# QUANTIFYING RESILIENCY OF COUPLED NATURAL GAS AND ELECTRICITY SYSTEMS: A SIMULATION AND PROPOSED METRIC FROM THE 2021 TEXAS POWER OUTAGE

A Thesis

by

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Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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August 2022

Major Subject: Energy

# ABSTRACT

Natural gas has become a major source of energy over the last decade due to new extraction techniques with overall lower costs, replacing more expensive existing coal power plants. As the natural gas infrastructure continues to expand, so does its interdependency with electricity generation infrastructure, creating crucial hotspots within the grid. Despite the continuous expansion and interconnectedness of the ERCOT grid, the interdependence between these two sectors led to cascading failures during high impact, low frequency (HILF) events as seen in Texas during February 2021.

The aftermath of the Texas February 2021 blackouts raised many questions regarding the electric grid's reliability and resilience. Many papers have discussed the need for a well-defined resilience metric for power systems, yet most literature stops short of conducting a thorough analysis for a grid system. A grid resiliency metric has the potential to analyze how well a grid can handle extreme cold-weather events and can help identify improvements to prevent an event like this from occurring again.

In this research thesis, a brief overview of the Texas February 2021 event is provided to understand some of the underlying effects of grid failure and to highlight the interdependent nature of the natural gas and electricity sectors. A literature review to understand the difference and existing work surrounding the definitions and quantification of reliability and resilience in power systems is also conducted.

The main goal of this research is to visually identify the various aspects that make up the natural gas side of the ERCOT grid system to formulate a resilience metric at the coupling of natural gas and electricity systems. This work also contributes to the existing data repository from the 2021 Texas event for greater accessibility for future studies. This work applies the proposed resilience metric to the data from the 2021 event and discusses limitations, considerations, and methods to improve resiliency onsite.

# ACKNOWLEDGMENTS

I would like to thank my committee chair, Professor Le Xie and my committee members Professor Pistikopoulos, Stratos and Professor Barteau, Mark for their assistance and willingness to help throughout the course of this research.

Special thanks go to Dr. Julien Walzberg and Dr. Cory Allen for their encouragement and time both over zoom and at the Texas A&M Energy Institute.

Finally, I would like to express my thanks to Jeff Sammons for his constant involvement on the administrative side of this process that significantly aided the completion of this thesis.

# CONTRIBUTORS AND FUNDING SOURCES

## Contributors

This work was supported by a thesis committee consisting of Professor Le Xie [advisor] of the Department of [Electrical & Computer Engineering] and Professors Stratos Pistikopoulos and Mark Barteau of the Department of [Chemical Engineering]. All other work conducted for the thesis was completed by the student independently.

## Funding Sources

No outside source of funding was provided.

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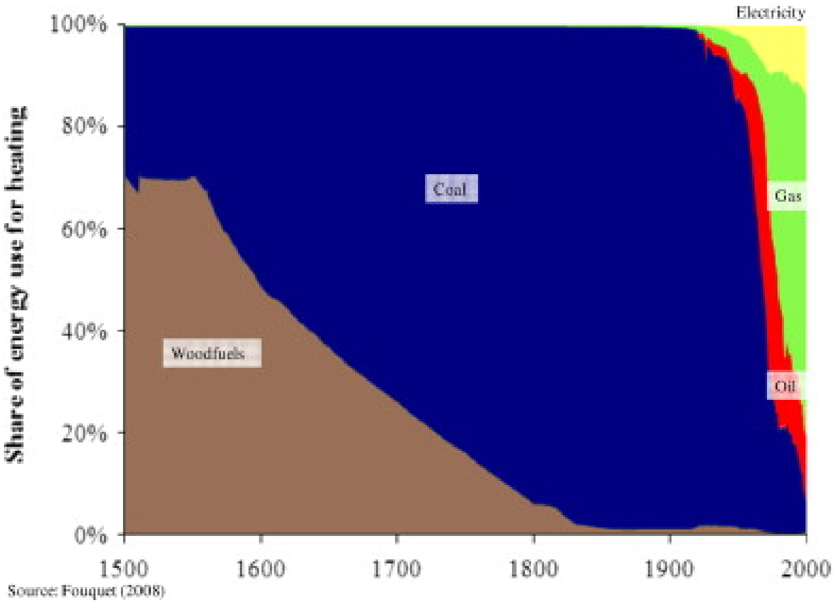
# 1. INTRODUCTION

## 1.1 Energy mix history and the energy future

Energy is a huge part of our lives. Since the kick-start of the first electric grid on September 4, 1882, in New York City, electricity use and infrastructure have steadily increased and arguably become a necessity like the basic three: food, water, and shelter. Energy is extremely diverse and can be used as fuel for cooking, transportation, heat generation, or electricity generation. Applications of energy vary by geographic area, but there is a strong correlation between a country's energy use and the size of their economy as countries shift away from labor intensive agriculture into energy intensive industries like manufacturing or information[1].

While global electricity generation and consumption have increased steadily, the sources used to generate electricity have fluctuated over time. As countries develop their economies, so do their energy requirements. Historically, societies have first utilized biomass as their primary fuel source, as wood was both abundant and easy to access[2]. Over time, as local resources become scarce and technological improvements develop, societies begin an energy transition to meet their growing demand. The first major energy transition occurred from wood to fossil fuels in the early 1700s when coal became the primary share of energy in many different areas of the world during the industrial revolution. This energy transition surged again in the late 20th century with the discovery and adoption of oil, which was abundantly available in large pockets and easy to store. Associated natural gas came next, as it was contained within the same fields that oil was being extracted and industries were now better suited to capture, process, and transport natural gas.

Today, the energy transition is slowly moving towards renewable energy sources and increased electrification, but this transition requires heavy reliance on fossil fuel energy sources to balance out the intermittent nature of wind and solar. The U.S. Energy Information Administration (EIA) predicts that natural gas production will increase in all cases over the next 30 years, allowing natural gas to help fill many electricity supply gaps worldwide[3]. While eventually we might see a shift away from natural gas, it is currently an abundant, stable, low-cost fuel that makes up a large share of the energy mix (Figure 1.1).



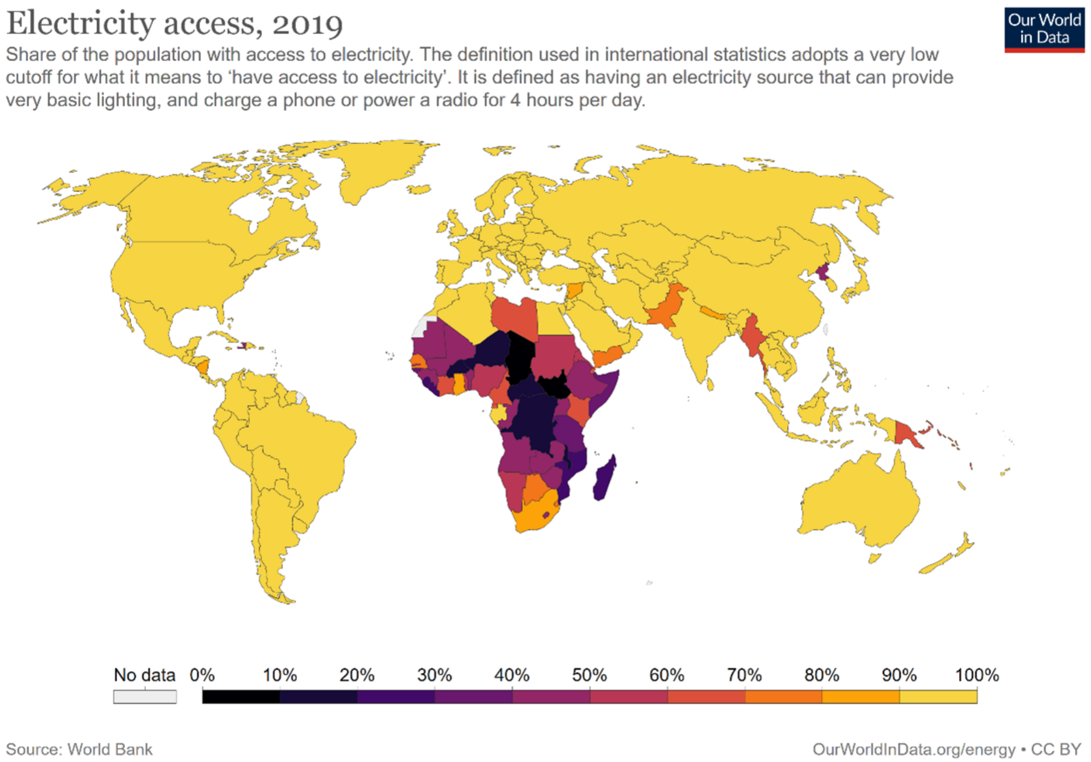
Source: Fouquet (2008)

Figure 1.1: Energy share for heating in the United Kingdom (1500 - 2000) [4]

Technology can help push societies to adopt new energy sources, but it can also sustain an existing source if extraction and processing are economically favorable as recently seen with natural gas in the last 10-15 years with hydraulic fracturing. As more sources of natural gas are more economically feasible for electricity production, coal plants have slowly been decommissioned. In addition to its wide availability, natural gas also plays an important role in the decarbonization efforts as a “cleaner” fuel that produces less emissions than either coal or diesel[5]. Natural gas also matches well with the developing renewable energy sources by providing critical support to non-dispatchable energy sources like wind and solar. While the decarbonization effort is not integral to the scope of this paper, it is important to note that policies, in addition to energy markets, play a large role in the current and future state of the energy mix seen today.

Currently, over 87% of the world has access to electricity with most regions having 100%

access for over the last 30 years[6] (Figure 1.2). As developing countries begin their own energy transitions, we may see an effort to push them past the coal and oil stages in favor of natural gas and renewable energy as part of the decarbonization effort. Thus, the natural gas market is finding itself at the forefront of the energy discussion and will continue to penetrate the energy market both domestically and globally.



Electricity access, 2019

Share of the population with access to electricity. The definition used in international statistics adopts a very low cutoff for what it means to 'have access to electricity'. It is defined as having an electricity source that can provide very basic lighting, and charge a phone or power a radio for 4 hours per day.

Source: World Bank

OurWorldInData.org/energy • CC BY

Figure 1.2: Worldwide access to electricity by country in 2019
[6]

Reducing greenhouse gas emissions is a large part of the international agenda with annual meetings like the Climate Change Conference that the United States has joined and left multiple times in the last decade under different governing parties. Many events and goals like this exist both domestically and internationally as climate science is more respected in literature and public perception. Specifically in the United States, natural gas markets have bloomed with the abundance of shale gas plays specifically in Texas. As such, the Electric Reliability Council of Texas (ERCOT) has slowly increased natural gas generation and phased out coal with wind and solar (Figure 1.3). Both wind and solar are non-dispatchable sources of energy like coal or natural gas, so there is a heavy dependence on the natural gas market to meet fluctuating energy loads.

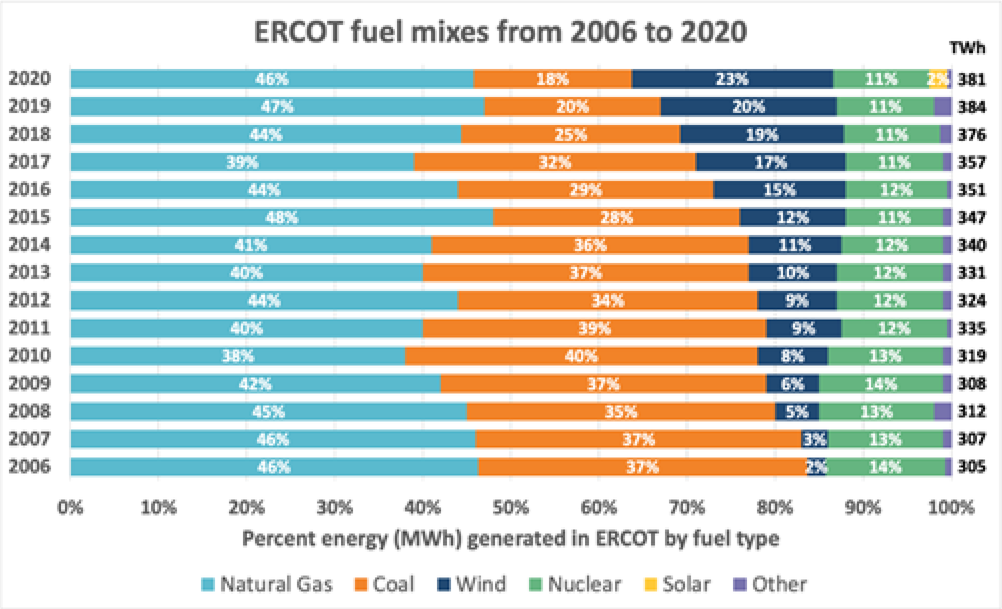


Figure 1.3: ERCOT generation percentages by fuel type 2006-2020
[7]

## 1.2 Natural gas supply chain in Texas

Texas is largest natural gas producer in the United States, accounting for 25% of nationwide natural gas production[8]. Texas contains several shale gas basins: Eagle Ford Shale and the Permian Basin which account for most of the natural gas produced within the state. Texas contains over 17,000 miles of interstate natural gas pipelines that export gas to primarily Mexico and Louisiana. Texas also contains several liquefied natural gas (LNG) plants along the Gulf Coast and account for half of the U.S. LNG exports. More than one-third of Texas households use natural gas as the primary heating fuel[8]. The natural gas supply chain can be broken down into three sectors: upstream, midstream, and downstream.

### 1.2.1 Upstream

Natural gas upstream processes relate to the exploration and production side of the industry. Exploration is a high-risk investment, and its success is crucial to the rest of the natural gas sectors. Gas exploration includes determining the presence of natural gas, designing the proper well construction and placement, and understanding the natural gas characteristics to determine the extent of processing that will need to occur once extracted.

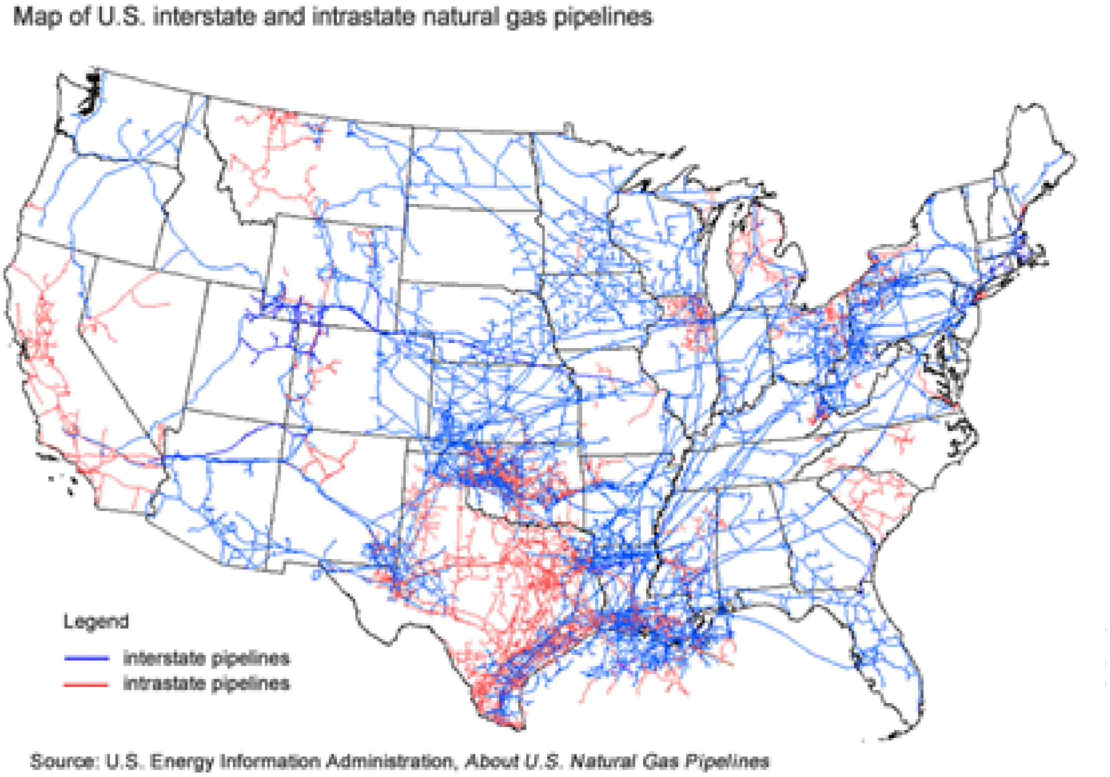
### 1.2.2 Midstream

Once natural gas is safely extracted from the ground it falls into under the midstream sector of transportation and processing. There are typically pipelines that connect natural gas wellheads to natural gas processing facilities spread throughout a region. Once the natural gas reaches the processing plant, the raw gas is separated from the water contained in it, turning it from wet gas into ‘pipeline quality’ dry gas. Natural gas can also be separated from the hydrogen sulfide content, turning it from sour gas into sweet gas. Several other separation processes also occur, and the amount of processing required for raw natural gas is determined by its raw composition and end-use. Failure to properly process natural gas into its end-product can result in serious problems relating to pipeline and powerplant damage or even explosions.

After processing, transmission pipelines are used to transport the natural gas from the pumping and processing areas to main service or end-use areas. Midstream processes can also include natural gas storage or transportation via truck or ship (e.g., LNG tanker). As the natural gas gets closer to its end-use location, the pipelines will split into smaller, shorter pipelines known as distribution pipelines (Figure 1.4).

### 1.2.3 Downstream

Distribution pipelines fall under the downstream category and ultimately deliver the gas to its destination. The flowrate and pressure at which the natural gas is delivered again depends on its end-use. Some large industrial and electric generation customers can receive natural gas directly



Source: U.S. Energy Information Administration, *About U.S. Natural Gas Pipelines*

Figure 1.4: U.S. natural gas pipeline network; high interconnectedness of Texas 2006-2020 [9]

from high-capacity pipelines, but a majority of end users receive gas from a local utility.

## 1.3 2021 Texas Power Outage

In February of 2021, many parts of Texas experienced electric grid blackouts (failure of electrical power supply across the grid) lasting up to three days due to lack of available generating capacity for the demand load during an extreme winter event contributing to the deaths of 246 people[7][10]. During this cold event dubbed “Winter Storm Uri” temperatures persisted at below freezing from 5 to 33, leading to the unexpected shutdown of various generators[7]. ERCOT conducted load shedding (demand reduction) measures to prevent damaging the grid infrastructure as load exceeded the provided generation, causing rolling blackouts among customers over extended periods of time. Many factors contributed to this blackout event including[7]:

- various generation equipment failures
- under-estimated demand forecast predictions
- under-stated weather forecasting
- high planned outages
- power plant complications
- inadequate weatherization of generators
- natural gas supply chain and system failures
- inadequate reserve natural gas stores

Despite weather predictions, load forecasting, and close monitoring of events, ERCOT underestimated the forced outages that occurred and was unable to maintain the normal operation of the grid (Figures 1.5 1.6). ERCOT was issued an Operating Conditions Notice on February 8th and on February 12th Texas was declared a state of emergency to help prepare for the approaching cold weather conditions[11]. Wind turbines were the first source of generation to experience unexpected outages due to freezing rain and other precipitation that caused ice to accumulate on the blades and in the nacelles of the wind turbines. In addition, natural gas generators began to have natural gas supply chain issues prior to the extreme cold period. Overall, this catastrophic event caused more damage and failures than two previous Texas winter storm blackouts in 1989 and 2011 and had the second longest outage in Texas history[12]. This has spurred research efforts in attempting to understand the shortcomings of the existing grid and come up with solutions to improve both the reliability and resiliency of the system to better handle future extreme weather-related events.

Despite relatively mild winters Texas has experienced in the past, extended sub-freezing temperatures are occurring more frequently as seen again in February of 2022. Inadequate winterization measures on generators has caused the Texas grid to experience rolling blackouts in both the 2021 and 2011 events, resulting in deaths and bankruptcy of many market participants that failed

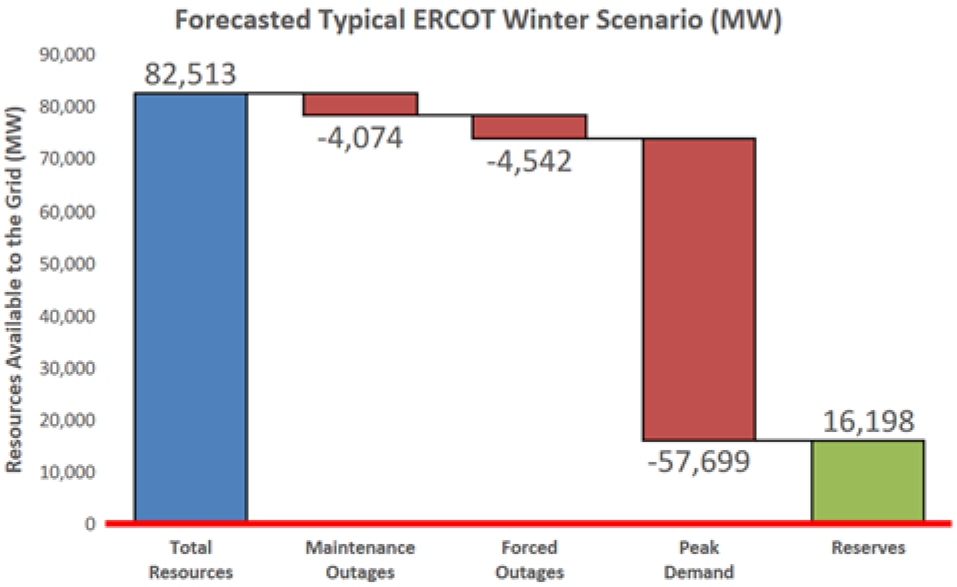


Figure 1.5: Waterfall diagram of anticipated effect of Winter Storm Uri on ERCOT grid [7]

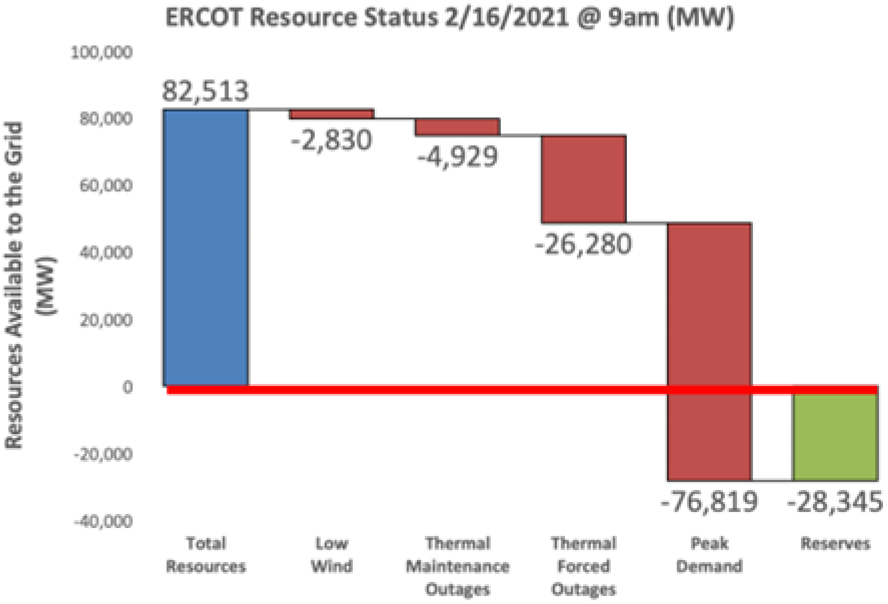


Figure 1.6: Waterfall diagram of actual effect of Winter Storm Uri on ERCOT grid on 2/16 [7]

to deliver power totaling roughly \$3 billion from the 2021 event alone[13]. While long term climate change effects are unknown, it is likely that climate variations may cause more extreme cold weather events in Texas, improving the need for grid solutions.

### 1.4 Reliability and resilience of natural gas and electricity systems

The term “resilience” has a non-linear usage between various fields over the decades. “Resilience” is originally derived from the Latin word “resilio” meaning to “jump back”[14]. While the specifics of how resiliency evolved in the science world is less important for this paper, it is important to understand that resilience is still not well-defined without context (Figure 1.7). Other than being confused with reliability (which is well-defined as being different than resilience at this point) resilience competes with the ambiguity of other terms being used like “stress-resistance” or “invulnerability”[15]. In addition, when using “resilience” in terms of disaster risk reduction (best application for this project) the next issue arises of how to define a disaster. Fortunately, while resilience as used in the ecology field can become very convoluted in understanding ecosystem systems in both a holistic and minute window, resilience in demand risk reduction for the electric grid can more or less be boiled down into factors that aid or prevent a generator in getting back up and running.

Although used inter-changeably by most people, reliability and resiliency mean two different things regarding the electric grid. Reliability can be defined as *the ability of a power system to deliver electricity in the quantity and quality demanded by the users*[17]. It can be represented as a binary metric where a functional grid is 1 and a failed (non-functional) grid is 0. Resiliency on the other hand is the ability of a system to recover, and, in some cases transform from adversity[16]. It is also the ability of a system to reduce the magnitude and/or duration of disruptive events. Its effectiveness depends on its ability to anticipate, absorb, adapt to, or rapidly recover from a potentially disruptive event[18]. Reliability of a system exists before and after a disruption event, while resiliency exists during the disaster and restoration phases. Ideally an electric grid would always be reliable and as such many metrics to quantify the reliability of grid systems exist such as the System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency In-

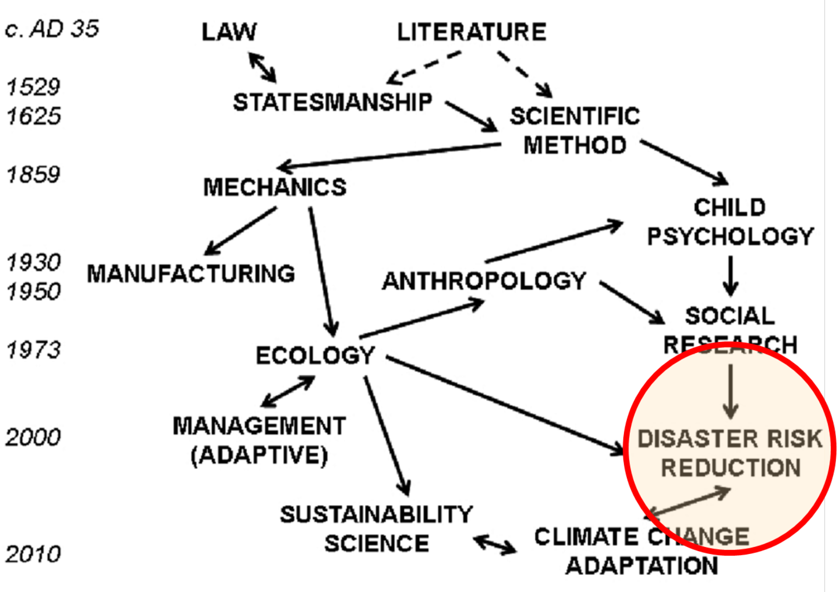


Figure 1.7: "resilience" as used in different areas of research over time [16]

dex (SAIFI), and the Severity Risk Index (SRI)[19]. In addition, many existing proposed resilience metrics conflict with existing reliability metrics or measures[20].

$$SAIDI = \frac{\sum Customer\ Interruption\ Durations}{\sum Total\ Number\ of\ Customers\ Served}$$

$$SAIFI = \frac{\sum Total\ Number\ of\ Interruptions}{\sum Total\ Number\ of\ Customers\ Served}$$

A reliable grid is one that works without disruption a majority of the time. A resilient grid is one that recovers quickly from disruption events. A reliable and resilient grid is one that operates without disruption often, and, during a disruption event, recovers swiftly. An electric grid's reliability can be vastly improved by increasing standby generating capacity but at a high cost. Through improving the grid's resiliency, the system can mitigate disruption events while also keeping system cost down. To be encapsulate resilience in terms of an electric grid (energy ecosystem) we will reference these definitions:

*"Local resiliency with regard to natural disasters means that a locale is able to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity, or quality of life and without a large amount of assistance from outside the community"*[21]

*"The power system resilience is the ability of this system to withstand disasters (low-frequency high-impact incidents) efficiently while ensuring the least possible interruption in the supply of electricity, sustain critical social services, and enabling a quick recovery and restoration to the normal operation state"*[22]

While certain parts of this definition like diminished productivity do not suit resilience in regard to a recovering grid system, the definition 1 does a good job of describing the goals of a resilient grid. One that prevents extended outages, grid damages, and reduced quality of life to customers on that grid. Unlike other types of resilience involving material properties or people, disaster resilience acts as a shock absorber or buffer that moderates the outcome to ensure only small-scale negative consequences[15]. Vulnerability is considered the opposite of resilience, but they are the antithesis metric of each other, meaning as a system becomes more resilience it is less vulnerable and vice versa15. Definition 2 directly relates to power systems and contains three components: withstand, adaptation, and recovery[22]. For the purposes of this research focusing on the natural gas and electricity systems, we defined resiliency specifically for this interconnection between them:

*"Once a disruption has occurred, resilience is the ability of the natural gas system and electricity system to minimize loss in quantity and quality of products through correction, coordination, and restoration measures."*

Another point brought up is whether resilience refers to physical infrastructure or people. It is difficult to argue that resilience does not apply to human actions since we are very capable of adapting, but another argument is whether infrastructure can be resilient since they do not adapt. Some argue that reducing vulnerability of these structures is important for their availability after a disaster, but whether they can adapt comes down to how the grid system makes decisions in the face of adverse cold weather conditions[15].

## 1.5 Problem Statement

**Problem:** Despite improved grid interconnectivity and generation diversity, grid failures still occur in the face of high impact, low frequency events.

# 2. SIMULATION OF ERCOT GRID DURING WINTER STORM URI

## 2.1 Approach

This section introduces our approach to the first stage of this thesis. The simulation side of this project consisted of taking existing work and data from the Texas 2021 power outage event and adding and adapting it to visually represent the natural gas and electricity generation infrastructure present in the ERCOT grid. Figure 2.1 summarizes the various steps taken to meet our research objectives for this part of the project which are:

- Contribute to the existing "2021 Texas Power Outage" database by collecting and storing new resolutions and types of data on GitHub
- Understand and visualize the interdependencies of the natural gas and electricity generation sectors during Winter Storm Uri through creating a synthetic simulation of the ERCOT grid over the period 2/14 – 2/19, 2021

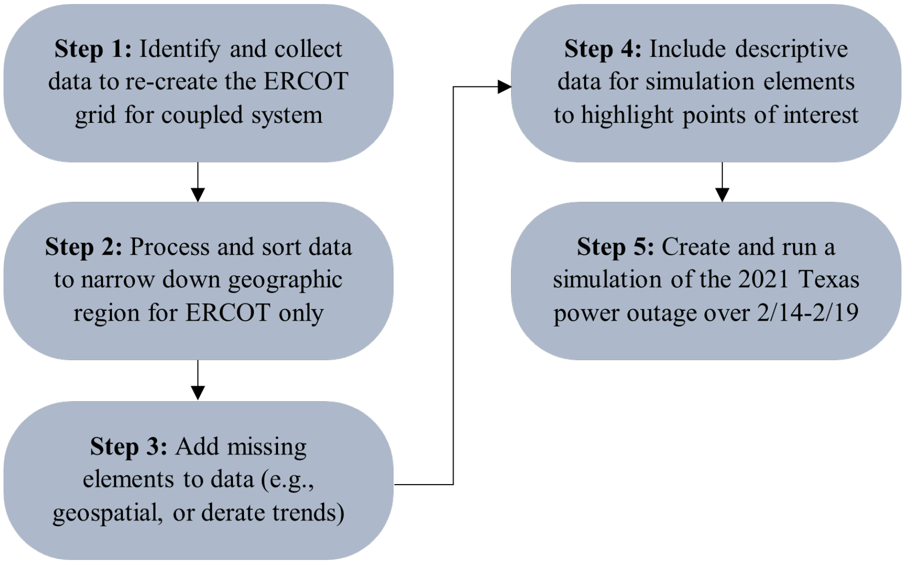


Figure 2.1: Flow chart of data collection and methods for creating a simulation of events

## 2.2 Data requirements and packages

The scope of the simulation is the ERCOT service area inside Texas. The project focused strictly on the natural gas and electricity generation infrastructure, so only that side of the energy mix is plotted represented on the map. Geographic data for all sites was collected from the U.S. Energy Information Administration which contained shapefile layers for many components of the U.S. energy mapping system. Geographic information for Texas and ERCOT shapefiles came from ERCOT's website.

Data surrounding the 2021 Texas power outages were derived from several different sources. Natural gas electricity generator derate data initially came from a ERCOT report, but the data frame was downloaded from the "2021 Texas Power Outage" GitHub[23]. Data regarding specific natural gas storage units was unobtainable, but general trends of this resource allocation was made available through Wood Mackenzie reports as seen in the University of Texas' paper[7]. Likewise, data trends for natural gas processing plants were obtained the same way and extrapolated to fit the scope of this simulation.

Next, these two types of data were combined to create a geospatial representation of capacity and flowrate values for individual plants for February 2.2 – 2.8. In total, three types of polygon elements were added: Texas and county borders (black), ERCOT service area (blue), and natural gas shale plays (pink) (Figures 2.2-2.4). Three node elements were added: natural gas processing facilities (red), natural gas powerplants (light blue), and natural gas storage facilities (green) (Figures 2.5-2.7). Finally, one polyline or line-string element was added: natural gas intrastate pipelines (pink) to indicate flows between the nodes (Figure 2.8).

Python was used as the primary tool for data collection, processing, and generating the simulation. The pandas and geopandas libraries were used for data and geospatial data processing. The folium plugin was used for map plotting and simulation.

Figure 2.2: Texas and county outline (black)

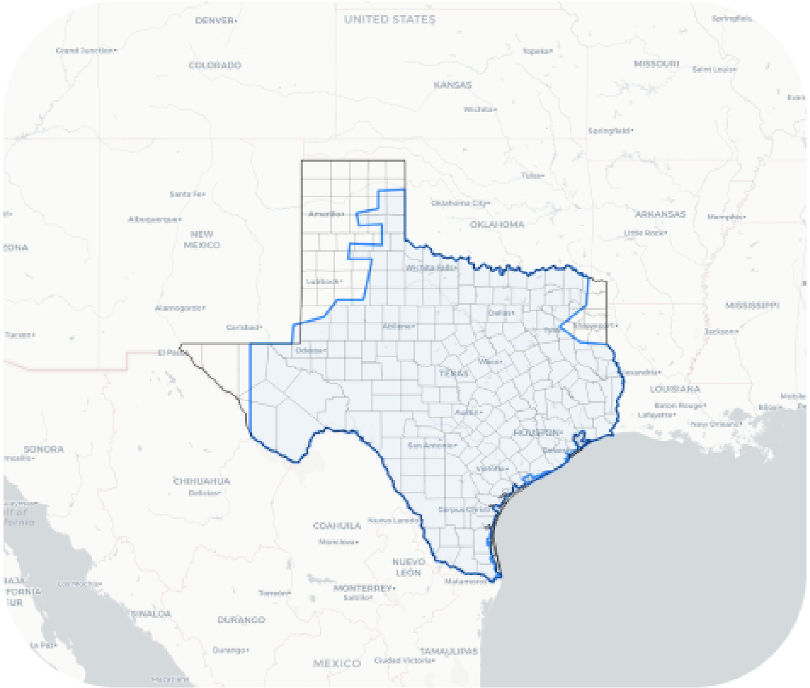


Figure 2.3: ERCOT service area (blue)

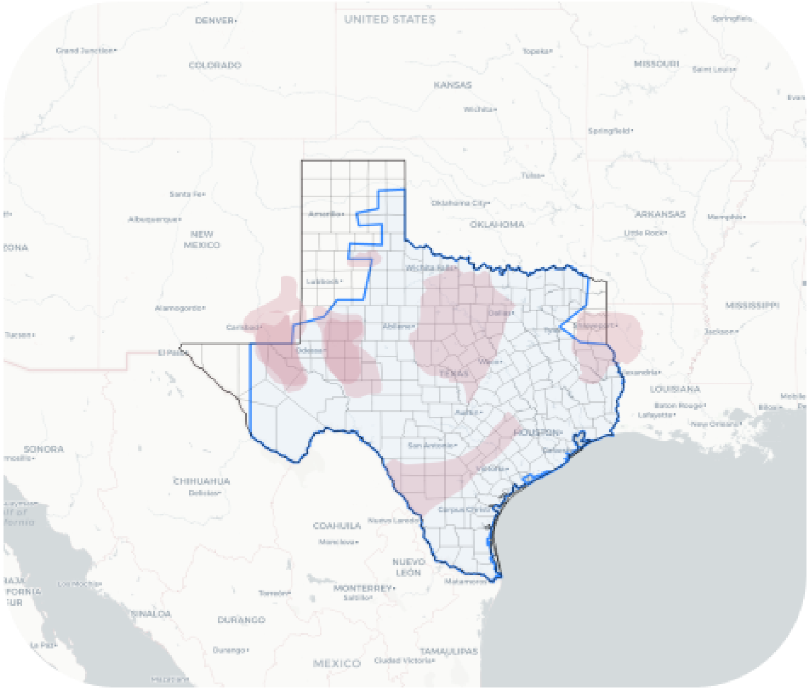


Figure 2.4: Natural gas shale plays (pink)

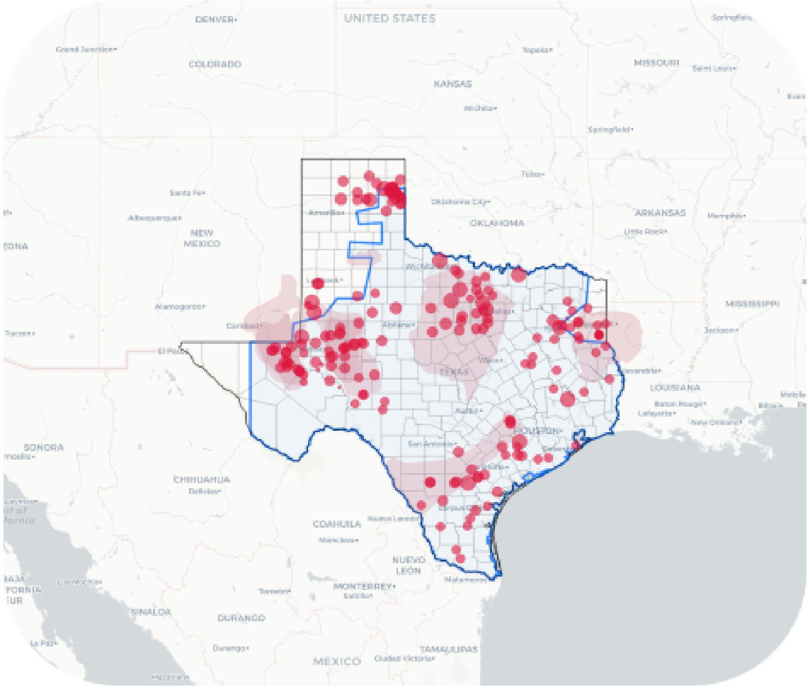


Figure 2.5: Natural gas processing facilities (red)

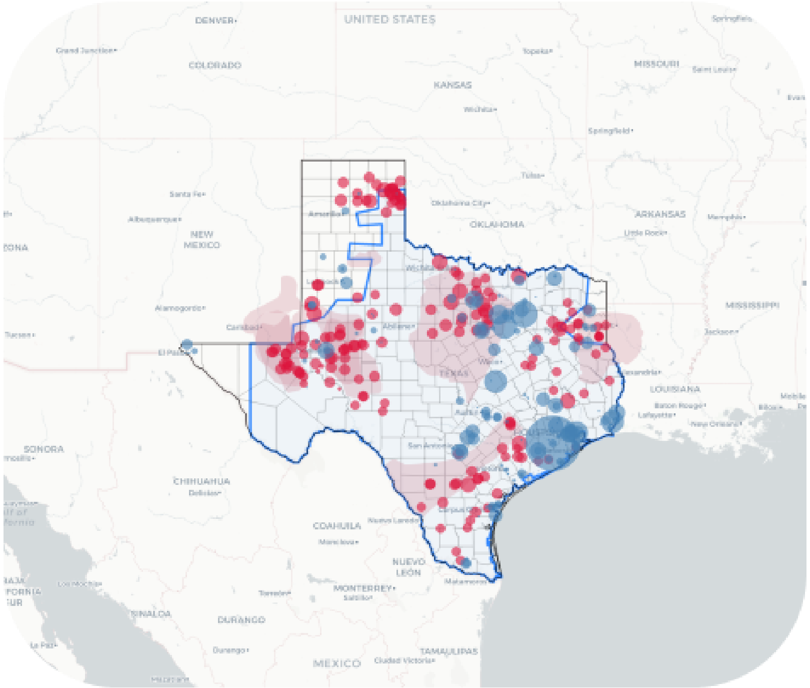


Figure 2.6: Natural gas electricity generators (light blue

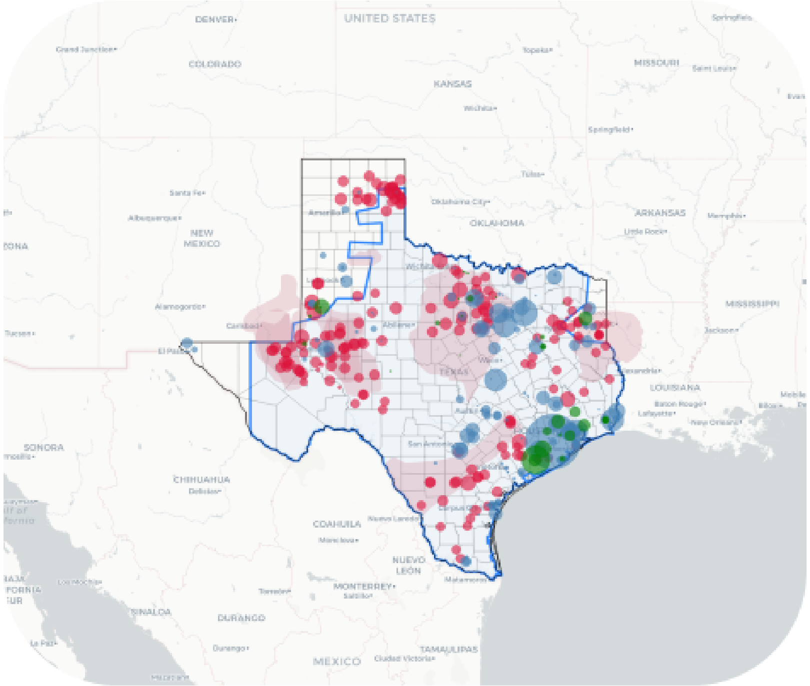


Figure 2.7: Natural gas storage facilities (green)

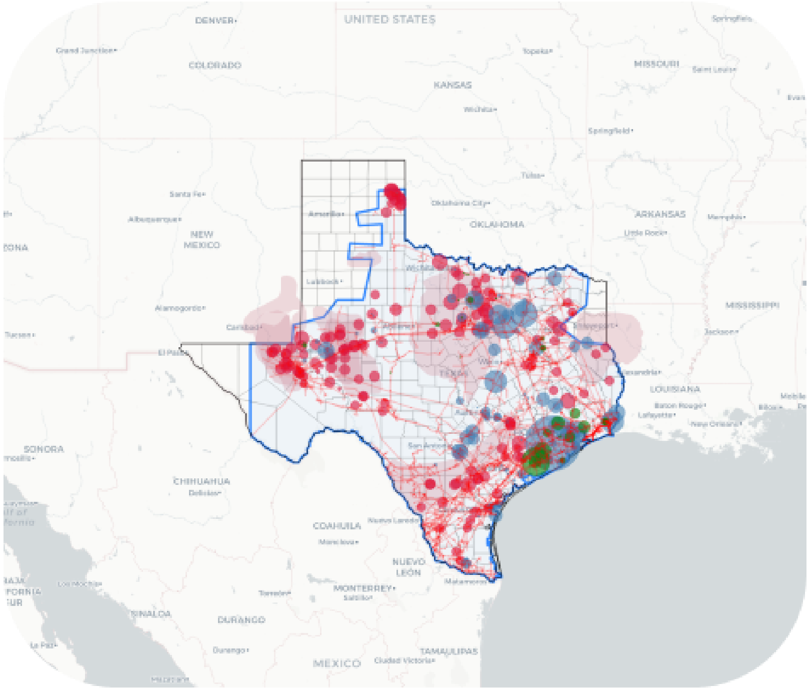


Figure 2.8: Natural gas instrastate pipelines (pink)

## 2.3 Running the simulation

The simulation to recreate the 2021 Texas power outages during Winter Storm Uri was generated using folium and hosted on an .html page. Data for the natural gas electric generators was the highest resolution data on 10-minute intervals from 2/14–2/19. The other two node datasets were not available at the resolution for individual time and location, so the final simulation was run at 1-hour intervals instead. The radius of each node corresponds to its generating capacity, throughput, or storage capacity depending on each type of unit. These nodes grow larger and smaller as the simulation runs to mimic the derating or processing failures of powerplants or natural gas processing plants over the five-day period. The simulation is visually scalable, so it can be viewed zoomed out, looking at holistically at ERCOT, or zoomed in to specifically analyze one node or area of interest. In addition, hovering the mouse over a node or pipeline will provide the user with descriptive data for that element of the simulation at that given time (Figure 2.9). Finally, the simulation can be paused, run back, and slowed down to allow for ease of analysis. This model can be utilized for other datasets and can incorporate transmission or pipeline flows if available. The data for this project is available on GitHub and a supplemental file is provided with this thesis of the running simulation used for this project.

Figure 2.9: Zoomed in snapshot of where pipeline operator and segment length data are provided

# 3. PROPOSED RESILIENCE METRIC FOR COUPLED NATURAL GAS AND ELECTRICITY SYSTEMS

## 3.1 Approach

This section introduces our approach to the second stage of this thesis. After collecting data to simulate the 2021 ERCOT power outage event, the next step involved developing a resilience metric for the coupled natural gas and electricity generation system. Figure 3.1 summarizes the various steps taken to meet our research objectives for this final part of the project which are:

- Develop a proposed resilience metric for the coupled natural gas and electricity generation systems
- Apply the metric to the Texas 2021 case study at two scales:
    - **scale 1:** metric application to entire ERCOT grid system
    - **scale 2:** metric application to specific individual electric generators

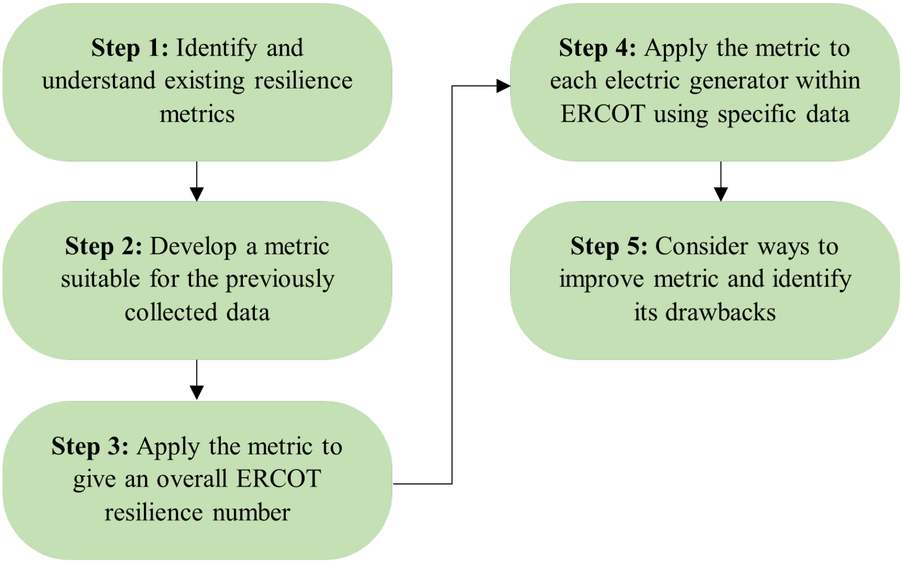


Figure 3.1: Flow chart of creation and application of resilience metric

## 3.2 Metric development

**Goal:** Resilience metric for coupled midstream natural gas and electricity generation system for HILF events.

In looking at existing literature surrounding resilience in power systems applications, several frameworks provide simple structures to break down a HILF event into three segments outside the realm of reliability. These three phases help quantify corrective, emergency coordination, and restorative phases (Figure 3.2).

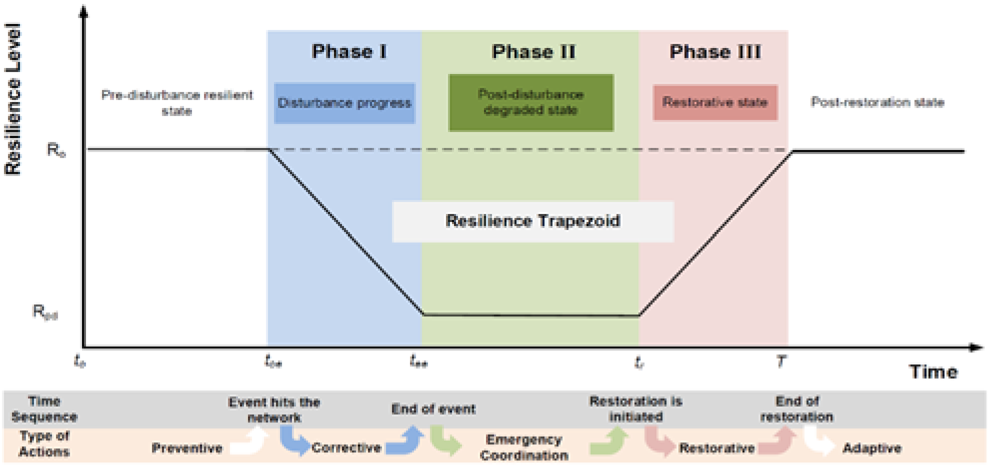


Figure 3.2: Resilience framework split into 3 phases for measurement [24]

The metric we propose is defined in the equation list below:

$$\textit{RI(cold weather)} = \frac{R1 + R2 + R3}{3}$$

- **Description:** *RI(cold weather)* stands for "resilience index" for an extreme cold weather event. *RI(cold weather)* is equal to the arithmetic mean of R1, R2, and R3 (see breakdowns of these variables below). The value inside the parentheses should in theory be applicable to other HILF events if they are quantified (e.g., tornados, hurricanes, and even cyber-attacks)

- *R1* = Resiliency at the corrective (phase 1) stage during the disturbance (e.g.cold weather constantly below freezing:32°F)
- *R2* = Resiliency at the emergency coordination (phase 2) stage when the disturbance event has finished and the coupled system is in a degraded state (e.g.temperatures return to normal but certain derated plants or processing facilities need to be addressed)
- *R3* = Resiliency at the restorative state (phase 3) where disturbance and post-disturbance have completed.This phase represents the duration of degraded state capacity back to complete restoration where normal grid operations resume.

$$R1 = \frac{\sum R1_t}{n} * \frac{1}{t_{final} - t_{initial}}$$

- **Description:** *R1* is the average of R1t multiplied by 1 over the duration of phase 1 (see breakdown for these variables below). The system resilience in phase 1 is lower the longer the duration of the phase. If no loss has occurred in *R1electricity* or *R1gas_process* then R1 indicates complete system resilience.

$$R1_t = \frac{\frac{\sum R1electricity_{i,t}}{n} + \frac{\sum R2gasprocess_{i,t}}{n}}{2}$$

- **Description:** $R1t$ is the average of R1electricity at time t multiplied by the average of $gasprocess$ also at time t. This returns a value between 0 and 1 and gives the $R1$ at each time interval during phase 1. Variable i is the specific unit (e.g., pipeline, processing plant, electricity generator etc). See breakdown for final set of variables below.

$$R1electricity_{i,t} = \frac{AvailableNatGasElectricityGen_{i,t}}{ScheduledNatGasElectricityCapacity_{i,t}}$$

- **Description:** $R1electricity$ is the available electricity generation at generator i at time t. Available Nat Gas is the generation capacity at the time of measurement and Schedule Nat Gas is the normal generating capacity of the unit.

$$R1gasprocess_{i,t} = \frac{AvailableNatGasProcessing_{i,t}}{ScheduledNatGasProcessing_{i,t}}$$

- **Description:** $R1gasprocess$ is the available natural gas throughput at processing plant i at time t.

$$R2 = \frac{\sum R1_{t2}}{n} * \frac{1}{t2_{final} - t2_{initial}}$$

- **Description:** Where $t2$ is the time intervals t for phase 2 for the duration that $R1_{t2}$ remains constant (at which point it changes, the system will enter phase 3). $R2$ is designed to measure the amount of time it takes from the end of the disruption to the beginning of the restoration phase.

$$R3 = \frac{\sum R1_{t3}}{n} * \frac{1}{t3_{final} - t3_{initial}}$$

- **Description:** Where $t3$ is the time intervals t for phase 3 where $R1_{t3}$ begins at the first restoration of generation and continues across the duration of $t3_{final} - t3_{initial}$ until the system returns to a normal operational state.

### 3.3 Large scale application to ERCOT grid

Creating the resilience metric is useful as a framework to be used in case studies but taking it a step further and applying it to the simulation data from part 1 of the thesis helps put an actual resilience number for this event as well as test the viability of the metric. While inputting the data into the metric calculations, there was some concern regarding how to measure the HILF event. There is need for a temperature component in order to properly calculate the time spent by each node in each phase of the event, but temporal data was not easily accessible at the resolution needed for this project. In addition, by performing the calculation with area specific weather, there becomes a time series mismatch where certain nodes are in different phases during the same time. This causes a problem when summing and averaging all the nodes for the larger, system-wide resilience metric. These issues help reinforce the point that quantifying resilience in power systems is a complicated problem, and that our metric was not an all-encompassing solution, but rather more useful when looking at individual generators. Nonetheless, this problem can partially be solved by using Texas average temperatures for the duration of the event. That data was easy to obtain and helps hold all nodes in the same phase during the same timestamps.

Defining a HILF event, regardless of nature of the event is difficult. For the sake of this thesis, a simple cold-weather HILF was defined as temperatures below 32°F which is a temperature that Texas infrequently experiences and the point at systems are not rated to perform. The limitation of using this method is that for the simulation dates (2/14 – 2/19) the average Texas temperature is under 32°F or what is considered the HILF event (Figure 3.3). This means that all the data in the simulation can only be run under phase 1, and thus an entire RI(cold weather) cannot be fully calculated since phase 2 and phase 3 take place after February 19th.

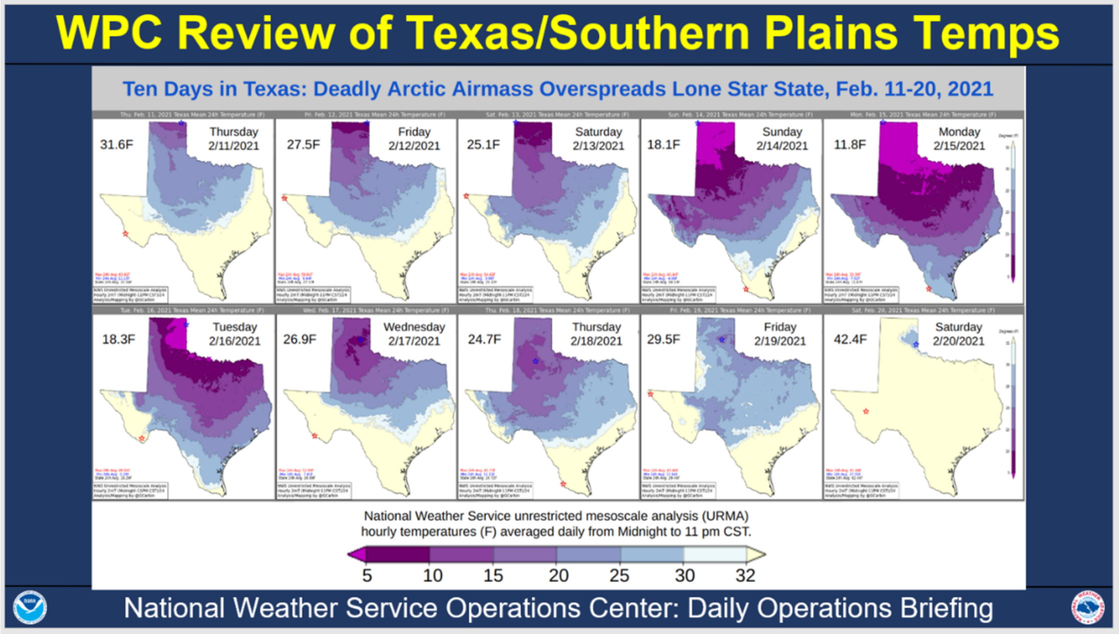


Figure 3.3: Average temperatures for Texas during Winter Storm Uri [25]

The final consideration is that since we only have data for phase 1, the time element of R1 will be considered as 1 over the total duration of this event in hours. This causes the resilience metric for R1 to be extremely small where it would otherwise be larger for generators coming back online at various points during this five-day period. Time duration is calculated in hours. Further work could improve this result by collecting generation, weather, and duration data for phase 2 and phase 3 of this event.

Calculated R1 of ERCOT grid over Winter Storm Uri Event: 0.0044

This number does not mean much on its own, but by zooming in and calculating a complete RI(cold weather) on a single node, we can get a better understanding of the numbers.

### 3.4 Small scale case study on individual generators

While problems emerged when dealing with non-synchronized phases when calculating an ERCOT level resilience index, this calculation is much easier at the individual level. Weather data was obtained for 49 natural gas electric generator sites that were previously modeled in the simulation. The interval for this weather data was available at daily intervals so the granularity of the metric is reduced, but the overall trends still apply for the event. At each timestamp, the resilience phase for the generator was determined by $Relec$ and temperature values. The criteria for the phase is as follows:

- **Phase 1:** < 32°F AND $Relec$ < 1
  - Where the HILF event is occurring due to below freezing temperatures
- **Phase 2:** >= 32°F AND $Relec$ < 1 AND = $Relec(t-1)$
  - Where the HILF event has ended (temperatures above freezing) and the derate is still occurring and actively recovering
- **Phase 3:** >= 32°F AND $Relec$ <= 1 AND > $Relec(t-1)$

  - Where the HILF event is still over, but the derate status of the generator is actively improving; meaning it is return closer to a normal operating state with each timestamp

Running the metric through all individual electricity generation sites using a daily time interval led to some interesting results. The R1 calculations (Figure 3.4) ranged from 1 almost down to 0, meaning that some sites had no derate during the times measured at this interval, while others had an extreme derate or complete generation failure. This is the first sign showing the restriction of having limited interval data for weather, since we know from the simulation that each of these generators have a derate at some point during the five-day period, it is just not apparent at this resolution. A total of 47 sites were able to have a calculated R1 value based on the criteria listed above.

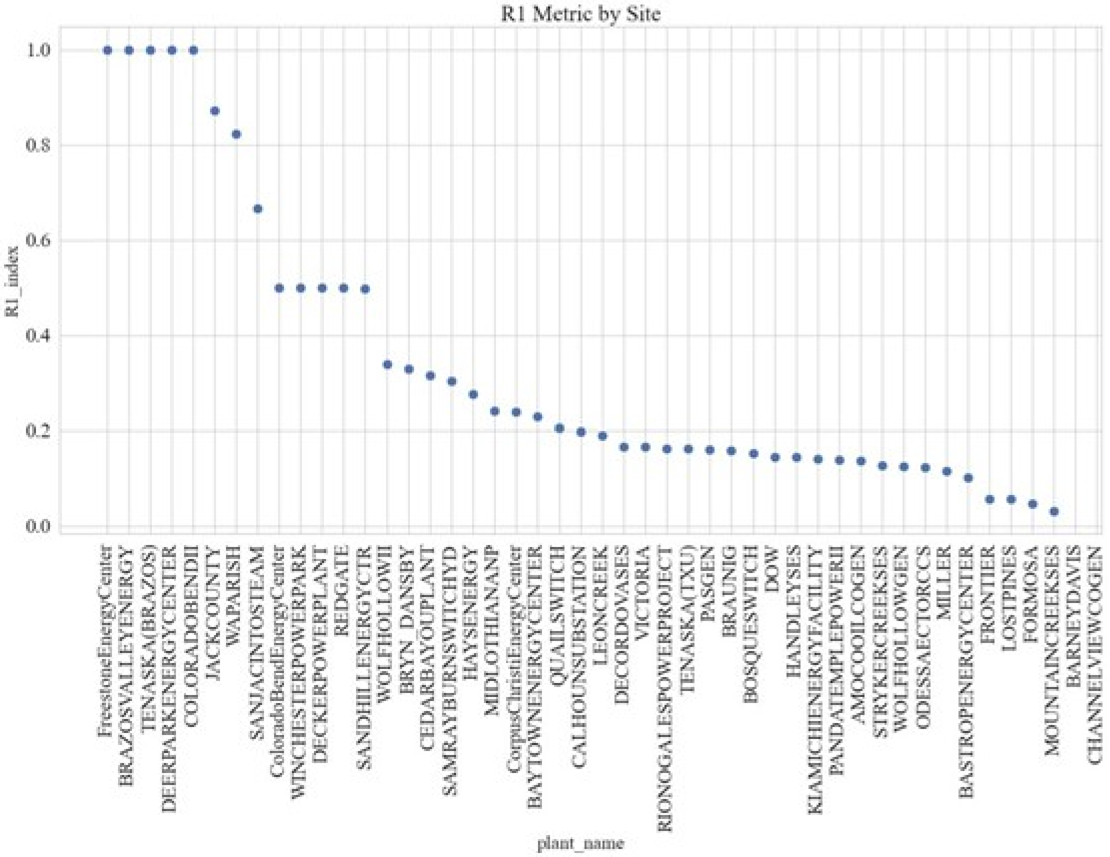


Figure 3.4: R1 index calculated for electricity generation sites (length: 47)

The R2 calculations (Figure 3.5) were managed for a total of 33 sites also having similar ranges to R1 calculations. High R2 values indicate a low derate value over a low time interval (i.e., 1 day for this dataset) meaning that for the five timestamps used in this calculation, if a site were to maintain most of their generation during phase 1 and only be in phase 2 for one day (i.e., 1 timestamp) the respective R2 value will be pretty high. Again, this value would likely be much lower if hourly intervals were used to adequately show phase 2.

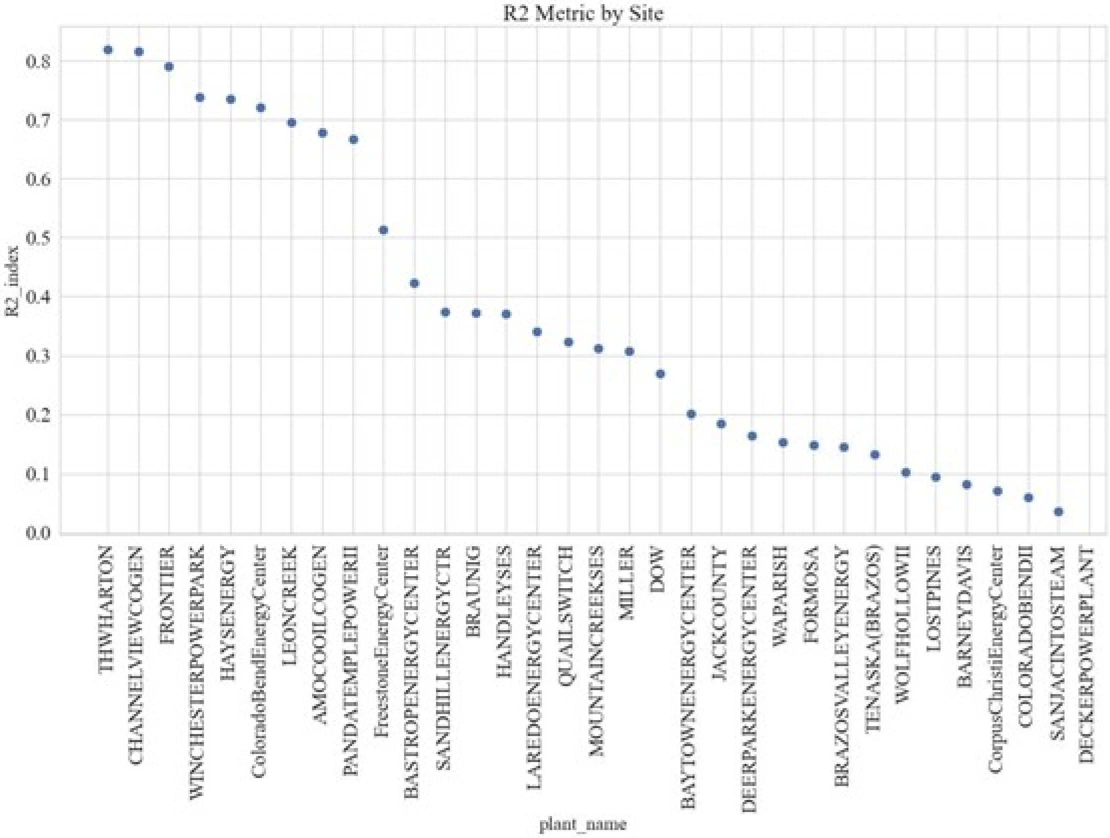


Figure 3.5: R2 index calculated for electricity generation sites (length: 33)

The R3 calculations (Figure 3.6) contained a total of 30 sites, meaning only 30 sites of the 47 had phase 3 conditions at some point during one of the timestamps. This calculated number is the smallest of the three since as we know from the system-wide calculation, not all generators returned to normal operating status within the 2/14 – 2/19 date range. Thus, if a generator does not meet the phase 3 criteria, it is unable to be calculated.

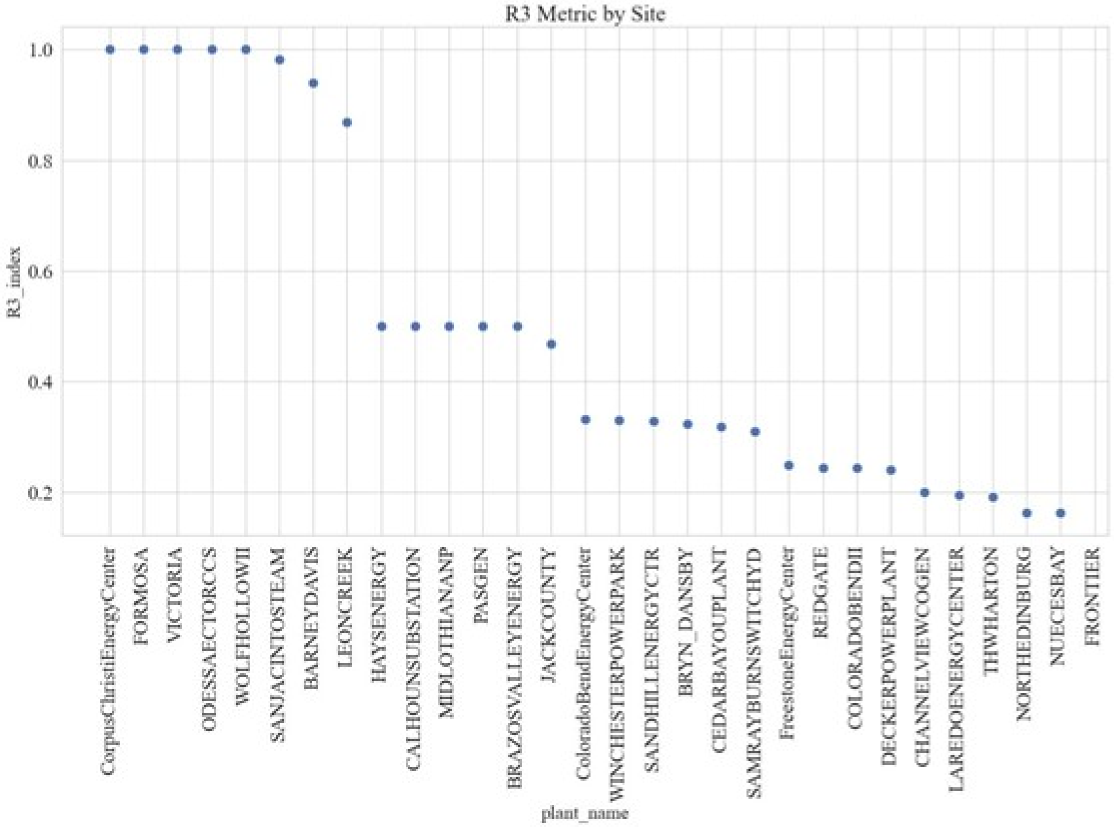


Figure 3.6: R3 index calculated for electricity generation sites (length: 30)

Finally, the RI index is calculated for the applicable sites. Unfortunately, at this resolution, only 13 sites contained a R1, R2, and R3 value to allow for the final RI calculation (Figure 3.7). If this test was re-run with available hourly data, more sites would fit the criteria for an RI calculation. The RI values ranges from .57 down to 0.4 as an average of the three phase resilience values. Given the comparison to the system-wide R1 value, this RI value is much larger than the system-wide RI value could achieve.

Since only the electricity side of the index was calculated without looking at the natural gas side for these individual tests it is clear that there is a strong interdependency between the electricity and natural gas sectors. When the other half of the coupled system is calculated in the metric

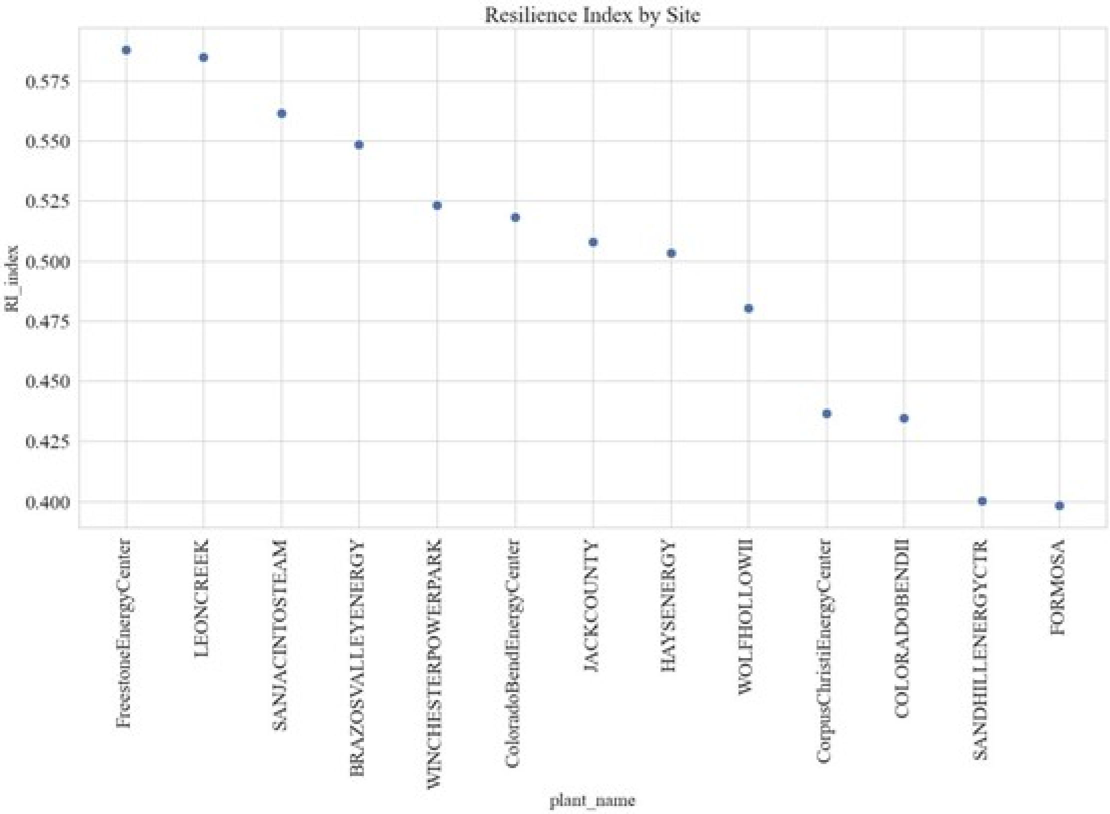


Figure 3.7: RI index used for electricity generation sites (length: 13)

(as seen in the system-wide R1), the resiliency drops as expected. By analyzing the metric at this zoomed in resolution, it allows for retroactive studies on HILF events. For example, each electricity generator can be ranked according to their resilience index without knowing any more information besides actual and scheduled capacity. Afterwards, a closer look can be taken at the generators that performed well to understand what factors make them more resilient than others (e.g., more interconnections to natural gas processing facilities, winterization packages, backup generation etc.).

# 4. DRAWBACKS AND CONSIDERATIONS

There are several drawbacks of the created resilience metric that are important to note. First, it is difficult to asses what quantifies as a HILF event. Not only is this an arbitrary description that varies depending on the type of system and type of event, but with these events occurring more frequently, at what point will they fall under the category of "normal operating conditions". If they eventually fall under normal operating conditions, than it is likely that they will be included in a reliability metric, reducing the usefulness of the resilience metric for historical data.

The data requirements to calculate the proposed resilience metric are very high and many data is proprietary or otherwise unavailable to the public at the resolution desired. While data for this study was made available by ERCOT for the study of this event, it might not always be the case and will make consistent use of this metric difficult across different cases.

Developing an interdependency specific metric will need a weighting or other relationship when being used in a grid level resilience metric. This metric only quantifies the resilience between the coupled natural gas and electricity generation sector, but to calculate a complete resilience index for a grid, other interdependencies and sources of generation need to be calculated and related to this metric.

Finally, when applying this metric to the complete ERCOT system, it was difficult to define $RI(coldweather)$ for a correct duration. For example, several units derate, recover, and then derate again within different spans of time across the network. This creates a time series mismatch that makes calculating the broader $R1$, $R2$, and $R3$ values difficult as operable units and weather vary by region.

Resilience in power systems is a complex topic in existing literature and through the proposed metric it is clear that this is not the complete solution. However, despite its limitations with the available data for this study, it is still useful for calculating resilience in higher resolutions at specific nodes for comparison and ranking.

# 5. CONCLUSION AND FUTURE STEPS

Despite the improvements made by the electric grid in the last several decades, it is still vulnerable to extreme weather events as see in ERCOT in February 2021. Through proposing a resilience metric for the coupling of natural gas and electricity generation systems within the ERCOT grid, further work to define and refine the quantification of resilience can be conducted. As a whole, grid resiliency need continuous research to accelerate increased communication between sectors while also preventing events like February 2021 from occurring again.

As stated above, looking at site specific resilience metric after an event can help reveal which solutions might be viable during HILF events. Additional studies are needed to help bring resilience for power systems up to the same standard as reliability. This study helps progress the quantification of resilience and opens research questions regarding other interdependencies within the grid system (e.g., water and electricity, oil and electricity, communication and transportation between sectors etc.) Through enhanced communication of all interdependencies, resilience of the system will undoubtedly improve. These future studies might lead to openings for grid resiliency improvement with smart grid applications. With additional tweaking, the proposed resilience metric could be applicable for use in smart grid scenarios (e.g., and additional measurement that fits into the resilience index relating to number of smart meters onsite or some way to measure the enhanced control through smart metering).

Finally, in looking at site specific areas for future research, the proposed metric can work in coordination with a future study on which solutions might help improve site resiliency. This includes solutions like onsite fuel storage (Figure 5.1), distributed electricity generators (Figure 5.2), or re-prioritization of natural gas delivery during disruption events (Figure 5.3).

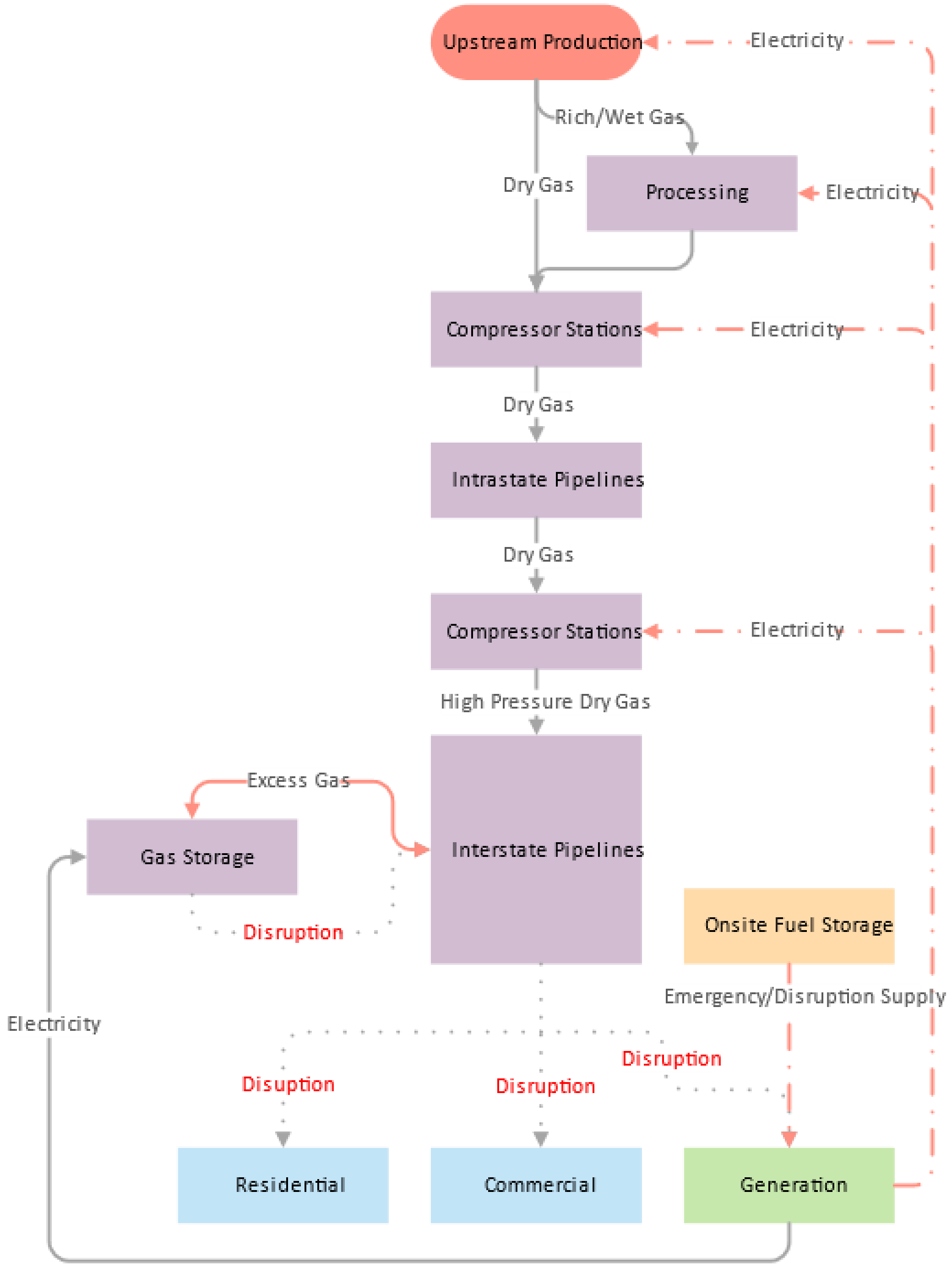


Figure 5.1: Proposed onsite fuel storage solution

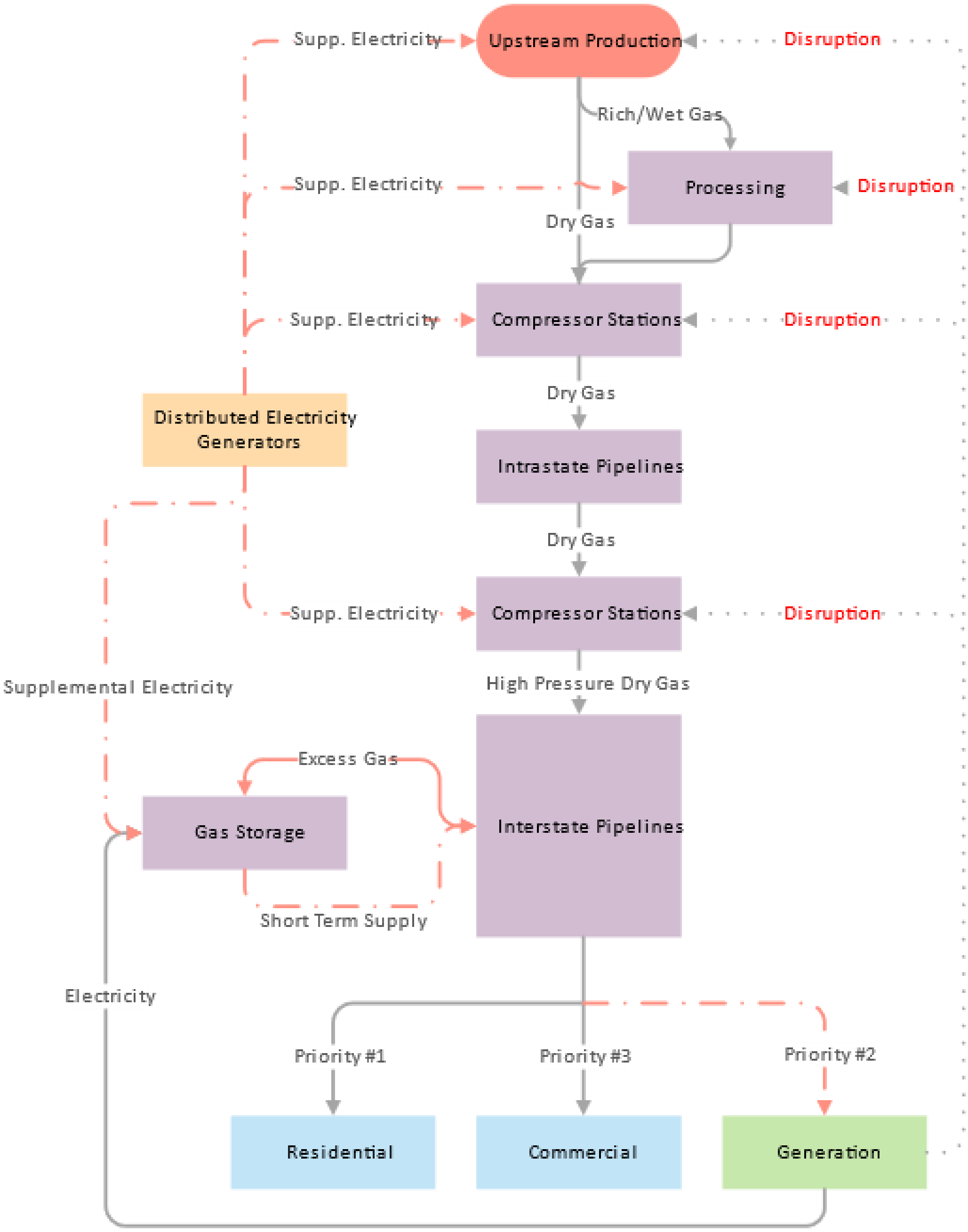


Figure 5.2: Proposed distributed electricity generator solution

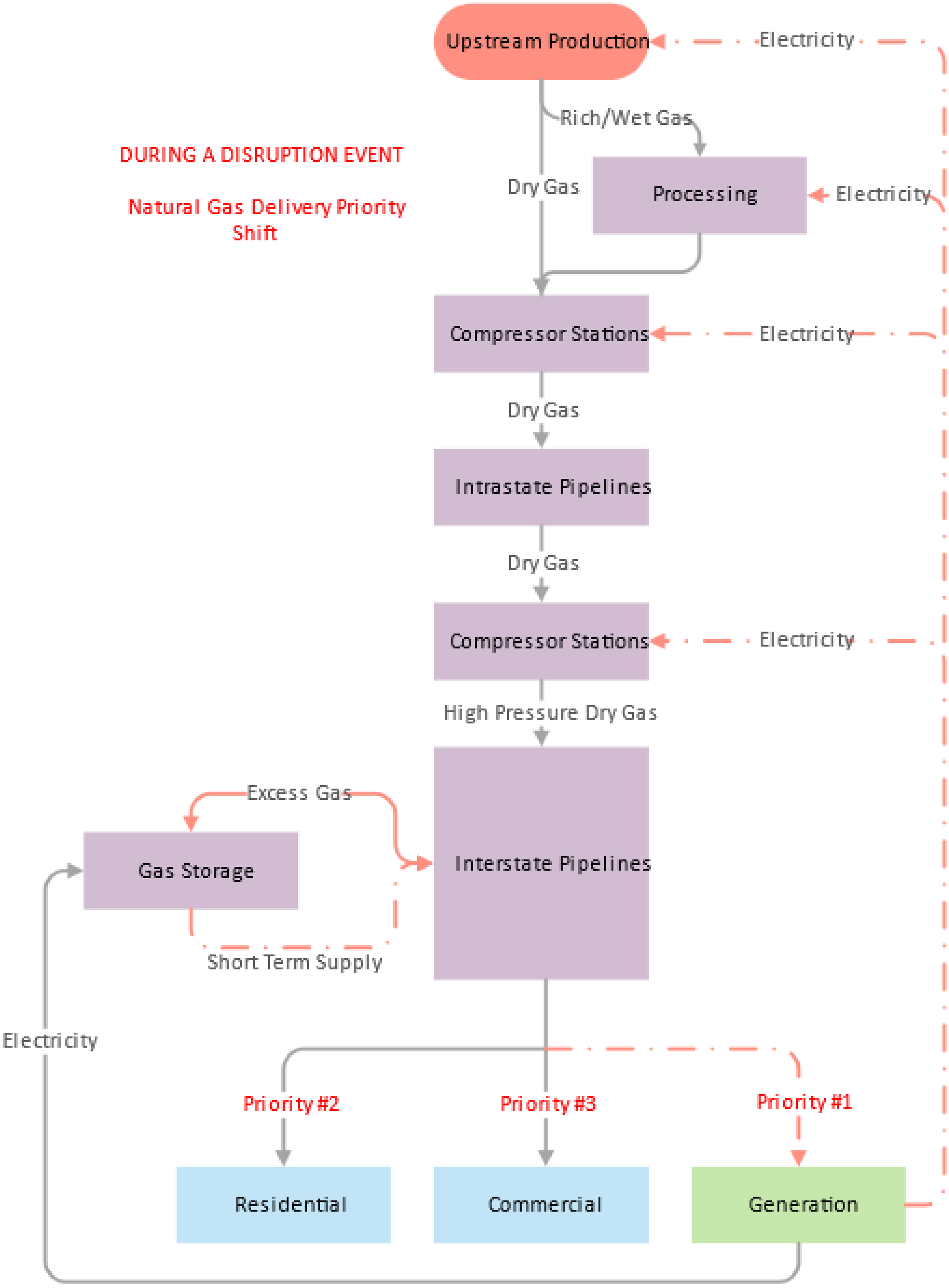


Figure 5.3: Proposed re-prioritization of natural gas delivery solution

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