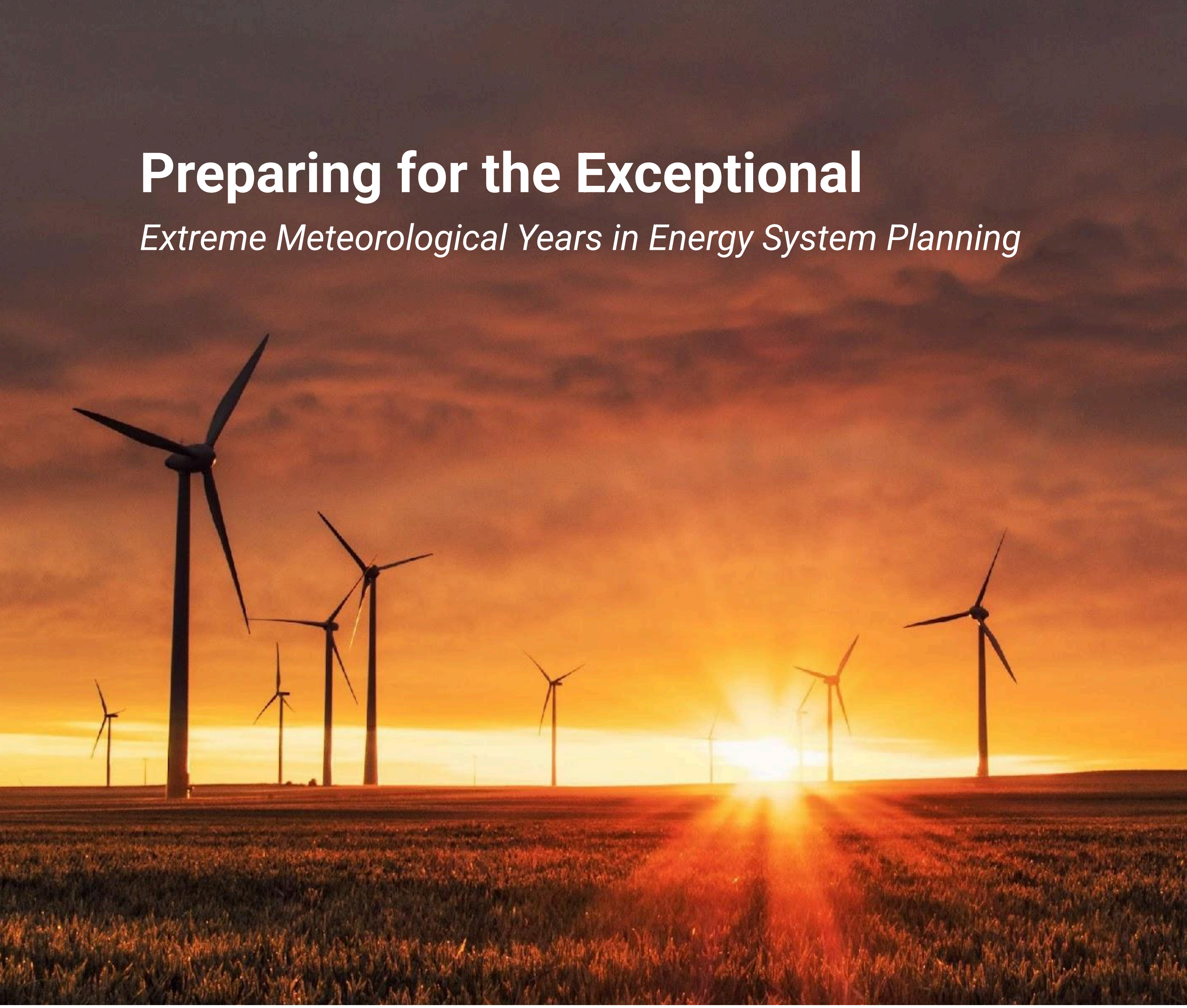
Preparing for the Exceptional

Extreme Meteorological Years in Energy System Planning



To Cite this Report:
Ford, V., Roman, J., Machuca, V., Ordonez, A., Keeney, N., Schroeder, N., and Doherty, O. 2026. *Planning for the Exceptional: Extreme Meteorological Years in Energy System Planning*. Cal-Adapt. https://doi.org/10.5281/zenodo.21401751

Date: July 2026
analytics@cal-adapt.org

Cal-Adapt
Supporting California's Energy Resilience, Reliability, and Planning

Executive Summary

Recent August 2020 and Labor Day 2022 heatwaves in California produced record-breaking high temperatures. Back-to-back days with little to no nighttime reprieve created unexpected high demand for cooling. As the days continued, unexpected power supply interruptions alongside continued cooling demand led to rotating power outages initiated by the California Independent System Operator (CAISO). Tens of thousands of Californians lost power, placing public safety at risk and calling into question the reliability of the state's grid [1-5].

Extreme weather events, such as the August 2020 Heatwave, cause severe, sometimes cascading impacts on public health and safety, infrastructure, and the grid. These extreme events will only become more frequent and perhaps more severe as the climate continues to warm. Proactively developing tools to help decision-makers identify paths forward for building a resilient and reliable grid is critical to ensure that not only can infrastructure withstand current extreme events but also withstand the stress from future projected extremes, meeting the potential demand of ratepayers.

Typical Meteorological Year (TMY) climate profiles remain foundational inputs to building and power system models [6], providing standardized hourly weather conditions for simulating energy demand and system performance under strain. **However, extreme weather events are increasingly shaping the design and operational needs of electricity systems more so than "typical" conditions**. Traditional TMYs are designed around median historical conditions and therefore suppress the types of extreme events that increasingly drive peak demand, grid strain, outage risk, and infrastructure vulnerability, such as the August 2020 Heatwave. As climate risks intensify, energy planners and decision-makers require climate profiles that better represent the range, timing, and persistence of extreme conditions without introducing unnecessary overdesign or cost.

To bridge the gap between energy demand planning needs and practical extremes characterization, **Cal-Adapt** has developed scientifically robust, stakeholder-vetted **Extreme Meteorological Year (XMY)** climate profiles designed specifically for a range of energy-sector applications. Recognizing that no single "extreme year" can satisfy all planning needs, Cal-Adapt provides two standardized methodologies tailored to common use cases:

- **Shock Extreme XMY climate profiles** for *short-duration*, *high-intensity events* such as the August 2020 and Labor Day 2022 heatwaves [3-4].
- **Persistence Extreme XMY climate profiles** for *sustained stress-testing simulations*, such as Summer 2020, which was the 4th hottest summer on historical record globally [6].

Delivered as pre-generated, policy-ready datasets that are aligned with California regulatory requirements, Cal-Adapt's XMY climate profiles provide trusted, transparent inputs for resilient energy planning and climate-informed decision-making supporting a reliable grid for ratepayers.

Key Takeaways

1. No single extreme-climate characterization can adequately represent the diverse conditions that drive energy-system risk. Because planning objectives range from peak demand events to prolonged heatwaves, coldsnaps, and compound stressors, relying on a “one-size-fits-all” approach can obscure critical vulnerabilities and lead to incomplete system resilience assessments.
2. Cal-Adapt collaboratively developed the first-of-its-kind open-source, scientifically robust extreme hourly profiles (XMY), vetted by industry users and applications, providing two types of XMYs for the most common use cases, such as demand planning for rare high-impact extreme events and peak load estimation.
3. Cal-Adapt’s open-access pre-generated XMY climate profiles provide an immediate, ready-to-use pathway for evaluating extremes that are missed by typical weather datasets. Cal-Adapt’s XMYs enable users to easily assess system vulnerabilities, quantify risk under high-impact scenarios, and begin integrating extreme-event planning into existing workflows while retaining the flexibility to customize extremes for specific operational requirements.

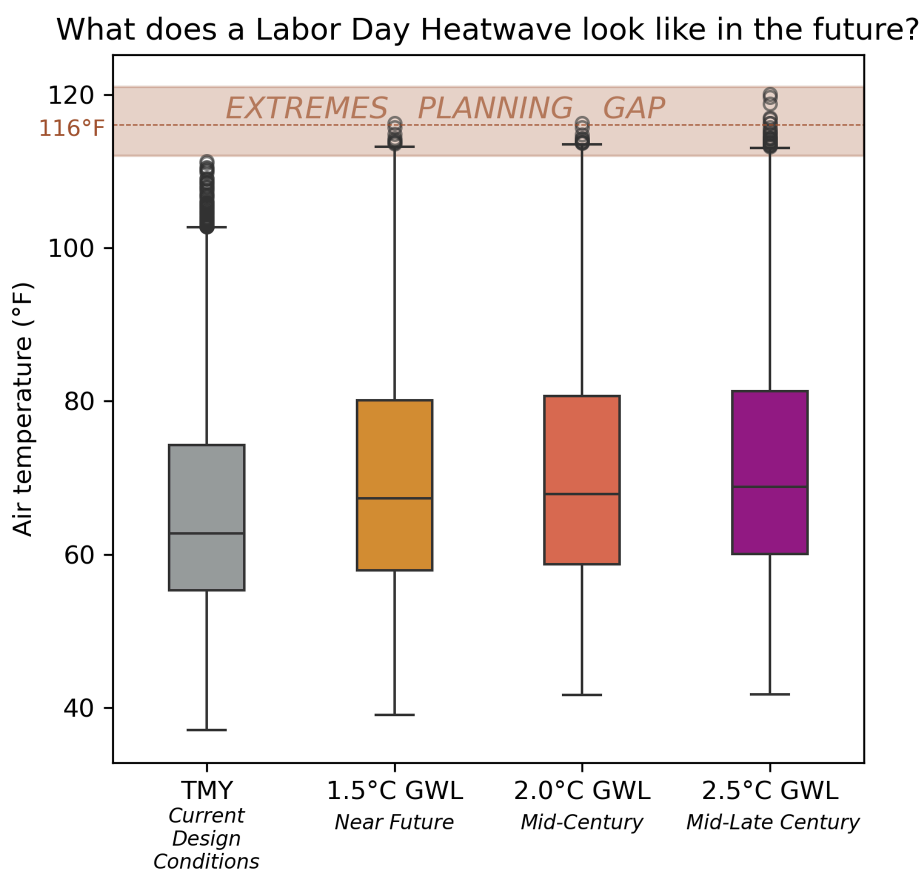


Figure 1. The Labor Day 2022 Heatwave produced record-breaking electricity demand exceeding 52,000 MW, yet current design standards rely on “typical” conditions. Boxplot distribution of temperatures for Sacramento comparing typical standards (TMY) to extreme heat tailored (XMY) future conditions at sector-relevant planning horizons.

Introduction & Motivation

Power system models often rely on climate profiles (or an 8760 timeseries) to simulate electricity supply and demand. For decades, the industry standard has been the ***Typical Meteorological Year* (TMY)**, an hourly climate profile designed to represent median historical weather conditions at a location over a climatological period of at least 15 years [6]. TMY datasets are generated by statistically evaluating key weather variables and selecting the most "typical" (or median) month for each calendar month, producing a synthetic year assembled from multiple historical years [6-7]. As standardized inputs to building and energy system models, TMY files provide a single, representative weather year for estimating electricity demand, including heating and cooling loads. These climate profiles are widely used for energy system modeling, equipment sizing, simulating solar energy conversion systems, and evaluating building standards and energy efficiency [3,7-8].

The increasing frequency, duration, and intensity of climate-driven extremes, however, expose a critical limitation of traditional TMY profiles: median weather conditions are insufficient for understanding system performance under stress. By design, TMYs suppress extreme events that increasingly drive operational risk and infrastructure vulnerability, including high-impact hazards such as extreme heatwaves, prolonged cold spells, wildfire, drought-related generation constraints, atmospheric river-driven outages, and compounding and cascading events [6, 9-10]. As a result, simulations based solely on historical typical conditions can substantially underestimate peak heating and cooling demand, grid strain, thermal discomfort, equipment degradation, and outage risk during extreme conditions [11-14].

This challenge is particularly acute for long-lived energy infrastructure and building systems that must remain resilient under future climate conditions for decades [15-16]. Underestimating extremes can leave systems underprepared, resulting in unreliability, while overestimating future conditions can drive unnecessary overdesign, higher costs, and reduced operational efficiency [9-10]. Energy planners require methodologies that accurately characterize the range, intensity, timing, and persistence of extreme weather conditions in ways that are scientifically vetted and operationally relevant.

***Extreme Meteorological Year* (XMY)** climate profiles provide the same weather variables in a TMY profile, but intentionally preserve or characterize extreme weather events within a one-year climate profile. Currently, there is no single recommended or accepted methodology for constructing an XMY [17], although there are several proposed approaches [e.g., 9, 12, 18-23], creating uncertainty for practitioners seeking trusted and appropriate-for-use datasets. Furthermore, no one XMY can meet the planning objectives for all use cases.

Different planning objectives require fundamentally different representations of climate risk, including intensity, duration, sequencing, and compounding factors. For example:

1. Peak electrical demand may require short-duration, high-intensity heat events that stress generation and transmission systems;

2. Building envelope and passive survivability analyses may require multi-day heatwaves or cold snaps that capture cumulative thermal loading and nighttime recovery failure;
3. Distribution and outage planning may require consistent hot, dry, and windy compound conditions.

Because these applications depend on different characteristics of extreme weather, no single "extreme year" or extreme climate metric can meet all planning needs. Instead, energy sector practitioners require a suite of standardized methodologies designed to represent different types of extreme conditions. Realizing the value of XMY datasets for California energy planning will therefore require clear guidance, updated standards, and trusted methodologies that support fit-for-purpose application across diverse use cases [9]

Cal-Adapt Approach

Cal-Adapt addresses this need through a new scientifically-vetted, stakeholder-centered approach to extreme climate profiles. These profiles were designed with and for end-users, taking into consideration the most common end use cases, standardizing methods alongside national partners to build trust, consistency, and confidence in which climate profile is most appropriate for a given application. The XMY methodologies presented here were collaboratively developed with national partners[1] to ensure consistent methods across Cal-Adapt and national climate data services platforms.

The challenge in contextualizing an XMY is the definition of "extreme", as end use cases of extreme weather conditions vary considerably across different intended purposes. For example, a utility load forecaster characterized extreme weather as *"18-20 degrees above average, placing pressure on the variance of reasonable expectation*" and obtaining a *"long-term forecast for both hot and cold bounds of energy sales*". While an asset risk capacity planner prioritizes understanding "*the absolute worst case scenario of massive heating demand in winter and massive cooling demand in summer*". Characterization of extreme weather must therefore prioritize end-use disaggregation (i.e., many different kinds of extremes) rather than annual performance [4]. Cal-Adapt provides standardized, purpose-built profiles tailored to common[2] energy-sector use cases for different extreme types:

(1) **Shock Event XMY**: An extreme climate profile that is representative of <u>short-term event-wise pulses</u> that increase peak demand, such as the Labor Day 2022 or the 1990 Winter Freeze [24]. The Shock XMY is built upon an <u>extreme cumulative distribution furthest from the median weather conditions</u> for a location over a climatological period[3].

(2) **Persistence XMY**: An extreme climate profile that is representative of <u>extreme sustained annual metrics</u>, such as California's recent extreme hot year 2014 [5], that can be applied for highly tailorable system stress tests. The Persistence XMY is built upon a

[1] Cal-Adapt collaborated on standardized approaches for Extreme TMY profiles with Argonne National Laboratory and the Electric Power Research Institute, so that both climate data platforms employed consistent methods for data products.
[2] While these two variations of XMYs represent the two most common use cases informed by stakeholders, there could be many different other types of XMYs for different applications.
[3] Shock XMYs are also referred to as Extreme Reference Years (ERY) on ClimRR.

given statistical extreme percentile of weather conditions for a location over a climatological period[4].

Unlike other products available nationally, Cal-Adapt's XMYs climate profiles are made available in Global Warming Levels (GWL) [25], compliant with California regulatory requirements, as well as in traditional time-based climatological periods. These pre-generated policy-ready climate profiles empower energy practitioners with the data clarity and transparency needed to drive stronger compliance, smarter planning, and more effective climate-informed solutions supporting a reliable grid for ratepayers.

Shock Event XMY: Extreme Event-Based Stress

The Shock Event XMY represents localized weather conditions that strain peak demand by emphasizing the range of variability within a distribution. This method identifies the weather-year distribution that differs most from long-term climatology. Where the TMY approach minimizes the error [6] between a candidate year and the long-term conditions, the Shock XMY approach maximizes the difference. For a step-by-step methodology, please see the Appendix.

The Shock XMY methodology offers the advantage of being an understandable extension of the existing TMY methodology and preserving the temporal consistency of day-to-day variability and natural diurnal cycles (Figure 2). However, the timing, duration, and sequencing of extreme events, or "shocks" within the profile, may not align with the operational conditions most relevant to a particular simulation or planning scenario. For example, peak temperature events may occur during periods of relatively low system demand or may not coincide with other compounding stressors to the grid. Additionally, the error-based selection method provides limited flexibility for tailoring events to specific return periods, dates, or desired intensity levels.

[4] Persistence XMYs are also referred to as Persistent Extreme Years (PEY).

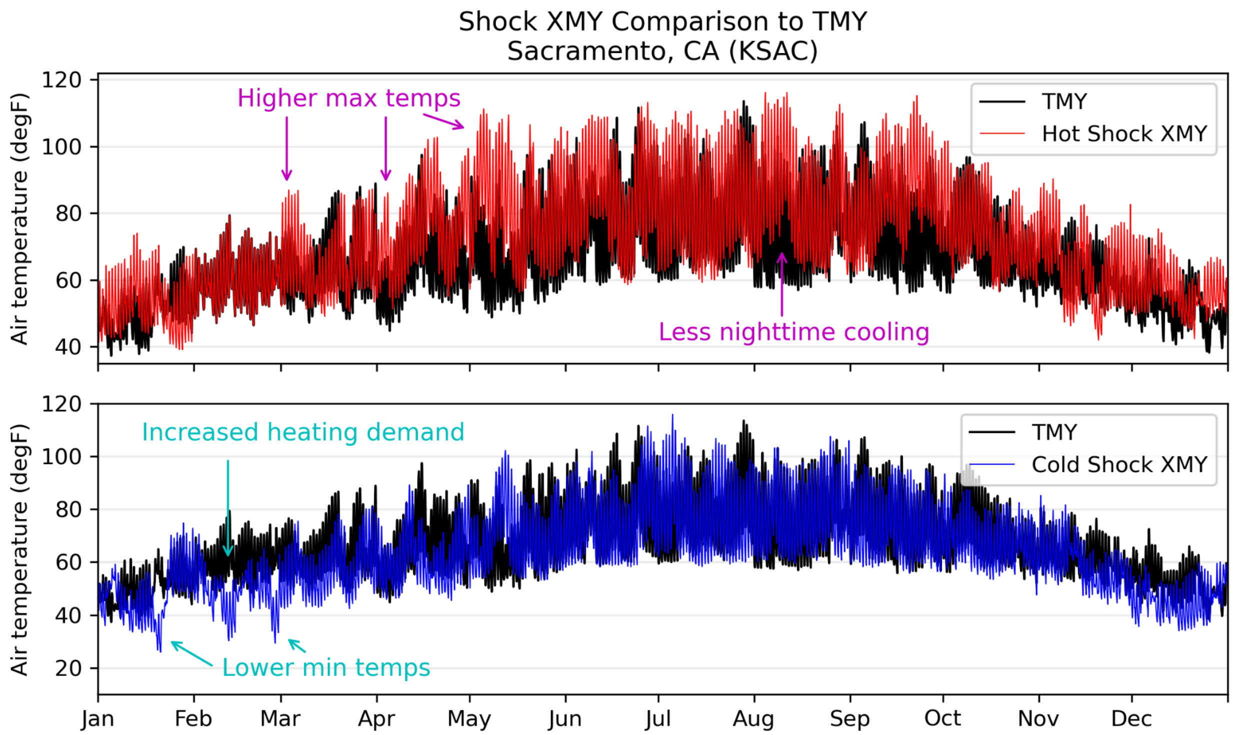


Figure 2. (Top) Hot Shock XMY profile compared to the TMY for the Sacramento Executive Airport (Sacramento, CA), with simulated heatwaves and associated impacts highlighted via arrows as examples for stress testing at mid-century (2.0°C GWL). (Bottom) Cold Shock XMY profile compared to the TMY profile for Sacramento, CA, with simulated coldsnaps and associated impacts highlighted as arrows at mid-century (2.0°C GWL).

Persistence Extreme XMY: Sustained Stress

The Persistence XMY represents localized weather conditions that stress an energy system by selecting hours associated with specific percentile-based extremes within the climatological distribution, prioritizing sustained statistical deviation from typical conditions. This method allows precise tuning to exact conditions to stress-test systems, such as “turning a dial” on the intensity of the desired extreme for specific periods (e.g., 2 weeks of abnormally hot conditions in October; Figure 3). The Persistence XMY is more indicative of overall extreme conditions, such as a “warmer than average summer” and is determined on an hour-by-hour basis (Figure 3). The design of the Persistence XMY approach specifically allows a user the ability to combine multiple percentiles to build a fully customizable extreme profile. For a step-by-step methodology, please see the Appendix.

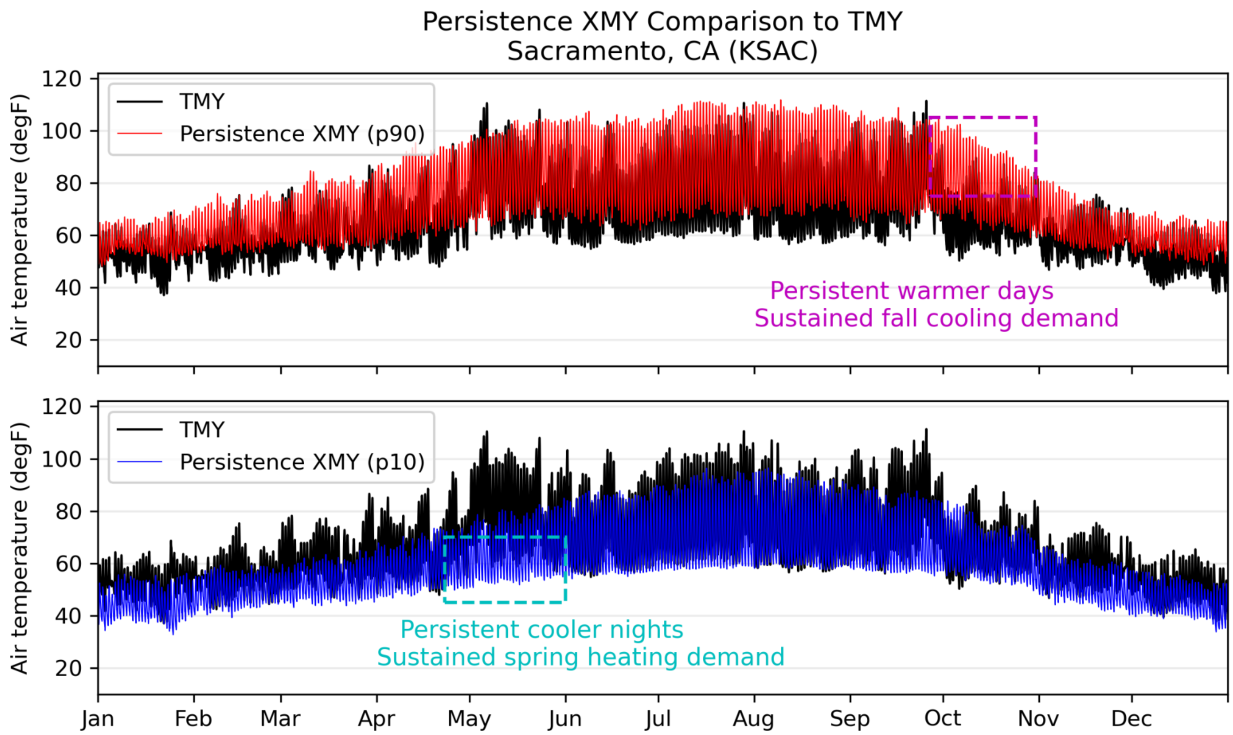


Figure 3. (Top) Hot Persistence XMY profile compared to the TMY profile for Sacramento Executive Airport (Sacramento, CA) at the 90th percentile extreme at mid-century (2.0°C GWL). (Bottom) Cold Persistence XMY profile compared to TMY for Sacramento, at the 10th percentile extreme at mid-century (2.0°C).

Use Cases

Preparing for extreme events that increase system strain requires climate-driven energy inputs that go beyond TMYs to include extreme and future-oriented climate profiles. XMYs can inform:

- Extreme peak heating and cooling load (Appendix: Figure 6)
- Demand planning for rare, high societal impact extreme events (Appendix: Figure 7)
- Risk and hazard assessment
- Grid resilience
- Financial analysis of asset investments
- Specific stress testing of peak demand windows for infrastructure planning (e.g., grid hardening).

Extreme peak heating and cooling load estimates

Peak electrical demand is often driven by a relatively small number of extreme temperature events, making the choice of a representative 8760 climate profile a critical factor in load estimation. Heat-focused extreme profiles can highlight higher peak cooling requirements associated with intense heatwaves, elevated nighttime temperatures, and sustained periods of thermal stress that increase air-conditioning demand. Cold-focused extreme profiles quantify peak heating requirements during severe cold events that challenge building systems and energy infrastructure.

As the climate warms (Figure 4), the frequency and intensity of extreme heat events are projected to increase [26], leading to larger peak cooling loads even in locations where annual average temperature changes may appear modest. The reduction in winter heating demand does not necessarily eliminate the need to evaluate extreme cold scenarios, as infrequent but severe cold events can still drive reliability estimates. Comparing peak load estimates across multiple extreme profile types and future planning horizons helps characterize the range of potential demand outcomes rather than relying on a single design condition.

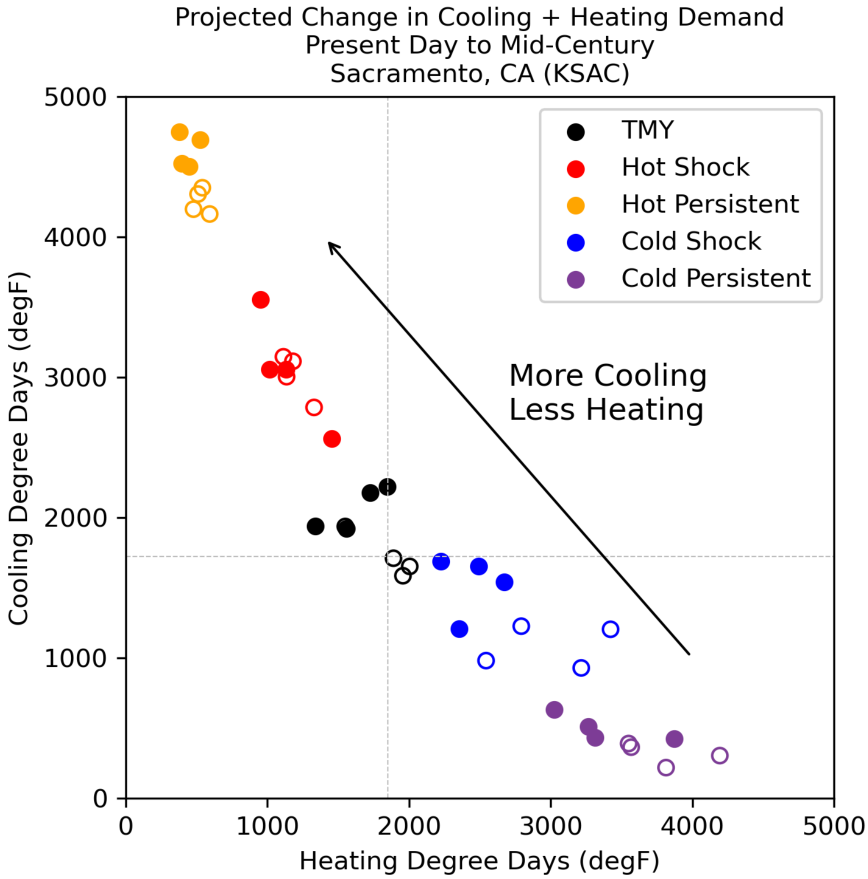


Figure 4. Projected change in cooling and heating degree days between present-day (1.2°C GWL, open-faced circles) and mid-century (2.0°C, solid circles) across Extreme Meteorological Year climate profiles compared to Typical Meteorological Year median conditions for Sacramento, CA. Dashed cross-hatch lines intersect at the multi-model mean present-day TMY CDD/HDD point (CDD: 1721 degree days, HDD: 1850 degree days). All 4 *a priori* bias-adjusted dynamically-downscaled WRF models are provided for each profile.

Demand planning for rare, high societal impact extreme events

Demand planning exclusively with typical meteorological datasets can substantially underestimate the magnitude and timing of peak energy demand during extreme heat events. By incorporating extreme profiles benchmarked against observed record-breaking events (Figure 5), planners can evaluate system performance under conditions that more closely resemble the stresses experienced during real-world emergencies, such as the Labor Day Heatwave in 2022. The comparison between a typical profile and an extreme heat profile demonstrates how reliance on typical conditions can mask temperature exposures that exceed standards by more than 15-20°F during the most critical periods for human health and grid reliability. Such differences translate into large increases in cooling demand, elevated system-wide peak loads, and increased grid risk. Extreme profiles provide valuable insight into the upper bounds of demand that infrastructure will be required to serve, particularly as climate change increases the likelihood of rare extreme events. Evaluating both typical and extreme conditions enables planners to quantify the potential consequences of under-design and identify vulnerabilities that would otherwise remain hidden.

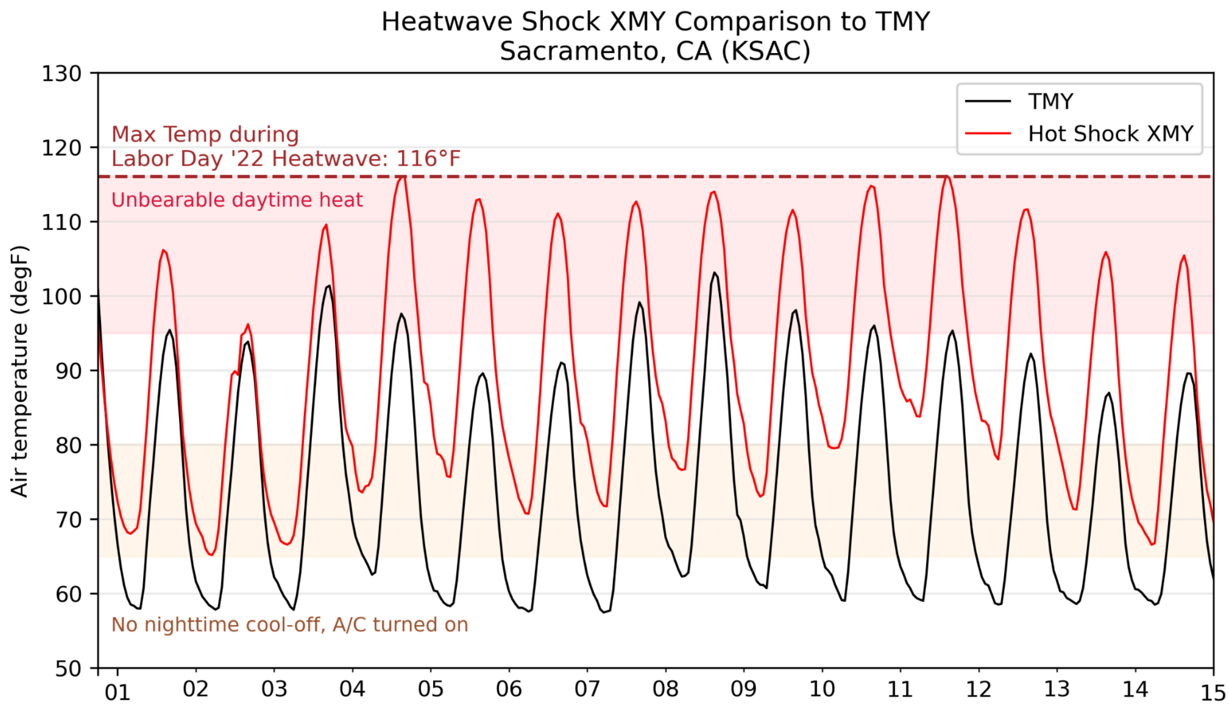


Figure 5. Comparison of Typical Meteorological Year conditions to a Shock Extreme Meteorological Year profile for Sacramento, CA during heatwave conditions at mid-century (2.0°C). As a reference, the Labor Day 2022 Heatwave maximum temperature is provided as motivating context for preparing for realistic extreme conditions. The Labor Day 2022 Heatwave was one of the hottest on record for California, with Sacramento reaching 116°F (46.7°C) [27] and record-breaking electricity demand of more than 52,000 MW [4]. The Labor Day 2022 Heatwave is estimated to be a 1-in-450 year extreme heat event [28].

Recommendations

Cal-Adapt Extreme Meteorological Year (XMY) profiles should be utilized alongside Typical Meteorological Year (TMY) profiles to characterize high-intensity events that are intentionally excluded from TMY profiles that have a large impact on human health, safety, and energy system planning.

Extreme weather events, such as the Labor Day 2022 heat wave, severely stress California's energy sector, and as the climate continues to warm, these extreme events will only become more frequent and perhaps more severe. Climate-informed data and tools that assist decision-makers with identifying paths forward are essential for building a resilient and reliable grid. Current data and tools, such as TMYs, do not meet these needs as they suppress extreme events that increasingly drive operational risk and infrastructure vulnerability, including high-impact hazards such as extreme heatwaves, prolonged cold spells, wildfire, drought-related generation constraints, atmospheric river-driven outages, and compounding and cascading events.

Cal-Adapt developed scientifically robust, industry-vetted Extreme Meteorological Year (XMY) climate profiles for energy-sector applications. Recognizing that no single "extreme year" can address all planning needs, the framework provides two standardized XMY methodologies tailored to the most common use cases: the Shock Extreme XMY for short-duration, high-intensity events such as heatwaves and coldsnaps, and the Persistence Extreme XMY for sustained annual stress-testing simulations.

Cal-Adapt's pre-generated XMY climate profiles provide a **ready-to-use foundation for immediate integration into planning and operational workflows**. Advanced, flexible tools and guidance are available as a user-supported data product, allowing users to further customize extreme weather scenarios to their specific objectives. In practice, TMY datasets can inform analyses focused on average annual performance, while XMY profiles should be incorporated into studies related to infrastructure sizing, resilience planning, resource adequacy, demand flexibility, and future grid stress testing. Using both profile types together enables planners and analysts to evaluate how systems perform under both expected and extreme operating conditions

Ready to make more Climate-Informed Energy Planning Decisions?

The following pre-generated extreme climate profile datasets are available via Cal-Adapt[5]:

1. Shock XMY Climate Profiles for 33 weather station locations within California, for both cold and hot extremes.
2. Persistence XMY Climate Profiles for 33 weather station locations within California, at the following percentiles: 5th, 10th, 40th, 60th, 90th, 95th percentile.

Fully customizable extreme climate profiles can be generated via the *Cal-Adapt Analytics Engine* for location, global warming level, percentile, and extreme profile type.

[5] Cal-Adapt Data Download Tool

References

[1] CPUC (August 16 2020) CPUC Letter to IOUs Regarding Energy Conservation. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/news-and-outreach/documents/news-office/key-issues/summer-reliability/cpuc-caiso-and-cec-response-letter-to-governor-newsom-081920.pdf?sc_lang=en&hash=9F04C3F6DD45D9314E86EE8CCFBA019F
[2] CPUC (August 19 2020) CPUC, CalSO, and CEC Response Letter to Governor Newsom. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/news-and-outreach/documents/news-office/key-issues/summer-reliability/cpuc-president-letter-to-utilities-regarding-conservation-081620.pdf?sc_lang=en&hash=9BDF3908CB68FCD38C5094F56F4B0FBB
[3] Milet et al. (2023) Excess mortality during the September 2022 heat wave in California. Sacramento, CA: California Department of Public Health, Office of Health Equity. https://www.cdph.ca.gov/Programs/OHE/CDPH%20Document%20Library/Climate-Health-Equity/CDPH-2022-Heat-Wave-Excess-Mortality-Report.pdf
[4] CalSO (2022) Summer Market Performance Report, Sept 2022. https://www.caiso.com/documents/summermarketperformancereportforseptember2022.pdf
[5] OEHHA (2019). Annual air temperature: Air temperatures have increased over the past century, with nighttime temperatures increasing to a greater extent. https://oehha.ca.gov/sites/default/files/media/epic/downloads/05air_temp_15jan2019.pdf
[6] Wilcox and Marion (2008) Users Manual for TMY3 Data Sets. *National Renewable Energy Laboratory* Technical Report NREL/TP-581-43156
[7] NSRDB: https://nsrdb.nlr.gov/data-sets/tmy
[8] Laxo (2023) Climate Forward? How Climate Projections Are(n't) Used to Inform Design. https://hga.com/climate-forward/
[9] Peltier et al. (2024) A climate-aware built environment: Integrating future weather data into building design today. https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722160818203_c563a22d-adf2-42fa-9e31-789b98700ad6.pdf
[10] NYSERDA (2020) Assessment of Future Typical Meteorological Year Data Files. https://www.resourcerefocus.com/ftmy-2020
[11] Li et al. (2023) Improvement of methods of obtaining urban TMY and application for building energy consumption simulation. https://doi.org/10.1016/j.enbuild.2023.113300
[12] Zeng et al. (2025) A review of future weather data for assessing climate change impacts on buildings and energy systems. https://doi.org/10.1016/j.rser.2024.115213
[13] Crawley (1998) Which weather data should you use for energy simulations of commercial buildings? Build Eng 104(2): 498-515.
[14] Levermore and Parkinson (2006) Analyses and algorithms for new test reference years and design summer years for the UK. https://doi.org/10.1177/0143624406071037
[15] Moazami et al. (2019) Impacts of future weather data typology on building energy performance – investigating long-term patterns of climate change and extreme weather conditions. https://doi.org/10.1016/j.apenergy.2019.01.085
[16] Nik (2016) Making energy simulation easier for future climate – synthesizing typical and extreme weather data sets out of regional climate models (RCMs). https://doi.org/10.1177/0143624411418132
[17] ASHRAE (2024) Energy Simulation Aided Design for Buildings Except Low-Rise Residential Buildings. https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/209_2018_l_20240830.pdf

[18] Crawley and Lawrie (2015). Rethinking the TMY: Is the "Typical" Meteorological Year Best for Building Performance Simulation? https://publications.ibpsa.org/proceedings/bs/2015/papers/bs2015_2707.pdf
[19] Crawley and Lawrie (2019) Should We Be Using Just “Typical” Weather Data in Building Performance Simulation? https://doi.org/10.26868/25222708.2019.210594
[20] Bass and New (2000) Future Meteorological Year weather data from IPCC Scenarios. https://www.osti.gov/servlets/purl/1735419
[21] ISO 15927-4 (2005) https://www.iso.org/standard/41371.html
[22] Tarkhan et al. (2025) Generation of representative meteorological years through anomaly-based detection of extreme events. https://doi.org/10.1080/19401493.2025.2499687
[23] Doutreloup et al. (2022) Historical and future weather data for dynamic building simulations in Belgium using the regional climate model MAR: typical and extreme meteorological year and heatwaves. https://doi.org/10.5194/essd-14-3039-2022
[24] Baker (1991). Devastating Arctic Outbreak In The Sacramento Valley. https://www.weather.gov/media/wrh/online_publications/TAs/ta9102.pdf
[25] Krantz et al. 2026. *Bringing Global Warming Levels into Regional Climate Planning for the Energy Sector*. Cal-Adapt. *Forthcoming.*
[26] NOAA (2020) Summer 2020 ranked as one of the hottest on record for U.S. Summer 2020 ranked as one of the hottest on record for U.S. | National Oceanic and Atmospheric Administration
[27] NASA Earth Observatory (2022). A Long-lasting Western Heat. https://science.nasa.gov/earth/earth-observatory/a-long-lasting-western-heatwave-150318/
[28] Xie et al. (2024) Record High 2022 September-Mean Temperature in Western North America. https://doi.org/10.1175/BAMS-D-23-0148.1

Appendix: Extreme Climate Profile Methodologies

Shock Event XMY: Extreme Event-Based Stress

The Shock Event XMY represents localized weather conditions that strain peak demand by emphasizing the range of variability within a distribution. This method identifies the weather year distribution that differs the greatest from long-term climatology. Figure 6 illustrates the methodology workflow to generate a Shock XMY climate profile.

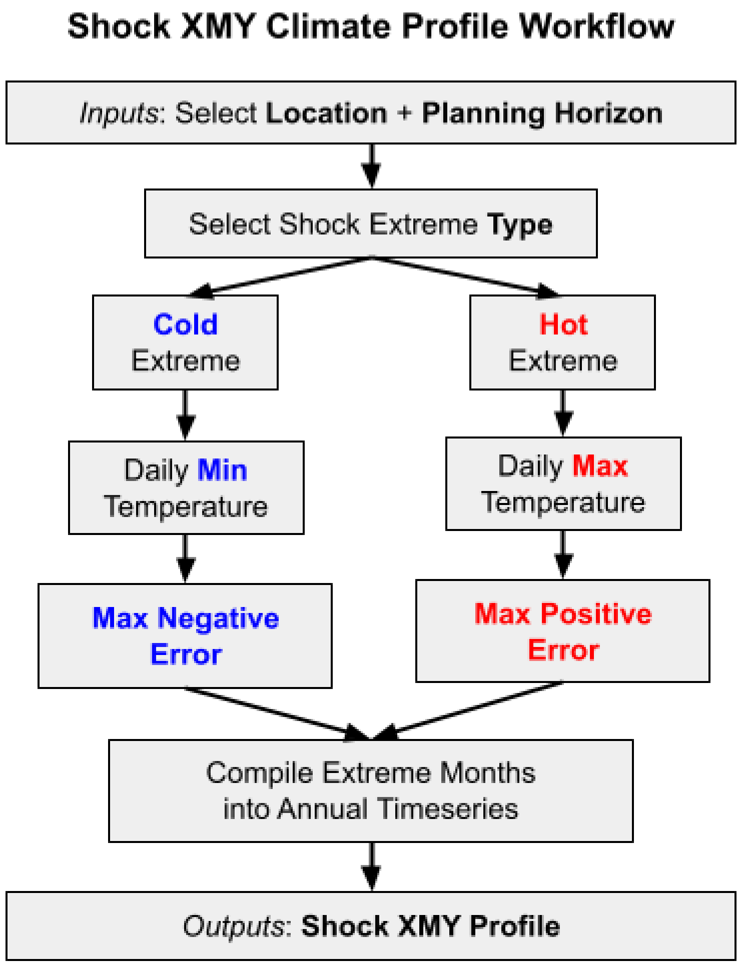


Figure 6. Shock XMY Climate Profile Workflow.

<u>Shock Event XMY Methodology [Maximized Error]:</u>
Step 1 – Select Location and Planning Horizon.
Cal-Adapt Shock XMYs are for point-based locations, meaning that a user will first select a specific location of interest, such as a power plant or an airport weather station. The user will also select a climatological period of time, such as a global warming level planning horizon centered around 30 years of data, or a time-based 30-year period. Cal-Adapt recommends a GWL-based approach to reduce multi-model uncertainty when using global climate models.

Step 2 – Select Shock Extreme Type.
Next, the *type* of extreme is selected: a hot extreme, representative of extreme heat conditions and heatwaves, or a cold extreme, representative of extreme cold conditions such as a cold snap. Based on stakeholder interviews, extreme weather conditions are most commonly characterized by the temperature profile, reflecting the critical role temperature plays in defining system stress.

Step 3 – Retrieve and Process Hourly Air Temperature.
Hourly air temperature is retrieved for the location and climatology selections as the determining environmental factor for extreme characterization. This differs from the TMY approach which includes 10 environmental metrics, including solar radiation and wind speed [1,16]. Air temperature is then resampled to the corresponding extreme type. For a cold extreme profile, the data is resampled to daily minimum temperature. For hot extremes, the data is resampled to daily maximum temperature. Cal-Adapt uses *a priori* bias-adjusted dynamically downscaled WRF model outputs as the data foundation for TMY and XMY profiles[6].

Step 4 – Calculate the Maximized Error between Climatology and Extreme Months.
For each month, two sets of cumulative distribution functions (CDF) are calculated: one for the long-term median climatology across all candidate years, and one for each year within the climatology (i.e., a candidate year). The candidate year is compared against climatology to quantitatively select the month that is furthest from the long-term median conditions, maximizing the error. For cold extremes, this translates to the lowest-value month or maximized negative error relative to climatology. For hot extremes, the highest-value month or maximized positive error relative to climatology is selected (Figure 7). This process is repeated for all months, per simulation. Doing so ensures that model data is kept intact within a single physically-consistent climate profile, rather than pooling across models which introduces multi-model uncertainty. Following TMY methodological best practice, years of abnormal volcanic activity are excluded from consideration due to the impact of aerosols on air temperatures.

[6] The *a-priori* bias-adjusted WRF models available on Cal-Adapt are used for TMY profile generation for two reasons: This subset of WRF models provide the requisite variables for TMY profiles, primarily the solar variables. Secondly, the bias-adjustment process ensures that the data is further localized to regional temperature trends.

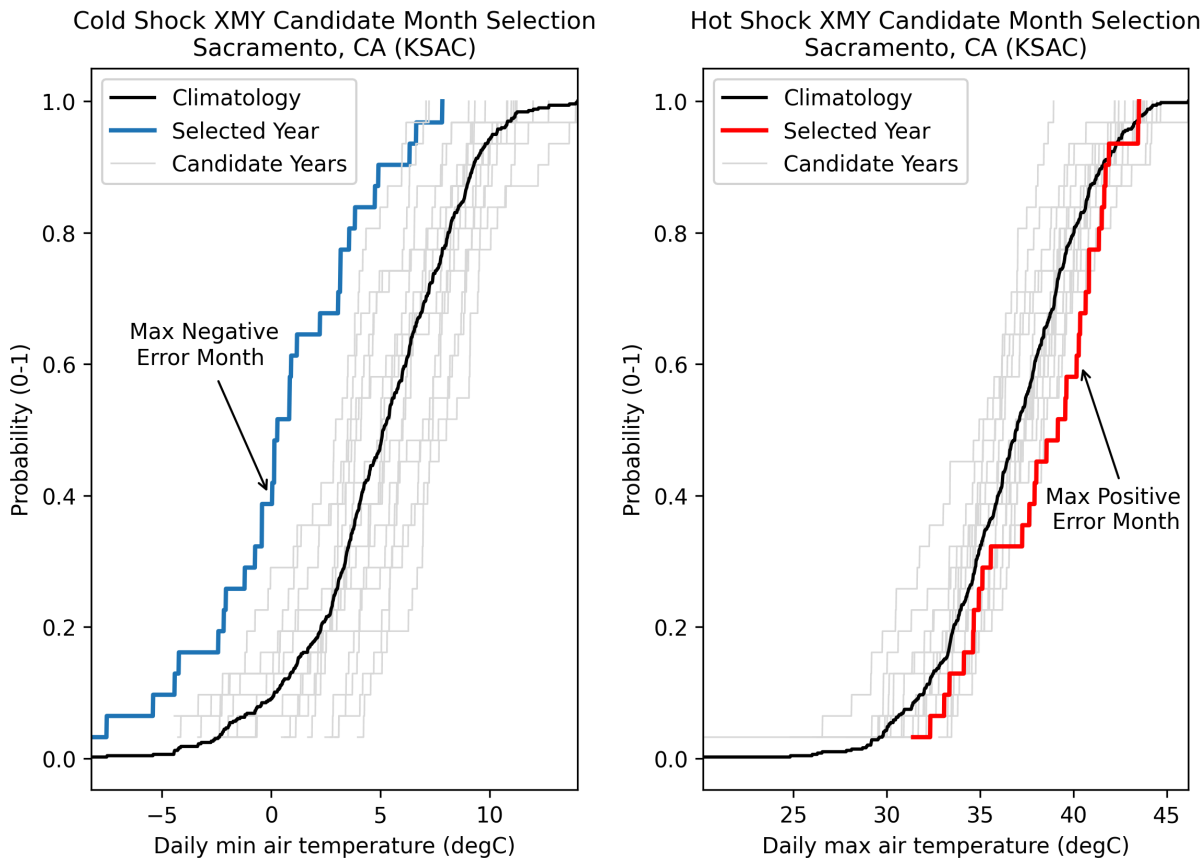


Figure 7. (Left) Cumulative distributions of January climatological conditions and the maximized error month for a Cold Shock XMY. (Right) Cumulative distributions of the July climatological conditions and the maximized error month for a Hot Shock XMY. For illustrative purposes, only one model is shown (MPI-ESM1-2-HR).

Step 5 – Compile Extreme Months and Generate XMY Profile.

Once the most extreme months are selected, the standard meteorological information included in a TMY profile are retrieved for contemporaneous months. XMY profiles therefore include: air temperature, dewpoint temperature, relative humidity, global irradiance, direct irradiance, diffuse irradiance, downwelling radiation, wind speed and direction, and surface air pressure for each of the designated months as determined by the extreme air temperature profile. In other words, if February 2005 is the most extreme month for a cold Shock XMY, all other variables are explicitly extracted for February 2005 to maintain a physically consistent profile. Smoothing at the monthly interface between months is performed via second-degree polynomial curve fit to prevent discontinuities at the month interface [3]. See Figure 2 for a full Shock XMY profile as compared to typical conditions.

Persistence Extremes: Sustained Stress

The Persistence XMY represents localized weather conditions that stress an energy system by selecting hours associated with specific percentile-based extremes within the climatological distribution, prioritizing sustained statistical deviation from typical conditions. This method allows precise tuning for exact conditions in order to stress test systems, such as "turning a dial" on the intensity of the desired extreme. Figure 8 illustrates the methodology workflow to generate a Persistence XMY climate profile.

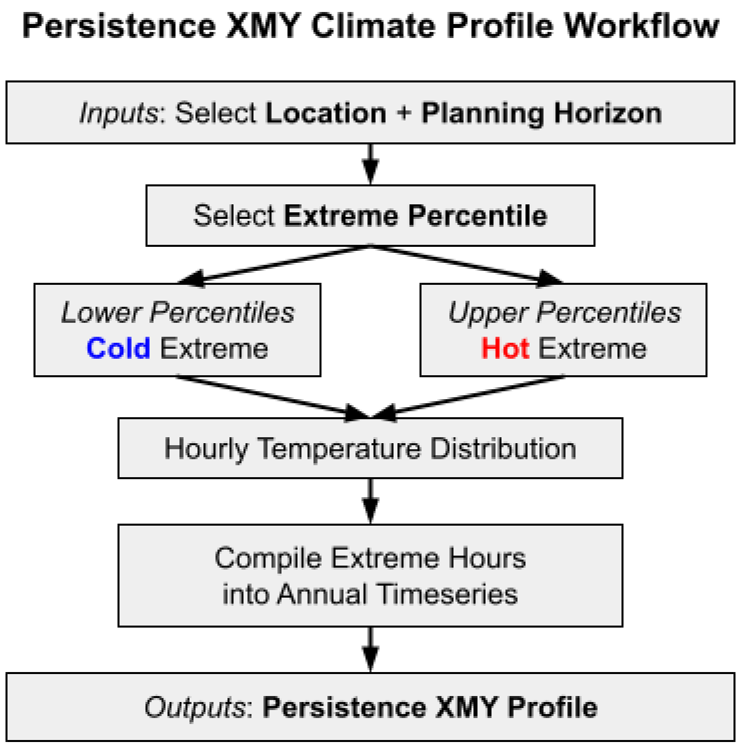


Figure 8. Persistence XMY Climate Profile Workflow.

<u>Persistence XMY Methodology [Percentile Based]:</u>
Step 1 – Select Location and Planning Horizon.
Cal-Adapt Persistence XMYs are for point-based locations, meaning that a user will first select a specific location of interest, such as a power plant or an airport weather station. The user will also select a climatological period of time, such as a global warming level centered around 30 years of data, or a time-based 30-year period. Cal-Adapt recommends a GWL-based approach to reduce multi-model uncertainty when using global climate models.

Step 2 – Select Extreme Percentile.
The Persistence XMY is calculated by applying the *Cal-Adapt: Standard Year methodology* in which the <u>desired percentile</u> is calculated from the long-term climatological distribution and the closest value from the distribution of simulation values at a given hour is returned for each hour of the year. The lower percentiles (below median conditions at the 50th percentile) represent

cold extremes. Upper percentiles (above median conditions at the 50th percentile) provide hot extremes.

Step 3 – Retrieve Hourly Air Temperature.
Hourly air temperature is retrieved for the location and climatology selections as the determining environmental factor for extreme characterization. This differs from the TMY approach which includes 10 environmental metrics, including solar radiation and wind speed [3, 18]. Based on stakeholder interviews, extreme conditions are most commonly characterized by the temperature profile, reflecting the critical role temperature plays in defining system stress. Cal-Adapt uses *a priori* bias-adjusted dynamically downscaled WRF model outputs as the data foundation for TMY and XMY profiles.

Step 4 – Calculate the Hourly Distribution.
Using hourly air temperature, the closest value to the desired percentile is returned for each hour of the year, per model. This process is repeated for all bias-adjusted model simulations. Doing so ensures that model data is kept intact within a single climate profile, rather than pooling across models which introduces multi-model uncertainty. Following TMY methodological best practice, years of abnormal volcanic activity are excluded from consideration due to the impact of aerosols on air temperatures.

Step 5 – Compile Extreme Hours and Generate XMY Profile.
Once the most extreme conditions are selected, the Persistence XMY is compiled into an hourly timeseries where each hour represents a specific percentile for that hour of the year (Figure 5). The standard meteorological information included in a TMY profile are retrieved for contemporaneous conditions. XMY profiles therefore include: air temperature, dewpoint temperature, relative humidity, global irradiance, direct irradiance, diffuse irradiance, downwelling radiation, wind speed and direction, and surface air pressure as determined by the extreme air temperature profile. See Figure 3 for a full Persistence XMY profile as compared to typical conditions.