Economic Assessment of Heat in the Phoenix Metro Area

Acknowledgments

For this study, AECOM conducted the cost of inaction assessment and benefit-cost analysis, while The Nature Conservancy (TNC) provided funding, expertise and also convened an Advisory Committee comprised of academic, policy, and practitioner leaders. The Advisory Committee played a key role steering this effort by providing general guidance and advice to the AECOM consultants and TNC team, as well as identified existing data and data sources and reviewed findings. We wish to thank the Advisory Committee for their time and commitment to this effort and for their invaluable insight into how heat is experienced in the Phoenix Metro Area.

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Executive Summary

Extreme heat impacts people and businesses in the Phoenix Metro Area. With a changing climate and a growing and aging population, it is anticipated that the magnitude of these impacts will only increase in the future.

The goal of this report is to estimate the economic consequences to the Phoenix Metro Area from failing to take action against extreme heat and to evaluate the costs and benefits of solutions designed to address these consequences.

To do this, a climate conditions analysis was completed to understand how temperatures may change in the future. These projected climate conditions were compared to baseline conditions for the Phoenix Metro Area to estimate what the cost of inaction would be on five indicators of human and economic well-being: mortality, morbidity, labor productivity, infrastructure, and critical services with a focus on energy demand. After quantifying the cost of inaction, solutions selected for their importance and viability in the region were evaluated using benefit-cost analysis. Two solutions implementation scenarios were analyzed: implementing cool roofs throughout the Phoenix Metro Area and expanding the urban tree canopy. The overall study process is outlined below.

Figure 1. Study Process

Conditions Analysis

Develop **daily minimum and maximum temperatures** for a baseline time horizon and two projected time horizons and two emissions scenarios using ten global climate models (GCMs) selected for the Phoenix geography.

The following time horizons were used:
Baseline: 1986-2005
Near-term: 2020-2039
Mid-term: 2040-2059

Cost of Inaction

Estimate the **economic consequences** under a no-action scenario related to:

1) Mortality
2) Morbidity
3) Labor productivity
4) Roadway infrastructure
5) Energy demand

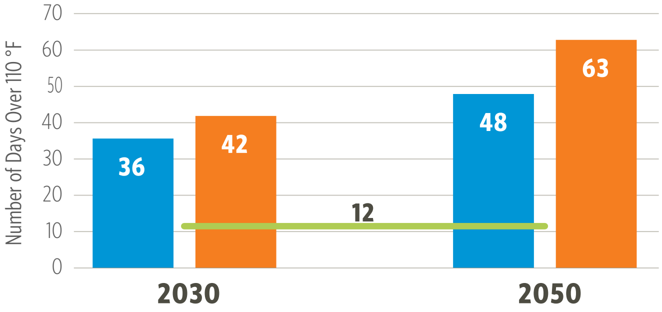
Benefit-Cost Analysis of Solutions

Estimate the **costs and benefits** of solutions:

1) Cool roofs
2) Tree canopy

The conditions analysis focused on two future timeframes (near-term, with a midpoint of 2030 and mid-term, with a midpoint of 2050) and two future emissions scenarios based on Representative Concentration Pathways (RCPs) recognized by the Intergovernmental Panel on Climate Change (IPCC): RCP 4.5, a medium stabilization scenario in which emissions are reduced and RCP 8.5, a high-emissions scenario. Near-term projections are for the years 2020-2039, centered around year 2030. Mid-term projections are for the years 2040-2059, centered around the year 2050. High-level results from the conditions analysis are shown below. Overall, the number of days over 110°F in 2030 and 2050 was estimated to be nearly three to five times the number of days over this threshold under baseline conditions.

Figure 2. Days with Max Temperature Over 110°F for 2030 and 2050



Notes: Results are shown as the mean of the results of ten GCMs for two emissions scenarios (RCP 4.5 and RCP 8.5). RCP 4.5 is shown in blue and RCP 8.5 is shown in orange. Results for 2030 represent annual averages for 2020-2039. Results for 2050 represent annual averages for 2040-2059. Baseline represents 1986-2005.

Table 1. Average Annual Economic Consequences of Inaction, 2020-2059

Indicator	Emissions Scenario RCP 4.5	Emissions Scenario RCP 8.5
Mortality	$898M	$1.2B
Morbidity	$4M	$5M
Labor Productivity	$855M	$964M
Roadway Infrastructure	$4M	$4M
Energy Demand	$116M	$116M
Total	**$1.9B**	**$2.3B**

Notes: Shown in $2021 as average annual consequences from 2020-2059 for RCP 4.5 and RCP 8.5 using mean of 10 GCMs. No financial discounting applied. Figures are rounded.

Based on the results from the climate conditions analysis, the cost of inaction was estimated for the two emissions scenarios, RCP 4.5 and RCP 8.5. Summary results are shown in Table 1 for each of the five monetized indicators. Overall, it was estimated that over the period of analysis (2020-2059), not taking action to mitigate against high heat would result in an average annual economic loss of $1.9 billion and $2.3 billion for RCP 4.5 and RCP 8.5, respectively.

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Table 2. Benefit-Cost Analysis Results for Solution Scenarios Analyzed

Solution Scenarios	Benefits	Costs	Benefit-Cost Ratio
100% Cool Roofs	$7.9B	$1.5B	5.24
25% Urban Tree Canopy	$15.3B	$4.0B	3.78

Notes: Shown in $2021 over the period of analysis (2020-2059) with a 5% discount rate. Figures are rounded. Note that the benefits quantified in this analysis are limited to the five indicators included in the cost of inaction, and do not include other potential benefits that these solutions may offer – such as aesthetic benefits, air quality improvements, greenhouse gas emissions reductions, or reduced stormwater runoff.

The two solutions selected were assessed for their costs and for the benefits they provide in terms of reducing the above economic consequences. It was found that adoption of cool roofs in 100% of buildings in the Phoenix Metro Area by 2050 and increasing urban tree canopy cover to 25% by 2050 both result in a positive benefit-cost ratio. In other words, the benefits these solutions offer related to mitigating heat impacts outweigh the costs to implement these solutions. For 100% cool roof implementation, the benefit-cost ratio was found to be 5.24. For 25% urban tree canopy, the benefit-cost ratio was found to be 3.78. Note that the benefits analyzed in this study are a subset of potential benefits offered by these solutions. For example, urban tree canopy can provide other important benefits – such as aesthetic benefits, reduction in air quality pollution (e.g., ozone), sequestration of carbon dioxide, or reduced stormwater runoff – that are not monetized here (Western Resource Advocates, 2009).

This study finds that not taking action to defend against heat in the Phoenix Metro Area may result in significant economic consequences. Furthermore, for the selected solutions scenarios, the benefits are estimated to outweigh the costs. As Phoenix continues to urbanize and its population expands, the benefits of adapting to extreme heat may only increase, as will the consequences of inaction. To implement the ambitious solution scenarios and realize the associated benefits, both the public and private sector will need to play an active role. Collective action is critical towards ensuring that the Phoenix Metro Area not only continues to be an attractive place to live and do business, but that it supports a resilient economy and way of life that allows all communities to thrive.

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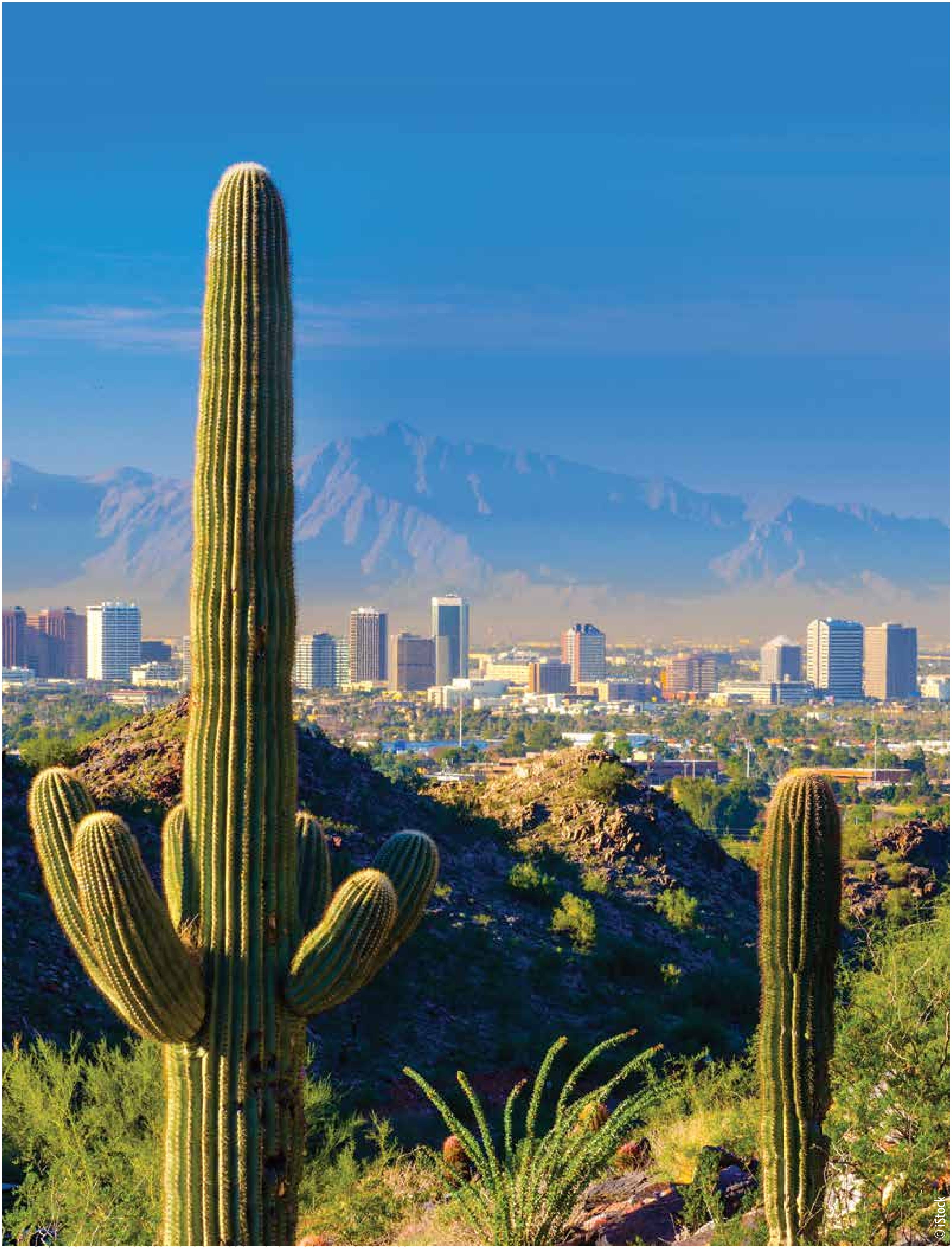

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Background

In the Phoenix Metro Area, extreme heat impacts residents and businesses. With a changing climate and a growing and aging population, it is anticipated that the magnitude of these impacts will only increase in the future.

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The goal of this report is to estimate the economic consequences to the Phoenix Metro Area from failing to take action against extreme heat and to evaluate the costs and benefits of solutions designed to address these consequences. The study includes: an overview of the Phoenix Metro Area demographics and built environment, a climate conditions analysis, a cost of inaction assessment, and a benefit-cost analysis of two solutions selected for their importance and viability in the region, as well as qualitative discussion of other potential heat adaptation measures. More information on methods and analysis is provided in Appendix A through Appendix D. Key study concepts and assumptions are noted below.

Key Study Concepts & Assumptions

A high-level overview of key concepts and assumptions for the analysis are noted below. More information can be found in Appendix A.

Baseline Conditions & Future Time Horizons: Unless otherwise noted, costs are presented relative to impacts estimated for a baseline period between 1986 and 2005. Near-term projections are for the years 2020-2039, centered around year 2030. Mid-term projections are for the years 2040-2059, centered around the year 2050.

Demographics & Economic Conditions: Economic consequence analyses typically follow one of two approaches: 1) analysis that is relative to current economic conditions and population or 2) analysis that accounts for how the structure of the economy and population could evolve and evaluates the losses relative to a hypothetical future. This analysis follows the first approach, though for certain indicators, as applicable, results are also shown adjusted for future conditions (e.g., projected employment).

Study Geography: This study focuses on the urbanized areas of Maricopa County, commonly referenced throughout the report as the Phoenix Metro Area, though also incorporates information on demographics and the economy at the county-level, as noted.

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Application of Data: Information presented here on the costs of inaction and the costs and the benefits of solutions are based primarily on existing published information. Data that reflects local conditions was prioritized. When local information was limited, studies from other geographies were reviewed and applied.

Annual Temperature Variability: Evaluating average impacts over 20-year intervals is useful to account for the variable nature of the environment. At the same time, however, such an approach may not capture acute heat events with significant economic outcomes. For example, in 2020 alone, Phoenix broke its record for the number of days over 100°F (145 days). While this study does not present results for specific short-term event periods, care was taken to preserve annual temperature variability throughout the analysis: temperature projections are based on a shift of real historical data, cost of inaction analyses are conducted for ten Global Climate Models (GCMs)[1] to present a range of results, and averaging across time periods was conducted at the end of all processing so as to maintain the peaks and valleys of daily temperature variability.[2]

Air Quality Projection Limitations - Heat and Ozone & Heat and Particulate Matter: In addition to Phoenix's high temperatures, it is also one of the worst metropolitan areas in the country for ozone and particulate pollution. Phoenix was ranked fifth for high ozone days out of 226 metropolitan areas in the 2021 the American Lung Association's "State of the Air" report by the American Lung Association and eighth out of 199 metropolitan areas for annual particle pollution (American Lung Association, 2021). Parts of Maricopa County are considered an ozone nonattainment and PM_{10} (particulate matter pollution) nonattainment area, as classified by the National Ambient Air Quality Standard designation (Arizona Department of Environmental Quality, n.d.). There are a number of uncertainties, however, related to projecting air quality. As such, air quality has not been projected as part of this study. For more information, however, on how air quality – and more specifically ozone and particulate matter – might affect each indicator, refer to Appendix C.

Financial Discounting: In general, discount rates are applied in benefit-cost analysis to account for the social "opportunity cost", or the time value of money,

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[1] A global climate model (GCM) is a complex mathematical representation of the major climate system components (atmosphere, land surface, ocean, and sea ice), and their interactions. For more information, please see: https://www.gfdl.noaa.gov/climate-modeling/

[2] The shift of real historical data to project future temperatures was dependent on an averaging process of the Localized Constructed Analogs (LOCA) downscaling projections relative to the observed data for LOCA calibration, which could introduce some smoothing.

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allowing for a comparison of future costs and benefits in present dollars. Per economic theory, the value of future benefits is assumed to be lower than the value of present benefits. For a subset of result reporting, in tables where costs and benefits are shown together, figures are presented with financial discounting applied. A 5% real discount rate was used in this analysis when evaluating the cost-benefit of the solutions. Table notes identify if values have been discounted.

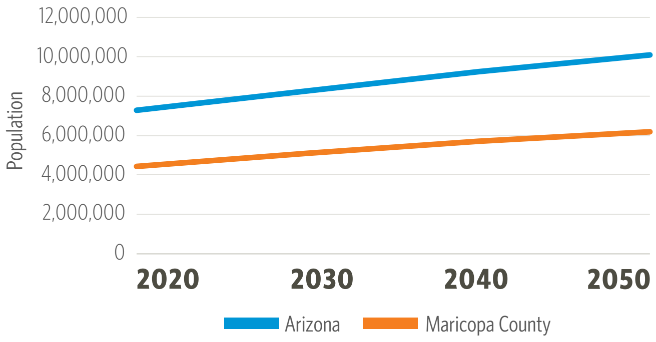
Escalation & Inflation: No general price inflation or cost escalation is included in the analysis. It is possible that construction costs and economic growth in the study area may outpace general price inflation in the future. Introducing escalation considerations extending out through the analysis period (ending in 2059) would require making assumptions that would include a high level of uncertainty.

Unquantified Benefits: The benefits quantified in the benefit-cost analysis relate to the adaptation measures' impact on decreasing heat and the resulting effect to the five indicators monetized in the cost of inaction analysis. Other benefits that could result from the chosen solutions, such as increased property value from expanding the tree canopy, have not been monetized due to resource limitations, lack of conclusive evidence on the relationships between the intervention and the benefit, data constraints, and/or potential double counting of benefits.

Demographics & Urbanization

While this study is based on current demographic conditions, the growing and aging population, as well as the rate of urbanization, may exacerbate economic consequences. Maricopa County has been among the fastest growing counties in the nation in recent decades. Between 1980 and 2020, the county's population grew from 1.5 million to 4.5 million (U.S. Census Bureau, 2021). The county is projected to grow to 5.1 million and 6.2 million by 2030 and 2050 respectively – more than double the rate of average U.S. population growth over the same period (Maricopa Association of Governments, 2021). The population density of Maricopa County is anticipated to increase 40%, from 481 people per square mile to 672 per square mile by 2050 (Maricopa Association of Governments, 2021).

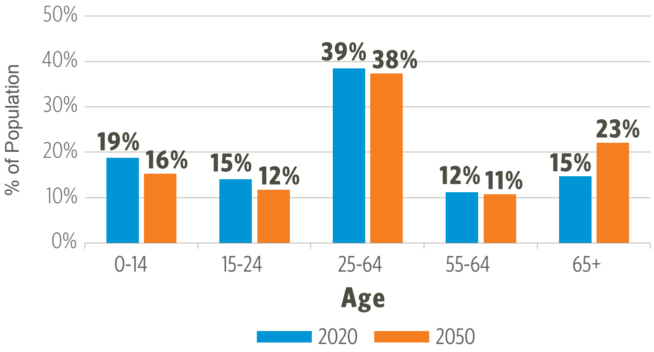
Figure 3. Projected Population Growth Through 2050



Notes: Arizona Commerce Authority

Between 2020 and 2050, forecasts indicate that the share of the county's population over 65 will increase from 15% in 2020 to 19% in 2030 and nearly 23% in 2050. The ratio of Maricopa County's working age population to dependents (children and retirees) will gradually fall over this period, from 1.9 in 2020 to 1.7 in 2030 and 1.6 in 2050, requiring municipalities to fund increasing infrastructure, climate adaption, and social services needs from a smaller relative base of market income.

Figure 4. Maricopa County's Population by Age Group 2020 and 2050, Projected



Notes: Arizona Commerce Authority

These changes in population will likely change the landscape of Maricopa County, including its built environment (e.g., roads, buildings, and other community assets). Maricopa Association of Governments (MAG) – representing municipalities in and around the county – projects some places will see much larger increases in density than others. Furthermore, based on general plans for the region, there is an anticipated significant shift from vacant land to single-family residential homes. If projections on land use changes manifest, even to some degree as projected, it is likely to cause increased urbanization.

Increased urbanization can exacerbate the Urban Heat Island (UHI) effect already observed and increase the number of people exposed to heat island effects. Prior studies have found that the UHI contributes about 15 +/- 5% of total climate variability across urban and rural areas in the Phoenix metropolitan area (Merkin, 2004).[3] New development has intensified and expanded the geographic areas that experience extreme temperatures, driven primarily by increases in nighttime temperatures (Hondula, Georgescu, & Balling Jr., 2014). Increased nighttime

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[3] Urban Heat Island Effect refers to the concept that urban areas experience warmer temperatures than surrounding rural areas as structures such as buildings, roads, and infrastructure, absorb and re-emit heat.

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temperatures, or the lack of cool periods, has significant consequences – such as making it more challenging for bodies to reset after hot days, thus worsening the impacts of heat on the human population. Maricopa County's projected increased urbanization could exacerbate extreme heat, particularly in areas with limited vegetation and high volumes of pavement or other hard surfaces (Guirguis, Gershunov, Cayan, & Pierce, 2018). It is important to note that the extent to which urbanization will impact urban heat has high uncertainty and relates in large part to the type of new development. For example, single-family residential homes may have landscaping while other uses, such as industrial, may not. The extent of UHI will depend in large part on the type of surface conversion and how much dark impervious surface increases. One study found that while urbanization increased the urban heat island effect in Phoenix since 2000, areas that had increased vegetation cover had greater cooling effect than the heating effect of urbanization (Wang, Myint, Wang, & Song, 2016).

It is important to note that heat is experienced differently across Maricopa County's geographies and populations. In addition to the difference in temperature between urban and rural places, subareas of urban communities can experience heat differently depending on tree canopy, concrete density, presence of water, and other features of the built environment. For example, temperatures can differ by 13°F between neighborhoods that are less than two miles apart depending on the presence of urban heat mitigation assets in each neighborhood (Harlan, Brazel, Prashad, Stefanov, & Larissa, 2006). The physical attributes of the built environment contributing to the highest temperatures, including minimal open space and vegetation, are more prevalent in communities with higher poverty rates and lower levels of educational attainment (McDonald, et al., 2021; Harlan, Brazel, Prashad, Stefanov, & Larissa, 2006). These communities not only face higher temperatures, but also have fewer resources to cope – or less adaptive capacity to respond to the impacts of rising temperatures. There are numerous community determinants of heat vulnerability. Examples include: access to air conditioning (AC), percent of the population below the poverty line, percent of the population living alone, percent of the population 65 years or older, and percent of the population of a race other than white (Reid, et al., 2009).

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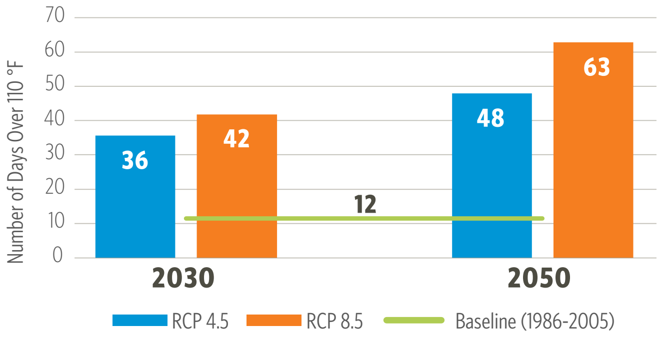
Climate Conditions Analysis

A climate conditions analysis was conducted to understand how temperatures will change in the Phoenix Metro Area. Without taking action, the climate in the Phoenix Metro Area is projected to get hotter.

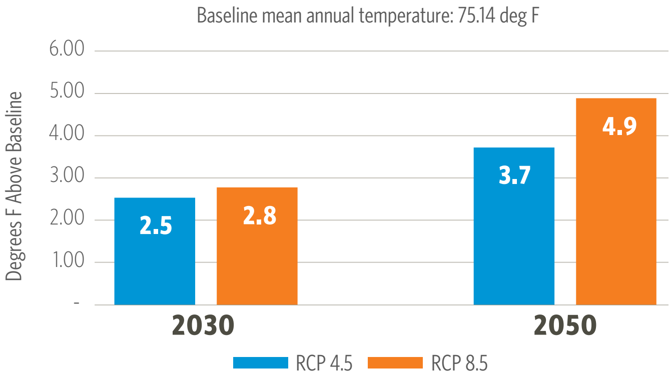
Highlights of the climate conditions analysis results are below, with more information provided in Appendix B. Under baseline conditions (1986-2005), the average number days over 110°F (not inclusive of 110°F) was 12. The average annual projected days over this threshold are anticipated to be between three and five times this amount for 2030 and 2050 based on the average of the ten GCMs modeled, as shown in Figure 5. Overall, annual mean temperatures are expected to increase as well. As shown in Figure 6, annual average mean temperatures are anticipated to increase between 2.5°F and 4.9°F relative to the 1986-2005 baseline depending on the timeframe and emissions scenario and based on the average of the ten GCMs modeled.

Figure 5. Days with Max Temperature Over 110°F for 2030 and 2050



Notes: Results are shown as the mean of the results of ten GCMs for two emissions scenarios (RCP 4.5 and RCP 8.5). Representative Concentration Pathways (RCPs) are scenarios recognized by the Intergovernmental Panel on Climate Change (IPCC) to depict different emission, concentration, and land-use trajectories. Results for 2030 represent annual averages for 2020-2039. Results for 2050 represent annual averages for 2040-2059. Baseline represents 1986-2005.

Figure 6. Annual Average Mean Temperature shown as Degrees Above Baseline



Notes: Results are shown as the mean of the results of ten GCMs for two emissions scenarios (RCP 4.5 and RCP 8.5). Results for 2030 represent annual averages for 2020-2039. Results for 2050 represent annual averages for 2040-2059. Baseline represents 1986-2005.

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Cost of Inaction

Understanding the economic costs of inaction is important for both understanding how heat will impact people and the economy and for evaluating potential mitigation and adaptation strategies.

Five indicators were selected for monetization for the cost of inaction analysis based on input from the Advisory Committee along with a literature review on the impacts of heat on the economy.[4] Table 3 lists the cost of inaction indicators selected, along with a brief description of the impact of heat on each indicator and the relevant metric(s) for monetization. Many other indicators were considered, including tourism impacts, transportation disruption, and quality of life, but, for various reasons, were not selected for monetization for this study.[5] A subset of these non-monetized indicators are discussed qualitatively.

Table 3. Monetized Cost of Inaction Indicators

Indicators	Description	Costed Metrics
Mortality	Extreme heat is correlated with an increase in mortality, which results from direct heat exposure (leading to heat stroke, dehydration, etc.) and other health impacts (such as cardiovascular or renal) that are triggered by extreme heat.	Value of a statistical life (VSL)[6]
Morbidity	Extreme heat is correlated with a range of negative (but non-life-threatening) health impacts that require medical attention. These impacts are either directly heat-related or triggered by extreme heat.	Patient healthcare costs associated with treating heat-related morbidity
Labor productivity impacts	Extreme heat can lead to declining labor productivity due to its impacts on physical and mental functions. Declining productivity can lead to fewer hours worked and reduced output.	Losses to Gross Regional Product (GRP)
Shortened life cycle of roadway infrastructure	Heat impacts transportation infrastructure in various ways. It can cause roadways to buckle, rut, and crack and these impacts lead to increased maintenance costs, context-sensitive design, and more frequent replacement (or reduced asset life).	Maintenance, replacement, and improvement costs of roadway pavement
Critical services: energy demand	Higher temperatures can lead to increased demand for energy due to air conditioning usage. This demand can in turn have ripple effects, such as the need for greater load capacity. The focus here is on the impact to the customer – higher electricity bills as a result of hotter summer months.	Costs associated with increased electric consumption

[4] While air quality was considered in the indicator selection phase, heat was determined to be the primary driver in the prioritization process.

[5] Other indicators vetted for consideration include restricted recreation, transit delays and cancellations, increased demand for electricity, agriculture yields, tourism impacts, real estate values, cost of regulations and compliance, school attendance, and quality of life.

[6] VSL is a value used to quantify the benefit of avoiding death and is based on estimates of how much people are willing to pay in order to reduce their risk of fatality.

Table 4. Average Annual Economic Consequences of Inaction, 2020-2059

Results	Annual Consequences, RCP 4.5	Annual Consequences, RCP 8.5
Mortality	$898,000,000	$1,178,400,000
Morbidity	$3,500,000	$4,600,000
Labor Productivity	$855,200,000	$964,000,000
Roadway Infrastructure	$4,100,000	$4,100,000
Energy	$115,800,000	$115,800,000
TOTAL	**$1,876,600,000**	**$2,266,900,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021 over the period of analysis (2020-2059) using mean of 10 GCMs. No financial discounting applied

While heat affects many aspects of daily living, impacts manifest differently across geographic, economic, and social contexts. Given that the Southwest region of the United States regularly experiences higher temperatures, Phoenix's infrastructure and economy is already more acclimatized to extreme heat than cities in more temperate or cooler climates. While that does not make Phoenix fully resistant to the impacts of heat, impacts are experienced in different ways and at higher temperature thresholds. As such, the methods used in the cost of inaction apply localized relationships between temperature and expected impacts whenever feasible. For example, the relationship between mortality and temperature is based on Sky Harbor temperatures and Maricopa County Department of Public Health data (Maricopa County Public Health Department, 2018). Additionally, when available and credible, regional costs were applied. More detail on the background of each indicator, the methods applied, and the results, is provided in Appendix C. High-level results over the full period of analysis (2020-2059) are shown below for each of the five cost of inaction indicators.

Non-Monetized Impacts

There are other potential costs of extreme heat that are more difficult to quantify, such as diminished business attraction and the decision of local businesses to relocate if the burden of extreme heat becomes too high for their operations or for the well-being of their employees. In addition to extreme heat, the urban heat island effect can contribute to air pollution levels, which is another factor that can influence business attraction and retention. These costs can manifest in various ways, some of which are described below.

Impacts to Retail and Tourism

Extreme heat reduces traffic at retail centers, particularly in areas dependent on outdoor dining and shopping malls. Tourism is also vulnerable to heat impacts that reduce demand for outdoor activities during months of high temperatures and limits feasibility of events such as sporting events and festivals. Environmental conditions have been shown to impact consumer spending as well. A study examined the influence of increased air pollution on consumer spending in Spain, finding that on days when ozone pollution was 10% worse than usual there was a $30-$48 million reduction in consumer spending, and on days when particulate matter pollution was 10% worse than usual, there was a $23-$35 million reduction in spending (Weinfurter, 2017).

Real Estate Development

Extreme heat can make real estate development more expensive due to increased costs of building construction and maintenance. Additional capital costs and the limitations on labor productivity and capacity in the face of extreme heat adds new challenges and expenses to the construction process (Urban Land Institute, 2019). Additionally, threats of future climate impacts have been shown to impact property values, especially as those risks become more evident and recognized (McKinsey & Company, 2020). However, there are benefits of incorporating heat resilience in future development and building upgrades and the failure to adopt heat resilient design may ultimately be more costly in the long run. Examples of these benefits include reduced stress on public infrastructure, increased occupant comfort and site visitation, enhanced asset value, lower vacancy rates, long-term utility cost savings due to lower energy use, and avoidance of replacing heat-damaged materials (Urban Land Institute, 2019).

Regulatory Requirements

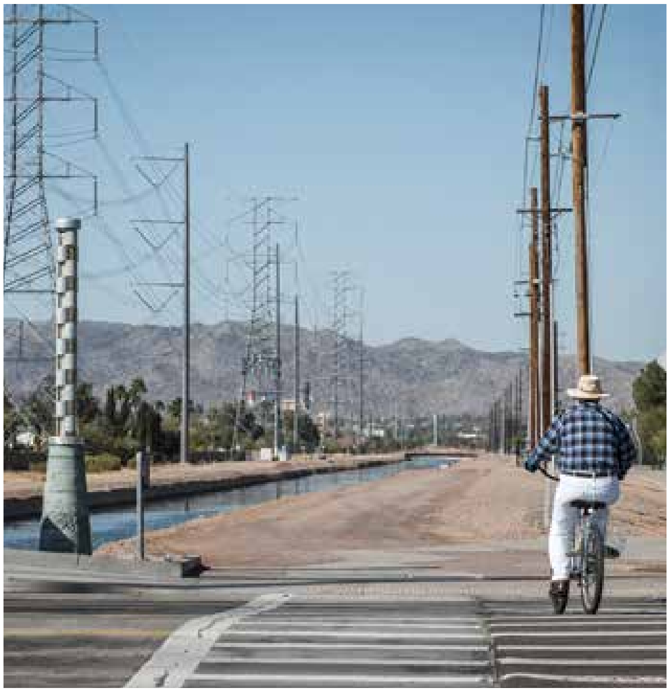
Businesses in regulated industries may be less likely to locate to areas struggling to meet air quality standards. As parts of Maricopa County are considered an ozone and PM_{10} nonattainment area, this could deter businesses from locating or staying in the area. A study by the RAND Corporation found that firms which emit these targeted pollutants have been less likely to locate to nonattainment areas due to additional costs of using extra technology to monitor emissions as well as lengthy permitting processes (Nataraj, Chari, Richardson, & Willis, 2013).

Quality of Life

Extreme heat can significantly impact the quality of life for residents, particularly in dense neighborhoods that lack vegetation (Gabriel, Mattey, & Wascher, 2003). Several studies have also found strong correlations between air quality and quality of life indices, some suggesting that environment tends to be among the highest quality of life considerations (Banzhaf & Walsh, 2008). Maintaining a qualified labor pipeline is important for businesses, so any decline in livability and the decision of residents to migrate would present a challenge for companies that rely on a growing and skilled workforce (Nataraj, Chari, Richardson, & Willis, 2013).

Extreme heat can damage the infrastructure relied on to provide reliable regional transportation for traded goods and commuters. Asphalt and pavement may prematurely become damaged as a result of heat, while rail tracks can also become less reliable. Air transportation is also susceptible to cargo restrictions, delays, or cancellation because of heat. For industries that rely heavily on transit infrastructure such as warehousing and distribution, delays and unreliability can lead to loss of business.

Extreme heat can also influence the degree to which people go outdoors for physical exercise and recreation activities, which can have adverse impacts on public health and can be associated with a decline in spending (Arizona State University, 2015; Tucker & Gilliland, 2007). Moreover, Askew and Bowker (2018) project that in the Rocky Mountain Region, which includes the Phoenix Metro Area, per-capita outdoor recreation participation in fishing, motorized water activities, hunting, primitive area use, and horseback riding on trails will decline through 2060 due in part to an increase in extreme heat. The impacts of decreased spending in recreation could have larger business impacts in rural communities, where outdoor recreation comprises a larger share of the economy (Askew & Bowker, 2018).



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Heat Solutions

There are a number of solutions that can alleviate the impacts related to extreme heat in urban environments, including gray infrastructure and nature-based solutions.

Some common examples of heat solutions include cool roofs, green roofs, reflective pavements, and urban trees and reforestation (Kats & Glassbrook, 2018). To select the most appropriate and effective solutions for the Phoenix Metro Area, the Advisory Committee was surveyed for input. Based on this, the research team completed a supplementary literature review to prioritize measures that have published evidence and adequate documentation on the relationship of their implementation and effectiveness on mitigating urban heat in the Phoenix Metro Area. Ultimately, two heat solutions were selected for benefit-cost analysis: cool roofs and urban tree canopy. A number of other adaptation measures were considered and their qualitative findings are discussed below.

Cool Roofs & Urban Tree Canopy Benefit-Cost Analysis

Cool roofs are those that have been designed to reflect more sunlight and absorb less heat than standard roofs. Made of highly reflective paint, sheet covering, or reflective tiles or shingles, cool roofs have the potential to reduce near-surface temperature and reduce energy demand for interior cooling, resulting in reduced greenhouse gas emissions, and improved air quality, among other benefits. Urban trees and urban tree canopy provide shade and transpire water, which have the effect of reducing urban surface and air temperature, improving thermal comfort, and reducing energy demand for interior cooling, greenhouse gas emissions, and stormwater runoff (Kats & Glassbrook, 2018). The solutions analyzed, and the implementation scenarios modeled for the benefit-cost analysis, are summarized in Table 5. These are high-level scenarios that are not based on specific site considerations. As such, the costs and benefits presented here for the adaptation measures may be higher or lower depending on more site specific context. For more information on the methods and results for the selected adaptation measures and benefit-cost analysis, refer to Appendix D.

For the cool roof adaptation measure, it was assumed that 100% of roofs would have cool roof materials by 2050, resulting in a daytime temperature reduction of 1.08°F with a reduction of 0.36°F by 2030 for partial

Table 5. Solution Scenarios Selected for Benefit-Cost Analysis (BCA)

Solution	Implementation Scenario Modeled
Cool Roofs	Replace existing roofs with light-colored materials with high solar reflectance. Assumes 100% cool roof implementation in Maricopa County by 2050.
Urban Tree Canopy	Plant drought-resistant trees in urbanized areas. Assumes 25% urban tree canopy coverage in Maricopa County by 2050.

Figure 7. Benefits Estimated for Solutions

▲ Global Cooling
📍 Site Specific

	Mortality	Morbidity	Labor productivity impacts	Life cycle impacts of roadway infrastructure	Critical Services: Energy Demand
Cool Roofs	▲	▲	▲	▲	▲ 📍
Tree Canopy	▲	▲	▲	▲	▲ 📍

implementation (Salamanca F., Georgescu, Mahalov, Moustaoui, & Martilli, 2016). Urban tree canopy coverage was assumed to reach 25% by 2050. The baseline urban tree canopy for Maricopa County was assumed to be just over 6% and cooling benefits were based on the net change in temperature from baseline conditions resulting in a daytime temperature reduction of 3.14°F by 2050, and a reduction of 1.44°F by 2030 for partial implementation (Department of Forestry and Fire Management, 2021; McDonald R. I., Kroeger, Zhang, & Hamel, 2019).[7]

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Benefits were calculated by quantifying two key benefit categories: site specific and global cooling benefits related to the five indicators evaluated in the cost of inaction analysis. For site specific benefits, cool roofs and trees may reduce temperatures within structures by reflecting heat or absorbing and/or shading the sun and result in reduced AC usage and direct energy savings to business and residents (Salamanca F., Georgescu, Mahalov, Moustaoui, & Martilli, 2016; McPherson & Rowntree, 1993; Kats & Glassbrook, 2018; McDonald, Kroeger, Boucher, Longzhu, & Salem, 2016; Stone, et al., 2014). Global cooling benefits refer to the economic and social impacts brought about by overall temperature reductions related to the widespread implementation of cool roofs and urban tree canopy. To capture the global cooling benefits, the models developed for the cost of inaction were re-run with the assumed overall temperature reductions, allowing for an estimated calculation of the impacts under new, reduced temperatures for both RCP scenarios and timeframes (2030 and 2050). These impacts were then compared to the cost of inaction results, allowing for an understanding of the net benefits. Figure 7 outlines the benefits estimated for each of the solutions.

In addition to these quantified benefits, cool roofs and urban tree canopy have been associated with several other benefits that have not been quantified in this study. Such benefits include: improved

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[7] The temperature reduction relationship was assumed to be linear and based on relationship of 2.5% canopy coverage resulting in 0.23°C temperature change for the City of Phoenix (McDonald R. I., Kroeger, Zhang, & Hamel, 2019).

Figure 8. Benefit-Cost Ratio Calculation

Benefits ÷ **Costs** X **Time** = **Benefit-Cost Ratio**

Benefits

Global Cooling: Reduce the temperature and re-run the cost of inaction indicators with new temperature projections. Subtract residual impacts from no action results to estimate benefits.

\+

Site Specific: Estimate reduction in energy demand.

÷

Costs

Capital & O&M costs*

*Note costs are premium above an assumed baseline

X

Time

Consider implementation timing and calculate cumulative costs and benefits, accounting for life cycles & financial discounting over period of analysis.

=

Benefit-Cost Ratio

thermal comfort for pedestrians and cyclists, carbon sequestration, improved air quality and associated benefits such as public health improvements and decreased expenditures on air pollution mitigation, reduction in electricity blackouts as a result of lower energy consumption, increased real estate value, water conservation, reduced stormwater runoff, and job creation and other economic development features (Trees Matter, 2021; McDonald, Kroeger, Boucher, Longzhu, & Salem, 2016; Kats & Glassbrook, 2018; Rhodium Group, LLC, 2014; Salamanca F., Georgescu, Mahalov, & Moustaoui, 2015).

Costs were estimated for each of the two strategies for both capital and maintenance expenditures. For cool roofs, the costs for implementation represent the cost premium relative to conventional roofing material. All costs were then compared to benefits in the benefit-cost analysis. The benefit-cost analysis accounts for the phasing of the solution's implementation, the recurrence of the annual benefits and maintenance costs, and the time value of money over the full period of analysis (2020-2059) to ultimately develop a benefit-cost ratio for each adaptation measure (Figure 8).

Table 6. Benefit-Cost Analysis Results for Solutions Analyzed

Solution	Benefits	Costs	Benefit-Cost Ratio
100% Cool Roofs	$7.9B	$1.5B	5.24
25% Urban Tree Canopy	$15.3B	$4.0B	3.78

Notes: Shown in $2021 over the period of analysis (2020-2059) with a 5% discount rate. Figures are rounded. Note that the benefits quantified in this analysis are limited to the five indicators included in the cost of inaction, and do not include other potential benefits that these adaptation measures may offer – such as aesthetic benefits, air quality improvements, greenhouse gas emissions reductions, or reduced stormwater runoff.

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Results over the full period of analysis (2020-2059) with a 5% discount rate are shown in Table 6. Overall, the benefits for the two modeled solution scenarios outweigh the costs. The benefit-cost ratio for 100% cool roof implementation is estimated to be 5.24, while the benefit-cost ratio for 25% urban tree canopy is estimated to be 3.78.

Other Solutions and Considerations

The benefit-cost analyses reflect high-level assumptions related to effectiveness of two selected solutions as they relate to the costs of inaction summarized in this study. In reality, however, there is a range of urban heat island adaptation measures. Below is a discussion of other potential solutions as well as findings from other studies on their effectiveness at heat mitigation, particularly as related to the Phoenix Metro Area.

Cool Pavement

Reflective pavements ("cool pavements") are a well-known urban heat adaptation measure. Cool pavements' light coloring has a higher albedo, which increases the reflectance of solar radiance and effectively reduces the surface temperature of the paved surface. Particularly in the desert climate of Phoenix, studies have shown that the increase in surface albedo results in a significant reduction of surface temperature (Golden & Kaloush, 2006; Middel et al., 2020; Yang et al., 2016) with a maximum of 16°C during peak temperatures (Golden & Kaloush, 2006). Likewise, studies have shown that subsurface temperatures beneath the cool pavement treatment are cooler than subsurface temperatures beneath regular asphalt surface, thus mitigating the negative impact of extreme heat on the life cycle of asphalt pavement. Findings from the first year of the City of Phoenix's Cool Pavement Pilot Program are in line with these broader academic studies (Arizona State University, 2021).

However, the evidence on the effectiveness of cool pavement on human-related ambient cooling and energy saving is mixed. Some studies conclude that the radiant heat reflected by cool pavements onto the building surface and human body increases building temperature, energy demand for cooling, and human discomfort (Azarijafari et al., 2021; Middel et al., 2020; Taleghani et al., 2016; Yang et al., 2016; Zaidi, 2020). Phoenix-based studies have found that cool pavements reduce near-surface temperature (the temperature at 2 meters above the road surface) by 0.5°C to 0.8°C while increasing mean radiant temperature (the temperature associated with human thermal exposure and discomfort) by 2°C to 4°C (Middel et al, 2020, David Sailor, Taleghani et al., 2016, Yang et al., 2016, Azarijafari et al. (2021). While cool pavements offer broader heat mitigation benefits, the variation of impacts across different temperature metrics suggests that the siting of cool pavement treatment areas is critical for their overall effectiveness.


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Permeable Pavement

Permeable pavements offer cooling benefits through water evaporation, making them an effective strategy for reducing high temperatures in wet climates. In wet conditions, permeable pavements enable water to vaporize, leading to reduced surface temperature. Studies have found that wet permeable pavements can lower surface temperatures by 1.2°C to 3.9°C (Cheng et al., 2019; Li et al., 2013). Li et al. (2013b) suggest that compared to other cool pavements with higher reflectance, permeable pavements do not reflect as much solar radiation, thus not generating as much thermal discomfort to pedestrians or increasing the temperature of adjacent buildings. The effect of improved human thermal comfort is consistent with other literature (Kubilay et al., 2019; Li et al., 2016; C. Wang et al., 2021; J. Wang et al., 2018). Under dry conditions, however, the evidence of the cooling effect of permeable pavements is mixed (Li et al., 2013; Stempihar et al., 2012). Studies have found that permeable pavements in dry conditions increase daytime surface temperature, as the permeable layers impede the heat transfer to the deeper layers of the ground (Stempihar et al., 2012; Li, et al., 2013b).

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Engineered Shade Structures

Engineered shade structures include both building-integrated features, like overhangs and shade tunnels, and free-standing external shading devices, like umbrellas, pergolas, shade sails, and canopies. External shading devices mounted on the facades of buildings, such as louvers and light shelves, decrease incoming solar radiation and improve the thermal comfort for humans inside of buildings and, thus, reduce cooling energy demand. Numerous studies using dynamic building energy simulation modeling suggest that buildings with movable external shading, which are optimized to deflect solar radiation according to the sun path, see energy savings ranging from 15% to 60% (Choi et al., 2017; Dutta et al., 2017; Evangelisti et al., 2020; Evola et al., 2017; Kim et al., 2012; Palmero-Marrero & Oliveira, 2010; Saelens et al., 2013, Dutta et al, 2017). These studies, however, are not localized to the Phoenix Metro Area. Current research suggests that the benefits of external shading devices are primarily limited to thermal comfort and energy demand.

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Free-standing, or lightweight, engineered shade structures are less effective in minimizing sun-exposed areas than their building-integrated counterparts; however, they may still increase thermal comfort. In a study documenting the cooling impacts of 1,988 independent shading devices in 159 unique locations in Tempe, Arizona, free-standing structures minimally reduced air and mean radiant temperature, though cooling magnitude varied by the type of shade device and ground temperature. These structures had a cooling magnitude of 11°C to 14°C at peak daily temperatures, compared to a magnitude of 15°C to 16°C for building-integrated devices like tunnels, overhangs, and arcades (Middel, AlKhaled, Schneider, Hagen, & Coseo, 2021). Nonetheless, free-standing engineered shade have the potential to improve outdoor thermal comfort.

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Conclusion

This study demonstrates that not taking action to defend against extreme heat in the Phoenix Metro Area may have significant economic consequences to residents and businesses alike.

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Under RCP 4.5, the average annual economic consequences are estimated to be nearly $1.9 billion: $900 million from increased mortality, $3.5 million from increased morbidity, nearly $900 million from losses in labor productivity, over $4 million from shortened life cycle of roadway infrastructure, and over $115 million in increased energy demand. Under RCP 8.5, the average annual economic consequences are estimated to be nearly $2.3 billion: $1.2 billion from increased mortality, $4.6 million from increased morbidity, nearly $1 billion from labor productivity losses, over $4 million from shortened life cycle of roadway infrastructure, and over $115 million in increased energy demand.[8]

Importantly, however, the benefits of investing in cool roofs and expanding the urban tree canopy have been estimated to outweigh the costs. Implementing cool roofs throughout the Phoenix Metro Area is estimated to have a benefit-cost ratio of 5.24, while expanding the urban tree canopy to 25% coverage is estimated to have a benefit-cost ratio of 3.78. As Phoenix continues to urbanize and the population expands, the benefits of adapting to extreme heat may only increase, as will the consequences of inaction. This study makes evident that to achieve these returns, and the widespread cooling benefits that they rely upon, adaptation measures must be pursued by both the public and private sector. Collective action will be critical towards ensuring that the Phoenix Metro Area not only continues to be an attractive place to live and do business, but that it supports a resilient economy and way of life that allows all communities to thrive.

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[8] Note these cost of inaction figures are shown without financial discounting applied. For information on financial discounting, refer to Key Study Concepts & Assumptions. Shown in $2021 as average annual consequences from 2020-2059 for RCP 4.5 and RCP 8.5 using the mean of 10 GCMs.

Appendix A

Study Concepts & Assumptions - Detail

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Baseline Climate Conditions

Unless otherwise noted, costs are presented relative to impacts estimated for a baseline period between 1986 and 2005. Near-term projections are for the years 2020-2039, centered around year 2030. Mid-term projections are for the years 2040-2059, centered around the year 2050. This approach follows other recent studies estimating the economic consequences of extreme heat (e.g., Atlantic Council) and relates to the climate conditions analysis. Based on the downscaling technique used, observed data is available from 1900-2005 (Atlantic Council, 2021). As such, 1986-2005 was used based on numerous methodological decisions, discussed further in Climate Conditions.

Other Conditions: Population, Economic, Technology, Acclimatization, and Urbanization

Economic consequence analyses typically follow one of two approaches: 1) analysis that is relative to current economic conditions and population or 2) analysis that accounts for how the structure of the economy and population could evolve and evaluates the losses relative to a hypothetical future. This analysis follows the first approach, though for certain indicators, as applicable, results are also shown adjusted for future conditions (e.g., projected employment). This first approach has been used in numerous national publications studying the economic consequences of climate change (e.g., American Climate Prospectus) and was chosen here as it allows for more interpretable results for decision-makers and decreases the need for alignment on assumptions related to future economic and demographic conditions (Rhodium Group, LLC, 2014).


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Acclimatization in this context describes physiological adaptations that occur to reduce the strain of environmental heat stress, such as increased sweating efficiency and ability to perform work at a lower core temperature and heart rate (Epstein & Moran, 2019). There is growing evidence that populations are becoming less sensitive to high temperatures though the degree of declining sensitivity varies between studies, locations, and time periods evaluated (Gosling, Hondula, Bunker, Ibarreta, & Liu, 2017; Sheridan, Dixon, Kalkstein, & Allen, 2021; Gasparrini, et al., 2015).

Acclimatization can also describe physical adaptations that mitigate the impact of heat stress, such as behavioral changes, AC, shade structures, and other technological advancements. For example, in Phoenix, 91% of homes have AC (includes all types – e.g., window units, central AC), in large part because the area's housing stock is much newer than most of the country (U.S. Census Bureau, 2019) and Arizona climate is more palatable with AC. Meanwhile, in a temperate region such as the San Francisco Bay Area, people are much less likely have AC (Knowlton, et al., 2009). Because of the widespread use of AC, a single 100-degree day in Arizona is not as impactful as a single 100-degree day in San Francisco, where people are less prepared for extreme heat events. The ubiquity of AC in the Phoenix region is an example of acclimatization. There are overall limits to acclimatization, however. For example, once Phoenix has 100% adoption of AC, with unrestricted use, in all buildings then that acclimatization pathway will have effectively reached its limit, aside from people running their AC longer and at lower temperatures in response to rising temperatures.[9] Likewise, there will be physiological limits to the temperatures that the body can withstand (Gosling, Hondula, Bunker, Ibarreta, & Liu, 2017).

Projecting the impacts of heat requires an understanding of historical and future changes in climate, population, and acclimatization. Currently, however, there are not robust theoretical frameworks that fully encapsulate the characteristics necessary to understand the relationship between heat, health, and the built environment, including economic well-being, underlying health conditions, the presence of vulnerable subpopulations, physiologic acclimatization, and locally available physical adaptations (Huang, et al., 2011). Likewise, future advancements in heat-mitigation technologies, ranging from cooling strategies to infrastructure durability improvements, the adoption rate for these strategies, and their projected impacts are simply unknown, and cannot be projected with confidence at this time (Knowlton, et al., 2009). This is also true of future mitigation or adaptation responses from affected parties, such as relocation of industry to reduce exposure. Given these limitations, this study does not account for future acclimatization, demographic changes, technological advances, or urbanization.[10] The projections assume that these factors remain the same as they are today (unless explicitly stated otherwise), an assumption shared by many of the studies analyzed for this report.

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[9] It is important to note that some adaptation strategies may also have negative economic and societal consequences – for example, burning more electricity to maintain cool air temperatures through increased use of AC is a very likely adaptation strategy, but one that has clear implications for greenhouse gas emissions as well as costs for the consumers and electric utilities. More information on the energy considerations related to this is presented in Critical Services: Energy Demand

[10] For labor productivity, results are shown both ways – once with current employment levels and again with projected employment. All other results are not adjusted for demographic changes..

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Annual Temperature Variability

Evaluating average impacts over 20-year intervals is useful to account for the variable nature of the environment. At the same time, however, such an approach may not capture acute heat events with significant economic outcomes. For example, in 2020 alone, Phoenix broke its record for the number of days over 100°F (145 days). That same year, Maricopa County experienced 323 heat-associated deaths, the most ever recorded for the county (Maricopa County Department of Public Health, 2020). While this study does not present results for specific short-term event periods, care was taken to preserve annual temperature variability throughout the analysis: temperature projections are based on a shift of real historical data, cost of inaction analyses are conducted for ten Global Climate Models (GCMs)[11] to present a range of results, and averaging across time periods was conducted at the end of all processing so as to maintain the peaks and valleys of daily temperature variability.[12]

Air Quality Projection Limitations: Heat and Ozone & Heat and Particulate Matter

In addition to Phoenix's high temperatures, it is also one of the worst metropolitan areas in the country for ozone and particulate pollution. Phoenix was ranked fifth for high ozone days out of 226 metropolitan areas in the 2021 the American Lung Association's "State of the Air" report by the American Lung Association and eighth out of 199 metropolitan areas for annual particle pollution (American Lung Association, 2021). Parts of Maricopa County are considered an ozone nonattainment and PM_{10} nonattainment area, as classified by the National Ambient Air Quality Standard designation (Arizona Department of Environmental Quality, n.d.). According to a 2015 Arizona State University (ASU) climate and health profile report, the most heavily populated counties in Arizona, like Maricopa County, have seen some decrease in Air Quality Index (AQI) ratings considered unhealthy for

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[11] A global climate model (GCM) is a complex mathematical representation of the major climate system components (atmosphere, land surface, ocean, and sea ice), and their interactions. For more information, please see: https://www.gfdl.noaa.gov/climate-modeling/

[12] The shift of real historical data to project future temperatures was dependent on an averaging process of the Locally Constructed Analogs (LOCA) downscaling projections relative to the observed data for LOCA calibration, which could introduce some smoothing.

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sensitive groups but an increase in moderate air quality days, and this trend is expected to continue in the near term (Arizona State University, 2015).

In terms of specific particulates, tropospheric ozone (O_3) has been the concern in the context of climate change because the production of secondary air pollutants (which contribute to the formation of ground-level ozone) depends strongly on meteorological conditions such as increased temperatures. Ground-level ozone forms when precursor chemicals mix with the air, sunlight, and other chemicals, including volatile organic compounds (VOCs) and nitrogen oxide, which are emitted from vehicles and industrial sources. While higher production of these precursor chemicals can result in greater ozone formation, there exist major sources of uncertainty around air quality projections. One study found major improvements in air quality in most major cities in the U.S. including decreased concentrations of $PM_{2.5}$ and reduced frequency of days in the year that O_3 exceeds standards, primarily driven by changes in temperature, and decreased emissions from mobile sources (Trail, et al., 2014). In the Southwest region, one study looking at Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 found that though some of the highest seasonal mean maximum daily 8-hour average O_3 levels are in the Southwest and West, the changes in the regions, when comparing historical periods, are comparatively small (Kim, et al., 2014). Furthermore, at extremely high temperatures, the relationship between ozone and temperature breaks down; once temperatures reach above the mid-nineties, ozone levels at many sites across the U.S. saw decreases in the ozone-temperature slope, defined as ozone suppression (Shen, Mickley, & Gilleland, 2016).


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Other limitations restrict the monetization of air quality impacts in this study. Air quality is affected by many factors such as drought, wildfire, land use and farming practices, wind/stagnation, technological advances and anthropogenic factors, all of which further complicate projections. Additionally, when considering the combined impacts of air quality and heat, numerous studies, such as those looking at public health impacts, have found that once heat variables are accounted for, the association of ozone and $PM_{2.5}$ on heat-health impacts, such as mortality, was weak (Yip, et al., 2008). Finally, many of the economic consequences related to air quality are based on the regulatory environment. For example, research has found that where businesses locate (i.e., business attraction) can be impacted by nonattainment designation zones for establishments that emit targeted pollutions (Nataraj, Chari, Richardson, & Willis, 2013). It is likely that the regulatory restrictions regarding nonattainment levels will evolve into the future, and it is possible that even what seems like an insignificant change in poor air quality metrics (e.g., an increase of one or two bad ozone days), could have cascading economic consequences. Given these limitations, air quality has not been projected as part of this study but when relevant, qualitative narrative is included to contextualize how air quality, and more specifically ozone and particulate matter, might affect each indicator in the Cost of Inaction analysis.

Appendix B

Climate Conditions Analysis - Detail

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The climate conditions analysis conducted for this study included projections for daily minimum and maximum air temperatures for a twenty-year baseline and two twenty-year future time horizons.[13] These were first calculated for Maricopa County and were then adjusted based on daily historical temperature data at the Sky Harbor station. Projections are applied for the analysis county-wide; further geographic variability for temperature projections are not included.

Emissions scenarios are used to describe different climate futures, all of which are considered possible depending on the volume of greenhouse gases emitted in the years to come. For this study, results for two future emissions scenarios were calculated based on RCPs recognized by the Intergovernmental Panel on Climate Change (IPCC); RCP 4.5, a medium stabilization scenario and RCP 8.5, a high-emissions scenario. Daily minimum and maximum temperatures were derived for each day of the year for three 20-year time horizons: baseline (1986-2005, median year 1995), near-term (2020-2039, median year 2030), and mid-term (2040-2059, median year 2050). It is considered best practice for climate impact assessments to use multidecadal averages centered on a year of interest (The Intergovernmental Panel on Climate Change, n.d.). Multidecade averages account for interannual variability and appropriately characterize the climate norm for the selected baseline and future time horizons (Federal Highway Administration, 2017) (California Governor's Office of Emergency Services, 2020). The 2030- and 2050-year timeframes were selected to be consistent with other climate impact

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[13] The temperature data is for 2 meters above surface.

Table 7. Summary of Projection Model Permutations

Metric	Model Runs	Permutations
Temperature Measure	Daily Min, Daily Max	2
Emissions Scenarios	RCP 4.5, RCP 8.5	2
Projected Horizons	Near term (2020-2039), Mid Term (2040-2059)	2
Global Climate Models (GCMs)	10 Priority GCMs	10
Total Projected Permutations:		**80**

analyses and align with planning horizons that guide governmental and business decision-making. As shown in Table 7, a total of 80 permutations were calculated for the temperature projections. These data are additional to the baseline data, which was collected for the observed data period for Locally Constructed Analogs (LOCA) calibration (1986-2005) and for Sky Harbor (as described below) to adjust temperatures that better reflect conditions in the urban core.

Data Sources for Conditions Analysis

LOCA Data

This analysis leveraged LOCA Downscaled Climate Projections data developed by researchers at the Scripps Institution of Oceanography (Lawrence Livermore National Laboratory, 2015). These data are based on the outputs of the CMIP5 ensemble of Global Climate Models (GCMs) recognized by the World Climate Research Programme and the United Nations' Intergovernmental Panel on Climate Change (IPCC).

The LOCA downscaling technique dramatically improves the resolution of GCMs from grid cells that are hundreds of square miles to a resolution of roughly 3.7 square miles by factoring in the systematic historical effects of topography on local weather patterns. While previous downscaling techniques typically formed the downscaled model day using a weighted average of 30 similar historical days, LOCA looks locally around each point of interest to find the one best matching day (Pierce & Cayan, 2017).[14]

While this dataset is currently recommended for climate impact assessments across the U.S., it does have important limitations. It does not a) attempt to estimate future changes in local development patterns and their potential impacts on future climate and b) does not account for the signal of the local built environment (Georgescu M. , 2021). While LOCA data has these limitations, it is important to note that additional analysis was conducted to make the projections be more representative of heat in the Phoenix urban core by applying the anticipated change in temperature to observed conditions at Sky Harbor (see below).

LOCA data used for this analysis were downloaded from the Lawrence Livermore National Laboratory Green Data Oasis (Lawrence Livermore National Laboratory, 2015). The datasets included daily minimum and maximum temperature projections for the years 2000-2060 for each grid cell within Maricopa County for two emissions scenarios and 10 selected GCMs (discussed below).

Selection of Priority GCMs

When processing climate model projections for local impact assessments, it is best practice to use results from multiple GCMs (California Governor's Office of Emergency Services, 2020). A review of academic literature was conducted to identify a subset of CMIP5 GCMs recommended for use in Arizona. In a paper on heat wave probability in the changing climate of the southwest U.S. the authors used LOCA downscaled data from a subset of 10 GCMs for a large study area including the southwestern quadrant of the continental U.S., which includes Maricopa County (Guirguis, Gershunov, Cayan, & Pierce, 2018).

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[14] For more information on the LOCA downscaling technique, please see: http://loca.ucsd.edu/what-is-loca/

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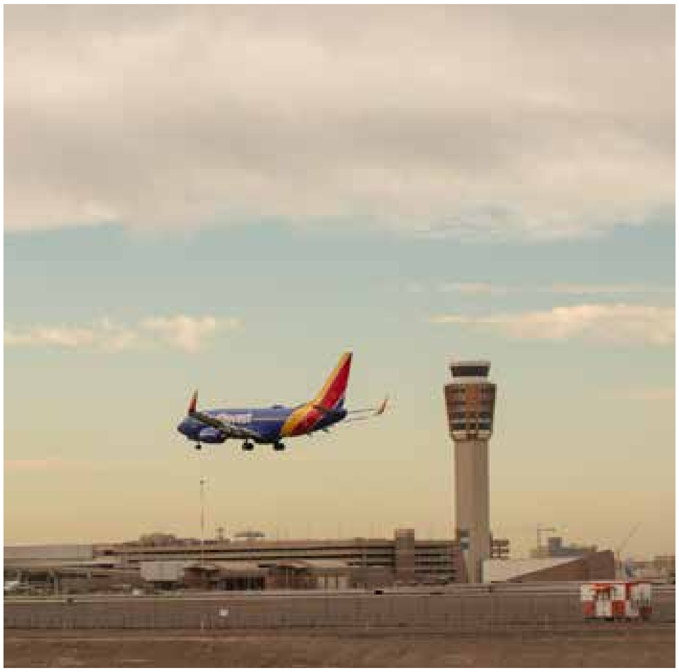

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For the selection of the 10 GCMs, the authors cite a California Department of Water Resources study that evaluated the performance of all 32 GCMs and recommended the 10 for use in California (California Department of Water Resources, 2015). The GCMs were evaluated based on 1) global measures 2) regional measures for the southwestern U.S., and 3) California metrics. The first two steps selected a subset of 15 and the third step eliminated 5 more based on poor modeling of California metrics. This research was also cited in technical studies for California's Fourth Assessment (Pierce, Kalansky, & Cayan, 2018). Based on a) Pierce et al.'s review of the CA DNR study for the California Fourth Assessment and b) their approval of using the 10 GCMs for the southwestern U.S. heat wave study, the project team for this effort concluded that the 10 GCMs are also best fit for Arizona.

The 10 GCMs are: ACCESS1-0, CanESM2, CCSM4, CESM1-BGC, CMCC-CMS, CNRMCM5, GFDL-CM3, HadGEM2-CC, HadCEM2-ES, MIROC5. These 10 GCMs were shown to all have comparatively little error when compared to regional southwest metrics. Note that some other models with low levels of overall error were eliminated because they were found to not sufficiently model individual metrics (such as droughts or El Niño patterns).

Observed Data for LOCA Calibration

Observed conditions using a high-resolution observational dataset developed by researchers at the University of Colorado (Livneh, et al., 2015) was used to train the LOCA downscaling algorithms (Pierce & Cayan, 2017). Observed data is available in the exact same resolution and format as the LOCA downscaled projections for the years 1900-2005. For this analysis, data for the years 1986-2005 were used. This time horizon was chosen based on the following factors: a) the length of the baseline time horizon should match that of the future time horizons (20 years), b) 2005 as the final year of the observed temperature dataset, c) recommendation of 1986-2005 as a baseline time horizon by the recently updated California Adaptation Planning Guide (California Governor's Office of Emergency Services, 2020), and d) use of 1986-2005 as a baseline time horizon in other publications (e.g., (Lay, et al., 2018)) consistent with U.S. EPA's Multi-Model Framework for Quantitative Sectoral Impacts Analysis (U.S. EPA, 2017).

Sky Harbor Baseline Temperature Data

Using the observed data and LOCA data, a delta method was applied to historical temperature data from Sky Harbor (National Center for Environmental Information, n.d.). This location was selected to better align the temperature projections with observed temperature in the Phoenix urban core. Daily minimum and maximum temperature data was downloaded from the Climate Data Online portal from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information for the 1996-2005 time period. The name of the NOAA station is the Phoenix Airport.[15] The method applied is based on approaches from numerous publications, in particular those with a focus on maintaining daily temperature variability to understand heat-health impacts (Gosling, Hondula, Bunker, Ibarreta, & Liu, 2017; Hondula, Georgescu, & Balling Jr., 2014; Petkova, et al., 2014).

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[15] Network ID: GHCND:USW00023183, Latitude/Longitude: 33.4277°, -112.0038°

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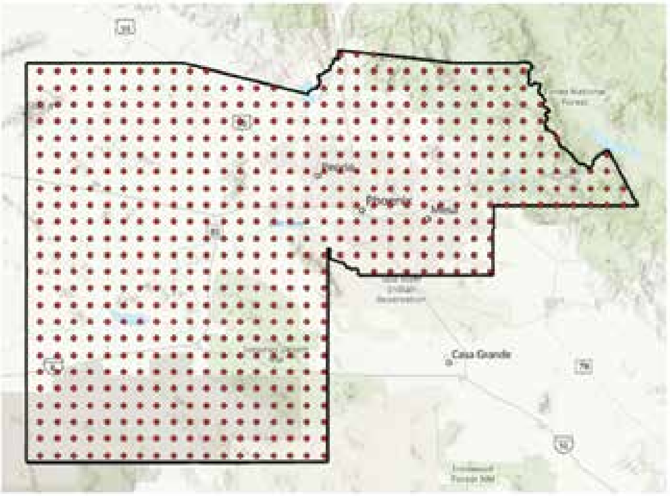
Climate Conditions Analysis Steps

The bulk of the analysis was carried out in Python, leveraging several relevant libraries to manipulate spatial/temporal data and to maximize computational efficiency (e.g., netCDF4, NumPy, Pandas, Fiona, and Shapely). Additional data processing was conducted in R and Excel. R is a programming language commonly used for statistical computing. The selection of time horizons and order of operations in the analysis was carried out based on best practices for processing temperature projection data, including use of multiple GCMs and averaging results across years rather than using a single year (Pierce, Kalansky, & Cayan, 2018).

Figure 9. LOCA Downscaled Projections Grid Points within Maricopa County



The analysis consisted of the following steps:

1) Accessed and downloaded daily climate projections (min and max temperature) for a rectangular area of interest encompassing Maricopa County for the 10 priority GCMs and two emissions scenarios from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections Archive (Lawrence Livermore National Laboratory, 2015). The applied downscaling technique translates the resolution of GCMs from grid cells that are hundreds of square miles to a resolution of roughly 3.7 square miles.

2) For each GCM/emissions scenario/time horizon permutation:

   a. Identified the subset of grid points located within Maricopa County and exported relevant data from the input netCDF datasets (see Figure 9)

   b. For each grid point, calculated daily minimum and maximum temperature for each day within a given horizon

   c. Calculated the average daily minimum and average daily maximum temperature for all grid points in Maricopa County.

3) For each temperature variable for each GCM, timeframe, and emissions scenario, the average daily minimum and average daily maximum temperature was assigned a percentile at the 1/20th of one percentile (2020-2039 and 2040-2059, respectively). Percentiles were also assigned to the average daily observed data for LOCA calibrations (1986-2005). Percentiles for observed data were then matched to the projected data and a difference was calculated – for example, if the 51st percentile in the observed was 86.8°F and in the projected it was 89.8°F, a change factor of 3°F was calculated.

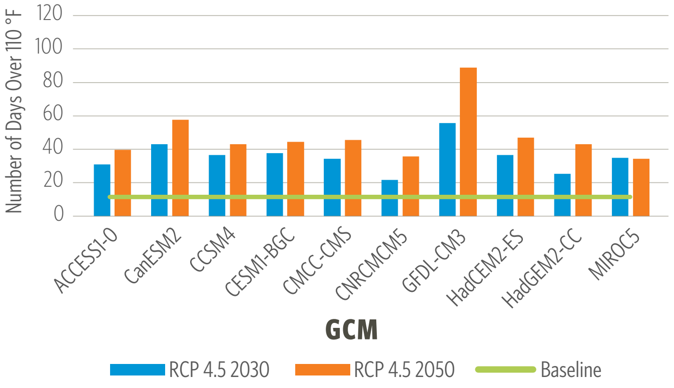
4) These change factors were then applied to observed temperature data at Sky Harbor (National Center for Environmental Information, n.d.) over the 1996-2005 time period to estimate annual projections for the 2020-2039 period and 2040-2059 period for each GCM and emissions scenario. Data was processed using R.

5) The final outputs consist of daily minimum and maximum temperatures for each day by time horizon and emissions scenario for each of the ten priority GCMs. Mean temperatures were calculated by averaging the minimum and maximum.

6) The cost of inaction was conducted based on calculations for each day and each year for every time horizon, emissions scenario, and GCM.

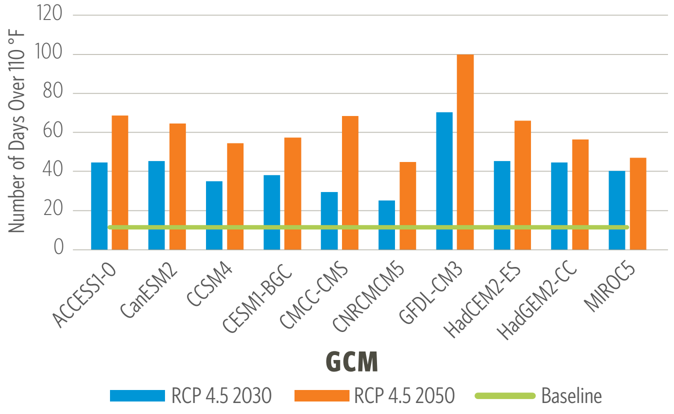
Climate Conditions Analysis – Results by GCM

Figure 10. Days with Max Temperature Over 110°F for 2030 and 2050 RCP 4.5



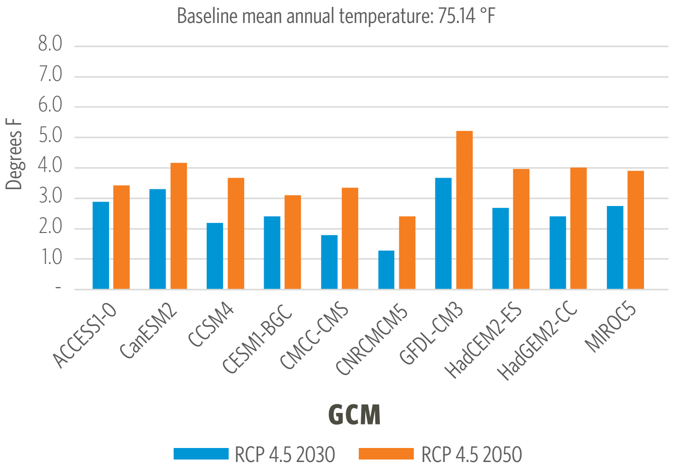
Notes: The results for RCP 4.5 2050 are occasionally lower than RCP 4.5 2030. This relates to the temperature projection data which, dependent on the GCM, can have lower projections for these timeframes. Note that RCP 4.5 is an intermediate scenario where emissions peak around 2040 and then decline. Results for 2030 represent annual averages for 2020-2039. Results for 2050 represent annual averages for 2040-2059. Baseline represents 1986-2005.

Figure 11. Days with A Max Temperature Over 110°F for 2030 and 2050 RCP 8.5



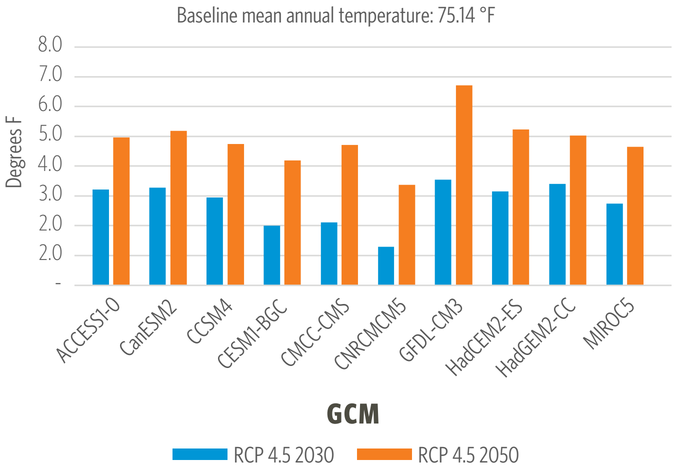
Notes: Results for 2030 represent annual averages for 2020-2039. Results for 2050 represent annual averages for 2040-2059. Baseline represents 1986-2005.

Figure 12. Annual Average Mean Temperature Degrees Above Baseline, RCP 4.5



Notes: Baseline annual average mean temperature is 75.14 F. The results for RCP 4.5 2050 are occasionally lower than RCP 4.5 2030. This relates to the temperature projection data which, dependent on the GCM, can have lower projections for these timeframes. Note that RCP 4.5 is an intermediate scenario where emissions peak around 2040 and then decline. Results for 2030 represent annual averages for 2020-2039. Results for 2050 represent annual averages for 2040-2059. Baseline represents 1986-2005.

Figure 13. Annual Average Mean Temperature Degrees Above Baseline RCP 8.5



Notes: Baseline annual average mean temperature is 75.14 F. Results for 2030 represent annual averages for 2020-2039. Results for 2050 represent annual averages for 2040-2059. Baseline represents 1986-2005.

Appendix C

Cost of Inaction – Detail

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Following is a discussion of the methodologies applied for each cost of inaction indicator and annual results. For all cost of inaction calculations, economic consequence estimates were evaluated for each year of the 20-year period of the projection time periods and averaged at the end to minimize smoothing effects. Results are presented for the range of GCM results (lowest and highest) and the mean relative to the baseline conditions (1986-2005).

Mortality and Morbidity

Background

In 2020, Maricopa County experienced 323 heat-associated deaths, the most on record for the county. The number of heat-related emergency department (ED) and hospitalizations in Maricopa County has been steadily rising in recent years, from 1,290 hospitalizations in 2006 to over 2,300 in 2017 (Maricopa County Department of Public Health, 2020). In addition to health impacts and loss of life, heat-related mortality and morbidity create a number of costs to society. These costs include direct losses, such as costs associated with providing and receiving healthcare, and indirect losses, such as lost productivity, or working hours. Recent research has found that higher temperatures significantly increase the likelihood of workplace accidents in both indoor and outdoor settings, and for many injury types not directly related to heat. Moreover, the net effect of injuries is far greater for low-income groups, who are more likely to work in dangerous occupations, live and work in places with greater heat exposure, and experience larger increases in risk on hotter days (Park, Pankratz, & Behrer, 2021).

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With temperatures expected to increase in the coming decades, heat-related mortality and morbidity costs can be expected to increase commensurately without significant intervention.

At the same time, heat-related mortality and morbidity are widely considered to be preventable (Reid, et al., 2009; Vanos, 2020). The increased mortality and morbidity rates in recent years are not caused by extreme temperatures alone but are also related to socio-economic and housing status and work type (Putnam, et al., 2018). For example, research suggests that many heat exposure deaths within Maricopa County are due to specific risk factors such as being homeless, having a low socioeconomic status, living in hotter neighborhoods, working outdoors, or not having access to operational AC (Harlan, et al., 2014). With appropriately calibrated warning systems, expanded cooling resources, and strategic planning of activities, heat-related deaths, emergency department (ED) visits, and hospitalizations can be reduced even in the context of rising temperatures. The fact that these health impacts are preventable to a certain extent indicate that there are economic losses that could be mitigated.

Projecting future impacts of heat on health is dependent on understanding historical temperature-mortality and -morbidity relationships within a specific geographic area. Since 2005, the Maricopa County Department of Public Health (MCDPH) has maintained a monitoring system that captures data on the relationship between heat and health, and specifically tracks both "heat-caused" and "heat-associated" mortality and morbidity (Iverson, et al., 2020). "Heat-caused" captures health events where the primary cause of death or diagnosis is related to excessive natural heat, whereas "heat-associated' is when exposure to excessive natural heat is listed anywhere on the death record or diagnosis (and includes heat-caused) (Arizona Department of Health Services, 2020).[16] Many studies, in particular those analyzing areas with less detailed monitoring programs, use "all-cause mortality" as their measure, capturing all "excess" health events triggered by extreme heat to account for the wide range of preexisting health-related conditions that may be exacerbated. Overall, given that heat-caused mortality can be more difficult to diagnose and are often misclassified, all-cause and heat-related are typically considered better indicators to understand the full scope of health impacts related to thermal environmental stress and thermophysiological strain (Berko, Ingram, Saha, & Parker, 2014). Studies focused on the impact of heat on health tend to focus on mortality rather than morbidity, in part because the societal and cost impacts of mortality tend to be greater than for morbidity and because there are often fewer robust sources available to track morbidity, especially in its milder forms that may not result in an encounter with the formal health care system (Knowlton, et al., 2009). Studies that do account for heat-morbidity tend to only capture cases that show up in the emergency department and/or lead to hospitalizations, which only allows for identification of the most extreme cases (Lippmann, Fuhrmann, Walker, & Richardson, 2013).

In understanding the impacts of heat on health, it is important to recognize that climatic conditions vary by geography, resulting in heat being experienced differently. There are a number of factors that can be considered when looking at heat-health impacts

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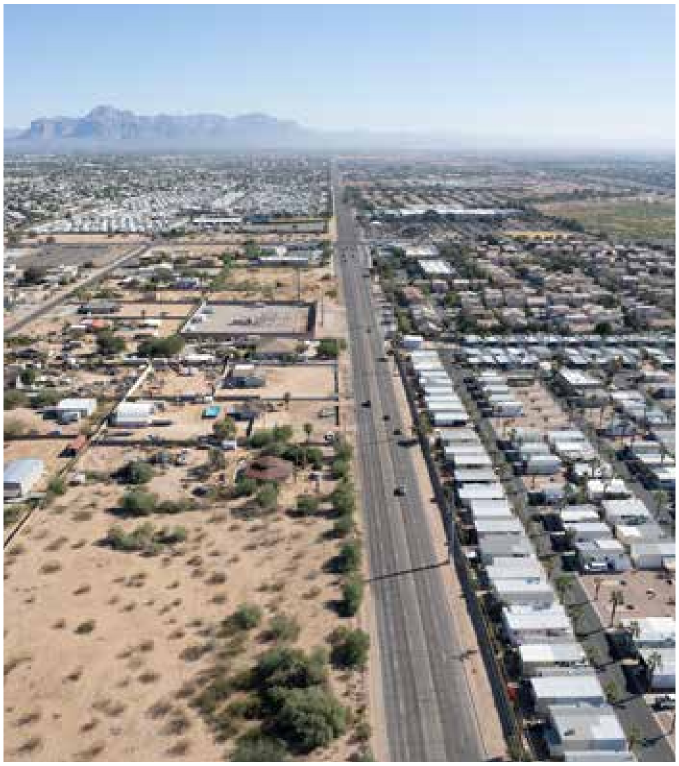
[16] In the literature, "heat-associated" is synonymous with "heat-related."

depending on the purpose of the study and local context. Examples include considerations related to time period, humidity, diurnal range (i.e., difference between day and nighttime temperatures), and temperature thresholds. Studies of heat-health events often limit their assessment to the warmer summer months (e.g., April to October) to reduce the confounding effects from the natural annual variability and seasonal fluctuation in all-cause mortality rates. This is noted to be appropriate for hot climates, such as the desert southwestern U.S. (Harlan, et al., 2014). The heat index, which combines humidity and air temperature into a single value, is commonly used to evaluate heat-health impacts but has been found to be more strongly correlated in humid locations like New York City or Chicago (Petitti, Hondula, Yang, Harlan, & Chowell, 2016); studies have found that air temperature in Maricopa County provided information that was not substantively different from the heat index, implying that areas with low relative humidity may be able to focus on air temperature metrics (Hondula, Georgescu, & Balling Jr., 2014). Diurnal range can also be important for understanding the impacts of heat on mortality and morbidity because the body needs the cooler nighttime temperatures (when the minimum daily temperature would occur) to recover from the day's hot temperatures. When the minimum temperature increases, and the diurnal range condenses, the body loses its ability to recover.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While it is common to apply temperature thresholds (e.g., greater than 100°F) to estimate heat-health impacts, a study on heat-related morbidity and mortality in Maricopa County found that the standard temperature threshold approach to measuring heat-health events is overly simplistic and failed to capture the full scope of health impacts. Indeed, heat-related morbidity can begin to appear at lower high temperatures (trigger points) than heat-related mortality. In a hot location like Maricopa County, using a single high threshold temperature (e.g., excess risk temperature, or ERT, for all-cause mortality) vastly discounts the number of days on which heat is associated with an increased risk of heat-related mortality and morbidity (Petitti, Hondula, Yang, Harlan, & Chowell, 2016).

Air Quality – Effects of Heat with Ozone and PM Exposure

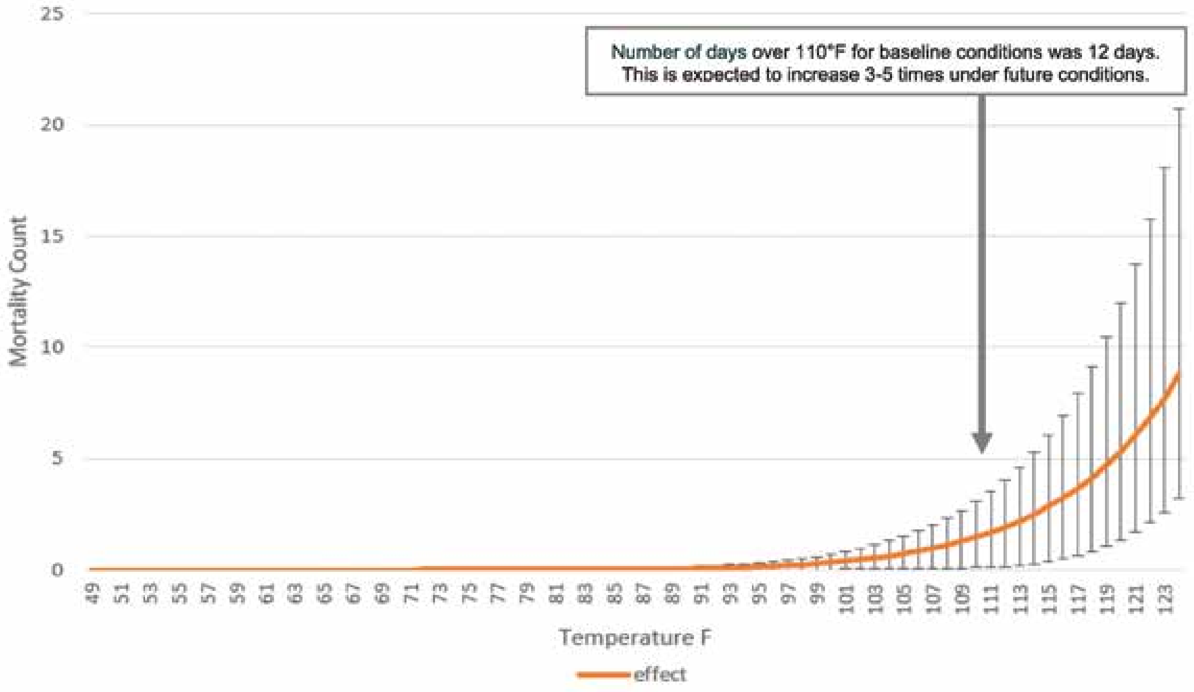
Yip et al., when analyzing the July 2005 heat wave, found strong associations between mortality and maximum temperature; they also controlled for all heat variables and looked into if PM_{10} and ozone were strong predictors of mortality but found that the association was weak (2008). In a study looking at temperature and mortality for nine U.S. cities, they found that results looking at all-cause mortality did not change when adjusting for $PM_{2.5}$ and decreased when adjusting for ozone (Zanobetti & Schwartz, 2008). It is possible that where ozone and temperature are highly correlated, some of the effects attributed to temperature could independently be attributable to ozone (Kim, et al., 2014). There is limited research on the independent or interactive effects of ozone and heat on morbidity (Knowlton, et al., 2009).

Mortality Methods

National studies have estimated increases in mortality associated with extreme heat often using temperature thresholds. Deschênes and Greenstone (2011) found that each additional day of extreme heat (above 90°F) raises annual age-adjusted mortality rate relative to a moderate day (50°– 60°F range) by about 0.11%, while Barreca (2016) finds that each additional day of extreme heat (above 90°F) increases the mortality rate by 1% relative to a moderate day (60°– 69°F range) (Barreca, Clay, Deschenes, Greenstone, & Shapiro, 2016). Southern regions of the U.S., however, have been found to have lower heat-related mortality when applying national thresholds (Yip, et al., 2008) and as noted above, thresholds may mask the number of days during which heat may be associated with increased heat-health impacts. There have been numerous studies looking at heat-health impacts in the Phoenix area for both all-cause mortality and deaths attributed directly to heat (Hondula, Georgescu, & Balling Jr., 2014; Yip, et al., 2008). Given Phoenix's relatively higher temperatures and the increased acclimatization of its population, it is important to reference localized research when trying to understand the heat-mortality relationship in the region (Harlan, et al., 2014).

Projections for heat-related mortality for this analysis are based on temperature-health exposure-response functions derived from administrative records. See Figure 14 for the TMax 1-Day exposure-response function. The mortality exposure-response functions are based on heat mortality surveillance data from the Maricopa County Department of Public Health for the summer months of 2006 through 2019 (Maricopa County Public Health Department, 2018).[17]

Figure 14. Exposure-Response Curves for Heat-Related Deaths, TMax 1-Day



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[17] The data set includes daily counts of heat-related and heat-caused deaths; there were 1,491 cases over the study period. The time series of daily heat mortality was time de-trended to account for population growth and the changing demographics of the study region. Each day's mortality total was divided by the ratio between its respective annual total number of deaths in Maricopa County and the total number of deaths observed in 2019. The exposure-response function was then derived from a generalized additive model for heat mortality as a function of temperature using a quasi-Poisson link function, with a penalized smoothing spline for the temperature effect. Predicted daily mortality counts with 95% confidence intervals were extracted from the model for each temperature integer that fell within the range of historical observations +/- 5°F. Models for one-day daily maximum and minimum temperature were created and applied for the summer months April through October, inclusive. Models were created using the mgcv package in R and RStudio software. It is important to note that underlying vulnerability is a key factor determining mortality and morbidity impacts. Over time, data has showed that the shape of the temperature-mortality curve varies based on the years include din the analysis, and that recent years' worth of data are associated with some of the steepest curves. For purposes of this analysis, the temperature-mortality relationship is held constant over the period of analysis to focus on the "direct" climate effect.

Table 8. Monetizing Mortality - Cost Inputs

Metric	Cost ($2021)	Source
Value of a Statistical Life	$11,940,000	USDOT

Rounded to nearest $50,000. All costs are adjusted to 2021 using consumer price index for All Urban Consumers (CPI-U) and Median Usual Weekly Earnings (MUWE) based on USDOT Guidance

Table 9. Average Annual Mortality Costs for TMax 1-Day Relative to 1986-2005 Baseline

TMax 1-Day Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
GCM Low	$334,700,000	$687,400,000	$427,100,000	$944,700,000
GCM High	$1,513,800,000	$2,308,600,000	$1,489,000,000	$2,756,200,000
GCM Mean	**$725,300,000**	**$1,070,700,000**	**$845,700,000**	**$1,511,000,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. 2030 represents an average of results for 2020-2039.2050 represents an average of results for 2040-2059. Results are shown as relative differences from the baseline period 1986-2005. It is noted that the results for RCP 4.5 2050 and RCP 8.5 2030 are occasionally lower than RCP 4.5 2030. This relates to the temperature projection data which, dependent on the GCM, can have lower projections for these timeframes.

Table 10. Average Annual Mortality Costs for TMin 1-Day Relative to 1986-2005 Baseline

TMax 1-Day Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
GCM Low	$277,300,000	$592,000,000	$355,400,000	$787,400,000
GCM High	$1,424,300,000	$2,078,300,000	$1,329,500,000	$2,433,500,000
GCM Mean	**$626,000,000**	**$930,900,000**	**$735,600,000**	**$1,314,400,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. 2030 represents an average of results for 2020-2039.2050 represents an average of results for 2040-2059. Results are shown as relative differences from the baseline period 1986-2005. It is noted that the results for RCP 4.5 2050 and RCP 8.5 2030 are occasionally lower than RCP 4.5 2030. This relates to the temperature projection data which, dependent on the GCM, can have lower projections for these timeframes.

The U.S. Department of Transportation (USDOT) value of a statistical life (VSL) was used to monetize mortality impacts, shown in Table 8.[18] VSL is a widely-used metric by that quantifies the approximate societal benefit of avoiding death; it is a societal-level measure and should not be interpreted to mean that a human life is worth this value or that any one death would cost society exactly this amount. VSL is derived from research on how much people are willing to pay in order to reduce their risk of fatality.

Mortality Results

All results are shown for the summer only period (April 1 through October 31) relative to the 1986-2005 for the TMax 1-day and TMin 1-day model runs. The baseline mortality for this period is estimated to be 112 deaths, monetized at $1.3 billion, for TMax 1-day and 99 deaths, monetized as $1.2B for TMin 1-day. The results for the TMax 1-day were used in the benefit-cost analysis.

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[18] Different agencies use different VSLs. For example, both FEMA and EPA also publish a national VSL. The EPA most recently published theirs in the *2010 Guidelines for Preparing Economic Analyses*. The EPA recommended VSL is $7.4M (2006). FEMA's National Risk Index most recent recommendation (July 2021) was $7.6M ($2020). Using the Bureau of Labor Statistics Consumer Price Index, these figures adjust to $9.8M (EPA) and $7.8M (FEMA) (U.S. EPA, 2010; FEMA, 2021).

Caption © Credit

Morbidity Methods

Heat-health studies tend to focus on mortality rather than morbidity, in part because bodies react differently to relative increases in heat exposure, impacting different systems and creating different symptoms, which makes morbidity more challenging to track and morbidity data less consistently available. The relationship between heat and morbidity ultimately depends on the affected bodily system (Mastrangelo, Hajat, Fadda, Buja, & Fedeli, 2006). Specifically, studies have shown that there is a weaker association between heat and cardiovascular and respiratory impacts (Petitti, Hondula, Yang, Harlan, & Chowell, 2016); (Knowlton, Rotkin-Ellman, Geballe, Max, & Solomon, 2011) while there is a stronger association between heat and impacts to the renal system (Kingsley, Eliot, Gold, Vanderslice, & Wellenius, 2016). Heat-related morbidity tends to be more common in at-risk populations, such as older persons or those with pre-existing conditions. Meanwhile, direct heat-health impacts, such as hyperthermia or heat stroke, are more commonly exhibited in younger people who are working or exercising outdoors (Maricopa County Public Health Department, 2018). This variety of heat-health impacts require that multiple health outcomes be considered at once, including morbidity type (e.g., renal vs. hyperthermia) and healthcare type (e.g., emergency department visit vs. hospitalization).

Similar to mortality, it is important to consider localized research when understanding heat-related morbidity impacts in the Phoenix region. Projections for heat-related morbidity for this analysis are based on morbidity exposure-response functions derived from hospital records from Maricopa County compiled by the Arizona Department of Health Services, gathered for the summer months of 2008 through 2012. See Figure 15 and Figure 16 for the TMax 1-Day exposure-response function for ED and in-patient visits (hospitalizations).

Figure 15. Exposure-Response Curves for ED Visits, TMax 1-Day

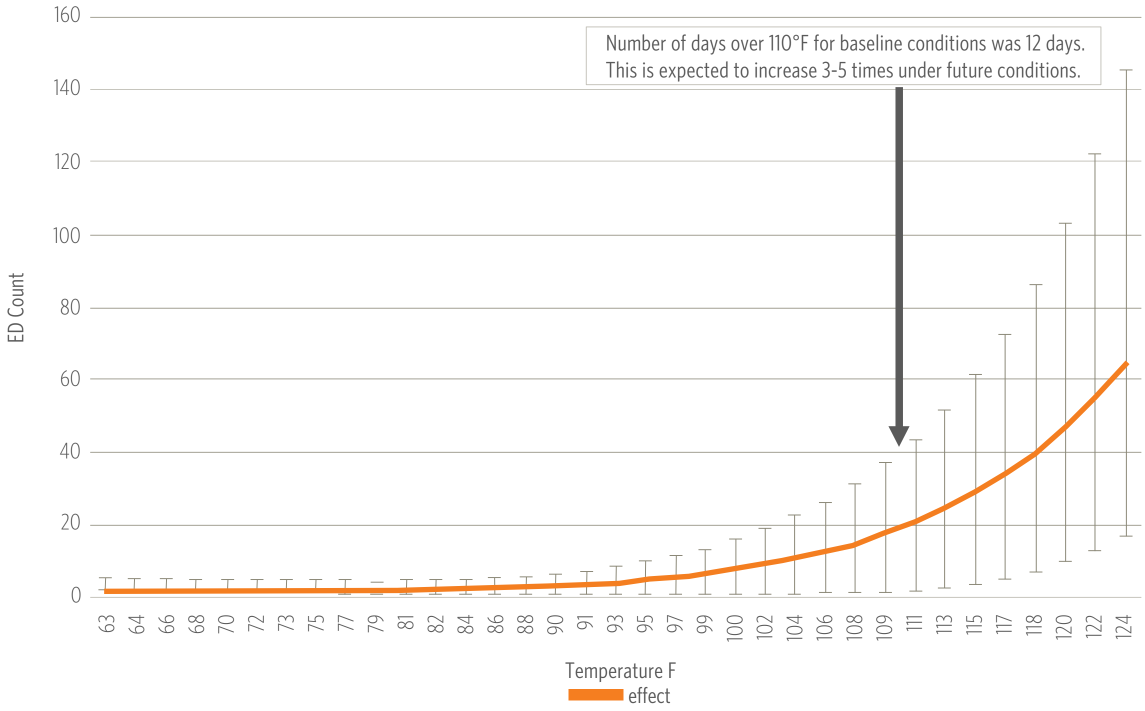
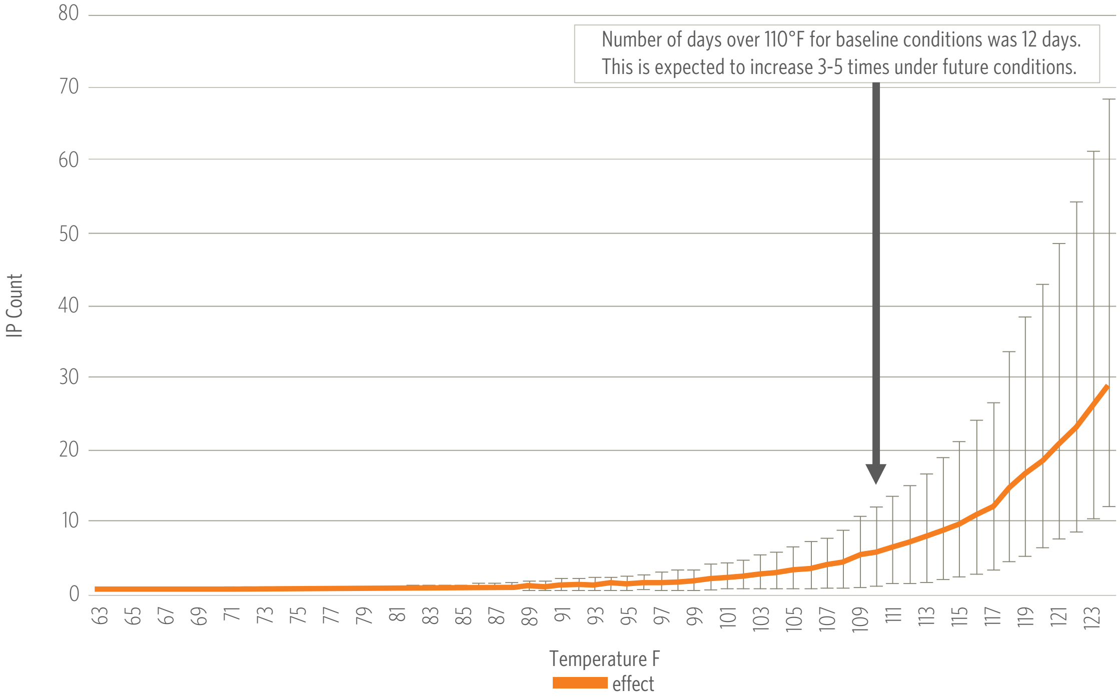


Figure 16. Exposure-Response Curves for In-Patient Visits, TMax 1-Day



Number of days over 110°F for baseline conditions was 12 days. This is expected to increase 3-5 times under future conditions.

Studies that estimate the cost burden of heat morbidity tend to use the "cost-of-illness" approach, which consider both the patient healthcare costs (out of pocket expenses and insurance payments) and the days of lost wages associated by the illness. Since this study analyzes lost labor productivity as a separate indicator, only patient healthcare costs are considered.[19] Cost inputs were derived from published studies that pulled healthcare costs for defined heat-health outcomes from national databases. For this study, cost inputs were sourced from the Knowlton, Rotkin-Ellman, Geballe, Max, & Solomon (2011) study because the authors use a similar case definition as the Petitti et al. study. The Petitti et al. study uses a comparable methodology for exposure-response functions as used here. These costs are summarized in Table 11.[20]

Table 11. Monetizing Morbidity – Patient Healthcare Cost Data

Metric	Patient Healthcare Cost ($2021)	Source
ED Visit	$1,066	Knowlton et al, 2011
Hospitalization	$11,343	Knowlton et al, 2011

Notes: All costs are adjusted to 2021 using consumer price index (CPI).

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[19] It is important to differentiate between healthcare charges and healthcare costs. The former represents the total charges that a healthcare provider may bill to insurance while the latter refers to only the costs incurred to the patient.

[20] Other published costs from Medical Expenditure Panel Survey (MEPS), Healthcare Cost and Utilization Project (HCUP), and Truven Health Analytics were found to be as follows: $330 to $2,000 for ED visits and $10,800 for hospitalizations.

Morbidity Results

All results are shown for the summer only period (April 1 through October 31) relative to the 1986-2005 baseline in (TMax 1-day) and (TMin 1-day) for emergency department (ED) visits and inpatient hospitalizations. The baseline ED visits for this period are estimated to be 1,900, monetized at $2 million, for TMax 1-day and 1,500, monetized at $1.7M for TMin 1-day model runs. The baseline hospitalizations for this period are estimated to be 460, monetized at $5.3 million, for TMax 1-day and 340, monetized at $3.9M for TMin 1-day model runs. The results for the TMax 1-day were used in the benefit-cost analysis.

Table 12. Morbidity – Average Annual ED Visit Costs Incurred by Patients for TMax 1-Day Relative to 1986-2005 Baseline

TMax 1-Day Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
GCM Low	$300,000	$600,000	$400,000	$800,000
GCM High	$1,200,000	$1,800,000	$1,200,000	$2,100,000
GCM Mean	**$600,000**	**$900,000**	**$700,000**	**$1,200,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. 2030 represents an average of results for 2020-2039.2050 represents an average of results for 2040-2059. Results are shown as relative differences from the baseline period 1986-2005. It is noted that the results for RCP 4.5 2050 and RCP 8.5 2030 are occasionally lower than RCP 4.5 2030. This relates to the temperature projection data which, dependent on the GCM, can have lower projections for these timeframes.

Table 13. Morbidity – Average Annual ED Visits Costs for TMin 1-Day Relative to 1986-2005 Baseline

TMax 1-Day Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
GCM Low	$200,000	$400,000	$200,000	$500,000
GCM High	$800,000	$1,100,000	$800,000	$1,400,000
GCM Mean	**$400,000**	**$600,000**	**$500,000**	**$800,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. 2030 represents an average of results for 2020-2039.2050 represents an average of results for 2040-2059. Results are shown as relative differences from the baseline period 1986-2005. It is noted that the results for RCP 4.5 2050 and RCP 8.5 2030 are occasionally lower than RCP 4.5 2030. This relates to the temperature projection data which, dependent on the GCM, can have lower projections for these timeframes.

Table 14. Morbidity – Average Annual Inpatient Hospitalization Costs Incurred by Patients for TMax 1-Day Relative to 1986-2005 Baseline

TMax 1-Day Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
GCM Low	$1,000,000	$2,100,000	$1,300,000	$2,900,000
GCM High	$4,700,000	$7,100,000	$4,600,000	$8,500,000
GCM Mean	**$2,200,000**	**$3,300,000**	**$2,600,000**	**$4,700,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. 2030 represents an average of results for 2020-2039.2050 represents an average of results for 2040-2059. Results are shown as relative differences from the baseline period 1986-2005. It is noted that the results for RCP 4.5 2050 and RCP 8.5 2030 are occasionally lower than RCP 4.5 2030. This relates to the temperature projection data which, dependent on the GCM, can have lower projections for these timeframes.

Table 15. Morbidity – Average Annual Inpatient Hospitalization Costs for TMin 1-Day Relative to 1986-2005 Baseline

TMax 1-Day Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
GCM Low	$600,000	$1,300,000	$800,000	$1,800,000
GCM High	$2,900,000	$4,300,000	$2,800,000	$5,100,000
GCM Mean	**$1,400,000**	**$2,100,000**	**$1,600,000**	**$2,900,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. 2030 represents an average of results for 2020-2039.2050 represents an average of results for 2040-2059. Results are shown as relative differences from the baseline period 1986-2005. It is noted that the results for RCP 4.5 2050 and RCP 8.5 2030 are occasionally lower than RCP 4.5 2030. This relates to the temperature projection data which, dependent on the GCM, can have lower projections for these timeframes.

Labor Productivity

Background

Extreme heat can impose additional direct costs on businesses because of declining labor productivity, costs of adaption efforts, and loss of business. For regions particularly at risk to the growing frequency of extreme heat days, the probability of accruing these added costs rises, potentially leading existing and prospective businesses to relocate to more temperate climates. A 2021 study estimated that labor productivity losses could double to nearly $200 billion by 2030 and reach $500 billion by 2050, with Black and Hispanic workers facing proportional productivity losses 18% greater than non-Hispanic White workers (Atlantic Council, 2021). While the loss of labor productivity due to extreme heat can be more easily quantified, it is difficult to estimate the aggregate costs and the degree to which businesses could relocate. This analysis calculates the potential future costs of lost labor productivity based on methods and findings from existing studies. This study focuses on lost labor productivity from a subset of higher risk industries that are identified based on the varying risks employees face working in potentially dangerous weather conditions. This subset is based on risk categorizations from the National Institute for Occupational Safety and Health (NIOSH), which define heat-exposed industries as agriculture, construction, transportation, utilities, and manufacturing (Center for Disease Control and Prevention, n.d.).

Air Quality – Effects of Heat with Ozone Exposure

A study authored by Graff Zivin and Neidell looked into the impact that ozone pollution had on agricultural workers, analyzing their daily harvest rates along with environmental conditions. Their results suggest that 10 parts per billion (ppb) change in average ozone exposure can lead to a 4% decline in productivity. Their conclusion emphasized the importance of considering air pollution's impacts on labor productivity in addition to health when considering regulatory thresholds for a certain pollutant (Graff Zivin & Neidell, 2012).

Labor Productivity Methods

Several national reports base their estimates of lost productivity due to heat on a 2014 paper by Graff Zivin and Neidell (e.g., American Climate Prospectus, EPA's Climate Impact and Risk Assessment, Zhang & Shindell, 2021), which discusses effects of temperature on allocation of time (Graff Zivin & Neidell, 2014). Using data from the National Climatic Data Center merged with data from the 2003-2006 American Time Use Surveys, the authors developed regression models to estimate the relationship between temperature and allocation of time to labor as well as leisure activities. Maximum daily temperature was the evaluated variable and was considered in increments of 5°F with the lowest bin starting at 25°F and the highest bin for days over 100°F. The 76°F to 90°F bucket variable was omitted from the regression, which allows the estimates to be interpreted as change in minutes allocated at each temperature range relative to a "normal" day where the temperature is between 76°F and 80°F. The analysis was conducted for workers in both high and low risk industry sectors. They found that for high-risk labor, time allocated to labor drops by 59 minutes on days with daily maximum temperatures over 100°F (compared to the 76°F to 80°F window). The authors also tested their results for acclimatization, in one case grouping counties into the highest third of summer temperatures and the coldest third. They found that the responses to high temperature were noticeably smaller in historically warmer climates, though the results were not statistically significant.[21]

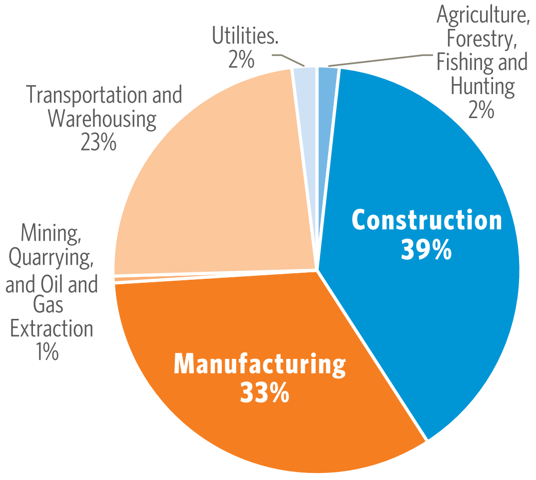
To calculate impacts on labor productivity, this analysis applied the Graff Zivin and Neidell methodology. Predictions are relative to the counterfactual in which the number of days above the temperature threshold is equal to the baseline average.[22] This number was subtracted from the projected number of days above the temperature threshold (100°F) from projected climate data for a future year. This difference in days were then multiplied by the coefficient of loss per day, or 59 minutes per day per worker. This loss is calculated as shown in the equation below:

Relative Loss = *ß x (Projected Days Above Temperature Threshold – Baseline Days Above Temperature Threshold) where ß is the coefficient estimating losses per day above temperature threshold*

To be conservative and in line with the more statistically significant results, labor productivity impacts were only quantified for high-risk sectors. High-risk industries were based on the NIOSH classifications and include manufacturing, construction, utilities, transportation/warehousing, and agriculture. Of the high-risk industries, construction and manufacturing made up the greatest percentage of jobs in Maricopa County in 2020 (Maricopa Association of Governments, 2019).

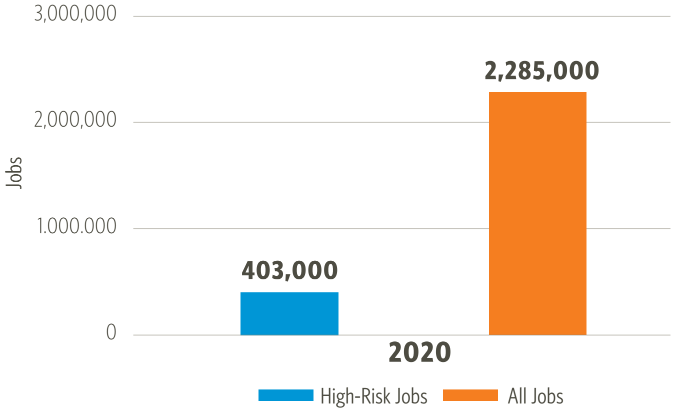
In 2020, high-risk industries comprised 17% of total jobs and contributed 21% of Maricopa County's gross regional product (GRP). Jobs data was pulled from EMSI for Maricopa County and excludes self-employed jobs. Total and high-risk GRP for Maricopa County was based on data from the Bureau of Economic Analysis and EMSI (EMSI, n.d.).

Figure 17. High-Risk Industry Sector Jobs in Maricopa County



Notes: Emsi, 2020

Figure 18. Maricopa County – High-Risk and All Jobs in 2020



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[21] Other studies have found statistically significant impacts on labor productivity for geographies with higher temperatures. Behrer & Park considered labor productivity in terms of output per capita by analyzing payroll data at the county level (Behrer & Park, 2017). The authors found a causal impact of extreme heat on local non-agricultural production and found the impact to be more pronounced for high-risk sectors (using NIOSH classifications of high-risk industries but excluding agriculture). They also found that while regions already exposed to high heat throughout the year experience smaller declines in output as a result of high heat days (suggesting they are better acclimatized to heat stress than in cooler areas) even the warmest climate distribution quartile was found to experience statistically significant impacts on output. Relative to a 70-95 temperature bin, payroll for highly exposed industries decreases 0.162% payroll per capita per day above 95°F relative to a 70-95°F bin (Behrer & Park, 2017).

[22] Park and Behrer use 1986-2011 as the baseline. Graff Zivin and Neidell use 2003-2006. This analysis uses the current conditions as baseline, as defined in the Climate Conditions Analysis (1986-2005).

Labor Results

Impacts were estimated both with constant employment and GRP and again with projections for future payroll and GRP given that there are published estimates for future employment in the region from MAG.

Table 16. Average Annual Labor Productivity Losses with Constant Employment & GRP Inputs Relative to 1986-2005 Baseline

TMax 1-Day Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
GCM Low	$532,700,000	$520,000,000	$483,400,000	$927,300,000
LOSS AS % OF COUNTY GRP	*0.2%*	*0.2%*	*0.2%*	*0.3%*
GCM High	$997,800,000	$1,243,000,000	$1,055,600,000	$1,512,200,000
LOSS AS % OF COUNTY GRP	*0.4%*	*0.5%*	*0.4%*	*0.6%*
GCM Mean	**$719,700,000**	**$990,600,000**	**$730,600,000**	**$1,197,400,000**
LOSS AS % OF COUNTY GRP	*0.3%*	*0.4%*	*0.3%*	*0.4%*

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. 2030 represents an average of results for 2020-2039.2050 represents an average of results for 2040-2059. Results are shown as relative differences from the baseline period 1986-2005. It is noted that the results for RCP 4.5 2050 and RCP 8.5 2030 are occasionally lower than RCP 4.5 2030. This relates to the temperature projection data which, dependent on the GCM, can have lower projections for these timeframes.

Table 17. Average Annual Labor Productivity Losses with Projected Employment & GRP Inputs Relative to 1986-2005 Baseline

TMax 1-Day Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
GCM Low	$753,500,000	$739,100,000	$687,500,000	$1,313,000,000
LOSS AS % OF COUNTY GRP	*0.2%*	*0.2%*	*0.2%*	*0.3%*
GCM High	$1,414,100,000	$1,760,000,000	$1,493,300,000	$2,138,500,000
LOSS AS % OF COUNTY GRP	*0.4%*	*0.5%*	*0.4%*	*0.6%*
GCM Mean	**$1,019,600,000**	**$1,403,100,000**	**$1,034,900,000**	**$1,696,400,000**
LOSS AS % OF COUNTY GRP	*0.3%*	*0.4%*	*0.3%*	*0.4%*

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. 2030 represents an average of results for 2020-2039.2050 represents an average of results for 2040-2059. Results are shown as relative differences from the baseline period 1986-2005. It is noted that the results for RCP 4.5 2050 and RCP 8.5 2030 are occasionally lower than RCP 4.5 2030. This relates to the temperature projection data which, dependent on the GCM, can have lower projections for these timeframes.

Shortened Life Cycle of Roadway Infrastructure

Background

While all of the Phoenix Metro Area's transportation networks are important to its economy, its roadways are the most ubiquitous. Over the last four decades, Maricopa County residents have made sizable investments in their roadway infrastructure through Propositions 300 and 400, which dedicated a significant portion of funding to the construction, expansion, and maintenance of freeways, highways, and arterial streets (Build America Transportation Investment Center, 2009). Likewise, under City of Phoenix's Transportation 2050 (T2050) Program, taxpayers are expected to invest $2.3 billion in the city's roadways by 2050, which equates to nearly 17% of the total T2050 tax revenue (City of Phoenix, 2020).

Longer periods of extreme heat are expected to compromise pavement integrity by softening the asphalt and increasing pavement deformation (rutting) from traffic (TRB, 2008). While small changes in temperature (e.g., one day of extreme heat per month) are unlikely to cause significant problems for pavement in the short term, the effects of extreme heat can accumulate over time and gradually become more significant over roadways' 20 – 30-year life cycle (Qiao, Santos, Stoner, & Flinstch, 2019). With temperatures in the Phoenix Metro Area expected to rise, along with increased frequency and duration of high-heat days, the quality of the region's newly constructed roads (and its other aging roads) is at risk of worsening at a faster rate and putting increased pressure on the city, county, and Arizona Department of Transportation's (ADOT) already constrained budgets.

Under current climatic conditions, ADOT is projected to need to spend upwards of $300 million per year in Maricopa County alone to properly maintain its roadway infrastructure (ADOT Roadway Maintenance Costs, 2019). Yet ADOT has historically budgeted only $75 to $100 million in annual maintenance costs for Maricopa County, indicating that the county is at risk of a sizeable budget shortfall in coming years (Kimley Horn, 2019). If high temperatures lead to roads deteriorating at a faster rate than currently anticipated, then this budget shortfall could become more dramatic. Likewise, in Phoenix, prior to T2050, budget limitations required that the City extend road life cycles to over twice their expected useful lives (65 years rather than 20 to 30 years), which led to poor quality roads (City of Phoenix, 2020). If hotter temperatures reduce the life cycle of Phoenix's T2050 roadway investments, then the City could find itself needing to increase its roadway maintenance budget like ADOT.

Air Quality – Heat & Mobile Sources / Heat & Particle Pollution

Pavement deterioration, which occurs at a faster rate under hotter temperatures, leads to road roughness, which is correlated with higher fuel usage and higher vehicle-related emissions. Likewise, the process of creating and laying asphalt also creates particle pollution (Qiao, Parry, Flintsch, & Dawson, 2015; Valle, 2017). Increased degradation of pavement coupled with increased maintenance and rehabilitation events will likely have a negative impact on Maricopa County's air quality.

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Shortened Life Cycle of Roadway Infrastructure Methods

Several studies examine the relationship between temperature, climate change, and asphalt pavement. Oxidized, or aging, pavement requires more maintenance and rehabilitation, which creates more costs over the course of asphalt pavement's useful life. Life cycle cost analyses (LCCAs) examine the total costs of capital investments, including construction, regular maintenance, and rehabilitation, and enable total cost comparisons between investment alternatives (U.S. Department of Transportation, 2002). Current pavement LCCA methodology typically assumes a static climate. However, given the inverse relationship between temperature and pavement quality, failure to include climate change, specifically increasing temperatures, in the LCCA can lead to a misrepresentation of the true maintenance needs, and their associated costs, of pavement that is experiencing increasingly hot temperatures (Valle, 2017).

Studies that have examined the relationship between climate change, temperature, and asphalt pavement LCCAs tend to project future temperatures under future climate scenarios and compare the projected temperatures against the current preferred asphalt pavement performance grade of those geographies. Performance grade (PG) refers to the temperature threshold that asphalt pavement mixtures are designed to withstand. For example, PG 64-16 refers to asphalt that is designed to perform between temperatures 64°C and -16°C (equivalent to 147°F and 3.2°F). Importantly, this temperature refers to that of the pavement – not of the air. Agencies select PGs that are suitable to their given climate, which is why these studies compare projected local temperatures against the locally preferred PG.

Numerous studies first determine whether the locally preferred PG will be suitable under future climate conditions by using American Association of State Highways and Transportation Officials (AASHTO) Pavement ME software (Valle, 2017; Chinwosky, Price, & Neumann, 2013).[23] A subset of these studies compares the LCCAs of the current PG and the PG that will be required to accommodate future temperatures to determine whether the additional capital costs associated with the higher-grade PGs are worth the reduced maintenance costs. Comparing LCCAs of PGs under current and future (hotter) climate conditions illustrates how current asphalt pavement will age faster and could become more costly over its expected

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[23] The American Association of State and Highway Transportation Officials (AASHTO)'s Pavement ME Design is a proprietary pavement design software that analyzes material selection and durability, base erosion, steel placement, layer specifications, and construction methods, among other design factors.

Caption © Credit

useful life. This study adapted the methodology by Underwood, Guido, Gudipudi, & Feinberg (2017) to develop localized estimates for how projected future temperatures will impact Maricopa County roadways. This methodology is centered around the idea the PGs are less reliable at higher temperatures, or at higher risk of deformation, and less durable (e.g., reliability less than 98%) pavement requires more repairs and maintenance and leads to an overall shortened lifespan of the pavement itself. A pavement grade that is intended to last for 30 years within a specific temperature range may instead last for only 15 to 20 years, for example, when temperatures exceed the design temperatures.

Underwood's methodology begins by calculating the projected daily pavement temperature for each GCM and each day in each future time horizon. To do this, the minimum temperature and the highest seven-consecutive day average maximum are identified for each year within each model. Within each GCM, the average of seven-consecutive day maximum and minimum temperatures are calculated across the 20 years included in each future time horizon. The average maximum and minimum temperatures of each GCM are then used to estimate the design temperatures from which the PG should be selected. Next, the projected design pavement temperatures are used to calculate the reliability (RLT, RHT) of the current PG against future temperature projections. When reliability drops below 98%, then pavement deformations can be expected to have more frequency and impact.

The final step is to compare the preferred PG of future pavement design temperatures against the current PG to assess whether the future preferred PG would shift up (or down). Understanding if a PG should shift from, for example, PG 64 today to PG 70 or PG 76 in 2030 or 2050 serves as a proxy for estimating the deterioration rate (or life cycle impacts) of the current PG. Given the variability in the GCM temperature outputs and thus the projected pavement design temperatures across the GCM, Underwood selects the median PG from the GCMs at each future time horizon. The median PG is then compared to the current PG to assess the difference between the current design temperature and the future design temperature. The below results assume that the current standard PG for City of Phoenix-managed roadways is 76-22 and that the PG for other Maricopa County roadways is PG 70-22.[24]


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To estimate the cost impacts resulting from temperature-induced shortfalls in grades, Underwood estimates the life cycle costs caused by reduced pavement performance, including changes to the construction, maintenance, and rehabilitation activities. Life cycle maintenance activities are estimated using AASHTO Pavement Design ME simulation tool (Underwood, Guido, Gudipudi, & Feinberg, 2017).[25] Underwood notes that, while roadway design and conditions are unique to each location, roadways generally share the same design specifications.

These life cycle activities and schedules, which are estimated per roadway type (e.g., interstate, state roads, U.S. routes, and local roads) are then applied to the total mileage per roadway type in Maricopa County. While Underwood, Guido, Gudipudi, & Feinberg's (2017) study considers nationwide increased costs

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[24] While City of Phoenix uses PG 76-22 for its roads, ADOT and MCDOT guidelines indicate a use of PGs ranging from 76-16 on the high end to 58-28 on the low end.
[25] The Pavement Design ME simulation tool considers population changes in its life cycle cost analysis.

of roadway infrastructure due to future temperature increases, this analysis adapted Underwood's analysis to only consider the impacts to Maricopa County's roadway network. Finally, this study uses the life cycle maintenance costs used by Underwood, Guido, Gudipudi, & Feinberg (2017), which are derived from the North Carolina and Arizona Departments of Transportation. For ease of estimating changes in life cycle costs, this analysis assumes that all roadways are new as of 2010.

Shortened Life Cycle of Roadway Infrastructure Results

Under both RCP 4.5 and 8.5 pavement temperatures are projected to increase a few degrees, which has the effect of reducing the reliability of the current standard PG and requiring that PG that is one grade higher be used. While future projected temperatures and resulting pavement temperatures will require that all roadways in Maricopa County use PG 76 by 2050, temperatures will not increase to such a degree that the preferred PG would need to increase by two levels. Given this, increased costs remain constant at a certain temperature threshold, which is evidenced by these results. Still, these estimates indicate that total pavement life cycle maintenance costs will increase by up to 4%, or nearly $230 million by 2050, not including the completion and addition of new roadways.

When these total life cycle costs are annualized over pavement's intended life cycle (30 years), Maricopa County roadways will likely need up to $8 million in additional maintenance and rehabilitation work per year. This price increase could happen as soon as the 2030 horizon in both RCP scenarios. Annual pavement maintenance needs currently cost Phoenix Metro Area transportation agencies over $100 million (Kimley Horn, 2019).

Table 18. Increase in Pavement Maintenance and Rehabilitation Costs Relative to Current Costs (2021)

Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
GCM Low	$0	$229,200,000	$0	$229,200,000
GCM High	$12,800,000	$229,200,000	$12,800,000	$229,200,000
GCM Median	$12,800,000	$229,200,000	$12,800,000	$229,200,000

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. With the assumption that all roads are new as of 2010, 2030 costs represent the increase in costs based on projected temperature increases in the first 20 years of a roadway life cycle. The 2050 costs represent the increase in costs in the total expected life cycle of roadways, which is expected to be 30 years. Projected temperatures are expected to cause pavement to degrade at a faster rate, requiring full replacement within less than 30 years. The full replacement costs, when under 30 years, are captured in these findings

Table 19. Increase in Annual Pavement and Rehabilitation Costs Relative to Current Costs (2021)

Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
GCM Low	$0	$7,600,000	$0	$7,600,000
GCM High	$640,000	$7,600,000	$640,000	$7,600,000
GCM Median	$640,000	$7,600,000	$640,000	$7,600,000

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. With the assumption that all roads are new as of 2010, 2030 costs represent the increase in costs based on projected temperature increases in the first 20 years of a roadway life cycle. The 2050 costs represent the increase in costs in the total expected life cycle of roadways, which is expected to be 30 years. Projected temperatures are expected to cause pavement to degrade at a faster rate, requiring full replacement within less than 30 years. The full replacement costs, when under 30 years, are captured in these findings

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Critical Services: Energy Demand

Background

Between now and 2050, climate-driven increases in ambient temperature are expected to increase demand for electrical use in residential, commercial, and industrial buildings. Demand for heating and cooling, which accounts for roughly half of residential and commercial energy use, fluctuates seasonally in response to outdoor ambient temperatures.[26] Studies that quantify the relationship between daily temperature increases and annual energy consumption find that higher temperatures lead to increased electricity consumption during the hottest times of the day and hottest periods of the year when electricity demand is already at its peak (Salamanca, Georgescu, Mahalov, & Moustaoui, 2015; Franco & Sanstad, 2008; Auffhammer et al, 2017; Mukherjee & Nateghi, 2018). The same studies find that in hotter locations that are more likely to have AC widely installed, electricity demand increases more rapidly with temperature increases and incremental increases in daily temperature cause electricity consumption to rise more rapidly than incremental decreases in temperature. For example, Auffhammer et al. (2017) estimate that the southern United States is expected to experience the greatest increases in load due to climate change, with substantial increases in the “peakiness” of electricity demand. Overall, average nationwide electricity demand in residential and commercial sectors is expected to increase by 0.7% to 2.2% from 2020 to 2039, meanwhile, Arizona, Texas, and Florida are expected to see the greatest increases in consumption, with increases of 9.6% to 21% from 2020 to 2039 (Rhodium Group, LLC, 2014).

Arizona’s two largest energy providers both saw record-breaking demand in 2020, with Arizona Public Service (APS) peaking at 7,659 megawatts (MW) and Salt River Project (SRP) peaking at 7,615 MW (Cheshire, 2020). In comparison, from 2013 to 2019, standard peak summer energy demand did not exceed 7,500 MW for APS and 7,250 MW for SRP (Burke, 2020) (Salt River Project, 2021). This record-breaking demand is correlated with record-breaking temperatures and, perhaps, the impacts of the COVID-19 pandemic, which led to more people working from home and using increased energy, including AC, more consistently throughout the day.

Climate-driven changes in AC use may require utility services to build additional capacity to meet higher demand when temperatures reach annual peaks in order to mitigate risk of grid failures (Rhodium Group, LLC, 2014). Risk triggers include reduced peak energy generation capacity in transmission and distribution networks, heightened strain on building AC systems, less flow capacity in lines and transformers, protection device malfunctions, and accelerated physical material degradation. In turn, these mechanical- and power-based failures have the potential to cause electrical service interruptions (Burillo, Chester, & Ruddell, 2016). Exposure risk to power outages have increased throughout U.S. metropolitan areas, with the potential for future heat disasters to cause longer-lasting power

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[26] The following analysis differentiates energy and electricity: energy describes work and heat available from all energy carriers, while electricity refers to a single type of energy usage. As of 2020, natural gas was the primary fuel used for electricity generation in Arizona, followed by coal, petroleum, and renewable energy (Energy Information Administration, 2021).

outages affecting a higher number of residents (Sailor D. J., Baniassadi, O'Lenick, & Wilhelmi, 2019). These power outages have consequential impacts on people and the economy.

This analysis, however, focuses on the impact that increased energy demand will have on consumers' monthly bills, as opposed to costs associated with critical service disruption events. On average, residential customers spend $1,100 from May to October on energy, a cost that is driven by AC usage and is unaffordable for many (Salt River Project, 2021).[27] For many people, accessibility and availability of AC can be a matter of life or death. Prolonged heat exposure and inadequate thermoregulation can result in a range of adverse health effects, including heat-related illnesses and death, and may disproportionately impact vulnerable populations. From 2006 to 2016, 42% of heat-related mortality cases in Maricopa County were caused by indoor exposure to heat (Iverson, et al., 2020). In 2020, 82% of indoor heat-related mortality cases had AC present at the time of death (Maricopa County Department of Public Health, 2020). In most of these cases (69%), the AC was functioning but not in use, suggesting that economic factors, such as costs, may have been at play.

Further, both APS and SRP are investing in system upgrades based on future climate change scenarios to accommodate future increases in energy demand in order to mitigate service disruptions, including those spurred by extreme heat events (Arizona Public Service, 2020) (Salt River Project, 2019). Additionally, the electrical grids managed by APS and SRP, among other Arizona electricity providers, are connected to a nationwide electrical grid and can rely on the larger grid infrastructure to send power in the case of power blackouts. This networked grid contrasts with the Electric Reliability Council of Texas (ERCOT), Texas' primary electrical provider, which operates its own electrical grid separate from other states. ERCOT's separated grid made it difficult for other regions to send excess power during the February 2021 blackouts (Schwartz, Collier, & Davila, 2021). Given nationwide electrical connectivity and capacity building efforts, Arizona is not expected to experience larger-scale, long-term blackouts like that of Texas in February 2021.

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Air Quality – Heat and PM

Increased AC use, driven by climate-induced temperature changes, will lead to an increase of particulate matter in the atmosphere, resulting in a positive feedback loop that further exacerbates temperature increases. In 2018, 42.6% of GHGs emitted in Maricopa County were due to electricity use. A portion of this percentage is linked to the generation of heat and cool air (Maricopa County Air Quality Department, 2018).

Energy Demand Methods

While the economic impacts of higher temperatures and energy demand take many forms, the direct cost of energy usage to consumers is an effective means of illustrating future impacts of climate change on society and the economy. As such, several studies discuss energy demand vis-à-vis heightened air conditioning demand during summer months for commercial, industrial, and residential buildings (Auffhammer & Mansur, 2014; Deschenes & Greenstone, 2011; Franco & Sanstad, 2008). According to a 2016 report by the Southwest Energy Efficiency Project (SWEEP), 87% of Arizona households use central AC compared to 61% of households nationwide (Energy Information Administration, 2009). Moreover, 25% of Arizona home energy consumption consists of AC usage, which is four times the national average for energy usage directed into home cooling (Harrington, 2015).

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[27] Summer energy bill data is for SRP customers only.

This analysis uses data provided directly from Salt River Project (SRP), a local utility, to estimate customers' future electricity costs in response to rising temperatures. Although there are multiple studies on the relationship between temperature and electricity demand, there are few studies on the relationship between future temperature projections and costs to consumers, particularly in the Arizona context. Projecting future costs to consumers in response to rising temperatures requires consideration of how electricity providers may adapt their sources, grids, and pricing mechanisms to accommodate future changes in demand. For example, APS and SRP are making investments in their grids to increase the capacity and resilience of their grids, which will allow the utilities to better accommodate (peak and non-peak) energy demand and, thus, mitigate future cost impacts for customers. Projections of future consumer electricity costs, however, would consider current grid capacity and pricing structures and, as a result, would overestimate costs.

Given the dynamic relationship between temperature, demand, grid capacity, and price, SRP has limited its cost projection data to a 1°F increase in average summer temperature, which it defines as May 1 through October 31. SRP estimates that a 1°F in average summer temperature will lead to $64 increase in residential bills and $205 increase in commercial bills during the six-month summer period (SRP, 2021).[28] Any changes in average summer temperature beyond 1°F will be met with grid investments that would result in price changes that are not currently known. The estimated increase in summer bills associated with a 1°F increase in summer temperatures were applied to the total estimated number of residential and commercial customers based on U.S. Energy Information Administration (EIA) 2020 customer information (Energy Information Administration, 2021).

Energy Demand Results

SRP estimates, based on current context, that a 1°F degree increase in temperature during the summer months of May through October could increase average summer residential bills by $64, or $10 per month. For commercial customers, bill increases are estimated to increase by $206, or $34 per month.[29] This study estimates that average summer temperatures will rise by 1 - 3°F by 2030 and 3 - 8°F by 2050, indicating that there is potential for average summer electricity bills to increase more if local electricity providers do not adapt and expand their capacity and pricing accordingly. Given that all GCMs in both timeframes and RCP scenarios reach the 1°F threshold of SRP's customer cost projections, there is no difference between them in the results.

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Table 20. Projected Increase in Annual Summer Energy Costs Relative to 1986-2006 Baseline

Results	RCP 4.5 2030	RCP 4.5 2050	RCP 8.5 2030	RCP 8.5 2050
Residential	$113,000,000	$113,000,000	$113,000,000	$113,000,000
Commercial	$41,400,000	$41,400,000	$41,400,000	$41,400,000
Total	**$154,400,000**	**$154,400,000**	**$154,400,000**	**$154,400,000**

Notes: Dollars rounded to nearest $10,000. Shown in $2021. No financial discounting applied. Relationship of energy cost increases based on recent usage data and applied to the number of residential and commercial customers, based on 2020 customer counts from EIA.

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[28] This temperature and electricity demand relationship is based on SRP data from 2016 through 2020.

[29] Commercial costs based on small commercial energy users.

Appendix D

Heat Solutions - Detail

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Cool Roofs

For the cool roof solution scenario, it was assumed that 100% of all roofs would be have cool roof materials by 2050. This was associated with a daytime temperature reduction of 1.08°F by 2050 and a reduction of 0.36°F by 2030 for partial implementation (Salamanca F., Georgescu, Mahalov, Moustaoui, & Martilli, 2016). The daytime temperature reduction was applied to the maximum daily temperature and cost of inaction indicators were re-run. The average results for the 10 GCMs were assigned to 2030 and 2050, with their respective temperature changes, while years in between were interpolated. For energy demand, the cooling effect of urban tree canopy is estimated to mitigate the 1°F increase in annual summer temperature, which was the impact costed in the cost of inaction (see Energy Demand Methods for more information on this 1°F threshold approach). For site specific benefits, it was assumed that future residential energy demand would decrease by 13% with the full implementation of cool roofs and earlier years were interpolated linearly (Salamanca F. , Georgescu, Mahalov, Moustaoui, & Martilli, 2016).[30] It was found that the global cooling impacts would not result in any change to the roadway infrastructure life cycle costs so there are no benefits associated with this category. Given that some of the roofs would be replaced towards the end of the period of analysis, residual benefits were included for the remaining periods of the life cycles. Average annual benefits for 2030 and 2050 with partial and full implementation for cool roofs are presented on page 56.

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[30] TThis temperature reduction was estimated based on Figure 4 of *Citywide Impacts of Cool Roof and Rooftop Solar Photovoltaic Deployment on Near-Surface Air Temperature and Cooling Demand* (2016) which includes the diurnal cycle of modelled 2-m air temperature differences averaged over the period of 10-days of extreme heat in July 2009 across the Phoenix Metro Area. An estimated reduction of 0.6°C, or 1.08°F for maximum temperatures was applied with 100% cool roof coverage relative to baseline conditions. The temperature reduction relationship was assumed to be linear.

Table 21. Cool Roof Average Annual Benefits with Partial Cool Roof Implementation in 2030

Results	RCP 4.5 2030	RCP 8.5 2030
Mortality	$120,200,000	$120,400,000
Morbidity	$500,000	$500,000
Labor Productivity	$69,900,000	$69,300,000
Energy – Global	$0	$0
Energy - Direct	$92,700,000	$92,700,000
TOTAL	**$283,300,000**	**$282,900,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied. No global energy cooling benefits because the 1°F threshold is not yet reached by this stage of implementation.

Table 22. Cool Roof Average Annual Benefits with 100% Cool Roof Implementation in 2050

Results	RCP 4.5 2050	RCP 8.5 2050
Mortality	$330,000,000	$389,500,000
Morbidity	$1,300,000	$1,500,000
Labor Productivity	$197,900,000	$167,700,000
Energy – Global	$154,400,000	$154,400,000
Energy - Direct	$278,100,000	$278,100,000
TOTAL	**$961,700,000**	**$991,200,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied.

Roofs were costed based on the square footage of roof to be replaced and roof type. Roof square footage was estimated based on building footprint and land use information published by Microsoft (Microsoft, 2018). Overall, based on land use footprint analysis, nearly 70% of the roof area is estimated to be single-family residential. Commercial, mixed use, multi-family residential, office, other/public employment were the remaining roof areas costed and make up an estimated 22% of roof area based on the building footprint approach. Vacant, industrial, agricultural, transportation, and open space were excluded from the costing and make up less than 10% of the estimated roof area using the footprint approach. It was assumed that most of these land uses already have light-colored roofs under baseline conditions and as such they were not included in the costs.

Table 23. Cool Roof Premium Cost Ranges

Roof Type	Slope Type	Description of Premium Application	Premium ($/SF)
Built-up Roof	Low	White gravel cap sheet - not separately applied	$0.50-0.75
Shingles	Steep	Select light color shingles	$0.25-0.75
Concrete Tiles	Steep	Select light concrete tiles - premium	$1.50-3.00
Clay Tiles	Steep	Add white glaze to terracotta	$5.00-8.00
Liquid Applied Coating	Both (low and steep)	Select white finish coat	$0.50-$1.00

Notes: Shown in $2021.

Table 24. Benefit-Cost Ratios for 100% Cool Roofs by 2050

Emissions Scenario	Benefits	Costs	Benefit-Cost Ratio
RCP 4.5	$7,829,200,000	$1,512,300,000	5.18
RCP 8.5	$8,006,700,000	$1,512,300,000	5.29
Average	**$7,918,000,000**	**$1,512,300,000**	**5.24**

Notes: Dollars rounded to nearest $100,000 with a 5% discount rate applied to the full period of analysis (2020-2059).

Urban Tree Canopy

For the urban tree canopy solution scenario, it was assumed that urban tree canopy coverage would reach 25% by 2050, which was chosen in part due to the City of Phoenix's resiliency goal of reaching 25% tree and shade canopy in pedestrian areas by 2030 (City of Phoenix, 2021). The baseline urban tree canopy for Maricopa County was assumed to be just over 6% and cooling benefits were based on the net change in temperature from baseline conditions resulting in a daytime temperature reduction of 3.14°F by 2050, and a reduction of 1.44°F by 2030 assuming 15% urban tree canopy coverage by this time (Department of Forestry and Fire Management, 2021; McDonald R. I., Kroeger, Zhang, & Hamel, 2019).[31] It is important to note that cooling benefits of urban trees are most felt within the more immediate proximity of the tree and that this is not accounted for in the high-level cooling assumptions applied in this study, which assigns a constant cooling benefit throughout the study area. Benefits per tree were assumed to reach full potential 12 years after planting to account for canopy maturation. The temperature reduction was applied to the maximum daily temperature and cost of inaction indicators were re-run. The average results for the 10 GCMs were assigned to 2030 and 2050, with their respective temperature changes, while years in between were interpolated. For energy demand, the cooling effect of urban tree canopy is estimated to mitigate the 1°F increase in annual summer temperature, which was the impact costed in the cost of inaction (see Energy Demand Methods for more information on this 1°F threshold approach). For site specific benefits, it was assumed that future residential energy demand would decrease by 15% with 25% canopy coverage and earlier years were interpolated linearly (McPherson & Rowntree, 1993). This reduction in energy demand was applied to the estimated number of households that would directly benefit from the planting of a new tree. It was assumed new trees would be planted in a location that maximizes cooling benefits, which is generally along a southwesterly edge. Because trees were assumed to be planted in urban areas for this study (rather than along highways) and since the City of Phoenix already uses pavement materials that are suited for extreme temperatures, the global cooling benefits of trees are not estimated to result in any changes to the roadway life cycle costs and as such there are no benefits associated with this category. Given that a portion of trees planted would have benefits beyond the period of analysis, residual benefits

Table 25. Urban Tree Canopy Average Annual Benefits with Partial Urban Tree Canopy Coverage in 2030

Results	RCP 4.5 2030	RCP 8.5 2030
Mortality	$379,000,000	$397,600,000
Morbidity	$1,500,000	$1,600,000
Labor Productivity	$281,300,000	$269,700,000
Energy – Global	$154,400,000	$154,400,000
Energy - Direct	$188,900,000	$188,900,000
TOTAL	**$1,005,100,000**	**$1,012,200,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied.

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[31] The temperature reduction relationship was assumed to be linear and based on relationship of 2.5% canopy coverage resulting in 0.23°C temperature change for the City of Phoenix (McDonald R. I., Kroeger, Zhang, & Hamel, 2019).

were included for the remaining periods of the life cycles. Average annual benefits for 2030 and 2050 with partial and full implementation for urban tree canopy are presented in Table 25 and 26.

Costs for trees were estimated for both upfront capital and annual maintenance costs, as shown in Table 27. Upfront capital costs are a weighted average of lower cost tree installation (e.g., trees planted in parks) and higher cost tree installation (e.g., trees planted in right-of-way that require supportive water infrastructure) as based on information provided by the City of Phoenix and combined with assumptions on where trees would be planted using existing tree distribution data (Davey Resource Group, 2014). Life cycles were assumed to be 40 years and it was assumed that 60% of trees planted would survive (McPherson, et al., 2004). Trees were estimated to be planted at a linear rate to reach 25% canopy coverage by 2050 with an underlying assumption of a 12-year duration to reach maturity. The existing urban tree canopy was estimated to be just over 6% based on data from Arizona's Department of Forestry and Fire Management on urban tree canopy cover for Maricopa County from 2016 (Arizona Department of Forestry and Fire Management, 2016). It was assumed just over 5.6 million trees would be required for 25% urban tree canopy with more planted to account for a 60% survival rate. Accounting for tree mortality, an estimated 9.4 million trees were assumed to be planted (Trees Matter, n.d.).

Based on the above assumptions related to costs and benefits, results over the full period of analysis (2020-2059) with a 5% discount rate are shown in Table 28.

Table 26. Urban Tree Canopy Average Annual Benefits with 25% Urban Tree Canopy Coverage in 2050

Results	RCP 4.5 2050	RCP 8.5 2050
Mortality	$836,900,000	$986,100,000
Morbidity	$3,300,000	$3,900,000
Labor Productivity	$610,800,000	$529,300,000
Energy – Global	$154,400,000	$154,400,000
Energy - Direct	$320,900,000	$320,900,000
TOTAL	**$1,926,300,000**	**$1,994,600,000**

Notes: Dollars rounded to nearest $100,000. Shown in $2021. No financial discounting applied.

Table 27. Tree Implementation Costs

Category	Cost per Tree
Upfront Capital	$490
Annual Maintenance	$16

Notes: Shown in $2021. Upfront capital cost rounded to the nearest $10.The capital value represents a weighted average of costs provided by the City of Phoenix which range from a low-end of $150 (e.g., for planting a tree in a park) to a high end of $700 (e.g., for planting a tree in a right-of-way with water infrastructure support needs). The weighting of the costs, or in other words the anticipated location of the tree planting, was estimated based on a plot sampling of about 3.1 million trees organized by land use from the 2014 Community Forest Assessment for Phoenix (Davey Resource Group, 2014). The O&M value is a weighted public and private average O&M based on the ranges provided in the Desert Southwest Community Tree Guide from 2004 (McPherson, et al., 2004).

Table 28. Benefit-Cost Ratios for 25% Urban Tree Canopy by 2050

Emissions Scenario	Benefits	Costs	Benefit-Cost Ratio
RCP 4.5	$15,073,442,622	$4,038,930,144	3.73
RCP 8.5	$15,490,530,957	$4,038,930,144	3.84
Average	**$15,281,986,790**	**$4,038,930,144**	**3.78**

Notes: Dollars rounded to nearest $100,000 with a 5% discount rate applied to the full period of analysis (2020-2059).

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