# Spatio-Temporal Insights into Recent Electricity Outages in the U.S.: Drivers, Trends, and Impacts

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***Abstract*—Electrification is known as the greatest engineering achievement in the 20st century, as its drives our daily lives and the operation of mission-critical systems and services. Any disruption in the electric power delivery infrastructure could impose catastrophic economical, social, environmental, and political consequences. Even though there are concerted efforts to mitigate or predict the power outages that may lead to larger-scale blackouts, the data made available by the U.S. Department of Energy (DOE) during 2015-2022 on electric emergency incidents and disturbances in the U.S. indicate that there is an increase in frequency and duration of power outages across the country. In this paper, we discuss a user-friendly visualization tool, a power grid outage dashboard, that sheds some lights on the patterns behind, regional vulnerability, and impacts of these outages. The developed dashboard helps in decision-making on the future allocation of funds and reinforcement investments to tackle the power outages in an effort to build a more reliable power system. Several examples indicate the importance of finding better forecasting and mitigation techniques for power system outages driven by some particular events and in different geographical regions across the U.S.**

***Index Terms*—interrupted customers, NERC regions, outage causes, outage impacts, outage trends, power outages.**

## I. Introduction

Electric power systems worldwide are being revolutionized by the growing digitalization and penetration of new technologies such as wide-area monitoring systems (WAMS) and a variety of renewable energy resources (e.g., solar and wind) with complex control procedures [1]. While such investments on grid modernization are primarily targetted to improve the power grid situational awareness, operational efficiency, and the reliability of the electric service delivery to end-use consumers, we have been observing an increase in the frequency and duration of electricity outages in the U.S., in some cases resulting in catastrophic blackouts. While the increased complexity of the system operation and control, random equipment failures, protective relay's miss-operations, and now-and-then cyber adversaries are all contributing to power outages, the climate change-driven severe weather events (e.g., hurricanes, storms, and extreme temperature) are found to be the major driver of the electricity outages in the U.S. [2], [3]. The recurrent power outages and blackouts in recent years calls for new solutions, tool, and decision-making platforms for a variety of stakeholders to help enhance the reliability and resilience of the electric power systems against power outages in general and extreme weather events in particular.

Reference [4] proposed a two-stage restoration scheme to facilitate the distribution system restoration following the high-impact low-probability (HILP) seismic disasters. Furthermore, [5] introduced an advanced model predictive control (MPC) based scheme to control the distributed energy resources (DERs), minimize the impact of transients and disruptions, speed up the response and recovery of particular system functions, and maintain an acceptable operational reliability. In [6], a multi-objective mixed integer linear programming optimization problem was formulated to minimize the amount of load curtailments and generation operation costs when a power system is impacted by a hurricane while adhering to system operational and technical constraints.

With the increased frequency of power outages, their prediction has attracted some research attention as emerging technologies became abundantly available such as high-resolution measurements from phasor measurement units (PMUs) and the growing developments in data-driven online optimization and machine learning (ML) techniques. For instance, [7] proposed a framework that predicts power outages based on the current weather conditions using graph neural networks (GNNs). In addition, [8] utilized a satellite-based Visible Infrared Imaging Radiometer Suite (VIIRS) night light data product as a surrogate for the power delivery to predict hurricane-induced power outages in areas having limited access to historical data records. Also, [9] proposed a data-driven model to predict the number of distribution network users that may experience power outages when a typhoon passes by.

With all the abundant research efforts and developments to mitigate and predict power outages, the U.S. Department of Energy's (DOE) Electric Disturbance Events Annual Summaries (OE-417) [10] have evidenced an increase in the frequency of power outages. Reference [11] indicated that the frequency of large blackouts in the U.S. is not decreasing from 1998 to 2006. Reference [12] provided a comprehensive analyses of large-scale power outages in the U.S. from 2002 to 2019, where it discussed the power outage data in different states across the U.S. In this study, we report and discuss our recent developments in building a power outage dashboard that presents and visualizes the spatio-temporal trends in power outages across the U.S. and demonstrates the causes and the

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main drivers behind the power outages. Furthermore, in the developed dashboard, the number of affected customers as well as the amount of power outage with the corresponding spatial and temporal characteristics under various types of outage-inducing events are visualized. The proposed dashboard will help grid planners and decision-makers understand the regional vulnerabilities to power outages, and facilitate making informed decisions on future investments and grid reinforcements for structural resilience.

The rest of this paper is organized as follows: Section II introduces the sources of the data and the data filtering and pre-processing approach implemented in the developed dashboard. Section III discusses the spatio-temporal trends, causes, and impacts of the U.S. power outages during 2015-2022, and Section IV summarizes the research findings.

## II. DOE's Electric Disturbance Events Database

To enhance the public availability of data for research and developments, the U.S. DOE requires electric utility companies to report any type of power outages within their regional territory, specifically named "form OE-417" report [10], [11]. In this study, we focus only on the time interval from 2015 to 2022 as the DOE transformed the way data is captured in 2015. The available dataset focuses on the time, month, and the date the power outage happened and restored, the affected states and the North American Electric Reliability Corporation (NERC) regions, the event type, the amount of power outages (demand loss), the number of customers affected, and any alert criteria indicated. Focusing on 2015-2022 interval, a total of 2,430 events are analyzed in this study.

### A. Data Pre-processing and Filtering

To build the power grid outage visualization dashboard, the downloaded data from the DOE dataset must be filtered and pre-processed. The pre-processing was done using Python 3.10 and the visualization was accomplished using Microsoft Power BI platform [13]. The following steps are conducted:

- The *sever weather events* include those driven by winter temperatures, wind, thunderstorms as well as those resulted from severe weather and a natural disaster.
- The *physical attack events* cover the actual physical attacks, the actual physical evens, the suspected physical attacks, and the potential physical attack events.
- The *sabotage events* include the ones with and without operation actions.
- Removed any extra spaces originally existing in the dataset that could lead to miss-counting or miss-classification of power outages.
- Created a separate outage entry for power outages in the dataset that are attributed to multiple event types. The number of affected customers and the amount of demand loss were accordingly assumed to be equally shared between all newly-generated outage events.
- Created a separate outage entry per NERC region [14] for power outages that are recorded in multiple NERC regions. The number of affected customers and the amount of demand loss were accordingly assumed to be equally shared between all newly-generated outage events.
- Assumed that the RF NERC region entry in the dataset is the same as that of the Reliability First Corporation (RFC) and that for SPP RE is the same as the one for Southwest Power Pool (SPP).

## III. Causes, Trends, and Impacts of the Recorded Power Outages in the U.S.

### A. Causes

After pre-processing and filtering the recorded data as described in Section II-A, we here shed some lights on the causes and the primary drivers behind these power outages. The studied events were recorded from 2015 to 2022, the statistics on which are shown in Fig. 1. This figure also illustrates the percentage frequency of each event happened through the years. Clearly, one can see that around 50% of the power outages lately are due to sever weather events such as thunderstorms, heat waves, or cold waves all driven by climate change. It is also worth noting that 17% of the total power outages are due to system operation mistakes, i.e., human error, 14% are due to vandalism, and 10% are due to transmission interruptions. Comparing these observations with those reported in [11], one can clearly notice a significant increase in frequency of all the major power outage drivers.

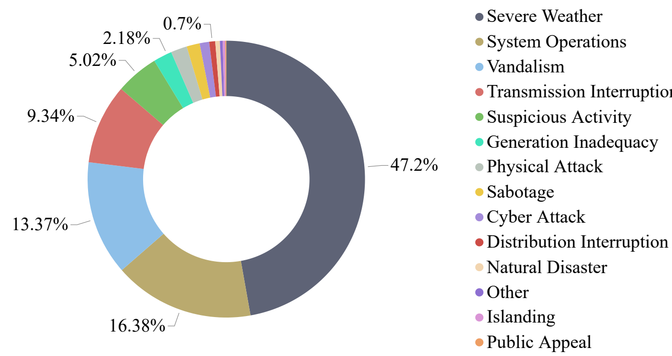



Fig. 1. Frequency (in %) and types of outage-inducing events in the U.S. recorded during 2015 to 2022.

### B. Trends

Despite the abundant literature focused on development of tools and mechanisms to mitigate and predict power system outages, Fig. 2 of the developed power outage dashboard shows an increasing trend in the total frequency of power outages in each year from 2015 to 2021. This can be seen in some specific events such as sever weather, system operations, vandalism, and transmission interruptions. Additionally, since 2019 (post COVID), the number of outage events is observed on the rise significantly. Furthermore, Fig. 3 shows a closer look at less-frequent outage events, where it highlights that there is an increasing trend recorded for the suspicious activities, a decreasing trend is found for sabotage events, and a stable trend is observed for those event driven by power generation adequacy and physical attacks. Figure 4 from the proposed power outage dashboard illustrates the monthly power outages occurred from 2015 to 2022. It indicates that the months with most recorded power outages are February, September, and July. This could be expected as these months are known for their extreme hot and cold weather realizations such as the blackout and outage events that happened in the state of Texas due to the cold storm in February 2021.

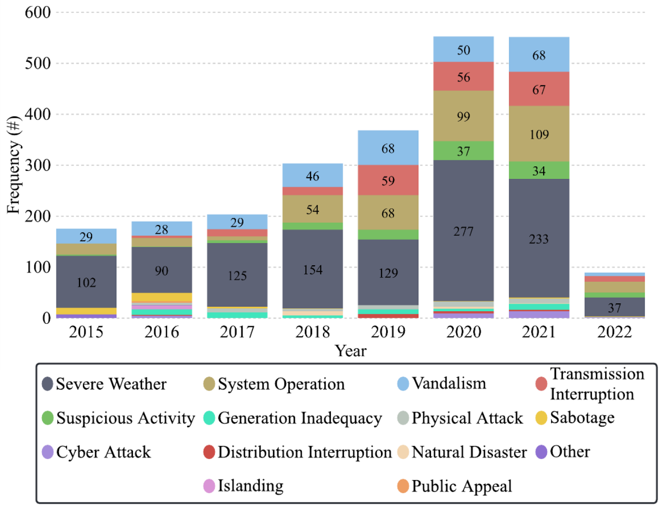



Fig. 2. The yearly frequency of power outages recorded from 2015 to 2022.

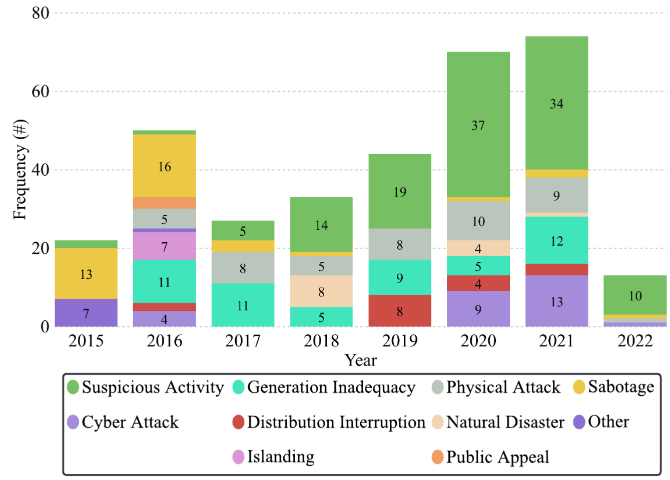



Fig. 4. The monthly frequency of power outages recorded from 2015 to 2022.

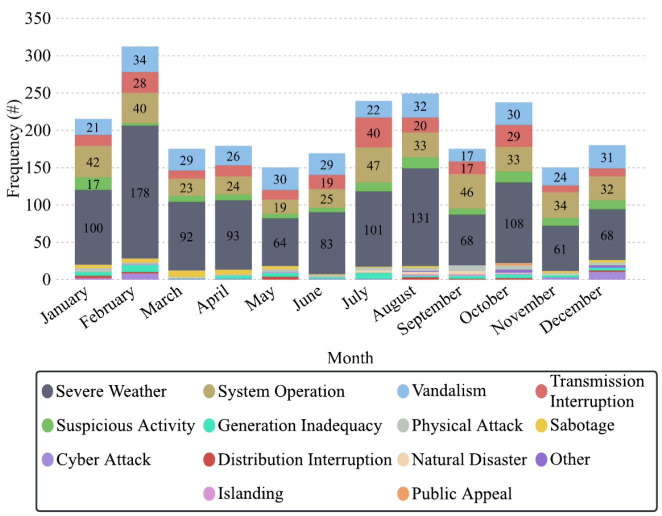



Fig. 3. The yearly power outages attributed to less-frequent events recorded from 2015 to 2022.

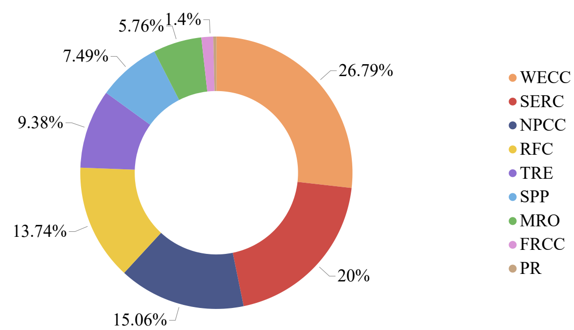



Fig. 5. Frequency (in %) of power outages for each NERC region recorded during 2015 to 2022.

## *C. Impacts*

While knowledge on the main underlying drivers and trends behind the recorded power outages in the past is useful, additional insights could be grained when the location of the outages and impacts they leave to the society are quantified and studied. Figure 5 from the developed power outage dashboard illustrates the percentage frequency of power outages recorded in each region within the NERC territory during 2015 to 2022. It indicates that most power outages occurred at the Western Electricity Coordinating Council (WECC), followed by the Southeastern Electric Reliability Council (SERC) and Northeast Power Coordinating Council (NPCC), respectively. In addition, Fig 6 from the developed power outage dashboard shows the total amount of power outages recorded per NERC region annually from 2015 to 2022. Some key findings from Fig 6 are highlighted in the following:

- On average, WECC, RFC, Texas Reliability Entity (TRE) and SERC regions demonstrate an increasing trend in the realized power outages.
- On average, Florida Reliability Coordinating Council (FRCC), SPP, and Puerto Rico (PR) regions are attributed a better performance with decreasing trends of power outages through the years.
- Since 2019 (Post COVID), the frequency of power outages at Midwest Reliability Organization (MRO) region has increased significantly.

Since each NERC region is composed of several U.S. states, Fig. 7a from the developed power outage dashboard illustrates the U.S. map with circles on each state, the radius size of which corresponding to the frequency of power outages. Furthermore, the circle's colors correspond to the NERC region in which the outage event occurred. The figure demonstrates that the states with most recorded outages during the analyzed interval are Texas, California, and Washington with 265, 252, 130 recorded outages, respectively. In addition, Table I captured from the developed power outage dashboard shows the frequency of power outages per U.S. state and NERC region, where most outage events are found to have been occurred in WECC, SERC, and NPCC regions with 651, 486, and 366 recorded outages, respectively. To visualize how each of the major outage-inducing events have affected the U.S. states and the NERC regions, Figures 7b, 7c, and 7d captured from the developed power outage dashboard show the U.S. map for power outages per U.S. state and NERC region for the following events: severe weather, system operation, and vandalism, respectively. Figure 7b indicates the most affected states during severe weather events from 2015 to 2022 have

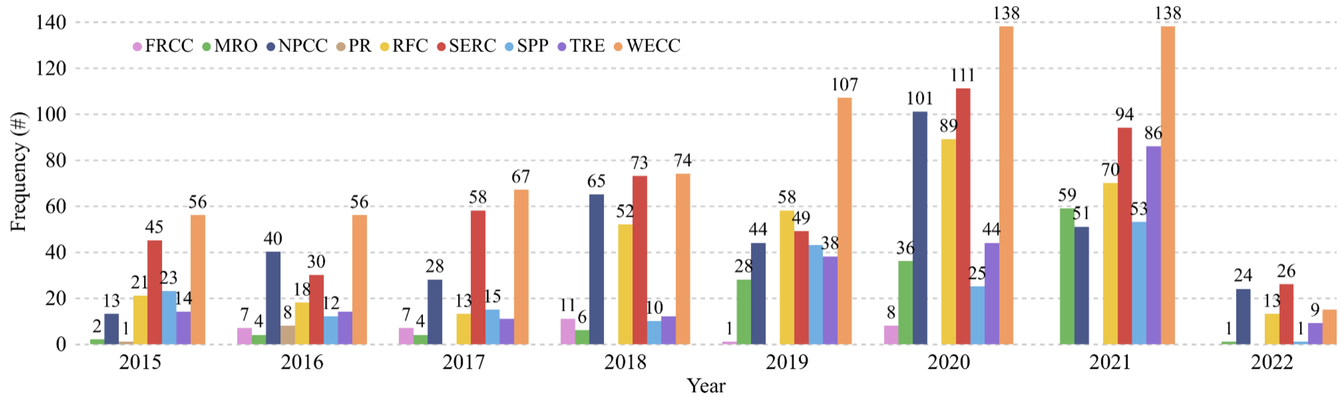
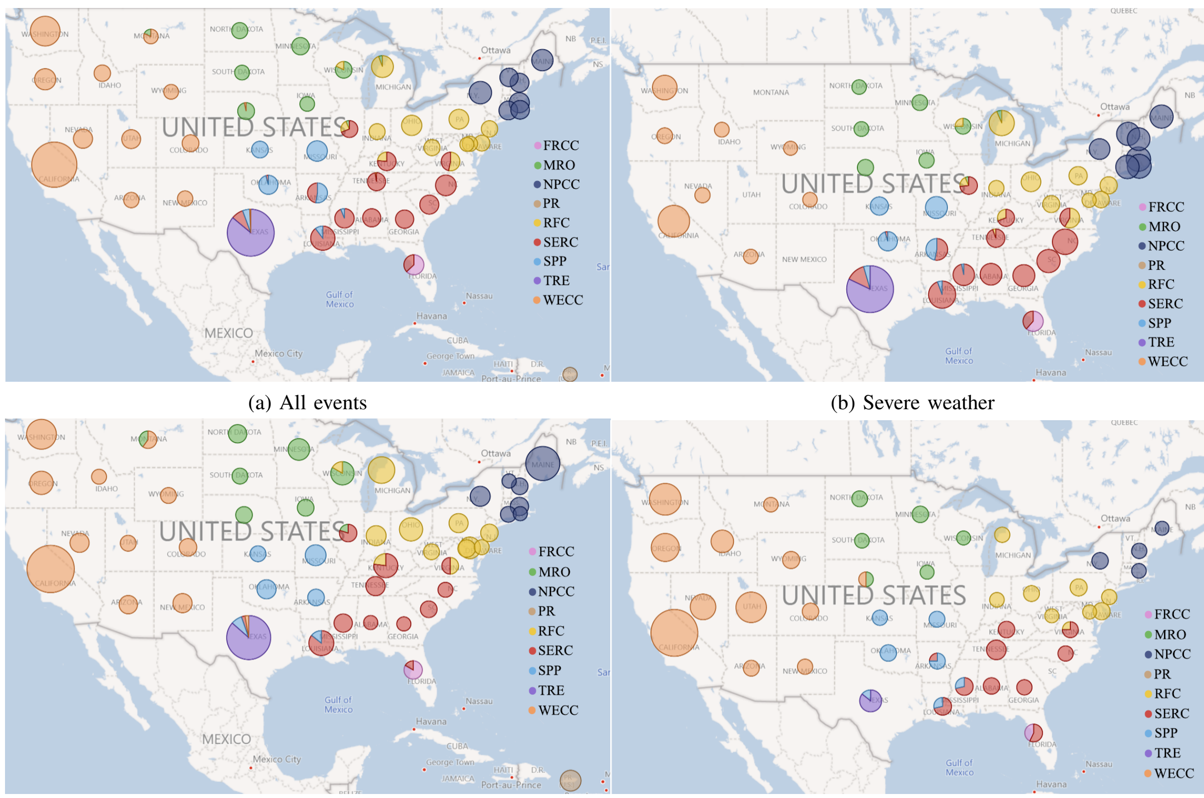



Fig. 6. The total number of power outages per NERC region recorded during 2015 to 2022.




(a) All events

(b) Severe weather

(c) System operation

(d) Vandalism

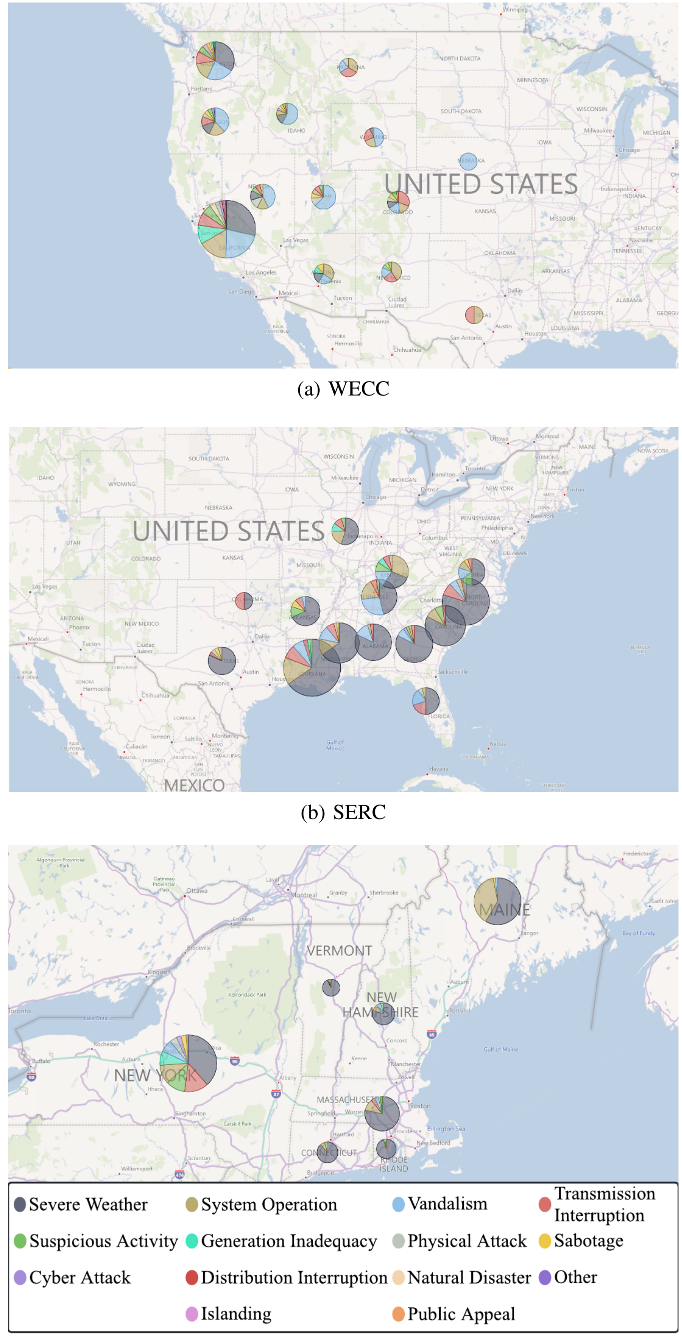
Fig. 7. Power outages across the U.S. per state and NERC region for the events recorded during 2015 to 2022.

been Texas, California, and North Carolina with 134, 72, and 47 recorded events, respectively. Additionally, some states were not affected by such events including Montana, Utah, Puerto Rico, and New Mexico. The most affected NERC regions by severe weather events seem to be SERC and NPCC. Regarding Fig. 7c, one can notice that the most affected states by the system operation events are California, Texas, and Maine with 41, 37, and 25 recorded events, respectively. Interesting observation is that all states in the U.S. were affected by this type of event. WECC and RFC regions are found to be the most affected regions by the system operation events. Figure 7d shows that the most affected states by vandalism events are California, Washington, and Utah all from the WECC region with 55, 30, and 28 recorded events, respectively. This implies that this event type highly impacts the WECC region and its served communities, calling for the development and deployment of effective mitigation and prediction techniques and strategies.

In order to visualize the underlying drivers behind the power outages in the most-affected NERC regions, Fig. 8 captured from the developed power outage dashboard shows the U.S. map for power outages per U.S. state and event type recorded during 2015-2022 for most-affected NERC regions (i.e, WECC, SERC, and NPCC). Figure 8a indicates that WECC region is heavily affected by the three outage events: system operations, vandalism, and transmission interruptions. Unlike the other NERC regions, the severe weather event is not the main contributor to power outages in the WECC region.

TABLE I
FREQUENCY OF POWER OUTAGES PER U.S. STATE AND NERC REGION RECORDED DURING 2015 TO 2022

| State \ NERC Region | FRCC | MRO | NPCC | PR | RFC | SERC | SPP | TRE | WECC | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Alabama | | | | | | 39 | | | | 39 |
| Arizona | | | | | | | | | 17 | 17 |
| Arkansas | | | | | | 25 | 28 | | | 53 |
| California | | | | | | | | | 252 | 252 |
| Colorado | | | | | | | | | 29 | 29 |
| Connecticut | | | 44 | | | | | | | 44 |
| Delaware | | | | | 22 | | | | | 22 |
| District of Columbia | | | | | 7 | | | | | 7 |
| Florida | 34 | | | | | 20 | | | | 54 |
| Georgia | | | | | | 40 | | | | 40 |
| Idaho | | | | | | | | | 26 | 26 |
| Illinois | | 2 | | | 7 | 20 | | | | 29 |
| Indiana | | | | | 22 | | | | | 22 |
| Iowa | | 12 | | | | | | | | 12 |
| Kansas | | | | | | | 28 | | | 28 |
| Kentucky | | | | | 10 | 32 | | | | 42 |
| Louisiana | | | | | | 78 | 9 | | | 87 |
| Maine | | | 65 | | | | | | | 65 |
| Maryland | | | | | 17 | | | | | 17 |
| Massachusetts | | | 55 | | | | | | | 55 |
| Michigan | | 4 | | | 64 | | | | | 68 |
| Minnesota | | 33 | | | | | | | | 33 |
| Mississippi | | | | | | 46 | 3 | | | 49 |
| Missouri | | | | | | | 57 | | | 57 |
| Montana | | 2 | | | | | | | 9 | 11 |
| Nebraska | | 28 | | | | | | | 1 | 29 |
| Nevada | | | | | | | | | 47 | 47 |
| New Hampshire | | | 45 | | | | | | | 45 |
| New Jersey | | | | | 25 | | | | | 25 |
| New Mexico | | | | | | | | | 17 | 17 |
| New York | | | 73 | | | | | | | 73 |
| North Carolina | | | | | | 59 | | | | 59 |
| North Dakota | | 23 | | | | | | | | 23 |
| Ohio | | | | | 56 | | | | | 56 |
| Oklahoma | | | | | | 2 | 44 | | | 46 |
| Oregon | | | | | | | | | 63 | 63 |
| Pennsylvania | | | | | 52 | | | | | 52 |
| Puerto Rico | | | | 9 | | | | | | 9 |
| Rhode Island | | | 43 | | | | | | | 43 |
| South Carolina | | | | | | 46 | | | | 46 |
| South Dakota | | 13 | | | | | | | | 13 |
| Tennessee | | | | | 1 | 37 | | | | 38 |
| Texas | | | | | | 22 | 13 | 228 | 2 | 265 |
| Utah | | | | | | | | | 45 | 45 |
| Vermont | | | 41 | | | | | | | 41 |
| Virginia | | | | | 23 | 20 | | | | 43 |
| Washington | | | | | | | | | 130 | 130 |
| West Virginia | | | | | 23 | | | | | 23 |
| Wisconsin | | 23 | | | 5 | | | | | 28 |
| Wyoming | | | | | | | | | 13 | 13 |
| Total | 34 | 140 | 366 | 9 | 334 | 486 | 182 | 228 | 651 | 2430 |




(a) WECC

(b) SERC

(c) NPCC

Fig. 8. Power outages per U.S. state and event type recorded during 2015 to 2022 for most affected NERC regions.

According to Fig 8a, California and Washington are the states that were impacted the most by these event categories. On the other hand, the SERC and NPCC regions were highly affected by the severe weather event as shown in Fig. 8b and Fig. 8c, as mentioned earlier. As shown in these figures, most states in the SERC and NPCC regions are affected mainly by severe weather events; some states are also affected by other types of events, such as Kentucky and Tennessee from the SERC region and New York from the NPCC region.

There is a need to minimize power outages due to their tendency to cause a great deal of environmental damages and economical losses in the society. For instance, the number of customers affected is a measure of how influential a power outage was. Figure 9 captured from the developed power outage dashboard presents a treemap for the number of affected customers per months and event type during 2015 to 2022. Clearly, many customers were affected in the months of August, September, and February. Even though February is attributed the most number of outages as compared to other months, as indicated in Fig 4, those outages did not affect customers as much as the ones happened in the months of September and August. Moreover, the main driver of these outages for most of the months is the severe weather.

Another measure of how severe a power outage was is the amount of demand loss. Therefore, the developed power outage dashboard presents a treemap on the amount of demand loss (in MW) per month and event type during 2015 to 2022 as shown in Fig. 10. It shows that the maximum amount of demand loss has been recorded in the months of January, October, and August. Note that while imposing the most significant power outage, two of these three months were not among the months with most number of affected customers. Also, one can conclude from Fig. 9 and Fig. 10 that the months of November and December are those typically found with the least number of affected customers and amount of demand loss, which is in line with the observations made in Fig. 4.

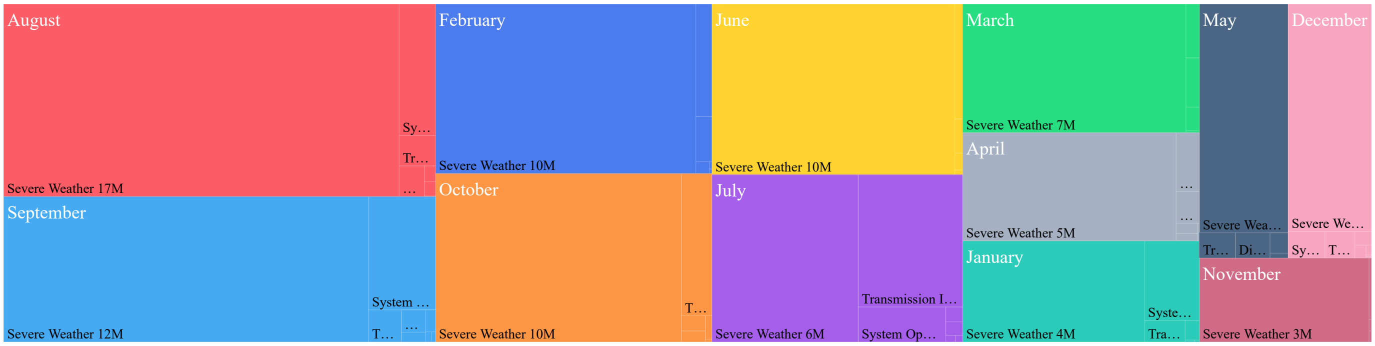



Fig. 9. Treemap for the number of affected customers due to power outages per month and event type from 2015 to 2022.

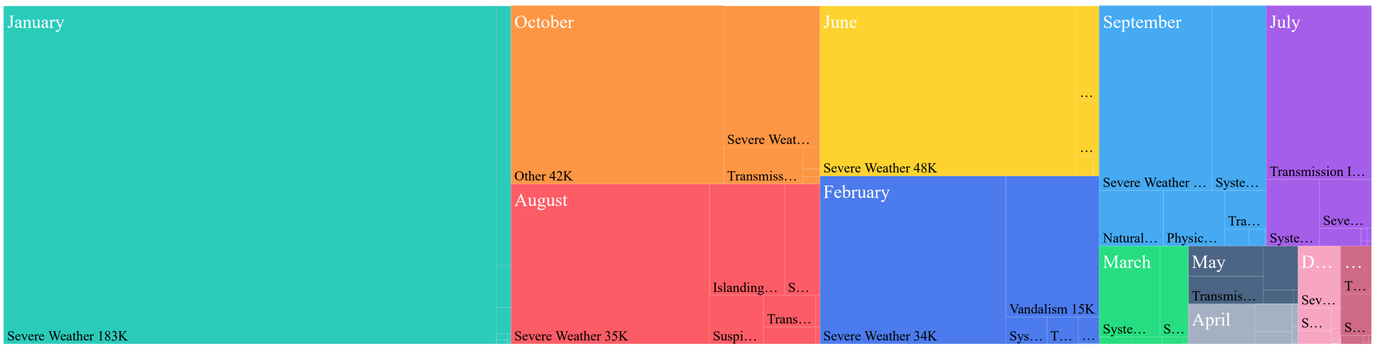



Fig. 10. Treemap for the amount of demand loss (in MW) due to power outages per month and event type from 2015 to 2022.

## IV. Conclusion

In this paper, we presented a developed dashboard for a better understanding of the U.S. power outages recorded during 2015 to 2022. Using the DOE's electric emergency incidents and disturbances dataset, the original data was filtered, preprocessed, and inserted in the developed visualization tool. The yearly records on power outages from 2015 to 2022 indicated that (1) the frequency of power outages has been increasing, (2) the most frequent power outages were found to occur in February, August, and July, (3) the main causes behind the recorded power outages were due to severe weather, system operations, and vandalism events, (4) WECC, SERC, and NPCC regions were the most affected NERC regions by power outages, (5) unlike other NERC regions which were mainly impacted by the severe weather event, WECC was mainly affected by system operation, vandalism, and transmission interruptions events, (6) some of the most affected U.S. states by the power outages were California, Texas, Washington, North Carolina, and Maine. Lastly, the severe weather was found responsible for the highest number of affected customers and amount of demand loss from 2015 to 2022. The developed dashboard will improve the decision-making process on future allocations of funds and investments to increase the reliability of the power gird in response to power outages.

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