Extreme Weather Analysis and Electrical Grid Resilience

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Abstract. The increasing frequency and intensity of extreme weather events, driven by global temperature rise, pose challenges to the safety and resilience of the electrical grid [3]. Our goal is to develop a reproducible methodology and software package that identifies areas of improvement for the performance of photovoltaic (PV) systems through severe weather, aiming to build resilience and avoid rotating outages. This study examines the impact of extreme weather by analyzing high temperatures, solar irradiance, and wind speed, with a focus on abnormal weather oscillations. By employing data-driven models to simulate extreme events, utilities and developers can enhance the efficiency of renewable energy, ensuring reliable distribution across the Western Electricity Coordinating Council (WECC). My research supports the development of intelligent planning algorithms for renewable-backed grids during heat waves, particularly in regions where electricity demand surges during high-temperature periods. Under the Renewable Energy Generation Risk from Outlier Weather (REGROW) project, led by the SLAC National Accelerator Laboratory, my data visualizations provide the ground truth that compares the data from the risk simulation and robust control for future optimization models. This research aims to strengthen grid resilience and contribute to climate change mitigation through reliable and efficient renewable energy.

I. INTRODUCTION

Aligned with the REGROW project's objectives of data curation and risk modeling for renewable generators, our study of the August 2020 heatwave contributes to the development of statistical methods and software tools designed to optimize grid performance, predict potential challenges, and implement strategies to assess correlated losses in solar and wind generators. National Renewable Energy Laboratory (NREL) partnered with SLAC to perform a case study of an extreme weather event, such as the California August 2020 heatwave, to gather data and test these strategies.

Abnormal events are defined as those deviating significantly from historical norms, like heat waves with temperatures 10–20°F above average or prolonged reductions in sunlight due to unusual atmospheric conditions. Extreme events involve physical damage to generators, such as hail-damaged solar panels or wind-damaged turbines [1].

Between August 14 and August 19, 2020, the western United States, including California, experienced an extreme heatwave, resulting in four of the five hottest August days on record since 1985 [2]. When a heatwave hits a grid, energy demand surges, potentially exceeding the available load supply. The electrical grid can only produce a certain amount of electricity at a time, which may lead to failures, forced rolling blackouts, equipment damage, and revenue loss due to power outages.

Given the wide range of risks posed by anthropogenic climate change, extreme weather events, and the vulnerability of power infrastructure to potential attacks, it is crucial to design energy systems with enhanced resilience. Photovoltaic (PV) systems, which play a vital role in mitigating climate change by reducing reliance on fossil fuels, are mitigated by dispersing generators over large areas, allowing for spatial averaging of local weather conditions [1]. The larger the collection of solar generators, the fewer variables there are, resulting in more stable fleet behavior.

This study uses simulation and optimization models to identify how PV systems can be improved to ensure reliable operation even during heatwaves. By focusing on these models, the research aims to ensure that PV systems like solar panels, wind turbines, and battery storage can continue to contribute effectively to the grid, even during periods of high stress, thereby supporting overall grid stability.

II. METHODOLOGY

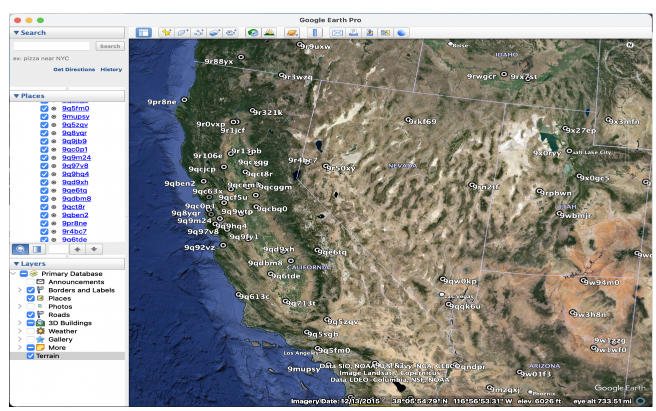


Figure 1. Google Earth of WECC Locations

Our analysis of extreme weather's impact on photovoltaic (PV) systems employed a data-driven approach, integrating Python programming with the interactive Marimo user interface. Curated data collected from the National Renewable Energy Laboratory (NREL) and NOAA's Storm Events Database focused on weather patterns across the Western Electricity Coordinating Council (WECC) region, including temperature, solar irradiance, and wind speed, to understand the effects of heat waves on electricity consumption and grid stability [3].

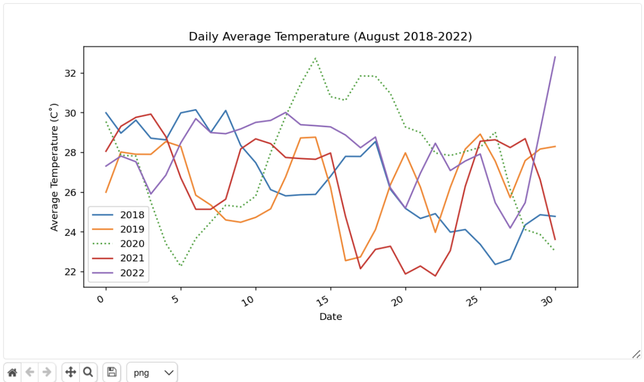


Figure 2. Daily Average Temperature in August

Estimating the trend of extreme weather events, such as the 2020 California heat wave, involves visualizing temperature anomalies over specific periods like August. This analysis compares temperature means of surrounding years across multiple grid locations and time scales, including hourly and daily data, to identify abnormal fluctuations. Weather anomalies, like significant temperature rises, are modeled as deviations from regular climate patterns, calculated by comparing hourly temperatures against the average of surrounding years for August, which serves as the baseline for each grid location.

The geographic locations of each node were decoded using latitude and longitude coordinates and plotted on Google Earth Pro for an overview visualization (Figure 2). Python libraries such as Pandas and Matplotlib were employed to manipulate and group these nodes by location and temperature. Throughout the research, version control and collaborative code review were managed through GitHub, ensuring effective troubleshooting and continuous improvement.

To narrow the data closer to the August 2020 heat wave, we performed a time slice using data frames that focused on specific days of the month for each selected location. Temperature values were overlapped and displayed to compare average daily temperatures (Figure 2). The process was applied to hourly and daily calculations, revealing that hourly data provided the most accurate representation of event impact. The Python library numpy was used to average hourly data for August into daily scales, which were then stitched together on a single graph.

Using Marimo UI, each node could be visualized through a toggle button, enabling direct comparison of temperature variations between counties. For example, node "9q5epc" in Los Angeles, CA, exhibited a temperature spike nearly 10°C higher than surrounding years, lasting 8-10 days. This prompted further analysis, including the calculation of heat wave intensity through temperature peaks and integrals. A heat map (Figure 3) provided a clearer visualization of these variations.

To measure the 2020 heat wave's scale, we calculated the integral and max residual temperatures by comparing 2020 temperatures to the predicted average from non-heatwave

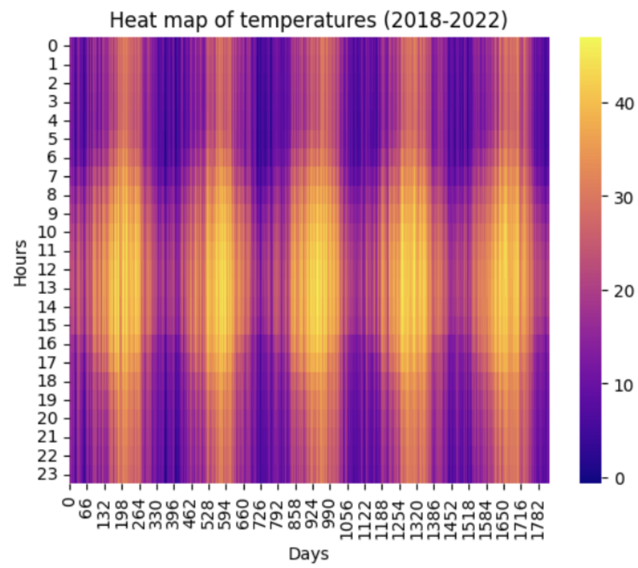


Figure 3. Temperature intensity in Southern California

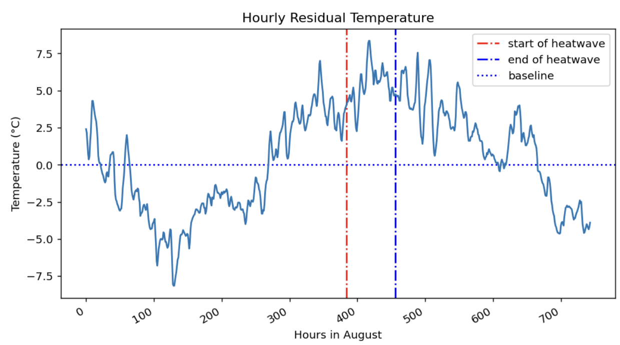


Figure 4. Temperature deviation in August 2020

years (2018, 2019, and 2021). The integral allowed for assessing heatwave intensity and duration. Observing (Figure 7), the first half of August showed an unusual dip below the median temperature, followed by a sharp peak in the second half, underscoring the increased intensity of temperature oscillations due to climate change.

```python
# Temperature Residual Function
def analyze_baseline(df):
    actual = df.loc['2020-08-01':'2020-08-31'].values
    predicted = np.c_[
        df.loc['2018-08-01':'2018-08-31'].values,
        df.loc['2019-08-01':'2019-08-31'].values,
        df.loc['2021-08-01':'2021-08-31'].values,
        df.loc['2022-08-01':'2022-08-31'].values
    ]
    predicted = np.median(predicted, axis=1)
    return actual - predicted
```

Figure 5. Residual Temperature Function

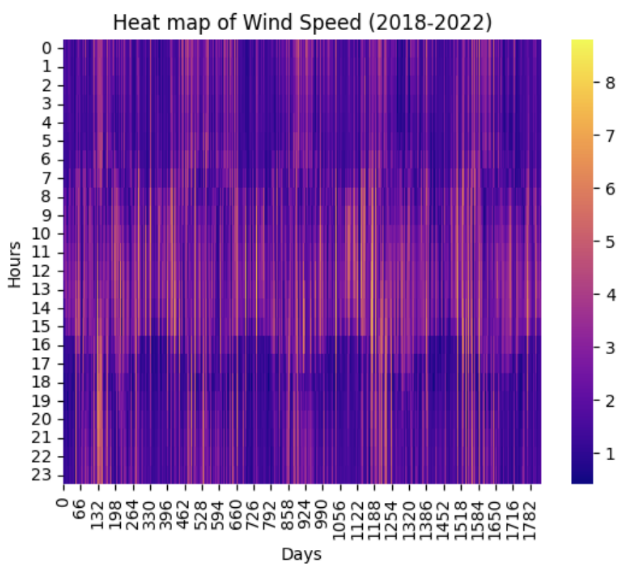
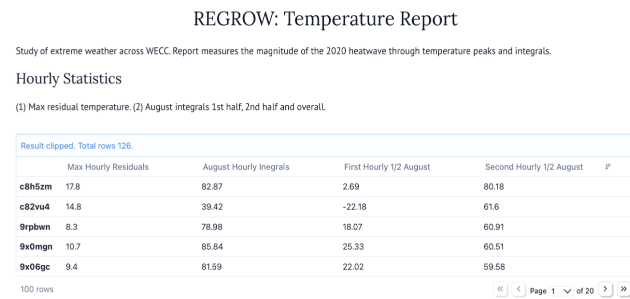


Figure 6. Abnormal Heat from Dry Hot Winds



REGROW: Temperature Report

Study of extreme weather across WECC. Report measures the magnitude of the 2020 heatwave through temperature peaks and integrals.

Hourly Statistics

(1) Max residual temperature. (2) August integrals 1st half, 2nd half and overall.

Result clipped. Total rows 126.

	Max Hourly Residuals	August Hourly Inegrals	First Hourly 1/2 August	Second Hourly 1/2 August
c8h5zm	17.8	82.87	2.69	80.18
c82vu4	14.8	39.42	-22.18	61.6
9rpbwn	8.3	78.98	18.07	60.91
9x0mgn	10.7	85.84	25.33	60.51
9x06gc	9.4	81.59	22.02	59.58

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Figure 7. Temperature Report with Max Residuals and Integrals

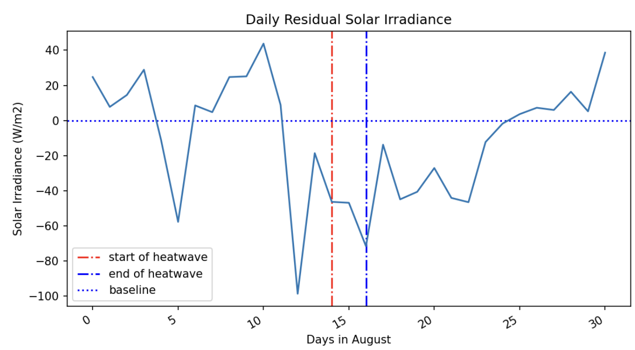

Figure 8. Reduction of Solar Irradiance Due to Wildfire Smoke

An important factor in understanding the causes of heat waves is the effect of anticyclones, weather systems with high atmospheric pressure at its center, and hot dry air trapped in high-pressure systems. Winds, such as the Santa Ana winds, can dry out the atmosphere, and anticyclones prevent hot air from rising, leading to increased ground-level temperatures [4]. The 2020 wildfires across California exacerbated these conditions. Wildfires caused smoke that would cover sunlight for days during and following the heatwave, reducing the amount of solar irradiation, as confirmed by the NREL data.

The initial plotting of wind speed on the heat map in (Figure 5) reveals intense areas of possible hot winds that may have contributed to the heating of the lower atmosphere. Solar irradiance, measured in W/m², showed a noticeable dip during the heatwave, indicating reduced solar energy. The correlated loss between smoke coverage and PV output becomes clearer when comparing the wind speeds from the WECC data, highlighting the interconnected impact of wind patterns on solar output. The possible increase in wind speeds, such as the Santa Ana wind, may have increased the dryness of the land, and heating of the lower atmosphere.

Our research on curated data sets of historical abnormal patterns and extreme weather events demonstrates that it is possible to identify instances where wind and solar generators produced below typical output levels. To investigate further, the same approach of calculating integrals, maximum residual temperatures, and daily averages for August was applied to solar irradiance data, examining the correlation between wildfires, smoke, and decreased solar output.

III. RESULTS

Research on these curated datasets covering historical abnormal patterns and extreme weather events revealed it is possible to identify where wind and solar generators produced less than typical output. For the node in Los Angeles, California, the calculation results provided concrete evidence of a heatwave, demonstrated by significant temperature anomalies.

The max residual temperature was recorded at 9.80°C, with an overall temperature integral of 25.48°C, including a -9.17°C dip in the first half of August and a sharp rise to 34.66°C in the second half. These results display the increasing intensity of weather oscillations, characterized by an initial negative dip followed by a steep temperature rise during the heatwave. The data was compiled into a report, sorted by descending temperatures to identify the counties most affected by the heatwave.

Understanding these patterns is crucial for preparing the grid and renewable energy systems. By anticipating extreme events, utilities and developers can utilize simulation software such as GRIP to quantify grid status and pole vulnerability, and REGROW to produce and store renewable energy from solar sources and lithium batteries, ensuring readiness when the next heatwave occurs.

IV. CONCLUSION

Climate change has intensified temperature oscillations over time, leading to more frequent and severe heat waves. This technical report analyzes node data by converting it into latitude and longitude coordinates, correlating with heat wave magnitudes using maximum temperature residuals and integrals. These fluctuations are visualized through graphs that highlight the patterns contributing to the development of intelligent algorithms for grid simulation and modeling.

Looking ahead, the REGROW project aims to apply this data modeling process to optimize energy storage, prevent rolling outages, and enhance renewable energy production and storage, including advancements in lithium batteries. As extreme weather events become more prevalent, the ability to predict, prepare for, and mitigate their impact on energy systems will be essential to maintaining reliable energy production and distribution.

By understanding the metrics from the temperature, solar irradiance, and wind speed data, this research lays the foundation for validation in simulation tasks with risk modeling and robust control for future optimization models.

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