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Grid Resilience Reports

Colorado

Energy & Resources | Networks
10/23/2024

Table of contents

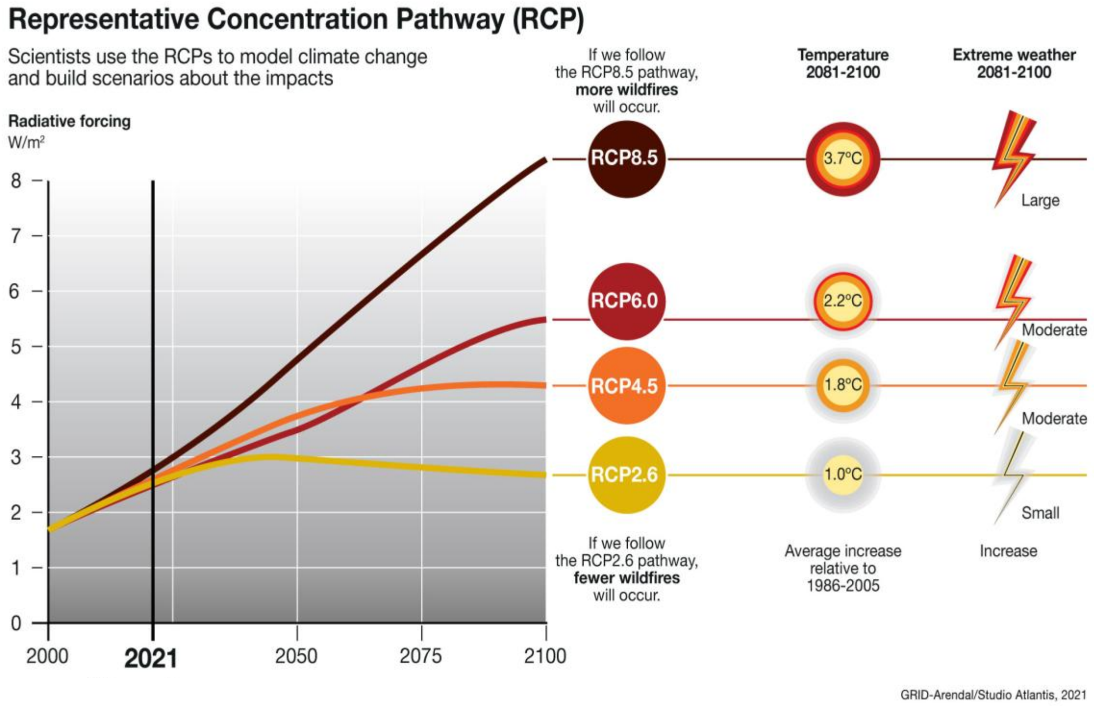
Grid Resilience Reports

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

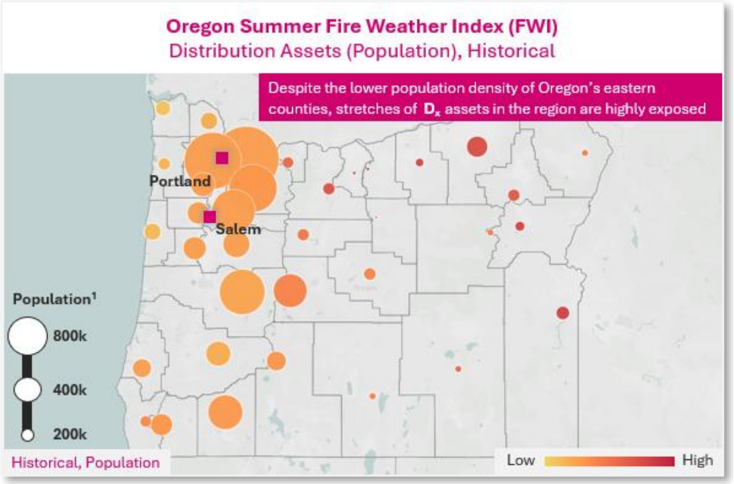
Output: Input metrics applied from a grid cell level to a county level

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)

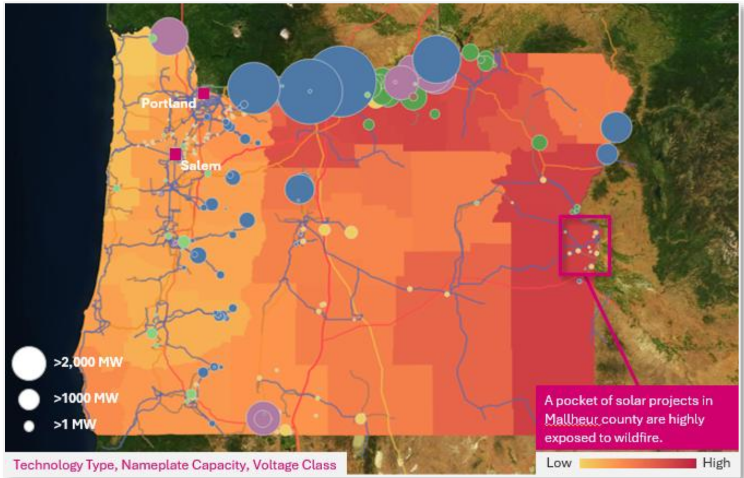
This report is standardized to include 3 different data visualizations that provide insights for Distribution, Transmission, and Generation across 7 extreme weather hazards

1 Distribution Maps



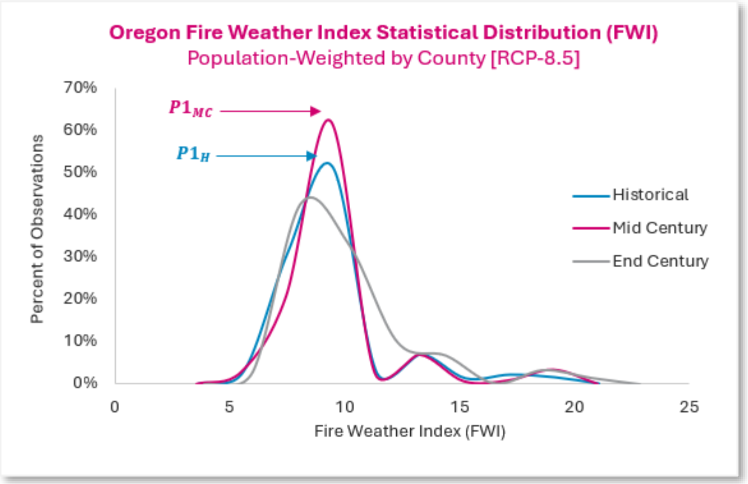
- **Purpose:** Uses population as proxy for volume of distribution assets given that the location of distribution assets is restricted.
- **Interpretation*:** Locate areas of high exposure by identifying counties with coincident large bubbles and dark colors. This indicates a combination of high volume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

Summary

L Low M Moderate H High

To better align with exposure, CO could consider expanded wildfire mitigation investment and evaluate whether existing hardening projects effectively address heat and cold

Key Takeaways

- Consider emergency response programs to act on new data and transmission and distribution hardening in W counties with high levels of fire exposure.
- Explore methods to offset generator derating and consider funding substation upgrade projects to mitigate the risk of direct asset failure.
- Consider new weatherization programs for thermoelectric assets and evaluate whether cold exposure is being adequately addressed by existing projects.

Hazard	Exposure	Change to Mid-Century	Generation	Transmission & Distribution (Tx & Dx)	AWPI*	Description
FIRE	H	↑	**Consider investment in emergency response and thermoelectric fortification** • CO could invest in emergency response projects that act on the new data gleaned from drone inspection and monitoring. • Consider initiatives to mitigate fire spread from contact with flammable fuel stockpiles.	**Consider Tx and Dx hardening in western counties** • Western counties could be prioritized for Dx hardening projects, especially areas with high asset density such as Mesa County. • High-voltage Tx lines running through western counties could be prioritized for hardening given high levels of fire exposure.	M	**Gen:** No proposed awards address generator wildfire exposure, although most gen assets face low exposure. **T&D:** Undergrounding, vegetation management, and other wildfire mitigation projects demonstrate alignment with exposure, but CO could prioritize western counties.
HEAT	M	↑	**Explore demand response (DR) or enhanced cooling methods to offset derating of supply** • DR programs exhibit synergies with ongoing microgrid investment and can combat thermoelectric production derates. • Innovative thermoelectric cooling combats production derates and drought exposure.	**Consider substation upgrades and more cost-effective Tx hardening methods** • Significant exposure to days >105 °F requires substation upgrades to avoid direct failure. • Widespread heat exposure necessitates upgrades that harden the entire length of a high-voltage (HV) transmission line, especially in the SE and SW.	M	**Gen:** Microgrids for Community Resilience (MCR) program addresses derating of large generators. **T&D:** No mention of substation upgrades, which face considerable extreme heat exposure and a high likelihood of failure.
COLD	M	↓	**Continue to monitor the efficacy of generator winterization upgrades** • Many utilities have indoor gas units and winterized wind generation but could continue to monitor whether these upgrades are working effectively.	**Explore opportunities to address cold and fire exposure simultaneously in western counties** • Icing exposure is likely to remain low due to warming temperatures and a dry atmosphere. • Consider vegetation management to address snow loading on trees near Dx assets.	M	**Gen:** No proposed awards address generator cold exposure. **T&D:** Hardening projects may address cold exposure but appear heavily tailored towards wildfire.

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

L Low M Moderate H High

CO could prioritize generator hardening investment addressing drought and consider substation fortification and distribution pole upgrades to combat flood exposure

Key Takeaways

- CO could evaluate whether undergrounding projects increase flood exposure and prioritize substation fortification and distribution pole upgrades.
- Assets could be upgraded to withstand wind speeds up to 130 mph in the most exposed counties under a worst-case scenario.
- CO could seek out information about drought trends, precipitation timing, and snow patterns to better assess the impact on WAPA hydro generation.

Hazard	Exposure	Change to Mid-Century	Generation	Transmission & Distribution (Tx & Dx)	AWPI*	Description
FLOOD	M	↑	**Generators are generally not significantly exposed to flood** • A solar project in Pitkin County is exposed, which could damage inverters or other ground-based equipment.	**CO could prioritize substation fortification** • Pockets of high-voltage substations are heavily exposed to flooding, especially in San Juan County, which can cause direct failure. • CO could also consider upgrades to aging or weak distribution poles.	L	**Gen:** Lack of exposure makes this a lower priority for investment. **T&D:** No projects targeting substations, unaligned with the significant substation exposure.
WIND	M	→	**Consider hardening for renewable generators in highly exposed regions** • Wind and solar assets in eastern counties are exposed to return values above their wind speed ratings, leading to asset damage.	**CO could consider Tx structure and Dx pole upgrades along a high-exposure corridor** • CO could prioritize Tx and Dx hardening along a high-exposure corridor running through the central region of the state.	M	**Gen:** No projects addressing generator exposure. **T&D:** Undergrounding addresses wind, but CO could also consider pole upgrades.
DROUGHT	M	→	**CO could monitor the impact of drought on WAPA hydro generation** • ~5% of CO electricity comes from WAPA. • Water scarcity's impact on cooling is less significant given the retirement of many thermoelectric assets by 2030.	**Drought exposure does not have a material impact on transmission and distribution assets**	M	**Gen:** Suggested projects for heat and fire exposure also address drought, including solar O&M advances. Currently none of these types of projects have been funded.
RAIN	M	→	**CO could consider other factors that impact hydroelectric output in the state** • Consider the possibility of more frequent extreme rainfall and changing snow patterns, not captured in annual metrics.	**Precipitation exposure does not have a material impact on transmission and distribution assets**	M	**Gen:** CO could gather additional information to assess the true impact of precipitation on hydro and pumped storage assets and its implications for resource planning and scheduling.

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

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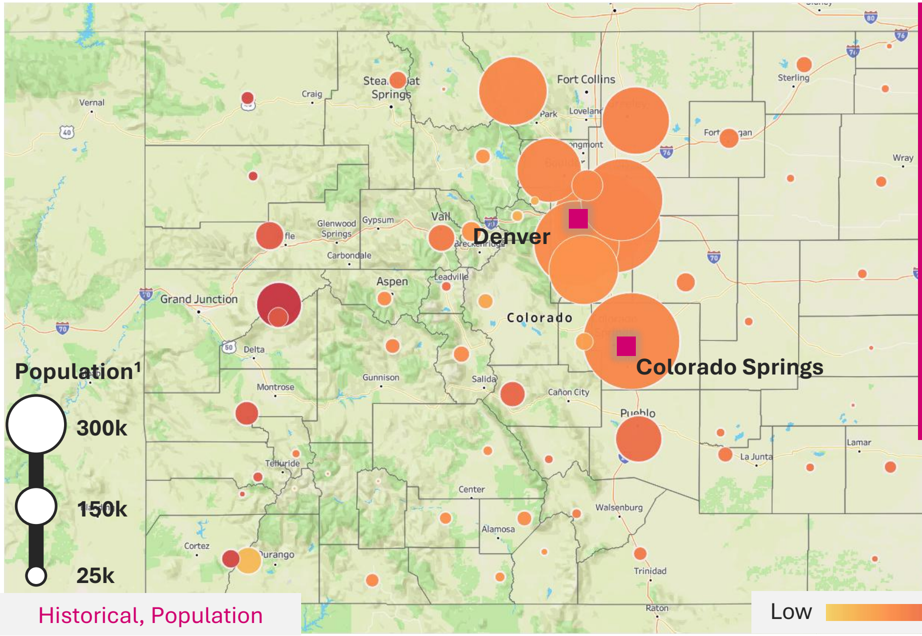
Wildfire

Asset Analysis

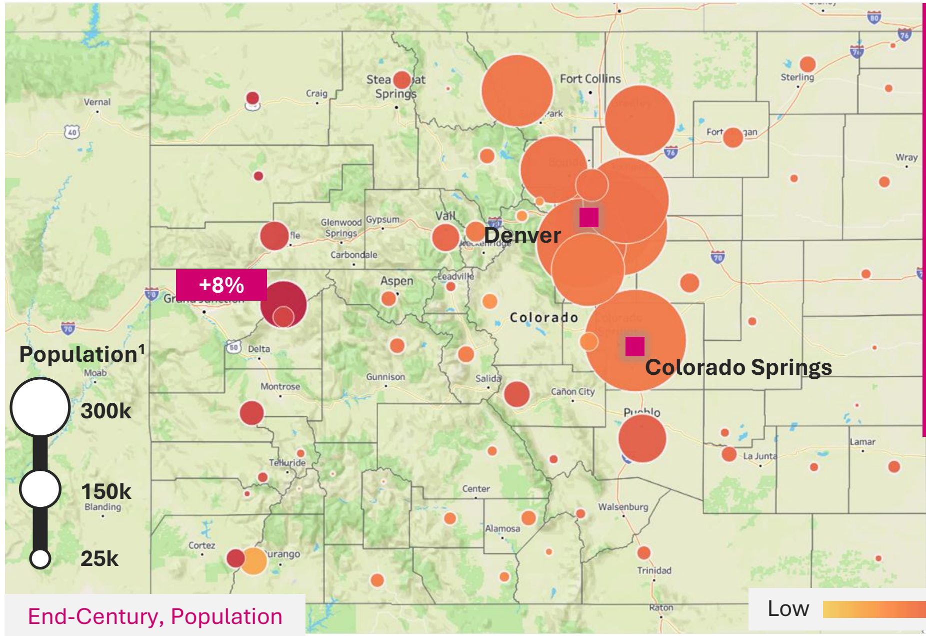
Proposed 40101(d) projects in Colorado largely address wildfire exposure, but CO could prioritize projects in western counties and the buffer region between population centers

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



Wildfire has historically been **highest in western counties**, but the potential for fire spread puts highly concentrated distribution pockets at risk.

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



Counties with smaller populations are more likely to be served by vulnerable, radial lines, which could be considered for hardening.

KEY OBSERVATIONS

- Wildfire exposure is concentrated in Colorado's **western counties,** corroborating findings from CO's EnviroScreen tool.
- Large population centers face about average wildfire exposure, but this could be **underrepresented given proximity to highly exposed counties.**
- Drone inspection, vegetation management, reconductoring, and undergrounding proposals indicate alignment with wildfire exposure.

KEY OBSERVATIONS

- FWI increases by about 3-6 points across the state, demonstrating the importance of utilizing **forward-looking climate projections for state-wide fire mitigation planning.**

Mesa County — **Mesa County faces peak state wildfire exposure,** which given the county's relatively high population exposes a high density of distribution assets.

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

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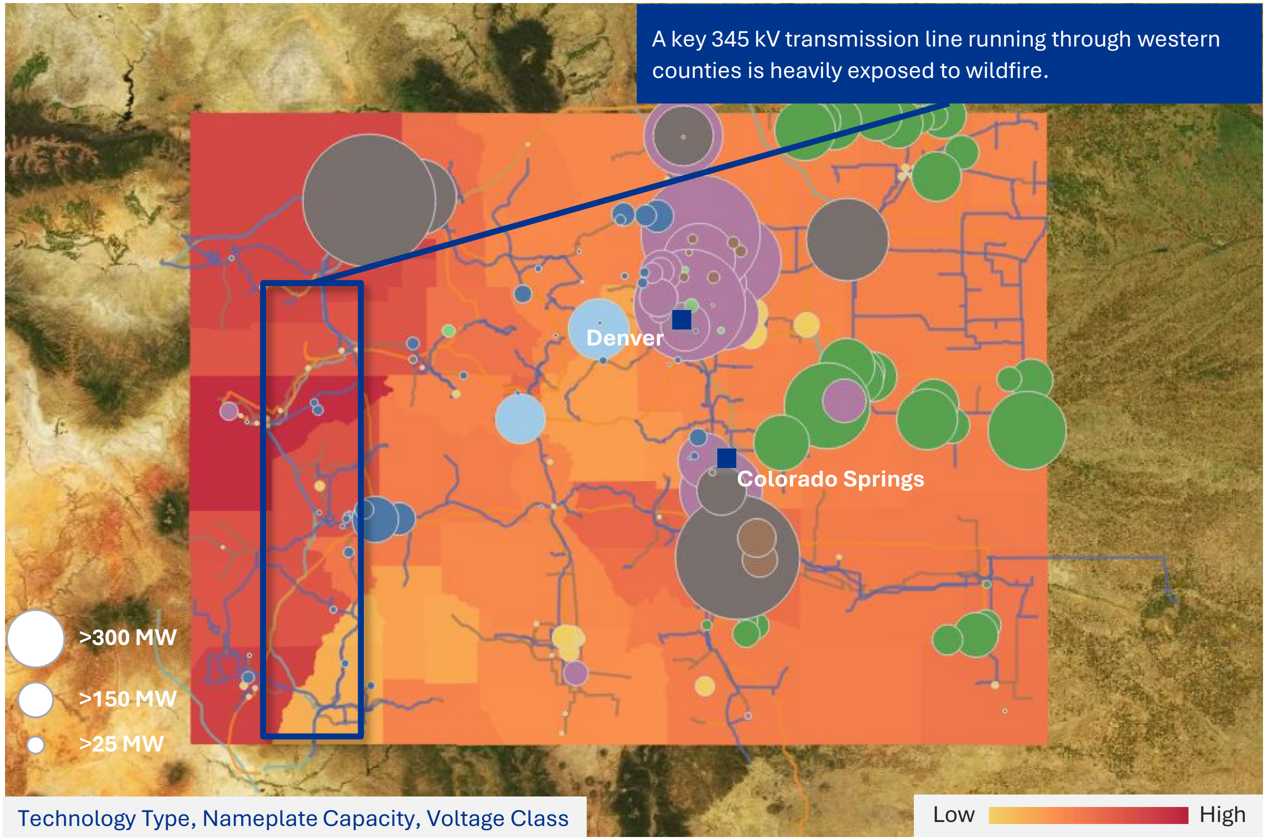
CO could prioritize transmission (Tx) hardening, asset access projects, and thermoelectric fortifications in western counties to address escalating wildfire exposure

Colorado 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, US Census Bureau, City and Town Population Totals

Key Highlights	Analysis
Transmission	• A high density of Tx assets are located in counties with high levels of wildfire exposure. • A key **345kV line cutting through southwestern counties faces peak state wildfire exposure,** demonstrating a potential priority for future hardening investment.
Restoration	• Wildfire causes **ingress/egress issues** through destruction of roads and transportation, slowing restoration times for all assets. • Drone inspection projects funded by CEO could cut restoration times by more effectively identifying issues, but **CO could consider other projects that address access issues posed by wildfire.**
Thermoelectric	• Coal and natural gas assets in Moffat and Mesa Counties face high wildfire exposure. • **Flammable fuel stockpiles can accelerate fire spread** if not fortified.

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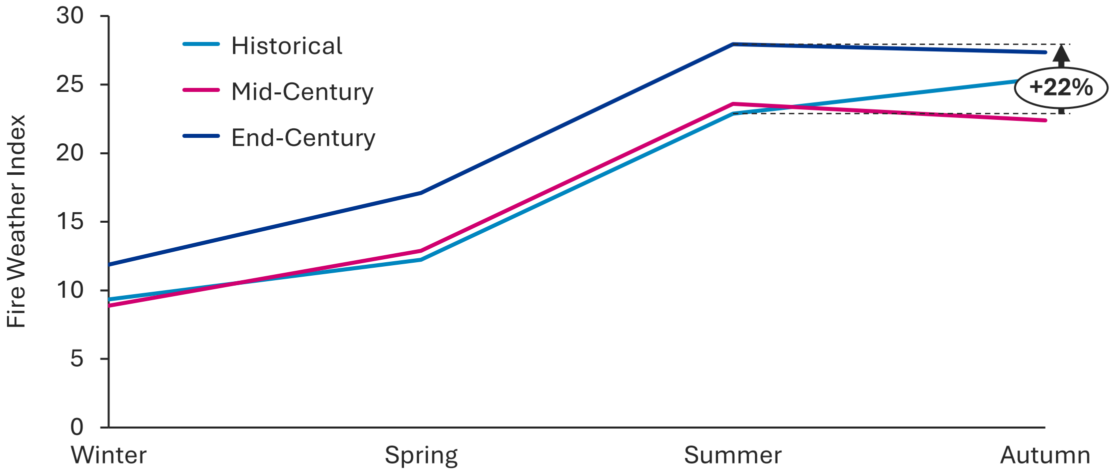
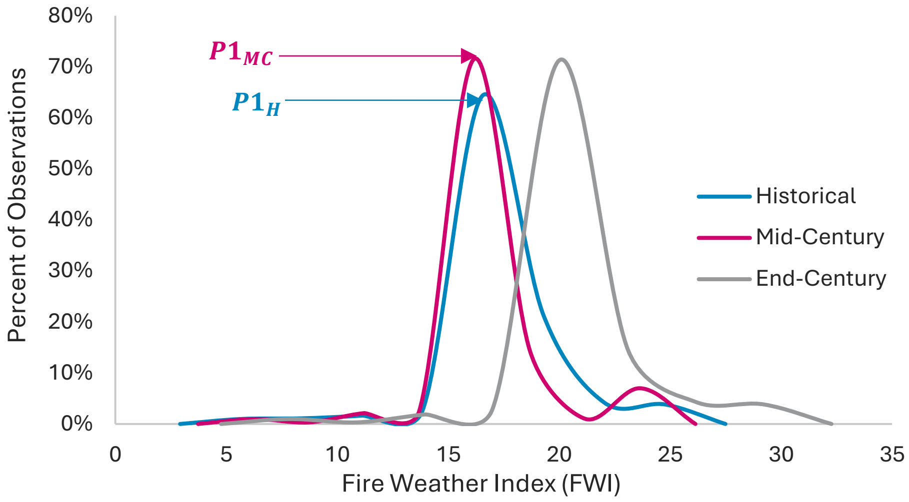
Wildfire exposure exhibits minimal change by mid-century, but increases drastically in severity by end-century across a majority of the state

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



Colorado 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 between spring and autumn by about 22% from historical FWI.
- Elevated wildfire exposure around the summer suggests a **lengthening of the wildfire season** combined with an **increase in severity.**
- The increase in the summer peak indicates that **wildfire season will reach peak severity in the summer by end-century,** compared to what is currently an autumn peak.

KEY OBSERVATIONS

- Rightward shift of the curve by end-century demonstrates an **increase in wildfire severity of about 5 FWI points across much of the state**.
- The bi-modal shape of the curve represents two distinct hazard regions within the state, **one large zone facing FWI between 15-20**, and a **smaller pocket facing extreme FWI exposure exceeding 22 points**.
- Increase in P1 represents a **wider spatial extent exposed to a FWI level of about 15 points by mid-century**.

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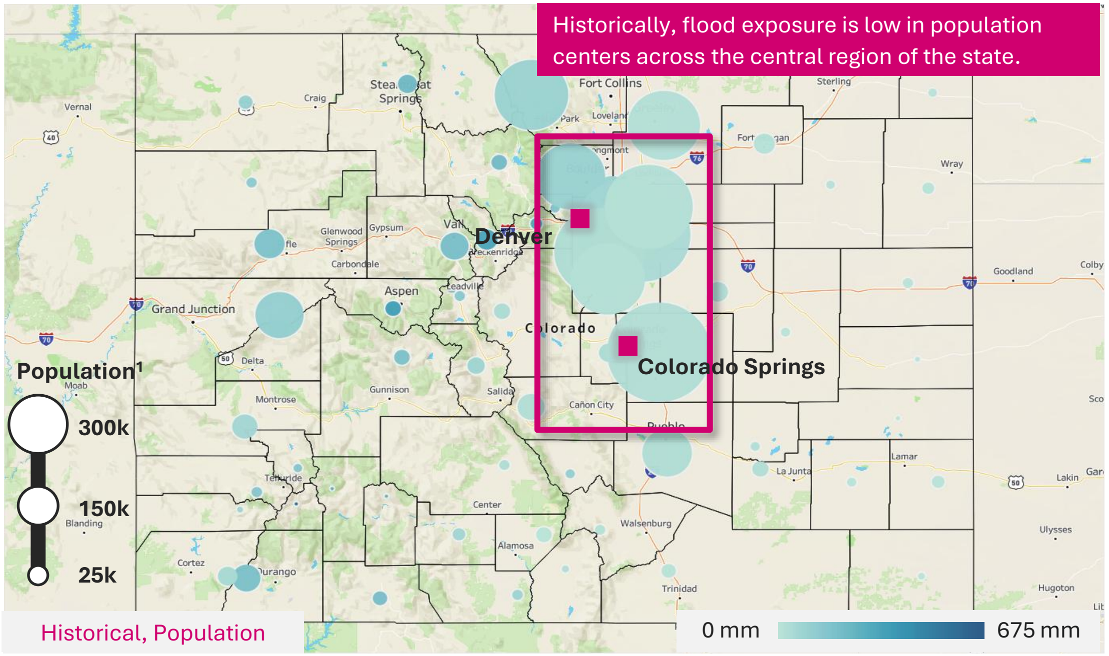
Flood

Asset Analysis

Flood exposure across the state is generally low, but CO could consider distribution fortification projects in mountain valley communities that face increasing exposure over time

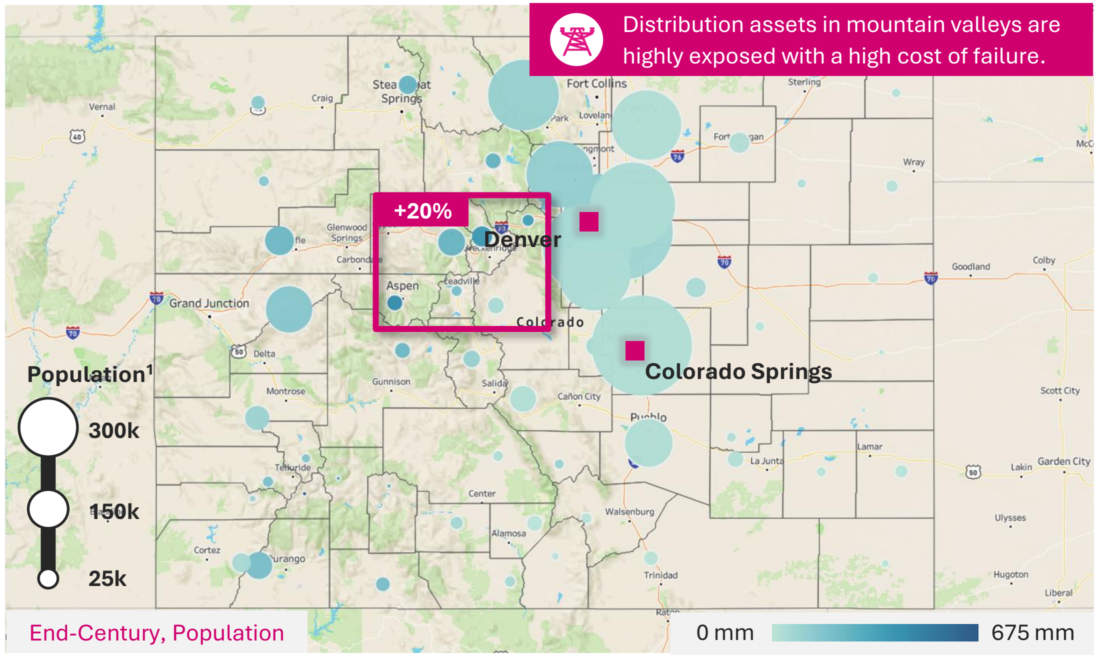
Colorado Average Annual Surface Runoff (mm/year)
Historical [SSP5-8.5]



KEY OBSERVATIONS

- Most flood exposure lies in the **central-west counties** given their mountainous terrain and significant snowmelt.
- Generally **low levels of flood exposure in central population centers** given their higher elevations and flat terrain.
- Currently no proposed projects explicitly address flood exposure.

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



KEY OBSERVATIONS

- CO could consider prioritizing projects to fortify low-lying Dx substations given the increase in flood exposure over time in western counties.

Summit and Pitkin Counties

Flood exposure is projected to increase about 20% by end-century, posing a substantial threat to low-lying substations and distribution poles.

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

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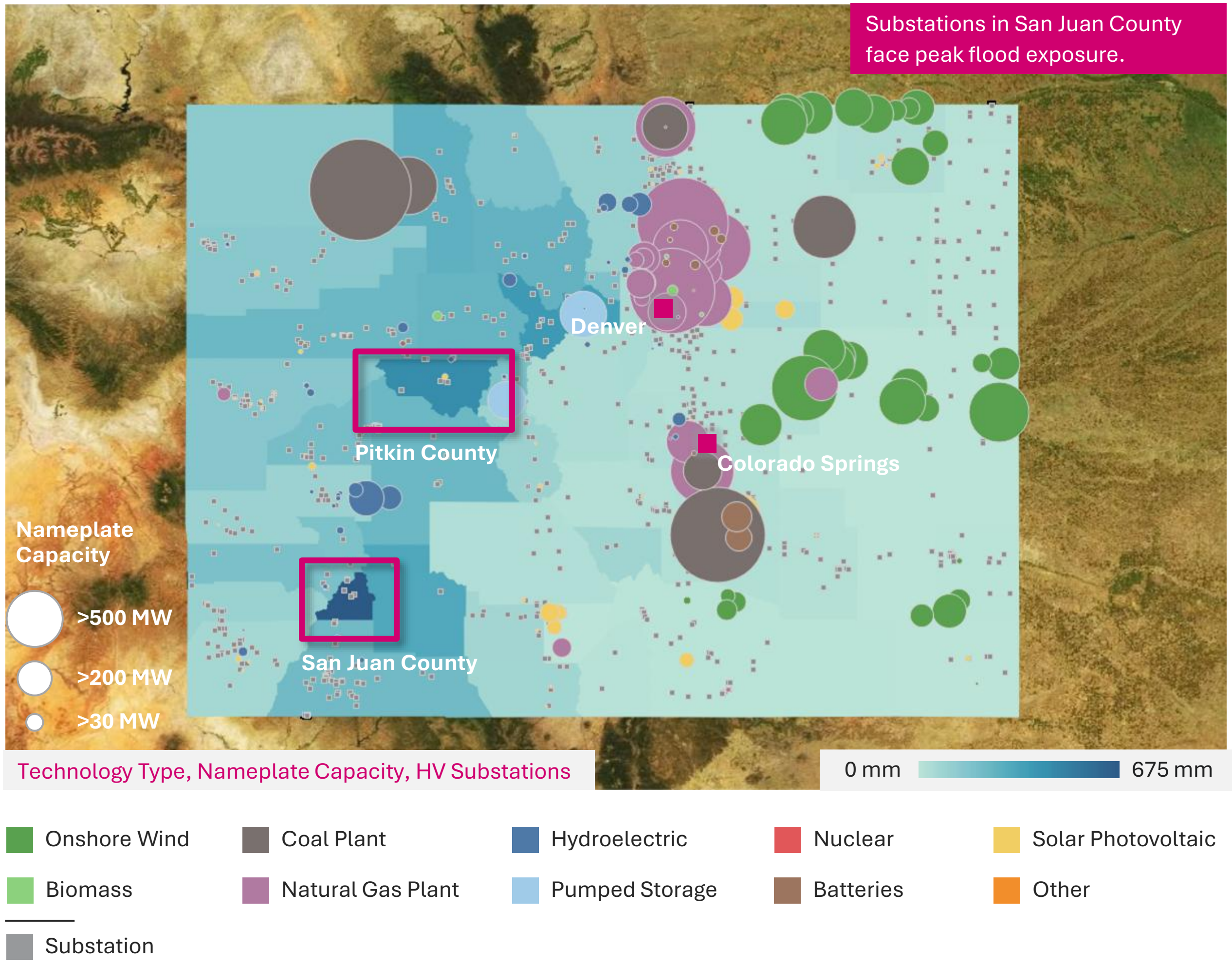
While generators generally face low levels of flood exposure, CO could prioritize low-lying substation upgrades in a handful of high exposure counties

Colorado Average Annual Surface Runoff (mm/year)
Population-Weighted by County [SSP5-8.5]



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

Key Highlights	Analysis
Substation	• High-voltage (HV) substations will be exposed to pluvial flooding. Fluvial flooding is a risk if located in flood plain or riverbank without necessary protections. • A pocket of **HV substations in San Juan County are heavily exposed to flood risk**, marking a priority for future hardening projects.
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	• Generators are largely not exposed to flood risk, indicating that **CO could prioritize transmission and distribution projects to address the hazard.** • A solar project in Pitkin County is highly exposed to flood, which could damage inverters and other ground-level equipment.

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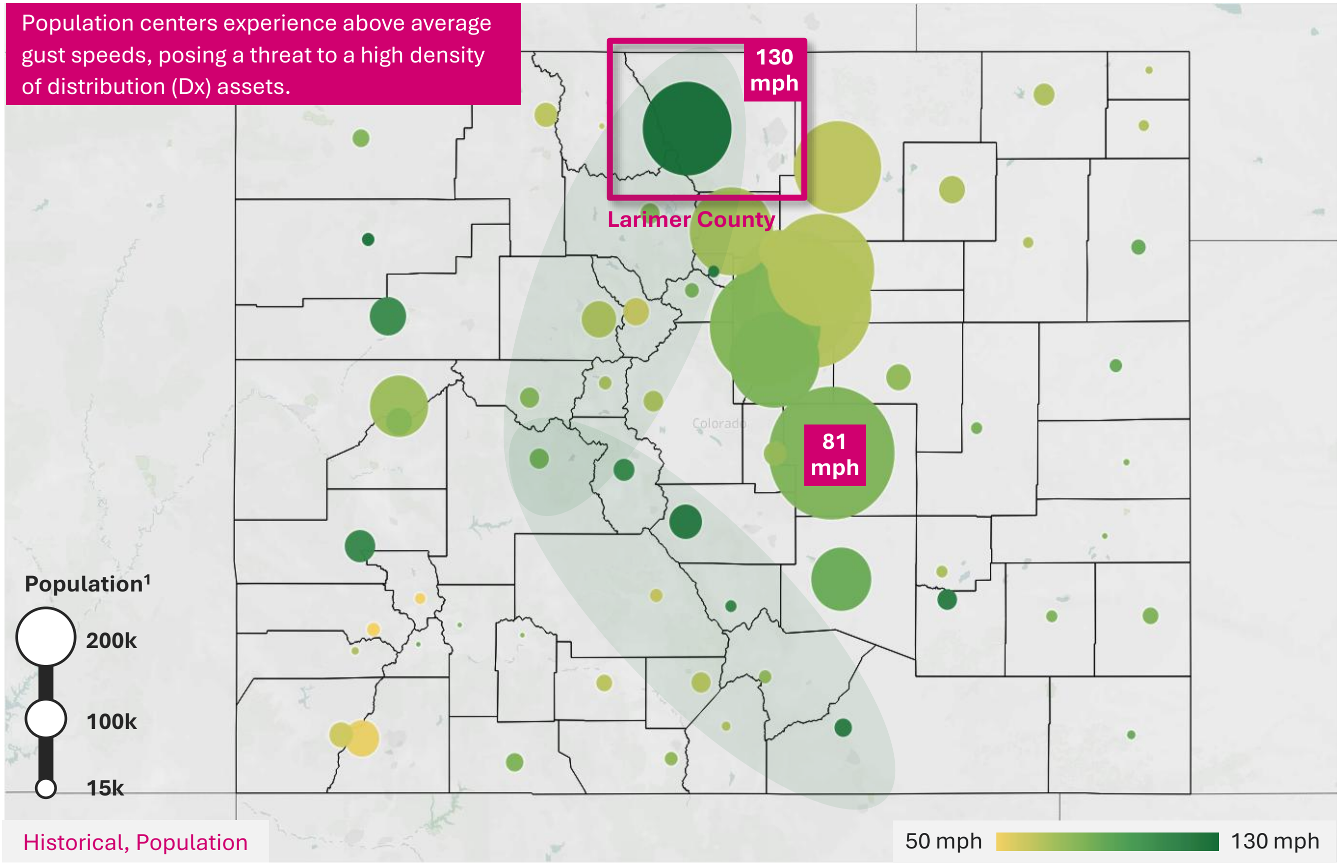
Wind

Asset Analysis

CO could consider pole upgrades along mountain ranges in the central region of the state to complement existing undergrounding and vegetation management projects

Colorado 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 could be addressed through **upgraded design standards** across a utility service territory.
Larimer County	• Larimer County has a population of approximately 400k and 100-year return value of 130mph, **indicating a high exposure area for Dx assets**. • Coincident extreme cold events put distribution lines at risk for galloping and sag.
High Exposure Corridor	• Gust speeds are highest along a corridor that roughly tracks mountain ranges in the state. • This corridor is also particularly exposed to wind-related damage given a proliferation of dead trees from beetle kill, demonstrating the importance of vegetation management projects in the region.

Source: DRI, EIA860, HIFLD

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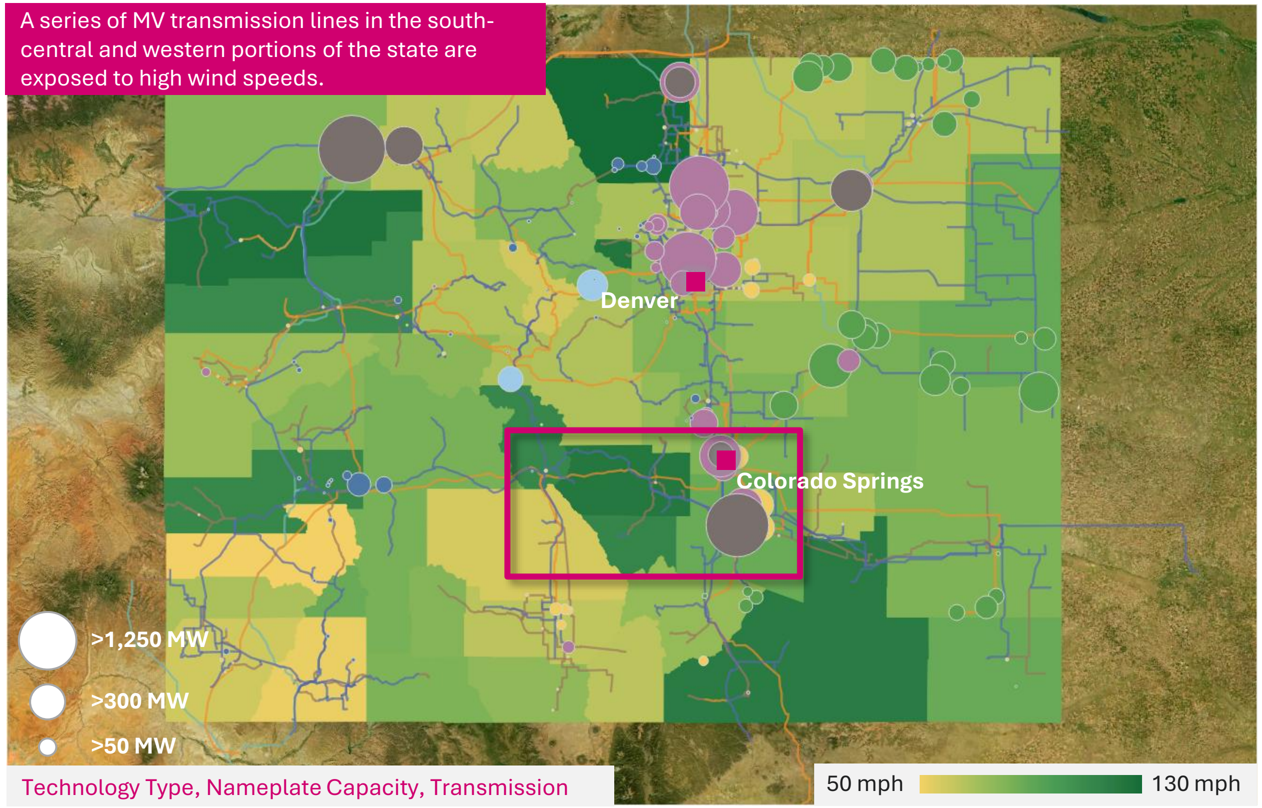
Medium-voltage (MV) transmission lines in the west and south-central portions of the state could be prioritized for hardening given their critical ties from large generators to load sinks

Colorado 100-year Wind Speed (mph)

Historical

A series of MV transmission lines in the south-central and western portions of the state are exposed to high wind speeds.



Technology Type, Nameplate Capacity, Transmission

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

Source: DRI, EIA860, HIFLD

Key Highlights	Analysis
Transmission	• A series of **MV transmission lines in the south-central and western portions of the state are exposed to high wind speeds.** • **MV lines in Fremont County are also exposed to peak state wind exposure.** • These lines are crucial for connecting large thermoelectric generators to demand pockets. **CO could focus on reinforcing transmission structures to mitigate risk.**
Renewables	• A handful of solar farms throughout the state are exposed to 100-year return period values of > 100mph. • Depending on the supplier, solar panels are only rated to 90 mph, **indicating need for rack reinforcement and vegetation management.**
Wind	• Wind farm cutout speeds can vary between 45-70mph, indicating that in high wind speed events, the turbines stop producing. • The cluster of large wind farms located in the eastern portion of the state are exposed to 100-year return period values far greater than the cutout threshold, impacting **critical supply near population centers**.

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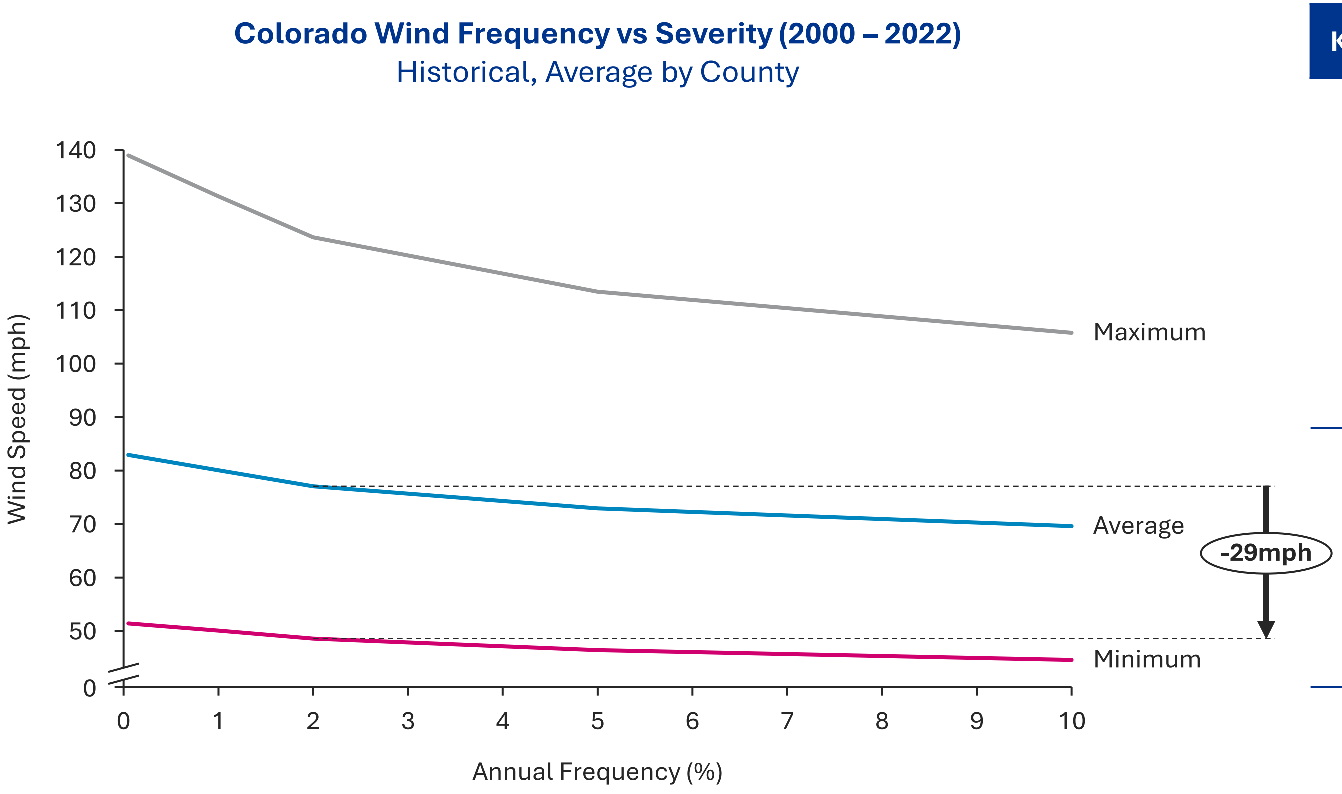
Historically, there is a 1% chance that the average wind speed seen across Colorado counties is ~80mph annually.



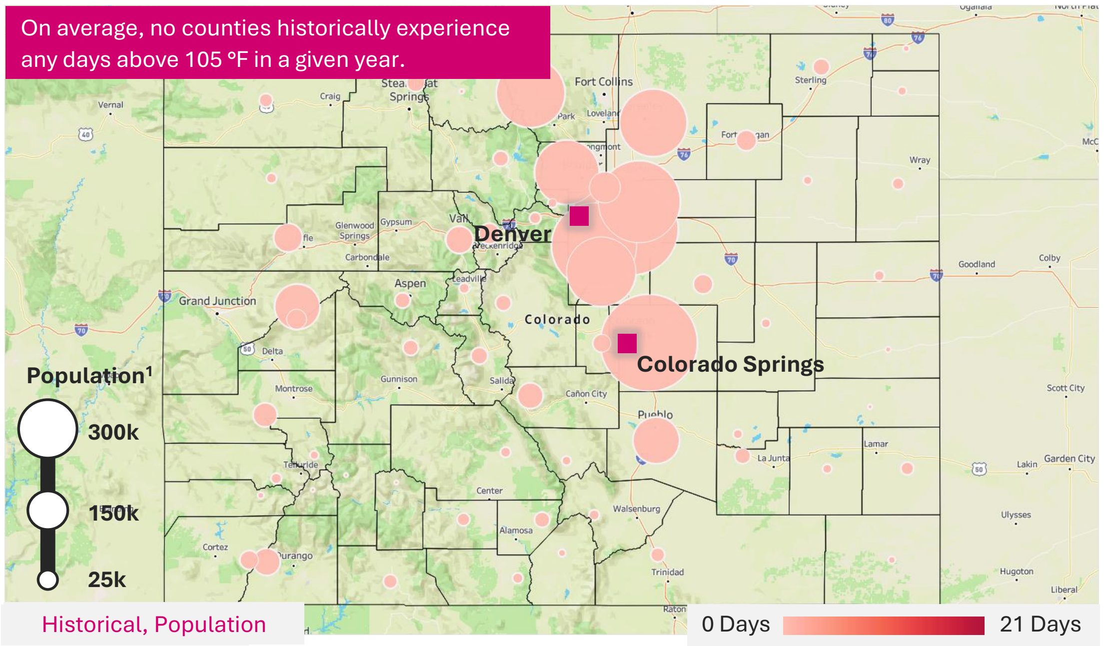
Key Highlights	Analysis
High System Averages	• Historically, there is a 1% chance that the average wind speed seen across Colorado counties is ~80mph annually. • Further out on the curve, the 10% annual likelihood drops to 69mph, indicating high system wind speeds are common across counties.
Volatility Across Counties	• There is a wide 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.

Heat

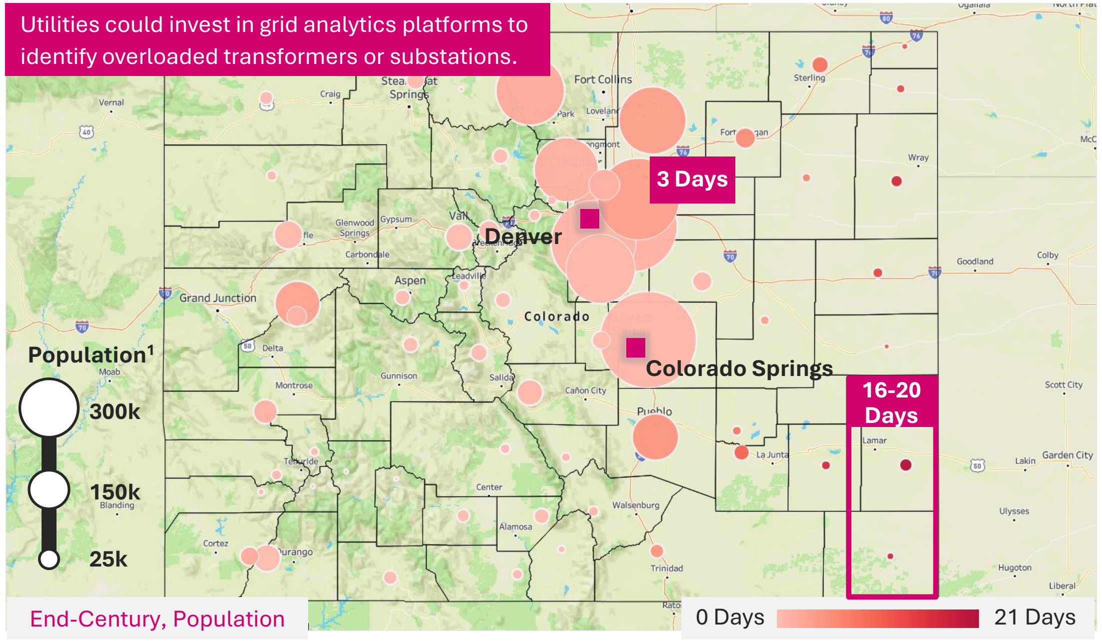
Asset Analysis

CO could consider distribution system upgrades addressing extreme heat to mitigate asset degradation, derating, and potential failure given escalating exposure over time

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



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



KEY OBSERVATIONS

- Currently, transmission (Tx) and distribution (Dx) assets have **no exposure to days above 105 °F.**
- 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

- Southeastern counties are expected to face **about 16-20 days >105 °F annually, causing high asset utilization, derating, and potential failure.**

Adams County — Adams County will face over 3 days **>105 °F** by end-century, exposing a high density of Dx substations and transformers to derating, accelerated degradation, and potential failure.

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

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

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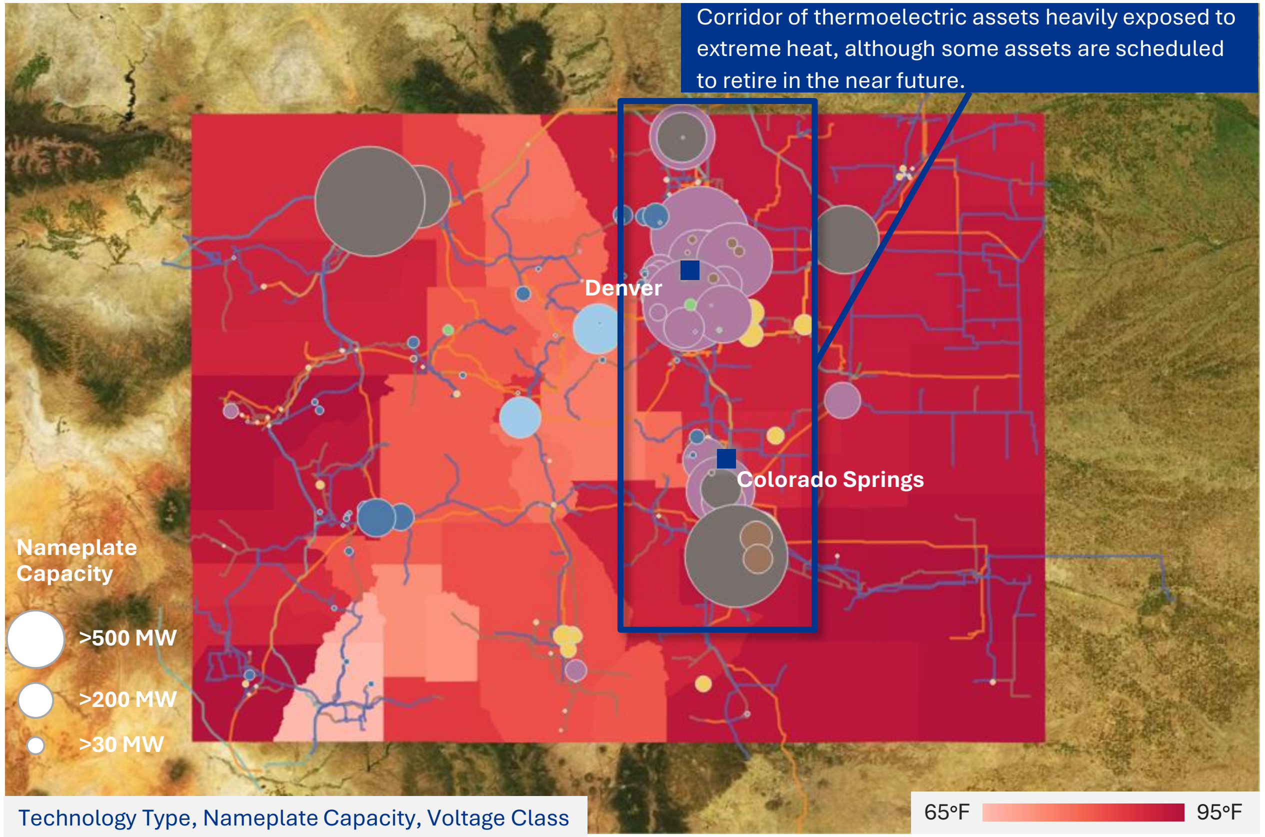
CO could consider additional investments to combat thermoelectric production and transmission capacity derates due to extreme heat given escalating exposure over time

Colorado 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, US Census Bureau, City and Town Population Totals

Key Highlights	Analysis
Thermoelectric	• Natural gas and coal assets in the **central portion of the state** are heavily exposed to extreme heat. • Thermoelectric generators that rely on water-based cooling methods will **experience production derates** as extreme heat raises average water temperatures. • CEO's proposed microgrid projects generally address derating during load shed events.
Transmission	• A significant portion of transmission lines are exposed to high levels of extreme heat in the SW and SE, which can cause capacity derates and line sag. • Undergrounding proposals address these issues, but CO could consider **more cost-effective adaptations like reconductoring to fortify transmission lines over longer distances.**
Renewables	• Extreme heat can cause **solar production derates and shorten battery energy storage system (BESS) lifespans.**

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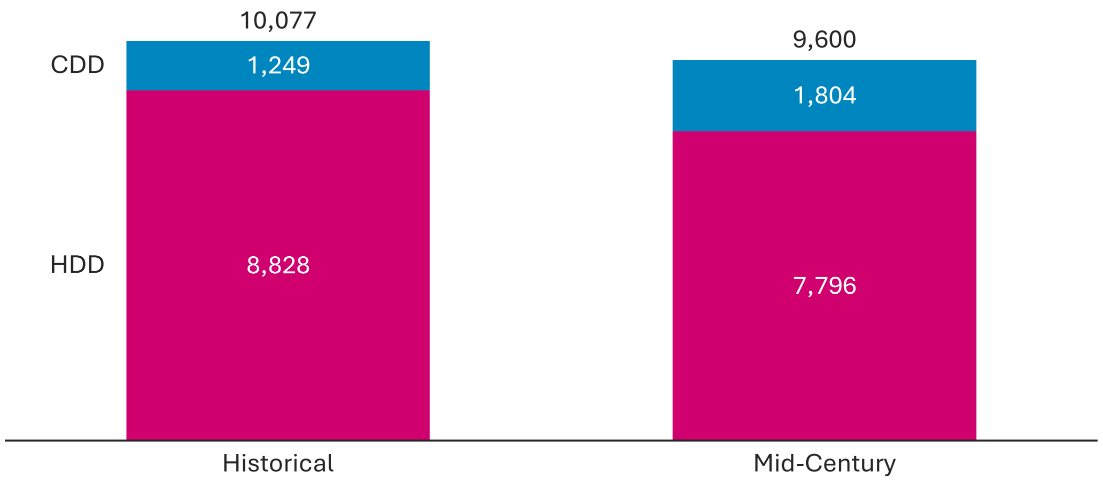
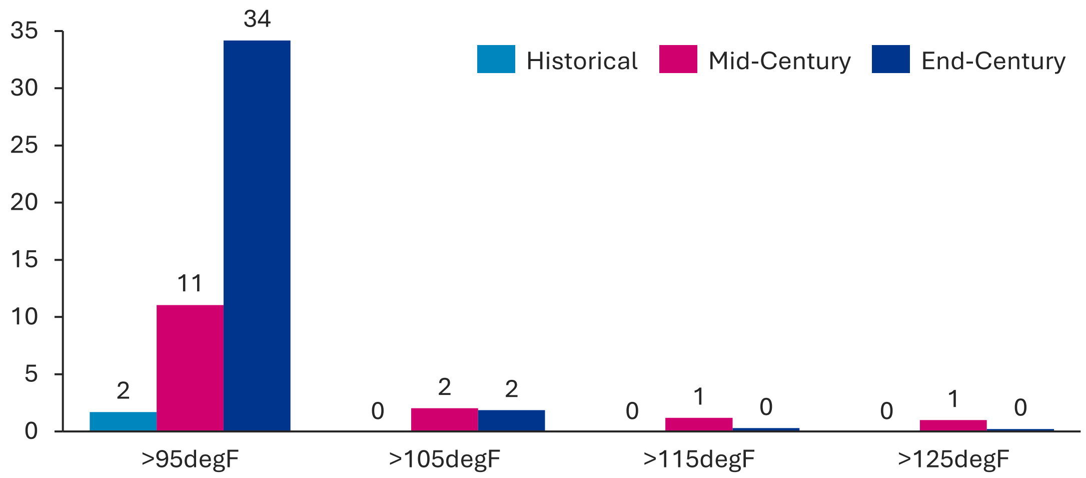
Days above 95 °F are projected to increase drastically over time, making derating and capacity violations key issues for CO to prioritize

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



Colorado Average Annual Days Exceeding Daily Max Heat Index Thresholds
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 average number of CDD jumping from about 12% to 18%.
- This increase in CDD results in **increased summer asset utilization and degradation**, but **impacts to winter utilization remain unclear** depending on heating electrification trends.
- CO could be mindful of the **impact of heating electrification on peak load** given significantly higher HHD levels than CDD levels.

KEY OBSERVATIONS

- >5x increase in days with heat index >95 °F by mid-century demonstrates an **increase in peak load** and will likely contribute to **derating** and **capacity violations** for transmission and thermal generating units.
- 2 days >105 °F by mid-century poses a **risk to distribution substations**, which can fail after two consecutive days above 104 °F.
- Utilities could prioritize planning for temperatures between 95-105 °F, making **derating a higher priority than asset failure.**

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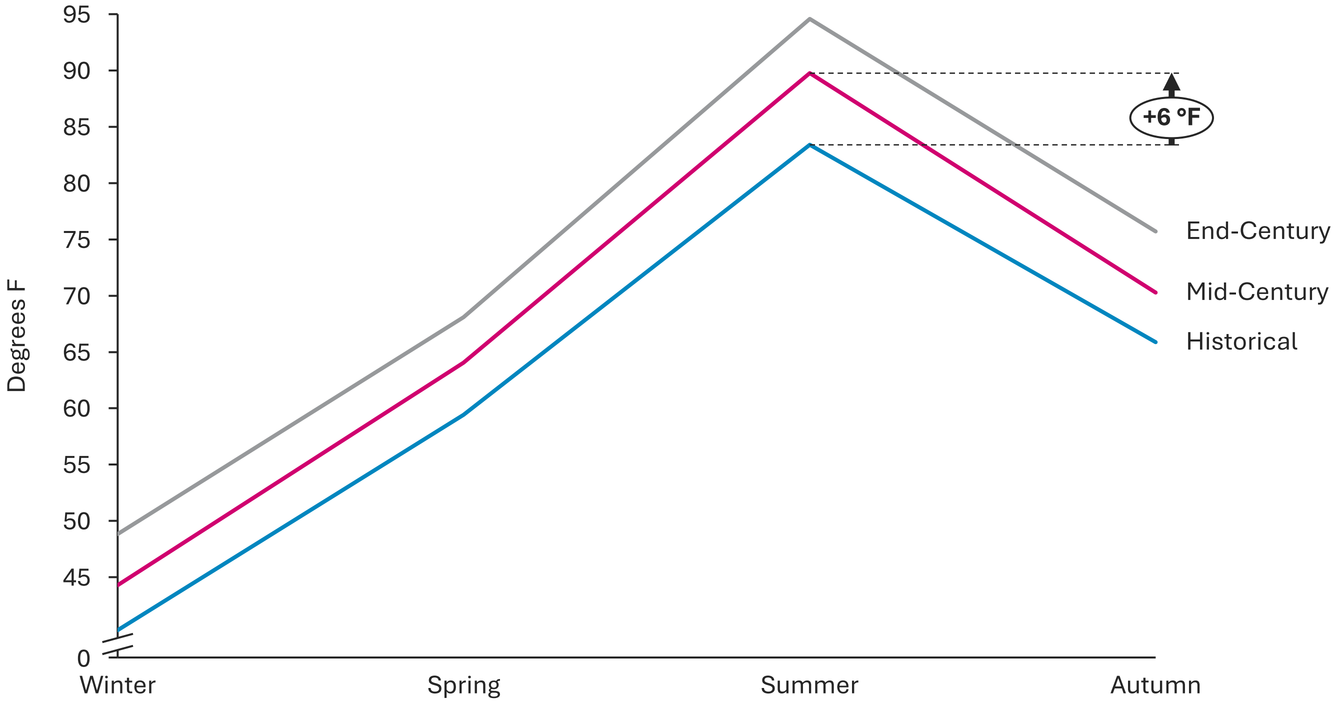
Average summer temperature maximums are projected to increase by mid-century, increasing the duration and magnitude of high system utilization

Colorado 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 6 °F increase in the average seasonal max by mid-century, **increasing system utilization and accelerating asset degradation.** • Average summer minimum temperatures are also projected to increase (slide 34), which **shortens the overnight cooldown period for assets.**
Shorter Shoulder Seasons	• There is generally less pronounced warming in shoulder seasons, although increased autumn maximums could **extend the duration of high system utilization and shorten maintenance windows.**

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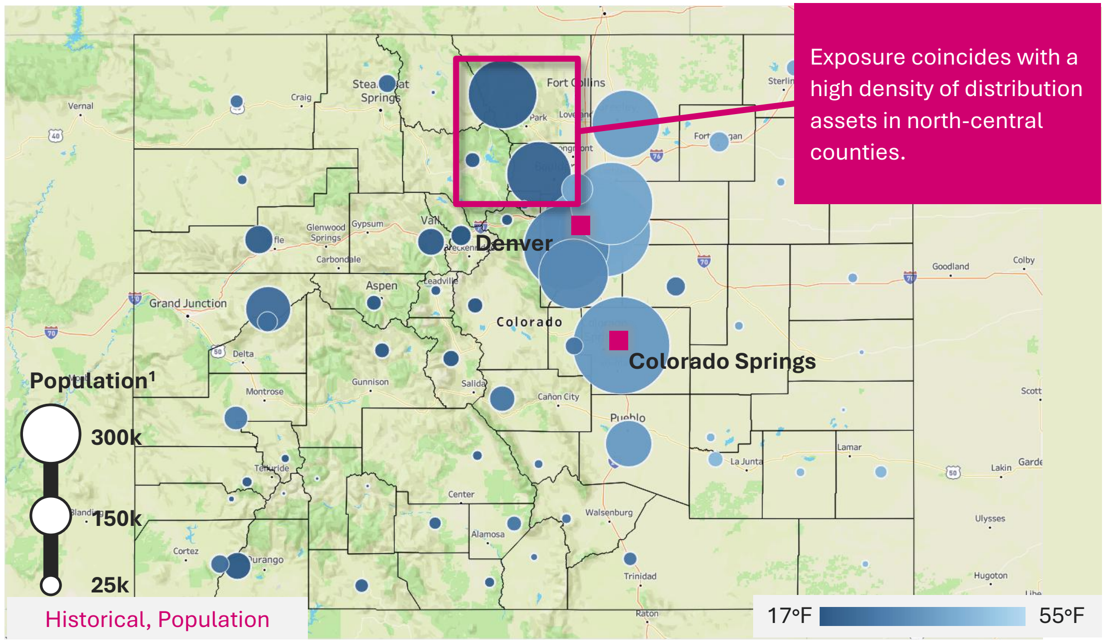
Cold

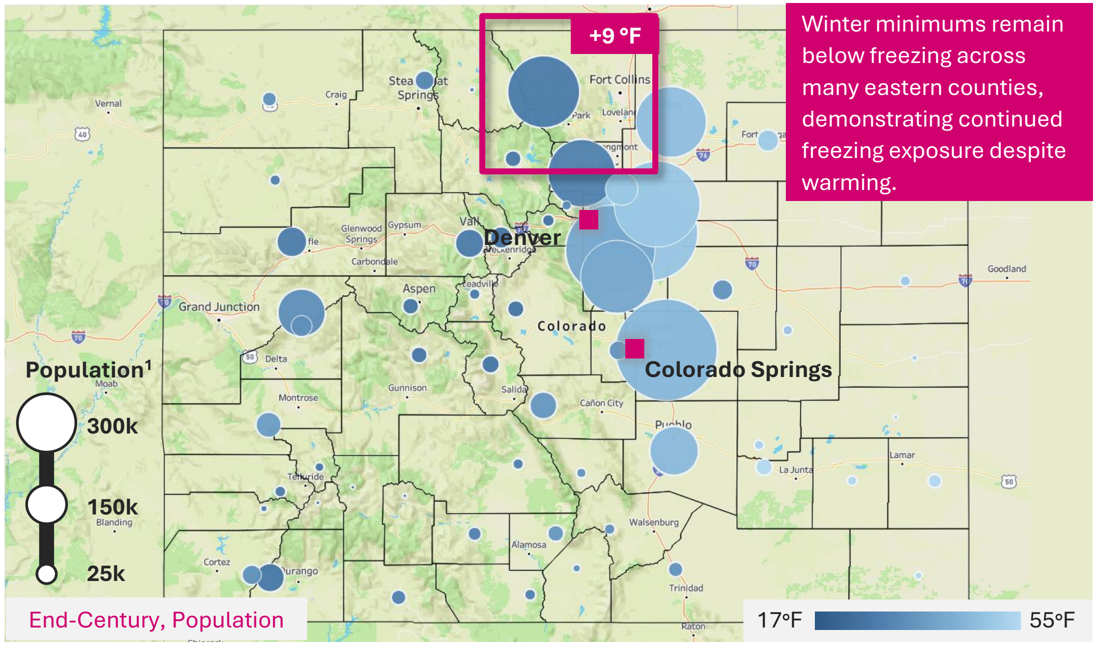
Asset Analysis

Western counties continue to face high extreme cold exposure year-round, prompting consideration of distribution hardening to combat freezing and snow loading

Colorado Average Annual Minimum Temperature (°F)
Distribution Assets, (Population) Historical



Colorado Average Annual Minimum Temperature (°F)
Distribution Assets, (Population), End-Century [RCP-8.5]



KEY OBSERVATIONS

- Extreme cold exposure is **generally concentrated in the western half of the state,** including population centers in the north-central region.
- Undergrounding and reconductoring projects appear tailored to wildfire, indicating that **CO may want to consider additional hardening in highly exposed counties to address cold exposure.**

KEY OBSERVATIONS

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

Larimer County

Larimer County is exposed to average annual minimum temperatures of ~28°F, indicting potential **freezing and snow loading for distribution assets.**

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

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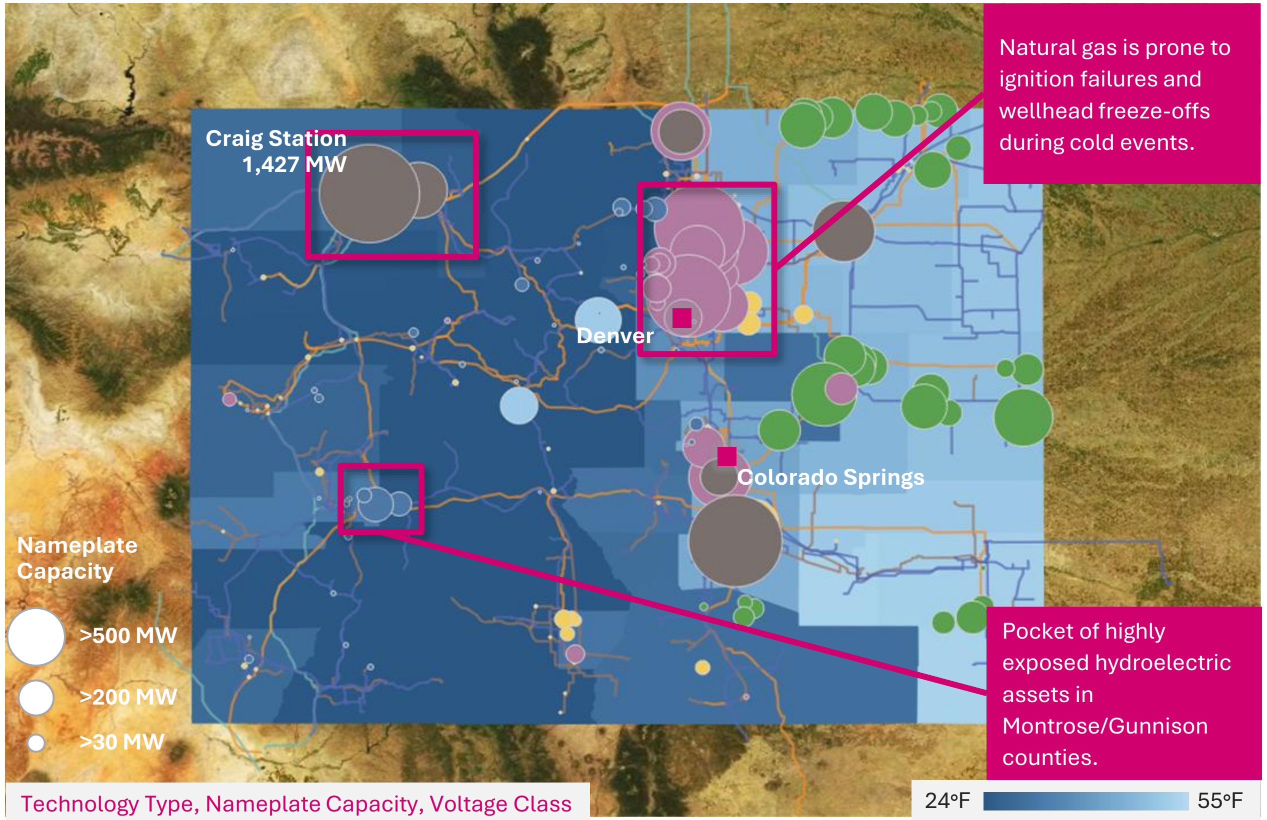
CO could prioritize hardening projects addressing extreme cold for heavily exposed thermoelectric assets and high voltage transmission lines in western counties

Colorado 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, US Census Bureau, City and Town Population Totals

Key Highlights	Analysis
Coal	• Coal plants in Moffat and Routt counties are heavily exposed to extreme cold, which can cause a variety of plant shutdowns and freezing of coal stockpiles. • **CO could consider generator hardening projects addressing extreme cold** given a high density of large, exposed thermoelectric assets.
Natural Gas	• Natural gas plants in the north-central region border counties with extreme cold exposure, which could cause **ignition failure or other performance issues.** • Asset owners could evaluate whether plants have significant heating infrastructure to prevent freezing events.
Hydroelectric	• Frazil ice formation and maloperation of spill gate motors can result in **plant faults or production derates.**
Transmission	• The **prevalence of below-freezing annual minimums** in many counties contributes to **Tx freezing risk and snow loading** that can cause asset failure. • CO could consider structure reinforcement upgrades to combat snow loading.

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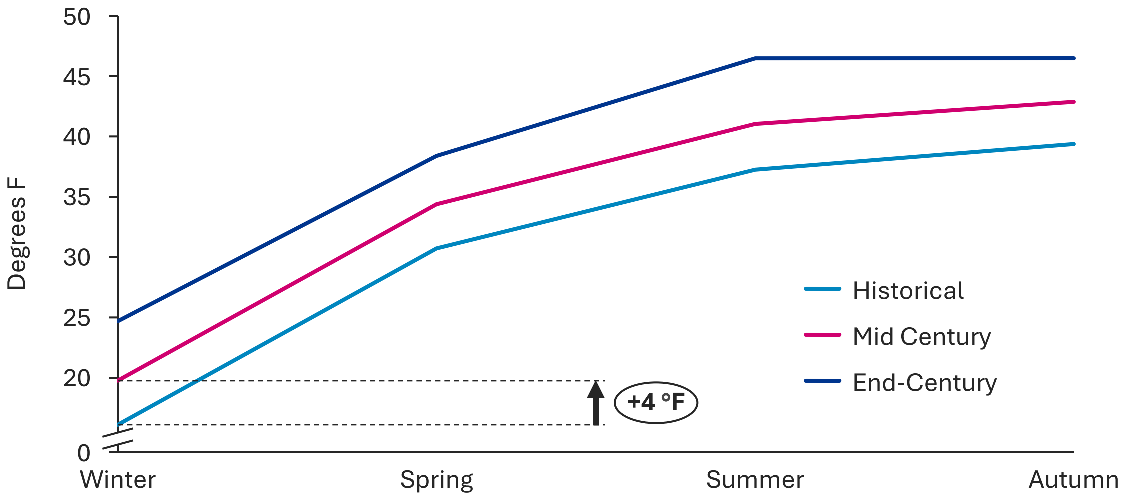
Winter minimum temperatures remain far below 32 °F despite moderate warming over time, indicating adaptations addressing freezing as a priority area for future CO investment.

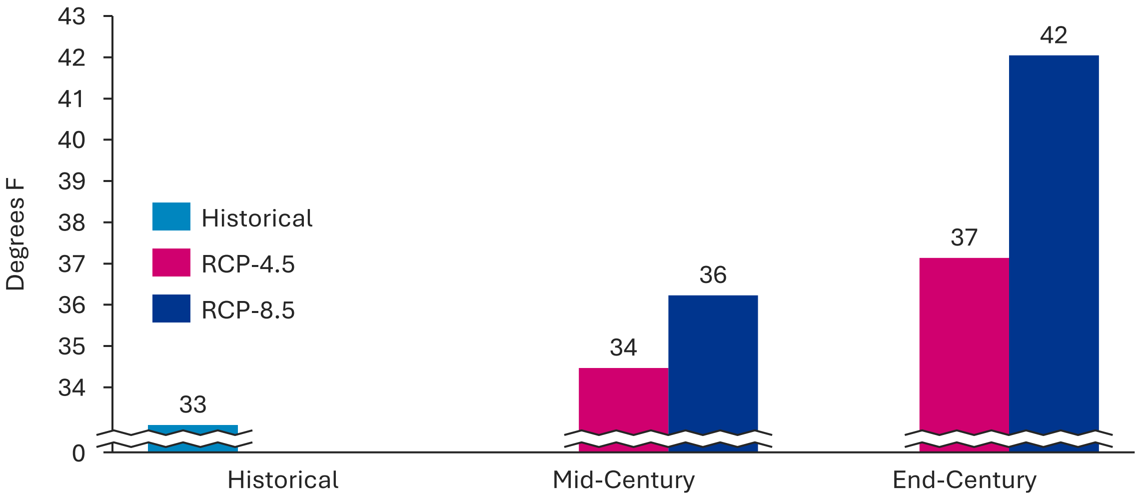
Colorado Average Seasonal Minimum Temperature (°F)
Population-Weighted by County [RCP-8.5]



KEY OBSERVATIONS

- Significant winter heating (+4 °F by mid-century) will decrease overall heating load, but the **impact on electricity demand ultimately depends on the speed of heating electrification.**
- Mid-century winter minimums remain well below 32 °F, indicating that **freezing and icing exposure persists despite warming.**
- Few proposed projects address freezing risk despite significant exposure, demonstrating a priority area for future CO investment.

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



KEY OBSERVATIONS

- Annual minimums close to 32 °F indicate **significant freezing exposure for most of the year**, demonstrating the need for relevant hardening upgrades such as undergrounding, reconductoring, etc.
- 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** despite moderate projected warming.

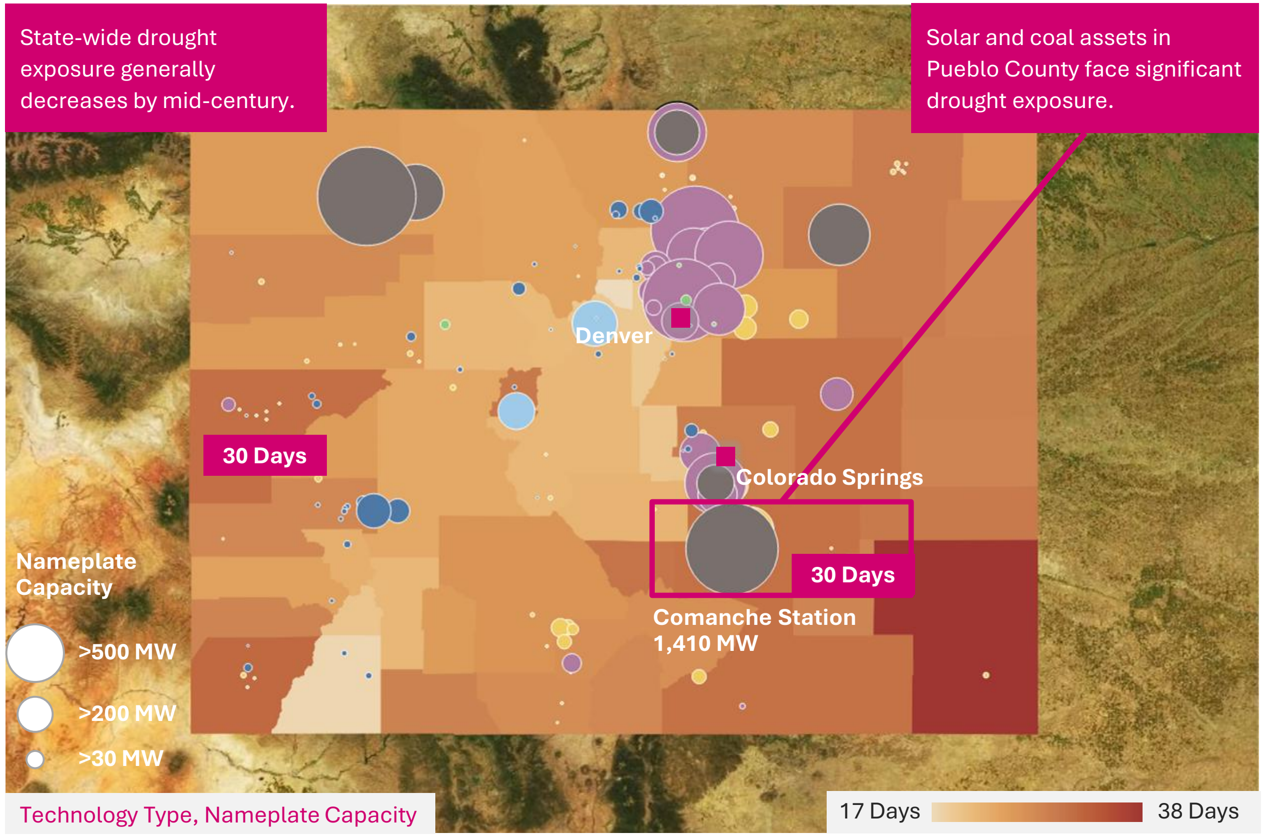
Drought

Asset Analysis

While drought exposure generally decreases by mid-century, CO could monitor trends given state-wide variation and consider integrating water scarcity forecasts into production planning

Colorado 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

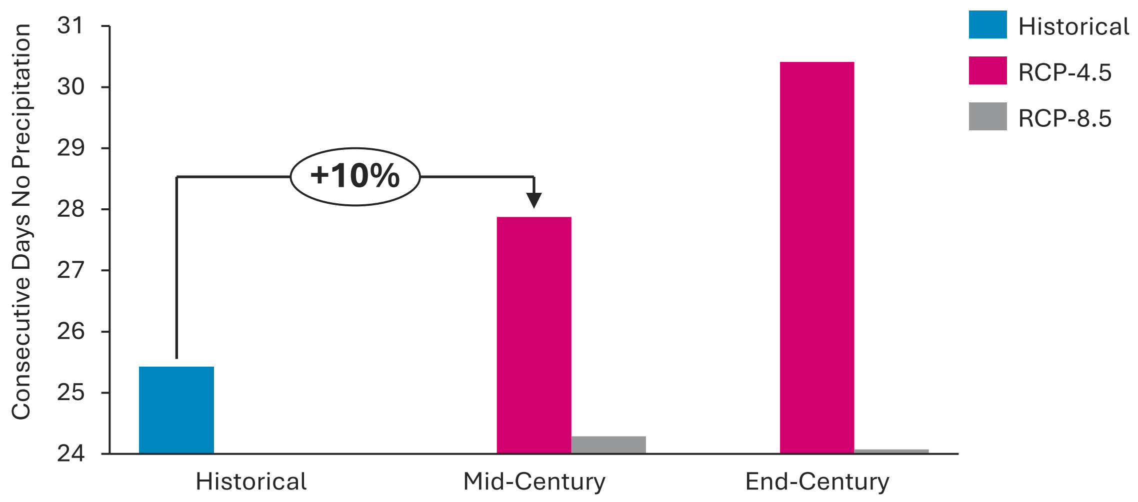
Key Highlights	Analysis
Hydroelectric	• A string of **hydroelectric plants along the Gunnison River** are exposed to above average state-wide drought levels. • Asset owners and grid operators could consider monitoring **drought trends throughout the river basin,** which can vary significantly throughout the state.
Coal	• Lack of water availability can **reduce coal cooling ability and disrupt flue gas desulfurization systems**, resulting in power production curtailments and increased emissions. • Many coal generators will retire before mid-century, making this a less urgent area for investment.
Renewables	• Drought conditions cause dust buildup on solar panels, hurting capacity factors. • In areas that also have high wildfire exposure, such as Montezuma and Mesa counties, **panel cleaning projects address two hazards simultaneously.**

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

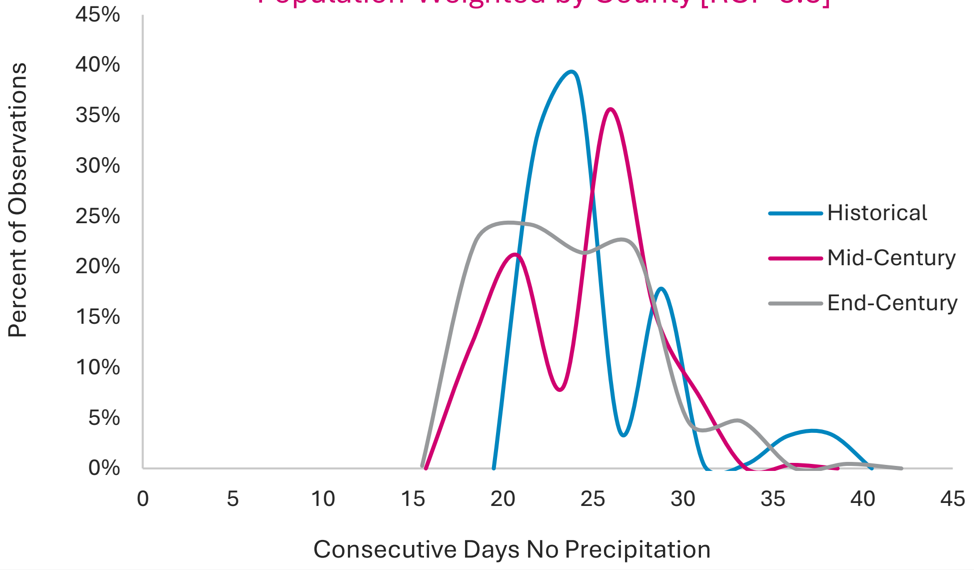
 |

Drought exposure is projected to vary by region and depends on warming levels, indicating that asset owners, particularly of hydroelectric generators, could monitor its trajectory closely

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



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



KEY OBSERVATIONS

- **Drought exposure increases by ~10% by mid-century** (under RCP 4.5), contributing to potential asset cooling failures and reduced hydroelectric generation.
- Significant gap between drought exposure under the RCP-4.5 warming scenario and RCP-8.5 scenario indicate that **drought does not scale linearly with temperature** and could be monitored closely by asset owners and grid operators.

KEY OBSERVATIONS

- Leftward shift of mid-century graph generally indicates **decreasing drought severity,** although a **larger spatial extent is exposed to about 25 consecutive days without precipitation**.
- Plateau shape of end-century curve indicates a **more even spread of drought exposure throughout the state.**
- Differing shapes indicate that **exposure will vary regionally, and thus could be monitored closely by asset owners**.

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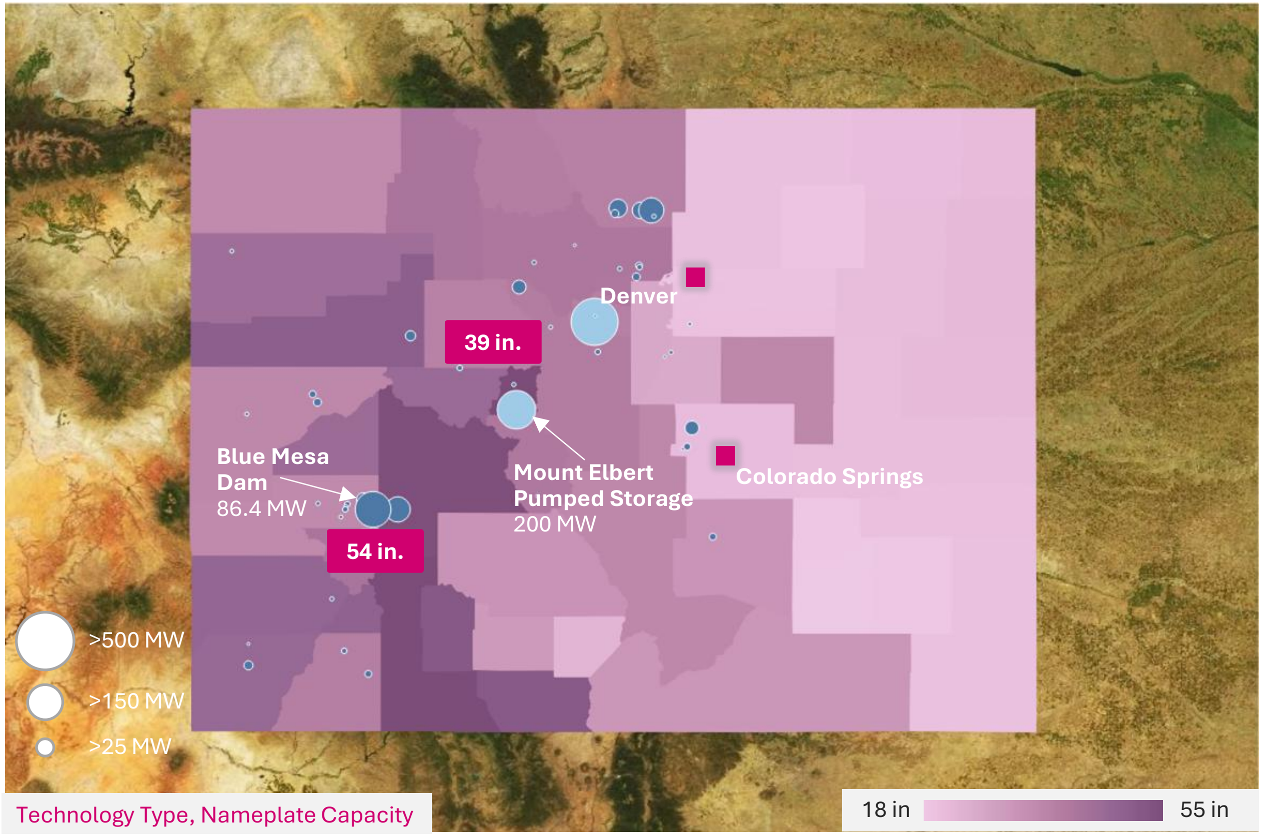
Precipitation

Asset Analysis

Precipitation remains relatively constant to mid-century, but CO could consider other factors that impact hydro output and cooling water availability such as timing and snow patterns

Colorado Annual Max Precipitation (in)
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
Timing	• Timing of precipitation has an important impact of hydro output. • Extreme rainfall events may overflow reservoirs and put more pressure on dams, increasing risk of failure. • **Blue Mesa Dam is exposed to peak state precipitation exposure,** meaning asset owners could consider hardening to address extreme rainfall.
Pumped Storage	• Mount Elbert Pumped Storage Plant in Lake County is exposed to above average precipitation and drought levels, indicating **a propensity for extreme rain.** • Extreme precipitation can cause reservoir overflow and asset damage, **prompting consideration of asset hardening.**
Changes to Snow Patterns	• While precipitation levels remain relatively constant to mid-century, precipitation type and timing is likely to change due to warming and could be monitored. • Grid operators could **consider the impacts of less snow and earlier snow melt when conducting long-term planning.**

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

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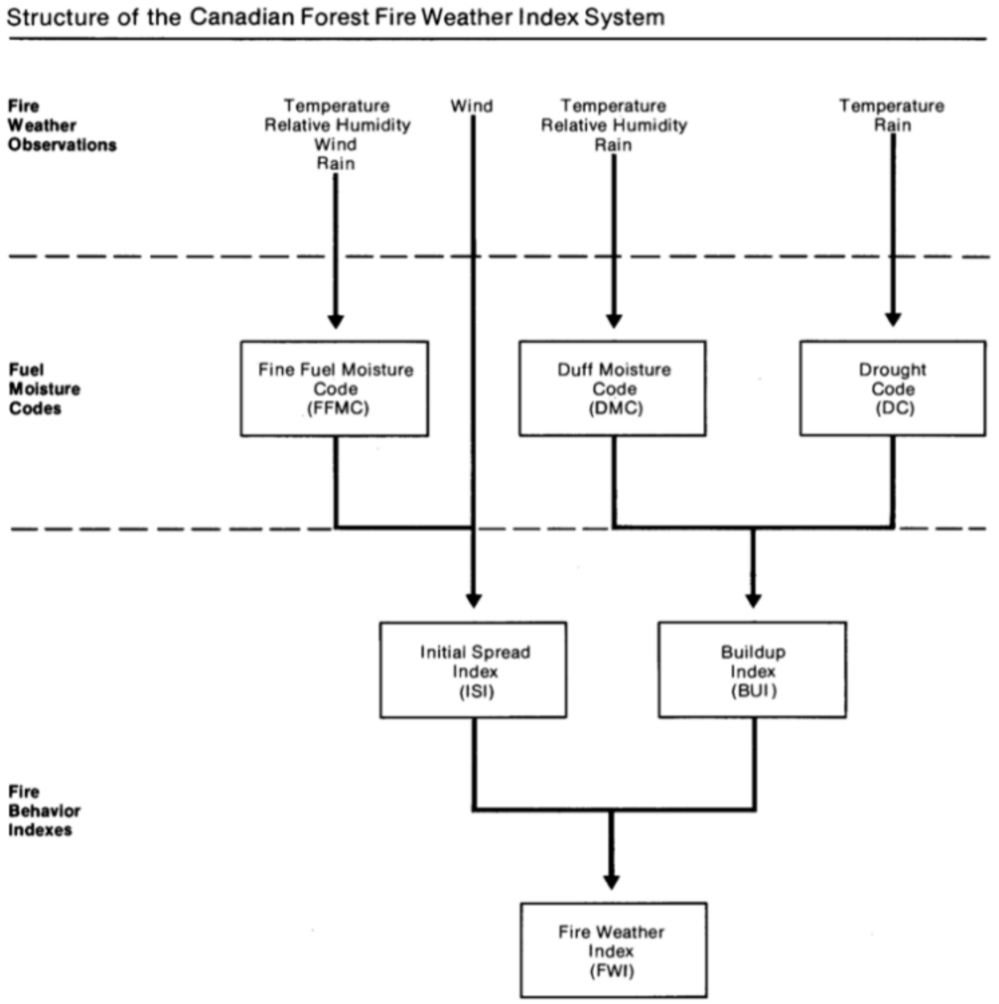
Appendix

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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