READi Insights: Extreme Heat Events and Impacts to the Electric System

September 2022

RECENT HEAT EXTREMES IN CONTEXT

Several heatwaves in the last few years have tested the reliability of the power system and contributed to wide-ranging discussions about resilience and resource adequacy. The July 2022 heatwave that impacted the United Kingdom and much of western Europe shattered daily high temperature records, damaged infrastructure, and pushed the grid to the brink of blackouts. The following week, nearly all of Texas and Oklahoma exceeded 100°F as the extremely hot summer in the south-central United States continued. Earlier this year, India experienced the hottest spring in the past 100 years while China endured one of the hottest summers on record.

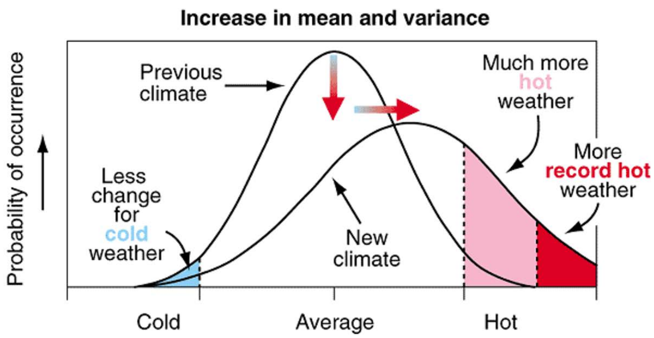
In the current period of global warming driven by elevated greenhouse gases, it is natural to wonder whether heatwaves are increasing in frequency and severity. There have been remarkable periods of heat in the past. For example, the 1930s Dust Bowl featured a persistent drought across the US Great Plains, caused by a combination of unsustainable agricultural practices and persistent high atmospheric pressure over the Plains. During this period, summertime record high temperatures were set, both locally and for the continental US. In many locales these record highs held for nearly a century, until 2021, when the continental US record high mean temperature tied the long-standing record.

Given that history, what, if anything, sets these recent years apart? Global warming has increased temperatures nearly everywhere, with temperatures increasing faster over land, at high latitudes, and at night. As average global temperatures rise, typical temperature fluctuations will more often exceed prior extreme heat thresholds due to the higher starting point (Figure 1). Moreover, studies show that the intensity of several recent heatwaves would have been all but impossible without climate change (e.g., 2021 Western North America and 2020 Siberia events). Finally, the latest global climate scientific assessment concluded "it is virtually certain that the frequency and intensity of hot extremes and the intensity and duration of heatwaves have increased since 1950 and will further increase in the

Table 1: Selected examples of recent record-setting heat events, reported as local daily extremes or regional monthly averages; * denotes tied records. Sources: EPRI analysis of ERA-5 data (Mumbai, Siberia) and MRCC cli-MATE data (Australia, Chongqing), NOAA NCEI Climate at a Glance (remainder).

	LOCATION	NEW RECORD	DATE	PREVIOUS RECORD	PREVIOUS DATE
DAILY RECORD	Livermore (East Bay Area), California	116 °F (46.7 °C)	Sept 5 and 6, 2022	115 °F (46.1 °C)	Sept 3, 1950
	London, UK	104 °F (40 °C)	July 19, 2022	100 °F (38 °C)	Aug 10, 2003
	Australia*	123.3°F (50.7 °C)	Jan 13, 2022*	123.3 °F (50.7 °C)	Jan 2, 1960*
	Portland, Oregon	116 °F (47°C)	June 28, 2021	107 °F (42 °C)	July 30, 1965
	Siberia	102 °F (39 °C)	May 2020	98 °F (37 °C)	May 2011
MONTHLY AVERAGE	Chongqing, China	96 °F (35.6 °C)	Aug 2022	90.4 °F (32.4 °C)	Aug 2006
	Mumbai, India	84 °F (29 °C)	Mar 2022	83 °F (29 °C)	Mar 2004
	Southern Plains and Gulf Coast, US*	85.5 °F (30 °C)	July 2022*	85.5 °F (30 °C)	July 2011*
	United States, Continental mean*	74 °F (23 °C)	June–Aug 2021*	74 °F (23°C)	June–Aug 1936* (Dust Bowl)

Figure 1: Simplified depiction of changes to the temperature distribution in a warming world. Source: IPCC WG1 TAR Figure 2. 32 (Folland et al, 2001).



future even if global warming is stabilized at 1.5°C" (Arias et al, 2021). In light of this understanding, it is critical for the power sector to prepare for a future with ongoing heat extremes.

WHAT ARE HEATWAVES AND HOW ARE THEY CHANGING?

Quantitative measures of extreme heat vary depending on purpose and jurisdiction but are generally defined by thresholds of hot temperatures relative to a location's typical climate conditions. For example, California's climate data portal Cal-Adapt defines an "extreme heat day" as a day when the daily maximum (or mean or minimum) temperature exceeds the 98th percentile of historical summer daily maximum (or mean or minimum) temperatures; a "heatwave" is defined as a certain duration (e.g., four consecutive days or warm nights) above the extreme heat threshold.

Specific definitions are used for different purposes. For example, heatwaves defined for human health generally incorporate a measure of humidity and wind (wind has an ameliorating effect) to better represent physiological stress. Warmer nighttime (i.e., daily low) temperatures have implications not only for human health, but also for energy demands to cool buildings throughout the night. This measure reached a new record high in July 2022 for average nighttime temperatures across the contiguous US. No matter the definition, extreme heat events and heatwaves have become more severe across the globe as the climate has warmed. Historical trends and a consensus among climate projections lead to a high degree of certainty that these events will continue to increase in frequency and intensity over the coming decades.

While a heatwave presents risk on its own, it can be even more impactful if it occurs alongside other adverse conditions, such as high humidity or drought. High levels of humidity, for example, can increase the risk of heat stress or exhaustion by reducing the body's natural ability to cool itself. High humidity also compounds the effect of extreme heat by lowering the efficiency of thermoelectric generation, thereby reducing electricity supply at the same time demand is high for air conditioning. Extreme heat can also interact with drought, accelerating wildfire risk. High temperatures increase surface evaporation and plant transpiration, which reduces soil moisture and thus intensifies stress on vegetation, contributing to a positive feedback loop of decreased precipitation that exacerbates already-dry conditions. Knowledge of climate variables and hazards correlated with extreme heat is integral to assessing risk associated with heatwaves.

HOW DOES EXTREME HEAT IMPACT THE ELECTRIC SYSTEM?

Extreme heat tends to occur across broad geographical areas, simultaneously impacting assets across the entire regional electric system. Increased end-use electricity demand is an obvious, but highly consequential, impact on the power system, as demand sharply rises to maintain cooling of indoor spaces. Although the energy required for cooling depends on several factors beyond temperature, including building characteristics and the efficiency of the cooling unit itself, an increase in energy demand clearly correlates to increased temperatures (EPRI, 2017), and the higher loads can strain the performance of other assets in the power system.

Increased electricity demand can also push transmission and distribution (T&D) infrastructure to the limits of design capacity. Warmer air temperatures reduce the capacity of transmission lines and increase line losses since a conductor's temperature is proportional to electrical resistance. Furthermore, electrical lines sag under high load and high heat conditions, increasing the chance of contacting a nearby object, which can lead to a line outage. Underground assets are also affected, as higher air and soil temperatures can accelerate corrosion and lower equipment capacity to dissipate heat, further reducing line capacity. These additional stressors can cause underground cables to fail, particularly in cable joints that have insulation defects. Similarly, the significantly higher load will challenge transformers as the higher ambient temperature may negatively impact transformer capacity, reducing life expectancy due to increased hot spots and accelerated aging of paper insulation.

Thermal generation assets, both nuclear and non-nuclear, can experience diminished capacity when higher air and water temperatures reduce cooling efficiency. Drought, often associated with heat extremes, limits the supply of cooling water at many generation facilities. The extended heatwave in Europe demonstrated these challenges as high-intake cooling water temperatures and drought conditions, in combination with other factors, forced more than half of France's nuclear fleet offline, representing more than three gigawatts of capacity. The loss of nuclear capacity increased demand for gas generation, straining Europe's already limited natural gas supply. As ongoing

Are Climate Models Capturing These Heat Extremes?

Scientists use global climate models to explore future meteorological conditions, such as temperature and precipitation, based on scenarios of greenhouse gas concentrations. Climate models work by solving geophysical equations for a spatial grid covering the Earth's surface, stepping forward in time from 1850 through 2100 to simulate daily weather that is representative of expected regional climate patterns (i.e., a 30-year climatology), but they are not designed nor expected to accurately predict the weather in a specific location on a specific day in the future.

The meteorological projections that come from an individual climate model represent one possible future. To understand the range of possible futures, numerous independent climate model simulations are combined to create an "ensemble" that collectively represents the range of possible weather for a given scenario. It should be noted, however, that these models may not resolve localized extreme weather events (e.g., at the city or county scale) as they are specifically designed to capture large-scale changes. This is especially true for the near-term climate projections over the next few years because the limited sample (e.g., 5 years of projections) constrains the potential for extremes compared to a long historical record. Perhaps an extreme heatwave will show up in the near-term projections, but most likely it will take decades of projections for this to occur. Moreover, a best practice when interpreting climate model output is to consider aggregate outcomes over a longer period than the year in question (e.g., 30-year climatology).

Several headlines following the 2022 UK heatwave emphasized that the recent heat extreme was more characteristic of what climate models had projected for the 2050s than the 2020s, with similar claims made about the June 2021 Pacific Northwest heatwave. However, this doesn't mean the climate models were wrong. Given that these heatwaves are considered the equivalent of 1 in 100- or 1 in 500-year events, it might take an order of magnitude more model simulations than are currently published in the climate data archive for these events to show up in any given year. The more extreme the event, the larger the ensemble needed to capture it; however, due to the computational intensiveness of today's climate models, the total simulations possible even with advanced supercomputers is typically a limited number. In short, the climate models are not wrong as they are not designed to capture every extreme; expecting them to do so can lead to incorrect conclusions.

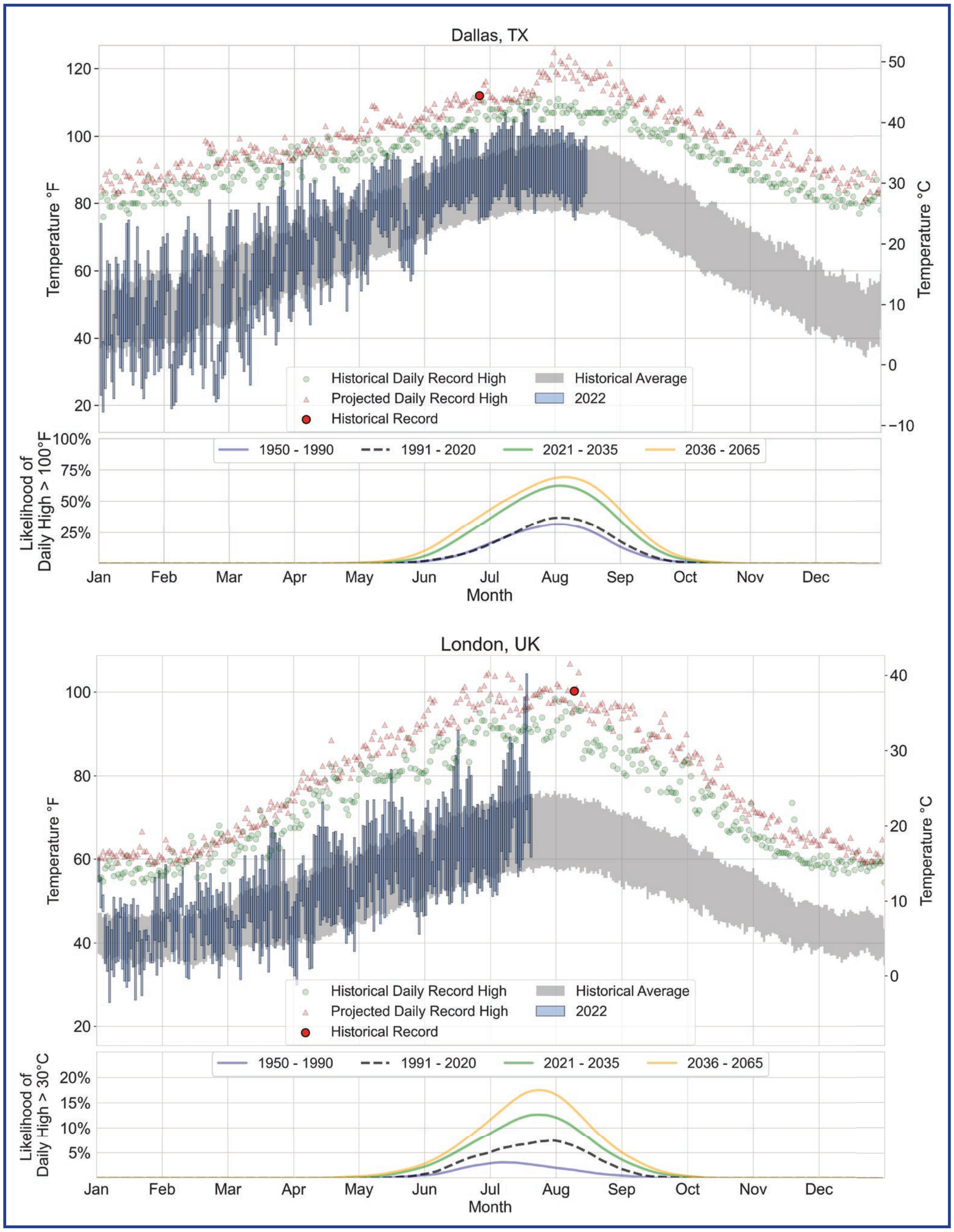


Figure 2: Temperature climatology with extreme heat for Dallas, Texas and London, UK. Top panel shows 2022 temperatures (°F, blue bars) for Dallas and for London Heathrow Airport, compared to the daily average temperature range (gray bars) from 1991–2020. This panel also shows daily high record temperatures (green circles), the single all-time record high temperature (red circle), and projected daily record high temperatures as modeled under SSP3-7.0 through 2050 (red triangles). The bottom panel shows the daily likelihood of a maximum temperature above 100°F for Dallas and 86°F (30°C) for London by day of the year for multiple time periods from 1950 to 2065, with the current climate normal shown with black dashed line. Historical data: Midwestern Regional Climate Center's cli-MATE data portal and the European data portal. *Projection data: Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP)* CMIP6 archive.

heatwaves cause receiving waterbodies to approach or exceed critical temperature thresholds, thermal discharges from generating facilities may trigger environmental health and compliance issues, forcing further curtailments.

Solar power also feels the effects of extreme heat as most panels are designed for peak capacity around 77°F (25°C) and begin to lose capacity at higher temperatures. Power output can decrease ~0.5% for every degree above 25 °C. Considering peak temperatures around 40°C, solar panels can experience capacity losses up to approximately 7.5%.

Regarding energy storage, lithium-ion batteries have an ideal operating temperature range of 59–95°F (15–35°C). Exposure to temperatures above that range can damage the battery and significantly reduce the amount of energy that it can store over time. An EPRI project observed an outdoor residential system in Arizona exposed to extreme high temperatures in 2020. After exposure to daily high temperatures at or above 110°F for 50 days (nonconsecutive) during July and August, the battery cells swelled, presumably from the heat, impacting their efficiency, which reduces available energy capacity. For these reasons, lithium-ion batteries are typically housed in temperature-controlled buildings. During extreme heat events, higher electricity loads are needed to cool those enclosures and protect the batteries, reducing the net output of the battery itself. Table 2 summarizes the primary possible risks to key energy assets and the system overall from heatwaves.

Across all asset types, extended periods of extreme heat can also elevate health and safety risks. Whether responding to failing transmission lines or conducting routine work in generation facilities with insufficient space conditioning, the risk of heat stress for employees increases at a time when repair work and recovery from asset failure are critical.

THE BIG PICTURE

During a recent heatwave in Europe, weeks of high temperatures peaking near 104 °F (40 °C) created a combination of high demand and faults within the power networks in both France and the UK. These outages remained localized, with the UK system outages impacting fewer than 20,000 customers in a system that serves close to 4 million. However, the compounding effects of rising demand for electricity (for example, the potential for increased cooling demand in historically mild climates such as the UK coupled with population growth and/or electrification) and stress on electrical assets increase the likelihood of widespread system blackouts. Impacts to individual assets may appear minor when viewed separately, but when aggregated over a large region and across several days, these individual impacts can quickly coalesce to push the entire power system to its limit and beyond. History and performance of power systems have shown that under severely stressed or adverse conditions a single point of failure on any given system can lead to consequential cascading outages that have significant repercussions on society, the economy, and human life.

The world continues to set new extreme heat records with increased frequency and intensity and, as global temperatures rise, these trends are projected to continue and worsen over the coming decades. Fortunately, our climate modeling capabilities continue to advance and improve, enabling assessment of the potential range of future conditions. Extreme heat event probability and severity translates into unique impacts and consequences on individual assets. In turn, these asset risks inform system-wide risk assessment and motivate the need to scrutinize design criteria while developing additional resilience measures and adaptation strategies.

This confluence of need and opportunity can empower the electric power industry to flip resilience strategy from a reactive to a proactive approach. Consequently, EPRI has launched Climate READi (REsilience and ADaptation Initiative) to integrate climate data science, asset impacts, and full system analysis with an assessment of adaptation strategies to provide a consistent and comprehensive methodology on resilience investment. The initiative's scope includes:

1. **Physical Climate Data and Guidance –** Guidance on the availability, suitability, gaps, specification, and interpretation of climate data to enable assessments at multiple scales, including at the asset and system level, and with consideration of how to treat inherent uncertainties in modeling.
2. **Energy System and Asset Vulnerability Assessment –** A consistent approach for power system stakeholders to apply climate-related information, including extreme weather and localized climate data at the asset level, with guidance for specific asset/system vulnerability analyses.

ASSET	DIRECT IMPACTS	POTENTIAL SYSTEM IMPACTS
Transmission and Distribution Lines (Overhead and Underground)	Lost capacity, line sagging, higher potential for sagging (contacting trees or objects)	Localized and/or regional system outages
Transformers	Increased risk of premature failure at high load conditions	Localized and/or regional system outages
Thermal Generation (Nuclear and Nonnuclear)	Loss of necessary cooling capacity; reduced output and/or forced plant outages	Reduced generation capacity
Solar Generation (Photovoltaics)	Reduced output	Reduced generation capacity
Battery Storage	Loss of net output capacity due to higher cooling loads	Loss of system storage capacity

Table 2: Summary of possible impacts to key energy generation and supply assets and the energy system from heatwaves.

3. **Resilience and Adaptation Planning and Prioritization –** A common risk-informed approach to prioritize hardening and adaptation options and apply a cost-benefit analysis to identify the specific investments to further climate resilience along with other electric system objectives.

Through collaboration with global thought leaders, this effort will culminate in a comprehensive, consistent, and industry-accepted approach to physical climate risk assessment that uses science-based insights to identify optimal resilience and adaptation investments, enabling the most effective future design and operation of a reliable, resilient, and affordable energy system to meet society's needs.

PUBLICLY AVAILABLE RESOURCES

1. Heat.gov – A source of heat and health information for the nation to reduce the health, economic, and infrastructural impacts of extreme heat.
2. CMRA – Climate Mapping for Resilience and Adaptation (CMRA) integrates information from across the federal government to help people consider their local exposure to climate-related hazards.
3. Copernicus Climate Data Store – A European Union comprehensive resource for climate data, providing easy access to a wide range of datasets via a searchable catalogue.
4. Climate Change Knowledge Portal – The CCKP provides global data on historical and future climate, vulnerabilities, and impacts.

REFERENCES

Adnett, K, Binnie, I. (2022) "Heatwave puts Europe's energy system to the test." 17 June 2022. Reuters. https://www.reuters.com/business/energy/heatwave-puts-europes-energy-systems-test-2022-06-17/ 5 Aug. 2022.

Arias et al (2021). Technical Summary. "In Climate Change 2021: The Physical Science Basis." Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

EPRI (2017) "Temperature Impacts on Electricity Demand for Cooling in New York State." EPRI, Palo Alto, California: 3002011593.

Folland, C.K., Karl, T.R., et al. (2001) "Observed Climate Variability and Change." Climate Change 2001: The Scientific Basis. In: Houghton, J.T., et al., Eds., Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 99-181.

Masters, Jeff (2022). "Australia ties Southern Hemisphere's all-time heat record of 123°F," retrieved on August 17, 2022 from https://yaleclimateconnections.org/2022/01/australia-ties-southern-hemispheres-all-time-heat-record-of-123f-epic-heat-cooks-argentina/

Masterson, V. "Why don't solar panels work as well in heatwaves?" 9 Aug. 2022 World Economic Forum, https://www.weforum.org/agenda/2022/08/heatwaves-can-hamper-solar-panels/ 10 Aug. 2022.

Natural Resources Canada, U.S. Department of Energy. "Final Report on the Implementation of the Task Force Recommendations, 1–17." (2006). https://www.energy.gov/oe/downloads/blackout-2003-blackout-final-implementation-report

NOAA National Centers for Environmental information, Climate at a Glance: Regional Time Series and National Time Series, published August 2022, retrieved on August 24, 2022 from https://www.ncei.noaa.gov/cag/

NOAA National Centers for Environmental Information, State of the Climate: Monthly Global Climate Report for May 2020, June 2020, Annual 2020, January 2021, June 2021, July 2021, August 2021, November 2021, Annual 2021, January 2022, April 2022, May 2022, June 2022, and July 2022, retrieved on August 17, 2022 from https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/

About EPRI

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