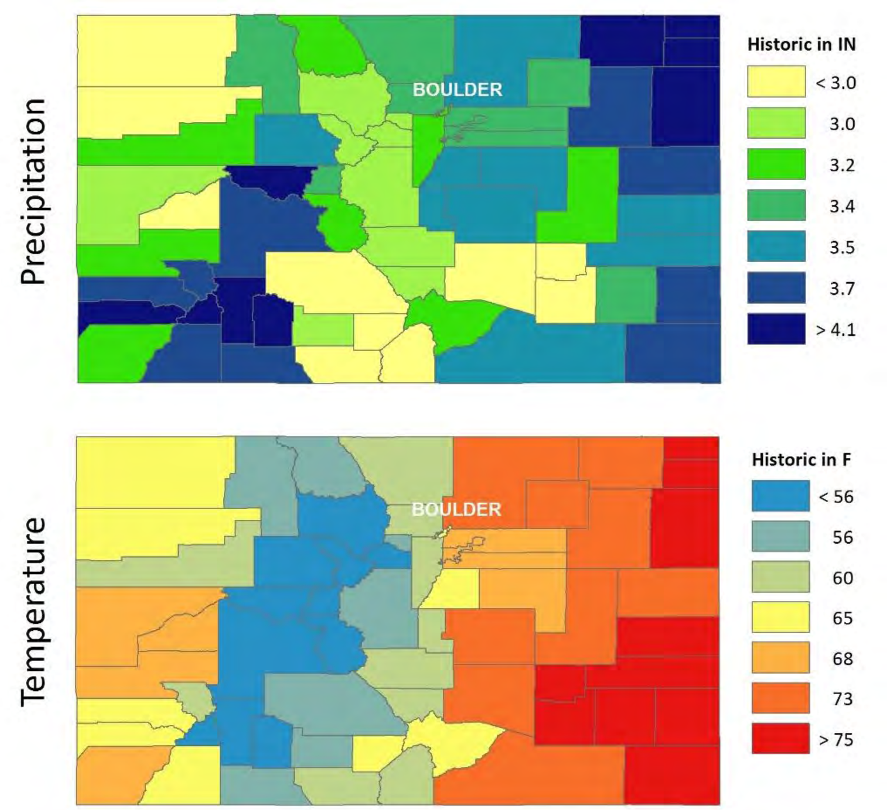


Figure 2: Historic Statewide Monthly Precipitation (in inches) and Average Temperature (in Fahrenheit)

2.2 FUTURE PROJECTED STATEWIDE CLIMATE

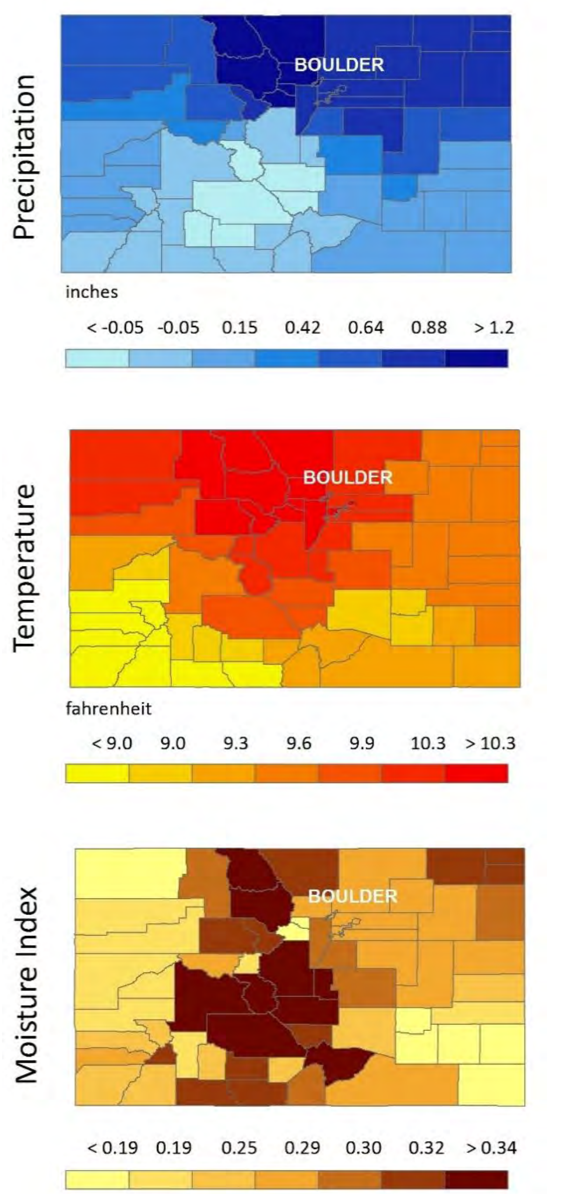


Figure 3: Maximum Projected Statewide Climate Change by 2050, Precipitation, Temperature and Moisture Index

On a statewide level, the climate projection for Colorado varies when examining the projections in 2050; halfway through the time period of study. As illustrated in the maps, precipitation is anticipated to be significantly increasing in the northern part of the state. The southwest and central in particular is projected to see a significant decrease in precipitation from the more extreme scenarios. However, the eastern part of the state, the northeast in particular, is projected to see wetter conditions. Thus, the overall outlook is mixed for the region from a precipitation perspective.

In contrast, the temperature outlook for Colorado is much more uniform, with the majority of the state getting warmer. The exception to this is the southwest, which is projected to have minimal warming.

In combination, the northeast section of the state is projected to have the greatest heating and wetter components, while the southwest and central could see dryer weather with minimal heating.

Humidity ("Moisture Index") is an important component of the impacts on the buildings analyzed for this report. For Colorado, the Moisture Index varies throughout the State. Boulder County (Indicated on the map) sees several different ranges for the 2050 monthly maximum projected.

Each of these components has specific impacts on the two buildings analyzed. More specific climate information related to the buildings and specific for the City of Boulder is shown below.

3 VULNERABILITY ANALYSIS

Vulnerability in the context of this analysis is the potential for infrastructure to be damaged by future climate impacts. Specifically, the potential for infrastructure is vulnerable if changes in temperature, humidity, and/or precipitation could lead to damages requiring increased costs to retain projected design life. This vulnerability can vary depending on the climate model in terms of both severity and timeline. This section presents the specific climate elements that are most relevant to the buildings analyzed in the North and South Boulder regions. This projected vulnerability of the projects is shown in terms of the 54 GCM models introduced previously.

3.1 CLIMATE IMPACTS: CITY OF BOULDER (NORTH AND SOUTH)

The City of Boulder sees specific climate impacts that differ slightly in terms of North and South geography. For this study, the Fire Station is located in a Northern climate zone and the East Boulder Recreation Center is located in the Southern Climate Zone (related to the City). The information displayed graphically in this section is for the average changes between the North and South regions; there are differences between these regions which specifically affect the building elements and are used for the analysis, but for purposes of illustrating the magnitude of changes, the average for the two regions is suitable.

For the climate elements analyzed in this study, precipitation, temperature and humidity, the largest impacts are seen from temperature and humidity increases. This is particularly true for the maximum GCM projections, although the median projection sees impacts in the latter half of the century.

Regarding temperature, Boulder sees significant variation in median and maximum future climates. By 2025, the maximum GCM projection indicates significant increases in maximum temperature annually, including approximately 4 degrees Fahrenheit increase from the baseline historical values. By 2050, the median GCM projection indicates approximately 2 degrees Celsius difference. By the end of the century, the maximum and median GCM projections indicate approximately 20 and 10 degrees Fahrenheit increases, respectively.

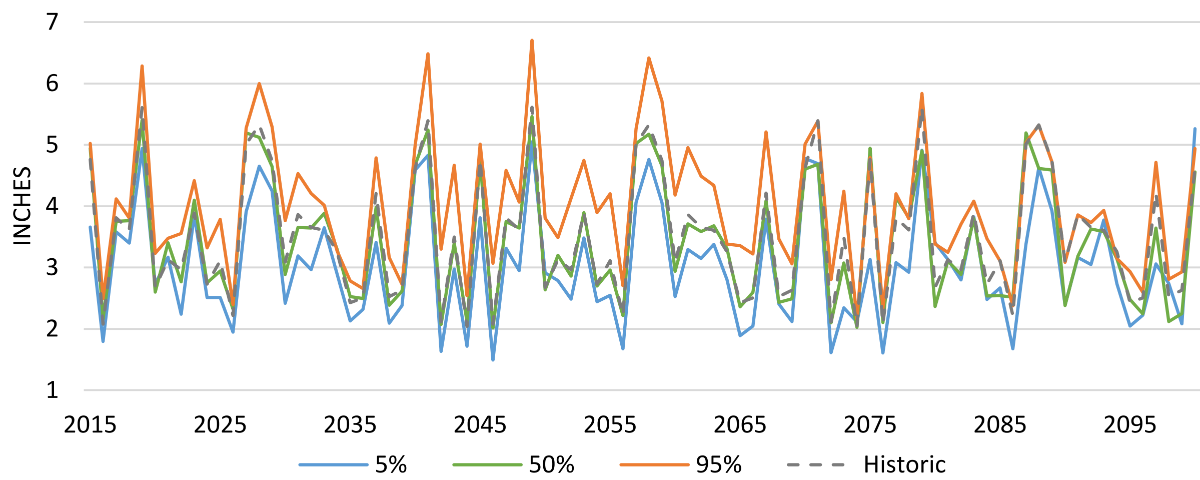


Figure 4: City of Boulder: Maximum Monthly Precipitation. The above line graph shows the projected precipitation in the City of Boulder for three different models: the 95%, 50% and 5% GCMs. The three projections are compared with the historic climate (dash line). The precipitation displayed corresponds to the maximum precipitation accumulated during a month. The climate models project more variability on precipitation and a clear trend is not identified. The 95% model projects increase of 1 inch in some of the year, while the 5% model projects a decrease of 0.5 inches.

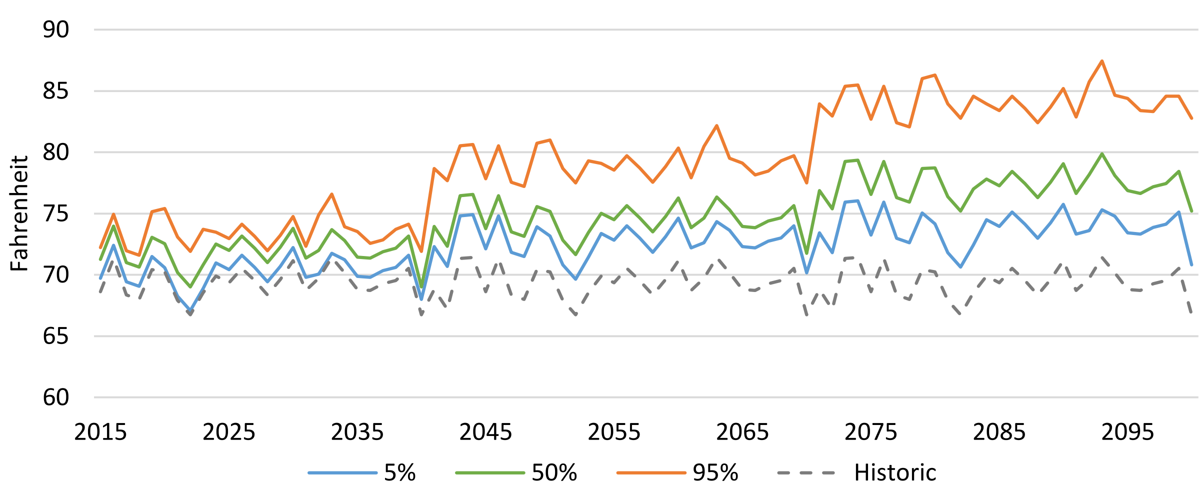


Figure 5: City of Boulder: Maximum Average Monthly Temperature. The above line graph shows the projected temperature in the City of Boulder for three different models, the 95%, 50% and 5% GCMs. The three projections are compared with the historic climate (dash line). The temperature displayed corresponds to the maximum average monthly temperature. For this project in Boulder, the average highest temperature is found in the summer season. All climate models project an increase of the temperature with a range of 5-15 Fahrenheit over the historic by the end of the century. All models predict significant changes around 2040 and 2070.

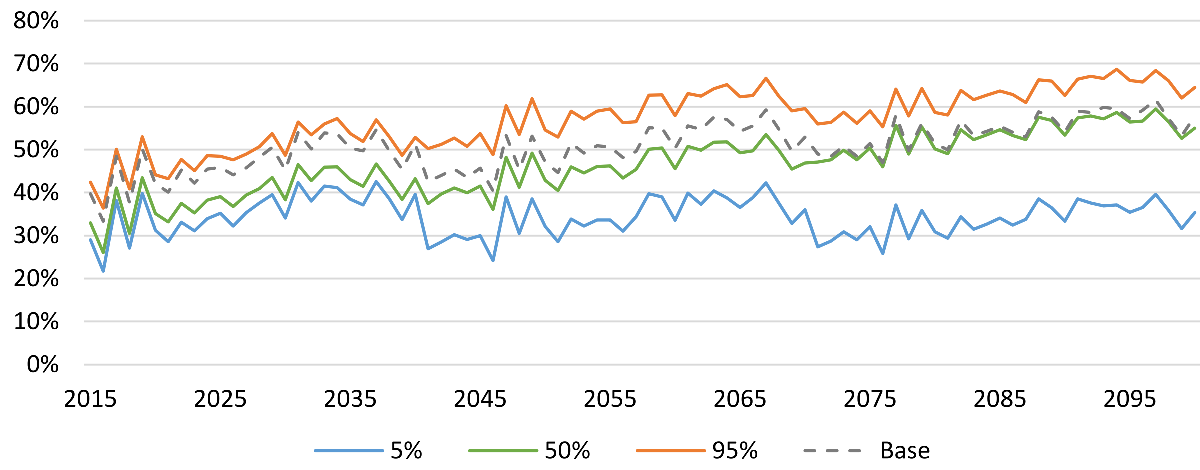


Figure 6: City of Boulder: Monthly Moisture Index. The above line graph shows the projected Moisture Index (MI) in the City of Boulder for three different models, the 95%, 50% and 5% GCMs. The three projections are compared with the historic climate (dash line). The Moisture Index is a variable that relates to the relative humidity and is widely used in building design. Lower MI means dry conditions while MI closer to 100% means high humidity conditions. The climate models project a significant variability on MI. By the end of the century, the 95% projects an increase of 10 points respect historic values, while the 5% projects a decrease of 20 points.

The change in humidity for Boulder has an impact on the buildings analyzed, particularly for the East Boulder Community Center and the air handling (HVAC) systems. This is seen in section 4 for the adaptation analysis as an incurred cost of climate change. The average changes for the City of Boulder are graphed above. The changes are incrementally small until about 2040. From then the 95th projections experiment an increase that reaches a maximum of 5 points above baseline by 2080. On the other side the 5th model projects a significant decrease of the humidity starting on 2040 and reaching almost 15 points by 2070. These trends continue to the end of the century, where a difference of approximately 10 and 20 is observed between the historic baseline and the minimum and maximum projections, respectively.

Additionally, when considering monthly variation throughout the year, there are changes that impact both buildings by 2050. The charts below show the 95th, 5th, and base percentile GCM changes projected by 2050 for both buildings.

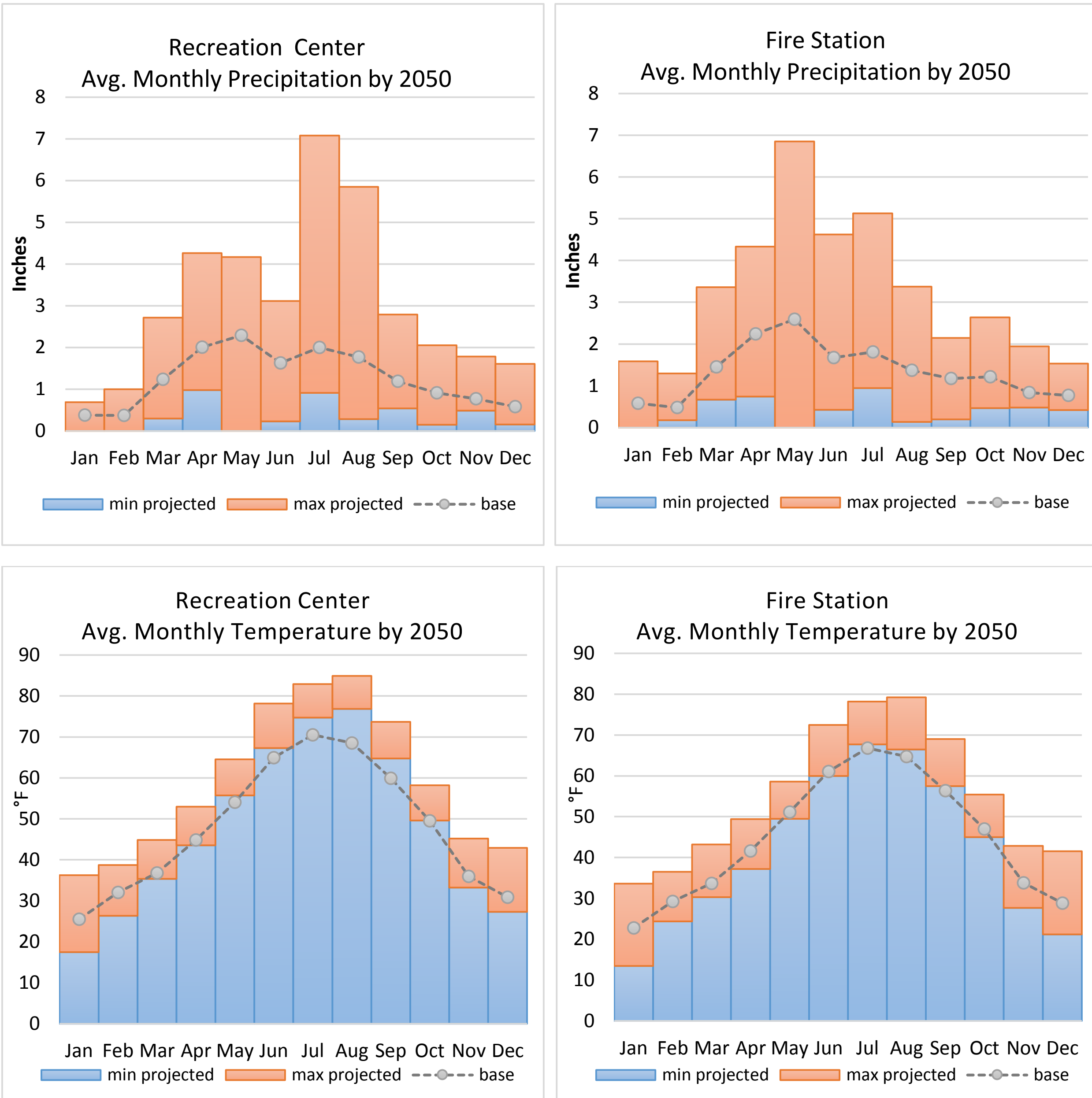


Figure 7: Average Projected Monthly Precipitation/Temperature by 2050. The GCMs have the capability to predict monthly temperature and precipitation through 2100. At the beginning of the report, the results of the climate projections are shown on a State-wide scale. The bar graphs above show the monthly projected climate data in 2050 for the two locations analyzed. Three values are graphed: the maximum and the minimum projected climate (among the 54 GCM) and the base climate (the base is equivalent to the historic recorded data). Temperature is predicted to increase a maximum of 10 degrees in every single month while the minimum predicted values are very similar to the historic data, with colder temperatures during winter season. No climate models predict lower temperature by 2050 during summer months. Precipitation has much more variability. The models project maximum increase of 2 inches in wetter months and a maximum decrease of 1.5 inches by 2050, as compared to historic data.

3.2 VULNERABILITY METHODOLOGY

The vulnerability analysis used in this study utilizes a stressor-response methodology which is based on the concept that specific materials and components will have specific responses to external stressors such as precipitation, flooding, and temperature. The methodology is not intended to be all-inclusive in terms of the broad set of factors that may impact infrastructure degradation such as land use, population movements, and localized geography. Rather, the functions provide a high-level indicator of the isolated effects that may occur given changes in climate factors. These effects are then applied to the individual infrastructure elements on an annual basis to determine specific vulnerabilities. The development of these factors is based on multiple inputs. A combination of material science reports, usage studies, case studies, and historic data were used to develop response functions for the infrastructure categories.

3.2.1 Building-Specific Vulnerability

The vulnerability of the buildings in this study is based on known construction techniques for non-wooden structures made of steel, masonry, and concrete. The vulnerability analysis evaluated climate impacts on internal building systems (mechanical and electrical equipment), external cladding and windows, as well as roofing and drainage systems. When evaluating the impacts to HVAC systems, it was assumed that if the airflow systems in the building need to be upgraded due to potential health implications, this upgrade would be undertaken. These incurred costs are determined based on changes to the Moisture Index which is defined by a Wetting Index (WI) and Drying Index (DI) to calculate the amount of moisture that a building will be subjected to under varying climate conditions. The table below summarizes the approximate cost of an HVAC upgrade and the projected decade an upgrade will be necessary based upon specific climate models, representing the 95th, 50th (Median), and 5th GCM models.

	Incurred Cost of HVAC system	Projected Decade of Cost Incurred		
		95th GCM	50th GCM	5th GCM
Recreation Center	$ 370,000	2040	2040	2085
Fire Station	$ 140,000	2025	2040	2055

Figure 8: Incurred Cost of HVAC system. Value and time of occurrence.

Below are two charts displaying the range of decades projected for HVAC upgrades by each of the 54 models. The recreation center sees most models projecting a necessary upgrade in 2040-2050, with a few models at the end of the century. The fire station sees a more variable distribution, with the earliest projections falling in the 2020 decade. The majority of models project a change necessary in 2040-2050 with approximately 10% of models falling in 2070-2080.

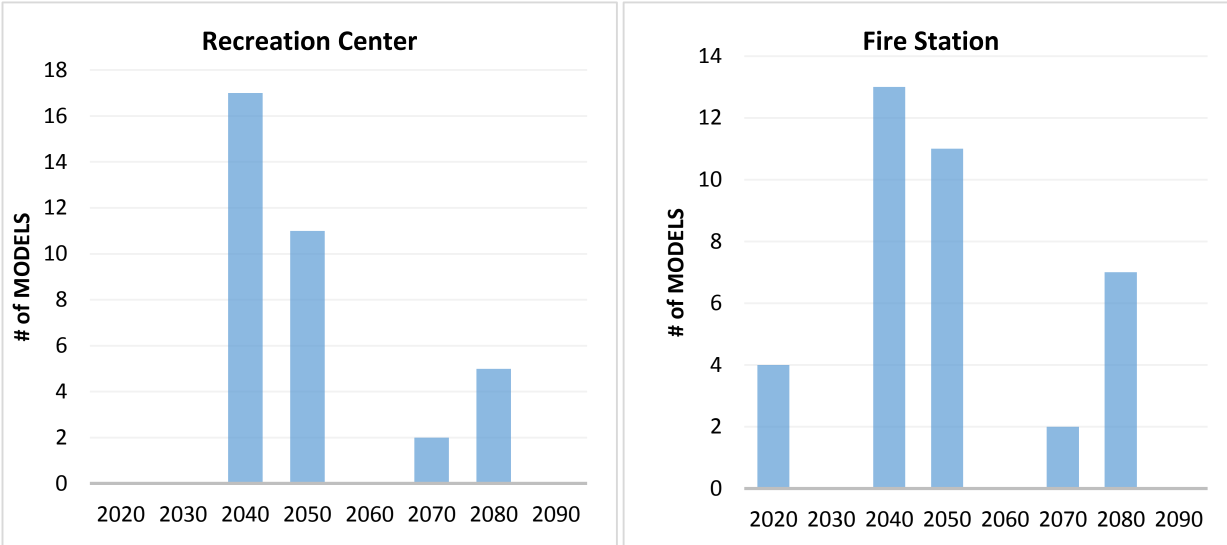


Figure 9: Incurred Cost Distribution by Decade. The histograms below show the potential distribution of the timing of the incurred costs as projected by the 54 GCMs. The incurred cost is the necessary cost of upgrading the HVAC system to hand increased air and humidity loads based upon occupancy and climate change. Most of the climate models predict that the incurred cost will happen between 2040 and 2050.

Although significant attention is given to impacts on HVAC systems, damage to roofing materials on flat-roofed (typically public) buildings such as hospitals and schools can be significant results of climate change. For these structures, roofing design, specifically drainage systems, is based on projected amounts of water that will exist on the roof from rain events. A failure to adequately size the roofing drain will result in water pooling on the roof. This pooling will result in failure of the roofing material as excessive moisture and standing water will ultimately lead to both material and sealant failure. When a greater precipitation drainage capacity is required due to changes in precipitation patterns, vulnerability is determined for the structure. Similar analysis is conducted on exterior cladding and windows to determine if changes in climate stressors will require additional maintenance to these features during the lifespan of the structure. In this analysis, there is no damage from precipitation on the roof of either building.

The last element of vulnerability of the two buildings in this study is the impact on energy consumption. Particularly, the impact on energy if no adaptation options are taken. These costs are based upon increased temperature and humidity.

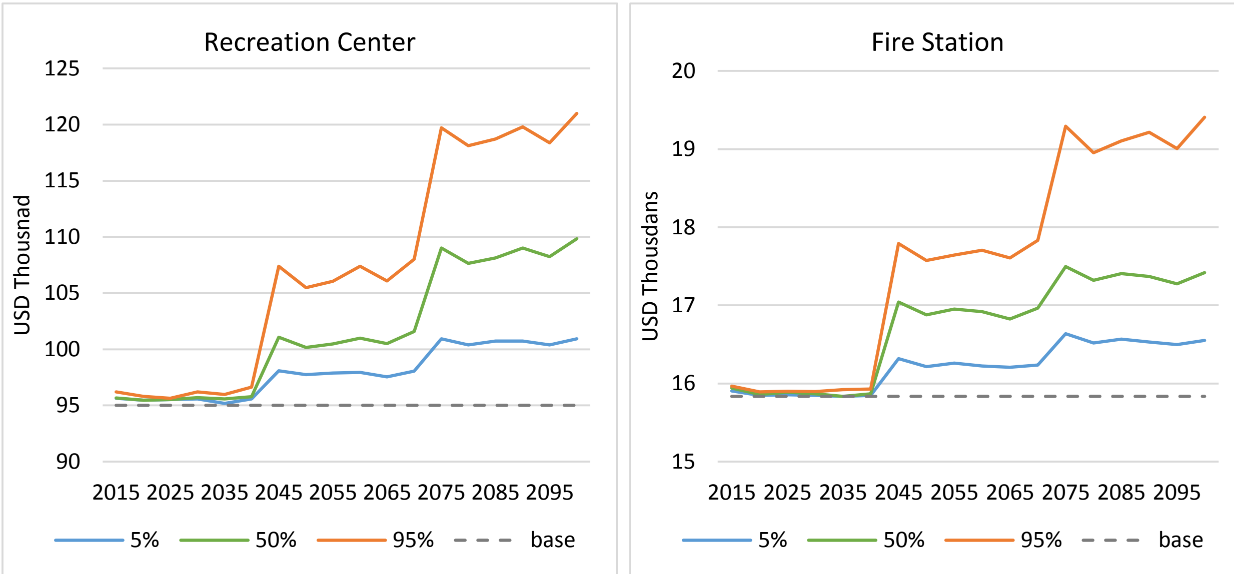


Figure 10: No Adaptation – Average Annual Energy Cost. The above figures show over time the annual energy cost of both buildings of study. The above line graph shows the projected energy consumption in each building for three different models, the 95%, 50% and 5% GCMs. The three projections are compared with the historic climate (dash line). Values follow the assumption that in both building the same interior temperature is required over time. The three climate models predict a peak on energy demand in 2045 and 2075. The rapid increase on maximum temperature will produce high energy consumption due to increased cooling needed during the summer season. The most severe climate model predicts increase of $ 2,000 of annual energy cost by 2050 for the Fire Station while predicts over $ 10,000 increase for the Recreation Center.

Additional data is available in supplemental files for each of the models and each of the years in the study.

3.3 Vulnerability Summary

In summary, the projects under review have vulnerability throughout the time period analyzed. Changes in humidity threaten the HVAC system function for both buildings with most models projecting changes around 2040-2050 that necessitate changes. Energy consumption is expected to increase, with significant increases projected around 2045 and 2075 due to increases in summer temperatures. Precipitation is variable in future climate models, but has no incremental impact on either building analyzed.

4 ADAPTATION ANALYSIS

Adaptation is the process of proactively modifying infrastructure to increase resiliency to projected climate impacts. Adapting to climate change in this study focuses on a "design strategy" approach that enhances design standards for infrastructure to reflect the risk of new and/or increased climate change stressors. In the modeling, adaptation proceeds on the basis of rules. Specifically, design approaches evolve as projected climate stressors indicate potential impacts that exceed current design parameters. For example, an increase in precipitation that is significant enough to require a change in drainage design results in a corresponding need for a design adaptation to mitigate this potential impact. This up-front adaptation results in a higher "up-front" cost to the project, but results in the elimination of climate-based maintenance costs to the project through the life-cycle of the project. In specific cases, this adaptation will also result in maintenance savings (operation savings) due to enhanced design and construction of the facility.

All adaptations included in this study reflect either standard engineering practices or specific adaptations provided for the project. Costs for these adaptations are based on historic cost data unless specific information is provided for the project. In this instance, specific cost data is utilized based where provided by the City.

For this analysis, adaptation focuses on upgrading the exterior windows to reduce energy consumption. The adaptation requires an investment cost, but it is repaid throughout the life-cycle of the windows by savings in energy costs.

4.1 ADAPTATION TIMELINE

The following timeline presents an adaptation timeline with potential adaptation options as well as the incurred costs necessitated by climate changes. The adaptation options are presented in two formats as follows:

- Necessary Adaptations – These adaptations occur when incurred adaptations are detected. Specifically, these adaptations come into play when HVAC adaptations are required due to health concerns. In these circumstances, the adaptation options are depicted as necessary at that time. Results are shown for the 95th, 50th, and 5th percentile GCM projections.
- Adaptation Considerations – The second form of adaptation are considerations for current or future adaptations. In these cases, vulnerability has been projected and IPSS is recommending that an adaptation be considered. The adaptations under consideration for this project are focused on energy savings through the installment of more energy efficient windows.

As illustrated, the adaptation timeline highlights when required and recommended adaptations are projected.

The timeline for the Wildland Fire Station highlights three main points:

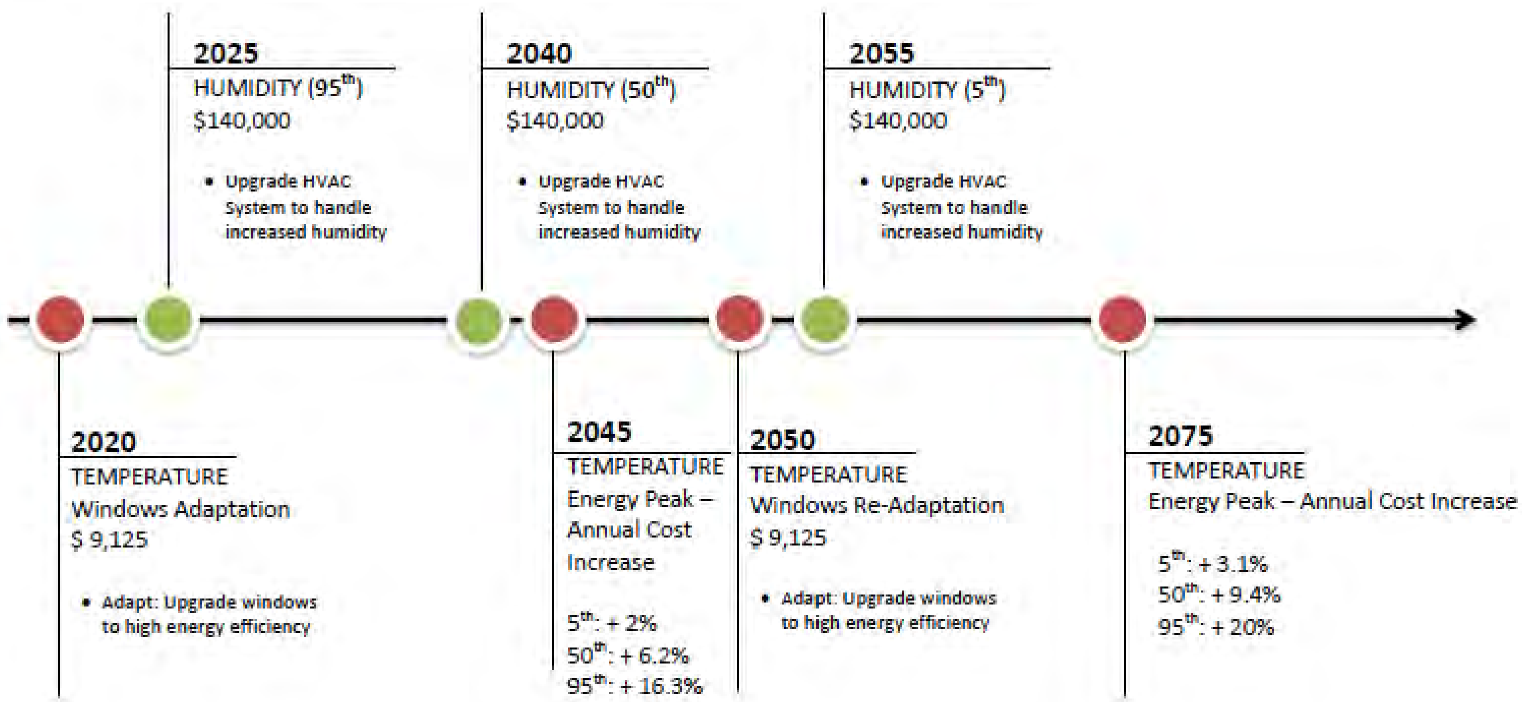
1. Changes in humidity will affect the HVAC system and capacity. An upgrade is projected to be necessary at 2025 (95th percentile climate model), 2040 (50th percentile climate model) or 2055 (5th percentile climate model). While these changes are spread over time, it is clear that by 2050

the HVAC system will need attention, if not before. This cost is estimated at $140,000 but may vary based upon specific design needs.

2. Changes in temperature will affect the energy consumption of buildings, specifically by increasing the need for air conditioning in the summer months. This will lead to an increased cost of between $13,000 - $14,000 annually between 2015-2050. Between 2051-2100, the annual cost increase is projected to be $42,000-$47,000. Cost differences are based upon the climate models, ranging from the 5th-95th percentile models.
3. Recommended adaptation includes upgrading all outer windows to higher energy efficient windows. This requires an investment cost of approximately $9,000 above the cost of current windows, but results in energy savings throughout the life-cycle (30 years) projected to significantly decrease energy spending enough to offset this investment cost. Reduced energy consumption also reduces greenhouse gas emissions. Adaptation savings (defined as the amount of money saved through reduced energy usage minus the cost of initial window upgrade investment) is projected at $32,000-$33,000 from 2015-2050 and $41,000-$43,000 from 2051 – 2100. Overall, adaptation can result in an energy savings of $73,000 - $79,000. Even if climate change does not occur, more energy efficient windows can save approximately $71,000 over this time frame.

Wildland Fire Station

	2020 2030 2040 2050	2050 2060 2070 2080	Life Time Energy Savings
Adapt	2020 – Windows Adaptation Investment: $9,125 Life-Cycle Energy Savings (2015 – 2050) 5^{th}: $32,000 50^{th}: $32,000 95^{th}: $33,000	2050 – Windows Adaptation Re-Investment: $9,125 Life-Cycle Energy Savings (2051 – 2100) 5^{th}: $ 41,000 50^{th}: $ 43,000 95^{th}: $ 42,000	5^{th}: $ 73,000 50^{th}: $ 75,000 95^{th}: $ 79,000 Base (no climate change): $ 71,000
No Adapt	Life-Cycle Energy Cost Increase (2015-2050): 5^{th}: $ 13,000 50^{th}: $ 14,000 95^{th}: $ 14,000	Life-Cycle Energy Cost Increase (2051 – 2100): 5^{th}: $ 42,000 50^{th}: $ 43,000 95^{th}: $ 47,000	

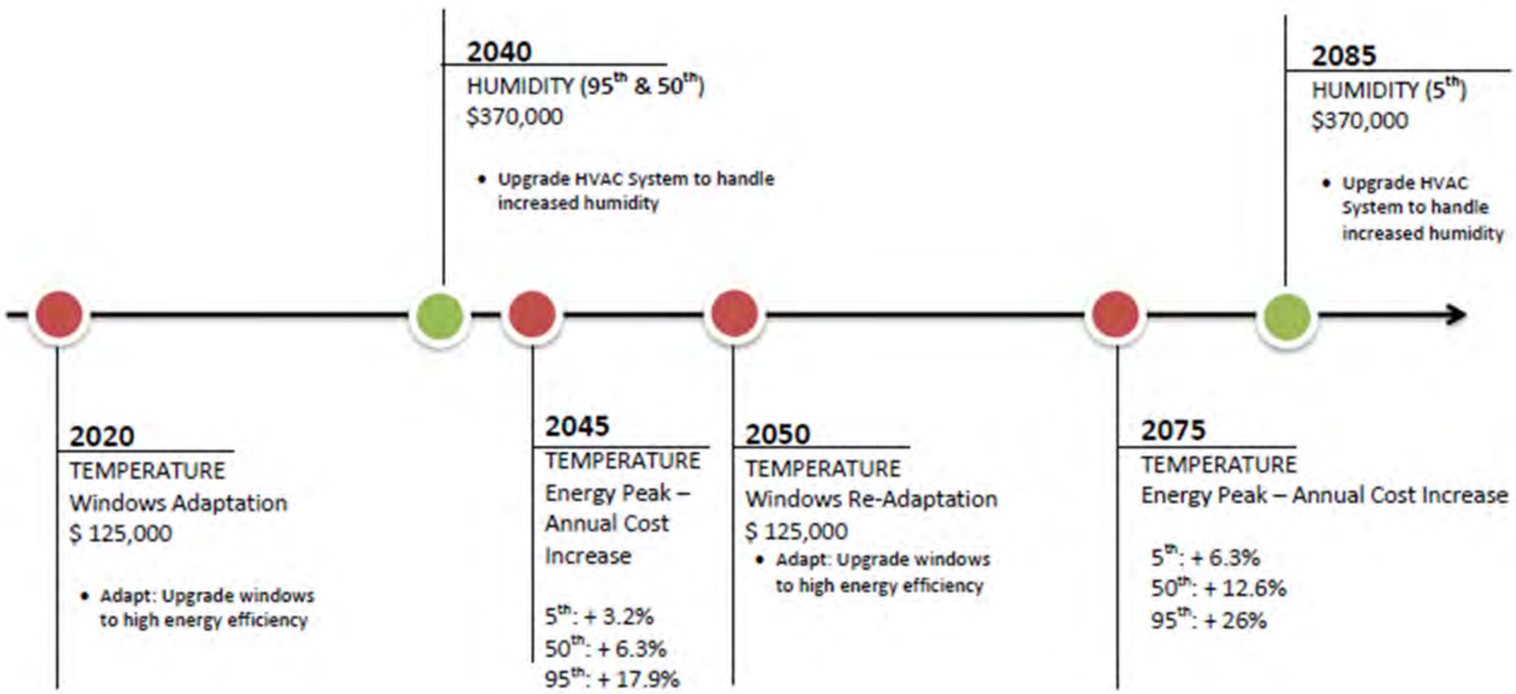


The timeline for the East Boulder Community Recreation Center highlights three main points:

1. Changes in humidity will affect the HVAC system and capacity. An upgrade is projected to be necessary at 2040 (95th and 50th percentile climate models) and 2085 (5th percentile climate model). While these changes do vary between the median and low end climate models, it is likely that by 2040 the HVAC system will need attention. This cost is estimated at $370,000 but may vary based upon specific design needs.
2. Changes in temperature will affect the energy consumption of buildings, specifically by increasing the need for air conditioning in the summer months. This will lead to an increased cost of between $136,000 - $146,000 annually between 2015-2050. Between 2051-2100, the annual cost increase is projected to be $498,000-$572,000. Cost differences are based upon the climate models, ranging from the 5th-95th percentile models.
3. Recommended adaptation includes upgrading all outer windows to higher energy efficient windows. This requires an investment cost of approximately $125,000 above the cost of current windows, but results in energy savings throughout the life-cycle (30 years) projected to significantly decrease energy spending enough to offset this investment cost. Reduced energy consumption also reduces greenhouse gas emissions. Adaptation savings (defined as the amount of money saved through reduced energy usage minus the cost of initial window upgrade investment) is projected at $384,000-$395,000 from 2015-2050 and $498,000-$571,000 from 2051 – 2100. Overall, adaptation can result in an energy savings of $882,000 - $966,000. Even if climate change does not occur, more energy efficient windows can save approximately $855,000 over this time frame.

East Boulder Community Recreation Center

	2020 2030 2040 2050	2060 2070 2080	Life Time Energy Savings
Adapt	**2020 – Windows Adaptation Investment: $125,000** **Life-Cycle Energy Savings (2015 – 2050)** 5^{th}: $ 384,000 50^{th}: $387,000 95^{th}: $395,000	**2050 – Windows Adaptation Re-Investment: $125,000** **Life-Cycle Energy Savings (2051 – 2100)** 5^{th}: $ 498,000 50^{th}: $ 528,000 95^{th}: $ 571,000	5^{th}: $ 882,000 50^{th}: $ 915,000 95^{th}: $ 966,000 Base (no climate change): $ 855,000
No Adapt	**Life-Cycle Energy Cost Increase (2015-2050):** 5^{th}: $ 136,000 50^{th}: $ 139,000 95^{th}: $ 146,000	**Life-Cycle Energy Cost Increase (2051 – 2100):** 5^{th}: $ 498,000 50^{th}: $ 528,000 95^{th}: $ 572,000	



4.2 ADAPTATION COSTS AND COMPARISONS

The table below summarizes the findings for the costs of adaptation of windows in each facility. Calculations are done based on the 95th, 50th, and 5th GCM projections and a baseline no climate change model is provided for comparison. The four categories of cost are; Adapt (includes the cost of upgrade windows and the cost of the projected energy consumption with the upgrade considered), No Adapt (includes the projected cost of energy consumption if buildings are not adapted), Adaptive Advantage (shows the differences between the Adapt and the No Adapt strategies) and Total Energy Saving (includes the saving on energy consumption if adaptation occurs, it does not include cost of adapt). These results show that significant energy savings can be had regardless of the projected future climate and even if no climate change occurs, the projected saving if adaptation is considered are significant. The saving are larger if more sever projections are considered with a maximum savings of $ 966,000 by 2100 if the 95th percentile projection occurs.

Cost Summary - in Thousands		Recreation Center					Fire Station			
		5%	50%	95%	Base - No Climate Change		5%	50%	95%	Base - No Climate Change
Adapt	2050	$ 3,708	$ 3,736	$ 3,801	$ 3,669		$ 625	$ 632	$ 640	$ 620
	2100	$ 8,188	$ 8,485	$ 8,945	$ 7,944		$ 1,405	$ 1,449	$ 1,522	$ 1,372
No Adapt	2050	$ 3,844	$ 3,875	$ 3,947	$ 3,800		$ 638	$ 646	$ 654	$ 633
	2100	$ 8,822	$ 9,152	$ 9,663	$ 8,550		$ 1,460	$ 1,506	$ 1,583	$ 1,425
Adaptive Advantage	2050	$ 149	$ 151	$ 155	$ 146		$ 14	$ 14	$ 15	$ 14
	2100	$ 633	$ 666	$ 717	$ 606		$ 55	$ 57	$ 61	$ 53
Total Energy Savings (Adapt)	2050	$ 384	$ 387	$ 395	$ 380		$ 32	$ 32	$ 33	$ 32
	2100	$ 882	$ 915	$ 966	$ 855		$ 73	$ 75	$ 79	$ 71

Figure 11: Cost Summary of Adapt and No Adapt strategies, Adaptive Advantage and Total Energy Saving from Adaptation. 95th, median and 5th percentile projections are compared to each other together with the base cost, assuming no climate change happens.

4.3 ADAPTATION ANALYSIS SUMMARY

In summary, the adaptation analysis demonstrates a savings in each of the percentile calculations once the initial investment is made in the facilities. It is important to take into account that initial investment is required to achieve the savings in the project. This total can be raised if new technologies are used for adaptations that go beyond standard adaptations.

Mandatory adaptations of the HVAC system are necessitated by the changing climate for both facilities. It is important to take a life-cycle cost perspective when evaluating different options, but this analysis shows that adaptation will occur, likely before 2050.

For energy savings, it is beneficial to invest in upgraded windows within the next few years to see maximum savings in energy consumption. The projected savings in energy consumption by adapting the building to climate change range from $ 880,000 to $ 966,000 for the Recreation Center by 2100. The projected saving in the Fire Station will be in the range of $ 73,000 - $ 79,000 by 2100 if adaptation is followed.

5 Risk Analysis

The uncertainty of future climate change scenarios creates an unanswerable scenario for all decision makers – namely, how does one know if a specific climate scenario or weather variation will actually occur. The answer to this by definition cannot be certain since it is impossible to have perfect foresight concerning weather and climate.

This section focuses on two central risks to the buildings analyzed in this scenario:

- A potential change in the ASHRAE Climate Zone definition based upon projected temperature, precipitation and humidity. A main unit for analysis is *cooling degree days* and *heating degree days*. Based upon these changes, risk is shown in terms of the entire range of models analyzed and the climate zone predicted at 2050. This is addressed in Section 5.1
- The probability of cost variation between different climate models: what happens if adaptation for one model is done, yet another climate occurs? This question of variability and probability is addressed in Section 5.2

5.1 ASHRAE Climate Zone Projections

A major source of risk and vulnerability in the two buildings is the potential changing climate zone according to the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) definition. ASHRAE's definition of climate zones is a critical component of building design and based upon climate conditions such as *heating degree days* and *cooling degree days.* For the two buildings analyzed, these projections can significantly alter the design and maintenance necessary for optimal building performance. The majority of models project Climate Zone 5. However, a majority of models predict the Fire Station will see Climate Zone 4 by the end of the century. The Recreation Center sees a range of models projecting Climate Zone 6 through 2060, with many models predicting Climate Zone 4 by the end of the century. The majority of models predict Climate Zone 5 for the Recreation Center throughout the time period analyzed.

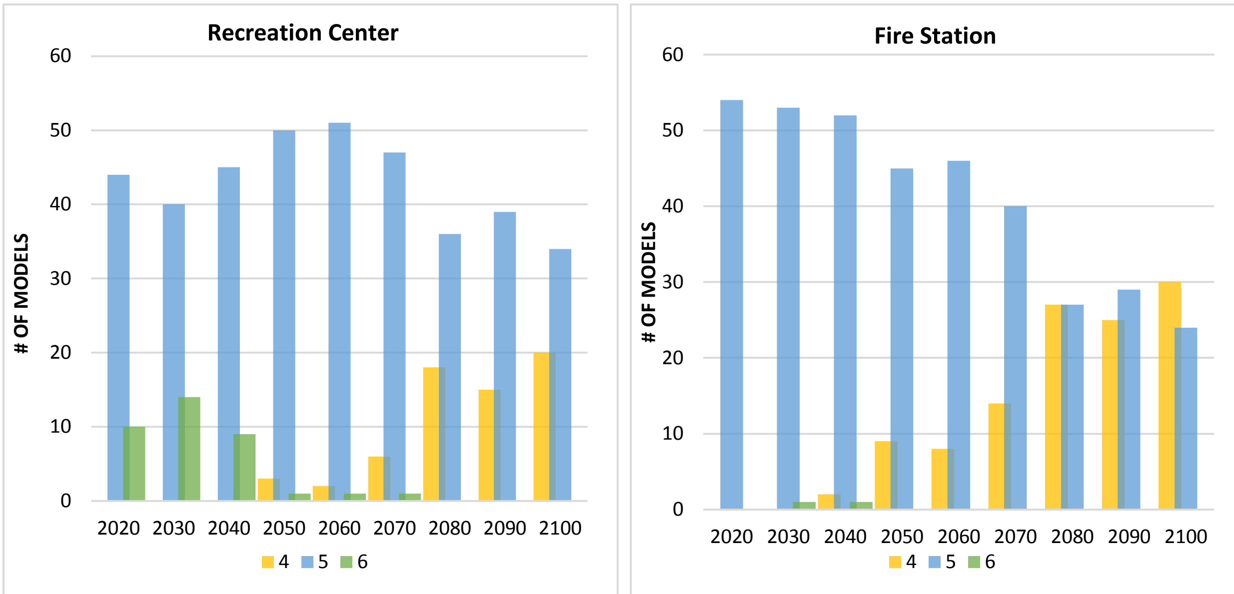


Figure 11: Projected ASHRAE Climate Zones. The two bar graphs above are histograms. Along the X- axis is a decadal time distribution from 2020-2100 indicating decadal time steps. The Y-axis shows the number of models (from the 54 GCMs) that project specific climate zone (following the definition of ASHRAE) in each of these decades. Changing ASHRAE Climate Zones could have a huge impact on the building design and construction and should be considered a critical part of risk analysis for both facilities. The Recreation Center will likely fall in the climate zone number 5 until 2070, as more than 40 models project this outcome. In the last 3 decades of the 21st century, a large number of models project a change from Zone 5 to Zone 4. The Fire Station sees more variability regarding climate zones. Through 2040, the building will be in the Climate Zone 5. Starting in 2050, the chances of changing to Climate Zone 4 increases substantially, reaching an equal likelihood of Climate Zones 5 and 4 by 2080. The potential for a future climate falling under ASHRAE Zone 4 is a possibility by mid-century.

5.2 Risk Island

The risk islands are a measurement that allows the comparison of risk and variability between different strategies (adapt and no adapt). The risk islands show the difference of what happens when you adapt to a specific climate model, yet a different one occurs. Each of the cells of the island is computed with the difference in cost between the expected outcome and the one that occurs. Then the differences are compared to the total expected outcome. If the difference represents less than 10% of the total cost, the cell is displayed in green. If the difference are between 10-20% of the total cost, the cell will be painted in yellow. Differences larger than 20% are shown in red. Green and yellow areas are denoted as a "safe zone," as the expected outcome is close enough to the actual occurring outcome. Climate models which have a majority of cells in green or yellow will imply less risk as the variability is lower. Climate models which have most of their cell in red, will be risk seeking decisions.

The risk islands for both buildings are created for the No Adapt and Adapt Strategy. The purpose of this risk analysis is evaluating which of the two strategies carries a potentially greater risk: which approach induces more variability and more possible regret?

As shown in the risk island for both buildings, if adaption strategy is chosen, the "safe zone" (green and yellow) is larger (by almost twice the "safe zone" in the no adapt strategy). For the Fire Station, if no adaption is chosen, only 26% of cells are in safer zones, while if adaptation occurs, 38% of the area is in green or yellow. For the Recreation Center the result are even more significant, with 26% and 48% of safer zone in the no adapt and adapt strategies respectively.

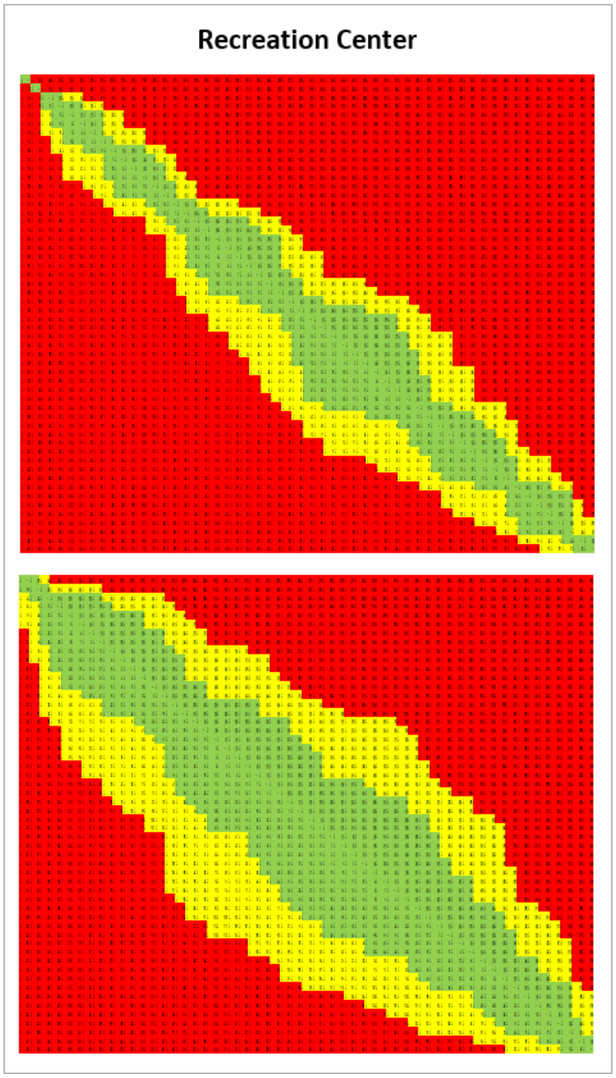


Figure 12: Risk Islands: No Adapt and Adapt Strategies by 2070. The 54 projected cost outcomes are compared to each other for both strategies; No Adapt and Adapt. Each of the cells in the above island is the cost difference between two different models projected cost. The diagonal represents each model compared to itself, so equals to zero. The green area shows cells where the differences are smaller than 10% of the projected total cost, the yellow are differences between 10-20% and red area value larger than 20% of the projected total cost. Strategies with most of their area in green and yellow will indicate less variability, as all the outcome will differ less than 20%. Strategies with most of the area in red will indicate high variability on the possible outcomes. The risk island for the No Adapt strategy is shown on the upper row while the risk island for the Adapt strategy is shown on lower row. The Adapt strategy indicated less variability than the no adapt strategy as the green and yellow area is almost double when comparing both strategies in the two buildings of study. More variability implies higher risk, as the difference between the potential outcomes is significantly larger. Then the risk of the No Adapt strategy is almost twice the risk of the Adapt strategy.

5.3 Additional Risk Perspectives

The current study does not include additional, non-climate, risk perspectives. However, additional risks including social risks, flooding risks, coastal risks, wildfire impact, and seismic overlays can all be included in future analyses.

5.4 Risk Analysis Summary

In summary, the risk analysis perspective focused on answering three key questions in this study as follows:

- What is the potential regret of adaptation if climate change does not occur?
- What is the risk choosing an adapt strategy?
- How much variability will there be on the impact of climate change in our infrastructure?

The Climate Zones projections show that significant likelihood of producing a shift on climate zones from 5 to 4 by the 2070. The chances are lower at first, but increase rapidly toward the end of the century. The variability is high and so our infrastructure should be prepared to be resilient to any of the possible outcomes.

Risk Islands help to understand risk and regret for each of two strategies consider in this study, No Adapt and Adapt. For both buildings choosing No Adaptation implies more risk and a higher possible regret, while Adaptation means a safer decision with lower risk and less regret.

6 SUMMARY

The current study presents the potential risk of climate change to the East Boulder Community Center and Wildland Fire Station in Boulder, Colorado. The study utilized the IPSS system to determine the cost impacts through 2100 on the two structures. The study utilized 54 IPCC-approved climate scenarios together with historic weather information to determine projected impacts. The combination of these projections with engineering-based impact scenarios provided the cost implications outlined in the study.

In summary, the study found that all scenarios indicate potential impacts to the buildings under consideration. Differences exist in terms of the magnitude of the impact and the timeframe in which the impacts will occur. However, when considering the appropriateness of an adaptation policy or a no adaptation policy, the scenarios indicate that by 2060, changes in precipitation, humidity, and temperature elements will impact the performance of the buildings' HVAC systems, energy use, and potentially have impacts on building design by a change in ASHRAE Climate Zone Definition.

This summary report includes: Highlights of findings from the analysis, changes in local climate affecting the buildings analyzed, increase in energy use if no adaptation action is taken, and a timeline for both buildings that highlights key future dates related to climate impact and costs.

According to the City of Boulder Climate Action Plan, there are six community strategies designed to reduce greenhouse gas emissions and become a more climate resilient city. More than 75% of Boulder's emissions come from energy use in buildings. The Climate Action Plan, combined with the recent naming of Boulder as one of the Rockefeller Foundations "100 Resilient Cities", provides an opportunity and imperative to consider the impacts of climate change on the buildings considered in this analysis and throughout the City. By understanding the impacts that a changing future climate will have on energy and operations, as well as design considerations, Boulder can take advantage of the challenge presented by climate change and turn it into an opportunity to create a more resilient and sustainable future.

6.1 HIGHLIGHTS OF ANALYSIS FINDINGS:

- Adaptation of windows by 2020 reduces energy costs significantly

East Boulder Community Recreation Center:

- By 2050, energy cost increases between 3 – 18% above current costs, depending on model.
- By 2075, energy costs increasing by 6-26% above current costs, depending on model.
- Increases in humidity necessitate HVAC updating as early as 2040 for the Recreation Center

Wildland Fire Station:

- By 2050, energy cost increases between 2-16% above current costs, depending on model.
- By 2075, energy cost increases between 3-20% above current costs, depending on model.
- Increases in humidity necessitate HVAC updating as early as 2025 for the Fire Station

6.2 ADDITIONAL ANALYSIS

The current test study indicates that vulnerabilities exist for the City of Boulder in public facilities. Additional analysis is recommended for both a broader set of infrastructure to determine similar vulnerabilities. Additionally, greater detail can be developed with additional information on specific infrastructure elements. We believe this will reveal similar opportunities for savings, resiliency, and sustainability in the City of Boulder infrastructure.

7 APPENDIX

7.1 COMMONLY USED ACRONYMS

IPCC – “Intergovernmental Panel on Climate Change” – The IPCC is the international governing body on climate science and the impacts of climate change. It is part of the United Nations.

IPSS – “Infrastructure Planning Support System” – IPSS is the modeling software used in this report. It uses 54 IPCC-approved GCM climate scenarios to model the impacts on infrastructure. It is designed and maintained by the Institute of Climate and Civil Systems.

GCM – “General Circulation Model”. This is the name for the climate models used in this analysis. 54 separate projections are utilized for this report. Commonly reported are the values from the projections representing the 95th, 50th (median) and 5th percentiles from among the range of 54.

HVAC – “Heating, ventilation, and air conditioning”. This stands for the air ventilation units used within buildings’ interior.

ADDENDUM:

THE IMPACT OF CLIMATE CHANGE:

VULNERABILITY, ADAPTATION AND RISK ANALYSIS

TWO BUILDINGS IN BOULDER, COLORADO

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1 PUBLIC BUILDING INFRASTRUCTURE MAP

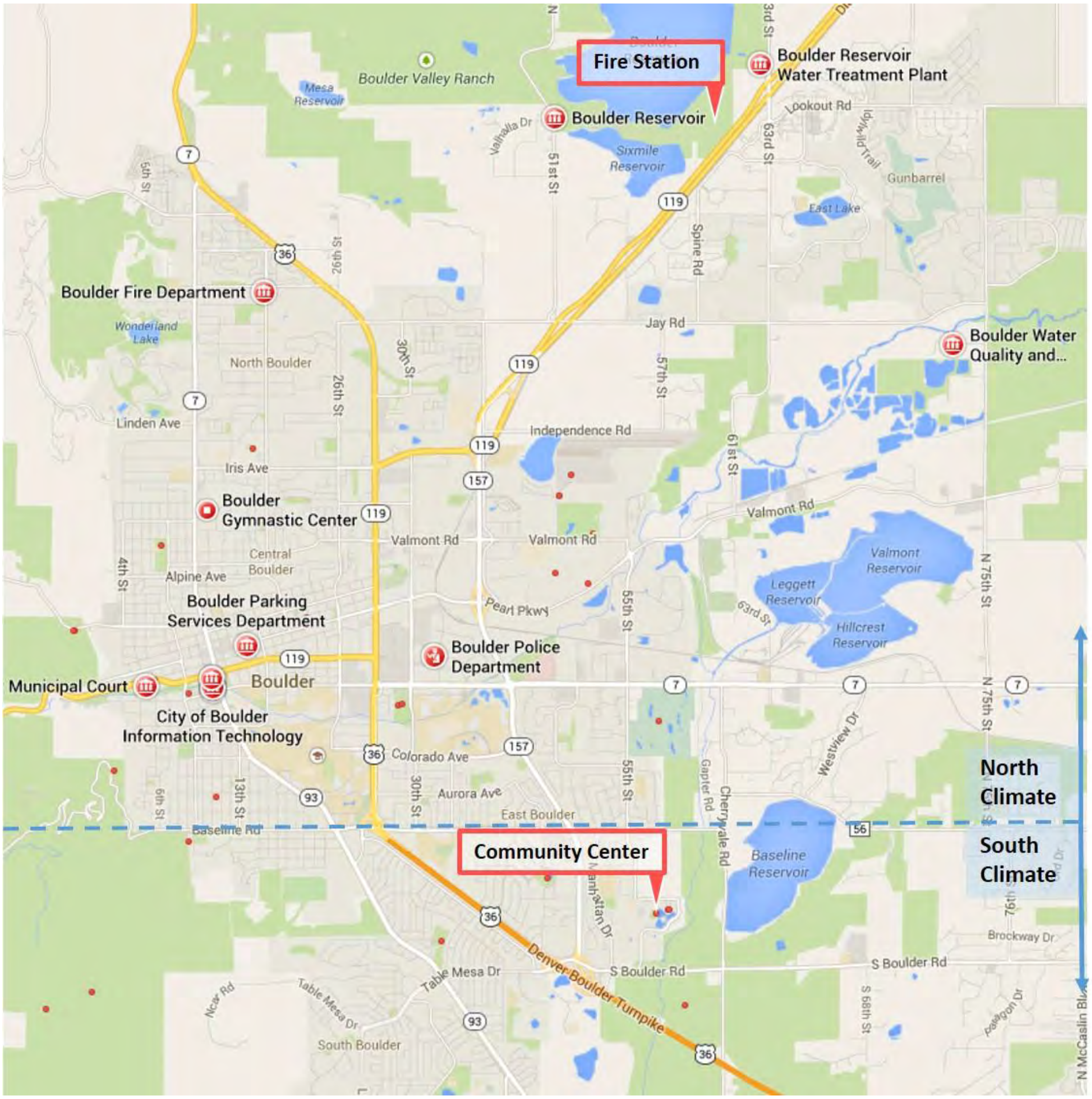

Figure 1: Public Building Infrastcucture Map.

There are more than 40 Public Buildings managed by the City of Boulder in two differentiated climate zones. Among the Buildings are City Offices, Transportation and Public Works Buildings, Fire Stations, Rec Centers, and Police Department Buildings. This report covers the East Boulder Community Recreation Center ("Community Center") in South Boulder and the Wildland Fire Station ("Fire Station") in North Boulder. The buildings are representative of the vulnerabilities that buildings in the City of Boulder are facing in that they:

1. Reside in the two spatial grids that comprise the City of Boulder in terms of historic weather data.
2. Have functions that require power consumption throughout the year on a consistent basis.
3. Are either in the design phase or are being prepared for a renovation.

2 Monthly Climate Projections

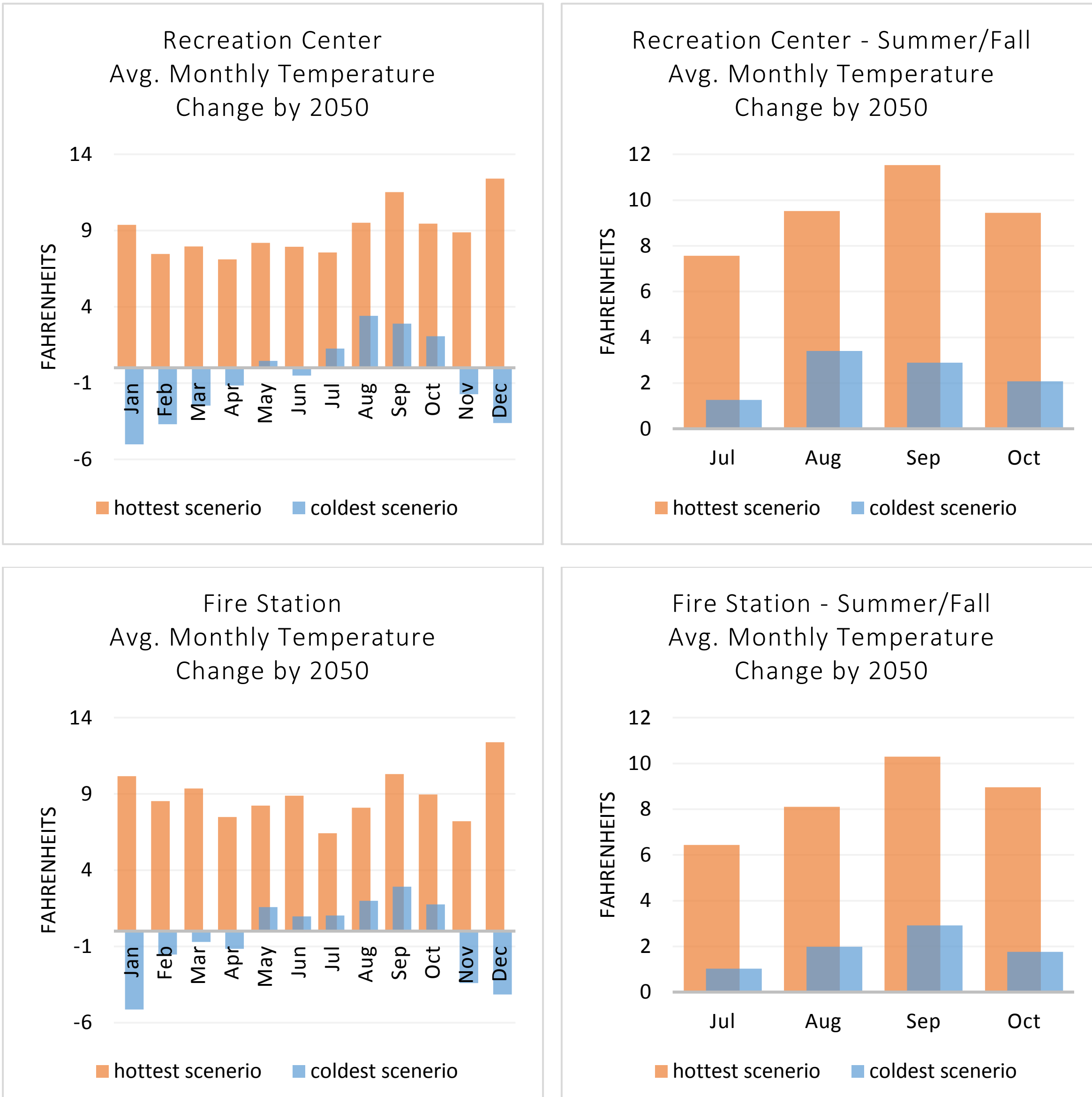

Figure 2: Average Monthly Temperature Change by 2050.

A key consideration for planning building maintenance will be the environmental conditions that the building will exist within. The City of Boulder will experience a significant change in environmental parameters through 2050. Of particular concern will be the increase in average temperature. As illustrated on the left of this graphic, year-round monthly average temperature in 2050 as estimated by the hottest and coldest model projections, show a potential increase of more than 6 degrees F throughout the year. The coldest scenario predicts colder winter months, but predicts more than a two degree increase in the summer.

The graph on the right highlights the increase in the summer months. The graphs shows a projected minimum increase of 1 – 3 degrees and a maximum increase of 6-11 degrees during this time period. This change is epecially significant in September where a 3 – 11 degree increase is projected which will impact every building within the City of Boulder.

3 ENERGY CONSUMPTION PROJECTIONS

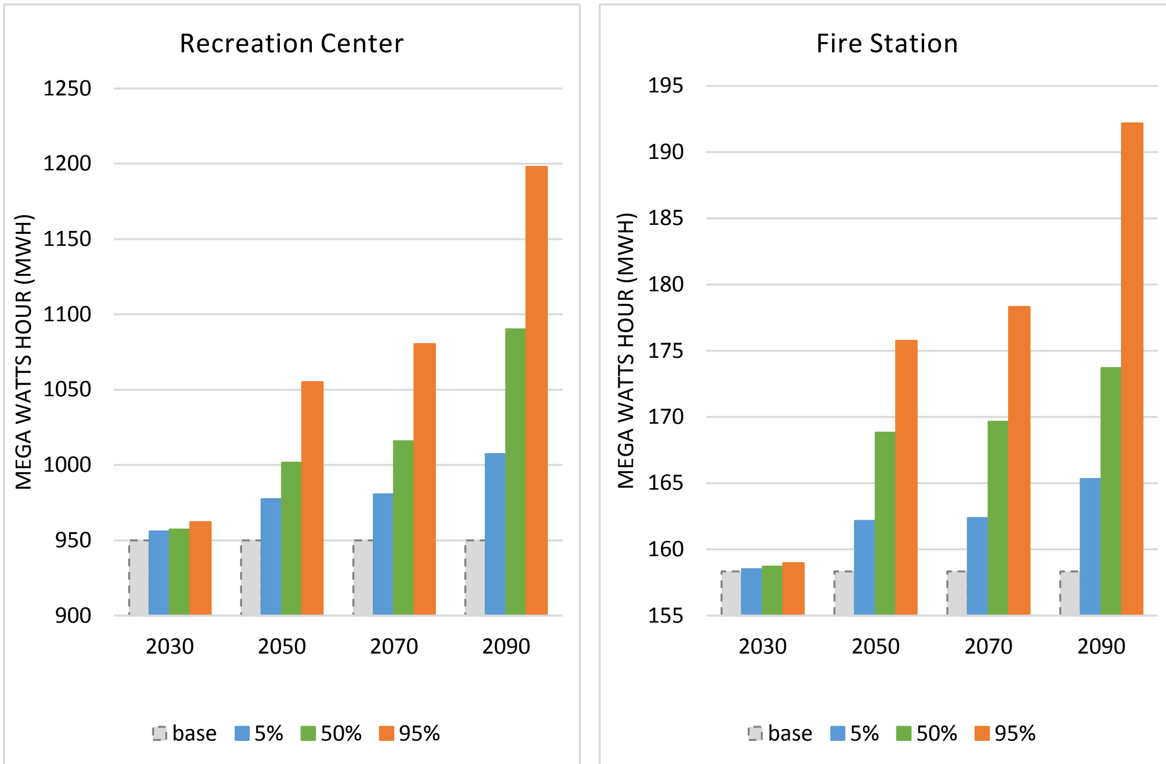

Figure 3: No Adapt Annual Energy Consumption.

Based on the projected temperature increases illustrated in the previous section, potential energy demand increases was calculated. As illustrated, the increase in megawatt hours required to address the increased average annual changes in daily temperature increases throughout the period of study. Using the 5%, 50% and 95% models, increases in demands continue throughout the period of study. On the Recreation Center, the minimal projections show energy increases in demands of up to 50 megwatt hours, while the 95^{th}% projections show an increase of 350 megawatt hours.

4 Energy Cost Projections by Cost Scenarios

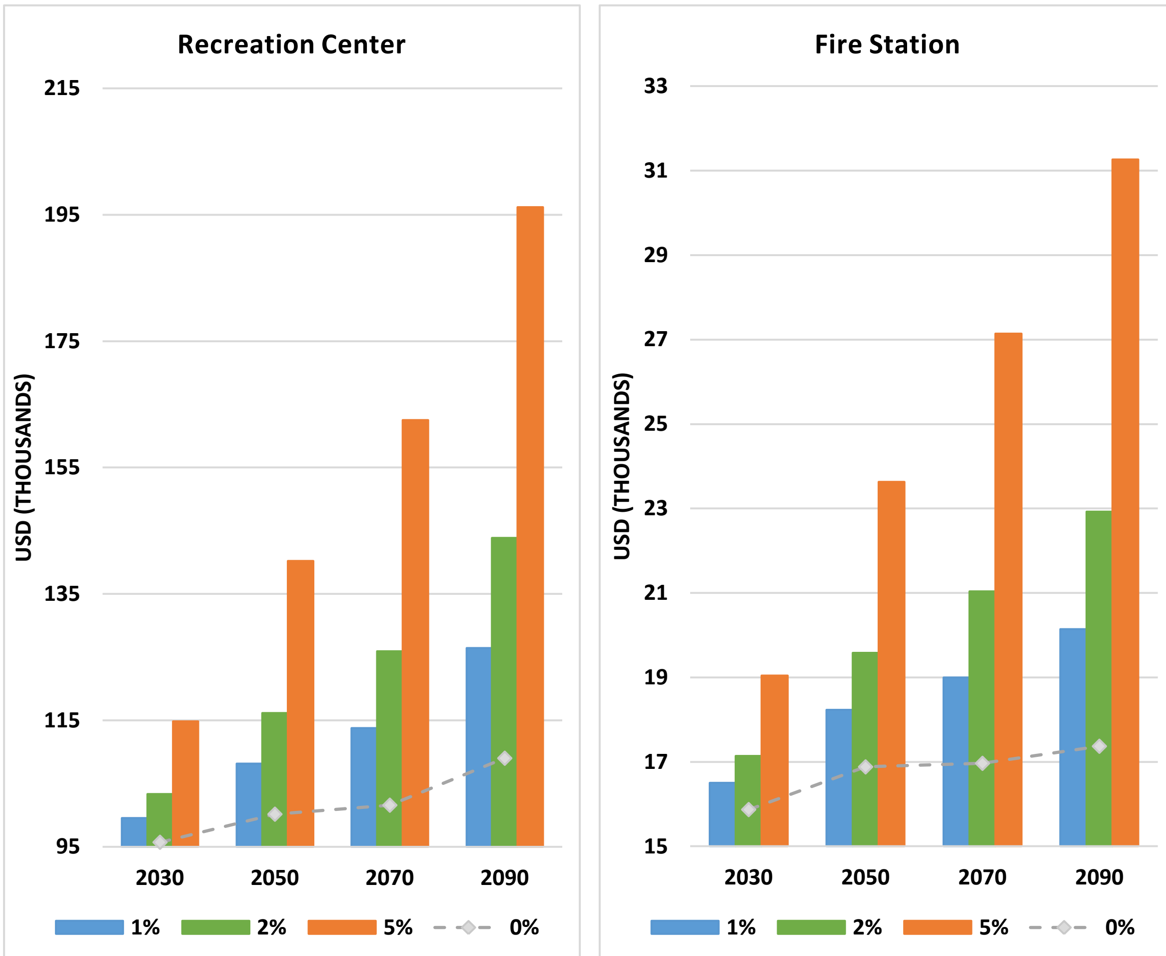

Figure 4: Annual Energy cost based on a 5-year cost increment. Cost projected by the median climate scenario.

Following the projected increases detailed in the previous section, a preliminary analysis of the potential energy cost increases were developed using the 50th percentile model. As illustrated in the graphs, four different cost increases are presented every twenty years. Once again, the trend of increasing each time interval is reflected in corresponding cost increases specifically generated from increased climate-induced demands.

5 OTHER VULNERABILITIES

5.1 FLOOD FREQUENCY

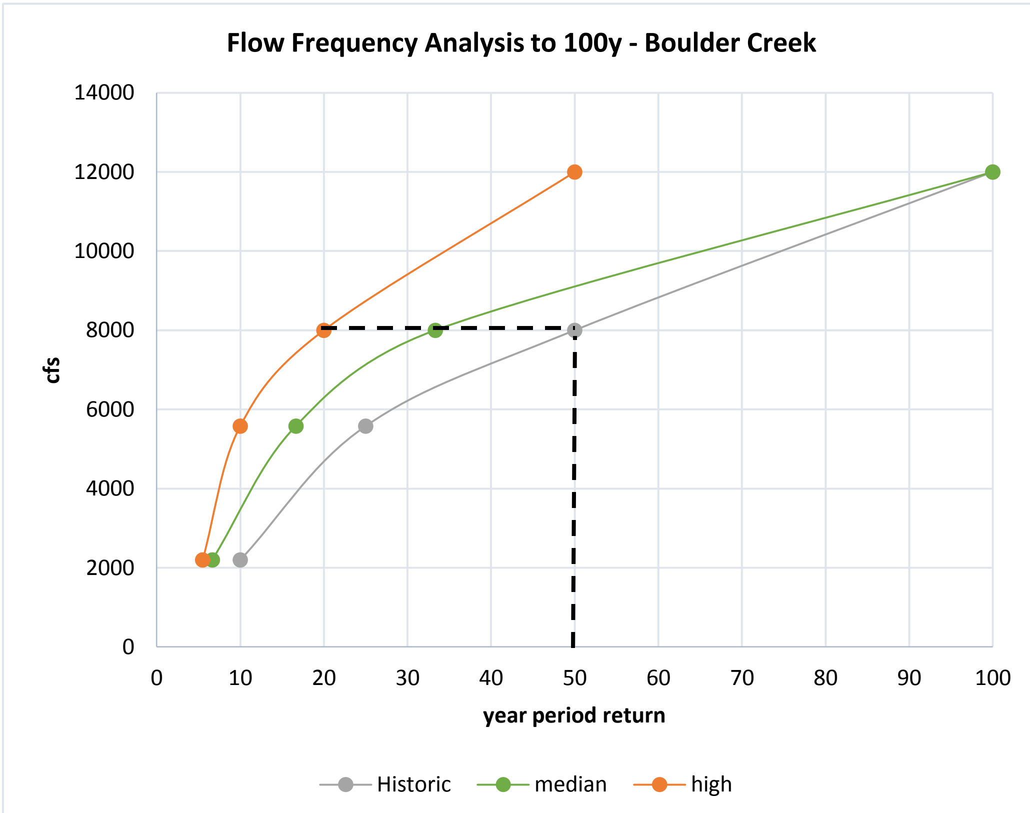

Figure 5: Flow Frequency Analysis, Boulder Creek Flow.

Although vulnerabilities directly related to temperature are the immediate focus of this study, it is important to recognize that aditional vulnerabilities exist to the City of Boulder infrastructure, both buildings and other components. For example, flooding is a primary historic concern in the City of Boulder. Using a rough calculation based on run-off calculations and return periods, the median and high end of the climate models are used to illustrate the change in flooding return periods. As illustrated, the median model indicates that the 100-year flood will remain the same, however the 50-year flood will become the norm for a 33-year flood. However, the high-end climate projections indicate that the 100-year flood will now be the norm for the 50-year flood and the 50-year flood will now be the norm for the 20-year flood. This has significant ramifications for road, bridge, and building design.

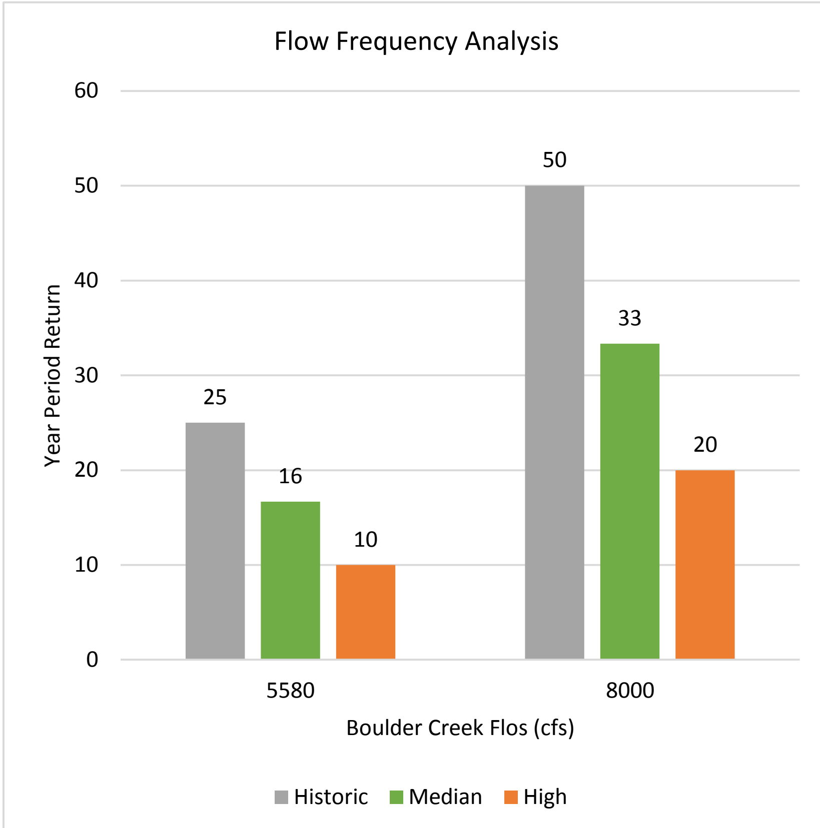

Figure 6: Flow Frequency Analysis. Change in frequency of two flooding event on Boulder Creek, 5580 and 8000 cfs.

5.2 TRANSPORTATION INFRASTRUCTURE

Although buildings are the primary focus of this initial study, the City of Boulder has significant vulnerability from climate projections in every infrastructure category. Beyond the flooding concerns highlighted above, the changes in precipitation and temperature will have notable impacts on road infrastructure. As an initial analysis of the overall Boulder County reveals below, the vulnerability of Boulder road inventory due to climate change leads to significant budgetary concerns. In this first assessment we have assumed a road inventory of 510 miles of paved road and 30 miles of unpaved road for the county of Boulder. The models predict an extra cost that range $1.25-1.75 M by 2030 in maintenance due to the severity of climate change. By 2070 the extra expenditures could range from $1.5-3 M.

These costs could be partially alleviated through proactive adaptation measures to key vulnerable routes. A full analysis includes a cost-benefit analysis based upon adaptation and no adaptation of all climate models available.

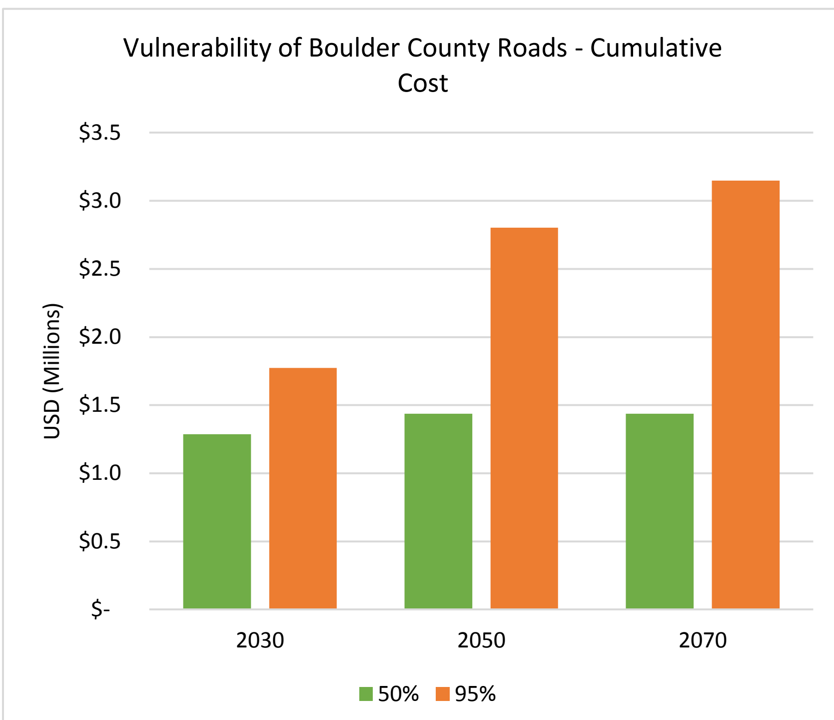

Figure 7: Vulnerability of Boulder County Roads – Cumulative Cost due to impact of climate change.