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Grid Resilience Reports

Arizona

Energy & Resources | Networks
12/11/2024

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Baringa

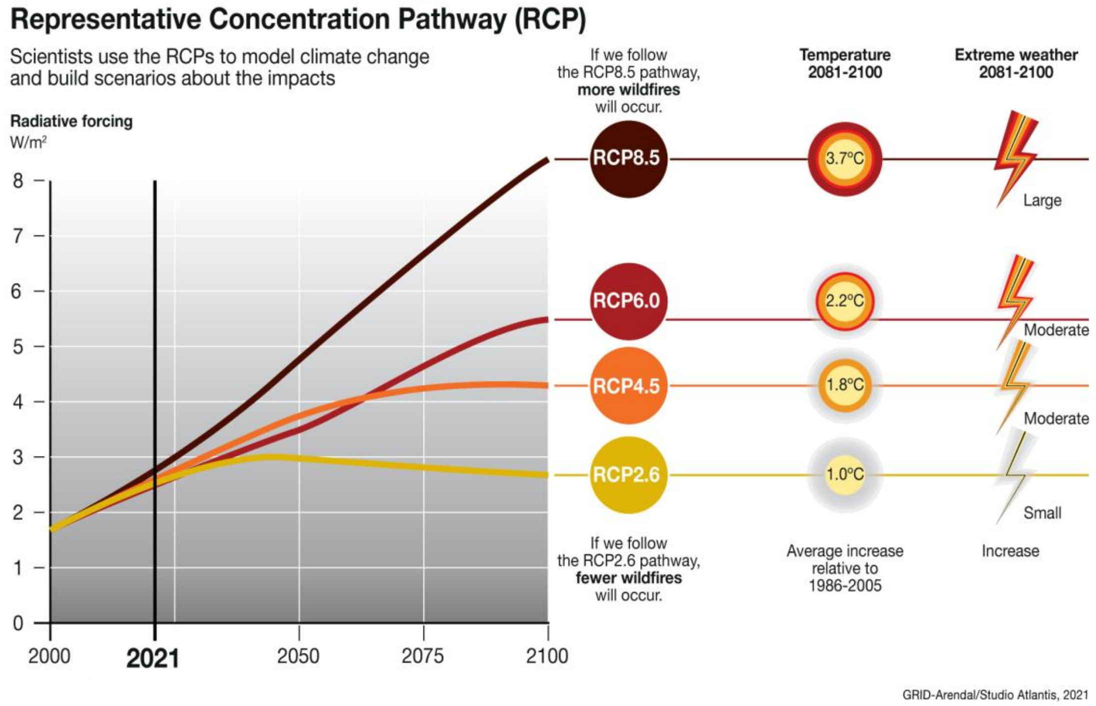
Grid Resilience Reports

Climate Science Background, Data Sources, and Analysis Approach

RCPs and SSPs provide viable climate pathways for an uncertain future

Generating Emission Scenarios

- **Representative concentration pathways (RCPs) project GHG concentrations:** Defined by the IPCC in 2014 as scenarios of future emission concentrations and other radiative forcing that align to climate projections.[1] RCPs use assumptions relating to policy decisions and individual behavior that may change future GHG emissions concentrations.[1] SSPs have largely replaced RCPs.
- **Shared socioeconomic pathways (SSPs) provide 5 'storylines' to contextualize RCPs** and to provide the various future pathways possible.[2] They consider how the world could evolve socioeconomically and politically, including how various levels of climate change mitigation and adaptation could be achieved and will influence future climate scenarios.[3]
- RCPs included in the CLIMRR dataset include RCP 4.5 and RCP 8.5.
- SSPs included in the Hydrosource dataset include SSP585, SSP370, SSP245, and SSP126.



Modeling Scenario: RCP 4.5

- **"Moderate" scenario**: Emissions peak around 2040 and then slowly begin to decline.[4] Temperatures warm about 3.2 °F from a 2000 baseline.[5]
- CO2 emissions plateau before falling mid-century, as energy use sharply declines and there is large scale reforestation.[6]

Modeling Scenario: RCP 8.5

- **"Rapid growth" scenario:** Emissions continue to rise throughout the twenty-first century.[4] Temperatures warm about 6.6 °F from a 2000 baseline.[5]
- CO2 emissions are three times higher than the present by end-century, with a large increase in methane emissions and continued fossil fuel use.[6]

[1] Source: ComEd Vulnerability Study 2023
[2] Source: Jupiter
[3] Source: Carbon Brief
[4] Source: Help (cal-adapt.org)
[5] CoastAdapt
[6] Climate Copernicus

Baringa leverages national downscaled climate datasets with high granularity to assign county-level climate exposure

	CLIMRR by Argonne National Lab (ANL)	HydroSource by Oak Ridge National Lab (ORNL)	RAWS by Western Regional Climate Center (WRCC)
Dataset Description	The Climate Risk and Resilience Portal (CLIMRR) provides highly localized climate projections from mid- to end-century using a supercomputer to model 60 climate variables.	HydroSource is a comprehensive national water energy digital platform consisting of hydropower-related data set, models, visualizations, and analytics tools.	The Wildland Fire Remote Automated Weather Stations (RAWS) data set provided by WRCC is a quality-controlled repository of hourly data for 17 select weather metrics from a network of weather stations across western states.
Data Provider Description	Argonne National Lab is a federally-funded science and engineering research center sponsored by the Department of Energy.	Oak Ridge National Lab is a federally funded research and development center sponsored by the Department of Energy.	The Western Regional Climate Center is one of 6 Regional Climate Centers in the United States. WRCC works jointly with NOAA to coordinate climate activities and conduct applied research on climate issues in the West.
Years Covered	Historical, Mid-Century, End-Century	1980-2099	2000-2022
Spatial Resolution	12 km (aggregated to county)	County	Weather station (aggregated to county)
Hazards	RAIN, FIRE, HEAT, COLD, DROUGHT	FLOOD	WIND

Baringa leverages national downscaled climate datasets with high granularity to assign county-level climate exposure (cont.)

	CLIMRR by Argonne National Lab (ANL)	HydroSource by Oak Ridge National Lab (ORNL)	RAWS by Western Regional Climate Center (WRCC)
Key Metrics	Seasonal Fire Weather Index; Annual Precipitation; Cons. Days w/o Precipitation; Days Above X°F Heat Index; Annual Cooling Degree Days; Seasonal Max Temperature; Annual Min Temperature; Annual Heating Degree Days; Seasonal Min Temperature	Annual VIC Runoff (SSP585)	Hourly Max Wind Gust
Mapping/Analysis	Used a Python script that returned the most extreme value (high or low depending on hazard) from grid cells intersecting a particular county.	Averaged across the 7 different climate model values provided for the SSP585 warming scenario to return a single, composite runoff level for each county in each year. 2000 was used for historical, 2050 for mid-century, and 2090 for end-century.	Mapped weather stations to their respective counties. If a county had multiple weather stations, the station with the highest average hourly value was selected to represent the county. Counties with no stations were mapped to the closest station in a neighboring county. GEV analysis was conducted using the pyextremes EVA function to derive return periods.
Rationale	• Reputable data provider • Accessible, open-source data allows for our methodology to be reproduced/quality checked • Provides climate projections for hazards with a significant climate signal • More than sufficient spatial resolution to gauge climate exposure at a county level	• Reputable data provider • Climate projections forecast change in exposure over time • Same spatial resolution as outage data (county level) • Data set includes pluvial flooding (from flash floods and surface runoff) which is more likely to contribute to outages because it is faster-acting and can hit urban centers	• Reputable data provider • Wind does not have a strong climate signal, so projections were not required • Sufficient density of stations per state to assign to counties • Quality checked • Hourly resolution was sufficient for deriving return periods

Baringa is leveraging forward-looking climate projections to inform its technical assistance work for states in WECC

Wind

Source: **Western Regional Climate Center (WRCC)**
Input metric: Hourly max wind speed (mph)
Output: Wind speed at key return periods via GEV distribution

Wildfire

- Source: **CLIMRR (ANL)**

Input metric: Fire weather index (FWI) by grid cell
Output: Maximum fire weather index by county

Precipitation

Source: **CLIMRR (ANL)**
Input metric: Annual total precipitation (in/year) by grid cell
Output: Max annual total precipitation (in/year) by county

Drought

Source: **CLIMRR (ANL)**
Input metric: Consecutive days with no precipitation by grid cell
Output: Max consecutive days with no precipitation by county

Heat

Source: **CLIMRR (ANL)**
Input metrics:

- Days above 95, 105, 115, 125 °F
- Annual cooling degree days
- Seasonal maximum temperatures

Output: Input metrics applied from a grid cell level to a county level

Cold

Source: **CLIMRR (ANL)**
Input metrics:

- Annual minimum temperature
- Annual heating degree days
- Seasonal minimum temperatures

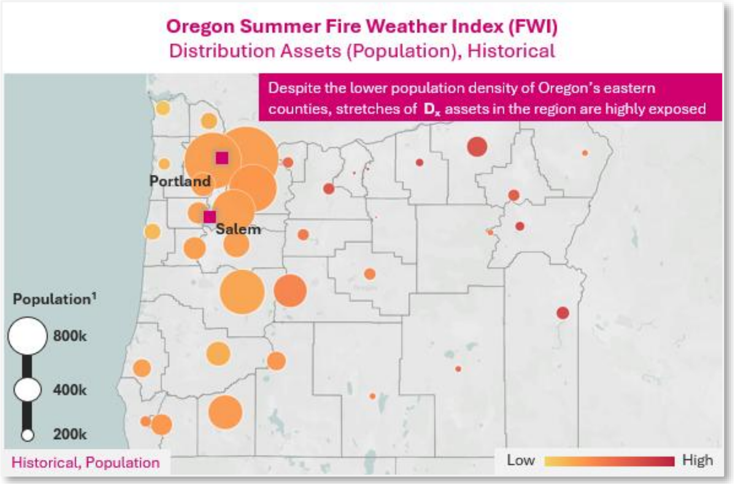
Output: Input metrics applied from a grid cell level to a county level

Flood

Source: **Hydrosource (ORNL)**
Input metric: Annual Variable Infiltration Capacity (VIC) model runoff (mm/year)
Output: Average annual VIC runoff (pluvial flooding) for 4 warming scenarios and 3 time periods (historical, mid-century, end-century)

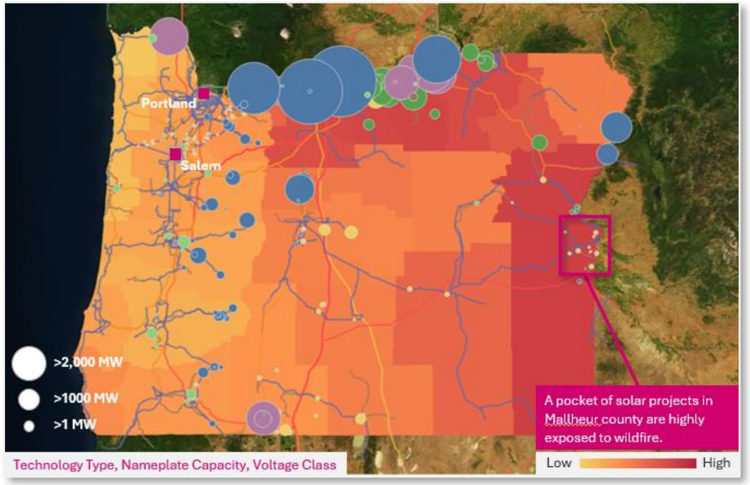
This report is standardized to include 3 different data visualizations that provide insights for Distribution, Transmission, and Generation across 7 extreme weather hazards

1 Distribution Maps



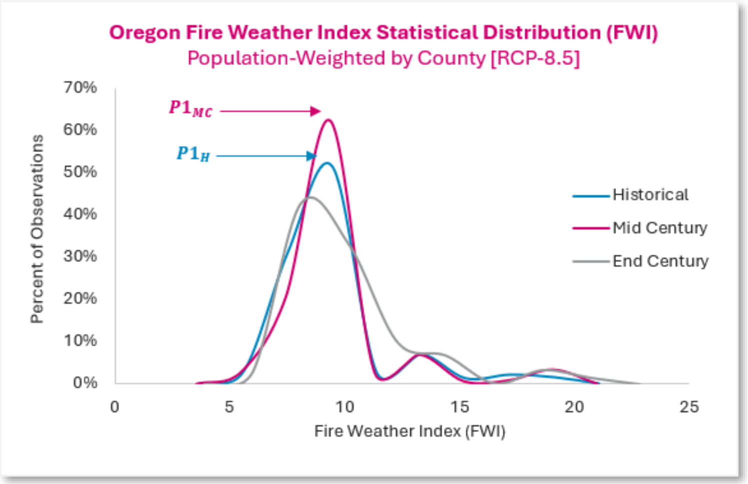
- **Purpose:** Uses population as proxy for volume of distribution assets given that the location of distribution assets is restricted.
- **Interpretation*:** Locate areas of high exposure by identifying counties with coincident large bubbles and dark colors. This indicates a combination of high volume of Dx assets and significantly high extreme weather projections.

2 Transmission & Generation Maps



- **Purpose:** Overlays transmission and generation assets on climate projections by county.
- **Interpretation:** Locate areas of high exposure by identifying assets in counties of high risk. Exposure differs by asset class and will be highlighted in Key Insights tables throughout.

3 Statistical Distribution Graphs



- **Purpose:** Contains statistical insights related to each metric. Indicates change in dispersion and severity of risk over time on average
- **Interpretation:** An increase in the width of the peak indicates a decrease in concentration of exposure, meaning more counties are exposed to more severe weather. A shift right in the curve indicates that on average, counties are experiencing more severe weather.

***Note:** Analysis addresses risk given volume of assets and does not account for risk to remote customers at end of radial distribution grids.

Asset Class Overviews

Executive Summaries

L Low M Moderate H High

AZ could consider increasing resilience spend to address escalating fire exposure in S/SW counties, and weatherize assets in NE counties given continued freezing/cold risk

Key Takeaways

- Confirm T&D assets in W counties are low risk due to limited vegetation. Focus wildfire mitigation investment in N. and NE. counties as well.
- Consider methods to address supply derating (VPPs) and Dx system capacity upgrades to avoid direct failure from heat in S/ SW counties.
- Focus generation weatherization, Dx pole upgrades, and Tx structure reinforcement on assets in NE counties facing continued freezing/snow exposure.

Hazard	Exposure	Change to Mid-Century	Generation	Transmission & Distribution (Tx & Dx)	AWPI*	Projects to Address Exposure
FIRE	H	↑	**Consider investment in emergency response planning and innovative solar O&M processes** • Enhanced monitoring coupled with emergency response planning could reduce restoration times. • Innovative solar cleaning projects or optimized maintenance scheduling could help combat derating during fires.	**Focus hardening efforts on Dx assets and HV import/export lines in N. and NE. counties** • HV tie lines to UT/NM, which are critical during extreme weather events, are exposed to wildfire risk due to high vegetation density. • Consider counties that border population centers where there are high volume of assets, but limited undergrounding given suburban/rural building.		**Gen:** Harden control houses, upgrade access roads, update emergency planning. **T&D:** Dx pole upgrades, undergrounding, pole wrapping, vegetation management, and enhanced monitoring.
HEAT	H	↑	**Explore flexible DER to offset derating of supply** • DER/VPP proliferation minimizes reliance on a pocket of natural gas, solar, and nuclear plants that will be heavily exposed to extreme heat.	**Consider substation/transformer upgrades and more cost-effective Tx hardening methods** • Significant exposure to days >105°F requires substation and transformer upgrades to avoid direct failure. • Widespread heat exposure necessitates upgrades that harden the entire length of a high voltage transmission line, particularly in Maricopa County.		**Gen:** Enhanced cooling, demand response, DERs/VPPs. **T&D:** Reconductoring, vegetation management, undergrounding, line upgrades, dynamic line rating (DLR).
COLD	M	↓	**Focus weatherization technologies on generation assets in NE counties** • Hydroelectric and wind generators face continued cold exposure in Coconino and Navajo Counties.	**Consider Dx pole upgrades and Tx structure reinforcement in NE counties** • Despite warming, assets in NE counites continue to face low minimum temperatures and potentially icing risk.		**Gen:** Generator heating, enclosures, enhanced design standards. **T&D:** Dx pole upgrades, Tx structure reinforcement, vegetation management, undergrounding.

* AWPI = Alignment with proposed investment (40101(d) Round 1 project proposals)

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L Low M Moderate H High

AZ could consider substation fortifications in central counties, Tx and Dx reinforcement in north-central counties, and enhanced data collection to better forecast hydro output

Key Takeaways

- Consider reinforcing Tx and Dx infrastructure in northern and Maricopa counties to address high levels of wind exposure, especially at high elevations.
- AZ could prioritize substation and Dx pole fortification in Yavapai and Greenlee Counties to address potential pluvial flood exposure.
- Improve data collection regarding drought and precipitation to more accurately forecast hydroelectric production from dams along the Colorado River.

Hazard	Exposure	Change to Mid-Century	Generation	Transmission & Distribution (Tx & Dx)	AWPI*	Projects to Address Exposure
FLOOD	L	→	**Most supply technologies are not significantly exposed to flood** • A handful of solar plants in Yavapai County are significantly exposed to flooding, which can inundate inverters and other ground-level equipment.	**Though low level of pluvial flooding exposure, AZ could conduct further analysis and research to identify specific low-lying substations at risk.** • HV substations could be exposed to flooding in Yavapai, Gila, and Greenlee Counties, which can cause direct failure.		**Gen:** Elevate ground-based equipment, flood walls, equipment enclosure, enhanced drainage. **T&D:** Substation elevation, flood walls, substation enclosure, Dx pole reinforcement/replacement.
WIND	M	→	**AZ could consider investments to buttress solar racking and anticipate turbine cutouts** • Solar plants in Yavapai and Mohave Counties are exposed to 100-year return values exceeding some solar panel wind ratings.	**Tx and Dx infrastructure in Maricopa and northern counties could be prioritized for reinforcement** • Critical HV juncture in Maricopa County could be considered for Tx structure reinforcement. • High-elevation N counties face high winds.		**Gen:** Enhanced equipment design standards, solar racking reinforcement. **T&D:** Tx structure reinforcement, undergrounding, decreased spans.
DROUGHT	H	↑	**Grid operators could consider using climate-adjusted inputs for hydro output forecasting** • Drought exposure the Hoover and Davis Dams increases 12% by mid-century. • Drought also derates solar and natural gas.	**Drought exposure does not have a material impact on transmission and distribution assets.**		**Gen:** Enhanced/closed-loop cooling systems, climate-adjusted supply forecasting, solar O&M innovation (panel cleaning).
RAIN	L	→	**AZ could seek out additional data to better understand future hydroelectric production** • Consider the impact of more frequent extreme rain events on hydro output and asset operation.	**Precipitation exposure does not have a material impact on transmission and distribution assets.**		**Gen:** Climate-adjusted supply forecasting, dam reinforcements, reservoir enlargement.

*** AWPI = Alignment with proposed investment (40101(d) Round 1 project proposals)**

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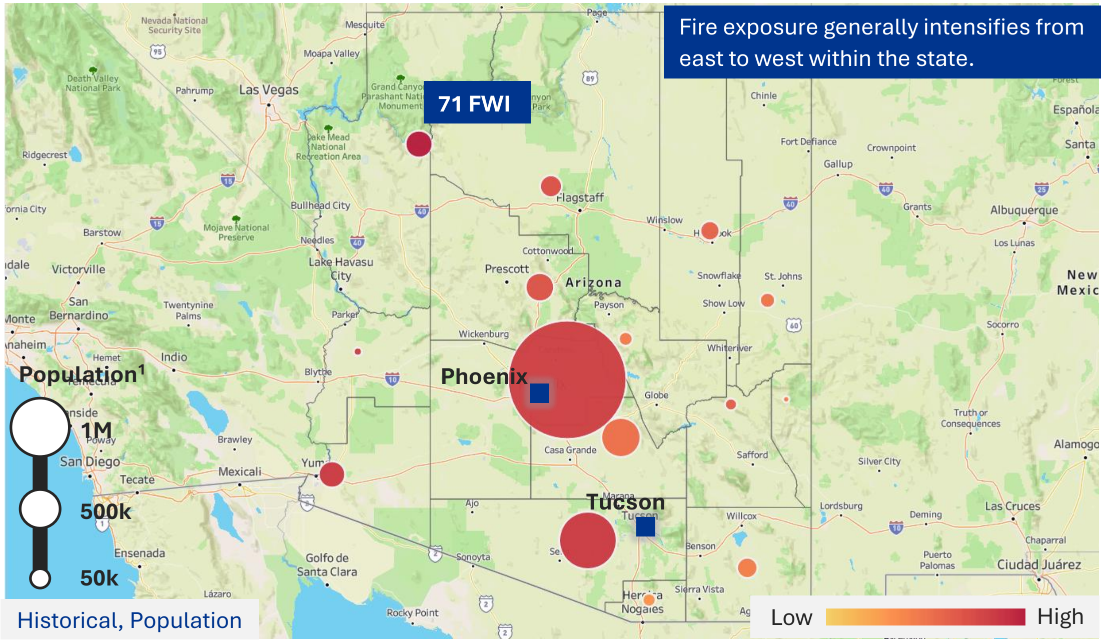
Wildfire

Asset Analysis

AZ could consider prioritizing counties that are adjacent to population centers where there is a large volume of Dx assets, high wildfire exposure, and limited undergrounding

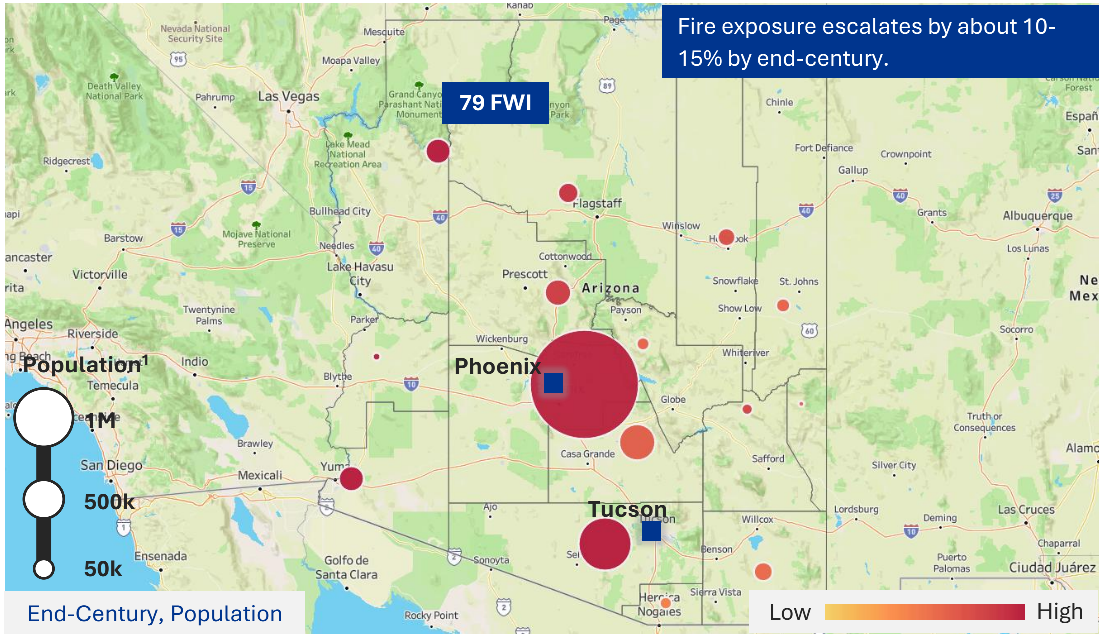
Arizona Summer Fire Weather Index (FWI)
Distribution Assets (Population), Historical



KEY OBSERVATIONS

- Historical **wildfire exposure is concentrated in Arizona's SW counties,** although FWI levels are generally high throughout the state.
- **Population centers in the central region of the state are heavily exposed,** posing a threat to a high density of Dx assets.
- Rural W counties are highly exposed and are more likely to be served by radial Dx lines that can cause prolonged outages if damaged by fire.

Arizona Summer Fire Weather Index (FWI)
Distribution Assets (Population), End-Century [RCP-8.5]



KEY OBSERVATIONS

- FWI increases by up to 8 points across the state, demonstrating the importance of utilizing **forward-looking climate projections for state-wide fire mitigation planning.**

●	**Mohave County**	Mohave County faces peak state-wide fire exposure (>98th percentile nationally) and has a large spatial extent, putting many radial last-mile Dx lines at risk.

Source: ClimRR, US Census Bureau, City and Town Population Totals

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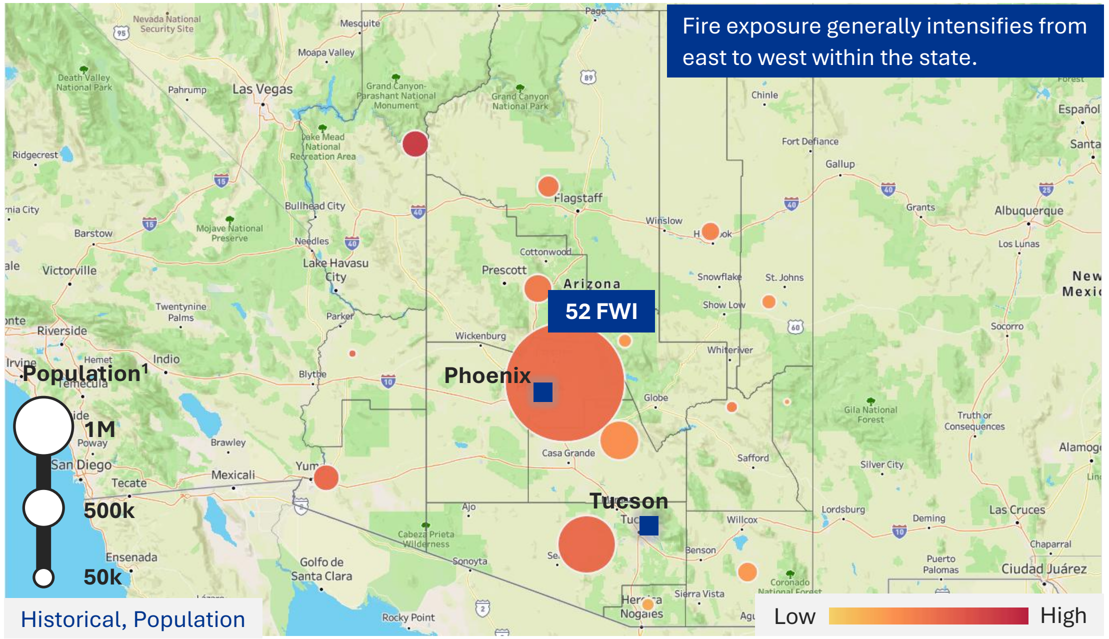
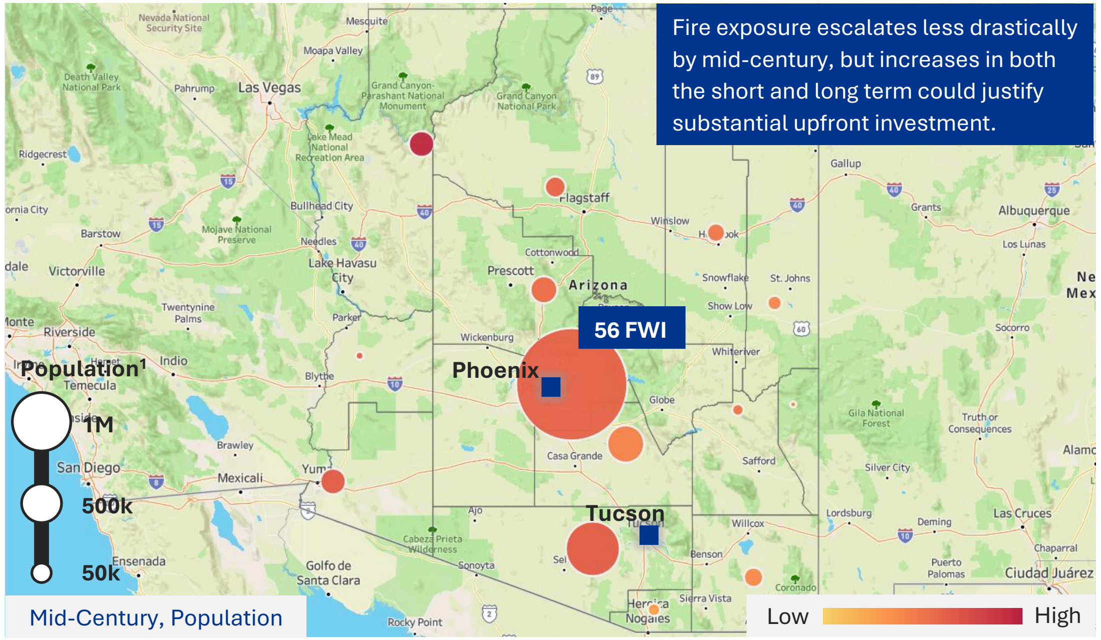
AZ could consider prioritizing counties that are adjacent to population centers where there is a large volume of Dx assets, high wildfire exposure, and limited undergrounding

Arizona Summer Fire Weather Index (FWI)
Distribution Assets (Population), Historical



Arizona Summer Fire Weather Index (FWI)
Distribution Assets (Population), Mid-Century [RCP-8.5]



KEY OBSERVATIONS

- Historical **wildfire exposure is concentrated in Arizona's SW counties,** although FWI levels are generally high throughout the state.
- **Population centers in the central region of the state are heavily exposed,** posing a threat to a high density of Dx assets.
- Rural W counties are highly exposed and are more likely to be served by radial Dx lines that can cause prolonged outages if damaged by fire.

KEY OBSERVATIONS

- FWI increases by up to 4-5 points across the state by mid-century, demonstrating the need for **near-term grid upgrades** to mitigate fire exposure.

Coconino County — Coconino County faces the most severe increase in fire exposure by mid-century across the state (48 → 54 FWI), justifying near-term grid hardening investment in the region.

Source: ClimRR, US Census Bureau, City and Town Population Totals

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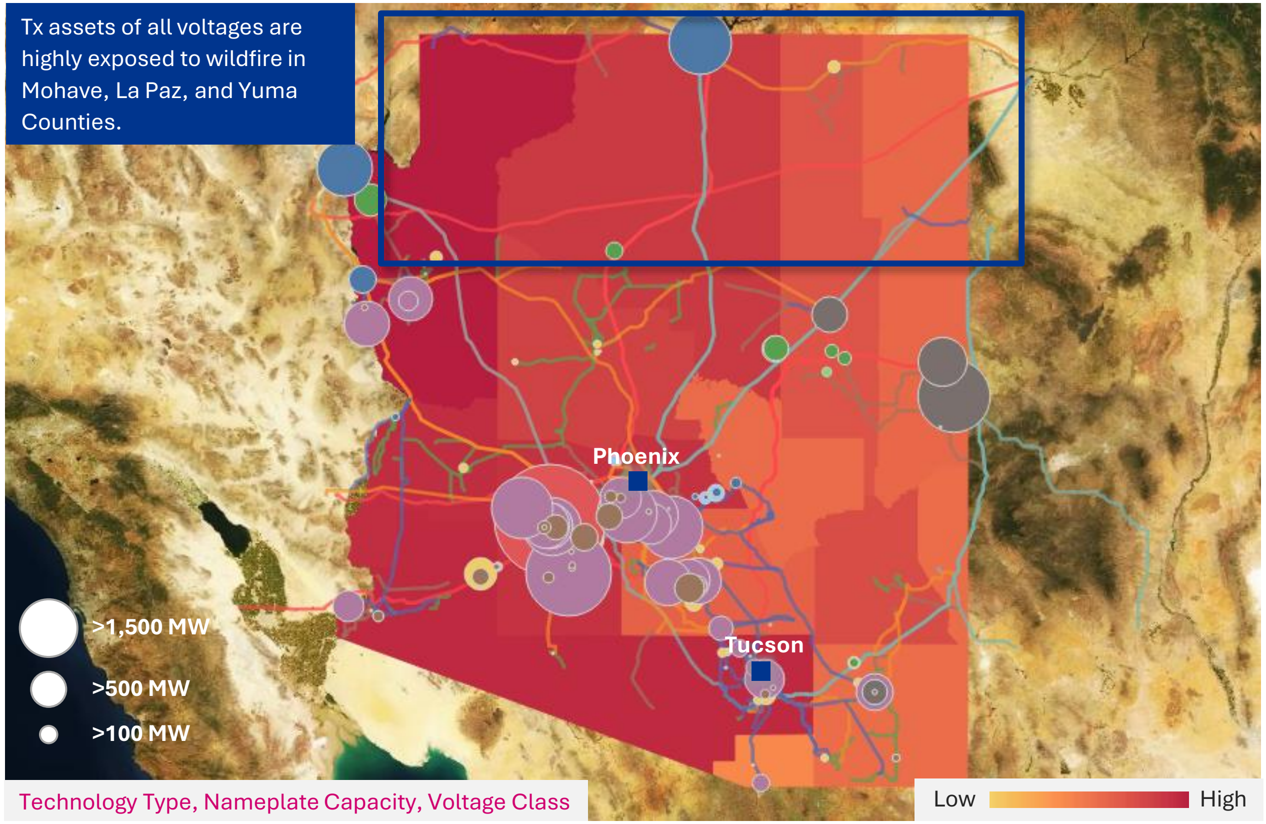
AZ could consider prioritizing hardening for highly exposed remote Tx assets in highly vegetated areas in the N. and NW. counties, especially those utilized for electricity import

Arizona Summer Fire Weather Index (FWI)

Generators & Transmission, Mid-Century [RCP-8.5]



Onshore Wind | Coal Plant | Hydroelectric | Nuclear | Solar Photovoltaic

Biomass | Natural Gas Plant | Pumped Storage | Batteries | Other

500kV | 345kV | 220-287kV | 100-161kV | <100kV

Source: ClimRR, EIA860, HIFLD

Key Highlights	Analysis
Transmission	• Remote transmission assets are critical for last mile rural customers and are highly exposed in western counties. • Although, western 500 kV Tx lines connecting AZ to CA/NV are highly exposed, limited vegetation in this region reduces risk materiality. • AZ could focus hardening investment in Tx hardening on HV lines in the N & NE given imports from NM and UT.
Solar	• Solar assets in Yuma and Pima Counties are highly exposed to wildfire. • Soot and ash from burns **decreases capacity factors solar assets** by collecting on panels and reducing irradiance. • **Very few proposed projects address generator exposure,** indicating a potentially overlooked resilience topic area for the state.
Restoration	• Wildfire causes **ingress/egress issues** through destruction of roads and transportation, slowing restoration times for all assets. • AZ could **consider funding projects addressing wildfire-related access issues** given its impact across all asset classes.

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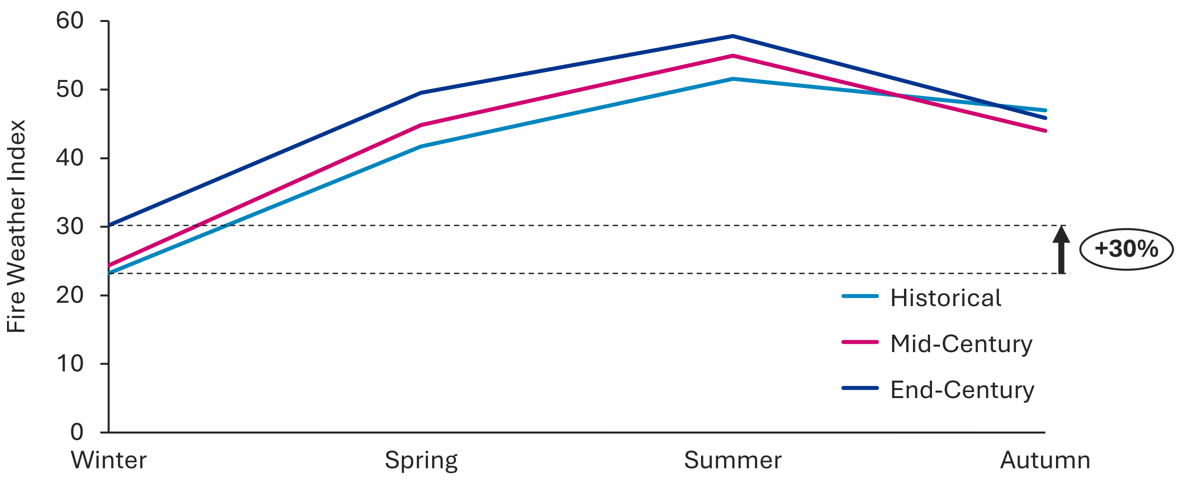
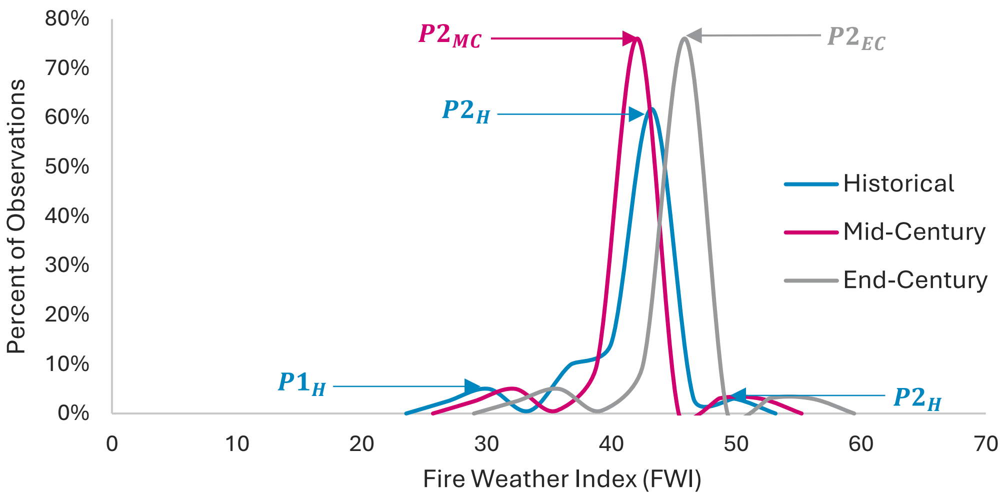
Fire exposure increases slightly by mid-century during the spring and summer, but intensifies more significantly by end-century from winter-summer in all regions of the state

Arizona Average Seasonal Fire Weather Index (FWI)
Population-Weighted by County [RCP-8.5]



Arizona Fire Weather Index Statistical Distribution (FWI)
Population-Weighted by County [RCP-8.5]



KEY OBSERVATIONS

- **End-century wildfire exposure is elevated**, with the sharpest increase occurring in the winter by about 30% from historical FWI.
- Elevated wildfire exposure from winter through summer indicates a **lengthening of the wildfire season,** starting earlier in the calendar year.
- The change in length of wildfire season suggests that **the window for scheduled maintenance during the shoulder seasons is diminishing, especially in the winter and spring.**

KEY OBSERVATIONS

- Increase in peak 2 (P2) by mid-century indicates that an **increasing percentage of the population** will be exposed to a **FWI level of about 40.**
- Rightward shift of the curve by end-century represents an **increasing severity in fire exposure across all 3 climate zones within the state.**
- **P2 largely represents Maricopa County's fire exposure** given its large population, with the other two peaks representing the northern (P1) and southern counties (P3) in the state.

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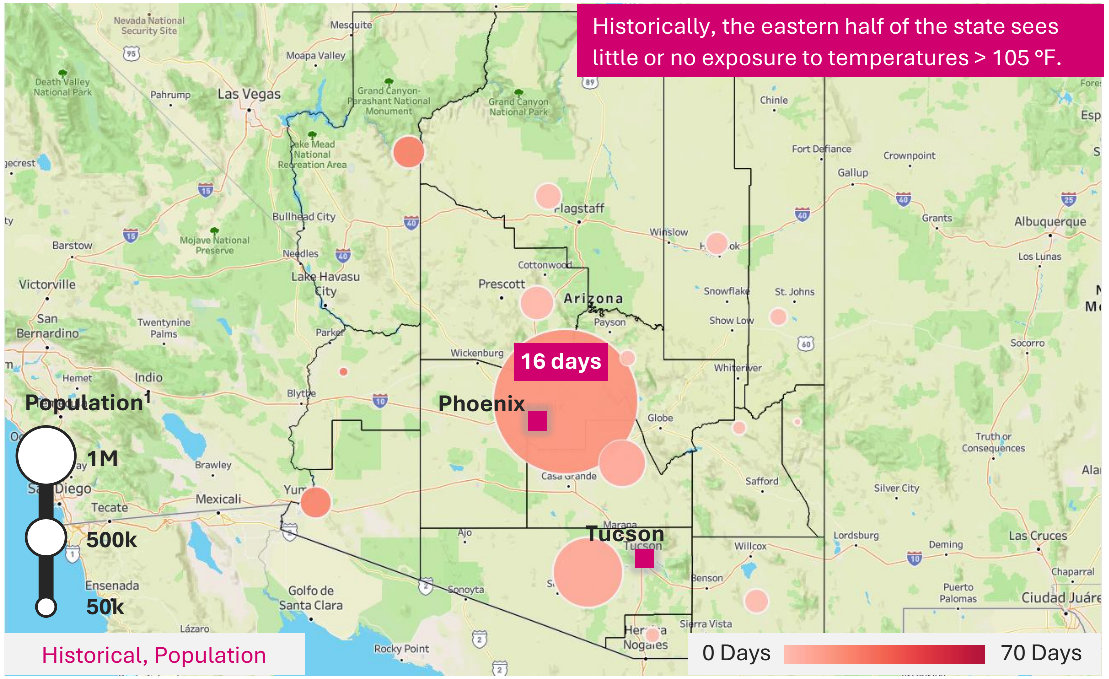
Heat

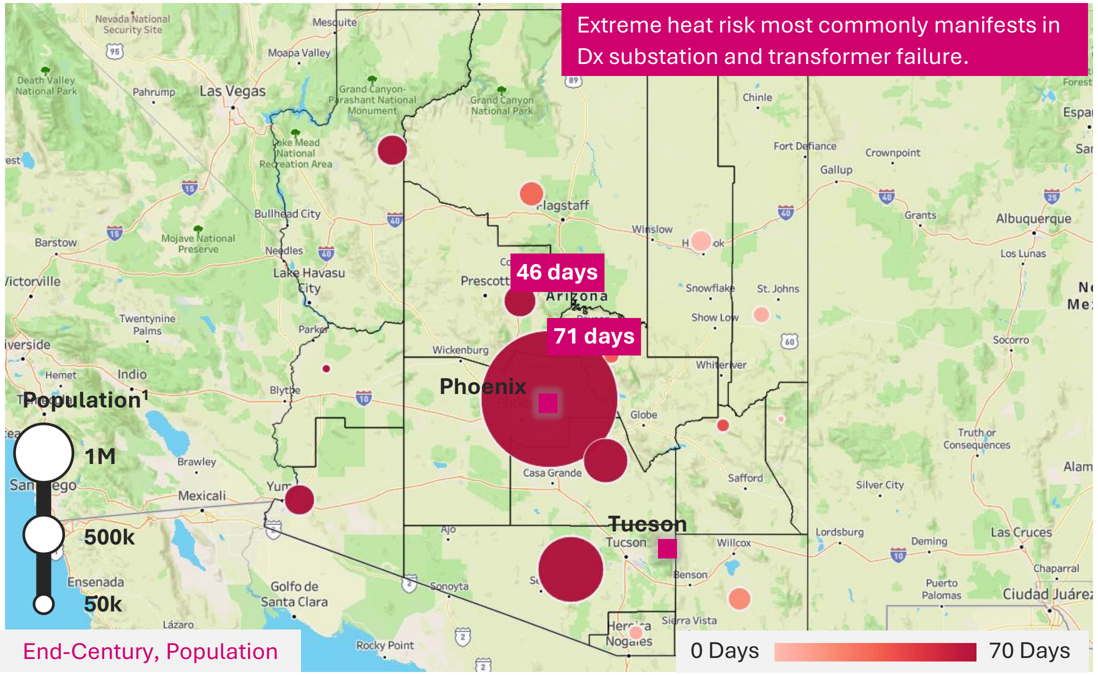
Asset Analysis

AZ could consider Dx substation and transformer upgrades to combat increasing heat exposure, especially in W counties that are not historically exposed to extreme temperatures

Arizona Days Above 105 °F
Distribution Assets (Population), Historical



Arizona Days Above 105 °F
Distribution Assets (Population), End-Century [RCP-8.5]



KEY OBSERVATIONS

- Historically, exposure to days > 105 °F is limited to western and southern counties in the state.
- 105 °F is a particularly important threshold for distribution assets and substations, **which can fail when exposed to two consecutive days above 104 °F.**[2]

KEY OBSERVATIONS

- By end-century, nearly every county is exposed to a significant number of days > 105 °F annually, causing **high asset utilization, derating, and potential failure.**

Yavapai County — Escalation from 2 days to 46 days of extreme heat exposure necessitates **substation, transformer, and Dx line upgrades to mitigate potential failure and avoid derating.**

¹Population bubbles are continuous and therefore labels are approximate. ²EPRI Climate READi

Source: ClimRR, US Census Bureau, City and Town Population Totals

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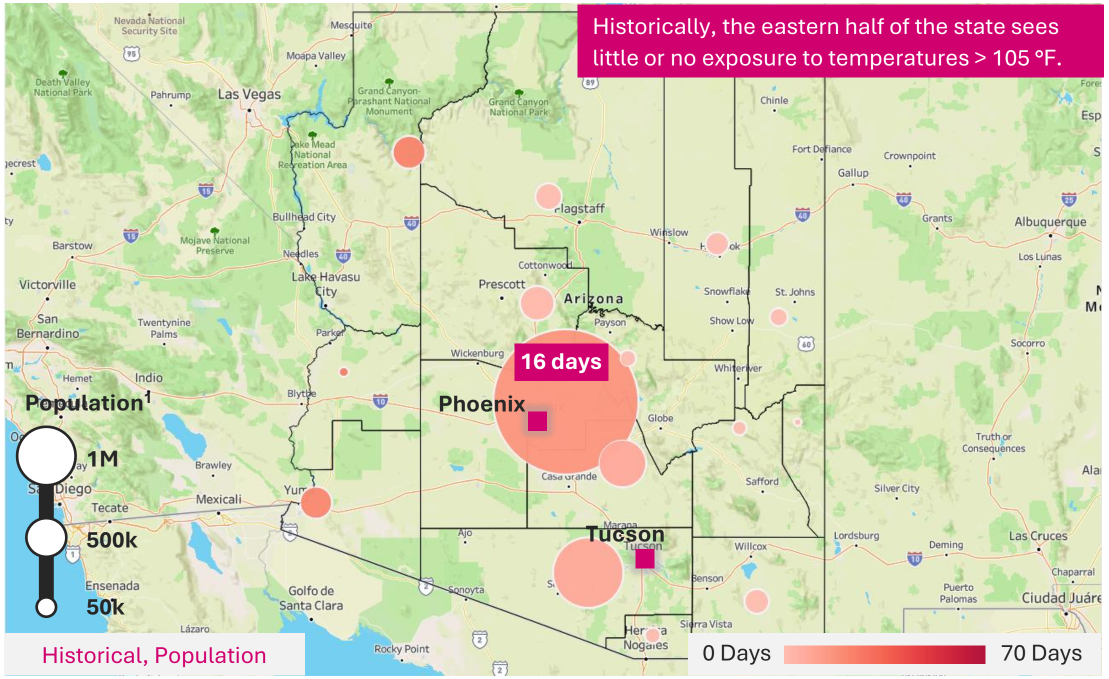
AZ could consider Dx substation and transformer upgrades to combat increasing heat exposure, especially in W counties that will experience substantial near-term warming

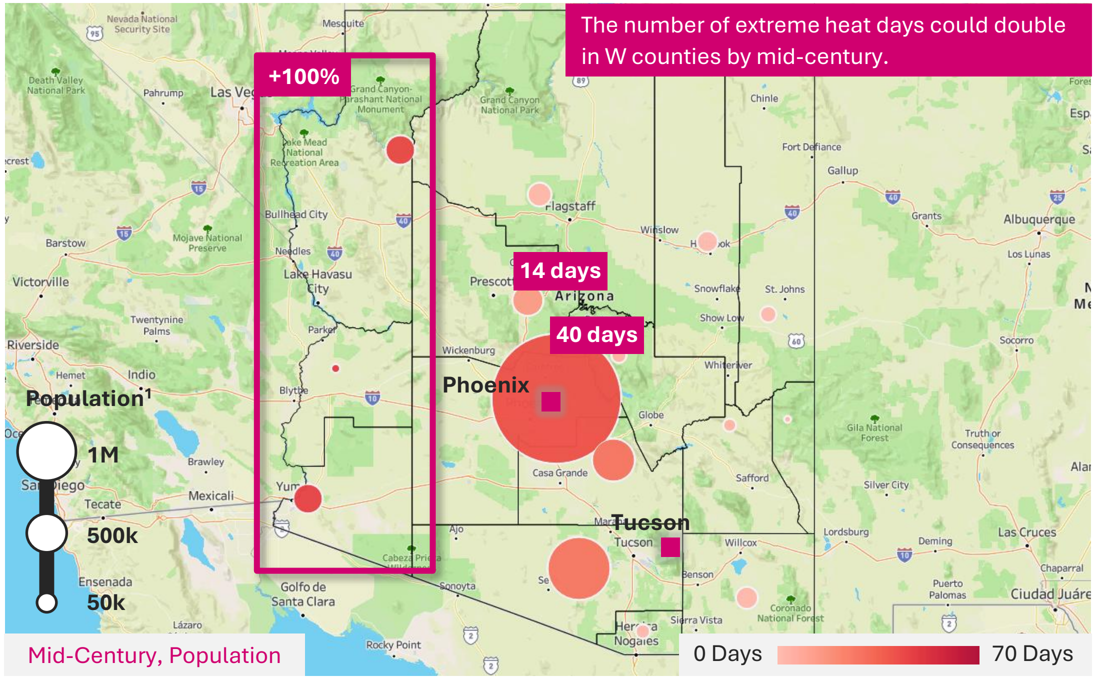
Arizona Days Above 105 °F
Distribution Assets (Population), Historical



KEY OBSERVATIONS

- Historically, exposure to days > 105 °F is limited to western and southern counties in the state.
- 105 °F is a particularly important threshold for distribution assets and substations, **which can fail when exposed to two consecutive days above 104 °F.**[2]

Arizona Days Above 105 °F
Distribution Assets (Population), Mid-Century [RCP-8.5]



KEY OBSERVATIONS

- By mid-century, W/SW counties are exposed to a significant number of days > 105 °F annually, causing **high asset utilization, derating, and potential failure.**

Yavapai County — Escalation from 2 days to 14 days of extreme heat exposure necessitates **substation, transformer, and Dx line upgrades to mitigate potential failure and avoid derating.**

¹Population bubbles are continuous and therefore labels are approximate. ²EPRI Climate READi

Source: ClimRR, US Census Bureau, City and Town Population Totals

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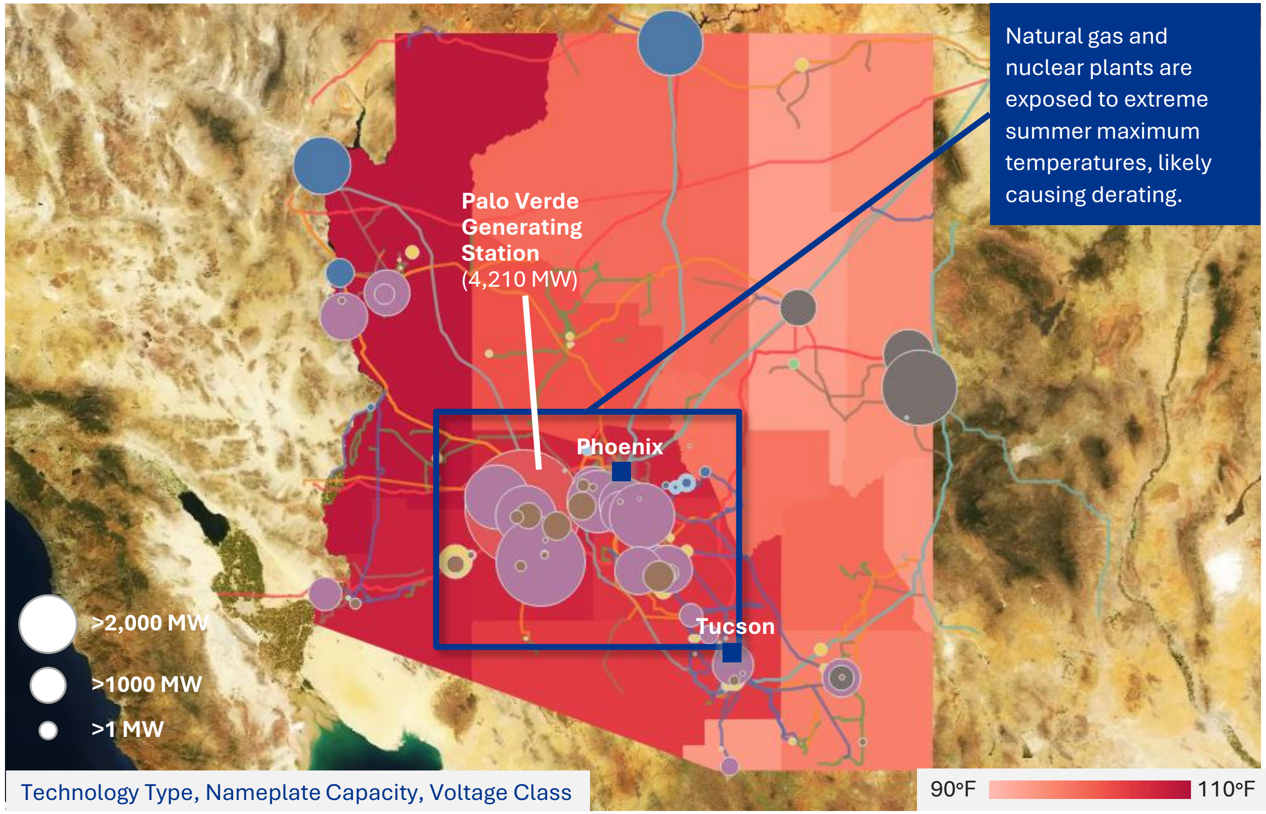
AZ could explore Tx upgrades, grid-enhancing technologies, and expanded virtual power plant programs with storage to address significant extreme heat exposure

Arizona Summer Average Maximum Temperature (°F)
Generators, Mid-Century [RCP-8.5]



Onshore Wind | Coal Plant | Hydroelectric | Nuclear | Solar Photovoltaic
Biomass | Natural Gas Plant | Pumped Storage | Batteries | Other
500kV | 345kV | 220-287kV | 100-161kV | <100kV

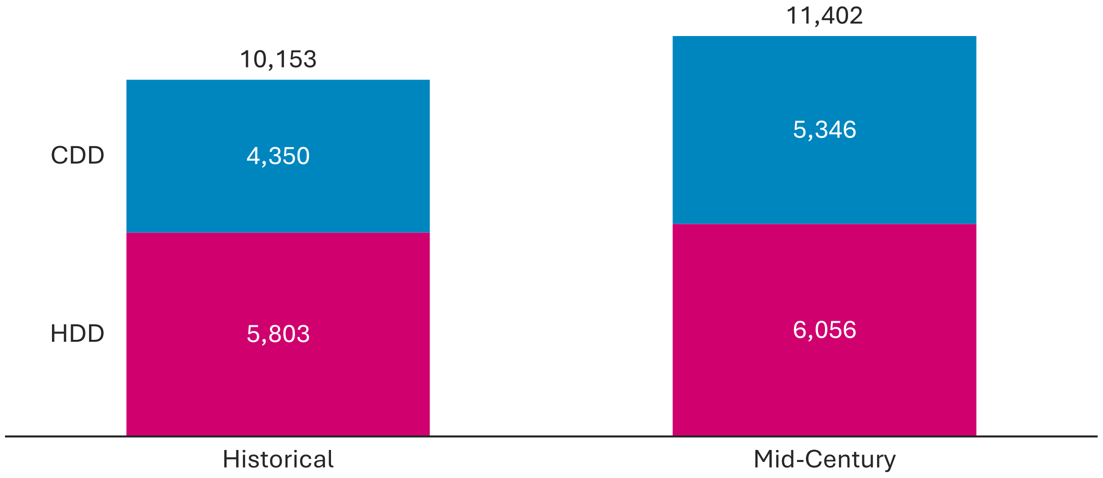
Source: ClimRR, EIA860, HIFLD

Key Highlights	Analysis
Thermoelectric	• While once-through cooling is limited in AZ, thermoelectric generators that rely on other water-based cooling methods will **experience production derates** as extreme heat raises average water temperatures.
Solar/VPPs	• Solar assets throughout the state are significantly exposed to extreme heat, contributing to **production derating** at temperatures above 77°F. • AZ could **consider expanding existing demand response and virtual power plant programs (including BESS)** to combat derating of generators during high load.
Transmission	• A high density of Tx lines in Maricopa and western counties are highly exposed to extreme heat, which can cause capacity derates and line sag. • **AZ could consider GETs and reconductoring** to address increasing extreme heat exposure. Undergrounding, though more expensive, remains a good option if there is multi-hazard exposure.

 |

Increasing exposure to extreme heat may contribute to derating, capacity violations, and substation failure, indicating the need for hardening in newly exposed portions of the state

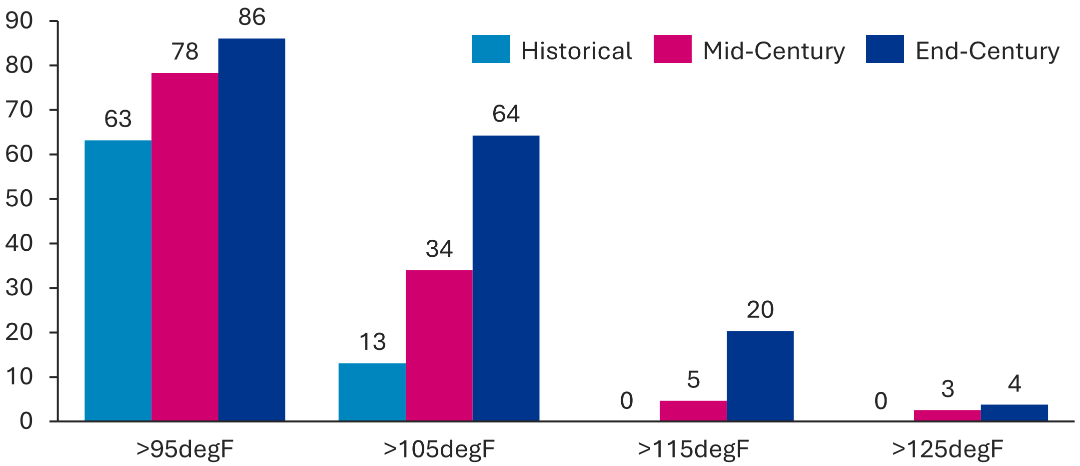
Arizona Average Annual Cooling & Heating Degree Days (CDD & HDD)
Population-Weighted by County [RCP-8.5]



KEY OBSERVATIONS

- Between historical and mid-century, **the ratio of CDD to HDD increases,** with the share of the average number of CDD jumping from about 75% to 88%.
- This results in **increased summer asset utilization and degradation**, but **impacts to winter utilization remain unclear** depending on heating electrification trends.
- Increasing HDD indicates that **freezing and cold exposure persists to mid-century** as extreme cold events may occur more frequently.

Arizona Average Annual Days Exceeding Daily Max Heat Index Thresholds
Population-Weighted by County [RCP-8.5]



KEY OBSERVATIONS

- Increasing extreme heat exposure will cause an **increasing system utilization and accelerating degradation.**
- Almost 3x increase in days > 105 °F by mid-century poses a **substantial risk to distribution substations**, which can fail after two consecutive days above 104 °F without sufficient cooling time during nightly lows.
- Increasing state-wide averages indicates that **new regions will be exposed to extreme heat and could be prioritized for hardening.**

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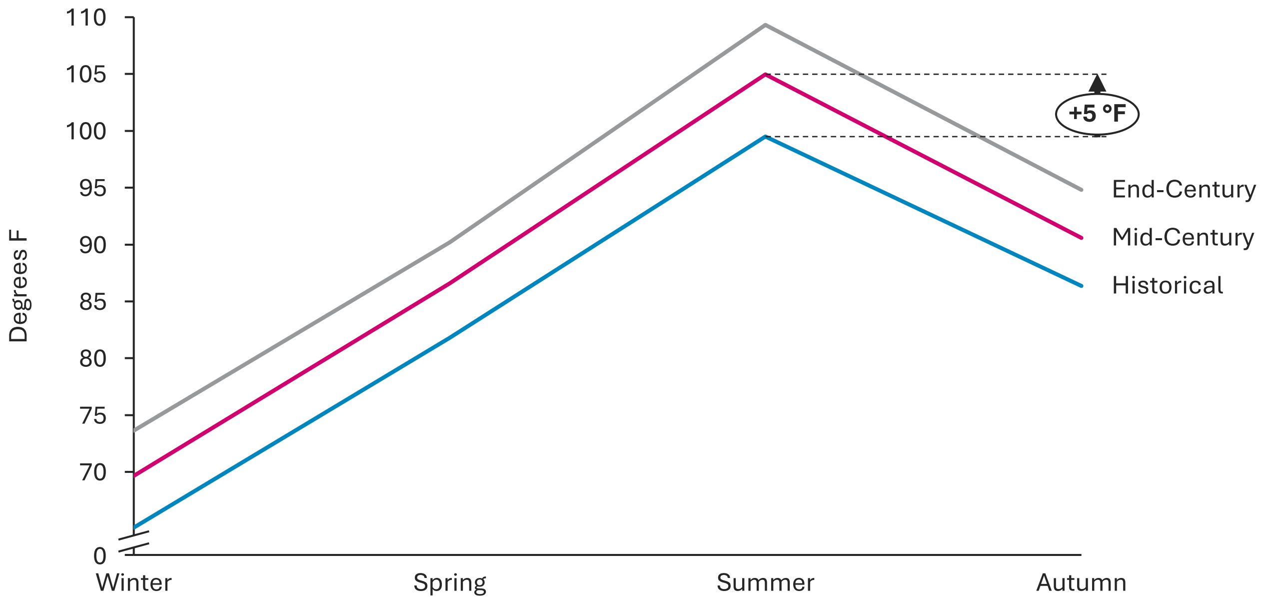
Average summer temperature maximums are projected to increase by mid-century, increasing the duration and magnitude of high system utilization

Arizona Average Seasonal Maximum Temperature (°F)
Population-Weighted by County [RCP-8.5]



Key Highlights	Analysis
Summer Warming	• **Heat risk increases most drastically in summer**, with a 5 °F increase in the average seasonal max by mid-century. • This yields **increases in peak load** and likely contribute to **derating** and **capacity violations** for Tx and thermal generating units.
Shorter Shoulder Seasons	• Warming is generally less pronounced in shoulder seasons, although increased spring and autumn maximums could **extend the duration of high system utilization and shorten maintenance windows.**
Extreme Heat	• Average maximums reaching 104 °F by mid-century and 109 °F by end-century indicates an **increasing frequency of extreme temperatures that can cause significant derating, capacity violations, and direct failure across all asset classes.**

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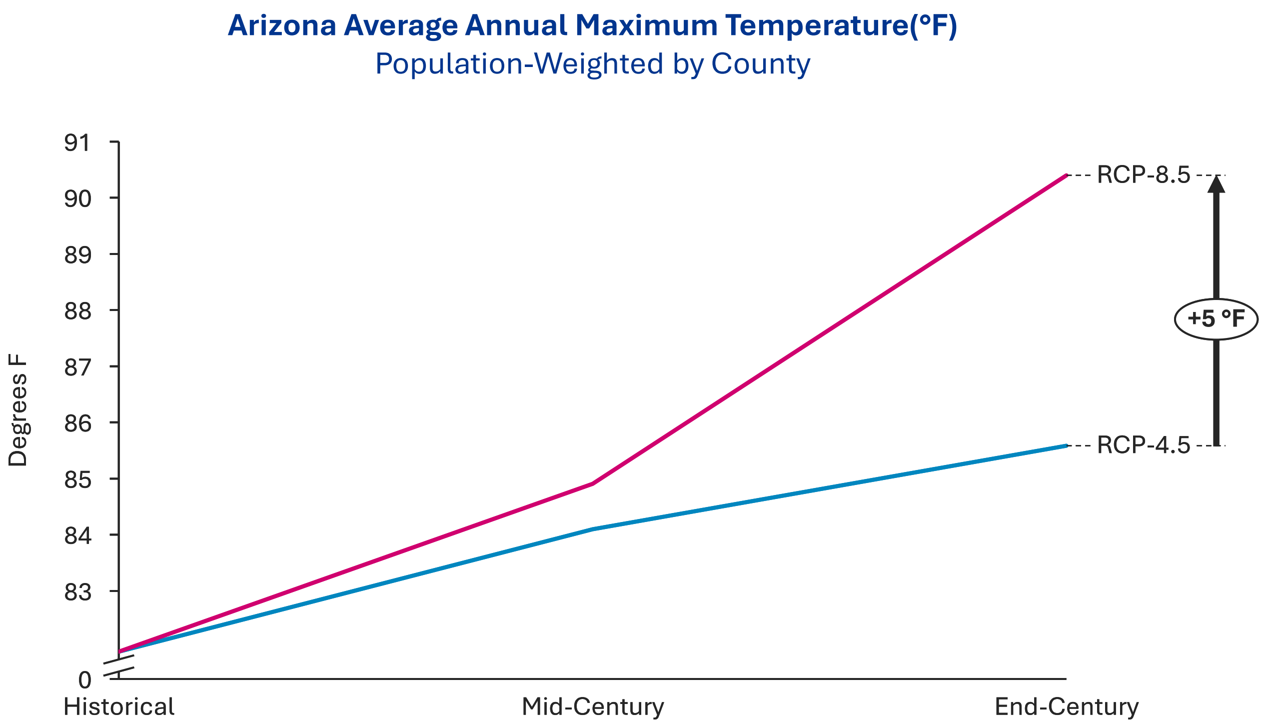
Average annual maximum temperatures are projected to increase under both warming scenarios, but the warming trajectories diverge by end-century



Key Highlights	Analysis
RCP-4.5	• **"Moderate" scenario**: Emissions peak around 2040 and then slowly begin to decline.[4] Temperatures warm about 3.2 °F from a 2000 baseline. • CO_2 emissions plateau before falling mid-century, as energy use sharply declines and there is large scale reforestation.
RCP-8.5	• **"Rapid growth" scenario:** Emissions continue to rise throughout the twenty-first century.[4] Temperatures warm about 6.6 °F from a 2000 baseline. • CO_2 emissions are three times higher than the present by end-century, with a large increase in methane emissions and continued fossil fuel use.
End-century Divergence	• Average annual maximum temperatures follow a similar trajectory under both warming scenarios up to mid-century. • By end-century, RCP-8.5 yields average annual maximum temperatures 5° hotter than RCP-4.5.

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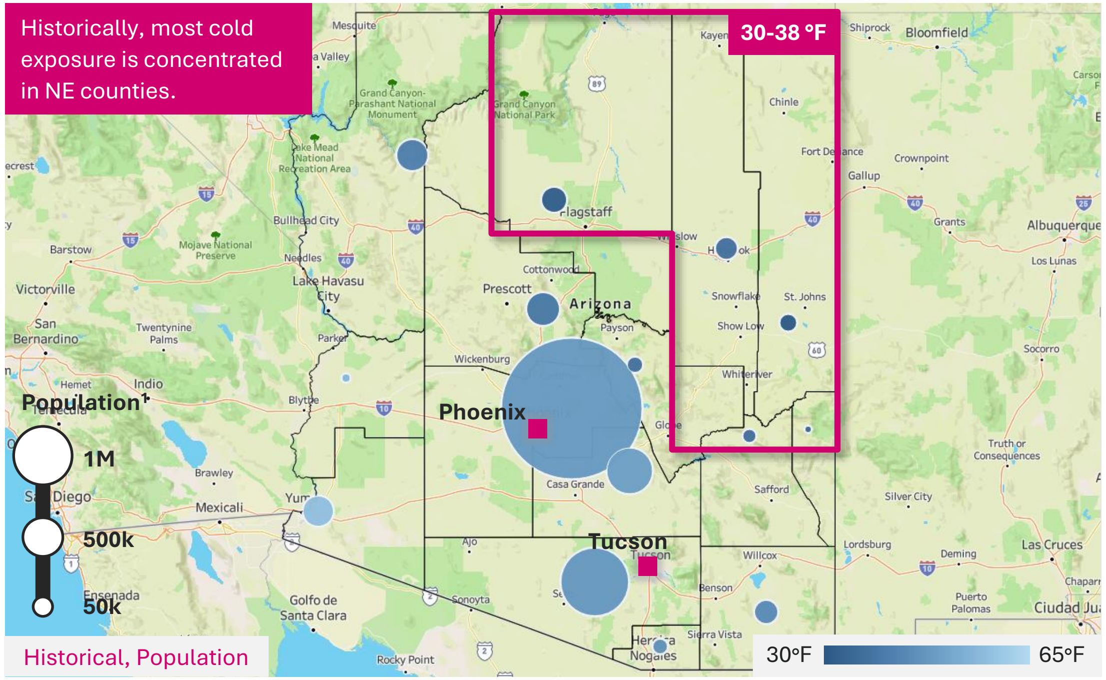
Cold

Asset Analysis

AZ could consider concentrating adaptations addressing cold in NE counties, where extreme cold events could continue to occur despite general warming across the state

Arizona Average Annual Minimum Temperature (°F)

Distribution Assets, (Population) Historical

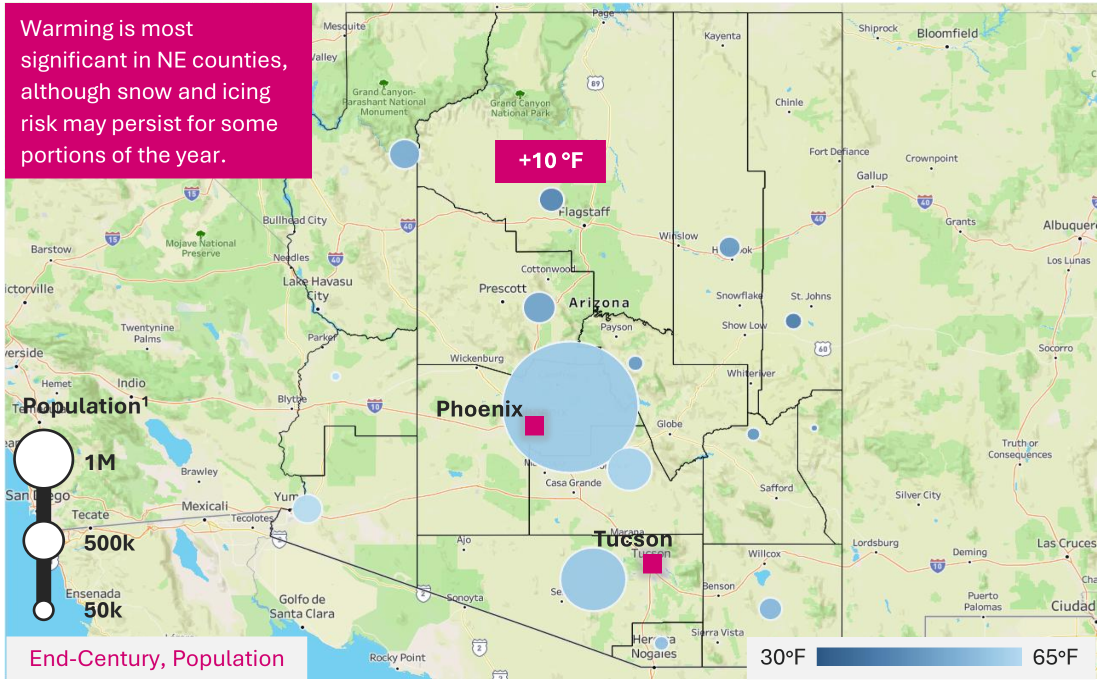


KEY OBSERVATIONS

- Cold exposure is generally concentrated in NE counties, where **near-freezing annual minimum temperatures pose a threat of asset icing/freezing,** especially during nighttime hours in winter months.
- AZ could **consider Dx pole upgrades and substation enclosures** to combat snow loading and potential freezing in NE counties.

Arizona Average Annual Minimum Temperature (°F)

Distribution Assets, (Population), End-Century [RCP-8.5]



KEY OBSERVATIONS

- Climate projections cannot predict acute extreme events like polar vortices and winter storms, **underrepresenting cold exposure.**

Coconino County — Coconino County is exposed to average annual minimum temperatures of about 41 °F, indicting potential **icing or snow exposure for Dx assets.**

Source: ClimRR, US Census Bureau, City and Town Population Totals

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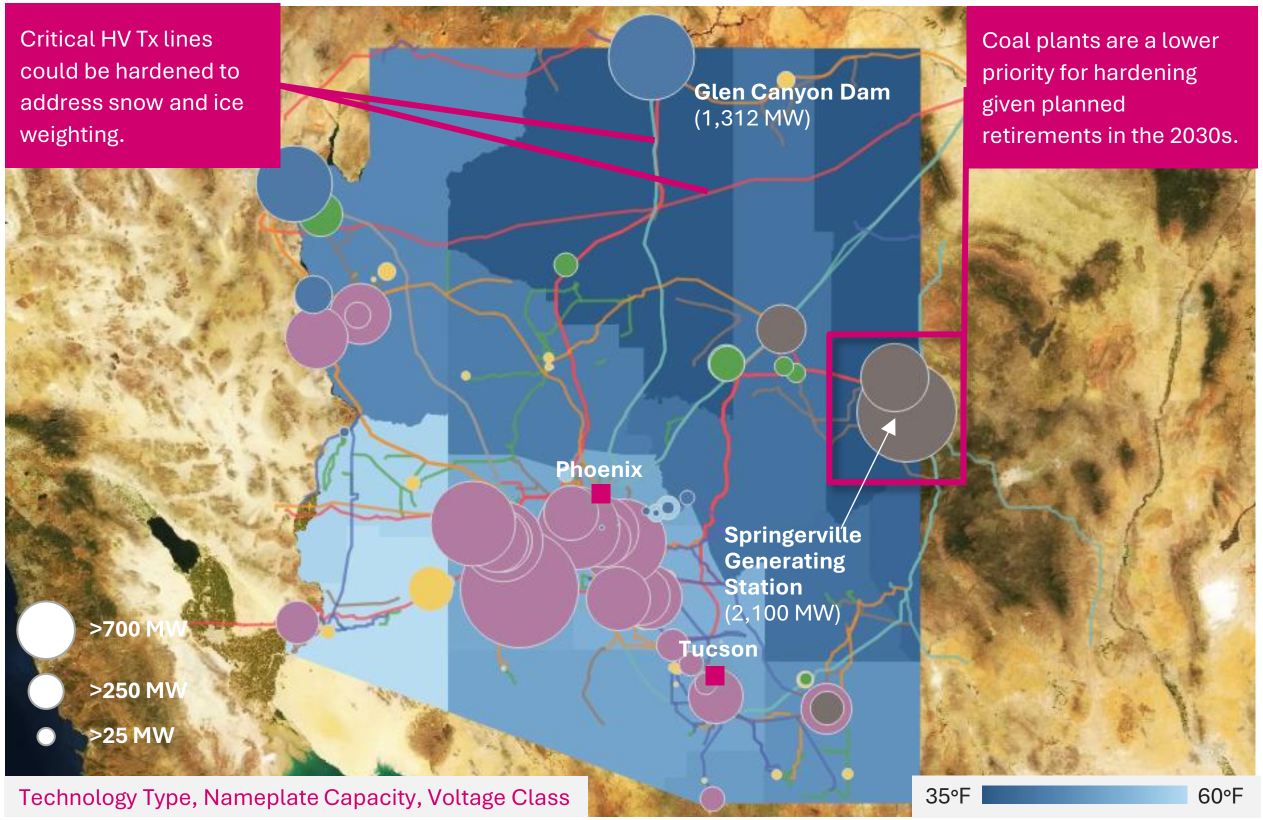
Despite limited cold exposure, AZ could consider resilience upgrades in highly vegetated NE counties to combat potential icing risk.

Arizona Average Annual Minimum Temperature (°F)
Generators, Mid-Century [RCP-8.5]



Onshore Wind	Coal Plant	Hydroelectric	Nuclear	Solar Photovoltaic
Biomass	Natural Gas Plant	Pumped Storage	Batteries	Other
500kV	345kV	220-287kV	100-161kV	<100kV

Source: ClimRR, EIA860, HIFLD

Key Highlights	Analysis
Hydroelectric	• Frazil ice formation and maloperation of spill gate motors can result in **plant faults or production derates.**
Coal	• Coal plants in Apache County are exposed to extreme cold, which can cause a variety of plant shutdowns and freezing of coal stockpiles.
Wind	• Wind plants in Coconino and Navajo Counties face cold exposure that can contribute to **asset failure and ice throw.**
Transmission	• **High-voltage lines are highly exposed to cold in NE counties,** particularly a tie line to NM and a line connecting Glen Canyon Dam to load centers. • AZ could ensure that these structures are sufficiently are rated to handle the additional weight of snow and ice.

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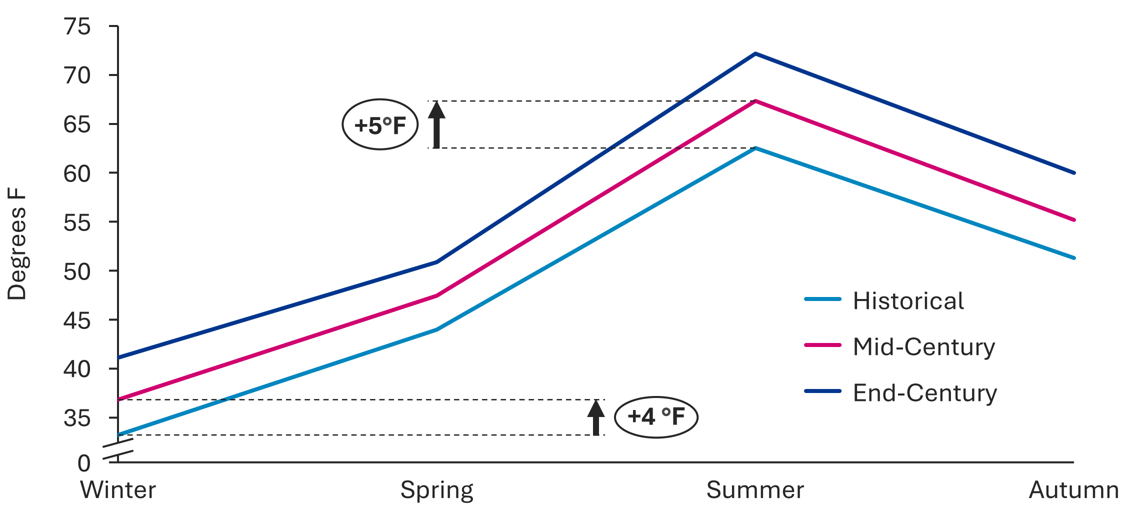
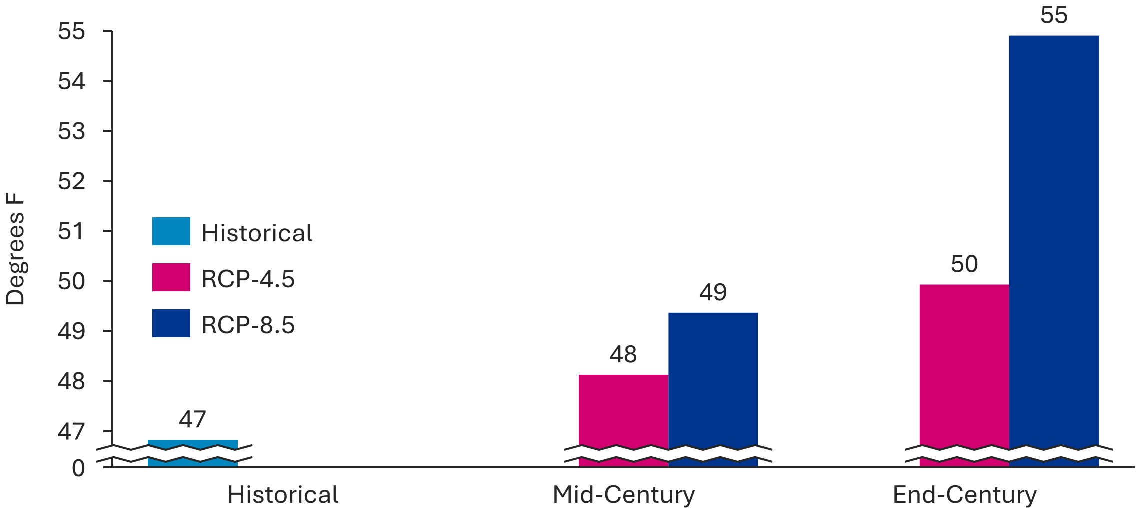
Warming will generally decrease heating load, but extreme cold events may still occur with similar frequency given average annual minimum temperatures remain relatively constant

Arizona Average Seasonal Minimum Temperature (°F)
Population-Weighted by County [RCP-8.5]



Arizona Average Annual Minimum Temperature (°F)
Population-Weighted by County [RCP-4.5, RCP-8.5]



KEY OBSERVATIONS

- Significant winter warming (+4 °F by mid-century) could decrease overall heating load, but the **impact on electricity demand ultimately depends on the speed of heating electrification.**
- Summer minimums remaining around 70 °F indicates that assets may be able to cool overnight, but this could continue to be monitored.
- Resilience upgrades like **undergrounding, covered conductors, or cable upgrades can address heat and cold exposure simultaneously.**

KEY OBSERVATIONS

- Only about 3 °F of annual minimum temperature warming (RCP-4.5) indicates that cold exposure could persist to end-century.
- Diverging temperature projections by end-century demonstrates projection uncertainty and the importance of continued monitoring.
- Regarding extreme cold, global climate models do not resolve for extreme cold events like polar vortexes, so **assets could still face similar levels of exposure to cold-related failures.**

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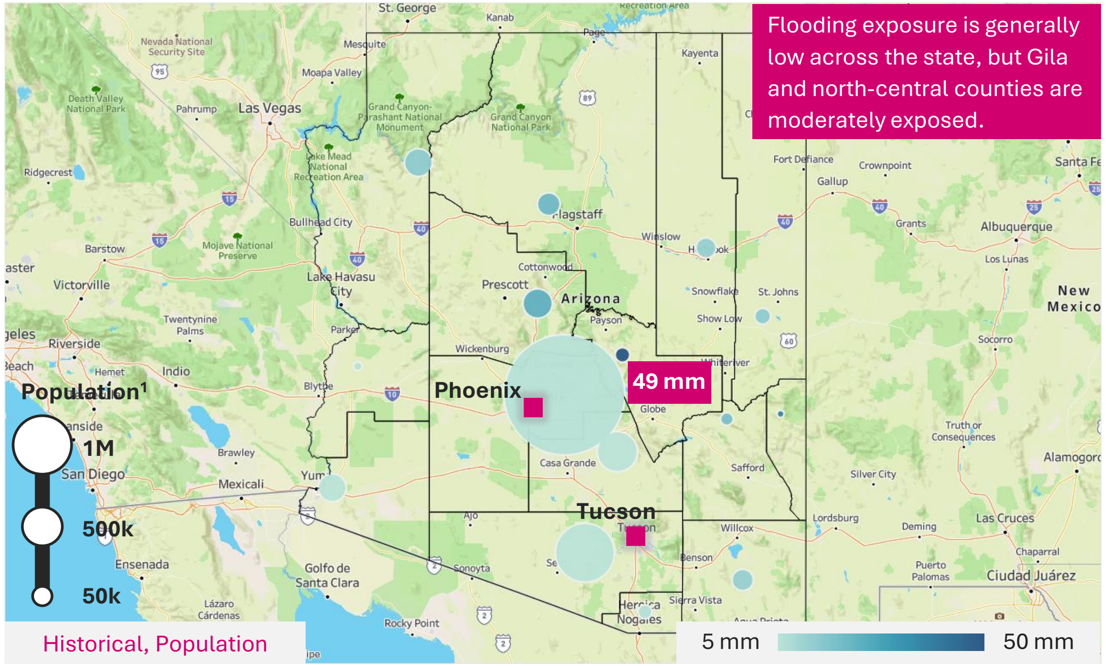
Flood

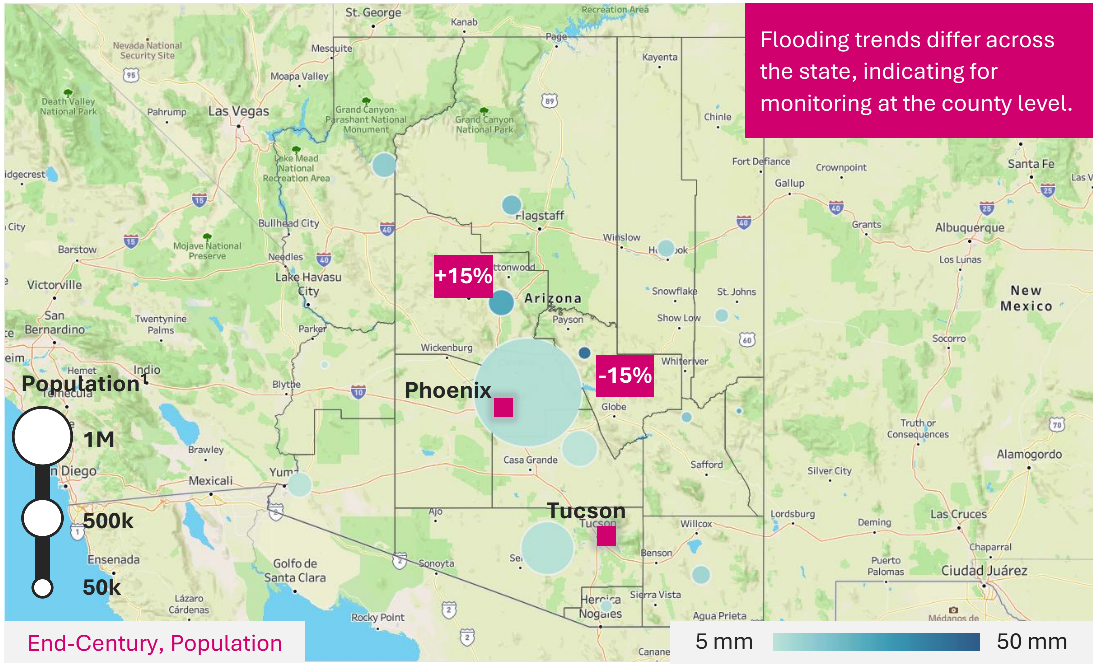
Asset Analysis

Pluvial flooding due to excess surface runoff is lower risk for most AZ counties. Substation flooding mitigations could be explored for low-elevation assets on a ad hoc basis

Arizona Average Annual Surface Runoff (mm/year)
Historical [SSP5-8.5]



Arizona Average Annual Surface Runoff (mm/year)
End-Century [SSP5-8.5]



KEY OBSERVATIONS

- Most flood exposure lies in **Gila County** due to its high annual precipitation levels and mountainous terrain.
- **Annual metrics do not capture the propensity of extreme precipitation events during monsoon season,** underrepresenting exposure.
- **Low soil permeability** in AZ **could increase the risk of pluvial flooding.**

KEY OBSERVATIONS

- AZ could consider funding projects to fortify low-lying Dx substations in Gila and Yavapai Counties given flooding exposure.

Yavapai County — **Flood exposure is projected to increase ~15% by end-century**, posing a substantial threat to a significant volume of substations and distribution poles.

Source: ClimRR, US Census Bureau, City and Town Population Totals

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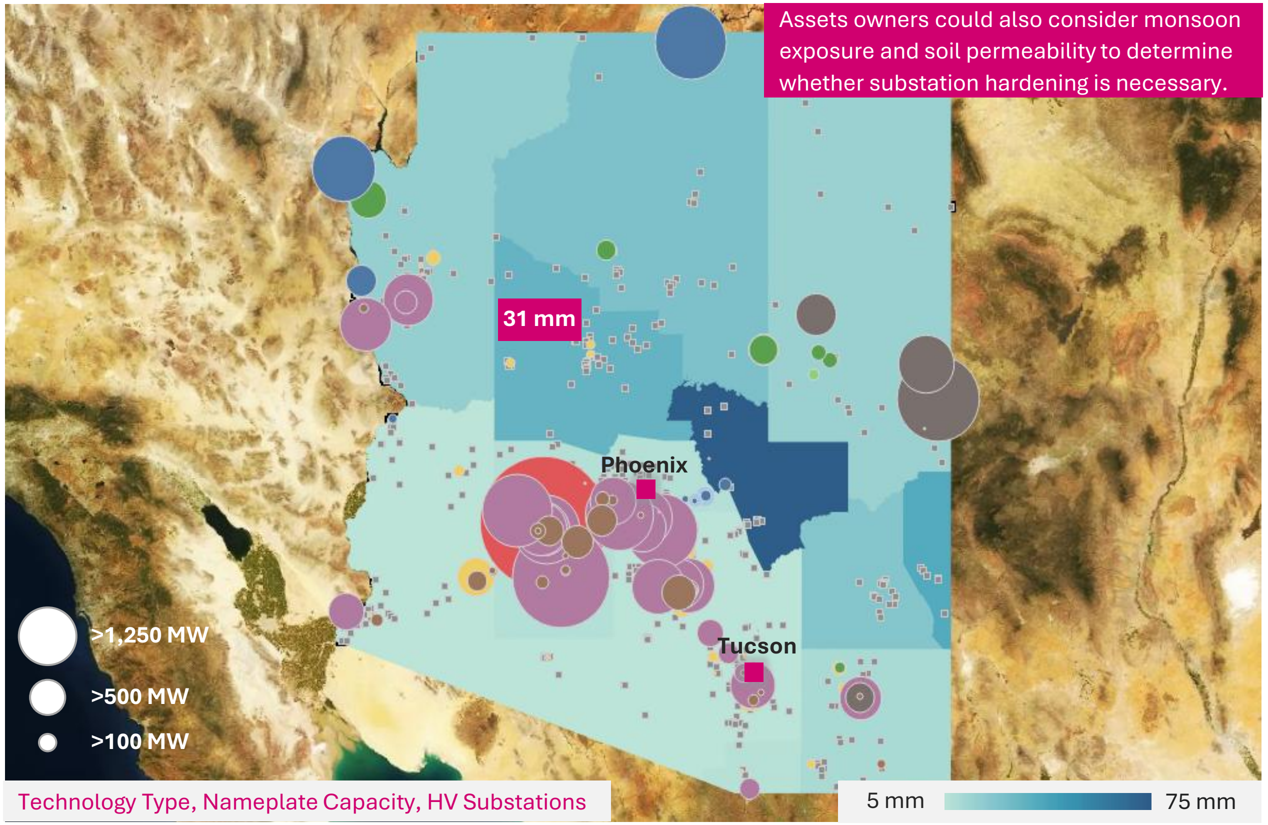
Baringa

AZ could prioritize the fortification of high-voltage substations in Yavapai County given the high density of assets, though flood risk is generally low across the state.

Arizona Average Annual Surface Runoff (mm/year)
Generators, Mid-Century [SSP5-8.5]



Onshore Wind | Coal Plant | Hydroelectric | Nuclear | Solar Photovoltaic
Biomass | Natural Gas Plant | Pumped Storage | Batteries | Other

HV Substation

Source: ClimRR, EIA860, HIFLD

Key Highlights	Analysis
Substation	• High-voltage substations will be exposed to pluvial flooding if elevation in low amongst surrounding topography. • **Significant pockets of HV substations could be exposed to flooding in Yavapai and Greenlee Counties** and could be considered for elevation or related hardening.
Restoration	• Flooding causes **ingress/egress complications** by washing out access roads, contributing to restoration issues. • Flooding can **affect on-site buildings or facilities**, making it more difficult to maintain adequate staffing for oversight and restoration.
Generators	• Most generator sites are not exposed to significant flood risk. • A handful of **solar plants in Yavapai County could be exposed to flooding,** which can inundate inverters and other ground-level equipment, contributing to asset failure.

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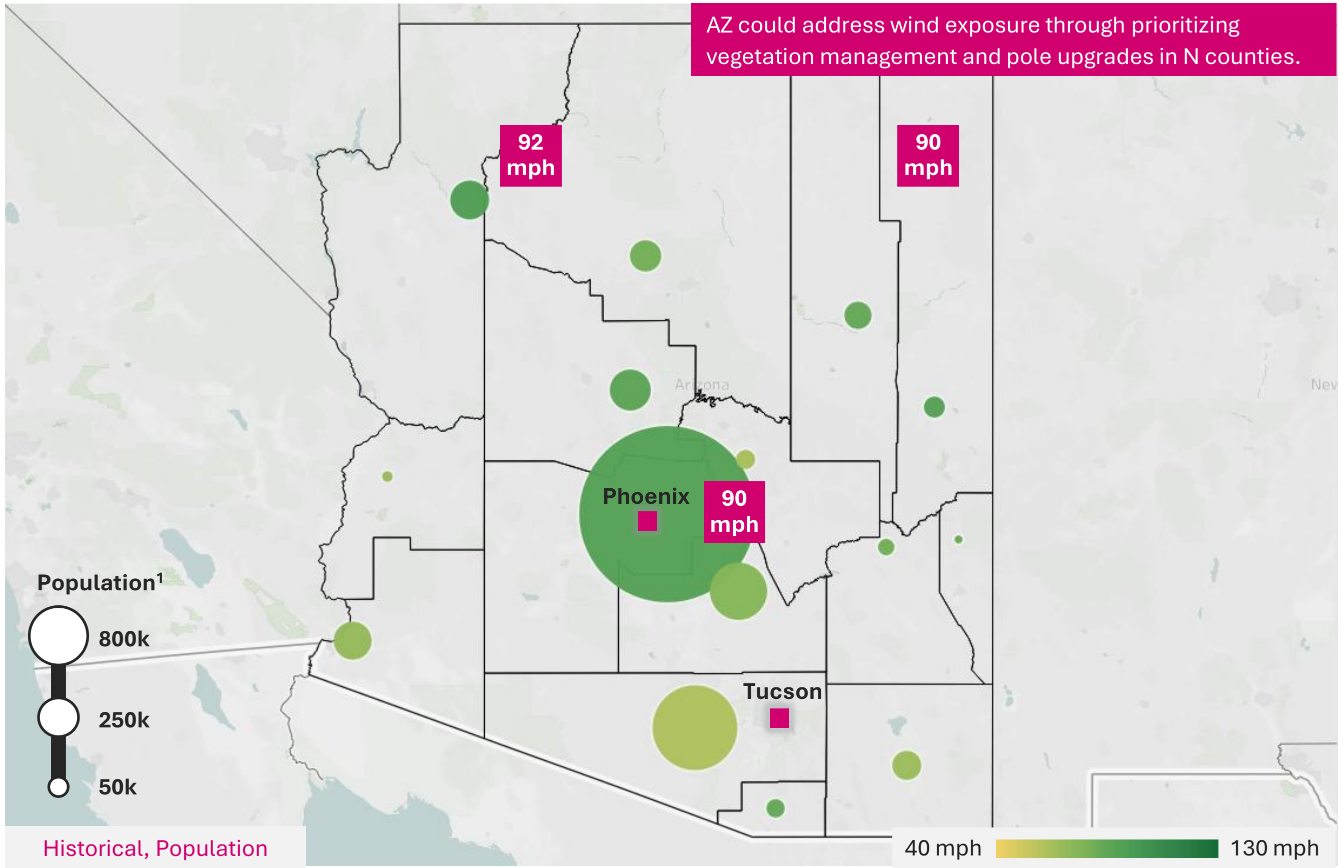
Wind

Asset Analysis

Vegetation management and Dx pole reinforcement/replacement could be prioritized for remote customers in northern counties given high vegetation.

Arizona 100-year Wind Speed (mph)
Historical

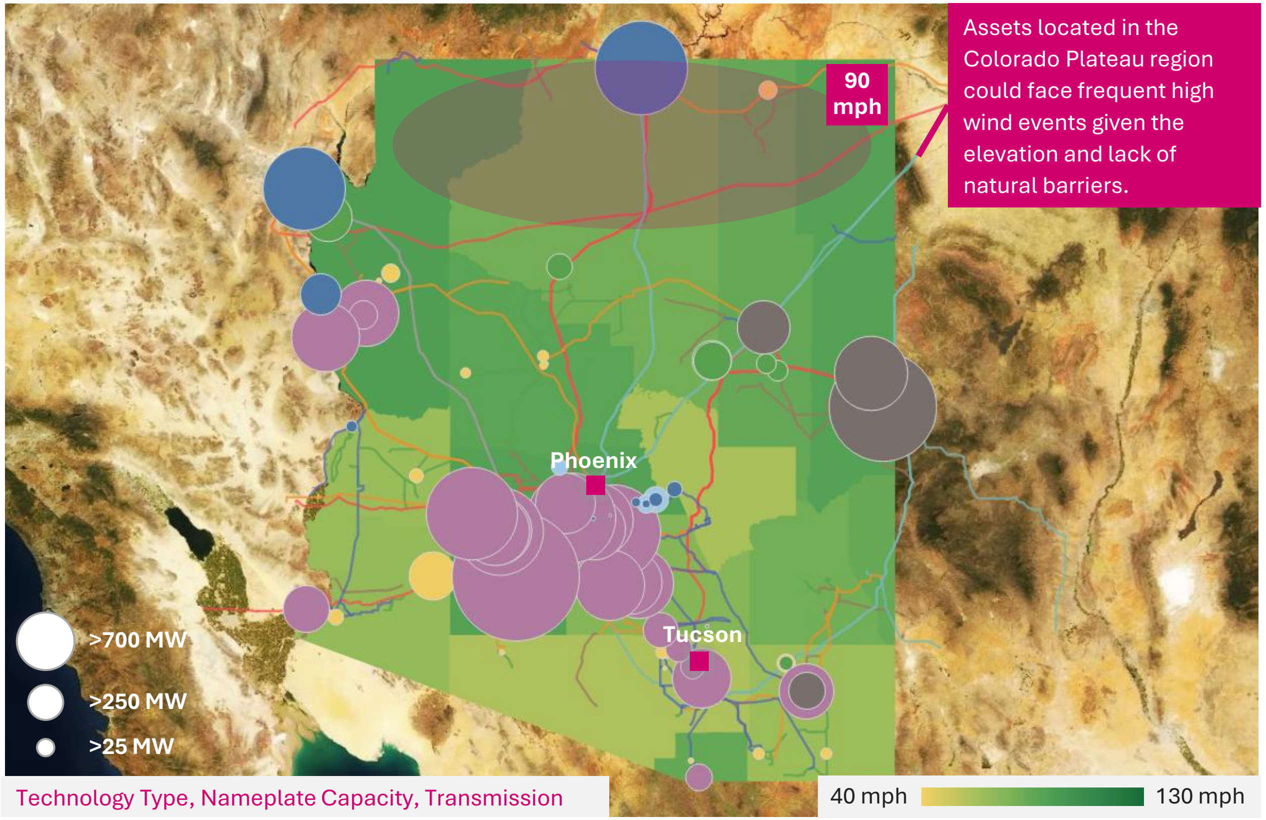


Key Highlights	Analysis
Distribution	• Given weak climate signals, wind speeds are derived using historical data and do not vary at high spatial resolution. • Rather than targeted investments, wind exposure should be addressed through **upgraded design standards** across a utility service territory.
Northern Counties	• **Wind exposure is generally highest in northern counties** given higher elevations. • AZ could **consider Dx pole reinforcements and vegetation management in rural areas of N counties** given dense tree cover.
Maricopa County	• Maricopa County has a population of approximately 4.5M and 100-year return value of 90 mph, **indicating a high exposure area for Dx assets**. • Explore suburban/rural areas within county where undergrounding is less common, but significant Dx assets remain.

Source: DRI, EIA860, HIFLD

Transmission lines in Maricopa County and the Colorado Plateau region could be prioritized for structure reinforcement or vegetation management to address high wind exposure

Arizona 100-year Wind Speed (mph)
Historical



Onshore Wind | Coal Plant | Hydroelectric | Nuclear | Solar Photovoltaic
Biomass | Natural Gas Plant | Pumped Storage | Batteries | Other
500kV | 345kV | 220-287kV | 100-161kV | DC

Key Highlights	Analysis
Transmission	• A crucial **transmission juncture in Maricopa County is highly exposed** • AZ could **consider reinforcing Tx structures in Colorado Plateau region of the state** given the high volume of exposed lines and their criticality in connecting generators to load in other counties.
Solar	• A pocket of solar farms in in Yavapai and Mohave Counties are exposed to high return values >90 mph. • Depending on OEM, solar panels are only rated to 90 mph, **indicating need for rack reinforcement and vegetation management.**
Wind	• Wind farms cutout speeds can vary between 45-70 mph, indicating that in high wind speed events, there the turbines stop producing. • **Wind farms in Mohave and Navajo Counties are exposed to 100-year return values significantly higher than typical cutout thresholds,** diminishing supply during extreme wind events.

Source: PDI, EIA860, HIFLD.

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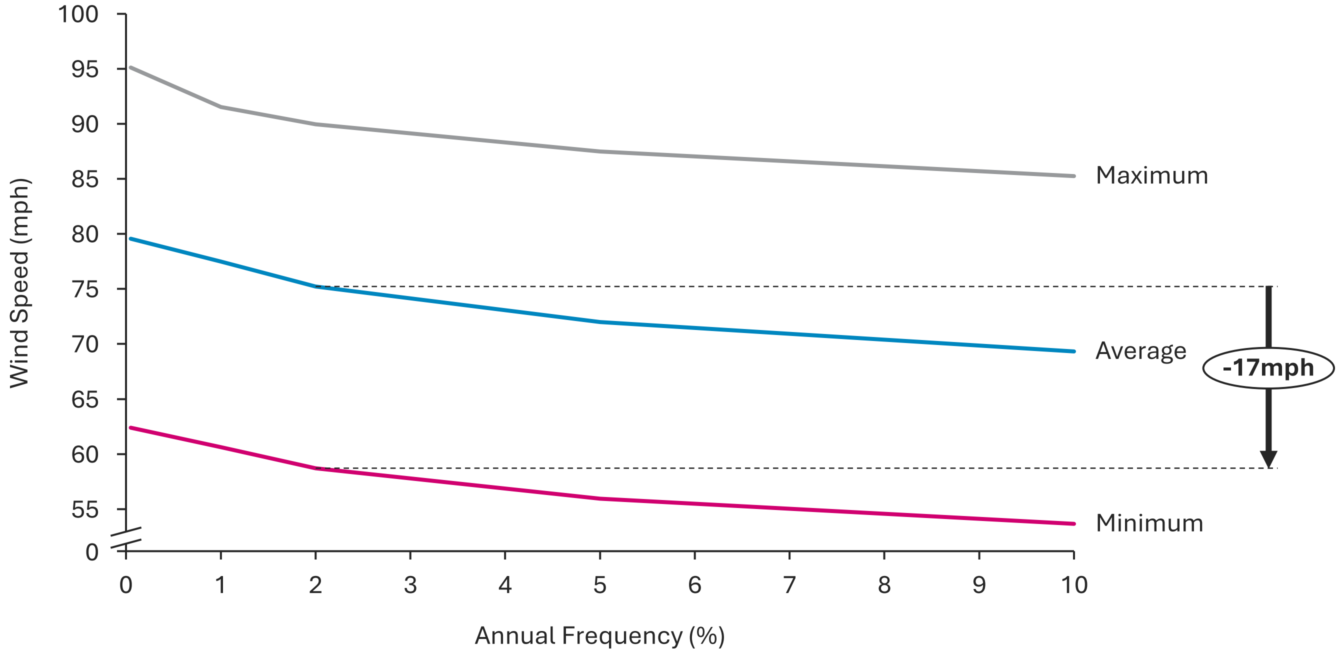
Historically, there is a 1% chance that the average wind speed seen across Arizona counties is ~77 mph annually.

Arizona Wind Frequency vs Severity (2000 – 2022)
Historical, Average by County



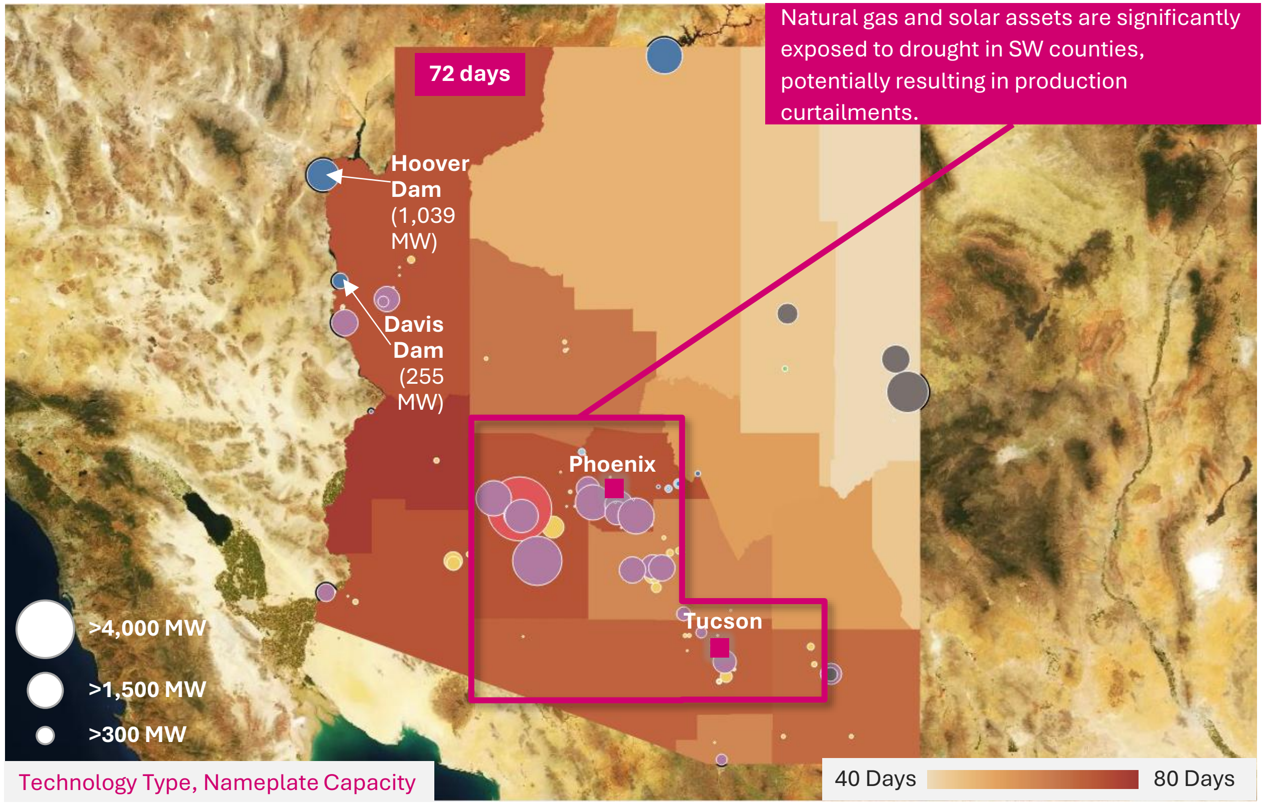
Key Highlights	Analysis
 **High System Averages**	• Historically, there is a 1% chance that the average wind speed seen across Arizona counties is ~77mph annually. • The 10% annual likelihood drops to about 70, indicating high system wind speeds are common across counties.
 **Volatility Across Counties**	• There is a sizeable band between the maximum and minimum counties around the mean. • This indicates that wind adaptations should be focused on a county basis rather than over large service territories.

Drought

Asset Analysis

AZ could consider forecasting hydro output using climate-adjusted inputs and exploration of modeling thermoelectric supply during drought season

Arizona Consecutive Days No Precipitation
Generators, Mid-Century [RCP5-8.5]



Onshore Wind | Coal Plant | Hydroelectric | Nuclear | Solar Photovoltaic
Biomass | Natural Gas Plant | Pumped Storage | Batteries | Other

Key Highlights	Analysis
Hydroelectric	• A string of **hydroelectric plants along the Colorado River** in Mohave County are exposed to near peak state-wide drought levels. • Asset owners and grid operators could be forecasting long-term production from these hydro facilities with **climate-adjusted inputs, as drought exposure in Mohave County is projected to increase 12% by end-century.**
Natural Gas	• In arid conditions, **air intakes for CCGTs and CTs can clog and degrade** due to dust and sand particles, decreasing efficiency and longevity of the generator. • Lack of water availability can **reduce natural gas cooling ability**, resulting in power production curtailments.
Renewables	• Drought conditions cause dust buildup on solar panels, hurting capacity factors. • In areas that also have high wildfire exposure, **panel cleaning projects address two hazards simultaneously.**

Source: ClimRR, EIA860, HIFLD

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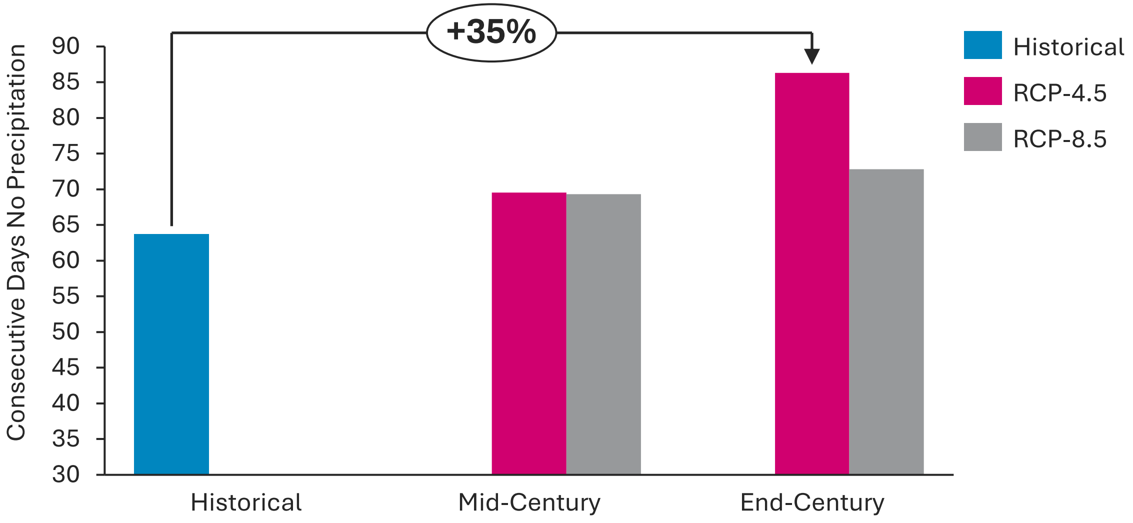
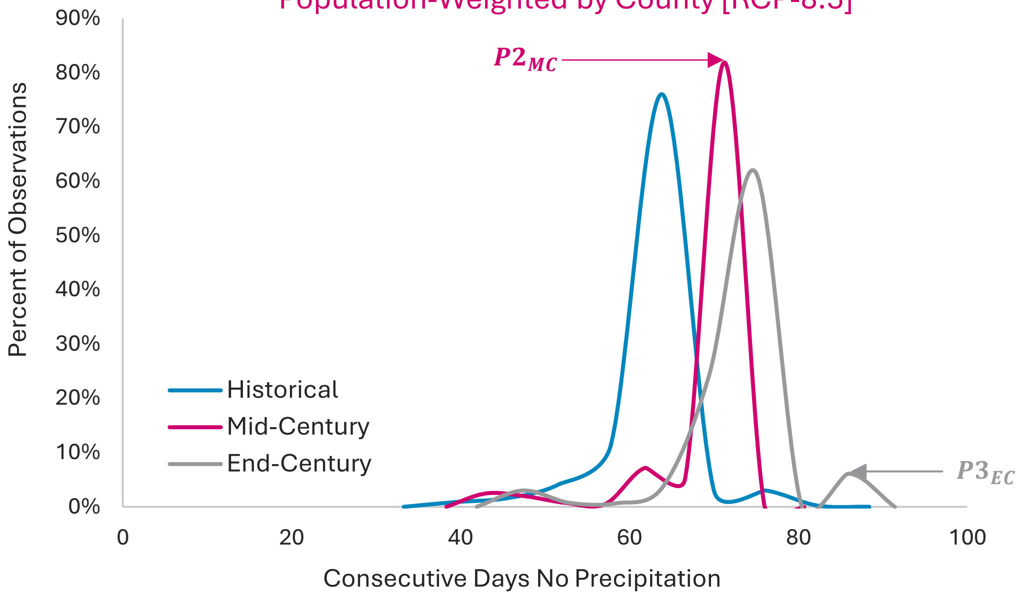
Drought exposure is generally projected to increase over time, but the magnitude of the change could vary widely depending on the warming scenario that is most closely followed

Arizona Average Annual Consecutive Days with No Precipitation
Population-Weighted by County [RCP 4.5, RCP-8.5]



Arizona Average Consecutive Days with No Precipitation Statistical Distribution
Population-Weighted by County [RCP-8.5]



KEY OBSERVATIONS

- Projections indicate a **mild to moderate increase in drought exposure.**
- **Drought exposure increases ~35% by end-century** (under RCP-4.5), contributing to potential asset cooling failures and reduced hydroelectric generation.
- Higher drought exposure for RCP-4.5 than RCP-8.5 demonstrates that **drought risk does not scale linearly with temperature** and could be monitored closely over time, especially by hydroelectric asset owners.

KEY OBSERVATIONS

- Rightward shift of both the mid-century and end-century curves represents **escalating drought exposure over time under RCP-8.5.**
- P3 of the end-century curve represents the development of **a small pocket of the state exposed to about 90 cons. days w/o precipitation.**
- The height of P2 in the **mid-century curve indicates drought exposure becoming more concentrated around 70 days** compared to historical and end-century, which are less concentrated.

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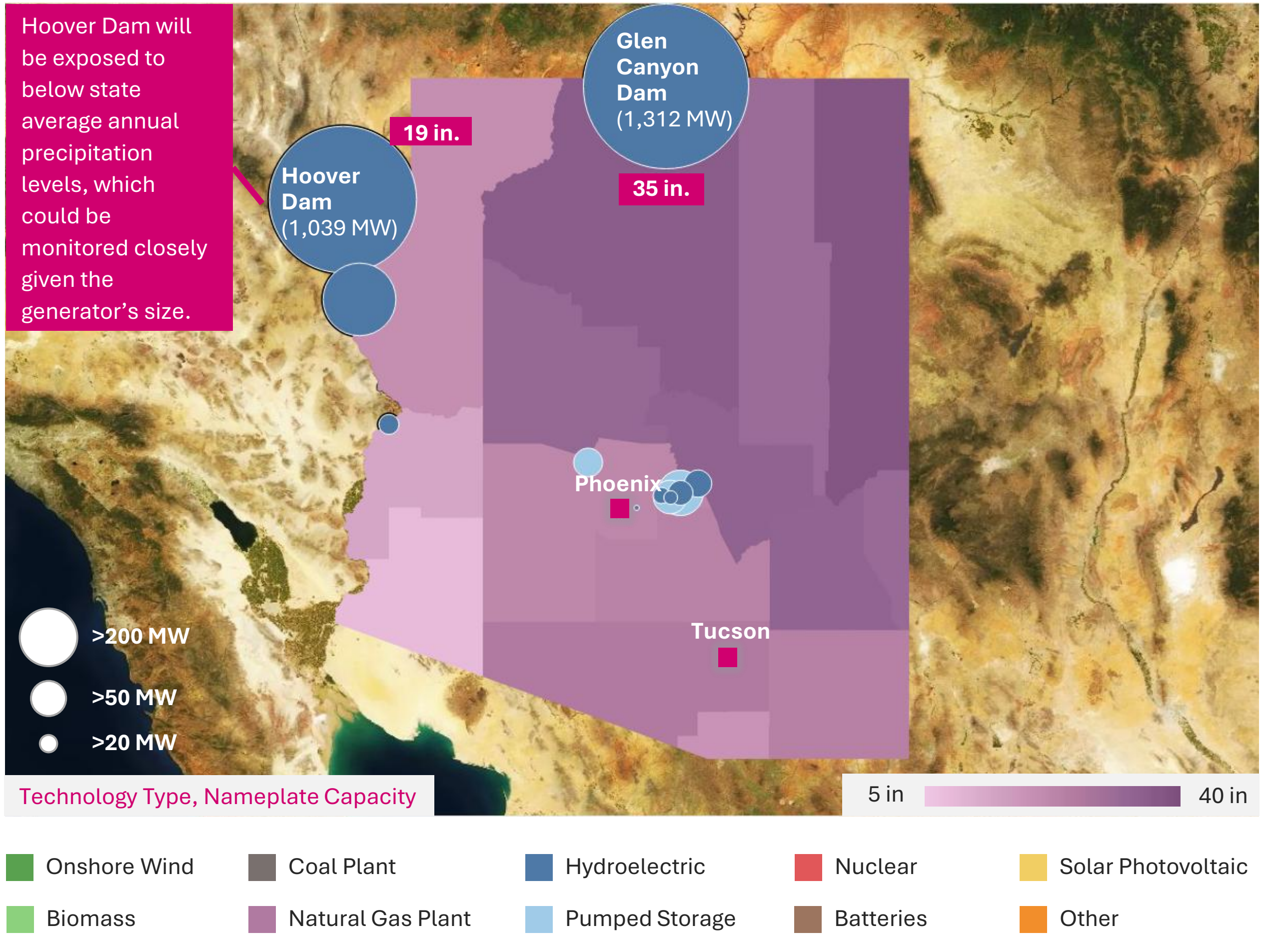
Precipitation

Asset Analysis

Precipitation levels stay relatively constant, but AZ could consider the impacts of extreme precipitation events, upstream conditions, and changing snow patterns on hydro output

Arizona Annual Max Precipitation (in)
Generators, Mid-Century [RCP5-8.5]



Key Highlights	Analysis
Extreme Events	• Timing of precipitation has an important impact of hydro output. • Extreme rainfall events are common in AZ during monsoon season, potentially **overflowing reservoirs and putting more pressure on dams, increasing risk of failure.** • Projections of increased drought and relatively constant annual precipitation indicate that **extreme precipitation events may become more likely over time.**
Upstream Coordination	• **Upstream precipitation and drought** will have significant impacts on hydro production. • AZ could **establish a relationship with the UT and CO SEOs** to share information about precipitation conditions and hydro output along the Colorado river.
Changes to Snow Patterns	• While precipitation levels remain relatively constant to mid-century, precipitation type and timing is likely to change and could be monitored. • Grid operators could **consider the impacts of less snow and earlier snow melt when conducting long-term planning.**

Source: ClimRR, EIA860, HIFLD

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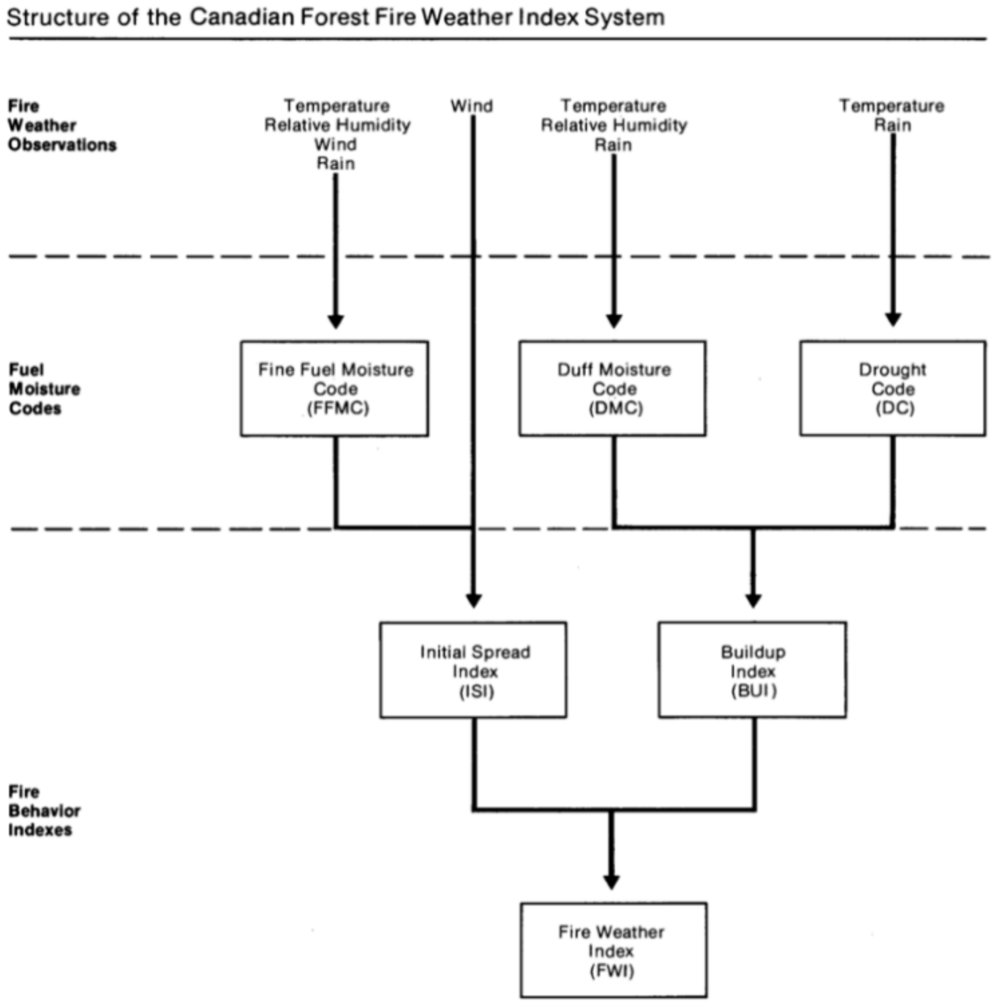
Appendix

Fire Weather Index synthesizes weather and moisture content data into a normalized value representing the danger of fire spread once ignition has occurred.



KEY TAKEAWAYS

- FWI is a useful metric for evaluating weather-based conditions that heighten the **danger of wildfire spread once ignition has occurred.**
- **Initial Spread Index**: Measures the **expected rate of fire spread,** based on wind speed and moisture content of fine fuels/forest litter (Fine Fuel Moisture Code).
- **Buildup Index:** Measures **the total amount of forest fuel available for consumption,** based on the **moisture content of intermediate organic layers**, such as decomposing plant matter (Duff Moisture Code), and the **moisture content of deep organic layers and soils,** which corresponds to drought measures (Drought Code).
- Daily FWI values were calculated using readings from Argonne's downscaled 12km climate data and averaged annually or seasonally across RCP-4.5 and RCP-8.5.
- Percentiles (below) were calculated based on **FWI values across all 12km grid cells in the contiguous U.S.**

FWI Class	Percentile range in historical period	FWI values in Class
Low	0–25th percentile	0–9 FWI
Medium	25–50th percentile	9–21 FWI
High	50–75th percentile	21–34 FWI
Very High	75–90th percentile	34–39 FWI
Extreme	90–98th percentile	39–53 FWI
Very Extreme	Above 98th percentile	Above 53 FWI

Source: ClimRR, US Census Bureau, City and Town Population Totals

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