Title: Heat Vulnerability Analysis And Mapping (HEVAM): Analysis of United States power grids vulnerability to climate changes

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HEAT VULNERABILITY ANALYSIS AND MAPPING (HEVAM): ANALYSIS OF UNITED STATES POWER GRIDS VULNERABILITY TO CLIMATE CHANGES

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ABSTRACT

The importance of the power grid under the energy sector umbrella is difficult to overstate, as it enables the function of nearly all critical infrastructure systems. The interconnected assets within electrical substations enable the function of our society and economy. With such a vast system of interconnected nodes, threats to the stability of this network come in many forms, from natural hazards to malicious threats. To quantify these impacts, we rely on a novel software-based asset survey system developed at George Mason University (GMU) utilizing satellite and street view imagery for classifying and geolocating over 38,000 component-level assets over 1,300 extra high-voltage substations. The ability to accurately differentiate components and spatially plot transmission and distribution assets allows for a more detailed analysis of vulnerabilities and external stressors beyond what is currently available in open-source repositories. We also rely on CMIP 6 climate models forecast to give us the forecasted max surface temperature over next few decades over the entire map of the United States. Combining both datasets and refining our research to improve component-level granularity, the study aims to provide deeper insight into the vulnerability of the power grids at their subcomponent level, to the climate changes over the future. Foundational research already supports precise simulation of performance under scenarios such as extreme weather conditions and prolonged heat waves, informing future strategies aimed at bolstering the resilience of the United States power grid against climate-related challenges, ultimately safeguarding the reliability of electrical distribution for all.

KEYWORDS

Heat Maps, U.S. Power Grids, Substation components, CMIP, Transmission, Distribution, Component Failure Rates, Temperature Exposure

INTRODUCTION

The United States' energy sector is a cornerstone of modern society, providing the fuel and electricity necessary to power homes, businesses, and industries. In 2022, about $1.7T, 6.7% of the GDP, was spent on energy by United States consumers alone, with annual energy costs per person being $5,159. The U.S. has 4% of the world's population and uses 16% of the world's energy. [1]. The importance of power infrastructure under this umbrella is difficult to overstate, as it enables the function of nearly all other critical infrastructure systems. Infrastructure components are becoming more complex and interdependent, forcing the use of a systems based approach as against their assessment in silos [2]. Similarly, policies to mitigate threats to the critical infrastructure threats must try to invest resources equitably across power stations and substations to support isolated failures and for better fault tolerance [3]. The operation, maintenance, and engineering of integral assets within electrical substations enable society to function, powering the economy, our societies and our world.

Over the decades, United States power infrastructure has grown extremely complex and vast, supporting the country's economic as well as population expansion. Consequently, the power grid networks are providing power flows in unprecedented magnitudes and directions, controlled by flow control equipment of unparalleled sophistication [4].

Investment estimates are projected up to a total of USD 9.2 trillion by 2050 to address infrastructure and power deficits, attain the Sustainable Development Goals (SDGs), and achieve net zero. Present day annual damages to infrastructure and buildings due to hazards are around USD 700 billion per year, and this number is expected to increase astronomically due to climate changes. While at present the average annual damages to infrastructure and buildings equate to around USD 700 billion per year (from climatic and non-climatic hazards), this number is expected to increase several fold over the 21st century because of climate change [5].

Similarly, the Great Acceleration curves, which encompass 12 indicators tracking the socio-economic and Earth systems with at least seven tracking the impacts on infrastructure, indicate extreme difficulty in predicting changes to systems, in part due to infrastructure complexity and in part due to external triggers such as climate changes and natural disasters. The Anthropocene era signals repeated shocks to the infrastructure due to this rapidly changing environment, thereby emphasizing on understanding the environmental triggers, and adapting the infrastructure assets, policies and educational practices to minimize variability and for security [6].

With the power grids size and complexity, and their dominant role for the country and for the economy increasing exponentially, it is of paramount importance to understand the climate change vulnerabilities that may impact their operations now and in the future, so that their functioning is safeguarded.

OUR STUDY GOALS

With this in mind, the aim of this study is to accurately model the impacts of extreme temperatures on infrastructure in a variety of climate scenarios. This has been undertaken by considering each and every substation as a combination of all the components within, rather than simply as a node within the power grid. We also take into account the substation categories and the failure rates of its components in our analysis. We rely on the max surface temperature forecasts as depicted by the climate change models based on the Coupled Model Intercomparison Projects (CMIP). Our study overlays these data sets to get exposure rates and failure curves for these substation components over a period of years till 2050. The goal is to have exposure rate analysis of power grid assets in relation to the impacts of extreme heat events. This gives us a launching framework for further analysis and actionable insights, that can influence future mitigation strategies and public policies.

OUR STUDY FLOW

The flow of our study is organized by the review of existing structures that covers power grid basics including substation types and high level substation components. We dive into climate change trends and their impact on the power grid networks. We also review existing studies that have been conducted in this arena, bringing out the gaps in the existing research, and the need for our study.

Our next focus is on the methodology and steps used in our study, starting with the source data sets. We then elaborate the research method steps that range from data collection, data aggregation and data analysis. We sum the data that can be used for actionable insights, and flow into our data analysis and inference based on our research. We finally conclude our study laying the groundwork for future research and discussions.

POWER GRID BASICS

Grid networks transport power via a network of over 1 million kilometers of high-voltage transmission lines [4]. These lines intersect at nodes known as substations, which consist of hundreds of components, and are used for the transportation and distribution (T&D) of power.

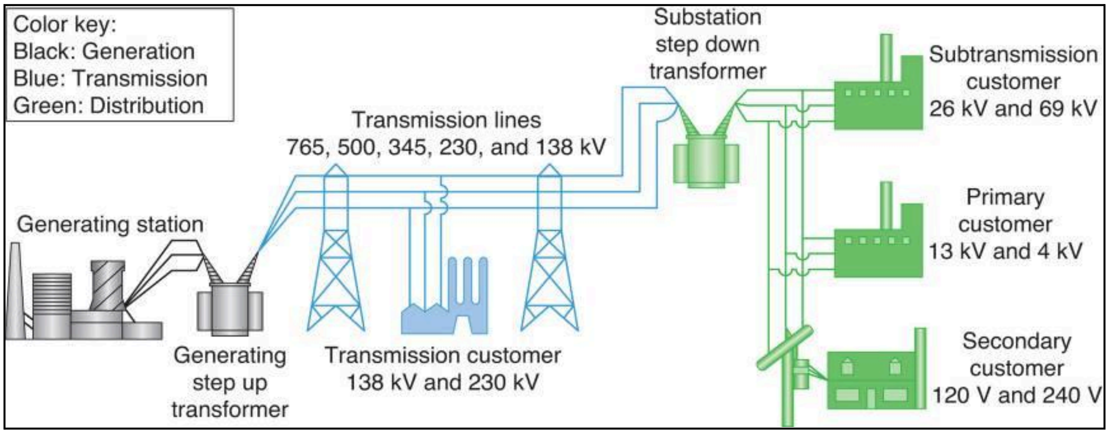


Figure 1: Power Grids and Substations [7]

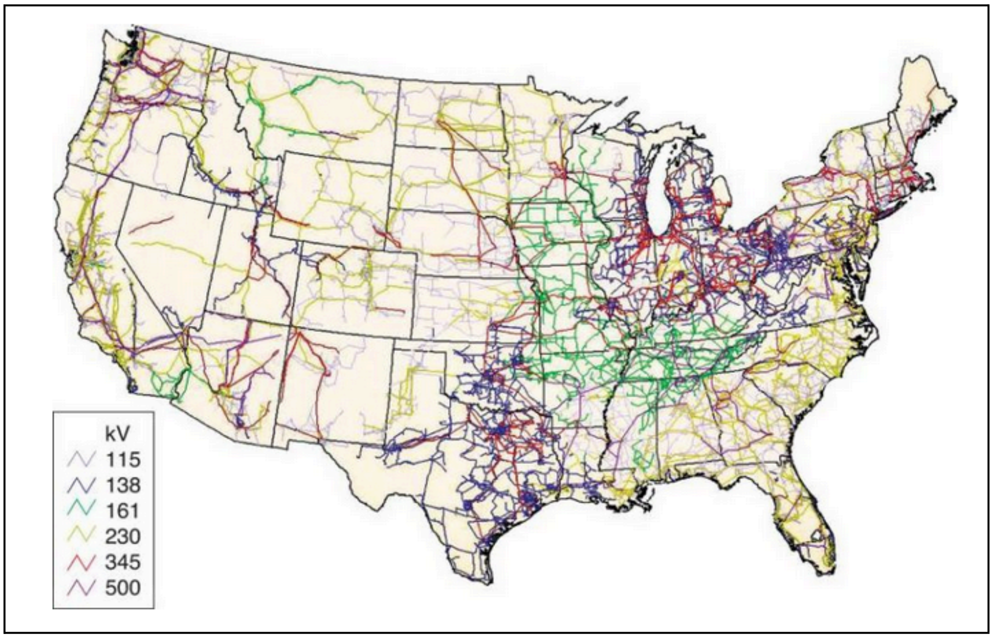


Figure 2: U.S. Power Transmission Grid Network [7]

A substation interconnects elements of an electric utility's system, including generators, transmission lines, distribution lines, and neighboring utility systems. Substations also interconnect transmission circuits and provide transformation between the network of different voltages. The T&D networks may include more than one voltage level, based on the size and complexity of the substations. Substations are interconnected via transmission lines, which could be overhead lines or underground lines. At a high level, substations can be organized into 3 categories: generator substations that generate power, transmission substations responsible for power transfer among high voltage transmission lines, and distribution substations for local power distribution [4][8][9].

Substations can be further subdivided into more categories, as explained below [9]:

Substation Type	**Description**
Air Insulated Switchgear Substation	Utilizes primary substation equipment with terminals in the air. Requires large clearances and occupies significant land area.
Gas Insulated Switchgear Substation	Uses solid or gaseous (SF6) insulation, reducing clearances and saving space, suitable for high voltage substations in urban areas.
Transmission Substation	Supports the transmission system and sectionalizes circuits during faults. Contains circuit breakers for switching circuits.
Subtransmission Substation	Converts high-voltage transmission lines to intermediate voltage sub-transmission lines or switches sub-transmission circuits.
Distribution Substation	Located in load areas, reduces voltage to distribution levels. Contains power transformers, circuit breakers, and voltage regulation.

Substation components can range from large high-voltage transformers to smaller components such as switchboards. Modern day substations rely heavily on electronic technologies such as high-voltage direct current transmitters (HVDC), thyristor controlled series compensators (TCSC), static VAR compensators (SVC), and so forth [10]. With such a vast system of interconnected nodes, threats to the stability of this network come in many forms, natural hazards being of particular note. The complexity of these components makes substations extremely vulnerable to extreme temperature events, even more so considering that many of them are situated above ground and are mostly unprotected. These events are projected to increase within the next few decades. With global climate change causing more frequent extreme weather events and prolonged heat waves, understanding how power grids are affected is crucial to designing resilient systems that withstand these challenges [11].

CLIMATE CHANGE TRENDS

Over recent years, overall average temperatures across the globe have been increasing, leading to an increased number of heat waves lasting for a longer duration. Global warming is the cause of increased heat stress around the world. Historical and projected data suggest that high temperatures caused by heat dome-like events are increasing in intensity at a higher rate than the average global temperatures. Daily Maximum Near-surface Air Temperature (TX), can be used as a simple heat indicator to analyze trends [12].

The polar vortex is a low pressure area with cold air that surrounds both of the Earth's poles. It is a region of winds that circulate from west to east in the stratosphere above the Arctic. When the vortex weakens, it can move south from the pole as warmer air moves north. It is known to weaken in summer with rising temperature and strengthen in winter, with falling temperatures. The overall increase in global temperatures is causing disrupted polar vortexes, areas of low pressure and cold air surrounding both of Earth's poles, spreading the reach of polar vortexes closer to the southern states in the U.S. [13].

Some climate models suggest weakening polar vortexes with global warming and rising temperatures. This will lead to colder winters in targeted areas, also indicating a connection between low sea ice extent in the Barents and Kara Seas of the eastern Arctic, sudden stratospheric warming events, and cold winters in North America [14].

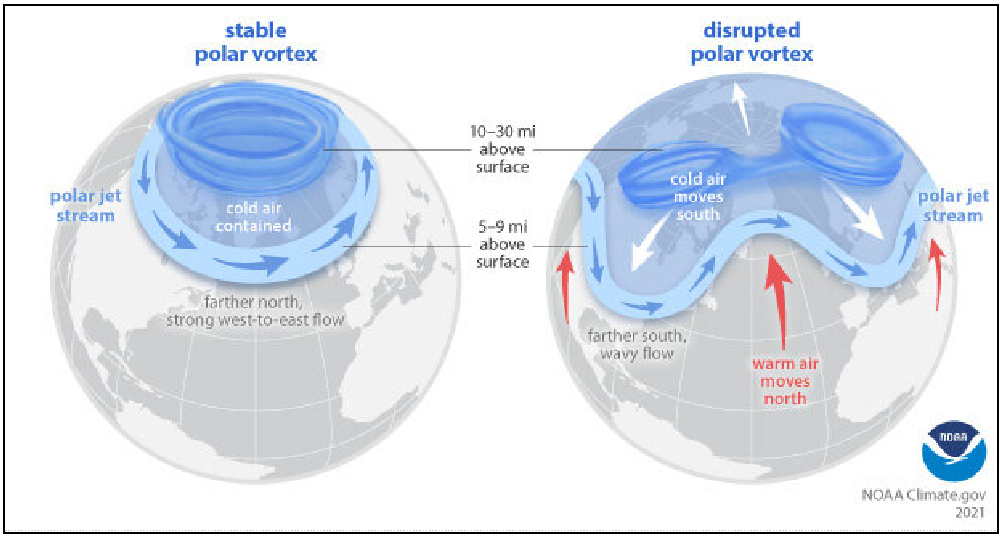


Figure 3: Polar Vortex [14]

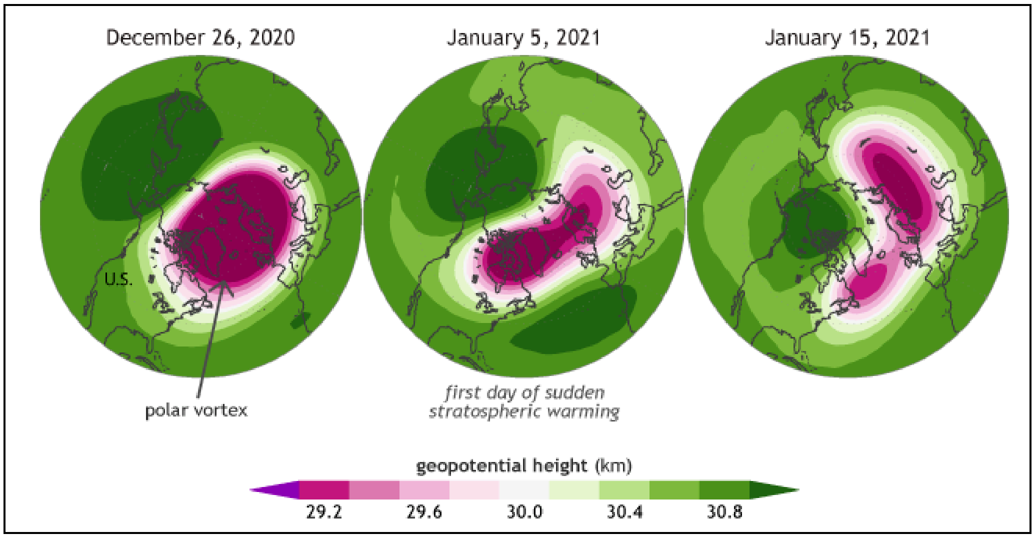


Figure 4: Disruptions in Polar Vortex [14]

CLIMATE CHANGE IMPACTS TO POWER NETWORKS

Changes in extreme climate and weather events have been increasingly observed since 1950. Climate change research shows strong linkage between extreme climate events and the human contribution via the greenhouse gases in the earth's atmosphere. Climate-related extremes, such as heat waves and cold waves droughts indicate significant vulnerability to climate change as a result of global warming. Specifically, events such as heat waves (periods of excessively hot weather and high humidity), and cold waves (periods of excessively cold temperatures) are projected to increase with climate change and both propose a threat to T&D infrastructure [15].

As the frequency of weather-related extreme events is increasing, infrastructure becomes the first line of defence for protection, especially during conditions such as flooding, storms, extreme cold and heat, wildfires and so forth. However, our infrastructures are most vulnerable as well, as these are designed based on historical conditions pertaining to Earth systems, which are rapidly changing with time [16].

The occurrence of heat waves in major cities across the United States has increased from an average of two heat waves per year during the 1960s to more than six per year during the 2020s, with the average heat wave season across 50 major cities being 49 days longer than it was in the 1960s [17].

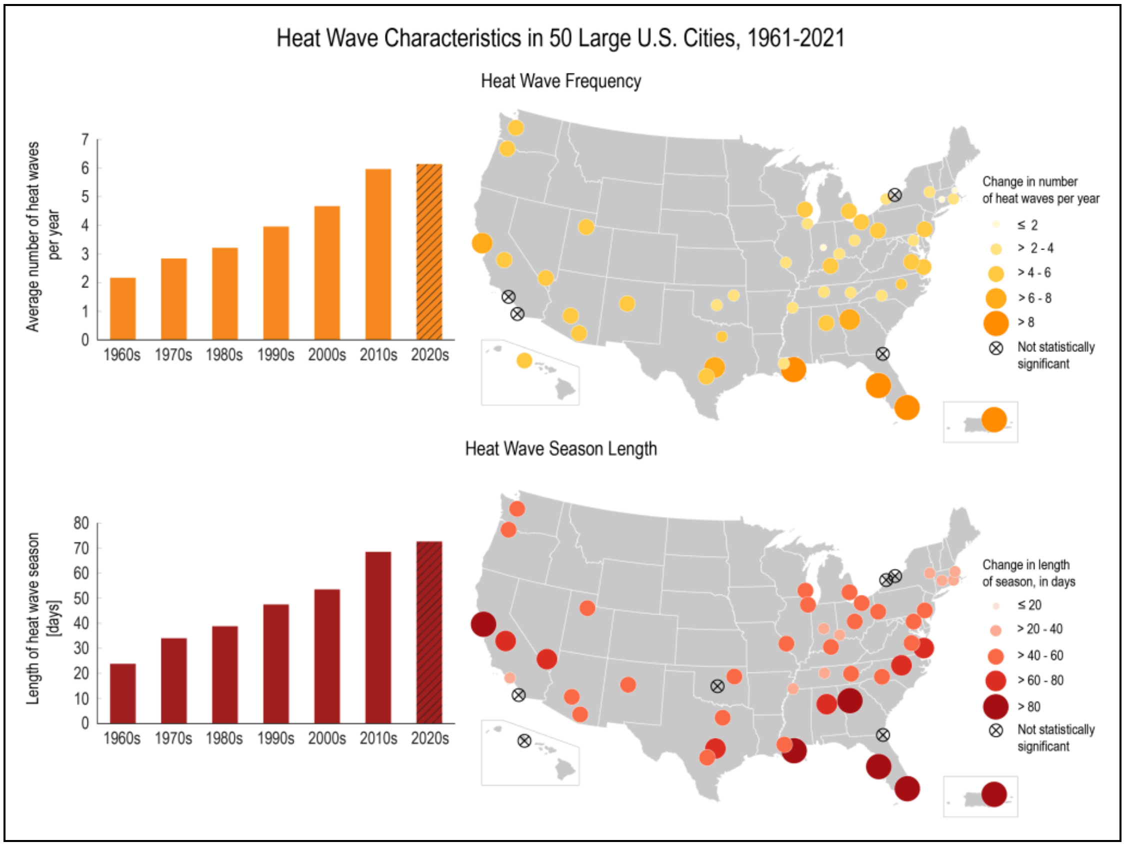


Figure 5: Heat wave recorded over decades in United States [17]

This makes it essential to understand the impact of extreme climate change scenarios on the power grid. Heat waves not only increase electricity peak load, but also cause reduced transmission capacity and generator functionality. This equates to output decline, just when their output electricity demand increases. This could cause severe power systems operations issues [18].

The capacity of transformers decreases by 1% for each °C; in copper lines the temperature of the resistance increases by 0.4% for each °C. Hence, total network losses increase 1% for every 3 °C. Similarly, cold waves, including freezing rain impact the energy sector causing breakdowns in power plants, generation and transmission failures, specifically damaging transmission lines insulation [19].

A study pertaining to impacts of extreme weather in Los Angeles County predicts loss of up to 20% safe operating capacity for generators, substations and transmission lines due to extreme heat exposures by 2060 [20]. Similar study on western U.S. pegs reduction in summer time power generation capacity by 1.1% to 3.0%, with the reductions going up to 8.8% in the worst case scenario of a ten year drought [21].

REVIEW OF EXISTING STUDIES

There have been numerous studies attempting to quantify the impacts of climate change on T&D infrastructure. However the variation between climate projections, modeling limitations and the regional bias of research interests, and broader categorization of power networks have led to a lot of uncertainties and gaps in these studies [22].

Unfortunately, the majority of prior studies have simply treated substations as simply points on a map rather than mapping at the component level, making it difficult to analyze impacts on the substation level. Another common trend is that many studies have opted to focus on impacts that affect the power lines themselves [23]. A plethora of research projects have also been focussed on impacts on energy generation using sources such as wind, solar, hydro and nuclear, but they do not analyze and aggregate the impacts at components level. Similarly, a study on the complex cyber-physical systems concisely summarizes the current research in those areas, highlighting the lack of mathematical modeling and different optimization methods [24].

SOURCE DATASETS

Climate changes over the past relate to a variety of environmental factors, both physical and biological, interjected with man-made variables. Climate models aim to simulate the regions, land and sea along with physical, chemical and biological variables to generate future climate projections, based on the past [25].

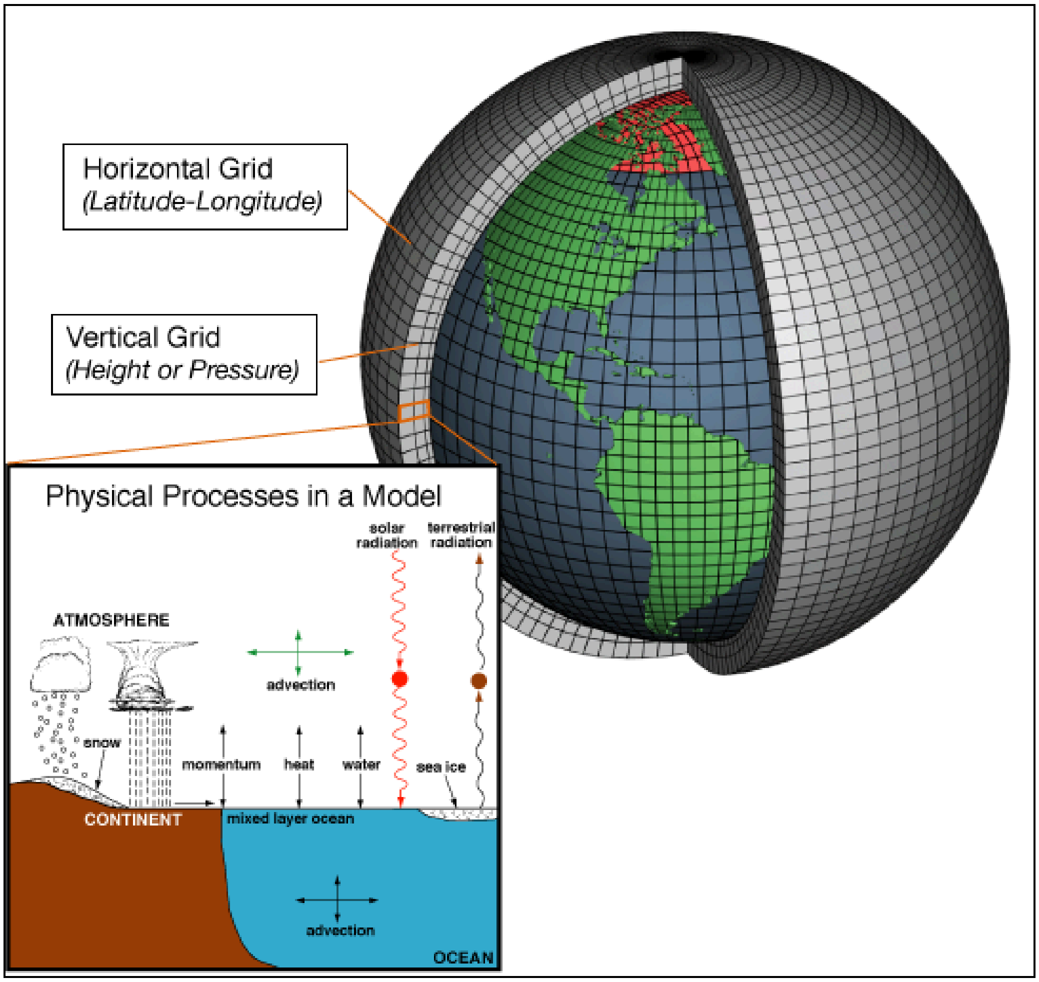


Figure 6: Climate model concepts at a high level [26]

The disparate efforts for studying outputs of coupled atmosphere-ocean circulation models are aggregated into a standard experimental framework, CMIP. A World Climate Research Program (WCRP) initiative, CMIP framework provides a common platform to assess climate models strengths and weaknesses, which will allow better development of future models [27]. A core objective of CMIP is to better understand and articulate past, present and future climate changes in relation to natural, geological as well as man-made impacts, assessing various models performance and accuracy on historical data, and quantifications for future projections spreads. An important goal of CMIP is to make this multi-models output data available freely and publicly in a standardized format [28].

CMIP version 6 (CMIP6) is the latest CMIP version that has its modeling output data available for public use. The CMIP6 Data Request consolidated data requirements from 23 Model Intercomparison Projects into a single database, available as xml through python packages, and can be browsed or queried online, and downloaded as data files [29]. CMIP6 encompasses runs from over 100 distinct climate models such as CESM, CanESMS, CIESM, EC-Earth3, MICRO6 and so forth, which are produced across 49 modeling groups [30].

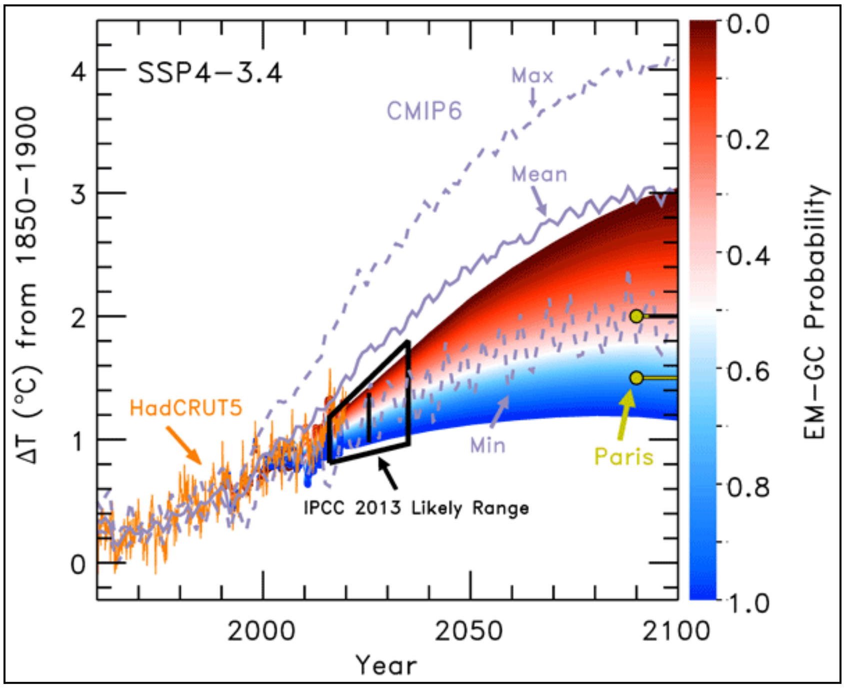


Figure 7: CMIP6 temperature changes over time projections [31]

CMIP scenarios, referred to as Shared Socioeconomic pathways (SSPs), represent changes in factors such as population, economic growth, urbanization and so forth. The numbers on SSPs represent the expected change in radiative forcing from the year 1750 to the end of the 21st century, 2100, e.g. SSP5-8.5. Different SSPs used in CMIP6 are as under [32]:

SSP	**RCP(s) associated with SSP**	**End of century CO2 ppm**	**Description**
SSP1	RCP 1.9 RCP 2.6	~390 ---	Sustainability: The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries.

SSP2	RCP 4.5	---	Middle of the road: The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns.
SSP3	RCP 7.0	---	Regional rivalry: A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues.
SSP4	RCP 3.4	---	Inequality: Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries.
SSP5	RCP 8.5	~1130	Fossil-fueled development: This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated.

This CMIP6 dataset is one of the two core datasets used in our study. CMIP6 daily maximum surface temperature projections for different substation coordinates spreading over the span of decades till 2100, are used for exposure calculations.

Another major dataset needed is the substations data, including their locations and components breakdown. This dataset is made available for the study by a novel application - The George Mason University (GMU) Power Grids Asset Survey Application, which is a web application published on github.io [33]. The application utilizes satellite and street view imagery for classifying and geolocating component-level assets within extra high-voltage substations. The ability to accurately differentiate components and spatially plot transmission and distribution assets allows for a more detailed analysis of the substations. The application dataset includes over 38,000 categorized components of over 1,300 substations in the United States. This is the second dataset that the study relies on.

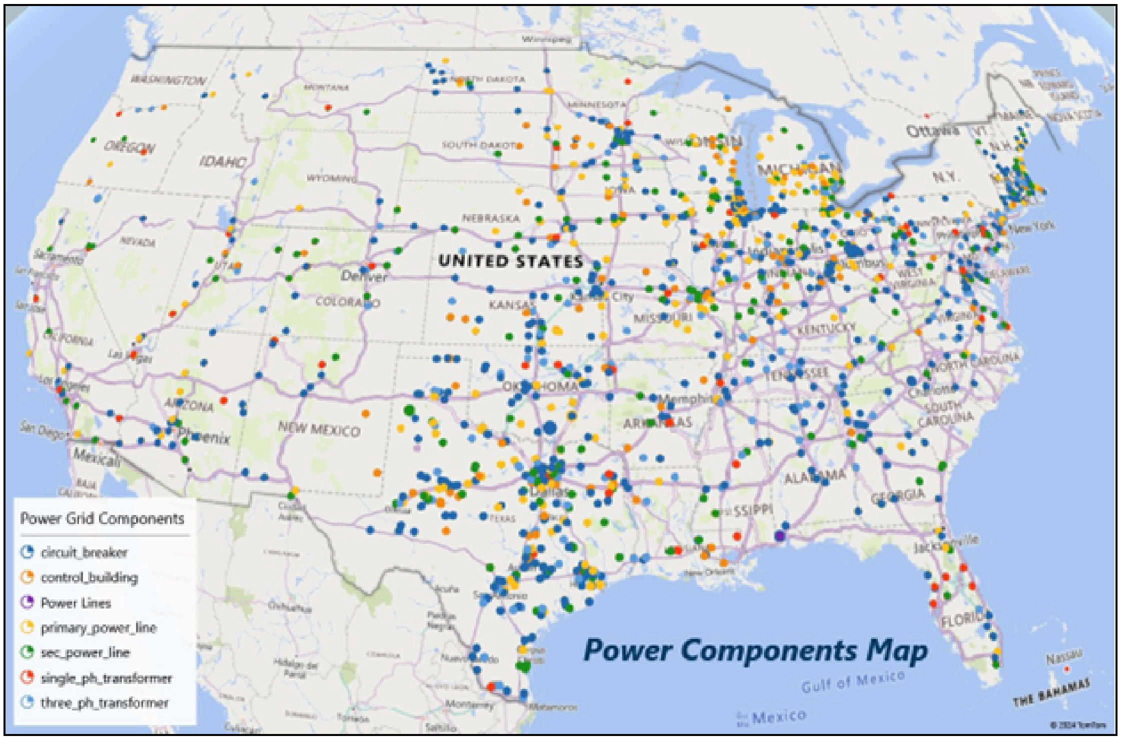


Figure 8: Power Components map

METHOD STEPS

Below are the method steps at a high level

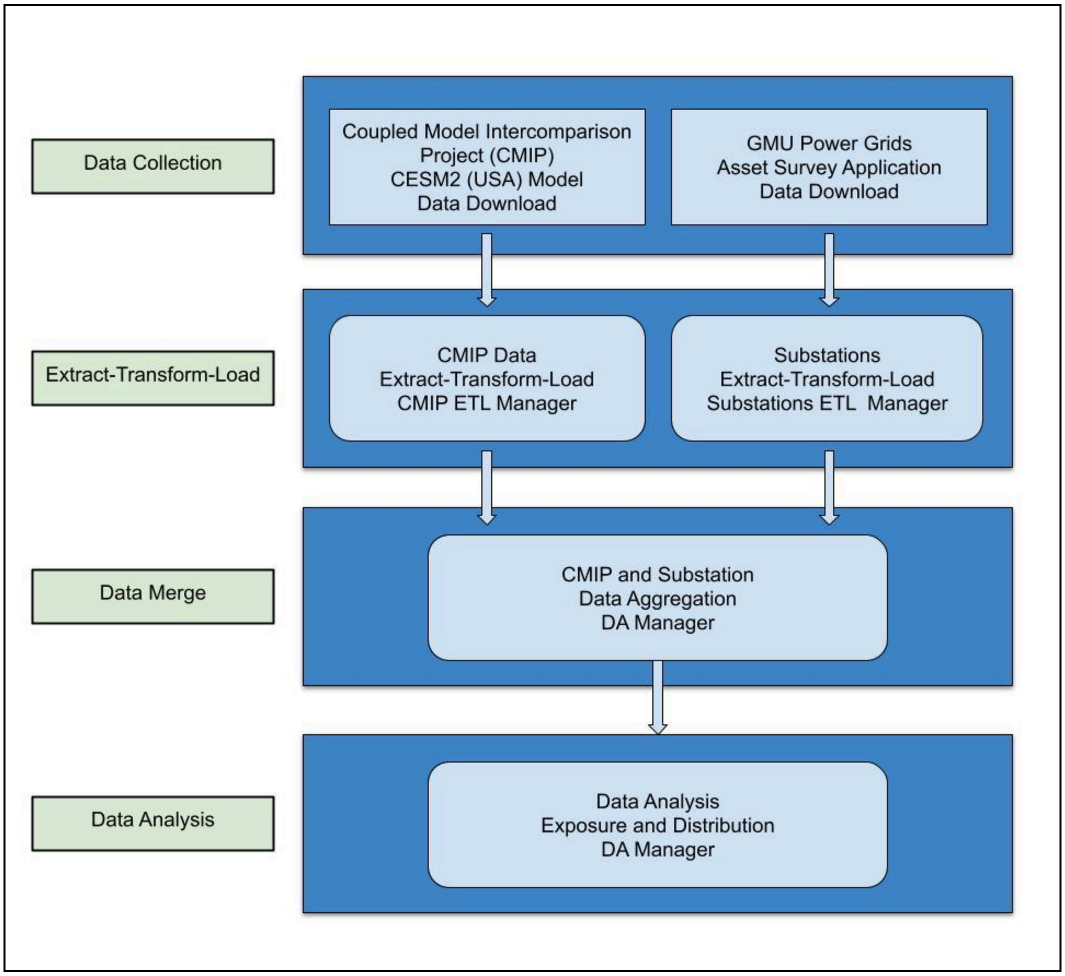


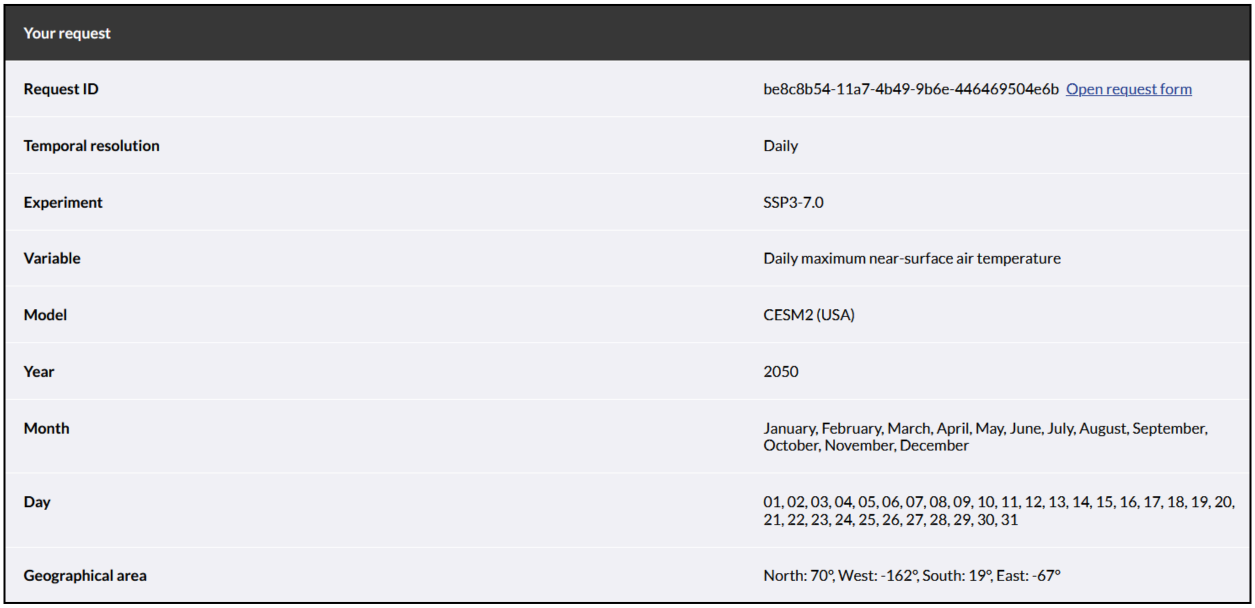
Figure 9: Study method steps

DATA COLLECTION

Copernicus Climate Data Store [34] is used as the data source for CMIP6 data. The site provides the ability to query the model based data via a web interface query page [35] as well as via service api calls. The data via the web interface is available for download on Copernicus request download page [36]. For our study, the Copernicus Climate Data Store query parameters used are as under:

Parameter Name	**Parameter Value**
Temporal Resolution	Daily

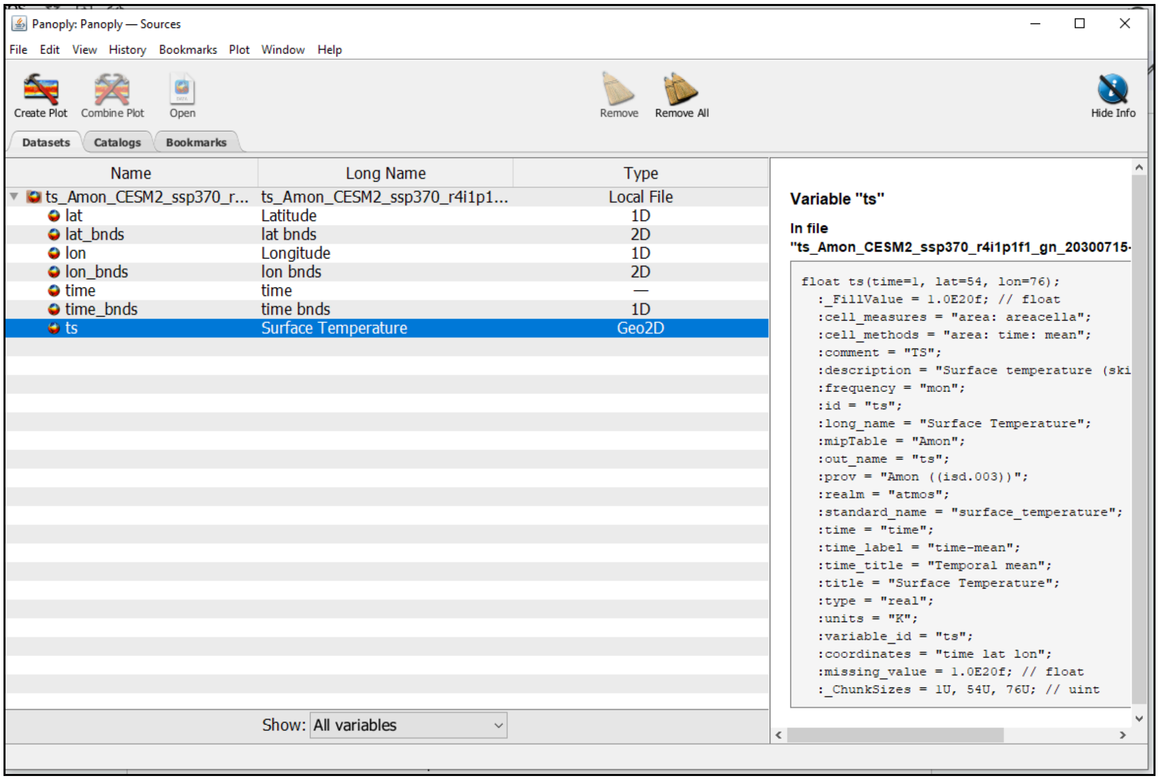
Experiment	SSP3-7.0
Variable	Daily maximum near-surface air temperature
Model	CESM2 (USA)
Year	<Varied years>
Month	<All Months>
Day	<All Days>
Geographical Area	U.S. (North: 70°, West: -162°, South: 19°, East: -67°)



Your request	
Request ID	be8c8b54-11a7-4b49-9b6e-446469504e6b Open request form
Temporal resolution	Daily
Experiment	SSP3-7.0
Variable	Daily maximum near-surface air temperature
Model	CESM2 (USA)
Year	2050
Month	January, February, March, April, May, June, July, August, September, October, November, December
Day	01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31
Geographical area	North: 70°, West: -162°, South: 19°, East: -67°

Figure 10: Copernicus Climate Data Store Request Page

The downloaded CMIP6 datasets are in the form of NetCDF (.nc) files. NetCDF (network Common Data Form) is a multidimensional scientific data file format that stores variables such as temperature, humidity, pressure, wind speed, and direction [37]. These .nc files cannot be consumed as is, as the substation data is in json format. So, the first step taken is to ensure that all the datasets are in a common format, the comma separated values (.csv) file format, a simple format for representing structured data [38]. To convert the .nc files into .csv files, we use a NASA GISS app, called Panoply [39], which is a cross-platform NetCDF, HDF and GRIB data viewer. The CMIP dataset files are converted into using the option ‘Export Labeled Text’ on the Surface Temperature time series.



Name	Long Name	Type
ts_Amon_CESM2_ssp370_r...	ts_Amon_CESM2_ssp370_r4i1p1...	Local File
lat	Latitude	1D
lat_bnds	lat bnds	2D
lon	Longitude	1D
lon_bnds	lon bnds	2D
time	time	—
time_bnds	time bnds	1D
ts	Surface Temperature	Geo2D

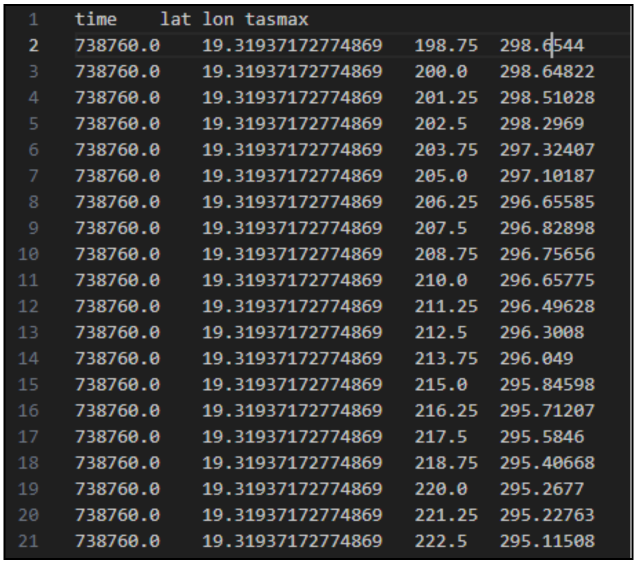
Variable "ts"

In file
"ts_Amon_CESM2_ssp370_r4i1p1f1_gn_20300715

```
float ts(time=1, lat=54, lon=76);
  :_FillValue = 1.0E20f; // float
  :cell_measures = "area: areacella";
  :cell_methods = "area: time: mean";
  :comment = "TS";
  :description = "Surface temperature (ski
  :frequency = "mon";
  :id = "ts";
  :long_name = "Surface Temperature";
  :mipTable = "Amon";
  :out_name = "ts";
  :prov = "Amon ((isd.003))";
  :realm = "atmos";
  :standard_name = "surface_temperature";
  :time = "time";
  :time_label = "time-mean";
  :time_title = "Temporal mean";
  :title = "Surface Temperature";
  :type = "real";
  :units = "K";
  :variable_id = "ts";
  :coordinates = "time lat lon";
  :missing_value = 1.0E20f; // float
  :_ChunkSizes = 1U, 54U, 76U; // uint
```

Figure 11: Panoply application viewer window for CMIP6 dataset .nl file

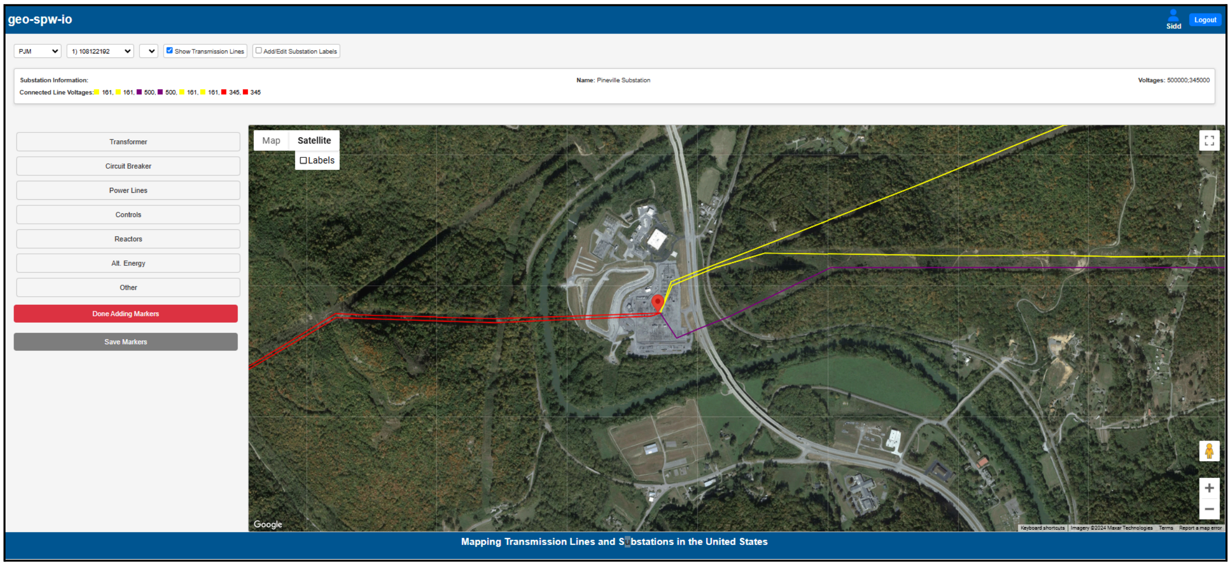
The exported data is a text file, which is in raw format. No comma delimiter exists for the rows, and this needs to be tweaked. This process of downloading the CMIP data in form of the .nl files and then exporting the text using Panoply application is done for all data point years (2025 - 2030 and then in multiples of 5 till year 2100). This gives the study a substantial data set to make meaningful analysis. A data sample is as under:



```
time     lat lon tasmax
738760.0    19.31937172774869   198.75   298.6544
738760.0    19.31937172774869   200.0    298.64822
738760.0    19.31937172774869   201.25   298.51028
738760.0    19.31937172774869   202.5    298.2969
738760.0    19.31937172774869   203.75   297.32407
738760.0    19.31937172774869   205.0    297.10187
738760.0    19.31937172774869   206.25   296.65585
738760.0    19.31937172774869   207.5    296.82898
738760.0    19.31937172774869   208.75   296.75656
738760.0    19.31937172774869   210.0    296.65775
738760.0    19.31937172774869   211.25   296.49628
738760.0    19.31937172774869   212.5    296.3008
738760.0    19.31937172774869   213.75   296.049
738760.0    19.31937172774869   215.0    295.84598
738760.0    19.31937172774869   216.25   295.71207
738760.0    19.31937172774869   217.5    295.5846
738760.0    19.31937172774869   218.75   295.40668
738760.0    19.31937172774869   220.0    295.2677
738760.0    19.31937172774869   221.25   295.22763
738760.0    19.31937172774869   222.5    295.11508
```

Figure 12: Data exported as text from the CMIP .nl file by Panoply application

The GMU Power Grids Asset Survey Application, which is a web application, gives access to the vast array of substation data at component level. This data can be downloaded from the published app, for which the authors have been granted access.



PJM
1) 108122192
☑ Show Transmission Lines
☐ Add/Edit Substation Labels

Substation Information:
Connected Line Voltages: 🟨 161, 🟨 161, 🟪 500, 🟪 500, 🟨 161, 🟨 161, 🟥 345, 🟥 345
Name: Pineville Substation
Voltages: 500000;345000

Figure 13: GMU Power Grids Asset Survey Application

The downloaded data has .csv files for the substations data with their location and subcomponents, line voltages and other attributes such as the attributes related to transmission lines and the requisite substations mapping [40].

Data Extract-Transform-Load (ETL)

A major component of our study is our HEVAM application, written in Python [41] as a part of our study. Our study has published this application code on Github [42], and made it freely available for use.

HEVAM application emcompasses the ETL processor, along with a data analyzer. ETL is a software concept of extracting data from different data sources, transforming it into a consistent data set for storage and loading it for analysis [43]. The HEVAM application converts the downloaded CMIP data sets and Substations data sets into actionable data sets, using ETL techniques. HEVAM application relies on advanced data sets processing libraries, Pandas [44] and NumPy [45].

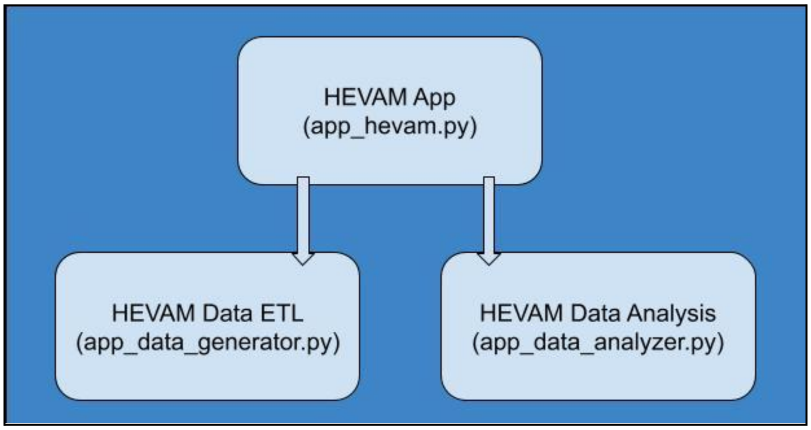


Figure 14: HEVAM Application class diagram

The etl generation involves converting the text based CMIP data sets into csv files with proper conversion of coordinates and temperature, and mapping of substations data with substations components. The data generator also maps the substation coordinates to the CMIP data coordinates, so that the temperatures and exposure can be calculated for the time periods.

DATA MERGE INTO ACTIONABLE DATASETS

The task of data merge for actionable data sets is done by data analyzer module that invokes the relevant processors for various subtasks, such as caching of the substations CMIP coordinates mapping, exposure calculation for different CMIP data sets, and aggregation into combined substations CMIP exposure csv for final analysis.

DATA ANALYSIS AND INFERENCE

The substations data allow for breakdown of components to understand how they stack up in substations. Below is the components stack for power stations based on geographical distribution.

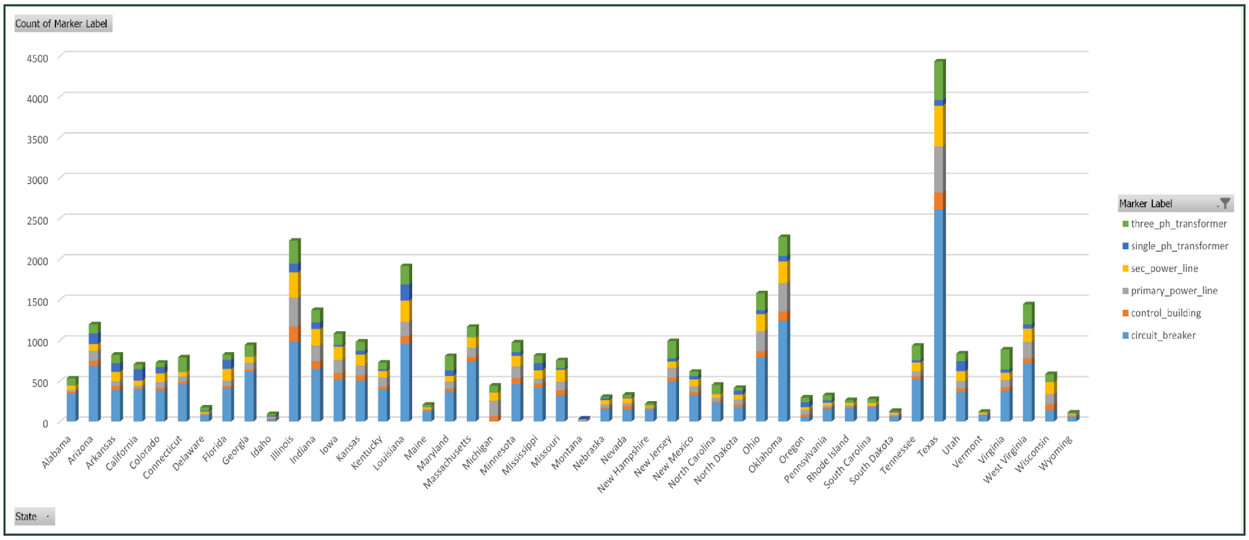


Figure 15: Components breakdown by geographic regions

Similarly, the voltage classes map based on the power grids data set is analyzed under:

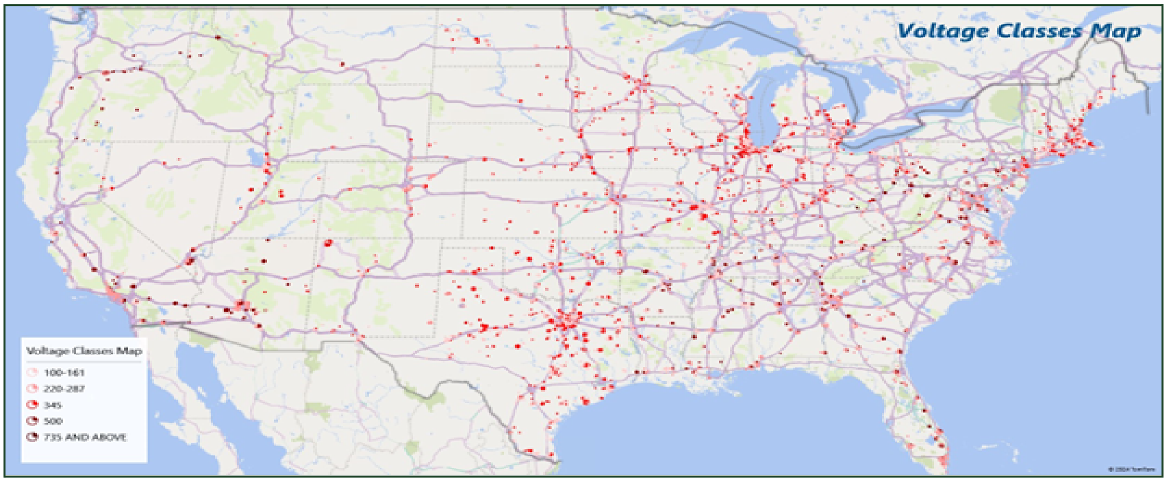


Figure 16: Voltage classes distribution

Here is the heat map spanning over half decades till 2050.

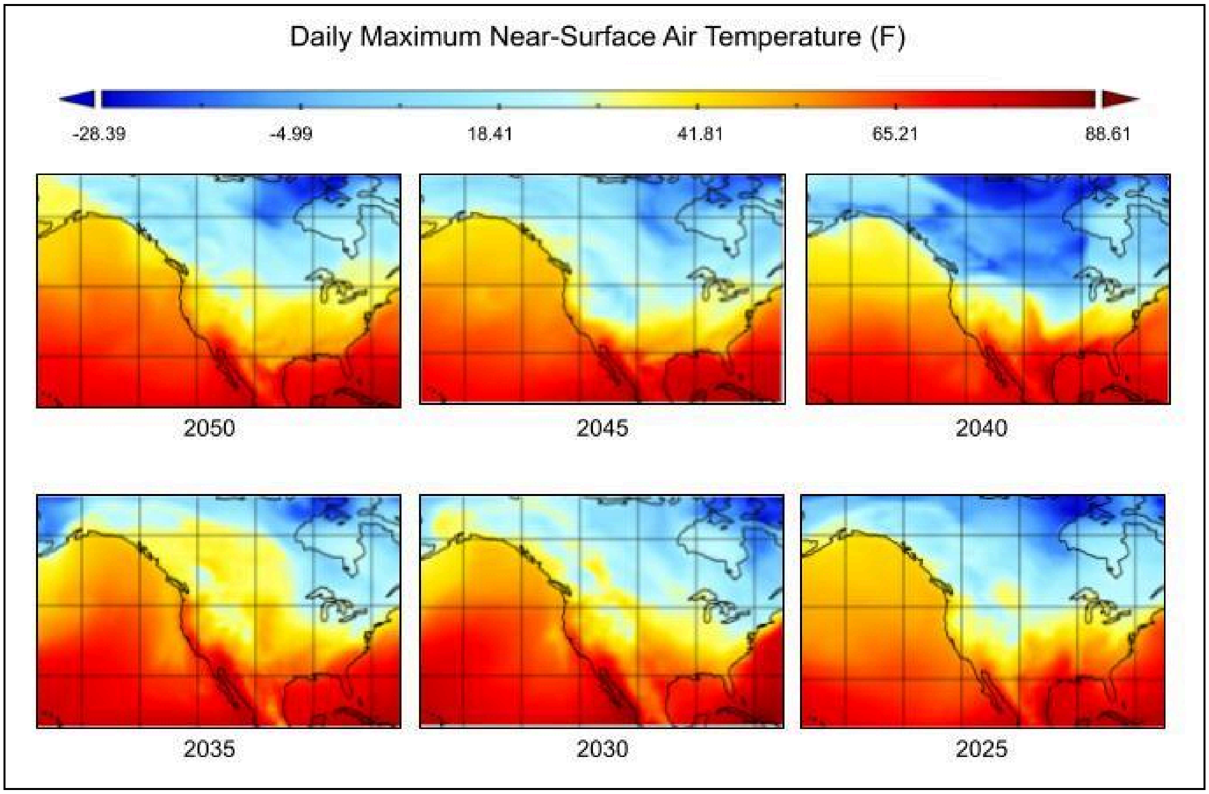


Figure 17: Heat map over U.S. over time

Heat Exposure per state is charted below as under in the study time frame:

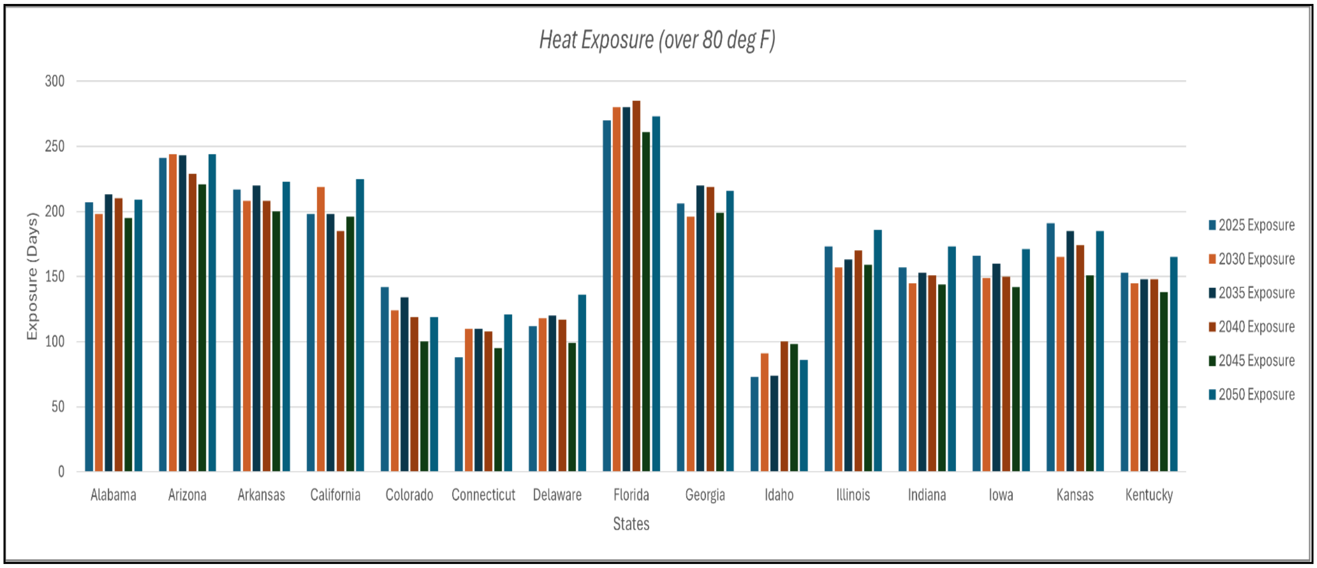


Figure 18: Heat exposure (over 80 deg F) by states A - K, over time

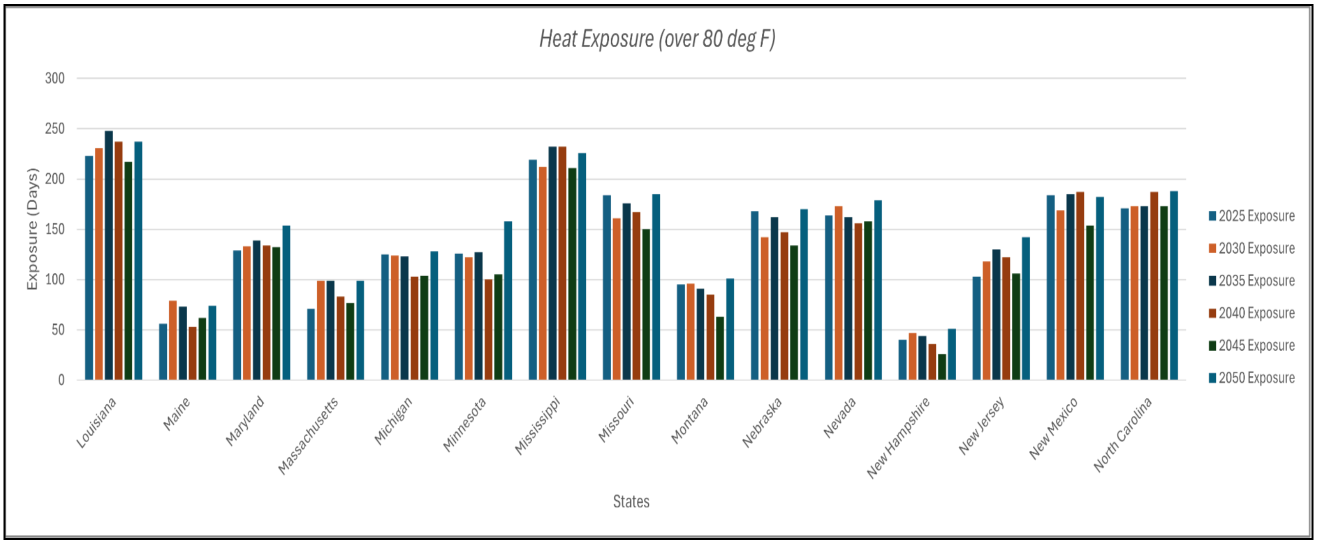


Figure 19: Heat exposure (over 80 deg F) by states L - NC, over time

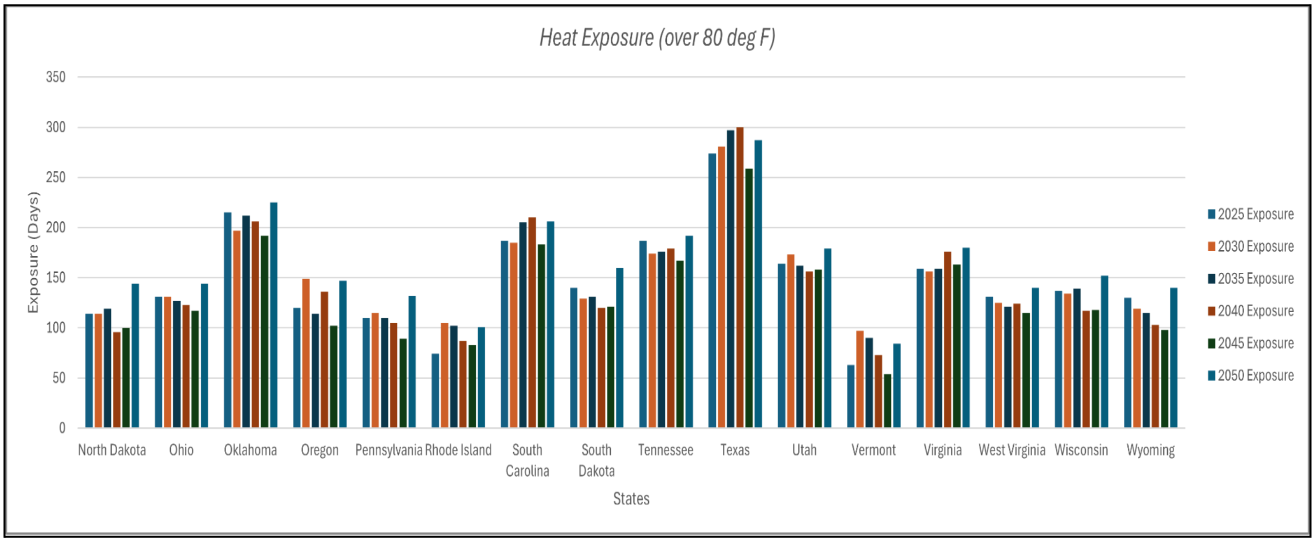


Figure 20: Heat exposure (over 80 deg F) by states ND - W, over time

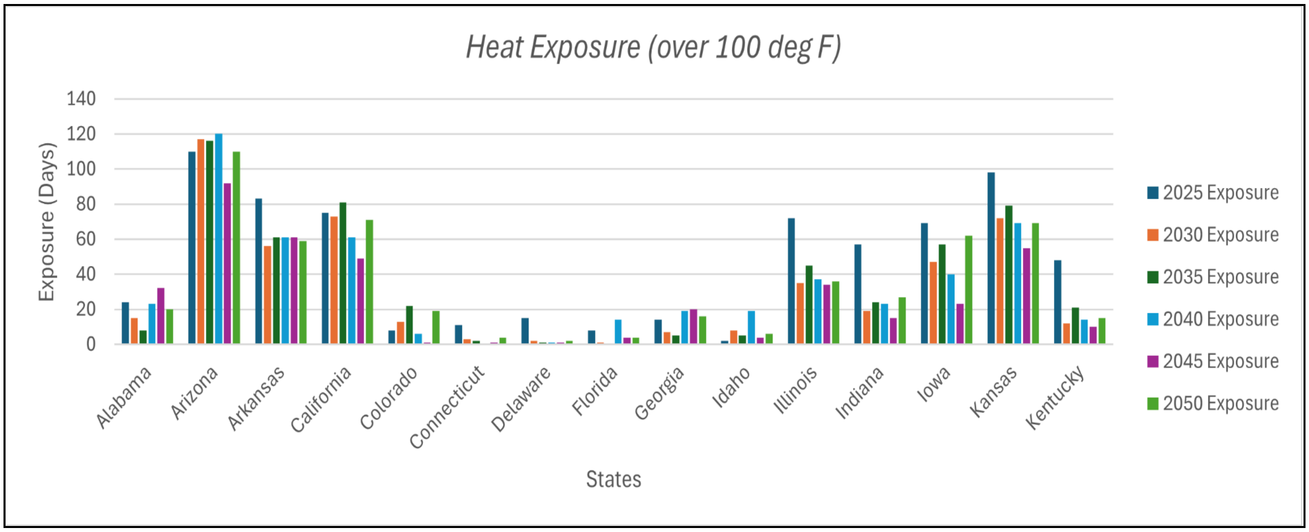


Figure 21: Heat exposure (over 100 deg F) by states A - K, over time

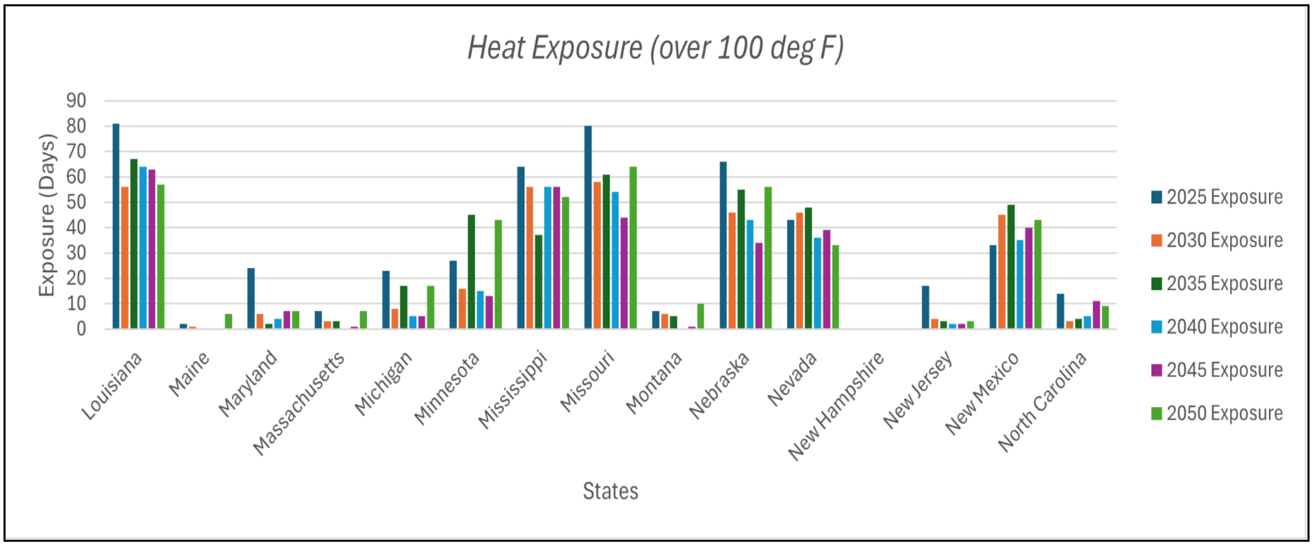


Figure 22: Heat exposure (over 100 deg F) by states L - NC, over time

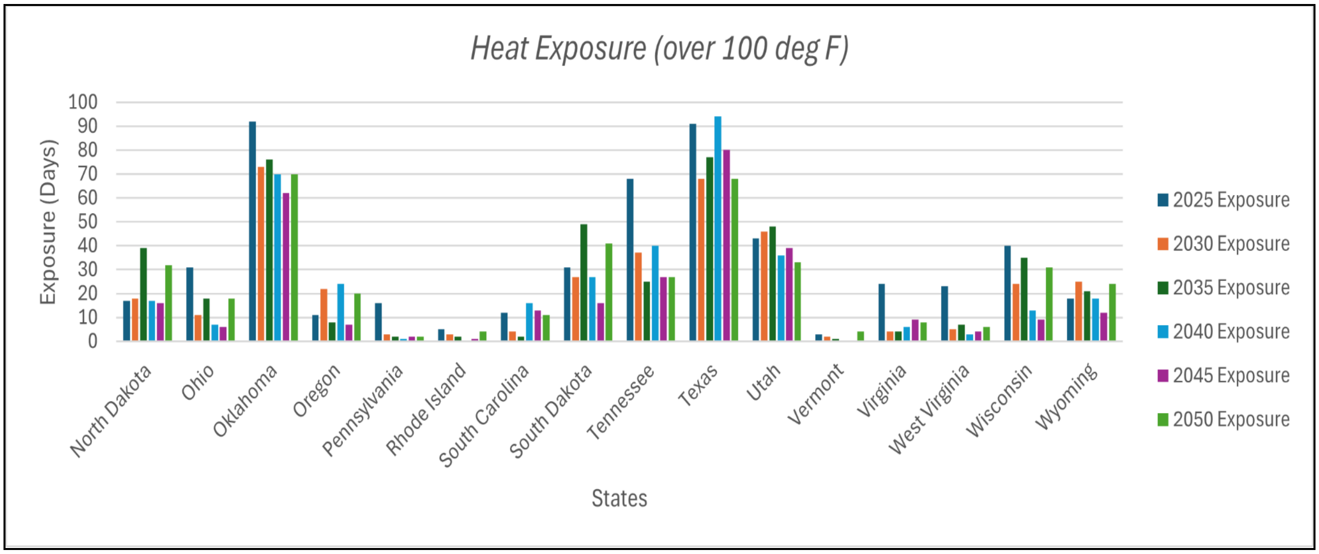


Figure 23: Heat exposure (over 100 deg F) by states ND - W, over time

The impact of the rise in exposure is extra stress on the power grids. As the temperature rises, the energy consumption for heating/cooling increases. Dose-response curve quantifies degradation of service in response to extreme heat exposures [46].

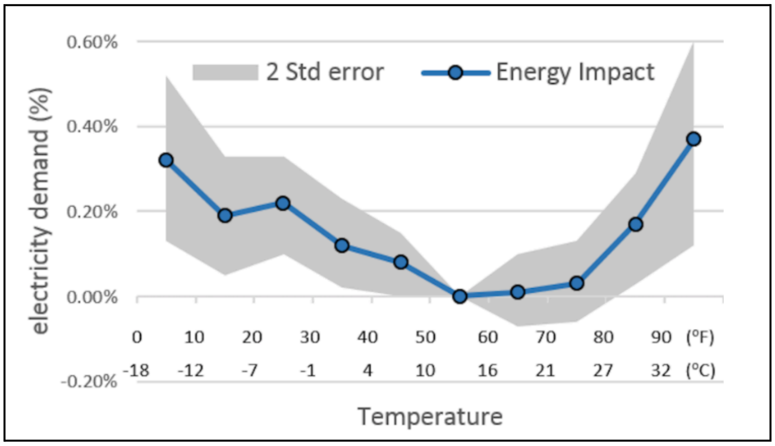


Figure 24: Impact of extreme heat exposure on energy consumption [46]

Heat exposure accelerates component failures. The below graph tracks accelerated cable aging due to extreme heat [47].

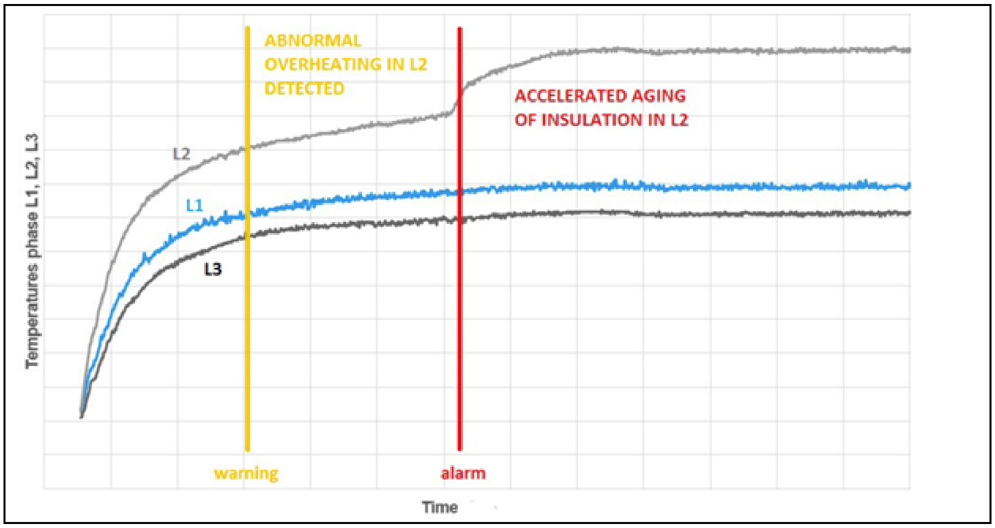


Figure 25: Insulation cable failure rates with heat exposure over time [47]

Capacitor banks are responsible for providing reactive power support to grids for maximum power transfer. Their failure rates are directly proportional to extreme temperature exposures. Another indirect reason is overvoltage and failure due to increased load [48].

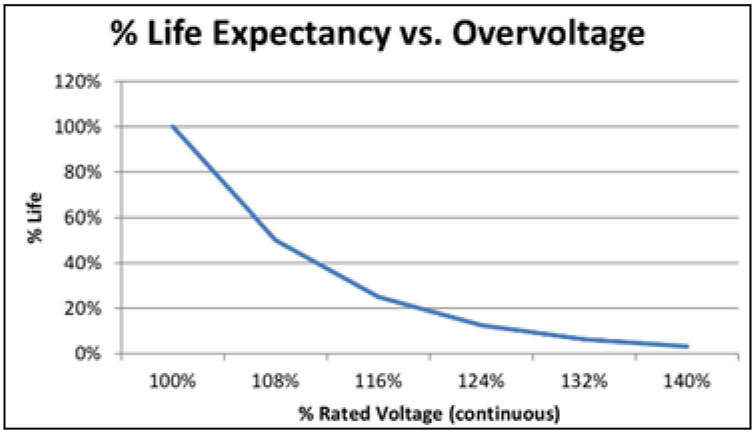


Figure 26: Failure rates of capacitor banks in relation to heat exposures [47]

One of the core components of power stations, the Power Transformers are directly impacted by the ambient temperatures, and as such, extreme heat exposures. This is due to changes in coolant oil temperatures that are affected by external temperatures, resulting in transformer aging and sometimes even breakdown [49]. Thus heat will have a serious effect on the rating factor of the power transformer [50].

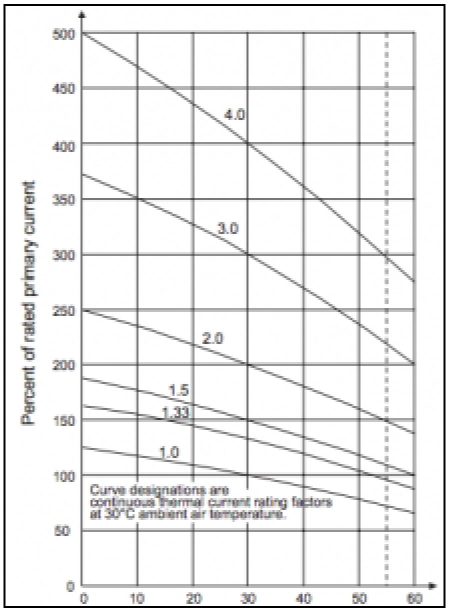


Figure 27: Power Transformer failure rate in relation to heat [50]

Another important power grid component, Thermal circuit breakers also need to be derated depending on the ambient temperatures. So from an electrical protection perspective, they carry a bigger risk as the ambient temperature rises [51].

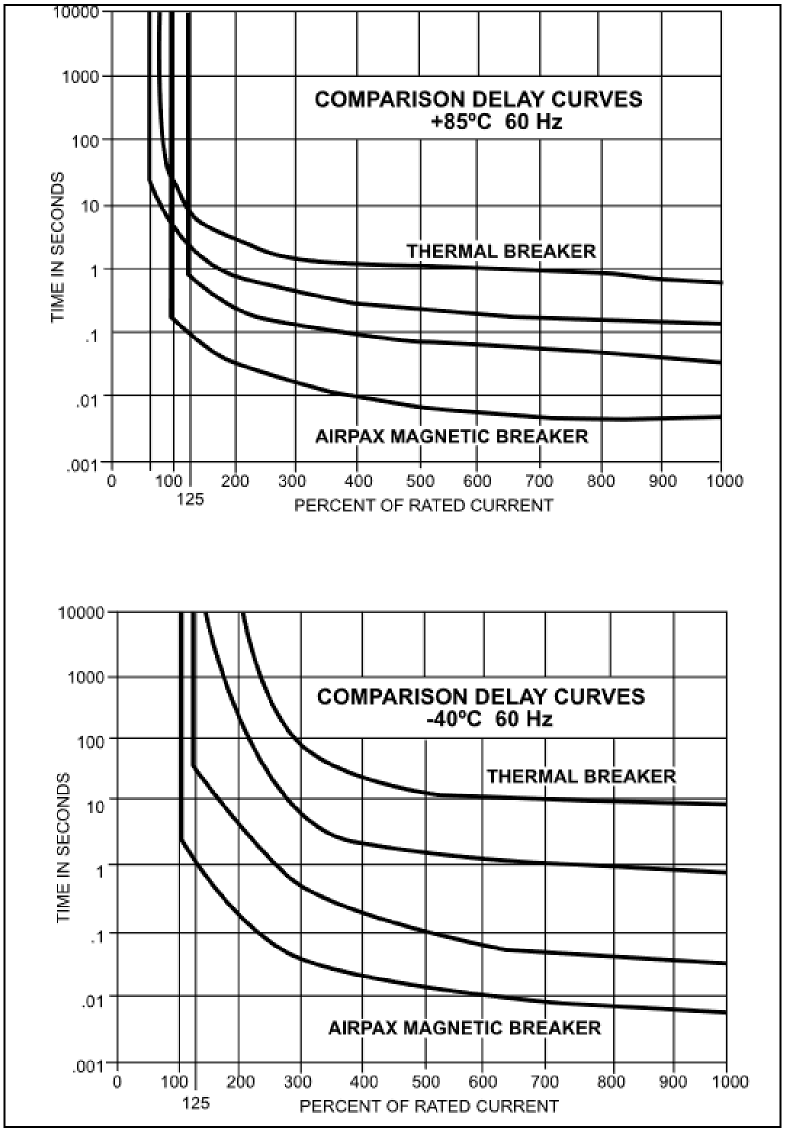


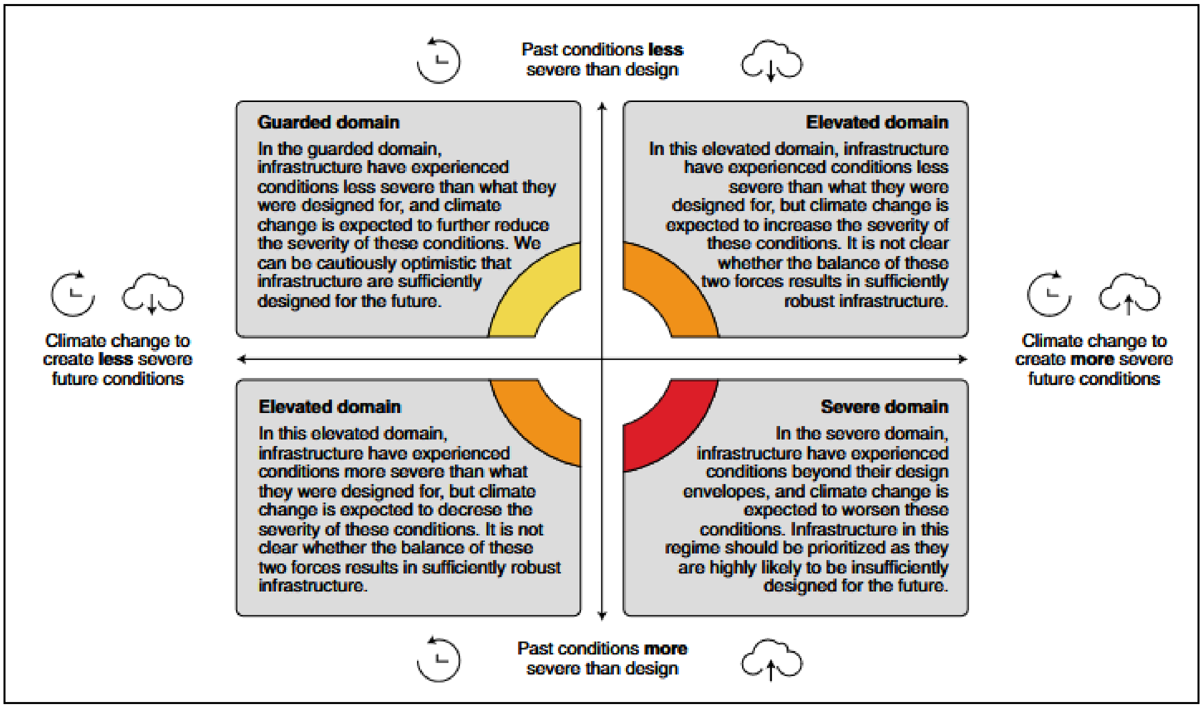
Figure 28: Thermal circuit breaker correlation with heat exposure [51]

CONCLUSIONS

Energy sector, namely U.S. Power grids, are the nation's and our economy’s backbone. Safeguarding them and mitigating exposure risks are critical for keeping the communities and for keeping our economy running. Our study incorporating climate change models predictions over the next 5 half-decades show higher exposure rates, possibility of larger number of occurrences of extreme temperatures, and for longer durations. This certainly poses a challenge for the power grid generation components, transmission and distribution components, as their failure rates increase with higher exposure rates.

Our study also draws out the increased failure rates of substation components such as power transformers, thermal circuit breakers and so forth, and ties them to locations across the U.S. over the half-decades timeline till 2050. This allows us to study regions' specific impact at subcomponents level due the temperature changes over time.

This provides substantial insights into making and planning infrastructure investments over the long term to account for such vulnerabilities. Similarly, public policies embracing theories such as the complex adaptive system theory to development of national system-of-systems models [2], these insights greatly shape such policies and decision-making. The findings also assist in mitigating risk in infrastructure decision making based on uncertainties, as depicted below:



Guarded domain
In the guarded domain, infrastructure have experienced conditions less severe than what they were designed for, and climate change is expected to further reduce the severity of these conditions. We can be cautiously optimistic that infrastructure are sufficiently designed for the future.

Elevated domain
In this elevated domain, infrastructure have experienced conditions less severe than what they were designed for, but climate change is expected to increase the severity of these conditions. It is not clear whether the balance of these two forces results in sufficiently robust infrastructure.

Elevated domain
In this elevated domain, infrastructure have experienced conditions more severe than what they were designed for, but climate change is expected to decrease the severity of these conditions. It is not clear whether the balance of these two forces results in sufficiently robust infrastructure.

Severe domain
In the severe domain, infrastructure have experienced conditions beyond their design envelopes, and climate change is expected to worsen these conditions. Infrastructure in this regime should be prioritized as they are highly likely to be insufficiently designed for the future.

Figure 29: Role of past and future climate uncertainties in Infrastructure domains [52]

FUTURE RESEARCH

While the current project elaborates on the heat maps and exposure rates over half decades, and relates them to the power grid substation components failure rates, this establishes a baseline for studying the vulnerability of power grids to extreme temperatures. It is imperative to take this analysis and convert this into actionable insights, both from engineering as well as from a policy perspective.

Future research can be done on the mitigation techniques to reduce the risk and failure rates of the power grid components over time and rising temperatures. This can also influence future policy decisions in regards to safeguarding national interests in the energy sector. Studies such as the National Infrastructure Systems Model Risk and Vulnerability (NISMOD-RV) integrate planning models for energy, transport, water supply and so forth, highlighting interdependencies in these sectors and the risks of infrastructure failure [53]. Such studies can be augmented with inputs for our study for regional analysis and resilience investments.

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Siddha Bambardekar voluntarily undertook this research as part of George Mason University's Aspiring Scientists Summer Internship Program (ASSIP). Edward Oughton gratefully acknowledges funding from (i) the NSF National Center for Atmospheric Research via the Early-Career Faculty Innovator Program (#1852977), and (ii) the ChronoStorm NSF RAPID grant (#2434136), co-funded by the GEO/AGS Space Weather Research and the ENG/CMMI Humans, Disasters, and the Built Environment programs.

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