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Assessing Critical Energy Infrastructure

Using Geo-Spatial Technologies

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Abstract:

This paper discusses the use of Geographic Information Systems (GIS) in mapping and analysis of incidents related to security and integrity of critical energy infrastructure. It includes a discussion of what GIS and related geospatial technologies involve; sources of energy infrastructure related geo-spatial data. As the leading energy producing state, Texas has a major economic reliance on the energy sector and the energy sector uses GIS and related technologies. The energy sector uses GIS extensively for its ongoing needs, but it also faces a range of threats such as floods, winter storms, cyber-attacks, sabotage, vandalism, and physical attacks that can be mapped and analyzed with GIS. This paper shows the use of GIS to map examples of all these threats and analyzes their spatial distribution throughout the United States, but with a central focus on Texas.

KEYWORDS: GIS (Geographic Information Systems), Energy Infrastructure, Electrical Grid Reliability, Fuel Pipelines, Physical Attacks, Cyber-attacks, Winter Storm Uri.

Introduction.

This paper examines the use of GIS in analyzing issues related to energy infrastructure. It does this by introducing important overarching concepts of what GIS and related geospatial technologies consist of and how they are used to map and manage energy infrastructure. It also discusses the nature of geospatial data available for mapping critical energy infrastructure and important sources of such data. To make the presentation focused on practical problems, specific examples of incidents have been selected and mapped. There are many varieties of energy infrastructure, but this paper focuses on two of the most critical. Those are fuel pipelines and electrical generation, transmission, and distribution facilities (the electrical grid). More specifically, the paper focuses on one major gasoline pipeline system and on electrical substations. Both of these components of energy infrastructure have proven to be vulnerable to a range of failures, fires, explosions, and attacks (El-Harbawi & Al-Mubaddel, 2020).

The authors choose to focus on one pipeline system which is deeply imbedded in the Texas economy and is, in fact, the largest fuel pipeline system in the USA. It is the Colonial Pipeline system. This 5,500-mile system connects refineries in Texas to the East Coast, terminating in the New York City region. Four distinct types of incidents faced by this pipeline system are mapped and analyzed. An October, 1994 flood event severed two Colonial System pipelines, spilling approximately 1.4 million gallons of gasoline and diesel and severing 35 other hydrocarbon pipelines in Houston, Texas causing multiple fires and explosions. A 2007 plot to blow up an extension of the Colonial Pipeline called the Buckeye Pipeline in New Jersey and New York along with a jet fuel tank farm at JFK Airport that it feeds. A two-million-gallon spill of gasoline from the pipeline detected in August, 2020 in North Carolina. Finally, the May, 2021 Darkside Web ransomware attack on the pipeline which shutdown the entire pipeline system for a week and which is the largest successful cyber-attack in U.S. history on infrastructure.

The second focus of the paper is electricity grid reliability, and this topic is analyzed by mapping 23 years of data of the years 2000 to 2023 on disruptions of the electricity supply and grid system. The data was obtained from the Energy Information Administration (EIA) on the selected topics of disruptions caused by cyber-attacks, suspicious surveillance, vandalism, sabotage, physical attacks. This data was analyzed on a nationwide basis although a limited number of examples of such issues occurred in Texas in most years. Also, the issues related to the failure of large portions of the Texas energy infrastructure during Winter Storm Uri in February 2021 are mapped and analyzed.

Geospatial Technologies and Their Use in Energy Infrastructure Security.

There are several geospatial technologies; these include first and foremost GIS, used for mapping and spatial analysis, and remote sensing and related aerial imagery technologies used to gather imagery, often then displayed, and analyzed by GIS. GIS has a layer structure. A visualization of the layer structure of GIS is shown in **Figure 1** which is specific to its application in energy infrastructure mapping. Global Positioning Systems (Department of Homeland Security, 2022). Unmanned Aerial Vehicles (UAV's, commonly known as drones) round out the suite of digital technologies used in a variety of applications for energy infrastructure security (Crino, 2020).

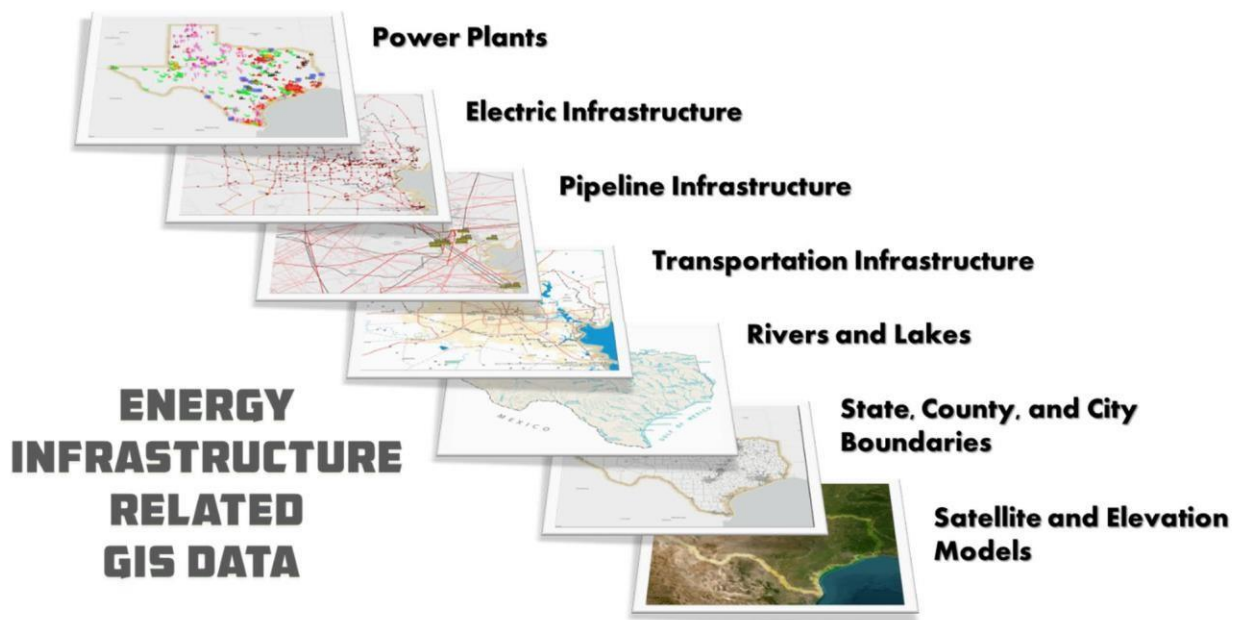


Figure 1. GIS layers most relevant for mapping energy infrastructure security issues.

These applications include mapping energy infrastructure particularly the electrical grid and pipeline networks, as well as in a range of cyber security applications (Federal Geographic Data Committee, 2016). Government agencies have identified GIS as a key element of safeguarding critical infrastructure. GIS is a key technology for public utilities in this regard and in general operations (Ajwaliya, et al, 2014).

Types of energy infrastructure.

There are a range of different types of energy related infrastructure. Probably the most important categories are the electric grid and pipelines. Pipelines are used to transport hydrocarbons, which can be further subdivided into crude oil pipelines, natural gas pipelines and

fuel (petroleum product) pipelines. This paper focuses on one of the most vulnerable of these types of pipelines to explosions, which are fuel pipelines (Biezma, March 2020). The electricity grid consists of transmission and distribution infrastructure and associated power generation stations. A key component are the electrical substations. Its important to note there are other types of energy infrastructure including storage facilities and export terminals for substances like liquified natural gas. The paper discusses in detail electricity generation and distribution infrastructure related issues. This is done in the context of electrical grid reliability issues related to physical attacks and other interruptions due to sabotage, cyber-attacks, and vandalism. In this effort we use GIS as well as aerial imagery from remote sensing. Both technologies have applicability to energy infrastructure management and mapping (Manonmani, et al, 2012). The data used in this effort was obtained from a variety of sources, but the predominant one was the Energy Information Administration. The GIS data portal of this Department of Energy agency is portrayed in **FIGURE 2** (Energy Information Administration, 2023).



Figure 2. Geospatial data available from the Energy Information Administration.

Colonial Pipeline System Related Issues.

The petroleum products pipeline infrastructure of the USA is portrayed in **Figure 3**.

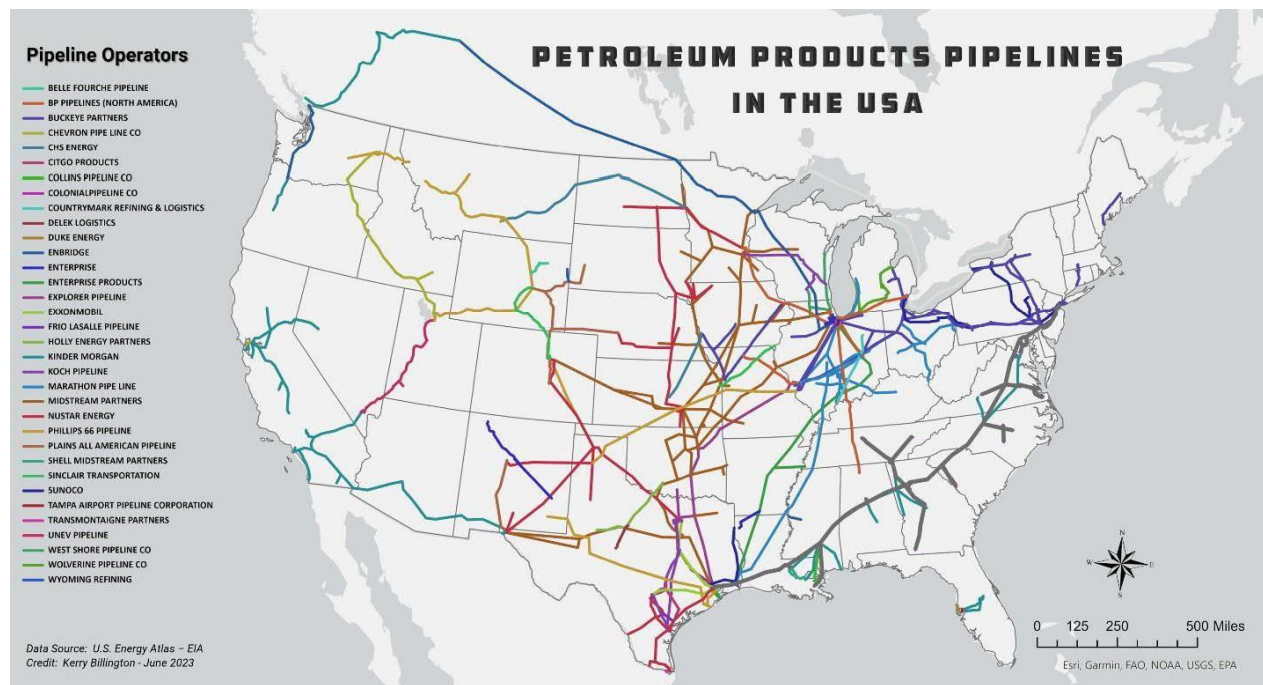


Figure 3. Map of the fuel pipelines in the USA. Note in grey the 5,500 miles colonial pipeline system extending from Houston, Texas to the New York City area is analyzed in detail in this paper (this is the pipeline in the South-eastern and East Coast portion of the map).

This infrastructure is clearly centered on Texas; the leading hydrocarbons, fuel production and renewable energy producing state. (Texas Governor’s Office, 2023). Many of these energy sources are interconnected to the nation by pipelines that originate in Texas. Some are as much as 80 years old, with many dating to the Second World War time period, when tankers were under threat from submarine attacks and fuel pipelines from Texas to the East Coast were first built. The petroleum related pipeline system can be further subdivided into crude oil pipelines and those carrying refined petroleum products. In general, refined products pipelines pose greater security hazards than crude oil pipelines (Beizma, et al, 2020). There are a wide range of security and reliability issues that face refined products pipelines, including slow leaks due to corrosion, breaks due to accidental physical damage, breaks due to natural disasters, physical attacks, and more recently, cyber-attacks.

The Colonial Pipeline system and the Buckeye Pipeline (to which it is connected) have experienced all these types of events over the six decades they have been in operation. The Colonial Pipeline System is the largest fuel (refined petroleum products) pipeline system in the USA. It consists of a 40-inch gasoline pipeline connecting multiple refineries in the Houston, Texas area to Linden, New Jersey. This pipeline was built starting in 1961. There is also a smaller 36-inch pipeline following the same route that carries a variety of fuels, including diesel, jet fuel

and heating oil. There are loops and laterals totaling 5,500 miles in extent, but both pipelines run from Houston, Texas to the New York City area (See **Figure 4**) (Colonial, 2023).

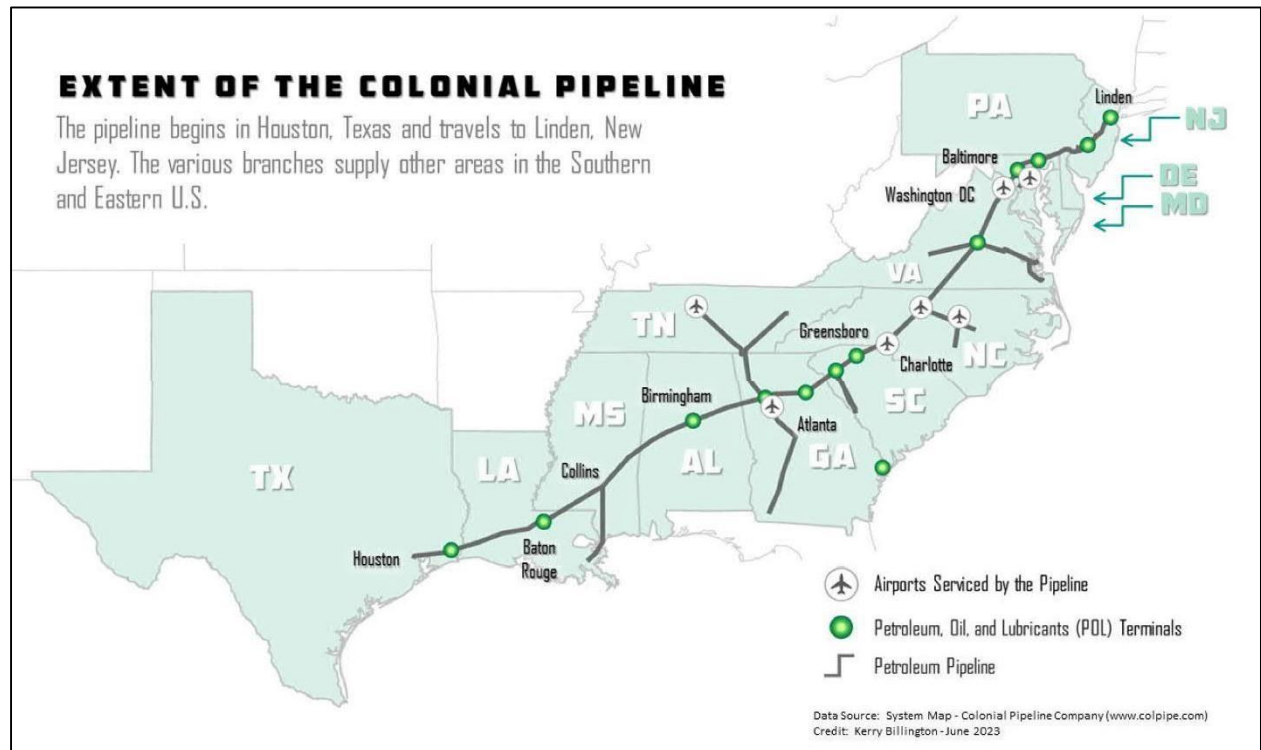
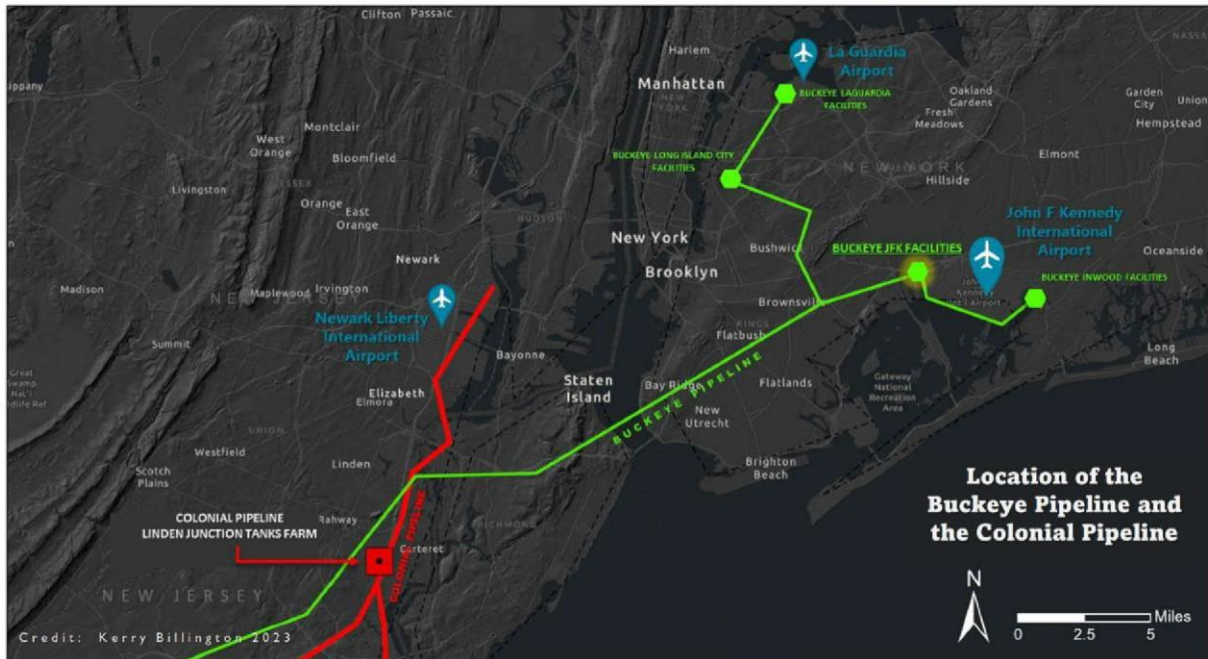


Figure 4. Extent of the Colonial pipeline system.

There are several airports that are dependent on the Colonial Pipeline system for distribution of fuel refined in Houston, Texas City, Port Arthur, and the Baytown areas of Texas. Retail gasoline stations in many markets in sixteen states are highly or solely dependent on the colonial pipeline system to supply the distribution hubs (racks) for gasoline trucks. Therefore, the Colonial Pipeline system is one of the most critical components of energy infrastructure in the nation. As mentioned above, this system has experienced a range of events that compromised its mission. **Figure 4, (above)** shows a series of issues that the Colonial pipeline system has experienced.

There is also a Buckeye Pipeline, which connects to the Colonial Pipeline system in the terminal at the Port of New York facilities in Linden, New Jersey (as well as in Pennsylvania). The Buckeye Pipeline takes jet fuel from the Colonial Pipeline and delivers it to JFK and La Guardia Airports in Queens, New York. This pipeline is critical to the operation of La Guardia and JFK Airports, both key U.S. airports (Buckeye Pipeline Partners, 2023). **Figure 5 Figure 6 and Figure 7** portray the inter-connection of the Colonial and Buckeye Pipelines and the jet fuel tank farm served by these pipelines at JFK Airport.



Figures 5, 6 and 7. The Colonial pipeline terminus in Linden New Jersey and its connection and extension to the New York City area via the Buckeye pipeline. The Colonial supplies Newark airport with jet fuel and the buckeye carries jet fuel primarily originating from the Colonial Pipeline via a smaller 8 -inch pipeline to La Guardia and JFK airports.

San Jacinto River Flooding Pipeline Breaks and Explosions, October 1994.

Chronologically, the first event to be discussed in relation to the Colonial Pipeline System occurred in October 1994. Gasoline pipelines are generally safe, but when suddenly ruptured they can unleash explosions and subsequent fires (Biezma, 2020). A flood in October 1994 triggered a catastrophic failure of both Colonial fuel pipelines (along with 6 other major hydrocarbon pipelines and 29 less significant pipelines) (NTSB, 1996). It was due to flooding of the San Jacinto River causing eroding of the bed of the river and severing the Colonial pipelines, leading to multiple explosions that cut other nearby pipelines. The flood was due to rainfall related to the remnants of Hurricane Rosa. Multiple days of rain in mid-October 1994 caused 15-21 inches of rain to fall on the San Jacinto River watershed. Releases from Lake Houston of this flood water led to the river downstream of Texas Highway 90 to rise from a usual height of 2.5 feet to 28 feet above mean sea level. This flooding by itself caused evacuations of over 20,000 Houston residents and 14 deaths (Interior Department, Geological Survey, 1994).

This evacuation probably reduced subsequent deaths from the explosion and fire that followed the failure of the Colonial Pipeline. Starting at 8:30 am on October 20, 1994 operators of the colonial pipeline noticed a drop in pressure and flow, indicating a major leak, but they did not know where the leak was happening, and at the time could only close valves manually in the field. Notably, one of their valves near the San Jacinto River was underwater and inaccessible. The Harris County Sheriff's Department began to receive calls of gasoline odor

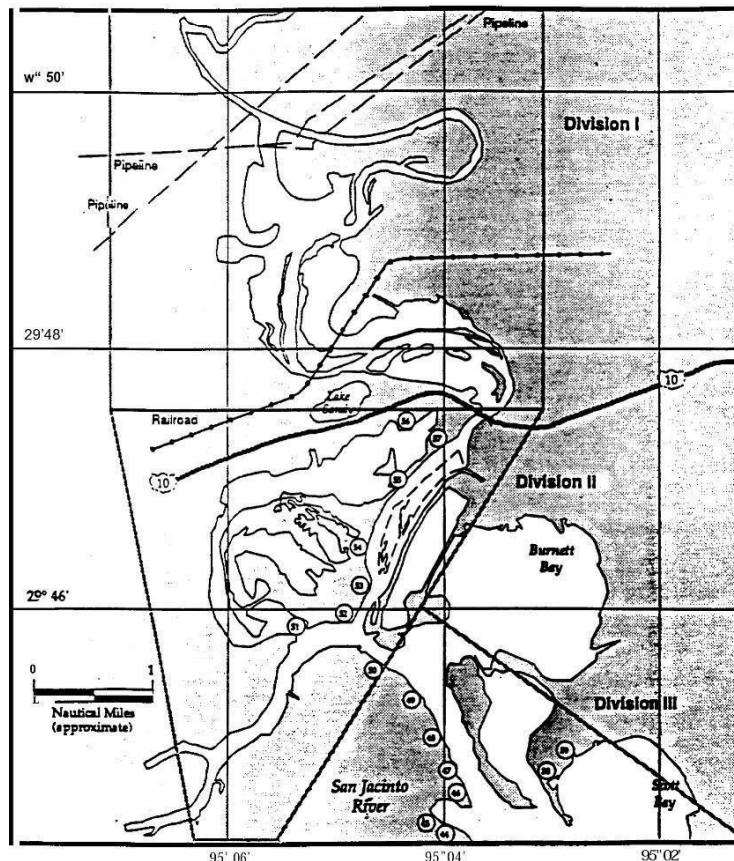


Figure 8. NTSB 1996 pipeline crossings map.

from multiple residents in subdivisions down river of the pipeline crossing that morning. This Crossing is shown in **FIGURE 8** from a 1996 report and in a new GIS generated map in **Figure 9**.

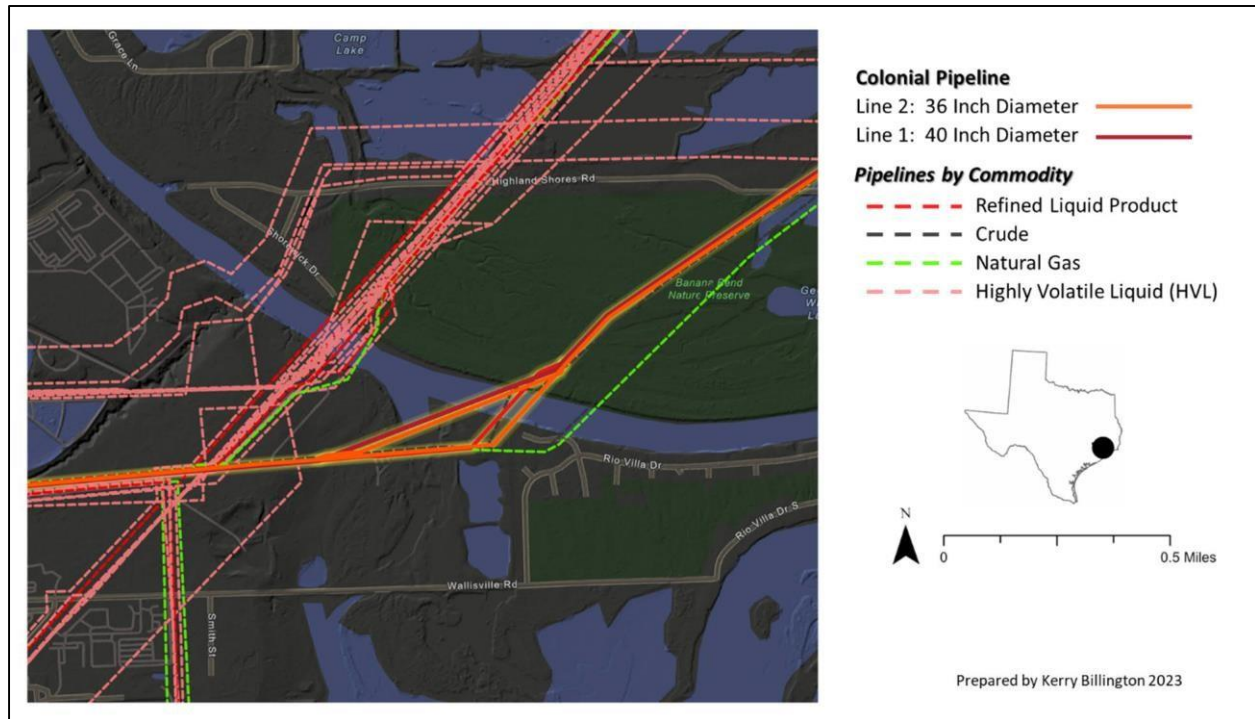


Figure 9. 2023 GIS generated pipeline crossings map.

The use of GIS to map this flooding was not easily available in 1994 even to the U.S. Government, although mapping of flood related erosion of pipelines was undertaken by geographers and hydrologists inspired by the 1994 San Jacinto River flood and spill a few years later (Bonn, et al, 1996). Today flood mapping with GIS is standard and a good example are the interactive flood mapping tools available online from the Harris County Flood Control District (Harris County Flood Control District, 2023).

Operators closed the pipeline within an hour of detecting system anomalies. However, all fuel between the widely separated valves drained into the river and it took a considerable time for operators to close these valves manually. Thus, the rupture of the 40-inch gasoline pipeline released between 800,000 gallons and 1.2 million gallons of gasoline into the San Jacinto River above Interstate 10. This gasoline was ignited, causing a large fireball and ongoing fire. Other pipelines also failed at the same time (in fact, an Exxon crude oil pipeline nearby had failed earlier the same morning but did not cause a fire and explosion). The explosion of the Colonial 40-inch pipeline caused the failure of the Colonial 36-inch pipeline releasing a smaller quantity of diesel fuel, and contributed to failures of other crude oil, liquidized petroleum gas and natural gas pipelines.

It took until 10:30 am, or two hours after issues were detected for Colonial Pipeline to shut down both pipelines. This was a slow response that was officially criticized by the National Transportation Safety Board which had oversight authority in 1996 (NTSB, 1996). Also, there was a good deal of uncertainty about what pipelines were present and ruptured, as maps and data were not at the time at the highly sophisticated level of today's GIS, but often on paper, and ultimately the "call before you dig" system was consulted by responders.

Due to the fires, the Harris County Sheriff's Department evacuated an additional 14,000 residents from downstream areas. Also, the Houston Ship Channel was closed for approximately a week and the closure of Interstate 10 was extended. The damage also had an impact on Houston Intercontinental Airport operations. Other agencies that responded besides the Company and the Sheriff's Department included the U.S. Coast Guard, the Texas Railroad Commission, and the U.S. Environmental Protection Agency (EPA) (NTSB, 1996).

On October 22, 1994, an EPA plan to conduct an "in-situ" burn of oil, gasoline and debris in the river was developed. While the plan was being formulated and plans for a boom to limit movement of flaming hydrocarbons under Interstate 10 and farther downstream was being prepared another explosion occurred. However, it was triggered by miscommunication with contractors that resulted in them using lighted flares placed in a plastic garbage can lid floated from upstream into the area of the gasoline leaks and oil slick to purposely trigger an additional large explosion and multi-day fire (NTSB, 1996).

This act, in fact, may have minimized environmental damage, but it injured some workers and was poorly planned. There were a reported 537 residents who sought medical assistance related to the fires, but only two persons were seriously hurt; one resident was seriously burned, and one worker seriously injured. There was extensive property damage in addition to the 37 ruptured pipelines. In addition to the port of Houston and Houston Ship Channel closures, several municipal water systems also had to shut down and there was a lengthy process of environmental cleanup and assessment. (National Transportation Safety Board, 1996). **Figure 10** and **Figure 11** show the mangled remnants of the Colonial pipelines in the receding waters on the San Jacinto River and the river on fire during the aftermath of the second explosion.

Figure 10. The Colonial and several other pipeline remnants in the receding channel of the San Jacinto River in October 1994. The flooding caused the river channel to shift, and don cut into the bed exposing the pipelines which then failed perhaps due to being hit by debris (including parts of homes) carried by the flood waters. In all 37 pipelines were impacted.





Figure 11. Fire on the flooded San Jacinto River in Houston region of Texas following the failure and explosion of the Colonial pipelines on October 20, 1994. The fires burned for several days. And a second fire was deliberately ignited by responders to

Plot to Bomb the Colonial/Buckeye Pipeline and JFK Airport, 2007.

A homeland security issue involving a pipeline tied to the Colonial Pipeline System happened in the summer of 2007. This involved the Buckeye Pipeline that carries jet fuel to the La Guardia and JFK airports, although JFK fuel pipelines and storage tanks were center (or rather, one end) of the conspiracy. The plot involved four men with affiliations to Islamic radical groups men who were from Guyana in three cases and Trinidad in the fourth case. One man worked in air cargo at JFK airport. Their collective plan was to detonate bombs next to the Buckeye jet fuel pipeline which they would dig up along a railroad, expose and bomb. This pipeline is 8 inches in diameter and buried approximately 4 feet deep. It runs for over 40 miles through urban areas in New York and New Jersey, particularly Linden and Queens.

Simultaneously they planned to bomb jet fuel storage tanks at JFK Airport. The expressed intention was that the resulting conflagration would cause all the jet fuel in the pipeline between both points to explode as well kill tens of thousands in Queens. The plot might have been improbable, but it involved planning in cooperation with criminals and collection of money from drug deals. The conspirators used publicly available satellite imagery and locations of prior pipeline leaks, such as one in 1985 to plan the attacks.

A confidential informant to the FBI involved in cocaine smuggling through the airport turned them in. Two men received life terms and two men received 15 years in Federal prison for planning an attack on an aviation facility. Interestingly, conspiracy to attack energy facilities is also a federal crime but it carries a 5–20-year sentence not a potential life sentence. The plan showed limited knowledge of the Buckeye Pipeline system that is publicly available and can be viewed in a GIS. This is because running parallel to the jet fuel pipeline is an 8-inch pipeline carrying gasoline, which is much more volatile than jet fuel. This gasoline pipeline does not extend to JFK airport, however. In the GIS generated map in **Figure 6** in **Figure 7** the image in the background is from Google. This is the same type of base map that the would-be terrorists used. Of course, they would have used a 2007 or earlier image but it would have been similar. (U.S. Attorney's Office, 2008).

Two Million Gallon Gasoline Spill from Colonial Pipeline and Associated Groundwater Contamination Remediation, Huntersville, North Carolina Beginning in August, 2020.

The next example of an issue involving the Colonial Pipeline system occurred in 2020 and the response to it is ongoing in 2023. Although sanctions for violation of the Clean Water Act may have been triggered and the Colonial Pipeline company has been assessed a fine of \$4.5 million by the State of North Carolina. It is most likely the largest loss of fuel from a pipeline in U.S. history. The incident lasted many months before detection, as a small crack in the main 40-inch gasoline pipeline leaked invisibly into the subsurface in a nature preserve in North Carolina (PHMSA, 2021). The leak at the Oehler Nature Preserve was slow and saturated the absorbent soil in the six-foot space above the pipeline for a long period. Free product moved down and spread out over the water table. The leak happened near a drainage divide of two creeks, so the contaminant plume, which was extensive, moved in two directions. Colonial Pipeline monitoring program did not detect the leak. This program includes flying UAVs over the pipeline right of way and tracking inventory. UAV's have been used not just for security and monitoring but in potential attacks on U.S. energy infrastructure (Barrett, 2021). The leak was discovered, instead of by UAV monitoring, by two teenagers riding ATVs along the pipeline right of way on the trail within the forest. This trail is visible in **Figure 12**.



Figure 12. Right of way and monitoring well Colonial pipelines. The lines leaked in Oehler Nature Reserve, Huntersville, N.C. The spill is currently estimated as totaling 2 million gallons of gasoline.

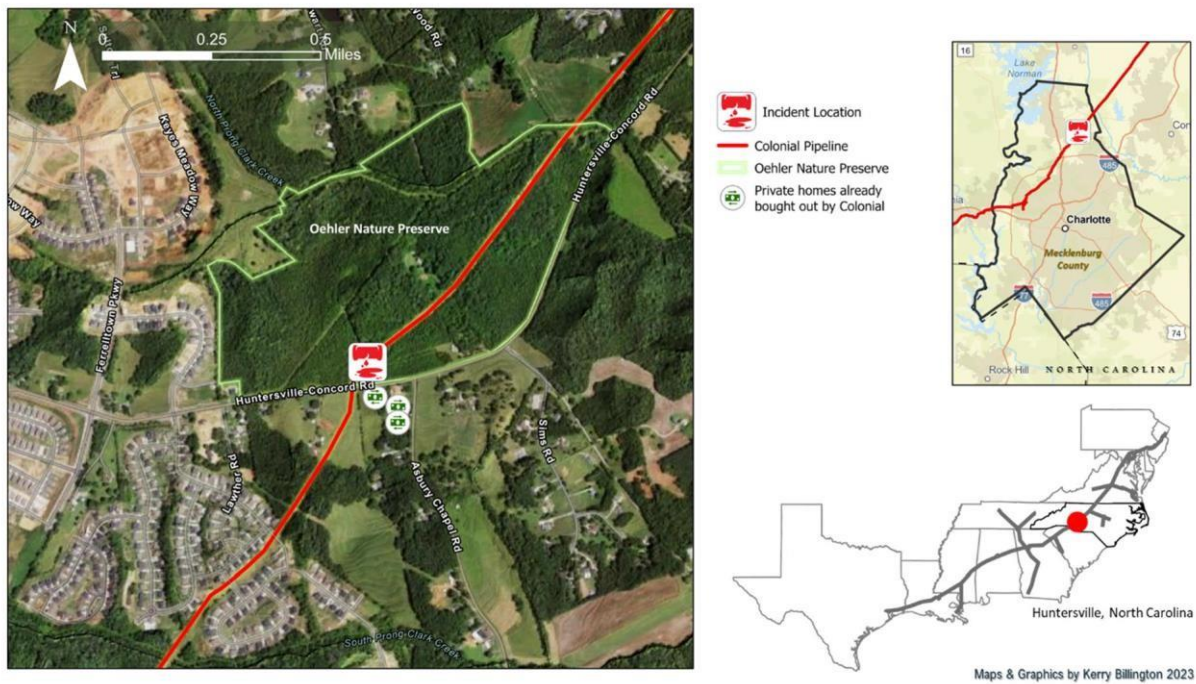


Figure 13. Location of the 2-million-gallon spill of gasoline from the colonial pipeline system that occurred beginning sometime in 2020.

Maps & Graphics by Kerry Billington 2023

The teens drove through a puddle of gasoline in August of 2020 but fortunately did not detonate a vapor cloud. The leak was reported by them promptly. The initial response from the Colonial Pipeline Company was briefly to close the pipeline and make repairs. The initial estimate of the release of gasoline was 63,000 gallons. Additional assessment has detected extensive soil and groundwater contamination. The current estimate of the quantity of gasoline spilled is 2 million gallons. The groundwater contaminant plume and monitoring wells are shown in **Figure 14**. (State of North Carolina, March 16, 2023).

This incident is instructive in that it helps to show that use of drones for pipeline right of way inspections may not be as effective as walking the pipeline route or even use of ATVs. Also, that a very large quantity of gasoline can leak from a large pipeline undetected. As fuel pipelines built in the 1940s (in the case of other fuel pipelines still in use) through the 1960s age, the likelihood of more leaks due to corrosion increase so monitoring must be more vigilant. (State of North Carolina, March 14, 2023).

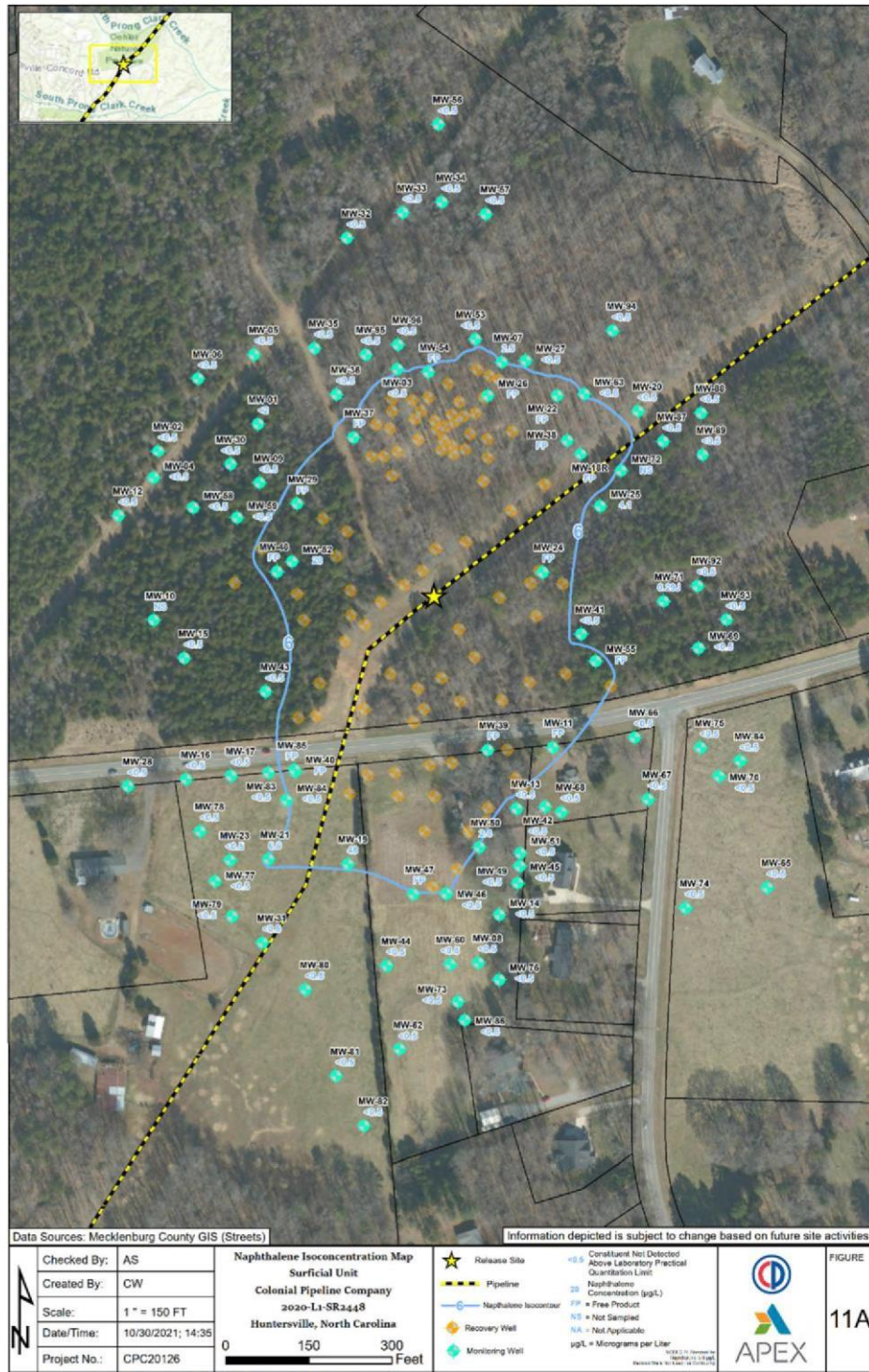


Figure 14. Map prepared by a contractor for Colonial Pipeline and included in a groundwater remediation report released in 2023 by the North Carolina Dept. of Environmental quality. Contaminated wells are shown in brown, the plume extent and “clean” wells are shown.

The Darkside Web Ransomware Attack and Shutdown of The Entire Colonial Pipeline System, May 2021.

The most recent Colonial Pipeline related incident occurred in May, 2021. This was a ransomware attack initiated by a hacker group called the Darkside Web. This group or its affiliates stole a significant amount of data from the Colonial Pipeline System data servers probably using a phishing approach initially. They then encrypted much of the company's data. They targeted customer data and encrypted billing related information without which the pipeline could not operate or collect money from clients. The ransomware seems to have been developed by a hacker collective in Russia. (FBI-CISA, 2021). One very interesting aspect of this attack is that the Colonial Pipeline company closed its entire pipeline system from May 7 to May 13, 2021. The GIS generated map in **Figure 15** shows of the Colonial system and the States it passes through.

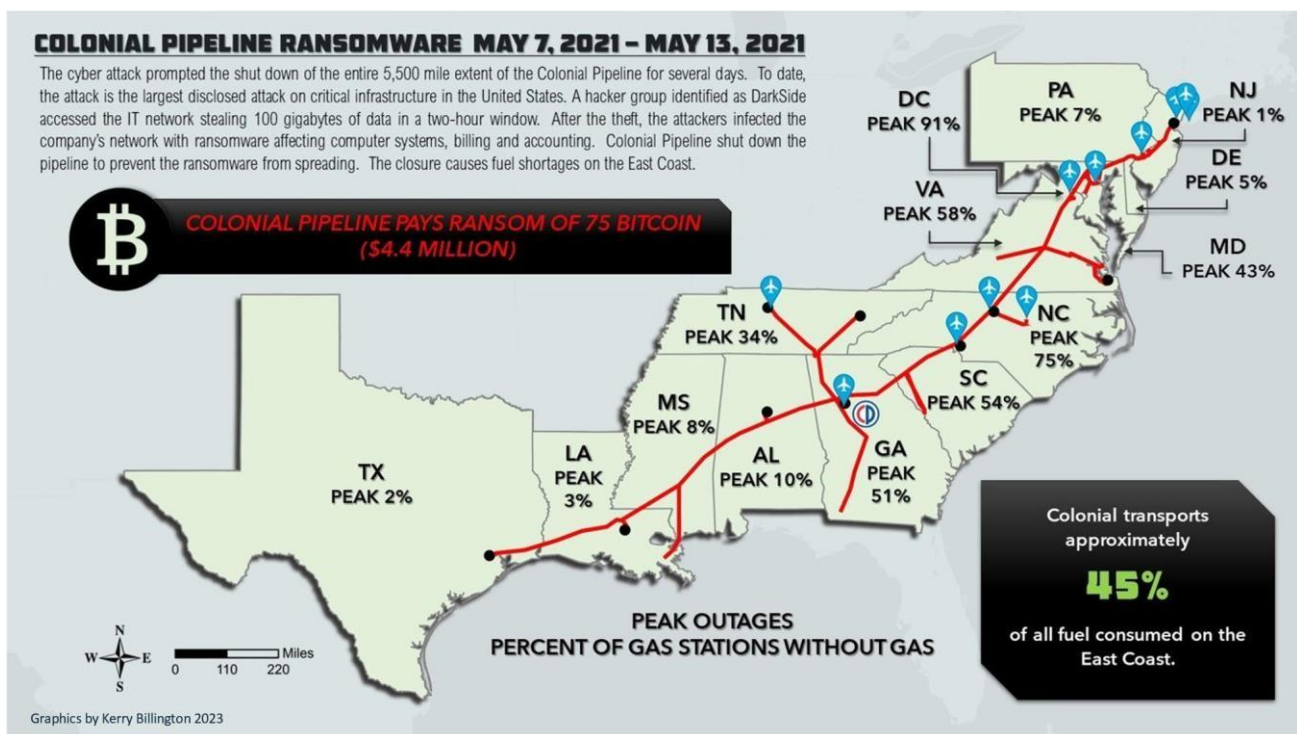


Figure 15. Infographic and map related to the 2021 ransomware attack that shut down this critical pipeline that delivers jet fuel and gasoline to east coast markets. The percentage of gasoline stations impacted in each state is noted Ranging from 2% in North Carolina.

The percentage of gasoline stations impacted in each state is noted Ranging from 2% in Texas to 75% in North Carolina.

In each state is a number representing the percentage of gasoline stations impacted by the closure. In some states like North Carolina and in the Nation's Capital the gasoline and diesel market are totally dependent on the Colonial pipeline system for deliveries. Gas prices did spike, and gas lines began to get longer. The crisis was averted before any airports were forced to close,

but it was a very serious blow to energy infrastructure and the most significant cyber-attack on U.S. infrastructure of any type. The company opted to pay the ransom demand.

The Company paid 75 Bitcoins which at the time had a value of roughly \$5 million. Subsequently in June of 2021, the FBI recovered \$2.3 million of the Bitcoin (OPA, 2021). The hackers did proceed to gradually restore data and the company was simultaneously able to restore some data and reopen the pipeline after a week. This is a disturbing incident, as no other energy related ransomware or other cyber-criminal activity has involved neither such a major impact nor such a large ransomware payment. Energy infrastructure is not high on the list of ransomware targets, with the health care industry being the top target (U.S. Department of Energy, 2021).

Electrical Grid Security and Reliability Issues.

In contrast to pipelines, where failures are rare (although they can be catastrophic), the electrical grid has frequent instances where there are interruptions of service, surges, and power spikes. Prolonged blackouts are less common, but the complexity of the electrical grid in the USA, particularly in the largest and most populous states such as Texas, means management of electric reliability is fraught with issues. Most issues are weather related, but some disturbances are deliberate. In this paper we map and analyze both types of issues.

The key cause of the growing instability of the electrical grid is the diversification and spatial spread of power generation sources and increasing reliance of consumers on greater amounts of electricity for supporting population growth and an information-based economy. This means that demand is growing at a time when supply is more problematic. Most electrical outages are due to severe weather and climate change might be increasing this potential source of trouble. Adoption of wind and solar energy in many states like Texas increases the complexity of electrical system management while making the supply much less reliable since the intensity of sunlight varies diurnally and seasonally and with hard to predict and constantly shifting weather patterns. Wind is also highly variable, sometimes it is too strong and often too weak or non-existent. There are two specific examples of widespread power failures in Texas tied to solar power inverter issues and one tied to wind power generation problems in 2021 and 2022 (NERC, 2021, NERC 2022). These regional issues in West Texas pale in comparison to the power supply (and natural gas supply) issues associated with Winter Storm Uri in February 2021. No attack against electrical transmission or distribution facilities in the U.S. caused more than local and temporary disruptions. The North American Electricity Reliability Corporation tracks electrical outages from all sources and publishes the results that are shared with the Energy Information Administration in annual reports (EIA, 2023)

To better understand the security threat posed by attacks on the grid the author's mapped 23 years of relevant incidents. The incident that caused the greatest loss of power was an attack in the Las Vegas area that caused loss of power for 110,000 customers for a few hours. This contrasts with the multi-day loss of power during Winter Storm Uri that impacted over 20 million Texans. We discuss disturbances of the electrical grid due to attacks on a nationwide basis first, then focus on the impact of Winter Storm Uri in Texas.

Mapping Attacks Against the Electrical Grid in the USA.

Mother nature can produce disasters, but humans can be destructive as well. Responding to electrical emergencies can be aided greatly by use of GIS for mapping these emergencies (King, et al, 2007). Over the 23-year period from 2000 to 2023 there have been 310 U.S. events where electrical power was disrupted by attacks. The most common type of incident is vandalism and can be as minor as spray painted slogans or theft of tools; theft of copper cable also happens (Lawson, 2005). Suspicions loitering has been recorded including

using drones and seen on closed circuit cameras. Sabotage is more frequent than in the past, but often does not cause an electrical outage in most cases. Some very concerted attacks have not caused loss of power to anyone including a 2021 attack using a modified DJI Mavic II drone with a copper bar suspended by a four-foot nylon ropes in Hershey, Pennsylvania (Barrett, 2021). Cyber-attacks have been uncommon but have increased since 2015 as seen in **Figure 16**; largely due to the ramp-up of cyber-security efforts by utility operators assisted by the Department of Homeland Security.

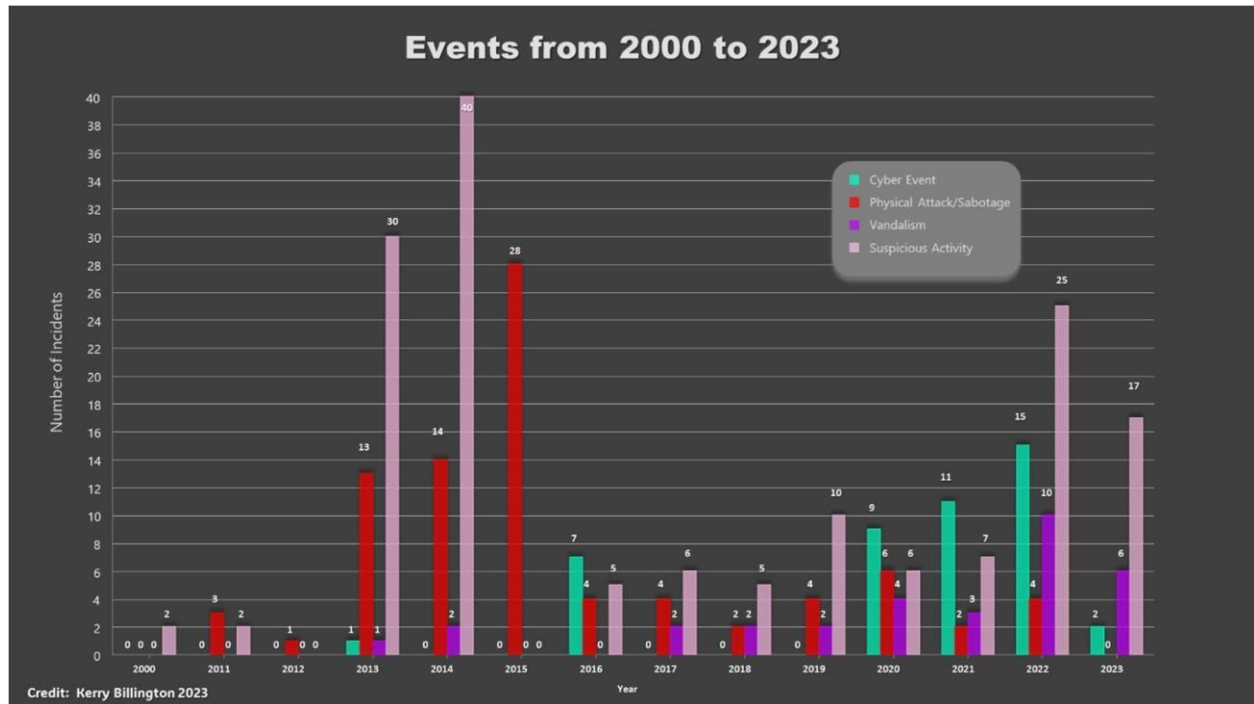


Figure 16. Bar Chart of the number and type of incidents involving disturbance to electrical infrastructure between the years 2000 and 2023. Note that the incidents include Cyber-attacks, physical attacks/sabotage, vandalism, and suspicious activity. These are all reported annually by NERC and available from the Energy Information Administration. Note the high number of attacks and vandalism in 2014 and 2015. Data for 2023 is for the 1st three months only.

Nevertheless, there have been physical attacks and sabotage and they reached their height in the years 2013-2015 declined but increased again since 2019 (EIA). The tactic of shooting at transformers and at individual solar panels have increased. On December 3, 2022, in Moore County, North Carolina, there were two attacks on electrical substations by rifle fire that impacted 40,000 customers (Fox News, 2023). Texas has been largely free of physical attacks in the last decade, with only minor issues in Travis County and Rusk County.

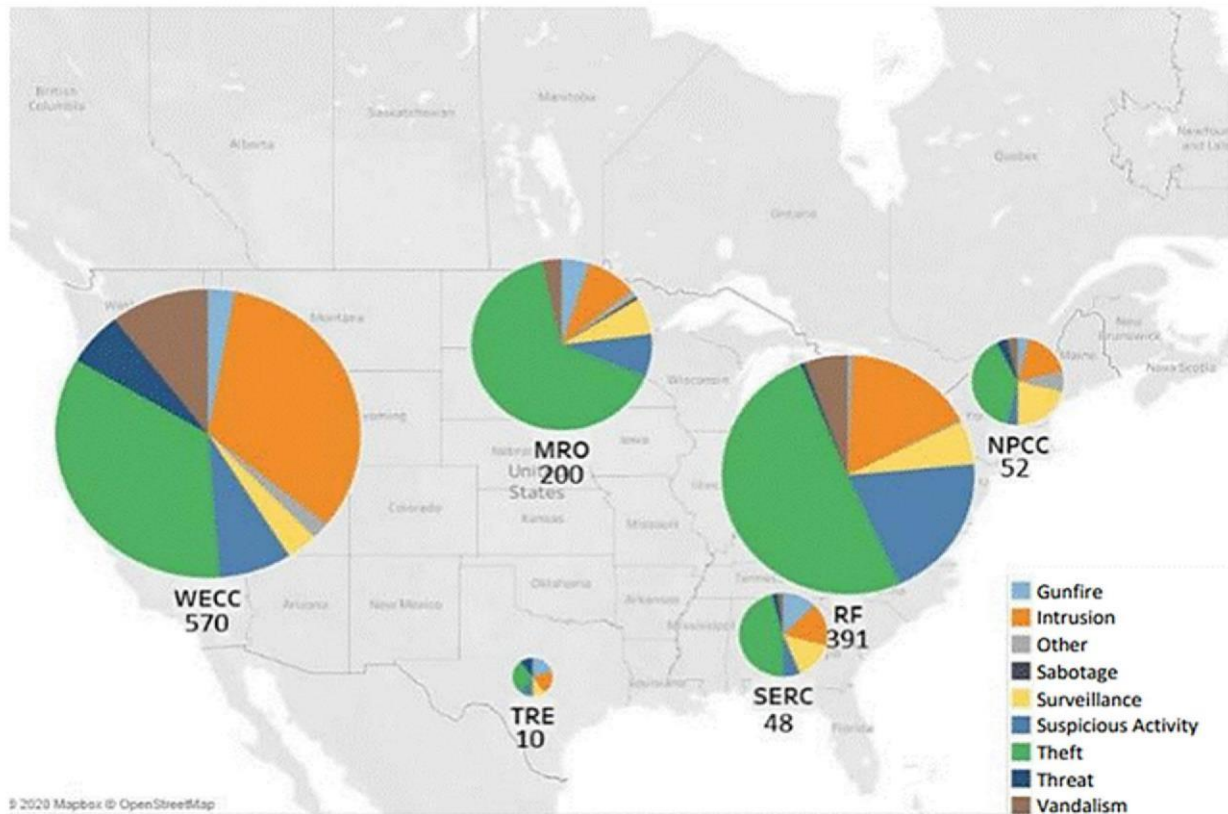


Figure 18. This figure is from the 2019 North American Electric Reliability Corporation (NERC) report on electrical reliability. It is figure 5.33 in that report. It is one of the few GIS generated maps available on the topic of attacks on the electrical infrastructure but is for a single year and only provides data by region. In that year the Texas region had the fewest incidents, and the Western region had the most incidents. Most of these incidents did not cause loss of power to customers. Even gunfire was often not the cause of a loss of power.

GIS maps of vandalism, physical attacks/sabotage, suspicious activity, and cyber-attacks by State, by County for all attack types and by individual attack type for the period from 2000 to 2023 are presented in **Figures 19, 20, 21, 22, 23 and 24.**

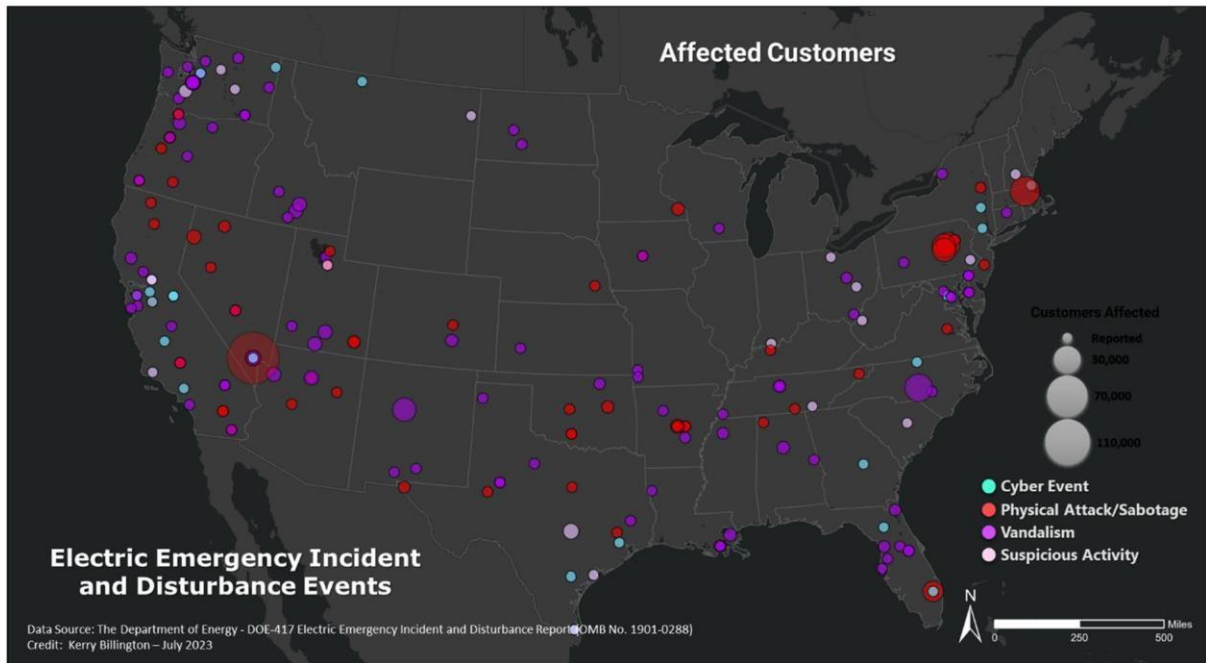


Figure 19. This map shows 23 years of data on disruptions to the nation’s electrical grid from physical attacks, sabotage, and cyber-attacks as well as vandalism and suspicious activity. The size of the circles indicates the number of customers who lost power. The color indicates the type of incident.

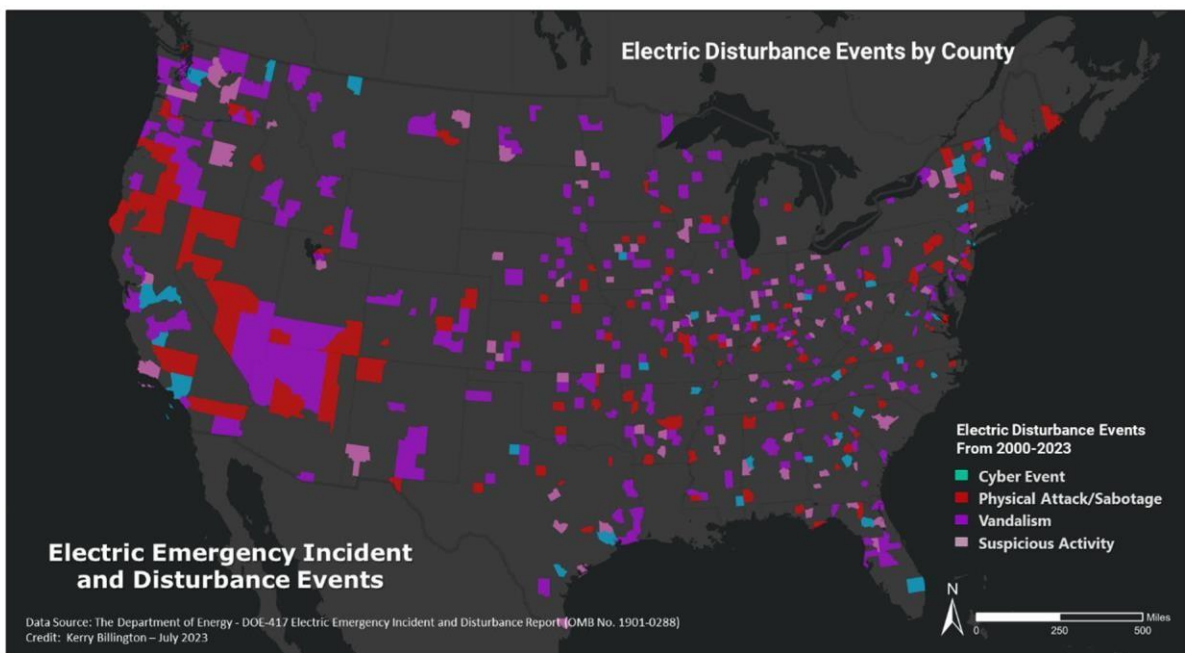


Figure 20. This map was made for the Institute for Homeland Security in the summer of 2023. It is based on 23 years of incidents reported by electricity providers to NERC and released by the Energy Information Administration. In the period 2000 to 2023 there were 435 incidents of physical attacks, sabotage, vandalism and cyber-attacks.

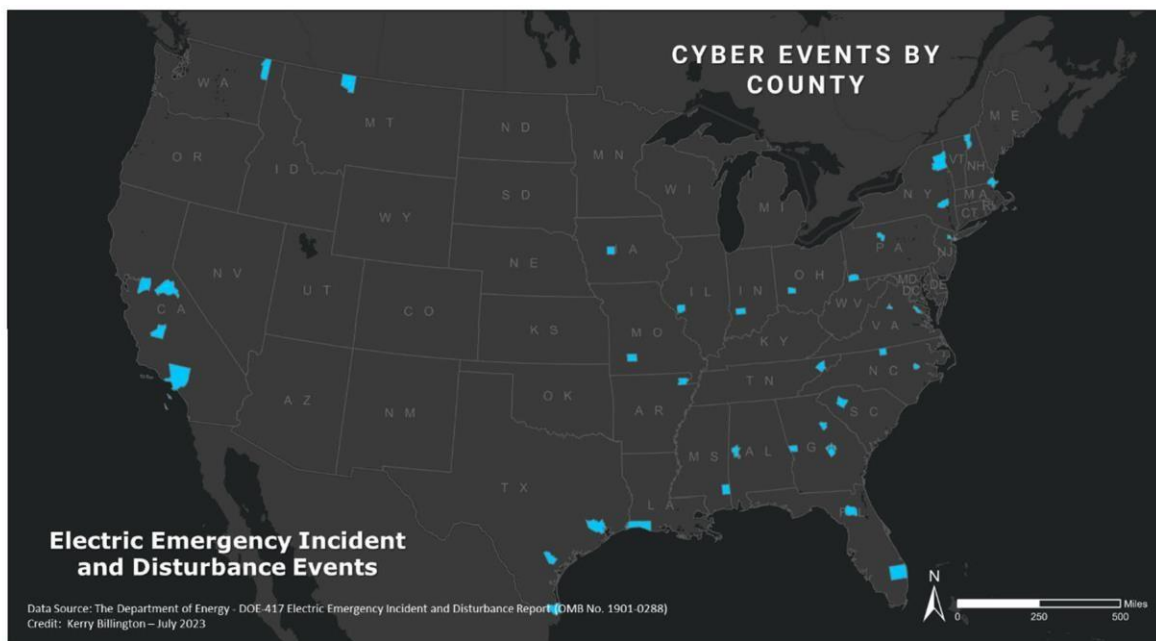


Figure 21. This map shows locations of cyber-attacks in the period of 2000-2023 on electrical infrastructure by county in the USA. It should be noted that many of these incidents do not cause loss of power to any customers. Most of these incidents occurred in 2015

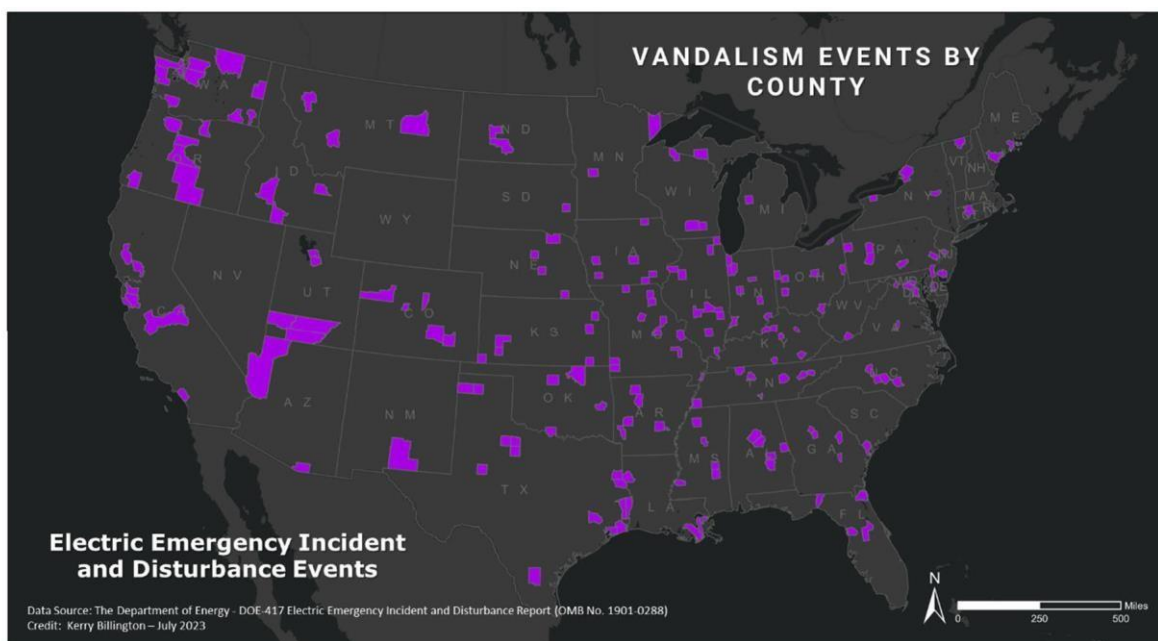


Figure 22. This map shows incidents of vandalism of the energy infrastructure of the USA by county in the period of 2000 to 2023. Most of these incidents did not result in loss of power by customers.

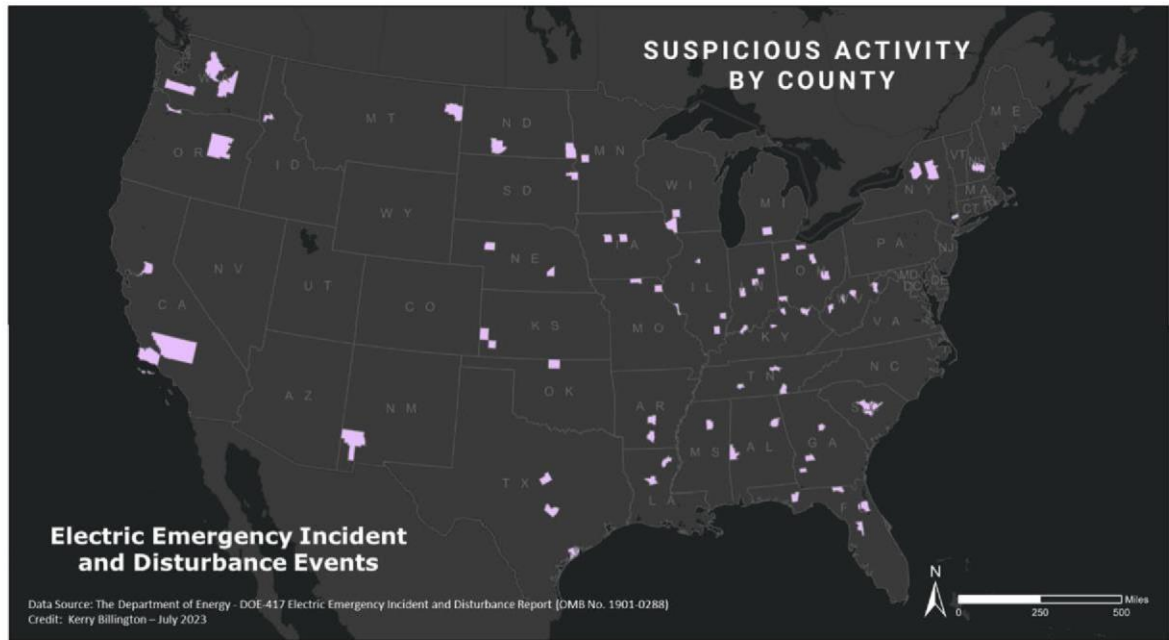


Figure 23. This maps shows suspicious activity by county involving the electrical infrastructure of the USA for the period of 2000-2023. Note that some incidents of suspicious activity by UAV's (drones) in Pennsylvania and in Arizona that involved over flights of nuclear power plants on multiple occasions were not reported by the Energy Information Administration.

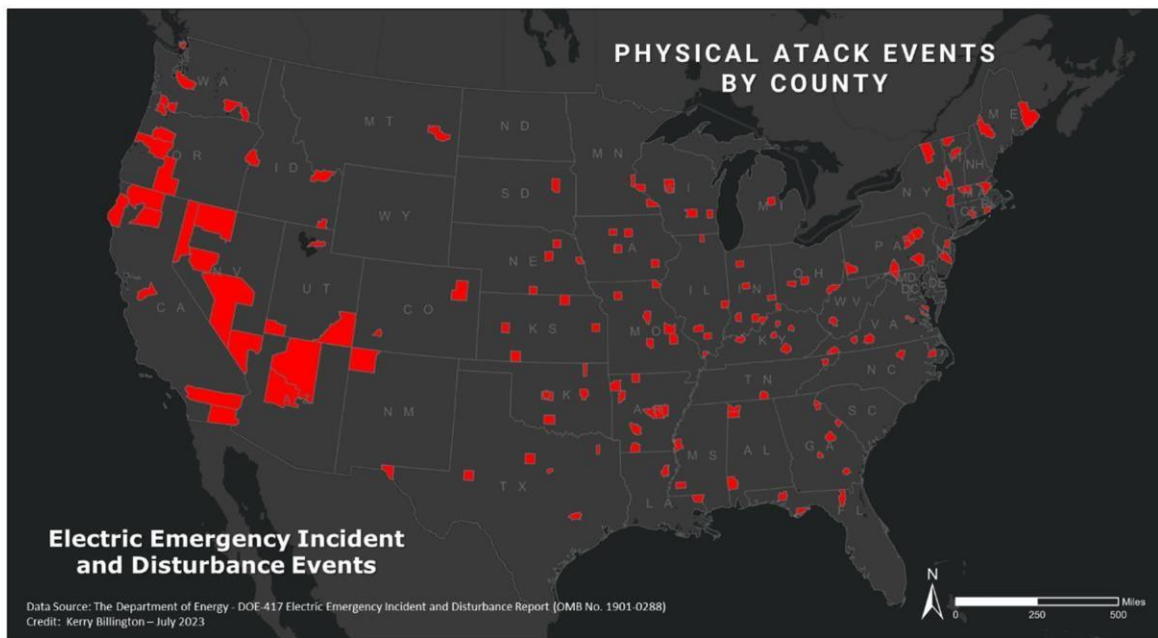


Figure 24. This map shows physical attacks and sabotage (including some incidents of sabotage by energy company employees of their own facilities). The map covers the period 2000-2023 (but only the first three months in 2023). Note the state of Nevada and Arizona appear to be heavily impacted, but these states have large counties which makes such maps somewhat misleading.

The single most damaging attack recently occurred in Pierce County, Washington in the suburban fringes of Tacoma (**Figure 25**). Four transformers were all attacked on Christmas morning 2021. Each was drilled into to release the mineral oil contents and cause a fire. The attacker's motivation was to burglarized businesses and ATM machines of cash left in them on Christmas eve on a morning with little activity. The attackers also planned to fell trees to bring down power transmission lines. \$3 million in damage was inflicted and 14,000 customers lost power for most of Christmas Day (U.S. Attorney's Office, Western District of Washington, 2023).

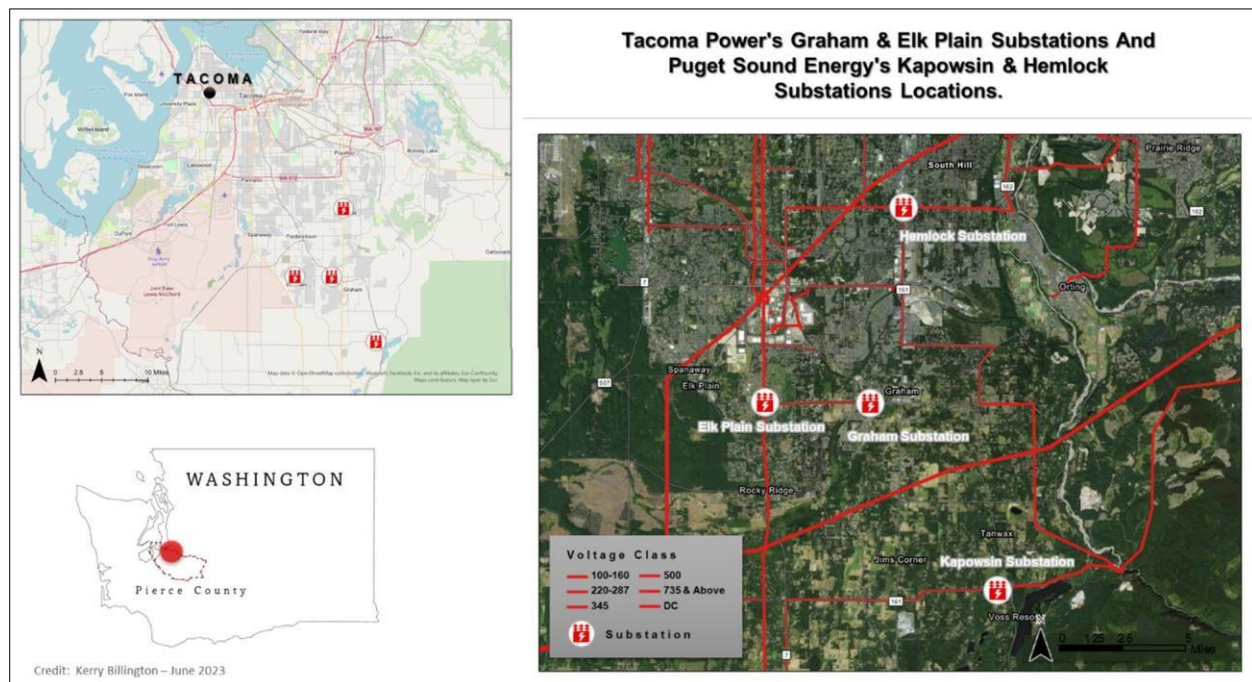


Figure 25. Three maps related to incidents on one day in 2021 in Pierce County Washington. The incidents involved four attacks by a pair of individuals on substations knocking out power for 14,000 residents on Christmas day. The attacks involved drilling holes into transformers to cause them to explode. The attacks caused \$3 million in damage. The motivation appears to have been to commit burglaries of businesses in the community which would not have functioning alarms

Winter Storm Uri; February 2021:

The Largest Blackout in Texas History.

Winter storm Uri was a slow-moving continent-wide disturbance which caused freezing rain, snow, ice, and sub-zero temperatures to reach as far south as Dallas and subfreezing temperatures to reach the Gulf of Mexico, for multiple days in Mid-February, culminating in record lows on February 15, 2021. **Figure 26** shows a map of the temperature deviations from normal for the period (Weather Service, 2021).

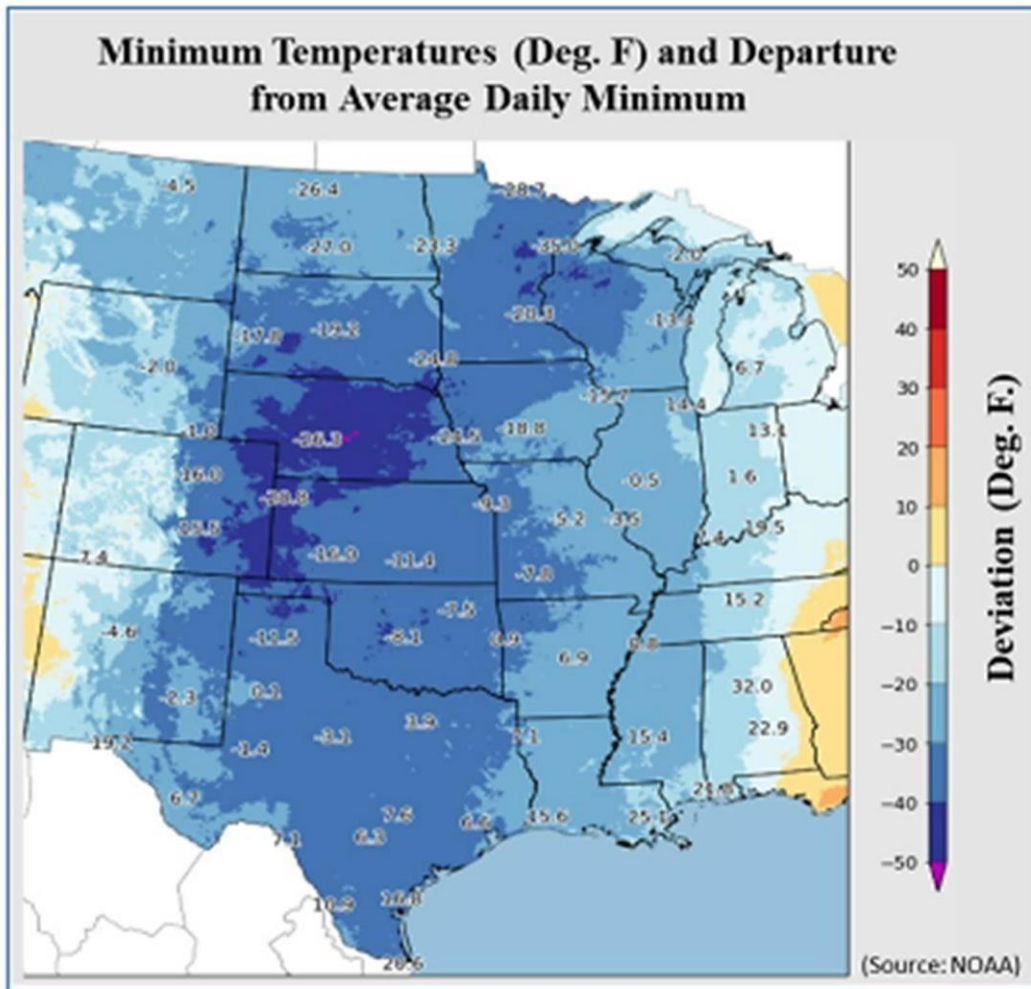


Figure 26. Map shows how extensive and cold winter storm Uri in February 2021 was in the U.S. Deviations of over 40 degrees below normal mid-February temperatures were recorded, but a similar storm occurred in 1983 and generally few all-time low records were broken, a lesson that energy facilities should note as there were not extensive blackouts in 1983.

Although not unprecedented, being matched by an event in 1983 and events in the late 19th century, it was a storm that the modern power grid in Texas could not cope with (Vasquez, 2013). This was in part due to the State's reliance of wind energy and natural gas transmitted by pipeline across multiple states and within Texas from the Permian basin and Eagle Ford shale regions and West and South Texas to urban demand centers at the opposite side of the State (FERC, 2021).

This event had multiple spatial factors, so mapping it in a GIS is a good way of understanding the extent of the event. With added effort the temporal dimension of the storm and power failure can also be understood. Wind energy was hard hit early in the storm because although the wind did blow during the storm, many wind turbines were coated with ice and shut down for as long as a week until they thawed out. This was a signal failure of the managers of the power grid and the operators of the wind farms to anticipate such conditions, as turbines can resist low temperatures if designed to do so. A bigger operational and design failure was that

more turbines (in fact most failed ones in Texas) were taken offline because the sub-freezing temperatures were measured by sensors designed to only allow them to operate under ideal conditions. Most of these turbines could have functioned during the storm, although lubrication oils might have been less effective. One lesson that has been learned programming changes allow the power plants to function in colder than anticipated have since been adopted. Since the storm came from the Northwest quadrant and wind generation is concentrated in the Texas Panhandle this part of the power supply failed early in the storm. Wind can provide as much as 40% of Texas power needs and this vital source was largely unavailable.

Solar power also suffered from issues with coating of the panels with ice and more solar electricity was lost due to transmission line issues. Also, solar power did not perform well due to short winter days and cloudy weather. This limitation was predictable, but without battery storage, solar is not an option for base-load power needs in periods of intense cold, such as during the night in a storm like Uri. One recent response has been a major increase in battery storage capacity in Texas and the State went through a cold spell in the winter of 2022 without a crisis.

Oddly, one of the usually most reliable sources of base-load power failed at a critical time. Nuclear power, though supplying less than 10% of Texas power, typically is reliable and not impacted by weather. Nuclear energy is supplied in Texas by four reactors at two power stations, one near Dallas and one near Bay City on the Gulf of Mexico. Bay City is usually a warm area, but the cold was intense in Uri even on the Gulf of Mexico. It was cold enough that cooling water for the South Texas Nuclear Project was colder than planned for and caused reactor intake pumps to register issues. They shut down, forcing the reactor to go offline at a critical time in the power crisis causing the grid to lose 1.3 gigawatts at the most critical hour when the coldest air was hitting Houston and San Antonio and demand was peaking for power. It is hardly an exaggeration to state that had this plant stayed online, the blackout might have been averted. This was an operational error, as the cool water would not have damaged the reactor. Thus, 25% of nuclear generation capacity and around 2% of Texas total generating capacity was unexpectedly unavailable at the worst possible time (Siegel, 2021). **Figure 27** shows the distribution of power plants by type that failed at some point in the storm.

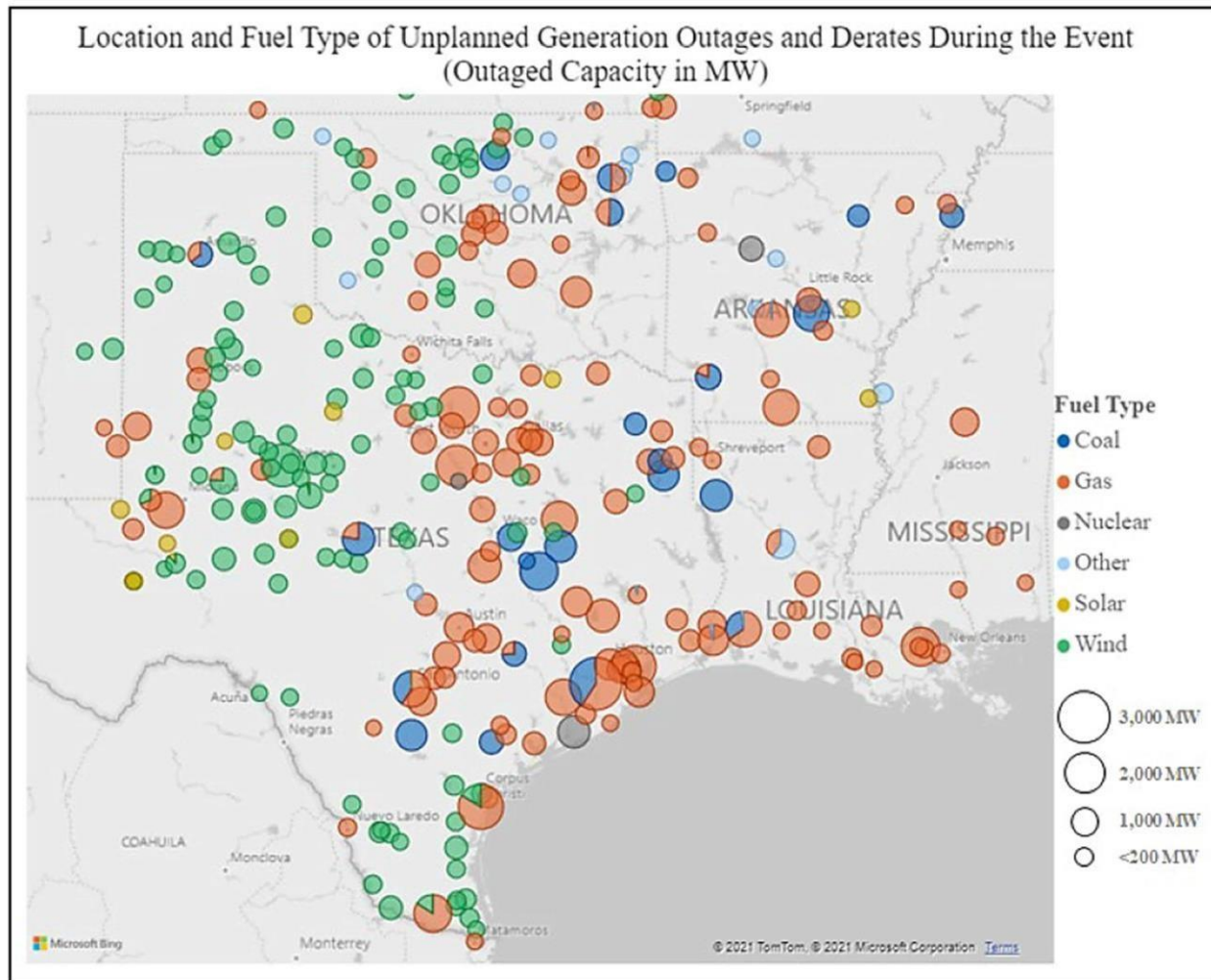


Figure 27. This map from the FERC Final Report on 2021 Winter Storm Uri shows the distribution of power plants that failed by generating capacity and type. Note “other” plants are co-generation facilities. Note: The South Texas Nuclear Project lost one of two reactors at the start of the crisis on February 15. Note also the impact extended beyond Texas, but prolonged blackouts were limited to Texas. Wind farms represent multiple turbines. 1,796 power plants were off-line at some point in the storm.

The performance of coal fired power plants located in Texas and as far removed as Memphis, Tennessee was also poor. These had a range of problems, mostly due to freezing or transmission issues, but in some cases due to external power supply issues that complicated their operation. In most cases, it was freezing of the air pollution control systems. Flue gas scrubbing depend on liquid water so freezing can impact them. Coal plants operate in other colder regions easily with these pollution controls, so winterizing coal plants is an appropriate response to strengthen the electric grid in Texas. (FERC, 2021).

Texas uses natural gas for two main purposes: domestic heating of homes (and the water inside them) and electrical generation (Judson, 2013). While there are gas fields near major urban areas like the Barnett Shale in Fort Worth, the main supply (in fact, the largest gas field in North America) is in the Permian Basin of West Texas. Electrical supply to the Permian Basin to run compressor stations to push gas through pipelines to the demand centers in the Eastern quarter of

the State has been an issue for many years. Also, gas pipelines have issues with freezing of condensate. Cold weather can therefore make it difficult to operate wells and pipelines. However, gas pipelines are routinely operated in places like the mountains of Western Wyoming in temperatures 50 degrees colder than pipelines that froze in Texas experienced, so operators are now working to insulate gas pipelines in Texas. (Hibbard & Schatzki, 2012).

The growing shut down of wind energy, solar energy and coal fired plants contributed to shortages in electricity that forced the shedding of load. In a very questionable set of policy and economic incentives, natural gas pipeline operators were prioritized for load shedding over residential customers. The pipeline companies had received preferential rates for electricity to agree to this measure. In February 2021 this shortsighted policy backfired for everyone as the pipeline operators could not deliver the gas needed to heat homes and power the state's gas-fired power plants. Thus, instead of temporarily shifting load, this policy contributed to an extended blackout (University of Texas, July 2021). **Figure 28** shows the shortages of natural gas that developed in the state as gas pipelines failed, and demand soared simultaneously.

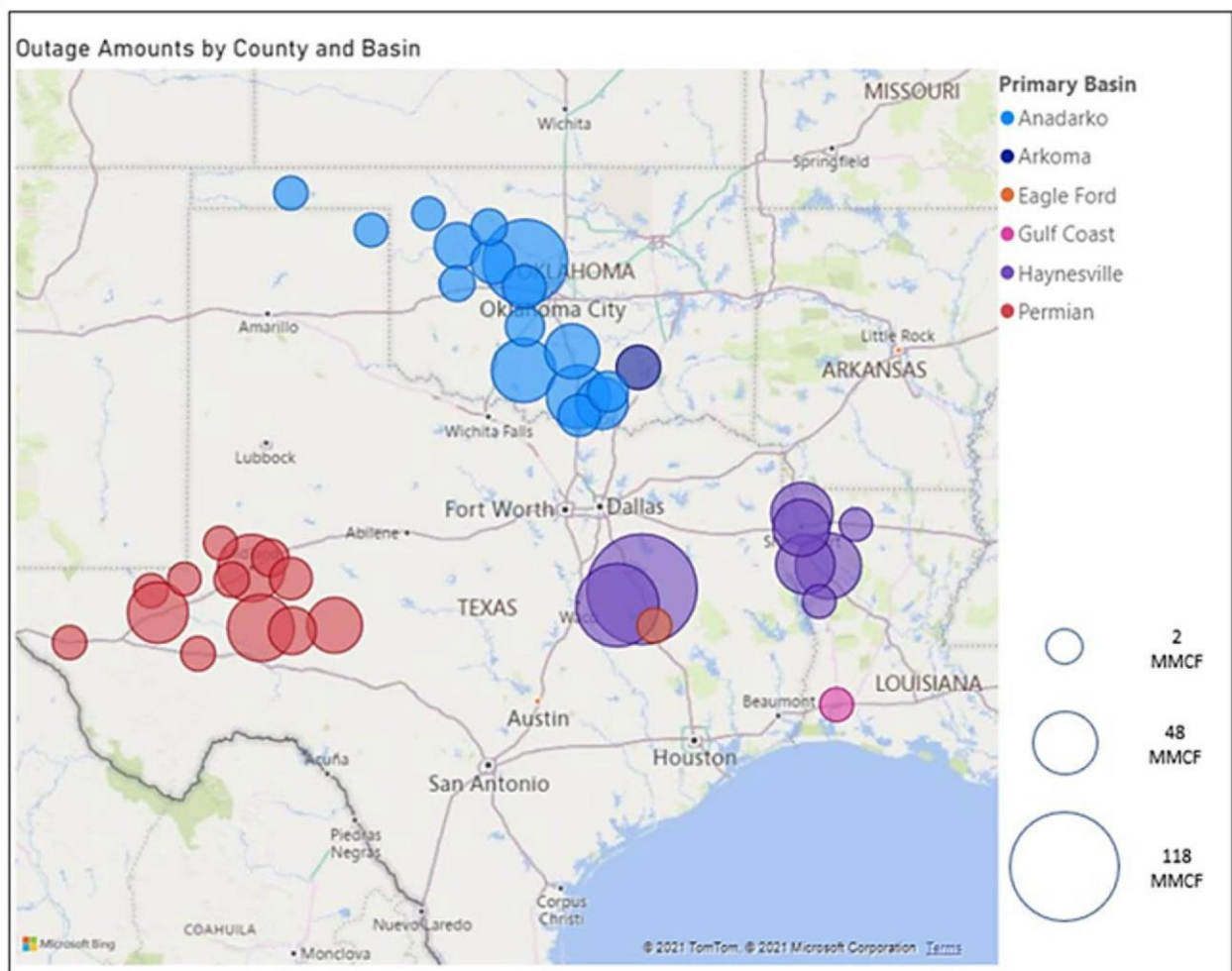


Figure 28. This map was figure 40 in the FERC Final Report on Winter Storm Uri. It shows the quantity of natural gas that was unavailable during Winter Storm Uri mapped by magnitude of the loss from a

specific pipeline and basin. The significance is that this natural gas was needed for home heating and to run gas-fired powerplants, lack of supply triggered power plant shutdowns throughout the region, it was the single largest factor in the subsequent blackouts.

The issue all come down to timing and magnitude of impacts. The power plants themselves were not well winterized in places like San Antonio. Co-generation facilities which are dependent on natural gas also failed along the Texas Gulf Coast. All the major sources of electricity suffered significant failures in February 2021. Thus, natural gas, wind, coal, solar, nuclear and co-generation all had a significant proportion of their capacity unavailable. Only hydroelectric power from Falcon, Amistad and Canyon dams did not fail to deliver and these sources supply less than 1% of Texas electric needs. Thus, a combination of factors caused what should have been a period of higher-than-normal demand and temporary shifting of load into a crisis where the frequency of the grid came perilously close to causing extensive damage and forced unplanned blackouts lasting up to a week and impacting 20 million people. 12 million people also lost tap water and estimates of the economic damage range from \$100 to \$250 billion. Additionally, perhaps 200 people died some of hypothermia in their darkened homes.

Some large areas of the state in “Deep-East Texas” including Conroe, Huntsville, and Beaumont, did not experience power outages because they are not part of ERCOT. They are part of the power pool covering Louisiana. Conversely, the loss of generating capacity extended beyond Texas into parts of Oklahoma, Arkansas, Louisiana and even Tennessee. But these were short lived, as these regions were able to shift power, as shown in **Figure 29** (FERC, 2021). A graph of the loss of power in Winter Storm Uri taken from the FERC Final Report is portrayed in **Figure 30**.

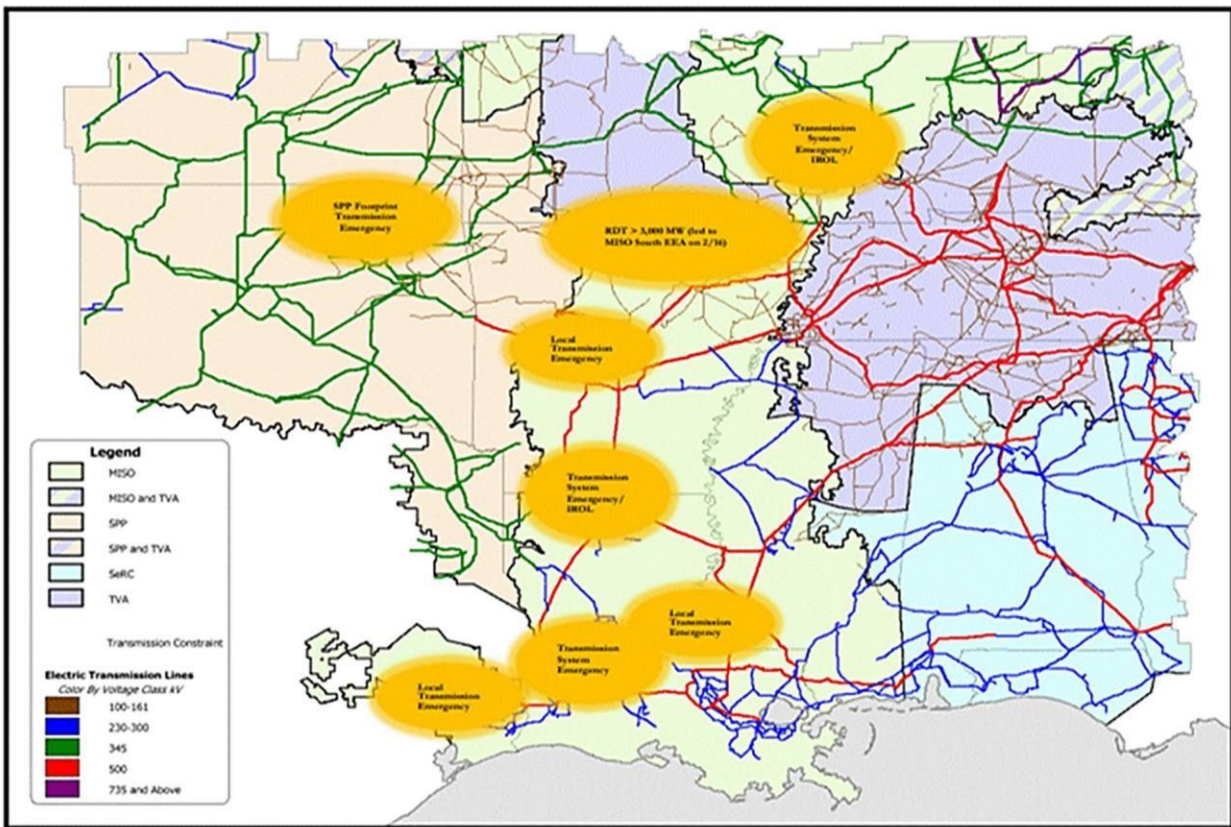


Figure 29. This map was figure 84 in the FERC final report on Winter Storm Uri. It shows the power pools for areas adjacent to Texas. Note that the South-west Power Pool does extend into Southeast Texas. Most of Texas is in the ERCOT region. Most of the extended blackouts were limited to the ERCOT region and part of Texas

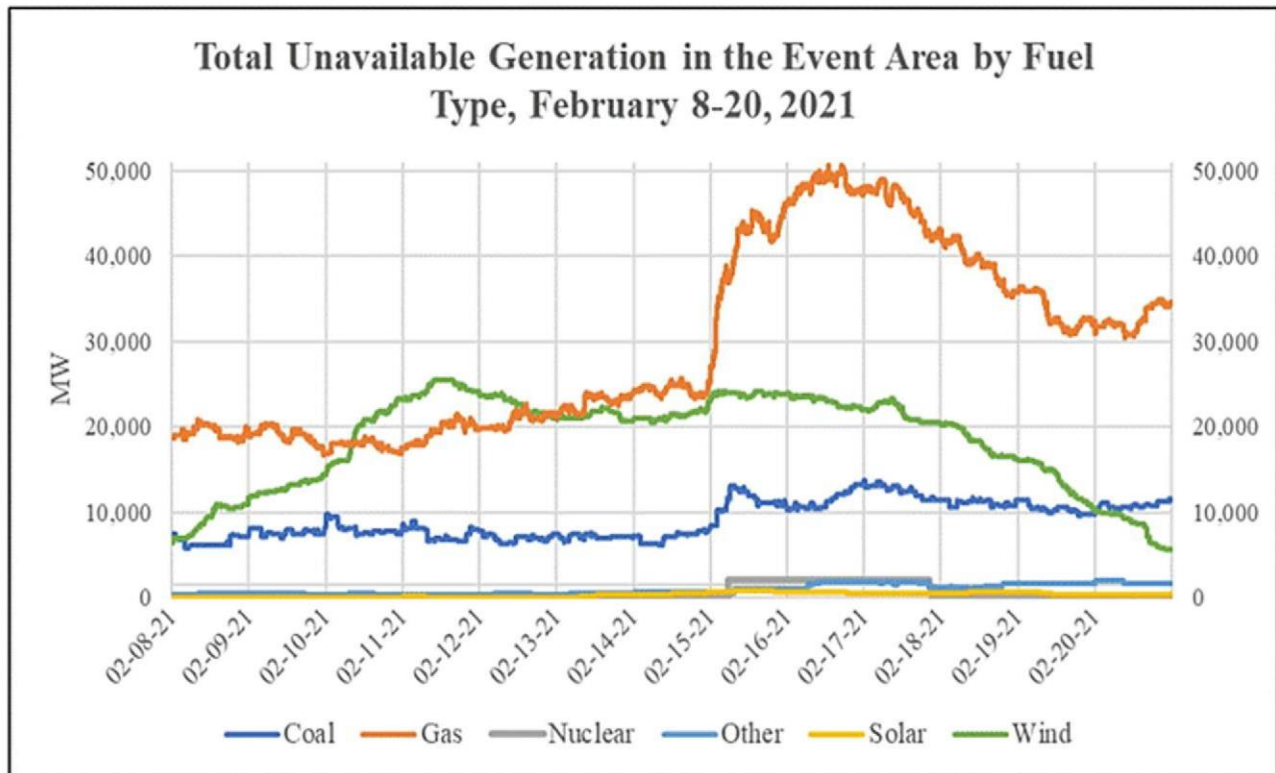


Figure 30. Graph of unavailable power generation in Winter Storm Uri by date starting February 8 through February 21, 2021. Note the increasing loss of wind energy early in storm, the large spike is loss of natural gas generation on February 15. The loss in nuclear and the loss in other (co-generation dependent on gas) coincided with the crisis in power supply on the night of February 14 and early morning of February 15, loss in coal came later.

Practical Applicability of this Research.

GIS and other geospatial technologies are central parts of management of the energy sector's infrastructure. The electrical grid and the pipeline system in Texas and the U.S., and indeed the entire world depend critically on GIS for mapping, management, and analysis of spatial data. These are spatially extensive applications and have used the technology in a key role since the 1980's (Greenfeld, 1998). Thousands of professionals in the energy sector use GIS daily with many of them solely focused on GIS coordination, data analysis, and building geospatial data.

In the security sphere, geospatial intelligence and mapping and analysis of incidents, pattern analysis, and study of vulnerabilities is a key capability. Notably, however, data has become much more widely available, and terrorists have repeatedly used satellite imagery and mobile maps in planning and carrying out attacks. Surveillance of facilities by drone is a known vulnerability for distributed facilities in fields like power transmission and distribution. Domestic terrorists have used drones in planning attacks and have attempted to use modified drones in attacks. GIS-generated maps are one of the most common ways of understanding widespread phenomena like the winter storm Uri power outage.

This paper is associated with both a video showcasing these maps as well as a *storymap* that is present on the SHSU portion of the esri online website. Parenthetically, esri is the world's leading GIS company and its software was used throughout the mapping of these events and by all U.S. and Texas State government agencies.

The appendix contains multiple figures taken from official FERC/NERC/ERCOT reports created with GIS. The authors are planning to geocode the 1796 power sources in Texas that failed during this massive event to generate more sophisticated spatial analysis of the spatio-temporal extent and magnitude of the event. Analysis of such maps and geospatial data can help prevent power outages and other reliability issues for critical infrastructure (Gopika, Et al, 2020).

Conclusion.

This research work opened some interesting avenues for understanding a very important issue; the security and reliability of energy infrastructure. While it was focused on Texas, some issues pertinent to Texas such as the Colonial pipeline also extended into other states. The electrical reliability issues posed by cyber-attacks, physical attacks, sabotage, and other issues while happening in Texas were also present in all other states and were mapped on a nationwide basis to elucidate patterns that might be present over time in data focused solely on Texas. Conversely, Winter Storm Uri, impacting other states was focused in its adverse impacts on the State of Texas. The authors would make the case that Texas has become more vulnerable to widespread power outages in weather events due to the growing complexity of the electrical grid, pressures from rapid growth, and greater reliance on renewable sources like wind and solar that are variable and weather dependent.

We can hope that more battery storage, prioritization of gas transmission facilities for receiving available power in winter storms, and winterization of gas wells, wind turbines, gas pipelines, and power plants, including older plants like coal fired power plant with air pollution control equipment that froze can avoid a replication of the loss of power experienced in 2021.

Disclosure Statement.

The authors are on the faculty and/or are graduate students at Sam Houston State University and are not affiliated with any of the energy or law enforcement agencies mentioned in this paper. They do not have any financial interests in these firms or organizations at the time this paper was prepared. Therefore, the authors report there are no competing interests to declare.

Biographical Note:

The lead author Dr. Mark R. Leipnik. received a PhD in Geography in 1995, focused on the application of GIS in the assessment and remediation of groundwater contamination at Vandenberg Airforce Base and was employed as an environmental scientist with the U.S. Department of Interior at Hoover Dam prior to joining the faculty of what is now the Department of Environmental and Geosciences at Sam Houston State University in 1996. He is author of two books and over 100 book chapters, journal articles and conference papers, most of which relate to environmental, law enforcement and spatial infrastructure applications of GIS.

Kerry Billington is a master's degree student in the Applied GIS Program at SHSU and was formerly a GIS Database Administrator at Amoco Production Company in Romania and Houston.

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APPENDIX I. HIGH RESOLUTION IMAGES OF MATERIAL IN THE BODY IN FIGURES.

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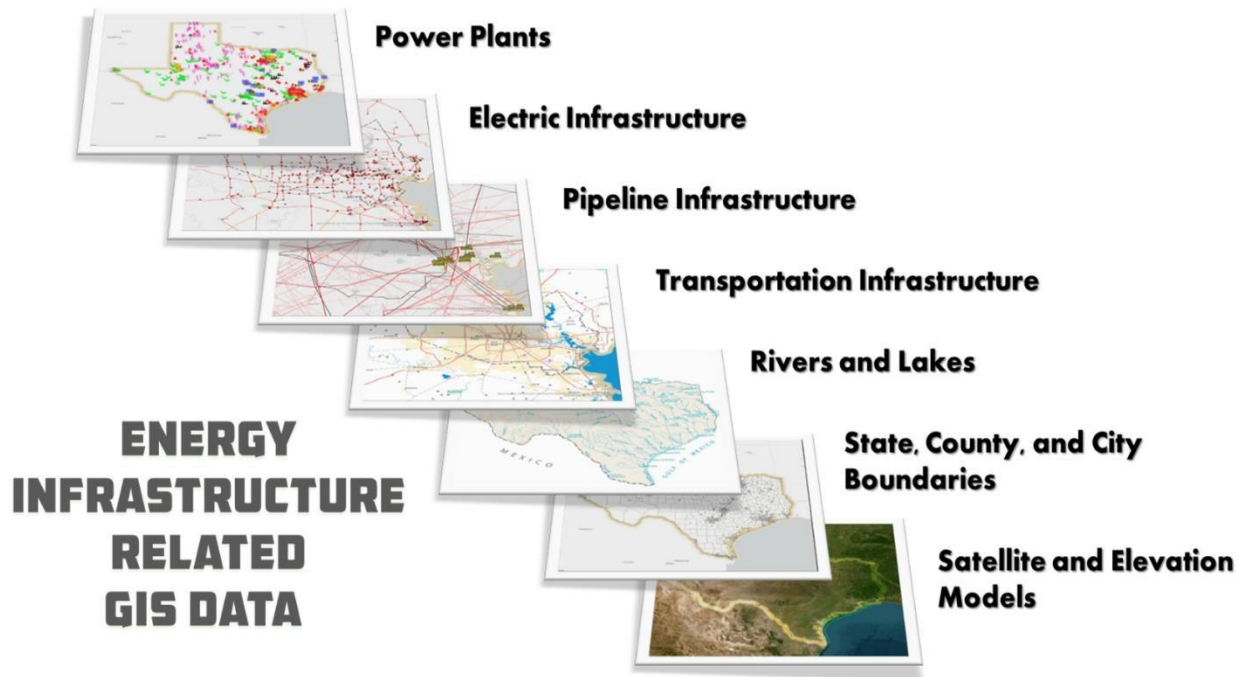


Figure 1. GIS layers most relevant for mapping energy infrastructure security issues

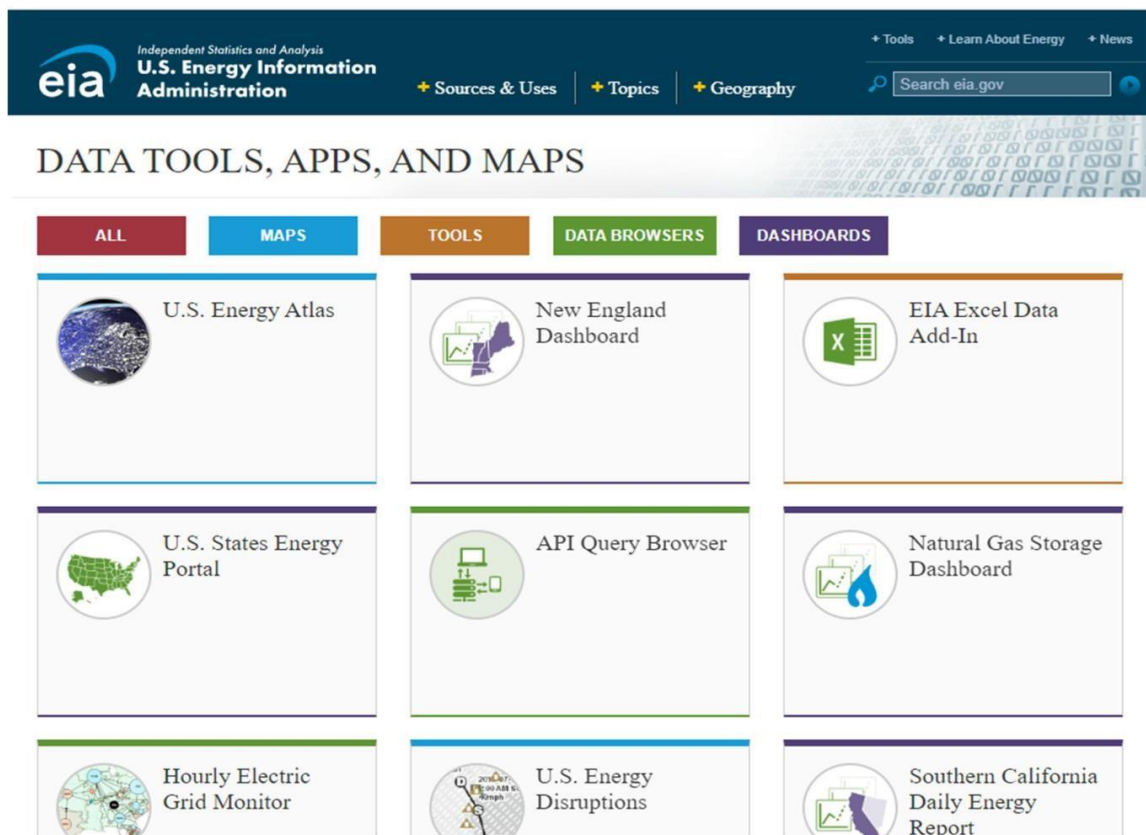


Figure 2. Geospatial data available from the Energy Information Administration. To access the website <https://www.eia.gov/tools/>

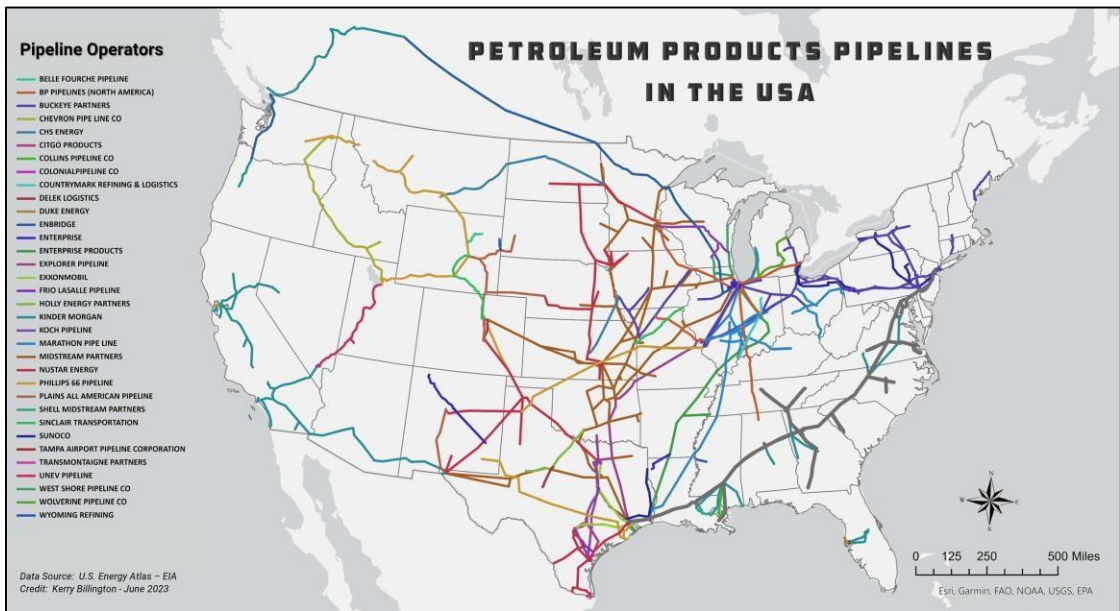


Figure 3. Map of the fuel pipelines in the USA. Note in grey the 5,500 miles colonial pipeline system extending from Houston, Texas to the New York City area is analyzed in detail in this paper (this is the pipeline in the South-eastern and East Coast)

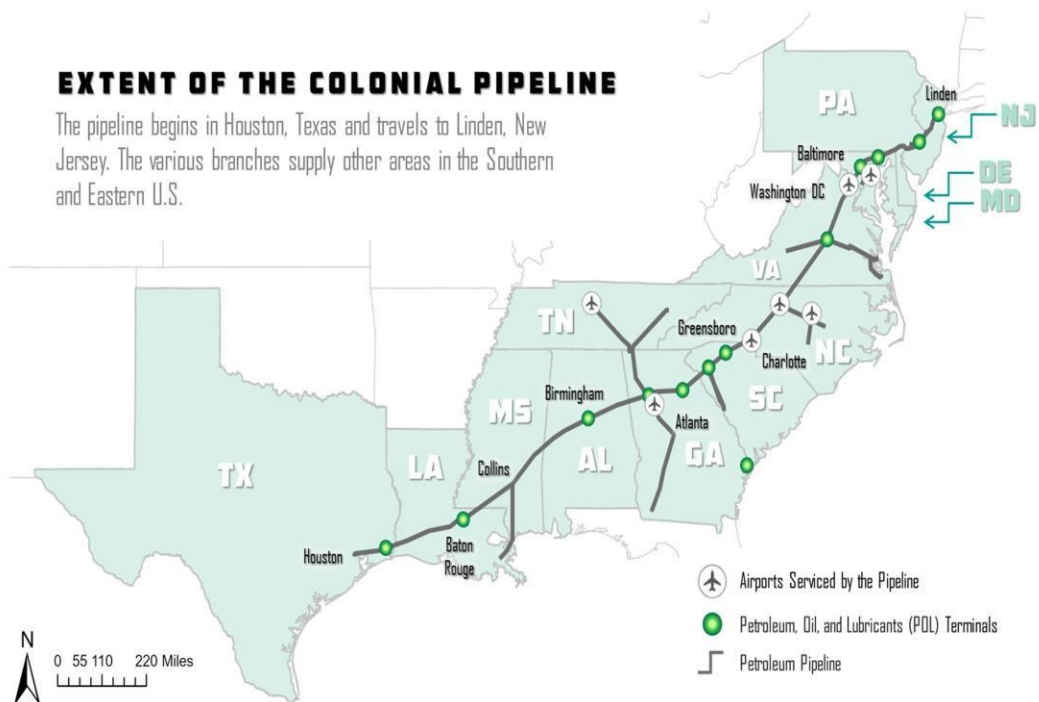


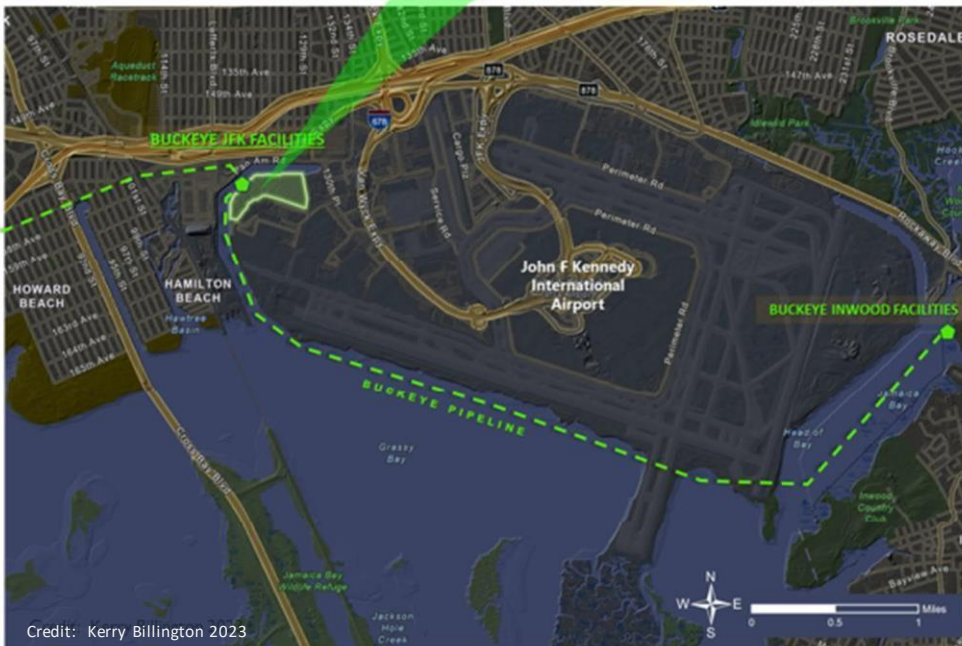
Figure 4. Extent of the Colonial pipeline system showing the various issues it has had in its 60-year history.

Data Source: System Map – Colonial Pipeline Company (www.colpipe.com)

Credit: Kerry Billington – June 2023



Figures 5, 6 and 7. The Colonial pipeline terminus in Linden New Jersey and its connection and extension to the New York City area via the Buckeye pipeline. The Colonial supplies Newark airport with jet fuel and the buckeye carries jet fuel primarily originating from the Colonial Pipeline via a smaller 8 -inch pipeline to La Guardia and JFK airports.



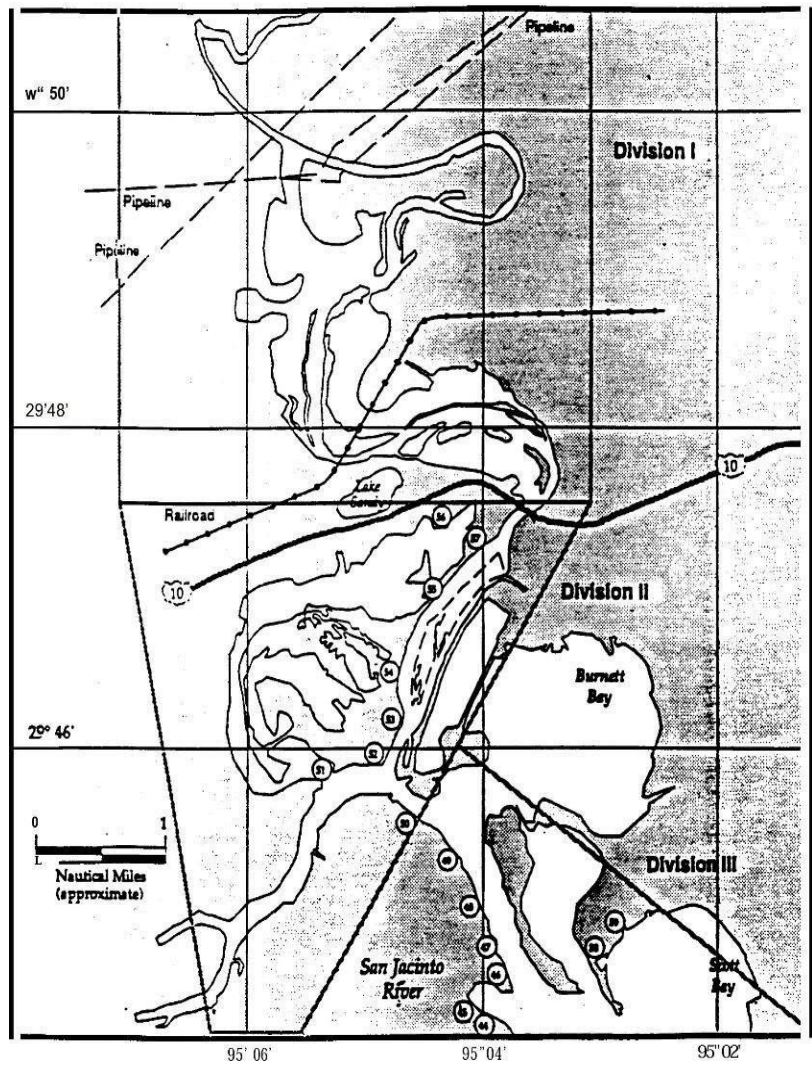
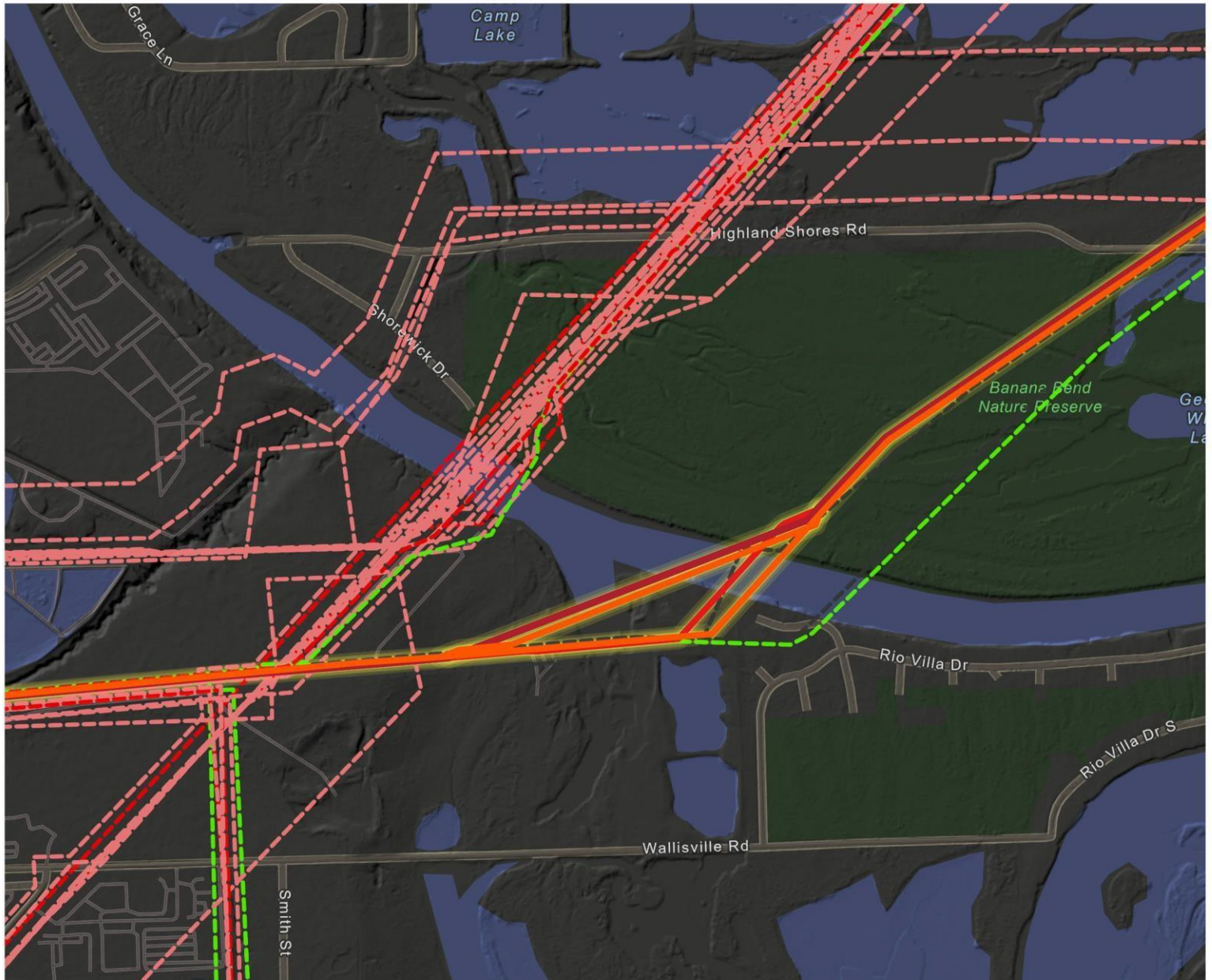


Figure 8. NTSB 1996 pipeline crossings map.



Colonial Pipeline

Line 2: 36 Inch Diameter 

Line 1: 40 Inch Diameter 

Pipelines by Commodity

 Refined Liquid Product

 Crude

 Natural Gas

 Highly Volatile Liquid (HVL)



Figure 9. 2023 GIS generated pipeline crossings map.



Figure 10. The Colonial and several other pipeline remnants in the receding channel of the San Jacinto River in October 1994. The flooding caused the river channel to shift, and don cut into the bed exposing the pipelines which then failed perhaps due to being hit by debris (including parts of homes) carried by the flood waters. In all 37 pipelines were impacted.



Figure 11. Fire on the flooded San Jacinto River in Houston region of Texas following the failure and explosion of the Colonial pipelines on October 20, 1994. The fires burned for several days. And a second fire was deliberately ignited by responders to



Figure 12. Right of way and monitoring well Colonial pipelines. The lines leaked in Oehler Nature Reserve, Huntersville, N.C. The spill is currently estimated as totaling 2 million gallons of gasoline.



-  Incident Location
-  Colonial Pipeline
-  Oehler Nature Preserve
-  Private homes already bought out by Colonial



Maps & Graphics by Kerry Billington 2023

Figure 13. Location of the 2-million-gallon spill of gasoline from the colonial pipeline system that occurred beginning sometime in 2020.

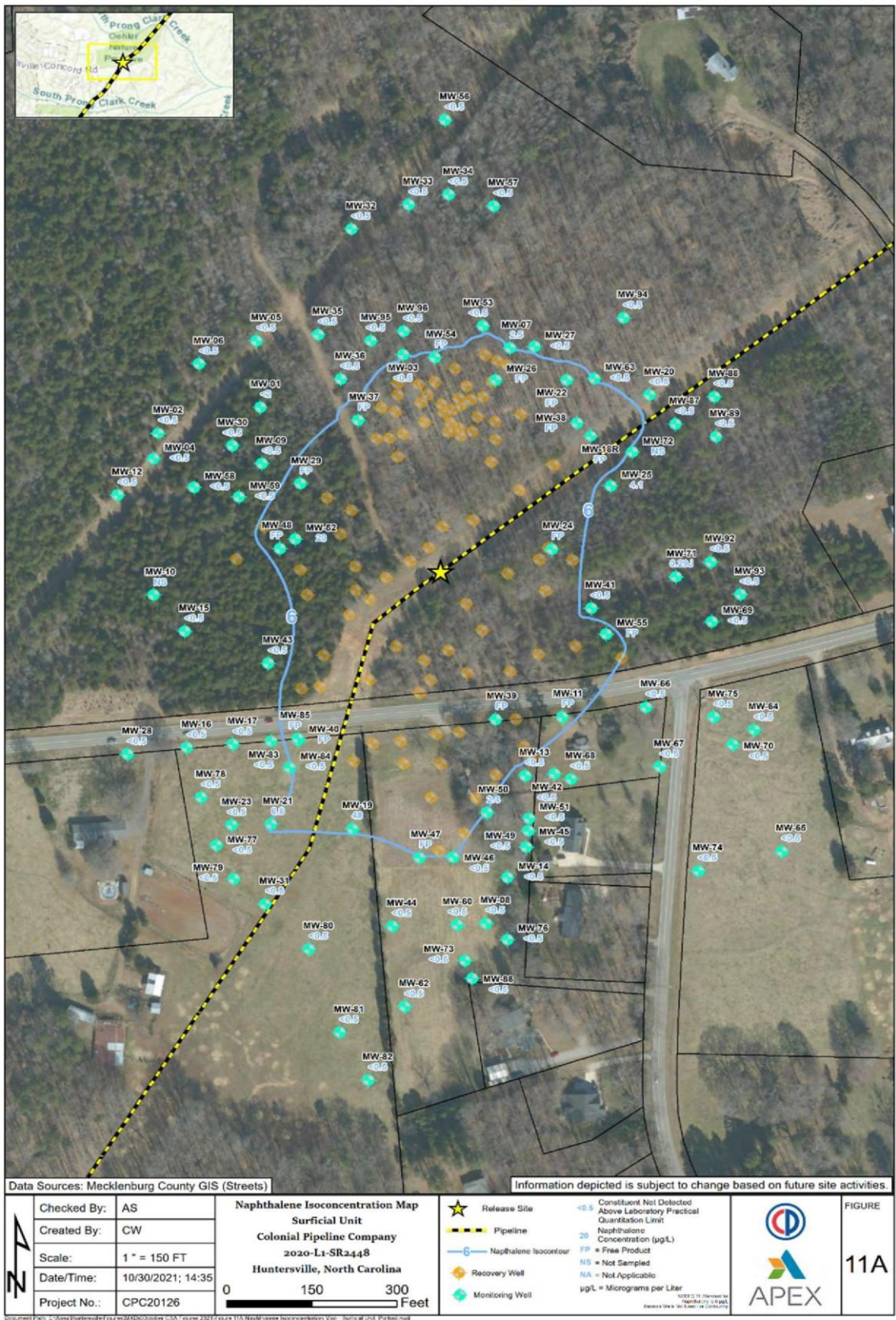


Figure 14. Map prepared by a contractor for Colonial Pipeline and included in a groundwater remediation report released in 2023 by the North Carolina Dept. of Environmental quality. Contaminated wells are shown in brown, the plume extent and “clean” wells are shown.

CBLDNIAL PIP LINE AANS DMWAAE MAY 7, 2021- MAY 11, 2021

The cyber attack prompted the shut down of the entire 5,500 mile extent of the Colonial Pipeline for several days. To date the attack is the largest disclosed attack on critical infrastructure in the United States. A hacker group identified as DarkSide accessed the IT network stealing 100 gigabytes of data in a two-hour window. After the theft, the attackers infected the company's network with ransomware affecting computer systems, billing and accounting. Colonial Pipeline shut down the pipeline to prevent the ransomware from spreading. The closure causes fuel shortages on the East Coast.

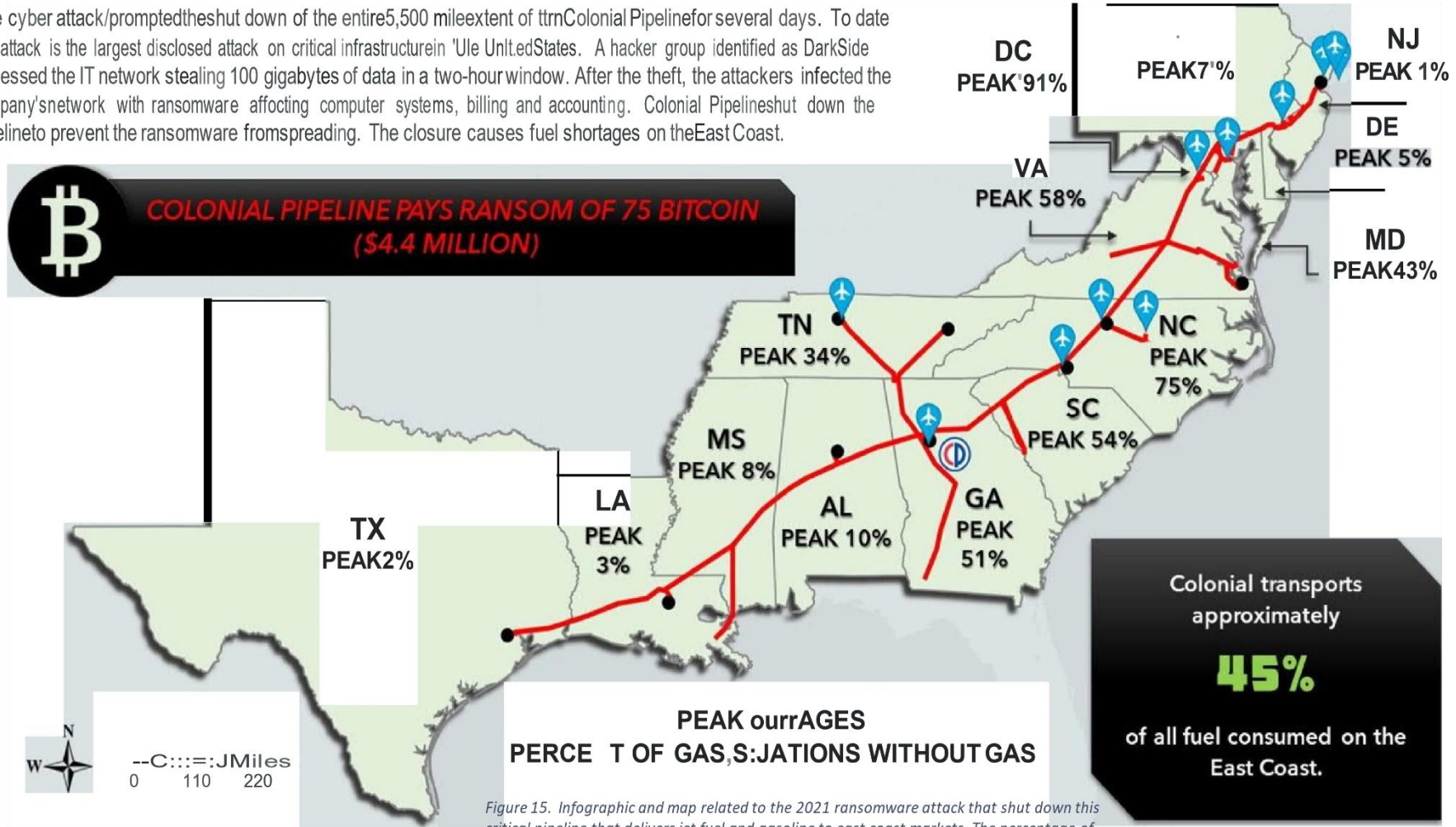
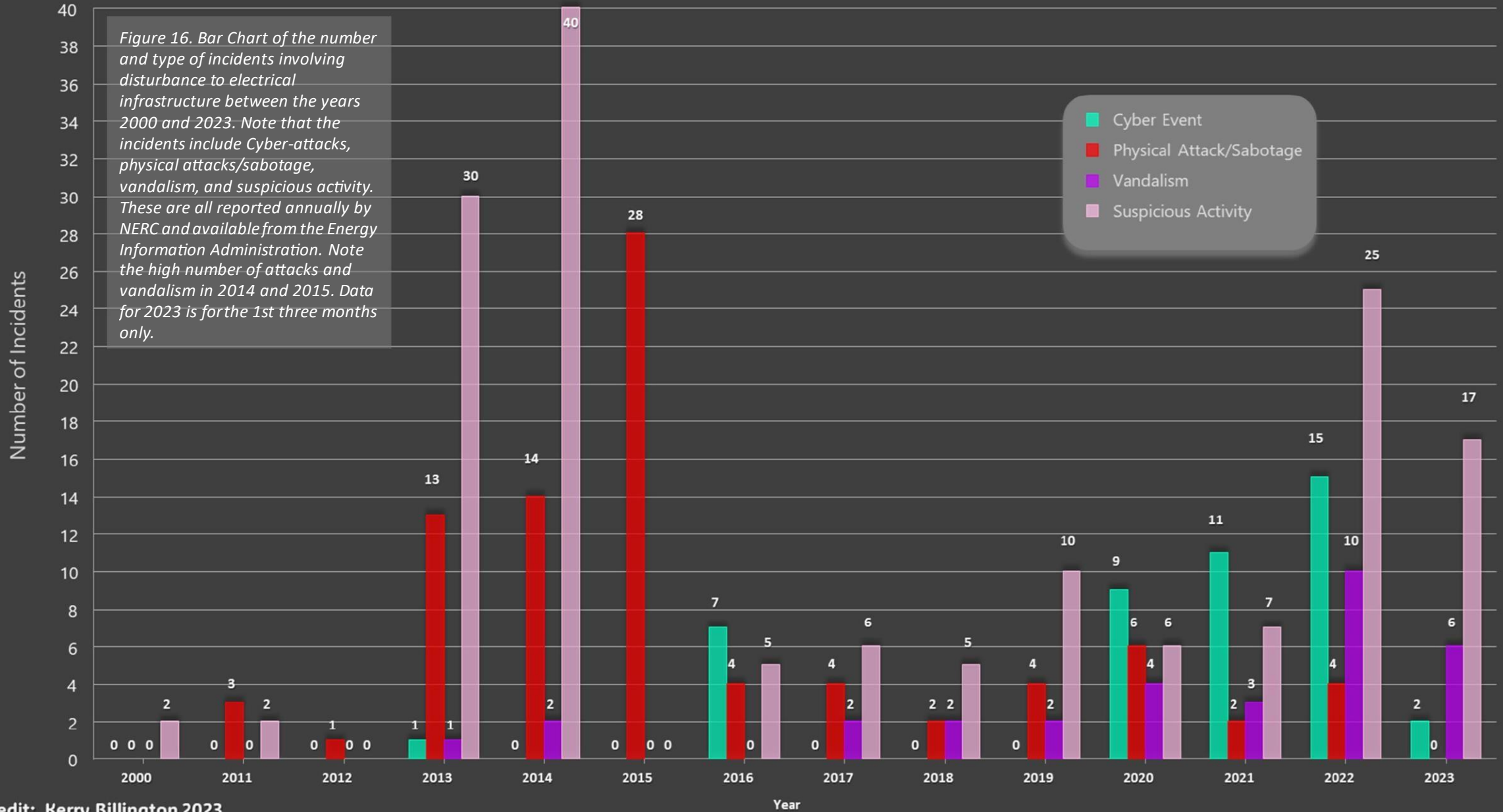
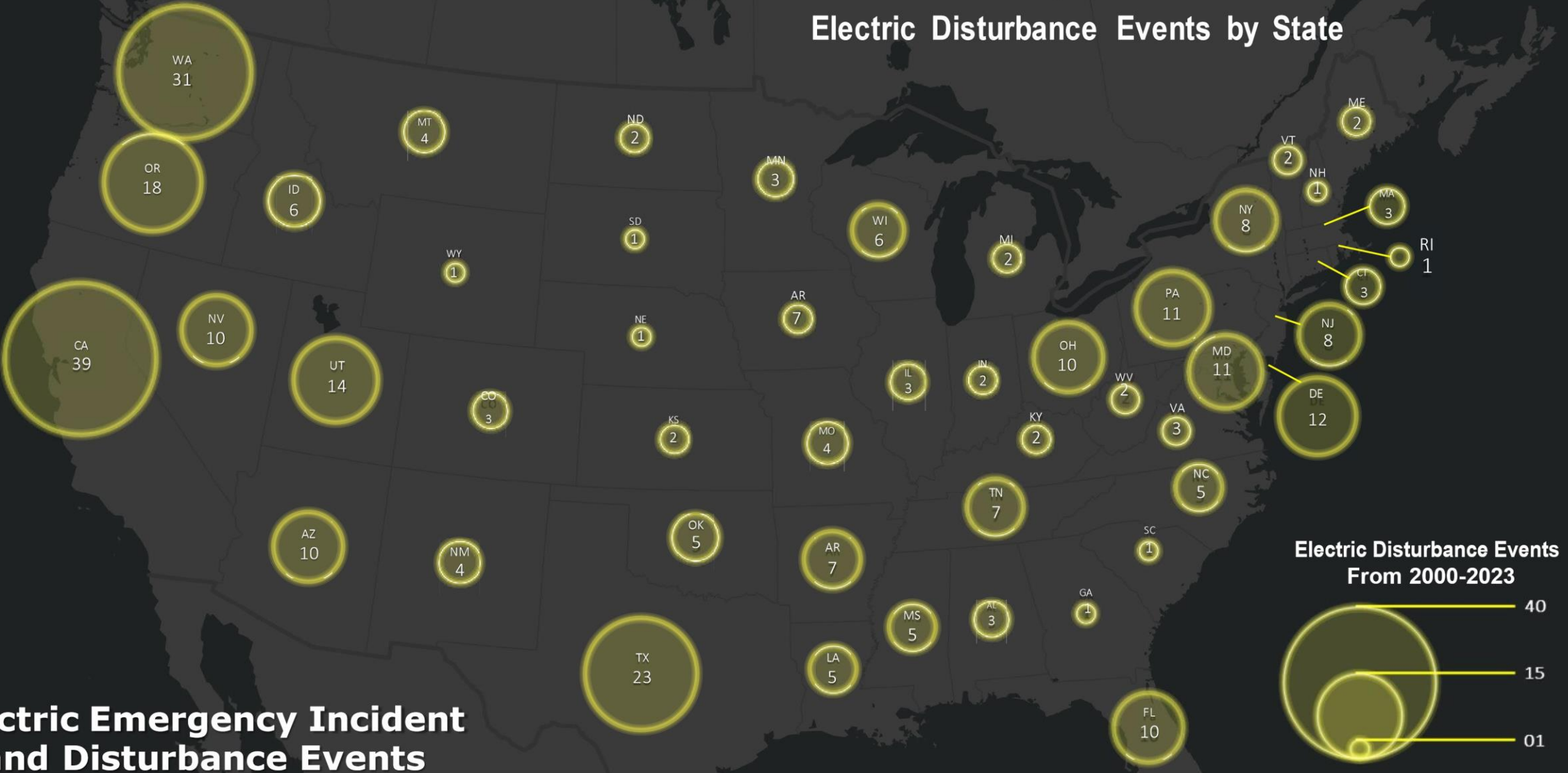


Figure 15. Infographic and map related to the 2021 ransomware attack that shut down this critical pipeline that delivers jet fuel and gasoline to east coast markets. The percentage of

Events from 2000 to 2023



Electric Disturbance Events by State



Electric Emergency Incident and Disturbance Events

Data Source: The Department of Energy - DOE-417 Electric Emergency Incident and Disturbance Report (OMB No. 1901-0288)
Credit: Kerry Billington – July 2023

Figure 17. This map shows the magnitude of attacks over the 23-year period by State.



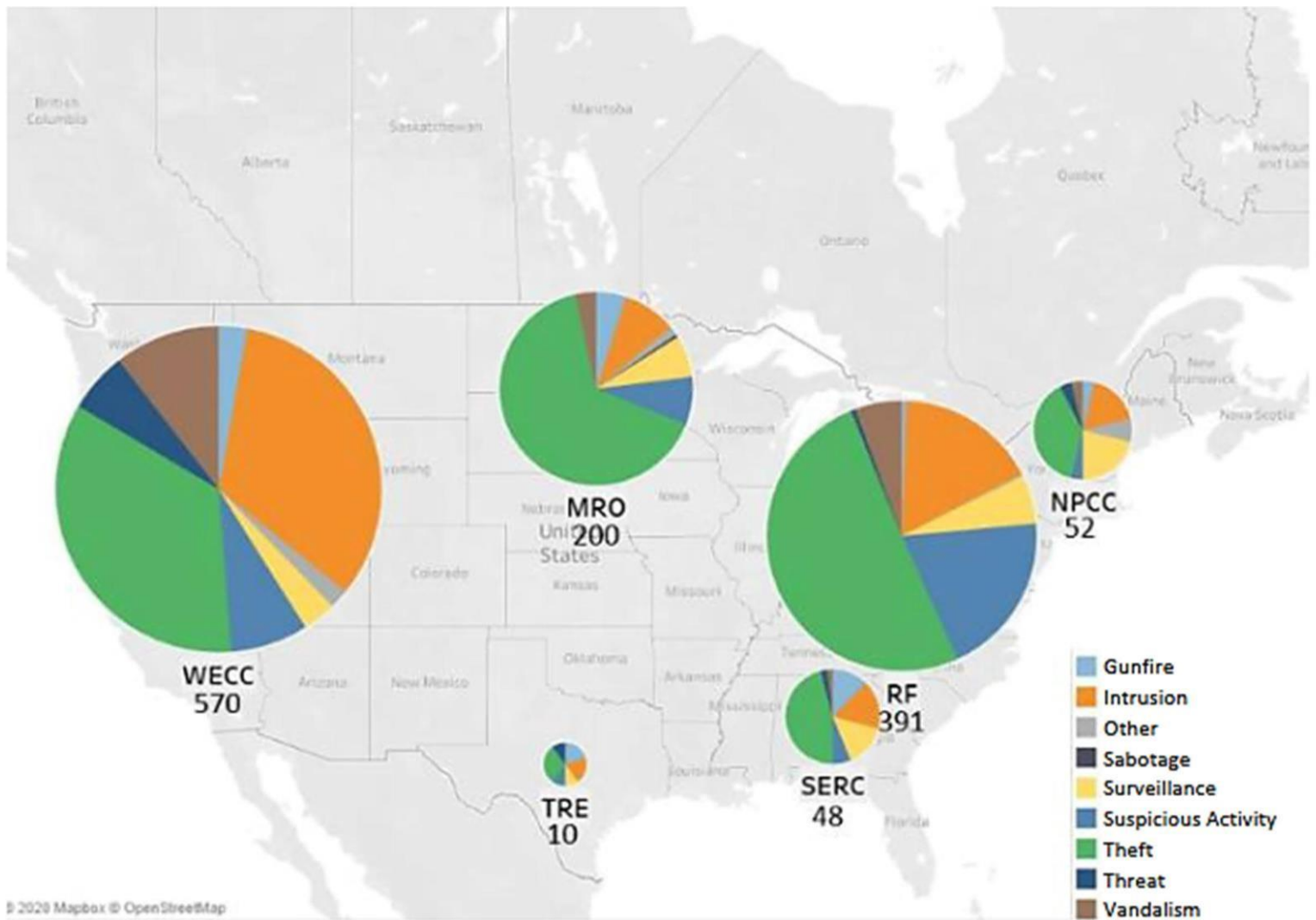
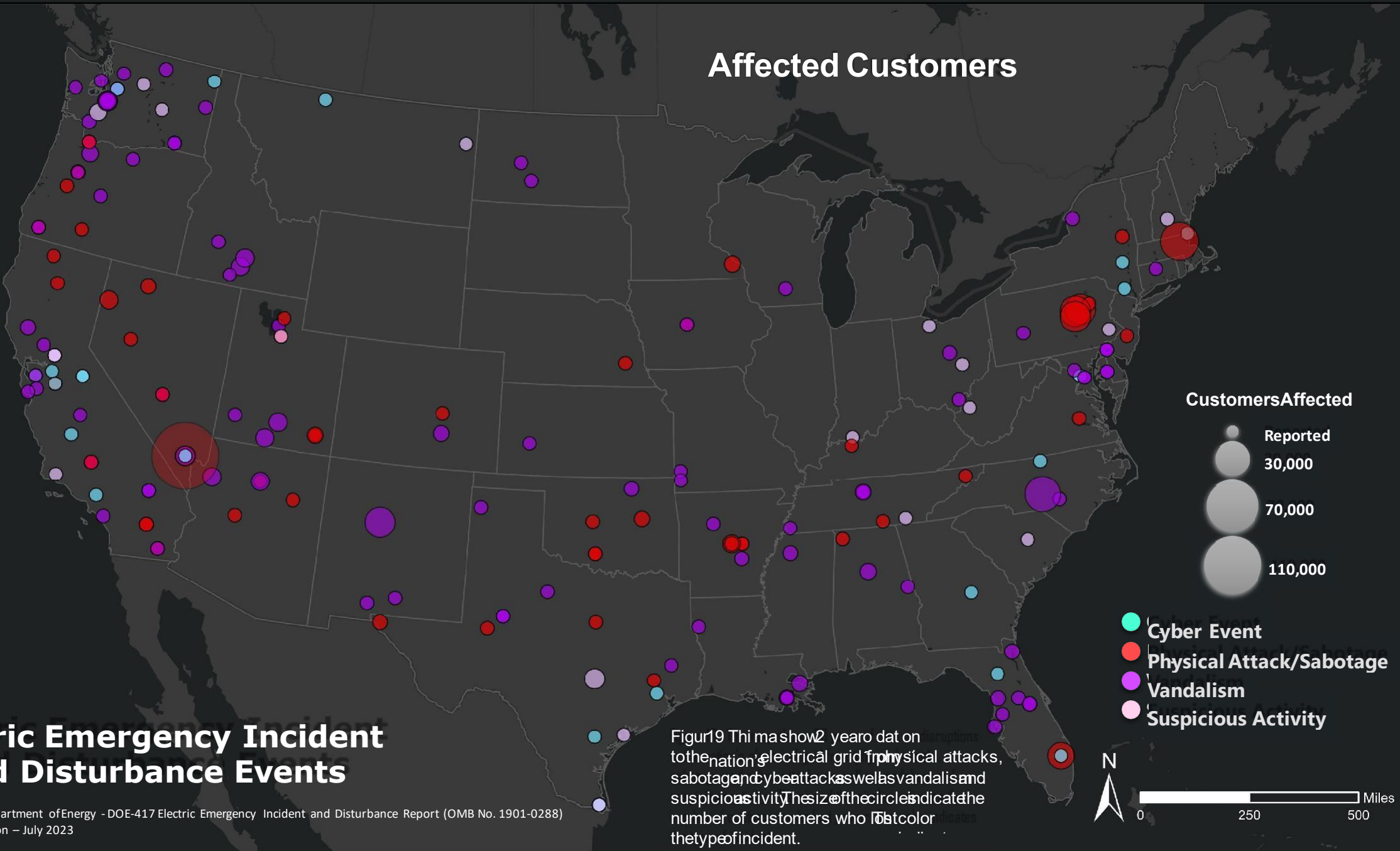


Figure 5.33: 2019 Physical Security Incidents by Regional Entity

Figure 18. This figure is from the 2019 North American Electric Reliability Corporation (NERC) report on electrical reliability. It is figure 5.33 in that report. It is one of the few GIS generated maps available on the topic of attacks on the electrical infrastructure but is for a single year and only provides data by region. In that year the Texas region had the fewest incidents, and the Western region had the most incidents. Most of these incidents did not cause loss of power to customers. Even gunfire was often not the cause of a loss of power.

Affected Customers



Customers Affected

- Reported
- 30,000
- 70,000
- 110,000

- Cyber Event
- Physical Attack/Sabotage
- Vandalism
- Suspicious Activity

Electric Emergency Incident and Disturbance Events

Data Source: The Department of Energy - DOE-417 Electric Emergency Incident and Disturbance Report (OMB No. 1901-0288)
Credit: Kerry Billington – July 2023

Figure 19 This map shows 2 years of data on the nation's electrical grid from physical attacks, sabotage, cyberattacks as well as vandalism and suspicious activity. The size of the circle indicates the number of customers who lost power and the color indicates the type of incident.

Electric Disturbance Events by County

Electric Emergency Incident and Disturbance Events

Electric Disturbance Events From 2000-2023

- Cyber Event
- Physical Attack/Sabotage
- Vandalism
- Suspicious Activity

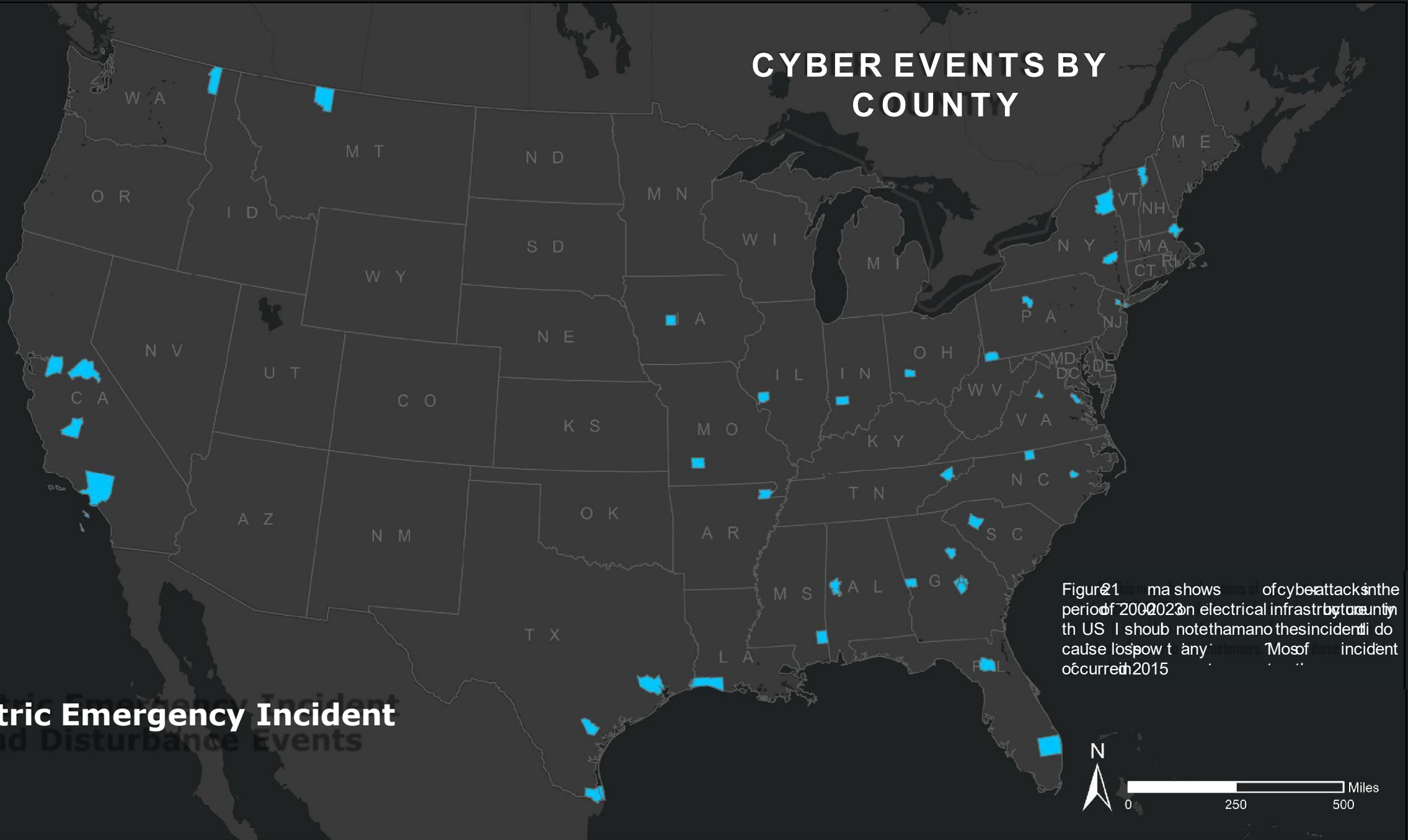
Figure 20 This map was made for the Institute of Homeland Security in the summer of 2023. It is based on 23 years of incidents reported by electricity providers to NER and released by the Energy Information Administration for the period 2000-2023. There were 435 incidents of physical attacks, sabotage, vandalism, and cyberattacks.



CYBER EVENTS BY COUNTY

Electric Emergency Incident and Disturbance Events

Figure 21. This map shows the number of cyberattacks in the period of 2000-2023 on electrical infrastructure by county in the US. It should not be taken as an indication of the incidents that cause loss of power to any area. Most of the incidents occurred in 2015.



VANDALISM EVENTS BY COUNTY

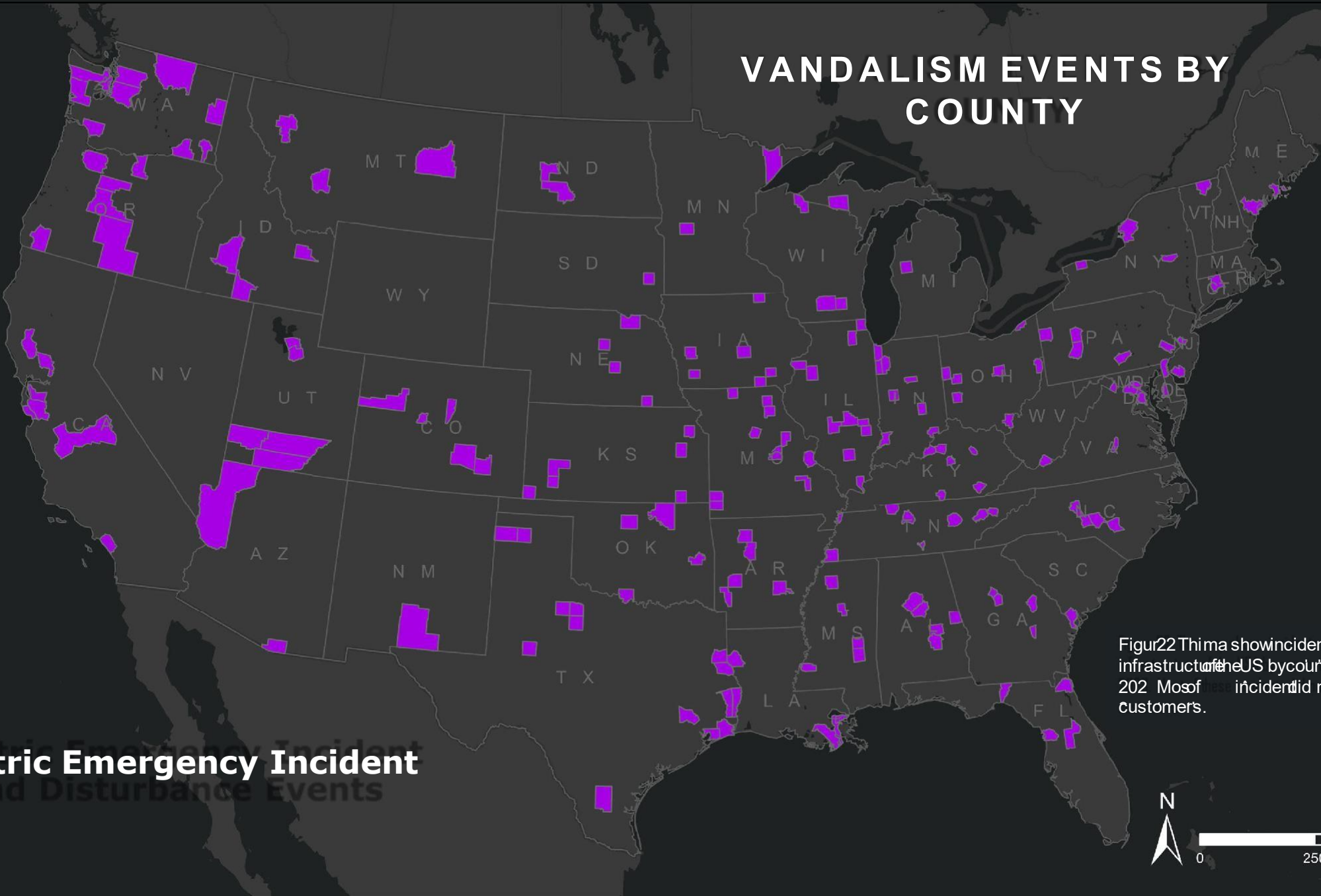


Figure 22 This map shows incidents of vandalism to energy infrastructure in the US by county in the period of 2000 to 2021. Most of these incidents did not result in loss of life or customers.

**Electric Emergency Incident
and Disturbance Events**



SUSPICIOUS ACTIVITY BY COUNTY

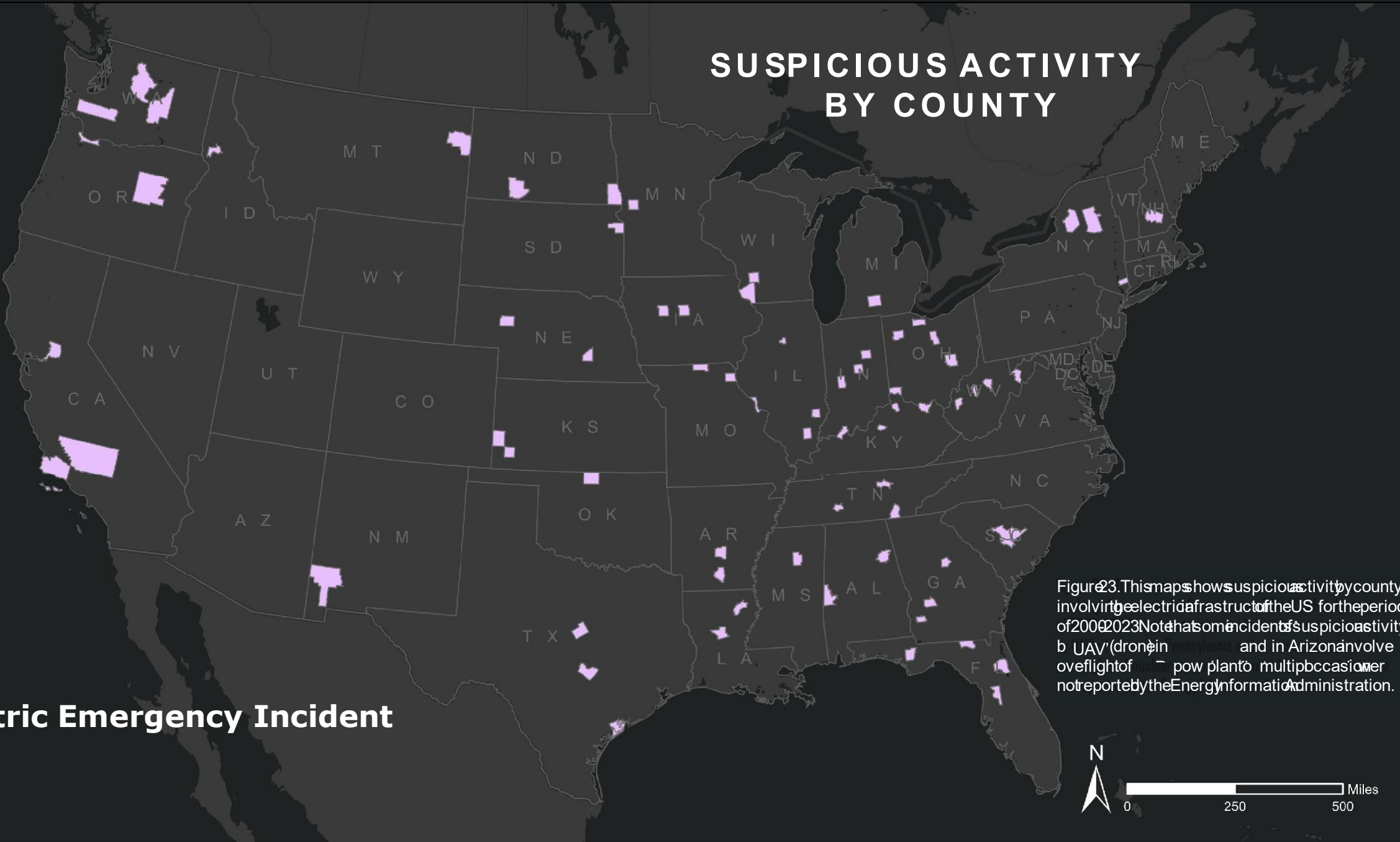


Figure 23. This map shows suspicious activity by county involving the electric infrastructure of the US for the period of 2000-2023. Note that some incidents of suspicious activity by UAV (drone) in Mississippi and in Arizona involve overflight of power plants, multiple occasions were not reported by the Energy Information Administration.

Electric Emergency Incident



PHYSICAL ATTACK EVENTS BY COUNTY

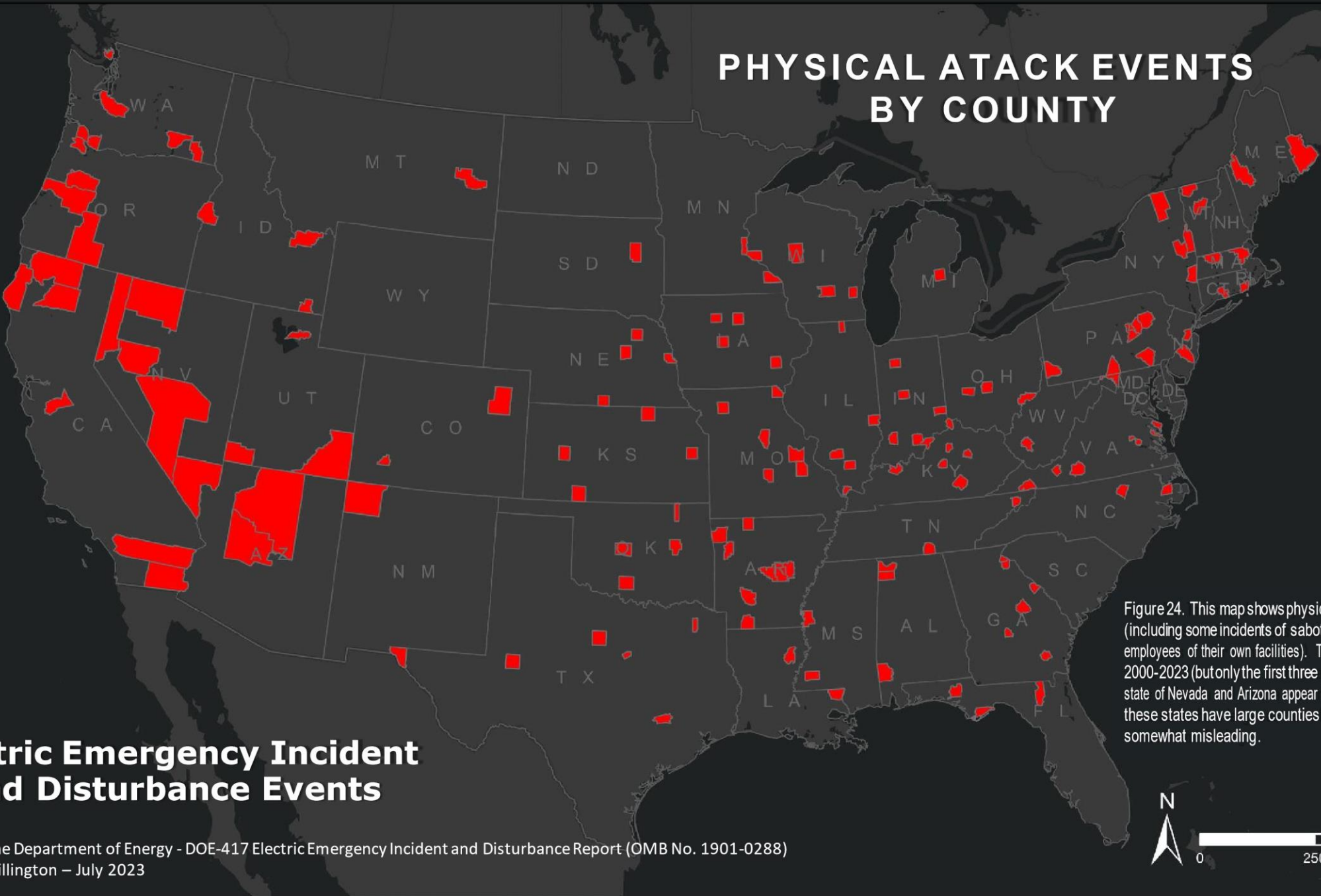


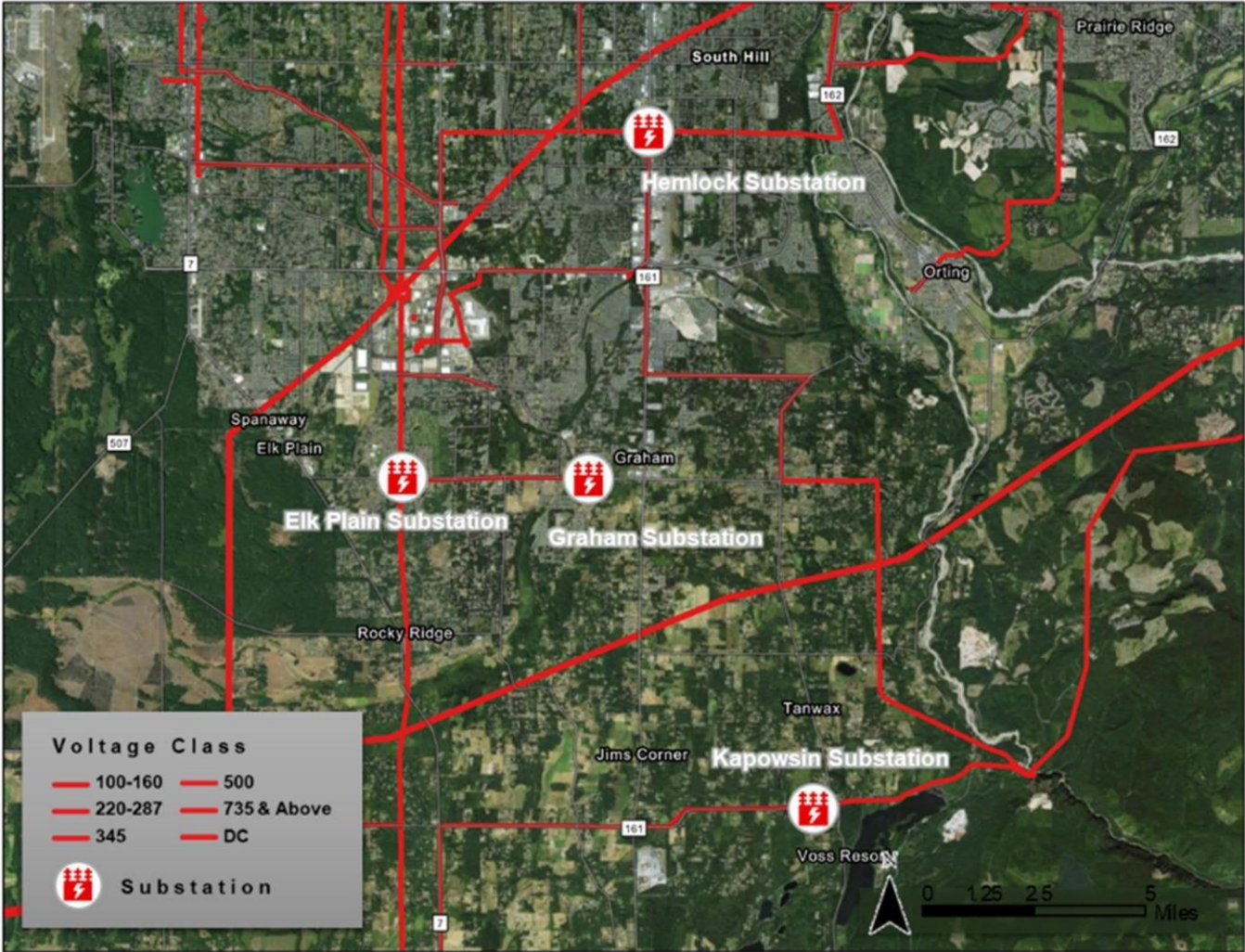
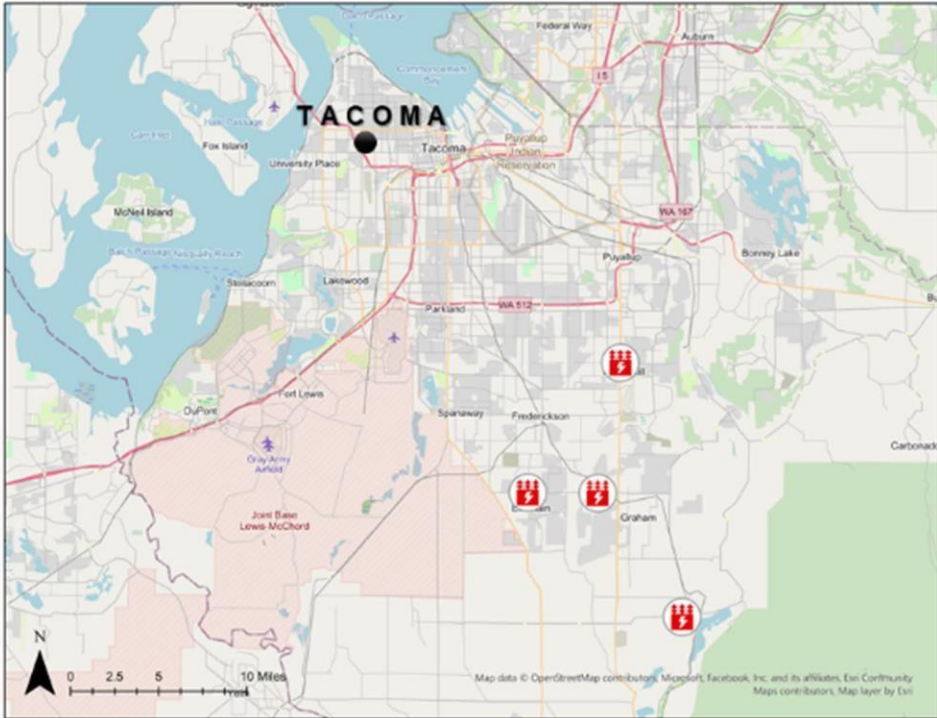
Figure 24. This map shows physical attacks and sabotage (including some incidents of sabotage by energy company employees of their own facilities). The map covers the period 2000-2023 (but only the first three months in 2023). Note the state of Nevada and Arizona appear to be heavily impacted, but these states have large counties which makes such maps somewhat misleading.

Electric Emergency Incident and Disturbance Events

Data Source: The Department of Energy - DOE-417 Electric Emergency Incident and Disturbance Report (OMB No. 1901-0288)
Credit: Kerry Billington – July 2023



Tacoma Power's Graham & Elk Plain Substations And Puget Sound Energy's Kapowsin & Hemlock Substations Locations.



Credit: Kerry Billington – June 2023

Figure 25. Three maps related to incidents on one day in 2021 in Pierce County Washington. The incidents involved four attacks by a pair of individuals on substations knocking out power for 14,000 residents on Christmas day. The attacks involved drilling holes into transformers to cause them to explode. The attacks caused \$3 million in damage. The motivation appears to have been to commit burglaries of businesses in the community which would not have functioning alarms

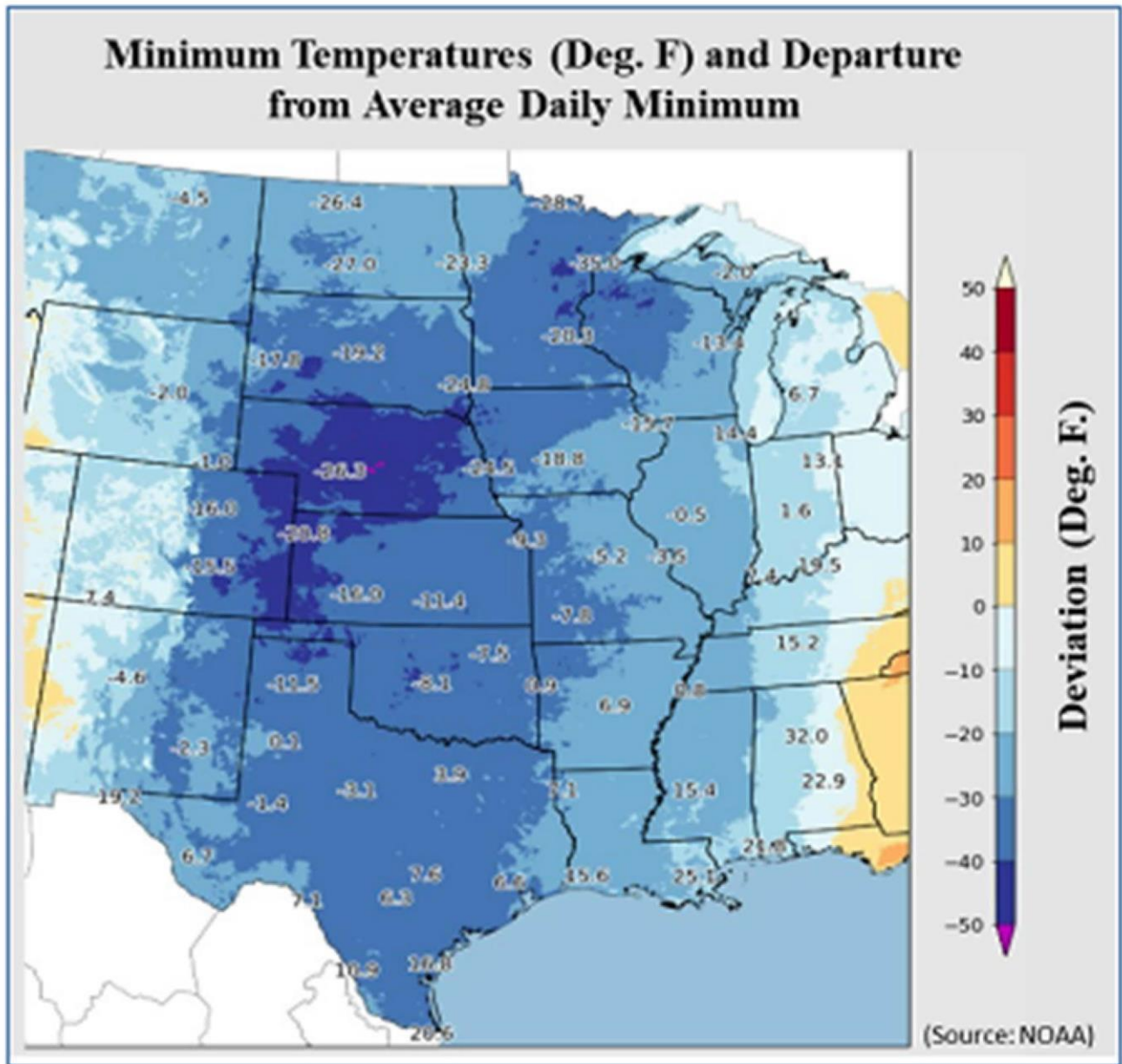


Figure 26. Map shows how extensive and cold winter storm Uri in February 2021 was in the U.S. Deviations of over 40 degrees below normal mid-February temperatures were

recorded, but a similar storm occurred in 1983 and generally few all-time low records were broken, a lesson that energy facilities should note as there were not extensive blackouts in 1983.

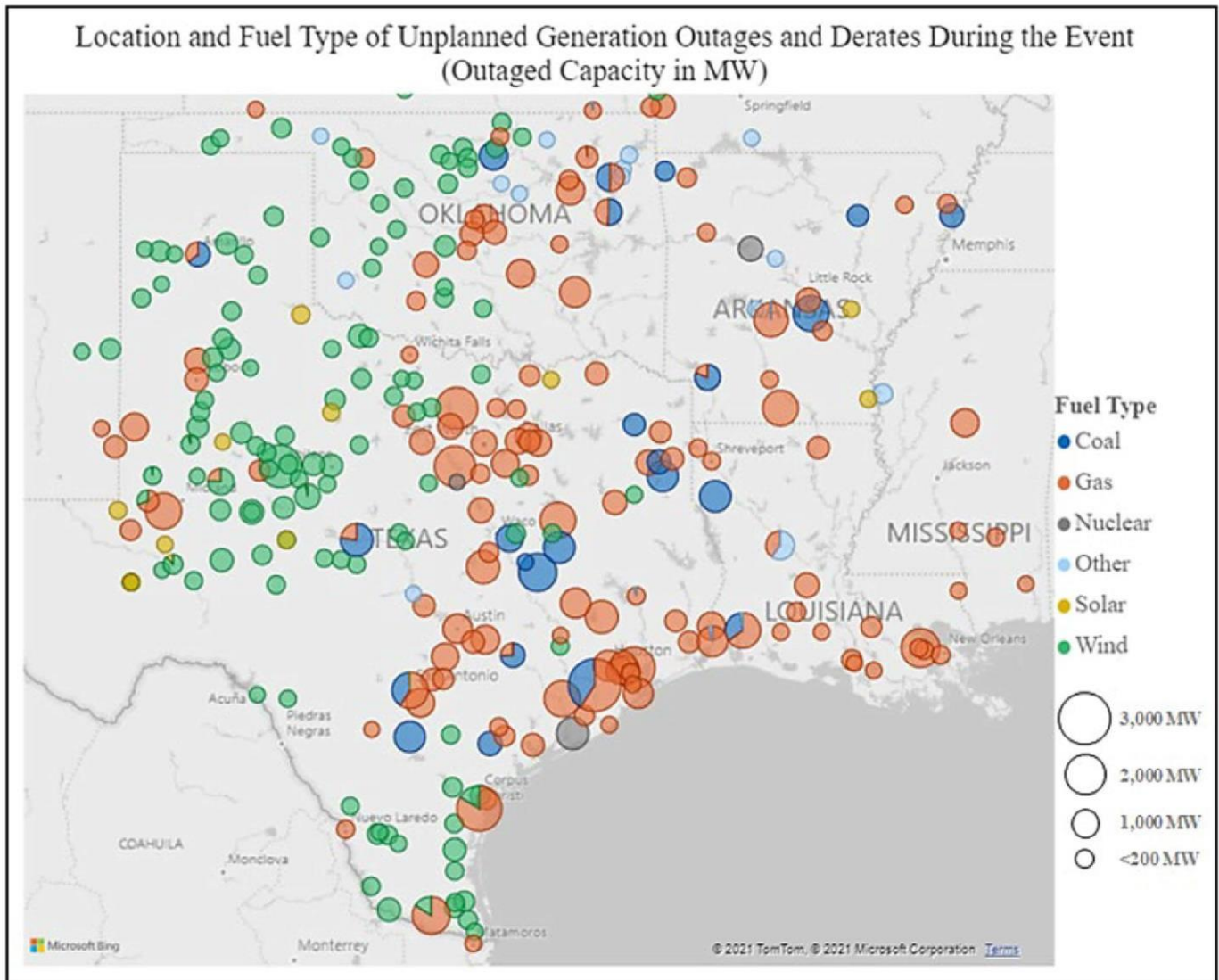


Figure 27. This map from the FERC Final Report on 2021 Winter Storm Uri shows the distribution of power plants that failed by generating capacity and type. Note “other” plants are co-generation facilities. Note: The South Texas Nuclear Project lost one of two reactors at the start of the crisis on February 15. Note also the impact extended beyond Texas, but prolonged blackouts were limited to Texas. Wind farms represent multiple turbines. 1,796 power plants were off-line at some point in the storm.

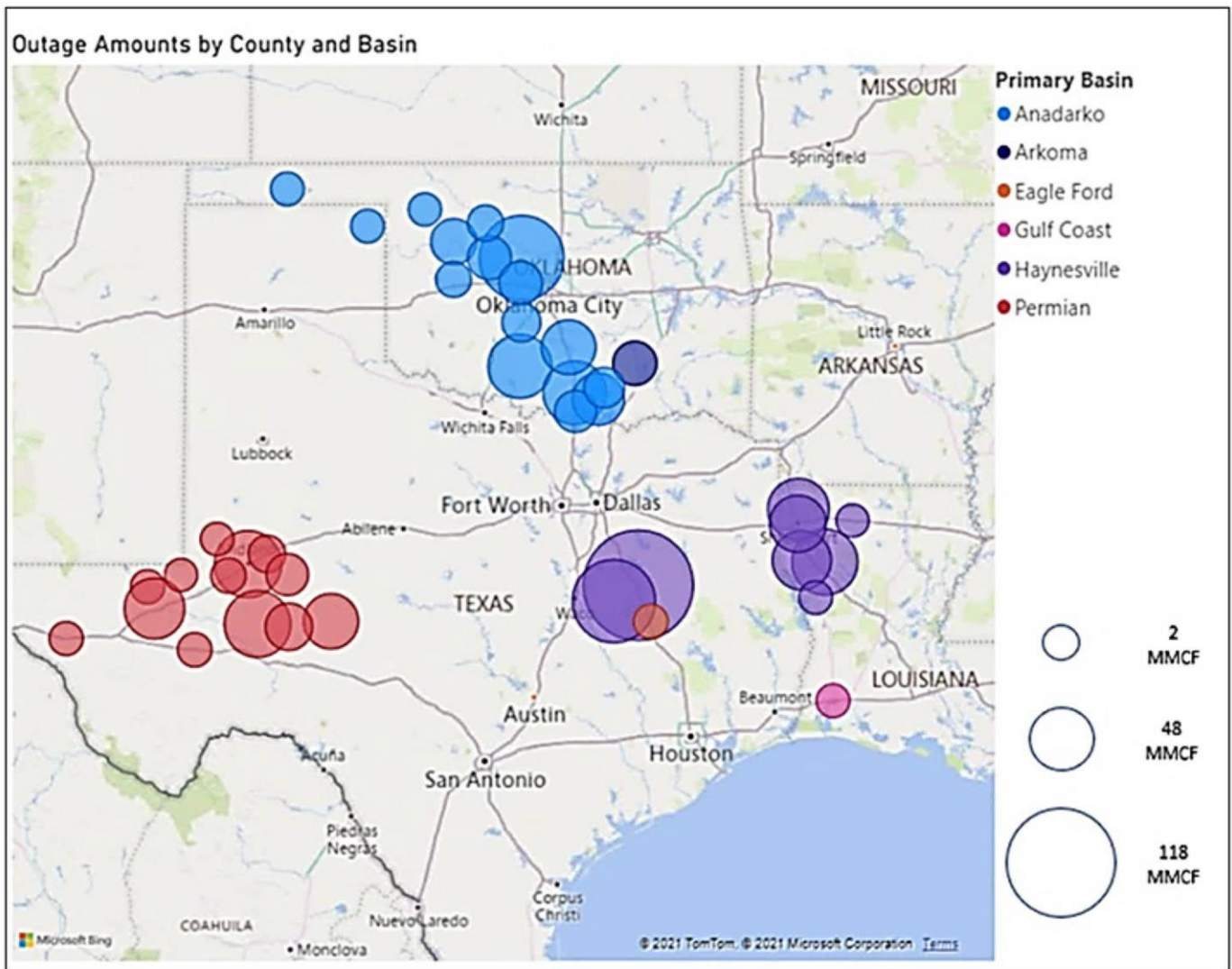


Figure 28. This map was figure 40 in the FERC Final Report on Winter Storm Uri. It shows the quantity of natural gas that was unavailable during Winter Storm Uri mapped by magnitude of the loss from a specific pipeline and basin. The significance is that this natural gas was needed for

home heating and to run gas-fired powerplants, lack of supply triggered power plant shutdowns throughout the region, it was the single largest factor in the subsequent blackouts.

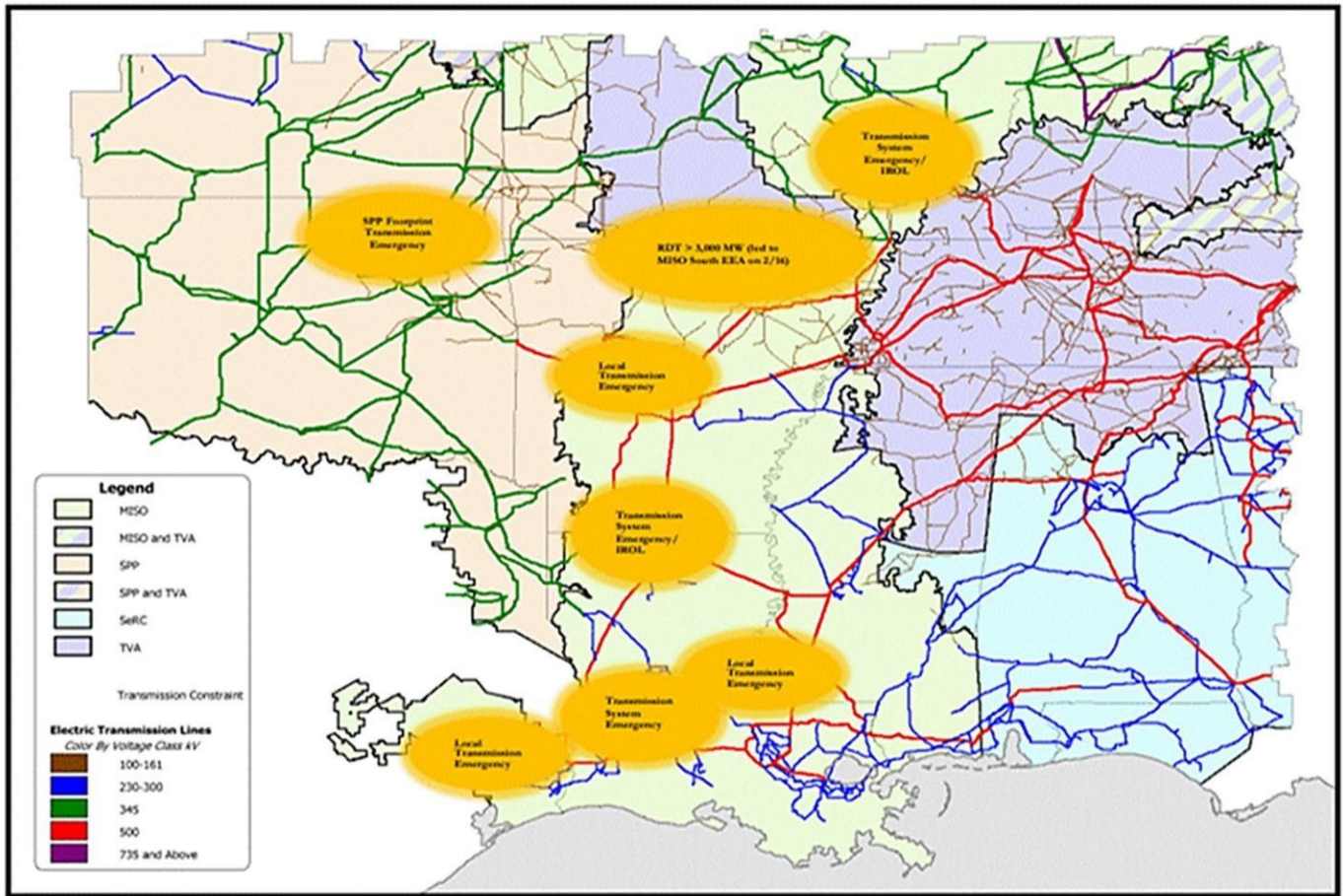


Figure 29. This map was figure 84 in the FERC final report on Winter Storm Uri. It shows the power pools for areas adjacent to Texas. Note that the South-west Power Pool does extend into Southeast Texas. Most of Texas is in the ERCOT region. Most of the extended blackouts were limited to the ERCOT region and part of Texas

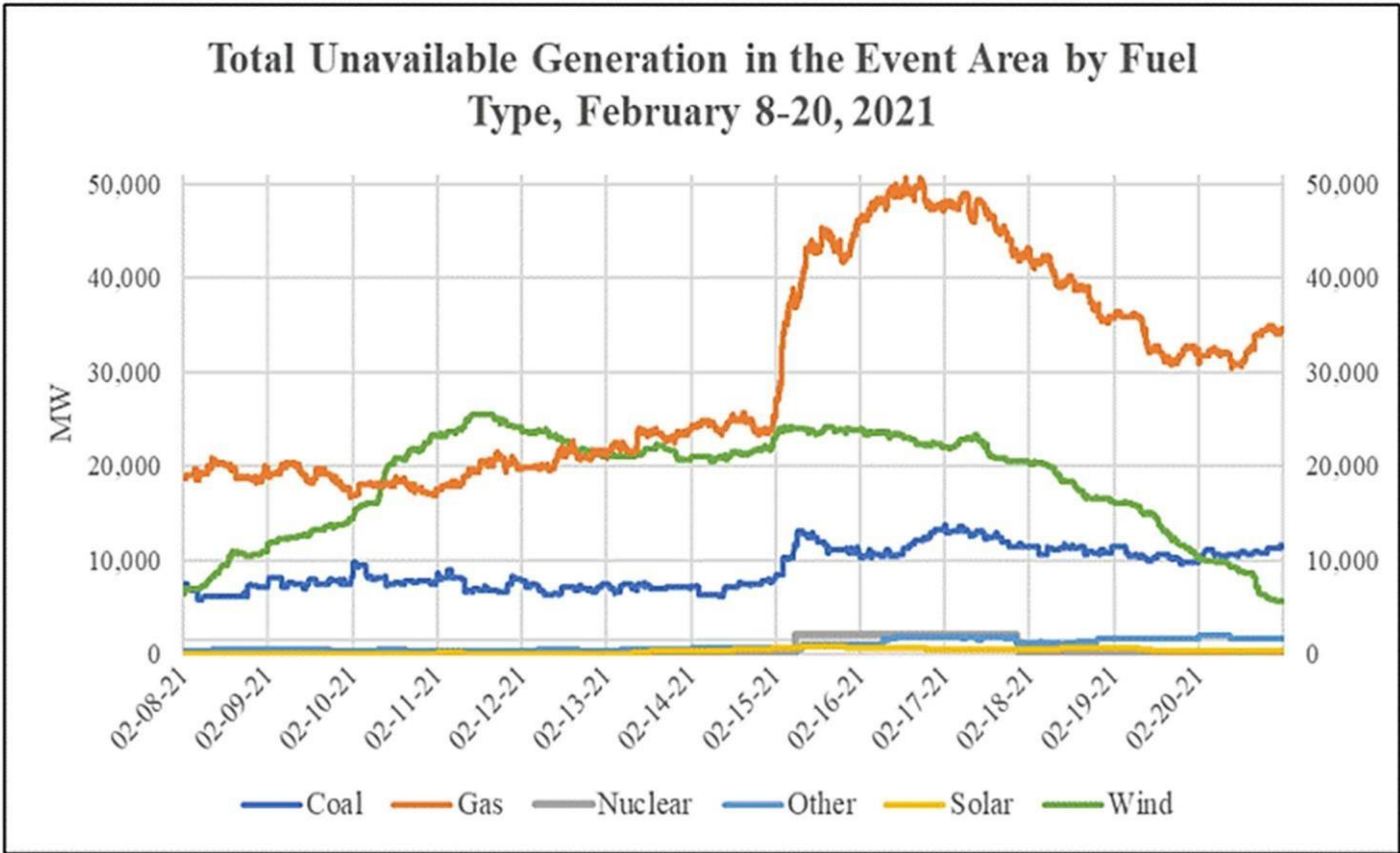


Figure 30. Graph of unavailable power generation in Winter Storm Uri by date starting February 8 through February 21, 2021. Note the increasing loss of wind energy early in storm, the large spike is loss of natural gas generation on February 15. The loss in nuclear and the loss in other (co-generation dependent on gas) coincided with the crisis in power supply on the night of February 14 and early morning of February 15, loss in coal came later.



INSTITUTE FOR HOMELAND SECURITY



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The Institute is a center for strategic thought with the goal of contributing to the security, resilience, and business continuity of these sectors from a Texas Homeland Security perspective. This is accomplished by facilitating collaboration activities, offering education programs, and conducting research to enhance the skills of practitioners specific to natural and human caused Homeland Security events.

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Leipnik, M.R. (2023) Assessing and Bolstering Critical Energy Infrastructure Security Using Geo-Spatial Technologies. (Report No. IHS/CR-2023-1031). The Sam Houston State University Institute for Homeland Security. <https://doi.org/10.17605/OSF.IO/GW2MH>