Evaluating and Strengthening Iowa's Power Grid for High Wind/Solar Penetration Levels

Prepared by
James McCalley
Colin Christy
Charlie Phillips
(others)

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Project Report #6b
Enhance Resilience Modeling

Prepared by

James McCalley, Principal Investigator
Colin Christy, Co-Principal Investigator
Charlie Phillips, Ph. D. Student

Iowa State University
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Executive Summary

This document was developed for the "Evaluating and Strengthening Iowa's Power Grid for High Wind/Solar Penetration Levels" project funded by the Iowa Economic Development Authority. The overall project objective, consistent with the Iowa Utilities Board's (IUB's) objectives in Docket No. INU-2021-000, is to apply expansion planning analysis emphasizing Iowa, exploring the challenges and opportunities of Iowa's grid in the forthcoming years.

The focus of this work (Task G6-3) is to provide a case study showing the applicability of Iowa State's resiliency-based co-optimized expansion planning (RCEP) tool for long-term power planning in the state of Iowa. Our case study will model the August 10, 2020 derecho and show how resiliency investments can be made ahead of time to minimize the combined economic costs of those investments and damage from the storm itself.

In addition, this report will summarize existing and provide a power-systems-focused definition for "extreme events," discuss the meteorology of derechos, discuss the difference between reliability and resiliency, and provide a high-level formulation of the Iowa State RCEP model. We hope that this provides the reader with enough foundational knowledge to understand the findings of our model simulation and how it may relate to planning and policy decisions.

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1. Introduction

The purpose of this report is to introduce the concept of *resilience* to extreme weather events in long-term power planning. The focus of the report will be on modeling the June 29, 1998 and August 10, 2020 derecho in Iowa State's resilience-co-optimized expansion planning (RCEP) model, and showing how that model can make economical, grid-hardening investments to reduce the total impact from an extreme weather event.

The August 10, 2020 derecho traveled 770 miles from southeastern South Dakota to western Ohio over a 14-hour period, and it produced widespread 100+ gusts over Central/Eastern Iowa to isolated portions of Northern Illinois [1]. Cedar Rapids experienced the strongest winds and greatest damage, with gusts near 140 mph – some of the highest values ever recorded during any derecho in history [2]. The derecho also spawned 26 weak tornadoes, including 15 in northeastern Illinois impacting the Chicago metropolitan area [1][2]. The storm caused over 7.5 billion dollars in damage (13.3 billion, inflation adjusted for 2024) and left two million without power, with some remaining without power for two weeks [3][1]. It is the costliest severe thunderstorm on record. The June 29, 1998 derecho was the 2nd most damaging derecho for Iowa in the past 30 years traveled over 600 miles from northeastern Nebraska into northern Kentucky. Damage was greatest from Central Iowa into Central Illinois. Polk County was particularly hard-hit due to an embedded mesocyclone within the derecho, bring F2-strength strength winds to Northern Des Moines. The 1998 derecho caused 125 million dollars in damage, with 100 million occurring in Polk County alone. (240 & 192 million, inflation adjusted for 2024) [4].

Chapter 2 defines what is meant by "extreme events," building off the some of the work done in Project Report #2: High-Risk Conditions and Events. In particular, we summarize the definitions provided by MISO and SPP in response to FERC Order 897, which directed transmission planners to provide a one-time report describing their extreme weather event vulnerability assessments and their definitions of extreme weather events (FERC does not provide an official definition). These definitions and vulnerability assessments have been heavily influenced by recent winter storms (Uri and Elliot), as these storms created widespread thermal generator outages and have motivated multiple new cold weather reliability standards from NERC. We also provide a power-systems-oriented definition of "extreme events" that differentiates between "energy security" events, which are periods with low renewables and/or high load where electricity demand may exceed supply, and "infrastructure damage" events, where physical electric infrastructure such as transmission lines, generators, and substation equipment can be damaged or disrupted by high winds or other types of inclement weather. These "infrastructure damage" events, and more specifically high-wind events from derechos, are the focus of RCEP and this paper.

Chapter 3 is dedicated to meteorology of damaging, thunderstorm-driven straight-line wind events, also known as derechos. Derechos are the most frequent and destructive "infrastructure damage" extreme weather events for the state of Iowa. This chapter also references some historical derechos and summarizes the findings of the latest IPCC (Intergovernmental Panel on Climate Change) report for how severe thunderstorms (including derechos) may evolve under climate change.

Chapter 4 defines reliability and resiliency as distinct concepts but also discusses how they can overlap, particularly in the context of severe events. Chapter 4 also reviews methods used to *quantify* resilience in other peer-reviewed studies, hazard modeling software, and the RCEP model itself.

Chapter 5 discusses the methods used to derate transmission lines according to wind speed and resiliency level. It also discusses a high-level formulation of the RCEP model. Chapter 6 discusses the results from the RCEP model run, and chapter 7 is conclusions. A works cited is at the end of the document.

2. Extreme Events

The power grid is very vulnerable to meteorology and this vulnerability will increase as renewable generation increases, society electrifies, and climate change results in changing weather patterns. On the supply side, the transition away from fossil fuels and towards wind and solar power means that power generation is becoming increasingly dependent on meteorological patterns. The electrification of transportation and heating systems means that demand is becoming more weather-dependent as well. In addition to demand/supply becoming more weather-dependent, wind/solar farms are less resilient structures than large thermal or hydroelectric generating stations and are more susceptible to damage from extreme weather events. Additionally, the increasing buildout of transmission lines renders the grid more susceptible to damaging and high-impact weather events, particularly those with high wind, freezing rain/icing, or wildfire risk. Given all these risks, it is critical to account for the increasing weather dependence of the grid in long-range power planning.

2.1 Meteorological and Societal Definitions

The term "extreme events" is often used in power systems analysis, policymaking, and in atmospheric science. But different types of extreme events have different impacts on society and require greatly different investments in the power system. In order to make informed decisions for power systems planning, we must define what type(s) of extreme events we want to plan for and how much "weight" we want to give to each event.

The sections below describe three "lenses" through which to view severe events. Our focus is on the power systems perspective. In this vein, we define an "extreme event" as a weather/climate event that contributes to creates the risk of an energy shortage, severely impacts power system infrastructure, or both.

Meteorological/Climatological Definition

The 6th Assessment Report of the Intergovernmental Panel on Climate Change defines an extreme weather or climate event as an event containing weather variable/s that are near the upper or lower bounds of events in the historical record (link). The distinction between weather and climate is based on timescales, and while exact definitions vary, weather events are usually shorter than 1-2 weeks while climate variables usually two weeks or longer.

There are two key distinctions here. First, an "extreme" event does not need to have significant impacts to energy or society. For example, a high of 70 degrees in Des Moines in January would be the warmest January day in nearly 150-years of record keeping and would qualify as an "extreme event," but it would have minimal impacts to society or power systems. Likewise, the rainiest month on record occurring on the heels of a multi-year drought when rivers are running low and fire danger is high would be an extreme event that could provide widespread *benefits* to society, with crops receiving much-needed precipitation and the dry, absorbent soil and antecedent low river levels mitigating flood damage.

Second, because our climate is warming and extreme events are defined in context of the historical record, we are seeing far more warm "extreme events" now than at any time in our history. Some of these, like warmer winter nights, are benign. Others, such as stronger hurricanes due to warmer ocean waters, can cause tens or even hundreds of billions of dollars of damage every year – sometimes from a single storm (Katrina in 2005, Harvey in 2017).

Societal Definition

Whereas meteorological definitions define extreme events as being towards the extremes of what has been historically measured, societal definitions usually involve the ability of a community or society to prepare, withstand, and recover from the event. These events are often referred to as "disasters" to better emphasize the impacts on society. Because this definition is somewhat nebulous, it can help to have certain "thresholds" to classify disasters by.

<u>NOAA Billion Dollar Disasters</u>

NOAA's "billion dollar disasters" database has detailed information on every disaster totaling 1 billion or more dollars in damages (adjusted for inflation) extending all the way back to 1900. The number of billion-dollar disasters has steadily increased due to both the increasing severity/frequency of some destructive weather events and the increasing vulnerability of our society to these events. NOAA categorizes its "billion dollar disasters" into 6 categories. These are as follows:

1. **Severe storm:** A storm is "severe" when it produces wind gusts of at least 58 mph and/or hail one inch in diameter or larger and/or a tornado.10 A tornado is a violently rotating column of air touching the ground, usually attached to the base of a thunderstorm. Derechos, also considered a severe storm, are widespread, long-lived wind storms associated with a band of rapidly moving showers or thunderstorms; if a severe storm causes wind damage extending more than 240 miles and includes wind gusts of at least 58 mph or greater along most of its length, then the event may be classified as a derecho.12
2. **Tropical cyclone:** A cyclone is a large-scale circulation of winds around a central region of low atmospheric pressure. A tropical cyclone is a warm-core, non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters with organized deep convection and a closed surface wind circulation about a well-defined center.13

3. **Winter storm:** A winter storm is a combination of heavy snow, blowing snow and/or dangerous wind chills.14
4. **Drought:** A period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected area.15
5. **Flooding:** An overflow of water onto normally dry land; the inundation of a normally dry area caused by rising water in an existing waterway, such as a river, over a widespread area for a climatologically significant period of time.17
6. **Wildfires:** A wildfire is an unplanned, unwanted fire burning in a natural area.18

2.2 Power Systems Definition

For power systems, we propose two categories of extreme events: "**energy security**" events, which refer to a risk of power shortfalls due to low renewable generation, high load, unplanned generator outages, or a combination of the three, and "**infrastructure damage**" events, which physically damage electrical generation, transmission, and distribution infrastructure. A succinct definition is below.

> "An extreme event is a weather/climate event that contributes to an energy shortage, disables/damages power system infrastructure, or both."

As we will discuss in depth in chapter 5, the "resilience" investments in the resiliency-based co-optimized expansion (RCEP) model are "grid hardening" investments that decrease the failure rate of electrical system components when they are exposed to extreme weather conditions. In other words, these "resiliency" investments are only applicable for "infrastructure damage" events. In RCEP, capacity investments are handled by enforcing a *planning reserve margin*, which ensures that power planners have enough generation reserves to meet demand during those high demand/low supply periods.

In "Project Report #2: High Risk Conditions and Events," Report 2, we defined "high risk" events that contributed to an energy shortage as periods of simultaneous low wind & solar, particularly when coincident with high loads. Extreme heat was explored in Report 2, but extreme cold is also a high-risk pattern. For the purposes of this report, "high risk" and "energy security" events refer to the same category of event.

Project Report 2 also defines "extreme weather events" as "a time and place in which the cost impact of weather, climate, or environmental conditions such as temperature or precipitation, ranks above a threshold value near the upper end of the range of historical values," and uses $1 billion as a threshold values. This is similar to the "societal definition" of extreme events given in Section 2.1, with the six categories of events being "types" of extreme events. For the purposes of this report, "extreme weather events" and "infrastructure damage" events refer to the same type of event. The only exception here are drought events, as these can cause billions of dollars of damage to agriculture (and therefore show as a billion-dollar disaster) but generally do not have an impact on GTD systems. They can result in energy security issues for hydro-rich regions such as the Pacific Northwest (in fact, drought during 2000-2001 was a contributing factor to the California Energy

Crisis), but given the relative lack of hydro generation in SPP or MISO, droughts present little risk for Iowa.

Note that there can be some overlap between each of these events. For example, extreme winter weather events like Winter Storms Uri and Elliot cause high loads due to frigid temperatures, but these frigid temperatures also resulted in massive unplanned outages of natural gas power plants due to unwinterized gas and power infrastructure. For example. Winter Storm Elliot had 90,500 MW of unplanned outages and 5,400 MW of firm load shed. [6]. As discussed below, the impacts from Winter Storms Uri and Elliot have led to an increased emphasis on cold-weather resilience so that power plants can reliably operate during sub-freezing temperatures.

2.3 FERC Orders 896/897

In 2023, FERC issued two orders - Orders 896 and 897 – that were aimed at increasing the reliability of the bulk power system during extreme weather events. These orders were motivated by a demonstrated lack of cold-weather resiliency in the natural gas and bulk electric systems during Winter Storm Uri in February 2021 and Winter Storm Elliott in December 2022.

Order 896 directed NERC to include transmission planning standards for "extreme heat and cold weather events that impact the Reliable Operation of the Bulk-Power System". Order 897 directed RTOs to conduct one-time extreme weather vulnerability assessments and report their findings to FERC. Additionally, Order 897 directed each transmission provider to define "extreme event."

These orders reflect the industry-wide recognition for more resiliency to extreme weather events. Order 897 is particularly notable because not only does FERC not provide a definition of "extreme event," - it delegates that task to transmission providers. The below definitions of "extreme event" were provided from MISO's and SPP's one-time extreme vulnerability assessments pursuant to FERC Order 897 [7] [8].

2.4 SPP 'Extreme Weather Event' Definition

SPP does not have an explicit definition of an "extreme weather event." Additionally, SPP does not have a distinct process by which it conducts extreme weather event vulnerability analysis, though they utilize weather forecasts for operational and planning purposes. However, SPP utilizes weather-related thresholds in their analyses that can help identify potential periods of power system stress. [7]

From an "operations" standpoint, SPP performs two types of analyses that are heavily weather-dependent. One is a "Seasonal Assessment" twice a year – (the "Summer Seasonal Assessment" and "Winter Seasonal Assessment") to identify hazardous weather conditions to the bulk electric system. The second is through their "Uncertainty Response Team," (URT) which uses weather and other inputs to identify forecast, risk, and capacity challenges during SPP's Multi-Day Reliability Assessment (MDRA), a security-constrained unit commitment process which spans from current day to 7 days in advance. For long-term planning purposes, SPP currently employs the NERC MOD-033 process to validate transmission planning cases through benchmarking against historical extreme weather events and is working with stakeholders to further develop assessment criteria for extreme event planning. [7]

SPP's seasonal assessments "consider" extreme events such as heavy rainfall, drought conditions, variability, and extreme cold or heat. The primary quantitative metric used is a 90/10 load forecast probability to identify the potential demand during extreme heat or cold conditions. SPP also tests high wind scenarios with power modeling software to determine transmission constraints under the current grid topology. SPP's URT uses weather inputs to calculate its load/wind forecasts, the uncertainty within these forecasts, and the risk of capacity shortage events. As such, even though SPP doesn't explicitly define an "extreme event," it uses weather inputs to identify potential energy security events within its 7-day forecast horizon. [7]

SPP mentions that a major long-term planning focus is resiliency towards extreme winter weather events. This is likely part of a broader push in the power systems industry towards resilience to cold weather events after Winter Storms Uri and Elliot, particularly with FERC's approval of NERC's cold-weather reliability standards EOP-011-4 and TOP-022-5 in February 2024. [9]. SPP does NOT include scenarios of increased transmission outages resulting from extreme storms, hurricanes, high wind, or wildfires in the Seasonal Assessments. [7].

To summarize, SPP does not have an explicit definition of extreme events, and the "high-risk" scenarios are ones where there is a risk of firm load shed due to a lack of renewable generation, very high loads, unplanned outages (especially due to lack of winterization), or a combination of all these factors. SPP does not explicitly state that they include resilience modeling to high wind events like the August 2020 derecho.

2.5 MISO 'Extreme Event' Definition

Like SPP, MISO splits its definitions for extreme events into operational purposes, which are handled by the MISO Reliability Coordinator (RC), and planning purposes, which are handled by the MISO Planning Coordinator (PC). MISO RC *does* have explicit definitions of extreme events, but MISO PC lacks an explicit definition.

MISO RC's Operational Risk Assessment (ORA) team is responsible for forecasting short-term weather risk and defines extreme events as the following:

- Hurricanes/tropical storms that impact the MISO footprint, especially ones that make landfall in MISO territory over extreme eastern Texas, Louisiana, and Mississippi.
- Severe thunderstorm activity that warrants a risk of "enhanced" or higher on the Storm Prediction Center's severe weather outlooks
- Extreme heat and cold waves. Heat/cold waves are placed in context of 10 & 30-year averages, but no exact threshold is given.
- "Extreme" or "exceptional" drought per the U.S. Drought Monitor, flooding (no threshold given), and wildfire smoke (no threshold given)

Like SPP, MISO's operational forecasting timeframes are split into seasonal and shorter-term components. MISO has two seasonal assessment processes, the Coordinated Seasonal Assessment ("CSA") study, which evaluates the performance of MISO's transmission system during anticipated conditions for the upcoming summer/winter seasons, and the Seasonal Risk Assessment, which is handled by the ORA and is more analogous to SPP's Summer and Winter seasonal assessments. Like SPP, the Seasonal Risk Assessment focuses on energy security risks due to extreme heat/cold, though seasonal hurricane forecasts are also considered. [8]. This makes sense given that MISO-South covers portions of the Gulf Coast while SPP is exclusively inland and does not extend much further south than the Louisiana/Arkansas/Texas border. MISO has three short-term forecasting components: a high-level, week(s) ahead monitoring of extreme events mentioned above, the input of weather data into MISO's Forward Reliability Assessment Commitment ("FRAC"), and real-time risk analysis assessment with control operators, who may make severe weather declarations if needed. The FRAC is a security-constrained unit commitment optimization algorithm that has up to 6 days forward commitment and is analogous to SPP's MRDA.

MISO PC defines extreme events as the following:

- "MISO defines an extreme weather event as a system condition that could negatively impact the Bulk Electric System."
- MISO notes that the types of extreme events can vary by region and rely on stakeholders to determine the types of extreme events that occur in their area.

MISO's planning coordinator function simulates extreme weather events in accordance with Table 1 of NERC TPL-001 (specifically, section 3.a.iv under "Steady State"). [8], [10]. MISO tries to simulate the system to mimic recent extreme events and run the simulation using power flow models. Similar to SPP, MISO has placed an emphasis on extreme cold events, extreme cold event impacts were modeled and considered in Tranche 1 of MISO's current Long Range Transmission Planning (LRTP) process. [8], [11]

To summarize, MISO does have an explicit definition of extreme events for their RC functions, but they do not have one for their PC functions. MISO's planning for severe events is in accordance with section 3.a.iv under "Table 1" of NERC TPL-001, which requires planning for "extreme events" that result in the "loss of two generating stations," such as wildfires and "severe weather e.g., hurricanes, tornadoes, etc." Note that only *examples* are given here for severe weather and that this is not an all-encompassing list of severe weather events with well-defined thresholds.

Like SPP, MISO has placed an emphasis on modeling severe winter weather scenarios and these results influenced the recommendations for Tranche 1 of MISO's current LRTP. Like SPP, MISO does not explicitly state that they include resilience modeling to high wind events like the August 2020 derecho.

2.6 Isolated, Sequential, and Compound Events

The impact of an extreme event is greatly magnified when it occurs in sequence or simultaneity with other extreme events. For example, a single rainstorm may only cause minor impacts, but a series of similarly wet storms could cause major flooding that would threaten substations, solar panels, and other low-lying/vulnerable electric infrastructure. Compound events simultaneously resulting in high demand and low production can similarly result in capacity shortages and extreme pricing as every available resource is dispatched to meet load – and can even result in load shed in some cases.

The most damaging compound events have both infrastructure damage and capacity shortage components, with two notable examples being Winter Storm Uri and Elliot in 2021 and 2022, respectively. This damage is further compounded when these events impact both the power and gas systems, as those winter storms did.

2.7 Types of Extreme Events

Below are some typical "extreme events" that impact the North American power grid. Some of these give a capacity shortage, others damage infrastructure, and still others do both.

Event type	Energy Security?	Infrastructure Damage?	Infrastructure impacts/damage	Future power system more or less vulnerable?
Summer heat wave	Yes	Yes	Ambient derates to thermal plants, lower efficiencies of solar PV, transmission line sag/derates, increased forced outages [12], overheating of other components (ex: transformers, substations	More (stronger heat waves, more VER)
Winter arctic outbreak	Yes	Yes	Gas well freeze-offs (reduced extraction), limited flow through gas pipelines (limited delivery), freezing/mechanical failures at all generators (esp. gas/wind, less so solar)	More (more electric heating, more VER)
Extended low renewables	Yes	No	NA	More (more VER)
Short-term low renewables	Yes	No	NA	More (more VER)
High net load during "outage season"	Yes	No	NA	More (outage season may shift)
Hydro drought years	Yes	No	NA	More, but biggest impacts in Columbia River/WECC (less snowpack)
Wildfires	No	Yes	Wind damage, sometimes heat impacts, reclosures disabled (longer restoration time), public safety power shutoff	More, but biggest threat is over WECC
Convective Features (derechos, tornadoes, large hail)	No	**Extreme**	Widespread, catastrophic damage to GTD, more localized damage from tornadoes, hail destroys solar panels	Mostly yes (solar panels more susceptible to hail), Tornado Alley may shift eastward (towards Iowa) in climate change
Freezing Rain	Maybe (wind turbine icing)	Yes	Downed powerlines (possibly extreme), decreased wind turbine gen	Yes (increased transmission, increased wind gen)
Floods	No	Yes	Maybe	Yes (stronger floods)
Hurricanes	No	**Extreme**	**Catastrophic wind and flood-related damage to electric infrastructure. Very long restoration times possible (esp. If occuring in remote area)**	Yes, but not Iowa (stronger hurricanes)

Table 1: Types of Extreme Events

3. Derecho Overview

High wind events are the most damaging types of weather events to Iowa's power system infrastructure. Most of these high wind events are associated with *derechos*: intense, fast-moving, long-lived squall lines that can bring triple digit gusts over hundreds of miles.

3.1 Definition

The National Weather Service defines a derecho as a "widespread, long-lived windstorm that is associated with a band of rapidly moving showers or thunderstorms." [13] Specifically, [14] distinguished a derecho from a "run-of-the-mill" convective wind event by meeting the four following criteria:

- "There must be a concentrated area of reports consisting of convectively induced wind damage and/ or convective gusts > 58 mph. This area must have a major axis length of at least 400 km (250 nm)."
- "The reports within this area must also exhibit a nonrandom pattern of occurrence. That is, the reports must show a pattern of chronological progression, either as a singular swath (progressive) or as a series of swaths (serial)."
- "Within the area there must be at least three reports, separated by 64 km (40 miles) or more, of either Fl damage (Fujita, 1971) and/or convective gusts of 74 mph or greater."
- "No more than 3 h can elapse between successive wind damage (gust) events."

The term "derecho" was first applied to this weather phenomenon in 1888 by Dr. Gustavus Hinrichs, a physics professor at the University of Iowa. Derecho is a Spanish word that is translated as "direct" in English, and Hinrichs named these storms as such due to their extreme, straight-line wind speeds. He contrasted these derechos with tornadoes, which instead have strong winds in a localized vortex underneath the parent thunderstorm's rotating updraft and whose name was derived from the Spanish word "tornar," which means "to turn." [15]

3.2 Serial vs Progressive Derechos

There are two main types of derechos: progressive derechos and serial derechos. Progressive derechos are extremely strong and fast-moving squall lines on the leading edge of a *mesoscale convective system (MCS)*, which is an organized cluster of thunderstorms that together act as their own weather system. Progressive derechos are typically the strongest/most well-known events, and the first event in 1888 that Hinrichs observed was a progressive derecho, as was the August 10, 2020 derecho. On the other hand, serial derechos tend to form along the cold front of a strong low pressure system and not on the leading edge of a mesoscale convective system.

Progressive derechos are most common in the late spring/summer, while serial derechos are more common in the winter and early spring as stronger midlatitude cyclones traverse the U.S. Most derechos that impact Iowa are progressive derechos [15].

The below diagram, adapted from [14], was taken from the Storm Prediction Center and has an idealized comparison of progressive and serial derechos near the midpoint of their lifetimes. The grey shaded area indicates the total region impacted by the derecho, the dotted lines indicate the squall line/bow echo with the derecho, and the solid lines represent the frontal systems associated with each derecho. Stationary fronts have alternating red semicircles/blue triangles and cold fronts have blue triangles only.

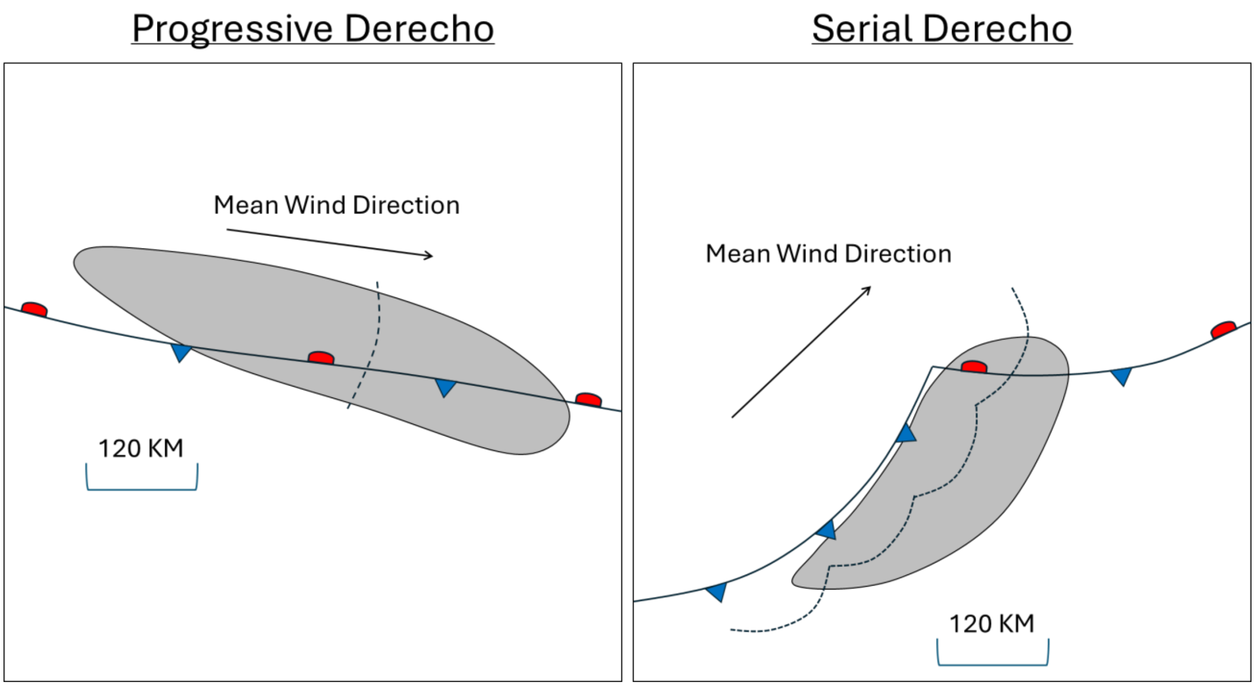


Figure 1. Progressive derecho vs. serial derecho

3.3 Derecho Environments

Derechos are most common when the mid-levels of the atmosphere are relatively dry. When this occurs, precipitation falling through the mid-levels of the atmosphere evaporates more easily. Because this change of phase from liquid rain to water vapor takes heat energy, the mid-levels of the atmosphere cool and become denser than the surrounding environment. This results in a "downburst," where this evaporatively-cooled air collapses through the atmosphere and brings damaging winds when it hits the surface and fan out in all directions. The downburst winds within the derecho also transfer the forward momentum from the storm to the surface resulting in additional speed, with the strongest winds aimed outward in the direction of travel. Most travel parallel to the wind direction near the tropopause, which gives further evidence for this momentum transfer of winds aloft down to the surface [16]

Both serial and especially progressive derechos have a very characteristic appearance on radar known as a "bow echo," so named because it resembles an archer's bow. Bow echoes were initially described by Ted Fujita (famous for the Fujita Scale rating for tornadoes) in [16]. The bow marks the area of the greatest evaporative cooling, strongest downdraft, and strongest surface-level winds, allowing this part of the squall line/derecho to advance ahead of other parts of the squall line.

The below image shows the life cycle of a progressive derecho with its associated bow echo and is adapted from [16]. The maximum intensity is at stage "3" when the bulge of the bow is the strongest and it takes on a spearhead-like appearance. [16]

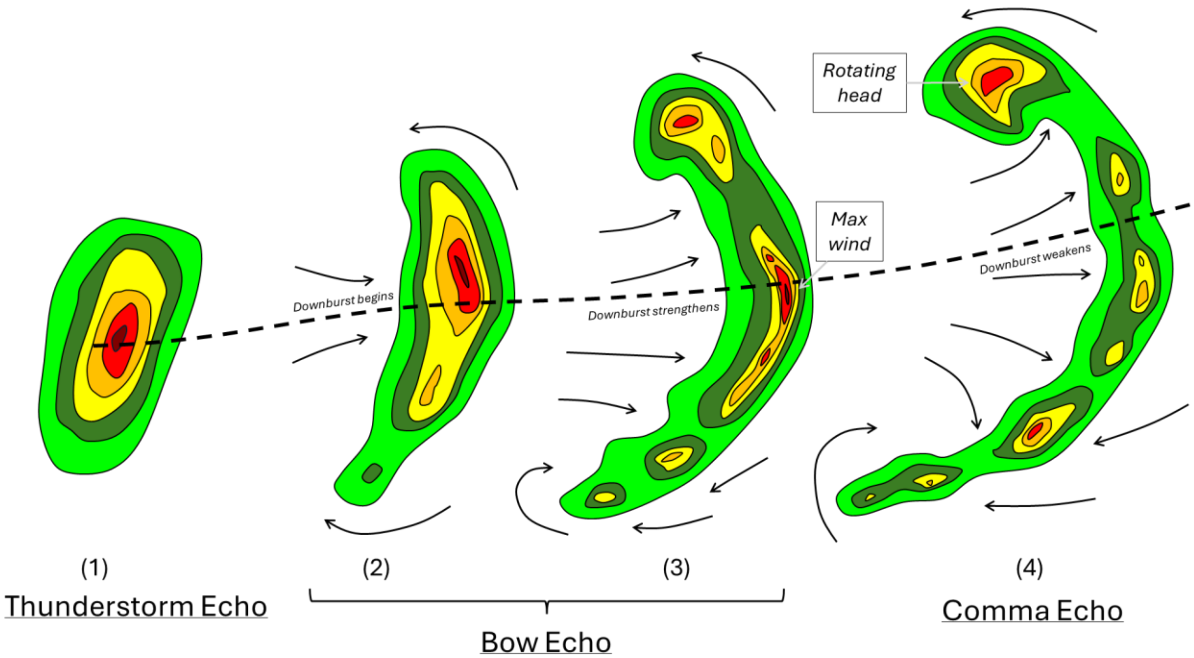


Figure 2: Lifecycle of a derecho.

3.4 Historical Derechos

Below is a non-exhaustive list of derechos that have occurred over the continental U.S. Derechos with a total cost exceeding 1 billion are highlighted in yellow. This table represents a partial list and was compiled from the Storm Prediction Center's Derecho Facts Page (link), the Des Moines NWS Office (link), and NOAA's Billion Dollar Disasters Database (link). Sources: [1], [15], [17]

Table 2. Major Historical U.S. Derechos

Date	States Affected	Name	Cost (2024, millions)
7/31/1877	NE, IA, WI, IL	The "Original Derecho"	
7/4/1969	MI, OH, PA, WV	The Ohio Fireworks Derecho	
7/4/1977	ND, MN, WI, MI, OH	The Independence Day Derecho of 1977	
7/4/1980	NE, IA, MO, IL, WI, IN, MI, OH, PA, WV, VA, MD	The 'More Trees Down' Derecho	
6/7/1982	KS, MO, IL	The Kansas City Derecho of 1982	
7/19/1983	ND, MN, IA, WI, MI, IL, IN	The I-94 Derecho	
5/17/1986	TX	The Texas Boaters' Derecho	
7/28/1986	IA, MO, IL	The Supercell Transition Derecho	
5/4/1989	TX, OK, LA	The Texas Derecho of 1989	1401
11/20/1989	PA, NJ, NY, MD, DE	The Mid-Atlantic Low Dewpoint Derecho of November 1989	

4/9/1991	AR,TN, MS, AL, KY, IN, OH, WV, VA, MD, PA	The West Virginia Derecho of 1991	
7/7/1991	SD, IA, MN, WI, MI, IN, OH, ON, NY, PA	The Southern Great Lakes Derecho of 1991	
3/12/1993	FL, Cuba	The Storm of the Century Derecho	
5/31/1994	UT, WY, ID, CO	The Utah / Wyoming Derecho of May 1994	
7/12/1995	MT, ND, MN, WI, MI, ON, OH, PA, WV	The Right Turn Derecho	
7/14/1995	ND, MN, ON, QB, NH, VT, ME	The Boundary Waters-Canadian Derecho	
5/30/1998	MN, IA, WI, MI, ON, NY	The Southern Great Lakes Derecho of 1998	2208.3
6/29/1998	NE, IA, IL, IN, KY	The Corn Belt Derecho of 1998	
9/7/1998	NY, PA, VT, MA, NH	The Syracuse Derecho of Labor Day 1998	
9/7/1998	MI, OH, WV, PA, NJ, NY, CT	The New York City Derecho of Labor Day 1998	
7/4/1999	ND, MN, ON, QB, NH, VT, ME	The Boundary Waters-Canadian Derecho	
8/9/2000	IN, OH, KY, WV, VA, NC, SC	The Appalachian-crossing Derechos of August 2000	
5/27/2001	KS, OK, TX	The People Chaser Derecho	
7/22/2003	AR, TN, MS, AL, GA, SC	The Mid-South Derecho of 2003	1723.9
5/8/2009	KS, MO, AR, IL, IN, KY, TN, VA, WV, NC	The 'Super Derecho' of May 2009	1265.8
6/9/2009	TX, OK, MO, NE, KS, AR, AL, MS, TN, NC, SC, KY, PA	Midwest, South, and East Derecho of June 2009	1939
4/4/2011	TX, AR, LA, KY, OH, TN, MS, AL, FL, WV, VA, MD, DE, NC, SC	The April 4-5, 2011 Southeast 'Derecho'	3885.3
4/19/2011	OK, TX, AR, MO, IL, IN, OH, KY, TN, MS, AL	The Ozarks / Ohio Valley Derecho of April 2011	1452.8
7/10/2011	CO, KS, NE, IA, IL, WI, IN, MI, OH, KY, WV, PA, MD, VA	The Cross Country Derecho of July 2011	1716.6
6/29/2012	IL, IN, KY, OH, WV, PA, VA, MD, DE, NJ, NC	The Ohio Valley / Mid-Atlantic Derecho of June 2012	3957
6/30/2014	IA, IL, WI, IN, MI, OH	The 'One-two Punch' Derechos of June 30 - July 1, 2014	
5/14/2018	OH, PA, WV, MD, VA, PA, NJ, NY, CT, MA	The Mid-Atlantic and Northeast Derechos of May 14-15, 2018	1712.9
8/10/2020	SD, NE, IA, MO, WI, IL, IN, OH	The August 2020 Midwest Derecho	13342.7
12/15/2021	NE, KS, MO, IA, MN, WI	The December Serial Derecho	2013.8
5/12/2022	KS, NE, SD, IA, ND, MN	The May 2022 Midwest Derecho	2949.6
6/13/2022	MI, IN, OH	The June 2022 Central US Derecho	3386.6
7/5/2022	MT, ND, SD, NE, MN, IA, WI, IL, IN, MI, OH	The July 2022 Derecho	
6/29/2023	NE, KS, IA, MO, IL, IN, KT, TN	The June 2023 Midwest Derecho	
5/16/2024	TX, LA	The 2024 Houston Derecho	1212
5/24/2024	NE, IA, IL	The May 2024 Tornado Outbreak and Derecho	
7/15/2024	IA, WI, IL, IN	The July 2024 Midwest derecho	

The two derechos used for this study (August 10, 2020 and June 29, 1998) were the strongest derechos for Iowa in the past 30 years. The 2020 event was much stronger, but the 1998 event is notable for causing extreme, localized damage over Northern Des Moines and Polk County due to an embedded mesocyclone within the larger derecho. Peak gusts in the 2020 derecho reached 140 mph in Cedar Rapids, IA, while the 1998 event saw peak gusts of 126 mph in Washington, IA and estimated F2 damage over portions of Polk County.

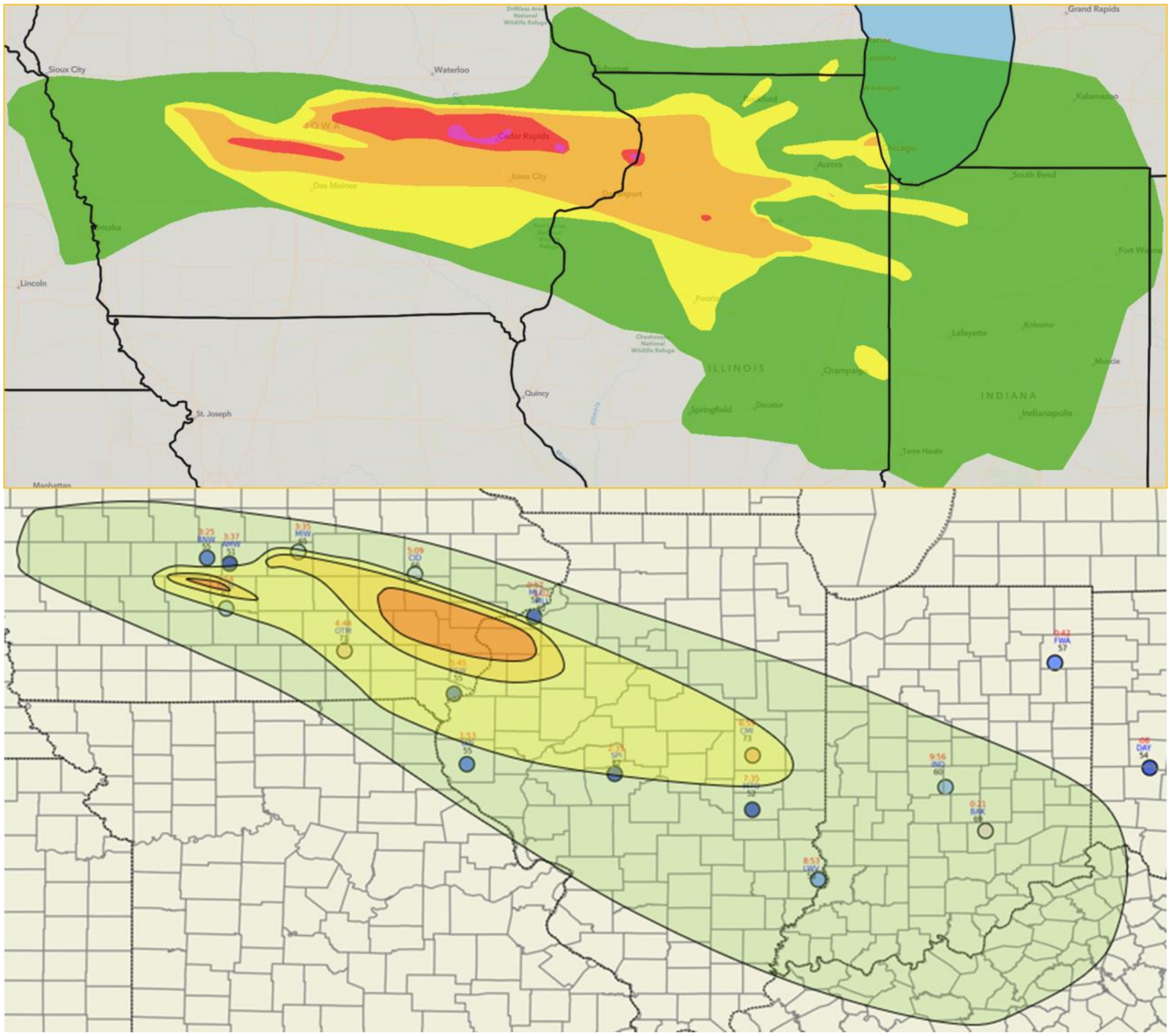


Figure 3. Wind speeds from 2020 derecho (top) and 1998 derecho (bottom)

3.5 Derecho Climatology

Derechos primarily occur east of the Rocky Mountains. There are two zones that see particularly strong and frequent derechos; one from Iowa eastward to the Ohio River Valley, and another from the Southern Plains to the Southern Mississippi Valley. The northern zone primarily experiences progressive derechos and these are most frequent from May through August. The southern zone sees a mix of progressive and serial derechos. Progressive derechos are more common during the cool months (September through April) as cold fronts move across the southern U.S. The below images are from [18] and show the distribution on derechos from May-August (left) and September-April (right) from 1980-2001.

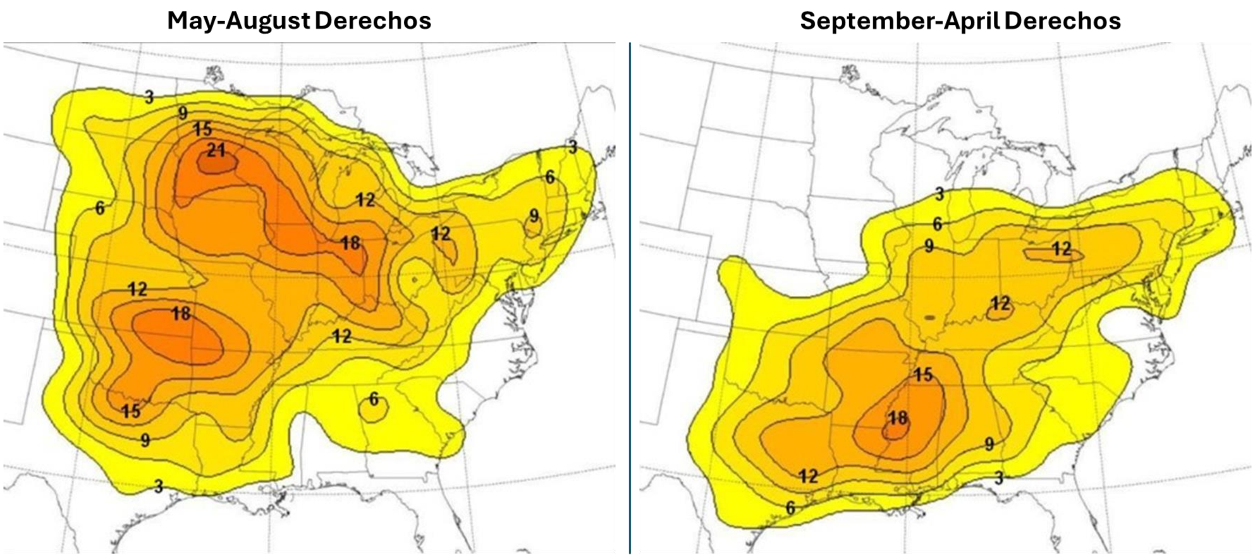


Figure 4. Warm & cool season derecho events across the United States (1980-2001)

3.6 Derecho Trends and Projections With Climate Change

There is relatively low confidence on how derechos and other severe thunderstorms will evolve under climate change compared to other types of extreme events like temperature extremes, floods, wildfires, or hurricanes. The IPCC 6th assessment report states that there is *medium confidence* in an increased frequency of springtime, severe convective storms over the U.S., but there is significant uncertainty in projected changes due to limited high-resolution simulations of these events. [19]

Historical Trends

In addition to low confidence in future derecho/severe thunderstorm trends, we also have low confidence in *observed* derecho trends due to improvements in observation techniques over the period of record. With the proliferation of high-resolution doppler radar, a greater network of weather observations and weather spotter reports, and population growth, we've seen a dramatic increase in annual thunderstorm counts over the last 100 years. For example, there was a sharp increase in the number of tornadoes measured in the early 90s due to the buildout of the WSR-88D doppler radar network, and the total tornado count increased 30% from the 1970s to the 1990s. However, the number of *violent* (EF-4/5) tornadoes has seen little change since 1970, as these tornadoes create catastrophic damage and can be easily recorded without doppler radar, while an EF-0 may leave very little evidence of its existence, particularly if it occurs over a rural area [20]. The lack of a trend in violent tornadoes implies that there has been no clear trend in overall tornado frequency/strength, but there is low confidence in this assertion.

Studies that attempt to adjust for these observational inconsistencies show that there is no trend in the number of severe thunderstorms, though there is an increase in the number of extreme precipitation events associated with these thunderstorms [21], [22]. Interestingly, the mean annual number of tornadoes has remained constant but there has been more year-to-year variability in tornados since the 1970s, particularly during the 2000s, with a decrease in the number of tornado days per year but an increase in the number of tornadoes on each of these days [21], [22]. There has also been a "shift" southeastward in Tornado Alley, with fewer tornadoes occurring over the Plains and more occurring over the mid-South U.S.A[23]

Future Projections

Modeling how convective events will evolve under climate change is difficult because modeling convection requires much higher resolution than all general circulation models (GCMs) currently have. Most climate models have a horizontal resolution of approximately 100-200 kilometers. To explicitly model convection, a model needs to have a horizontal resolution of 4 kilometers or less. However, it is computationally prohibitive to run a GCM at this type of resolution.

Right now, there are two primary approaches to projecting severe thunderstorms/convection in a warming climate. The first is called *downscaling*, and it involves taking the low-resolution output from a GCM and using it as input data into a high-resolution (<4km) model covering a limited surface area. This allows the high-resolution model to take the GCM data and model things like convective storms or topographical features that a low-resolution model might not capture. The second is to look at the environmental conditions shown in a GCM and draw statistical correlations between those conditions and their impacts to convection without doing any explicit downscaling. However, the relationship between simulated environments in GCMs and convection has been insufficiently validated, so this second approach has low confidence.

GCMs also have *high confidence* that climate change will create an environment with more convective available potential energy (CAPE) in the tropical and subtropical regions. CAPE is a measure of atmospheric instability, and the higher the CAPE, the stronger the updraft of the thunderstorm and the more powerful it can become. This implies that convection would become stronger and more frequent under climate change, but CAPE is just one of many variables impacting storm development, and as previously mentioned, the relationship between simulated environments in global climate models (GCMs) and the actual occurrence of convective events has not been robustly validated. Still, the increase in CAPE is one of the main reasons the IPCC has medium confidence in the increased frequency of severe, springtime convective storms.

Damage Trends

While there is limited *meteorological* evidence that derechos have strengthened in recent decades, they are far more destructive now than before and will continue to become more destructive in the future. A look at NOAA's "Billion Dollar Disasters" database shows that out of all the disaster types, severe thunderstorms (which include tornadoes, derechos, and hailstorms and are the primary disaster type over the Plains and Midwest) have seen the largest increase in frequency of Billion Dollar Disasters. [1].

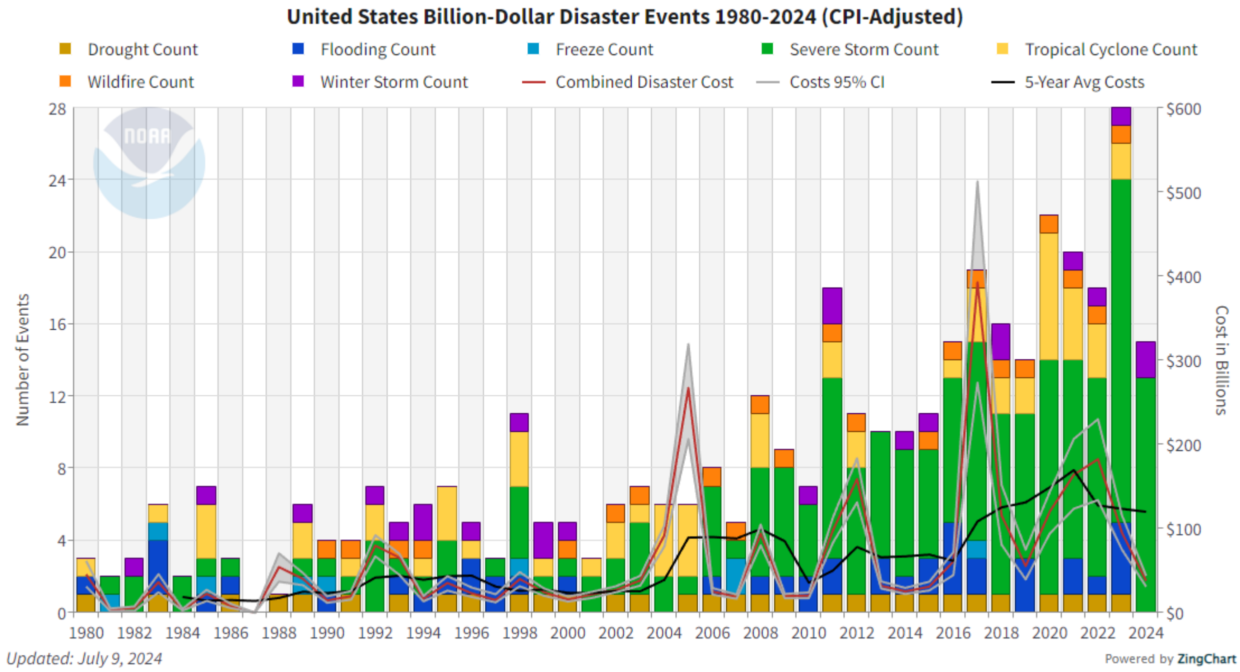


Figure 5: United States Billion Dollar Disaster events from 1980 through 2024.

The increase in billion dollar disasters is primarily a function of increasing population/wealth, which means there are a greater number of assets at risk to severe events *and* these assets are more expensive. Climate change absolutely increases the intensity of some of these events (heat waves, hurricanes, wildfires, floods, and droughts are all good examples), but the primary increase in damages – particularly for severe thunderstorms – is due to more expensive/widespread infrastructure, not stronger & more frequent derechos. Regardless, this trend in increasing damage is expected to continue through the upcoming decade/s regardless of trends in severe weather, and if we do see more/stronger convective thunderstorms, that will only add to the damage.

4. Power System Reliability vs. Resiliency

4.1 Reliability Definition

The North American Electric Reliability Corporation (NERC) defines a reliable bulk-power system as one that is able to meet the electricity needs of end-use customers even when unexpected equipment failures or other factors reduce the amount of available electricity. The bulk-power system (BPS) refers to the combination of electric generation and transmission infrastructure across North America, but it does not cover low-voltage distribution infrastructure that is responsible for delivering electricity to homes and businesses. [24]. The BPS is normally considered to include voltage levels of 69 kV and above.

NERC provides explicit definitions of a reliable power system via their *reliability standards* [25]. These standards are approved by FERC and are enforceable in all interconnected regions of North America.

At a high level, NERC divides reliability into two categories: adequacy and security. Adequacy means having sufficient resources to provide customers with a continuous supply of electricity at the proper voltage and frequency. Resources refer to a combination of electricity generating and transmission facilities that produce and deliver electricity, and demand response programs that reduce customer demand for electricity. Maintaining adequacy requires system planners and operators to account for scheduled and reasonably expected unscheduled outages of equipment. Adequacy is often characterized probabilistically, based on steady-state assessment. Resource adequacy focuses on generation alone and assumes transmission capacity is infinite. [24]

Security addresses the question of whether the system performance following a disturbance is acceptable. Security covers natural disturbances such as short circuits and the unanticipated loss of system elements and human-made hazards physical and cyberattacks. Security uses both steady-state and dynamic assessments. [24].

Stability

Stability is a subset of security and refers to the ability of the power system to regain a set of operating equilibrium after being subject to a disturbance. The main distinction between security and stability is that stability solely refers to the ability of the operating system to maintain operating equilibrium after a disturbance, while security addresses all other aspects of system performance. For example, two systems may have equal stability margins, but one may do so at a greater risk of overloading equipment or resulting in voltage violations. The below image is retrieved from [26] and shows the different types of power system stability within the bulk power system

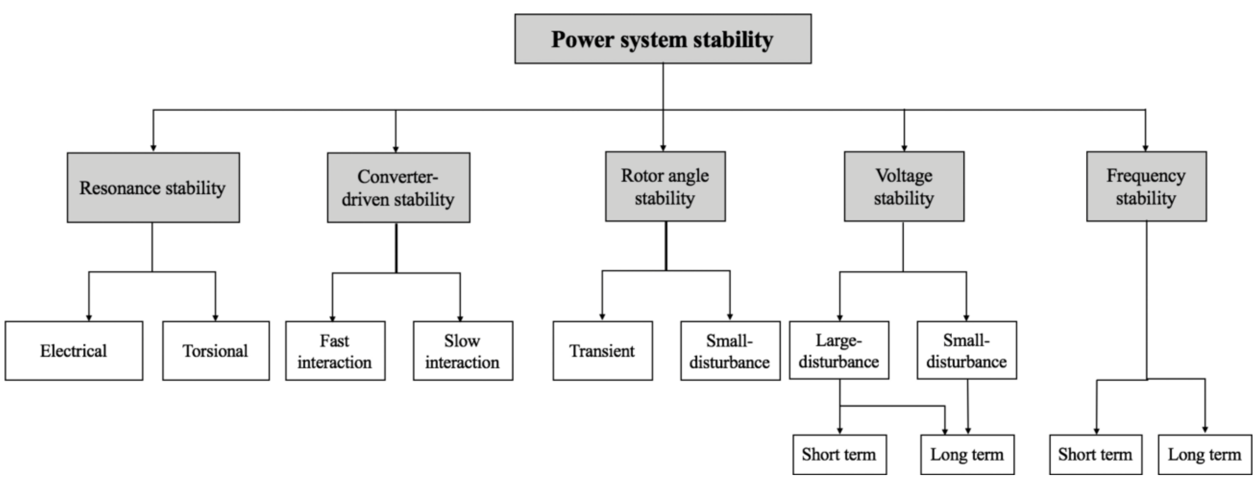


Figure 6: Types of power system stability

Stability is negatively impacted by the increase in inverter-based resources such as wind and solar and decommissioning of large thermal or hydroelectric facilities. This is because the heavy, grid-synchronized turbines in thermal/hydroelectric plants are able to maintain rotor angle stability through system faults due to the large momentum of the spinning turbines [26]. The displacement of these synchronous generators by inverter-based resources results in less voltage/frequency stability due to faster changes in total energy production (example: a cloud passing over a solar farm) and places more torque on the turbines due to larger differences and more rapid changes in grid frequency relative to that of the turbine. The below image is retrieved from [27] and shows that grid frequency drops after a system contingency in both high-inertia and low-inertia systems, but the drop is 'deeper' in a system with low inertia (and high renewable energy sources, or RES).

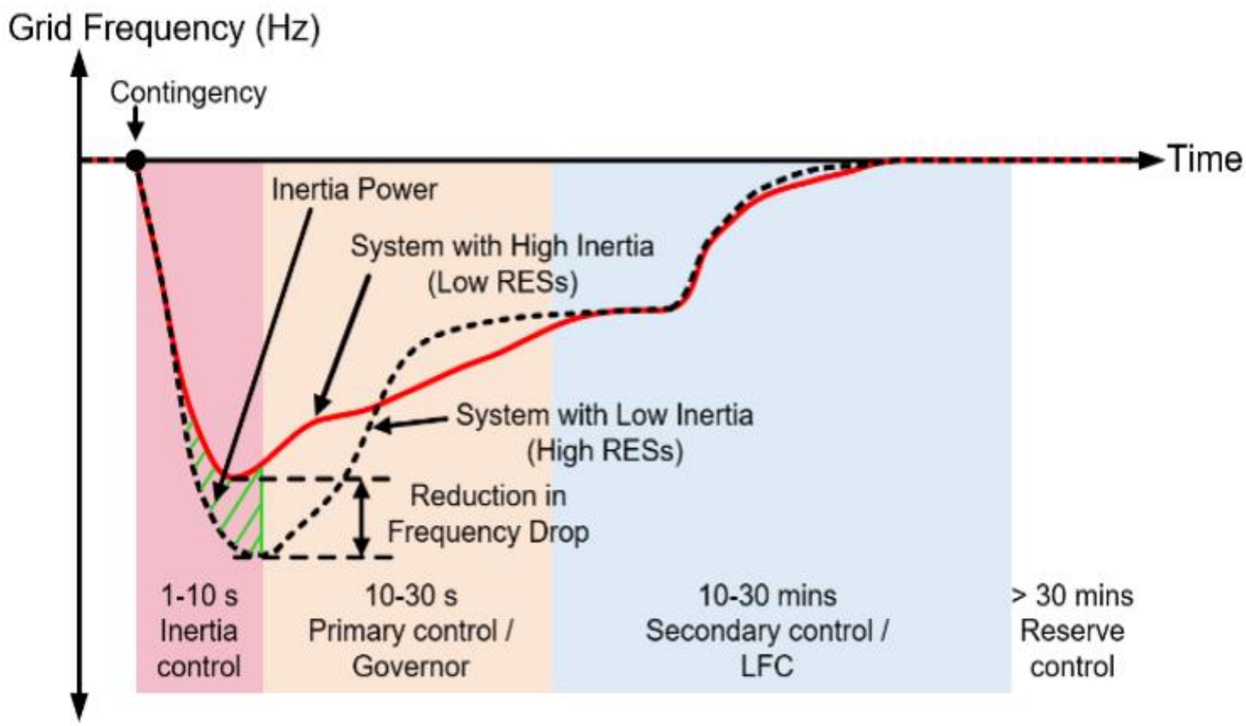


Figure 7: Frequency response after a contingency in high & low inertia systems

As we will discuss in section 4.2, a system is *resilient* if it can maintain reliability under extreme events. When doing resiliency assessments, one must take into account both the extreme event itself and the evolving generation mix, as renewable energy sources are much more weather-dependent than traditional synchronous generators and come with unique planning and operational challenges.

Resource Adequacy

<u>Resource adequacy</u> refers to the ability of the bulk electric system to meet demand at any given time, including losses [24]. Historically, resource adequacy has consisted primarily of supply-side resources, but there are now an increasing number of demand-response programs that allow grid operators to increase or decrease the aggregate demand on the electric grid.

There are several commonly-used metrics to quantify resource adequacy. The most commonly-used metric is the Loss-of-Load-Expectation (LOLE), which refers to the number of time units where demand will exceed supply. Both SPP and MISO use a LOLE threshold of "1 day in 10 years," and this is the industry standard for expansion planning. [28] [29] [24]. LOLE is often used interchangeably with Loss-Of-Load Probability (LOLP), which expresses the percentage risk of the loss-of-load over a given time. [30].

The LOLE threshold is commonly used to derive the Planning Reserve Margin (PRM). The planning reserve margin is expressed as a percentage of the total available capacity relative to the peak demand. For example, a planning reserve margin of 15% means that there is a total capacity 15% greater than the expected peak demand. It is a best practice to derive the planning reserve margin from the LOLE because some generators have higher forced outage rates than others. In other words, one system with a planning reserve margin of 15%, but a higher rate of forced outages, would be less reliable than a system with a planning reserve margin of 15% and fewer forced outages. However, a 2011 NERC report also postulated that the planning reserve margin may become less important – or even obsolete – as dispatchable generation is removed from the grid and replaced with renewable generation. [30]

The LOLE does not consider the magnitude of the supply shortfall – only the frequency at which it is expected to occur over a given time period. The magnitude of the shortfall is given by the Expected Unserved Energy (EUE) also called Expected Energy Not Served (EENS) [30] [24]. Unlike LOLE, there is not an "industry standard" value for EUE. EUE may become more valuable as renewable generation sources displace fossil fuel generation and the grid becomes more weather-dependent and vulnerable to periods of low renewable generation. [30].

Finally, another important resource adequacy concept is the Effective Load Carrying Capacity (ELCC). The ELCC measures the contribution of a generator or group of generators towards reducing the LOLE over a given period. For example, solar farms located in an area where peak solar generation aligns perfectly with peak loads would have a high ELCC, but if the solar generation was reduced during peak loads or the farms where located in an area where peak load and solar generation were not perfectly aligned, the solar farms would have a lesser contribution towards reducing LOLE and thus a lower ELCC. [30]. For wind/solar siting purposes, it is important to balance ELCC with other metrics like capacity factor so that plants can not only produce high average generation throughout the year but generate when it is most needed.

Task G6-2 discusses resource adequacy in more depth and shows Iowa State's process for incorporating GE-MARS – software used to model resource adequacy – into ACEP to ensure that the ACEP futures comply with defined planning reserve margins, LOLE thresholds, and other constraints.

4.2 Resiliency Definition

Resiliency is a separate, but related concept to reliability. Reliability focuses on the ability to deliver electricity to customers on demand even in the midst of unexpected system faults. FERC defines resiliency as the following:

> The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such events" [31].

Another definition, proposed by [32] is the following:

> "Resilience is the ability to minimize and recover from the consequences of an adverse event, for a given state of the system."

Ibanez et al. and others [33] acknowledge that there is no universal consensus on the exact definition of resiliency. Moreover, the notion of resilience is present across many disciplines, and relatively little work has been done in defining it as it explicitly relates to the bulk electric system. This contrasts dramatically with reliability, which is defined via a set of Reliability Standards issued by NERC that are legally enforceable.

That said, most definitions of resiliency; including the two above, focus on absorbing, withstanding, recovering, and adapting to extreme events. The "resilience trapezoid," shown below, is a commonly-used high-level diagram that quantifies power system resiliency by plotting system degradation against a timeline of the event [34]. A resilient system aims to reduce the system degradation for each phase; in other words, to 'reduce the size' of the trapezoid.

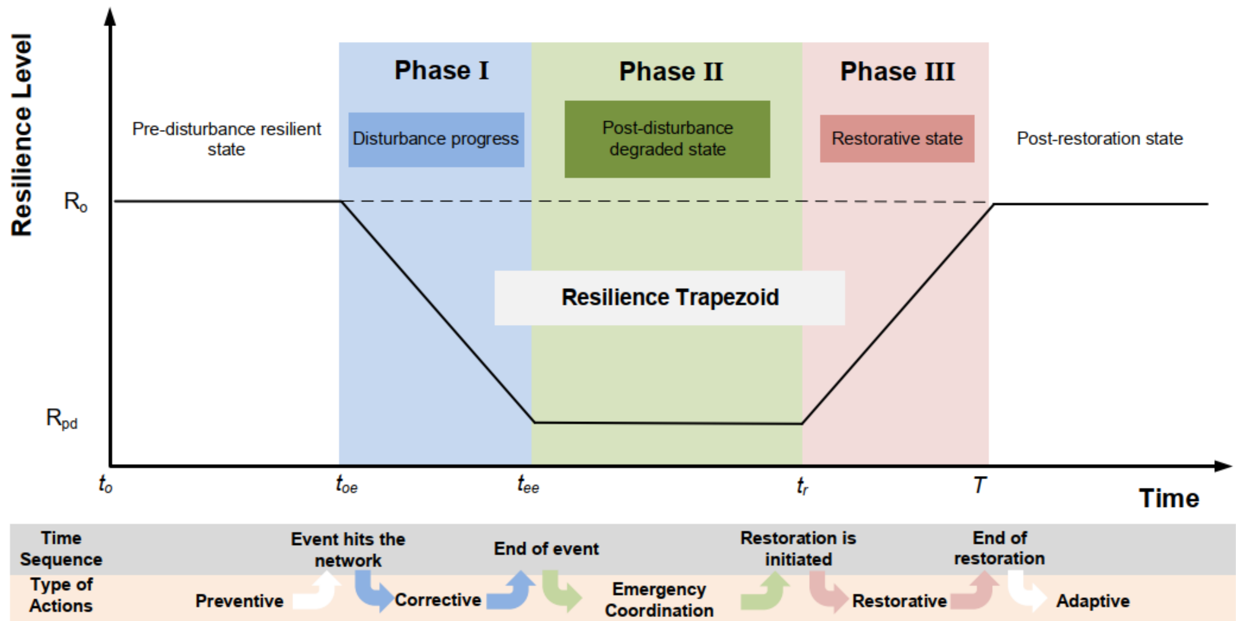


Figure 8: The "resilience trapezoid" associated with a disturbance.

4.3 Resiliency vs. Reliability

[34] distinguishes resiliency from reliability in the following three ways:

1. **Disturbance types**: while both resiliency and reliability describe the operation of the system during disturbances, resiliency focuses on high-impact low-probability disturbances (like a derecho that topples transmission lines) while reliability has a greater focus on low-impact, high-probability disturbances, like tripped circuit breakers or voltage instabilities.
2. **Time frames:** reliability focuses on the real-time operation of the system, both in steady-state and with transient disturbances. Resiliency focuses on discrete events and covers not only the ability to maintain reliable operation during severe events, but the ability to anticipate these events, rapidly recover from them, and adapt to future events.
3. **Users/infrastructure impacted:** Reliability focuses on the ability of the consumer to receive a continuous, on-demand source of electricity. Resiliency expands this focus to the grid operators and staff and the impacts on infrastructure. For example, a series of system

faults due to a severe storm could have the same impact on consumers from a reliability perspective but could be vastly different from an infrastructure perspective depending on how damaged the infrastructure was.

Reference [24] adds a fourth distinction:

4. **Cost metrics for resiliency:** Resilience also attempts to minimize the physical and opportunity costs to consumers. An example is the change in the cost of natural gas after Hurricanes Katrina and Rita destroyed offshore oil rigs in the Gulf of Mexico and transportation systems/pipelines along the Gulf Coast [24]. With the dramatic increase in fracking since Hurricanes Katrina and Rita, natural gas production is more geographically diversified, natural gas prices are more resilient to hurricanes, and consumers are better protected against unexpected increases in their natural gas or electricity bills

Reliability during an extreme event depends on the resiliency of the bulk power system. For example, the natural gas extraction, distribution, and generation system over Texas during Winter Storm Uri was not *resilient* to cold weather, and this caused *reliability* risks where there was insufficient supply to meet demand and load shedding was required to maintain system frequency. This is where reliability and resiliency "intersect" and where the distinctions can become a little more confusing. For example, NERC's cold weather Reliability Standards EOP-011-4 (emergency operations) and TOP-002-5 (operations planning), which were issued in response to the major gas/electric disruption during Winter Storms Uri/Elliot, are better viewed as *resilience investments* that ensure reliable operation during extreme winter storm events, even though they are defined as Reliability Standards [9].

4.4 Quantifying Resilience

Several mathematical tools are used to quantify resilience. These tools are implemented in the RCEP model. Section 5 will discuss how these tools are implemented in RCEP, while this section will provide a background of each tool and motivation for its use. Given the lack of NERC standards for resilience and the relatively high-level definition proposed by FERC, quantifying power system resilience is a new and growing research area [35], [36], [33], [24].

Resilience Trapezoid

The "resilience trapezoid" above has been mentioned in [37], [36], [38], [39], [34], [33], and was extended from a "resilience triangle" model first proposed in [40]. It is used as a conceptual tool for visualizing the stages of and power system performance during/after an extreme event.

Infrastructure vs Operational Resilience

Reference [36] further divide resilience into "infrastructure" and "operational" resilience. Infrastructure resilience refers to the ability of grid components to withstand and recover from extreme weather events. Operational resilience refers to the resiliency of the overall bulk electric system to extreme events. Though the two are related (more infrastructure damage is usually correlated with higher operational disruption), operational resilience realizes that some infrastructure components are more critical to system operation than others and it validates this using OPF models. By quantifying both infrastructure and operational resilience, planners not only gain insights into how much resilience investment they should make in infrastructure, but what locations have the highest priority for investment.

Both infrastructure and operational resilience are accounted for in RCEP. Infrastructure resilience investments are explicitly modeled in RCEP using fragility curves, which are discussed further below. Meanwhile, operational resilience is implicitly modeled, as RCEP optimizes the location and capacity of new generation investments to minimize the total cost of the generation and transmission portfolio, which includes the cost due to storm-related derates and loss-of-load.

Fragility Curves and Bus Multipliers

Fragility curves relate the intensity of a severe event on a structure to the probability of that structure failing. They are used extensively in catastrophe (CAT) risk modeling and risk assessment in the private and public sector. One of the most well-known methodologies utilizing fragility curves is FEMA's Hazard U.S. (HAZUS) model, which are used to produce loss estimates for flood, hurricane, and earthquake hazards. Fragility curves for electric infrastructure under extreme weather events have been empirically generated in previous studies [36], [41], [5], and they are a key component of the RCEP model.

Though fragility curves are used for transmission line failures in the RCEP model and other studies [36], [41], the concept can be extended to other variables. As an example, FEMA's HAZUS earthquake model technical manual shows a variety of fragility curves relating groundshaking motion the failure probability of a structure, with more resilient structures having a lower failure probability for a given spectral displacement [42].

Hazard modeling – whether using fragility curves or some other method – comes with many sources of uncertainty. The more complex the system is, the larger this uncertainty tends to be. One source of uncertainty is defining the fragility curves themselves, as we often lack sufficient data to ascribe failure probabilities for certain components. Another is that resilience levels can vary widely between infrastructure, and fragility curves that may accurately describe some portions of the power system network may be inaccurate for others. A new, high-voltage transmission corridor built within the last decade would likely be much more resilient to certain wind gusts than an older transmission corridor of similar voltage, which may have degraded components and did not benefit from advances in hazard modeling before being deployed.

A third area of uncertainty involves the modeling of extreme weather events. Many of the weather datasets we have are ill-suited for power systems modeling due to inadequate resolution, non-coincident variables, lack of verification, or other issues. For example, [41] use a low-resolution climate "reanalysis" dataset called ERA-Interim to model wind speed, and they relate historical component failures to the modeled wind speed to estimate fragility curves. While the reanalysis dataset is likely the best dataset for this task, it only *estimates* the weather conditions at a single point and does not use the actual, observed weather conditions that occurred, as measured by a specific weather station. Moreover, the ERA-Interim only has a horizontal resolution of 31km and "smooths" terrain as a result, rendering it ill-suited to model weather patterns in areas with high topographical variability. While resilience modeling can yield useful insights, it is critical to quantify and communicate these sources of uncertainty to policymakers to ensure that investments are made wisely.

4.5 Adaptability

Adaptability, also known as resilience enhancement, refers to the investments made to increase the resiliency of the bulk electric system to future high-impact low-probability events [36]. Resilience enhancement is typically “motivated” by one or more high-impact low probability events that exposed a lack of resilience in the current power system.

As mentioned previously, cold weather resiliency has been a large focus for the electric power and natural gas industries after Winter Storms Uri and Elliot, and in February 2024, FERC approved cold weather Reliability Standards EOP-011-4 (emergency operations) and TOP-002-5 (operations planning), which were submitted by NERC in October 2023. These cold weather reliability standards focused on resilience enhancement to natural gas infrastructure and better gas/electric industry coordination, and they were aimed to reduce the risk of unplanned outages of natural gas units during cold weather.

Further West, many utilities (particularly in California) have increased their resilience to wildfire patterns by investing in better vegetation management, better weather modeling, public safety power shutoff (PSPS) programs, repairing and/or undergrounding transmission lines, and in some cases, disconnecting high-risk communities from the bulk electric system and creating remote grids, thereby negating the need for transmission infrastructure in high-risk regions [43]. These resilience investments both reduce the risk of wildfires and ensure that public safety power shutoffs are limited in scope and duration.

5. Methods

This section describes the methods used to derate transmission lines and gives a high-level formulation of the RCEP model.

Our work was divided into three main parts. The first was to use meteorological observations and damage reports to construct 8 unique weather regions for each event and to assign a wind gust profile to each weather region. The second is to define wind speed fragility curves corresponding to each resiliency level, similar to the process in [5], and to define a derate for each line as a function of the region/s the line encompasses and the resilience level of that line. The third is to run our resiliency-based capacity expansion model, finding the generation and transmission mix (and the optimal resilience investment for each transmission line in the network). The following sections explain these steps in detail.

Our work used a 201-bus network of the Eastern Interconnection developed by [49]. This network had its highest granularity over MISO, which was reduced from 20,000 nodes to 161 nodes via Kron Reduction. The remaining 40 nodes were used from the DOE Interconnections Seams Study and were overlaid onto this MISO network [50].

5.1 Constructing Weather Regions and Timeseries

The Midwestern U.S. averages a "moderate" or "strong" derecho, with wind gusts exceeding 75 mph, every 1-2 years [15], [51]. The two strongest derechos over the past 30 years for the Midwest – and Iowa in particular - were the "Corn Belt Derecho" of June 29, 1998 and the "Great Midwest Derecho" of August 10, 2020, with the 2020 event being the stronger of the two. Maximum wind speeds were measured at 123 mph in the 1998 derecho at Washington, Iowa, and the 2020 derecho brought estimated 140 mph gusts to Cedar Rapids, Iowa based on official storm damage surveys from the National Weather Service. These two events were chosen for our study due to their Midwest focus, their extreme wind speeds and damage to electrical infrastructure, and their relatively recent occurrence, with a plethora of high-quality, publicly-available observations available. The 2020 derecho, being the more significant and recent event, was extremely well documented, with the 1998 event a little less so.

To construct weather regions on the 201-bus network and create timeseries for these regions, there were three steps.

Step 1: Create Wind Speed Contour Map

First, we created wind speed contour maps of each derecho. An official map had already been created by the National Weather Service for the 2020 derecho and, after doing a "sanity check" with surface observations over the derecho, we used this map [2]. A map was not available for the 1998 storm but we created one using a combination of observed wind speeds from official, airport stations, damage reports from the National Weather Service & local authorities, outage statistics from utilities, and county disaster declarations from the Iowa Governor.

Step 2: Create Weather Regions

Second, we divided these maps into 8 distinct weather "regions" of various sizes. The regions were user-defined and were created based on a combination of the timing and maximum intensity of derecho wind gusts. These regions were generally aligned from west to east, except for regions 3 and 5/6 which were created to provide higher resolution over the two swaths of widespread 100+mph gusts over the derecho. Region 6 had the very highest winds, with peak gusts estimated at 140 mph in the Cedar Rapids area based on official storm damage survey estimates from the National Weather Service. [52]

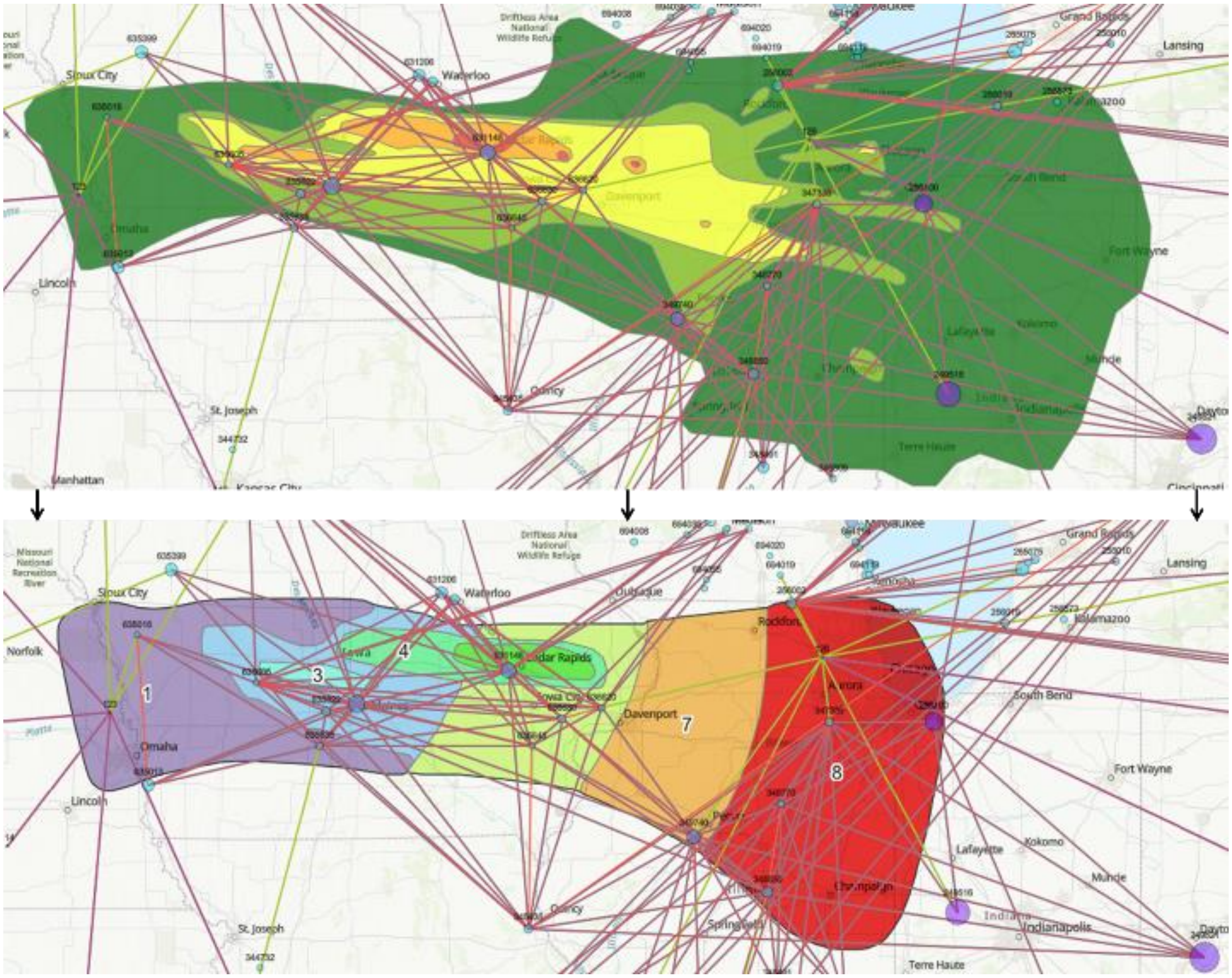


Figure 9: Wind speeds and regions for Aug 2020 derecho.

Step 3: Wind Speed Profiles

Third, we assigned each weather region a "wind speed profile" that was representative of the wind speed and timing that region experienced during the derecho. The weather stations used for each weather region were well-sited ASOS, AWOS, and Iowa DOT stations that kept power throughout the event. Because the derecho knocked out power and/or destroyed many well-sited weather stations, the wind gusts from some of these stations were not representative of the meteorological region as a whole. To better represent the wind speeds in a region, the wind speeds for regions 2-6 were multiplied by a "scale factor" so that the wind speed timeseries over that region better correlated to the actual winds in the area, while still maintaining the characteristic derecho signature with a sharp rise and fast drop.

The table below shows the weather stations that were used for each region. For regions 2-6, the maximum wind speeds measured at some of the weather stations were less than the estimated peak winds, as stations in the windiest locations were destroyed or lost power before the strongest gusts arrived. To "simulate" the gusts in those regions, we multiplied the timeseries from a given weather station by a scalar so that the maximum gust in that time series was commensurate with the estimated winds over that area from the National Weather Service based on a combination of damage estimates, doppler radar velocity data, and surface observations.

Table 3. Weather Stations used for each Region

Region	Weather Station Used	Station ID	Scale Factor	Time Shift (mins)	Max Gust	Gust Timing (CDT)
1	Eppley Airfield (Omaha)	(KOMA)	none	none	67	09:11
2	Des Moines International Airport	KDSM	1.1	none	82	11:04
3	Ankeny Regional Airport	KIKV	1.47	none	115	11:15
4	Marshalltown IADOT	RMTI4	1.20	none	109	11:43
5	Marshalltown IADOT	RMTI4	1.54	+52	140	12:35
6	Iowa City IADOT	RIAI4	1.3	none	80	13:10
7	Quad Cities IADOT	RQCI4	none	none	93	13:50
8	Chicago-O'Hare International Airport	KORD	none	none	62	15:49

Because Region 6 did not have any weather stations that withstood the peak winds of the storm, an IADOT station at Marshalltown was used and the onset of the derecho was delayed ~52 minutes to 12:35, as weather stations in the Cedar Rapids area show a large spike in winds at approximately that time before losing data.

The below plots show the sustained wind speed, wind gusts, “simulated gusts,” and “gust dataset,” along with the wind direction. The bars indicate the period of maximum 20-minute average wind speeds for each region during the model run.

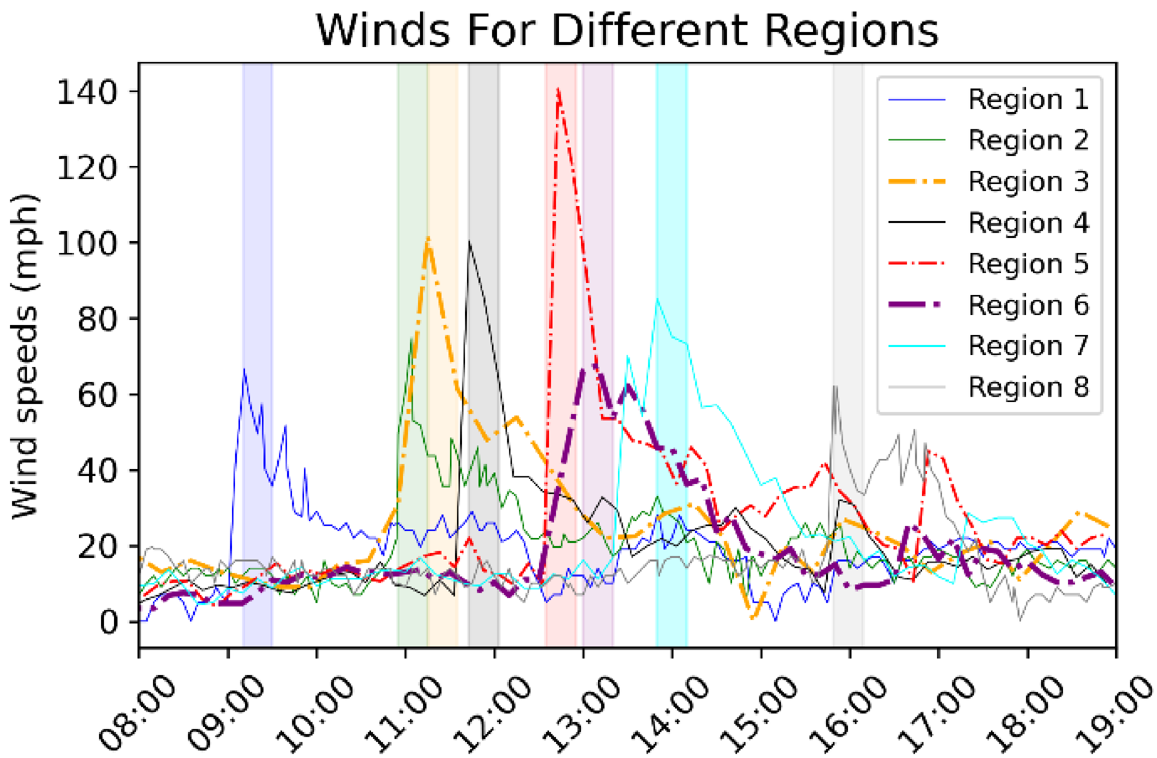


Figure 10: Wind gust profiles for each region

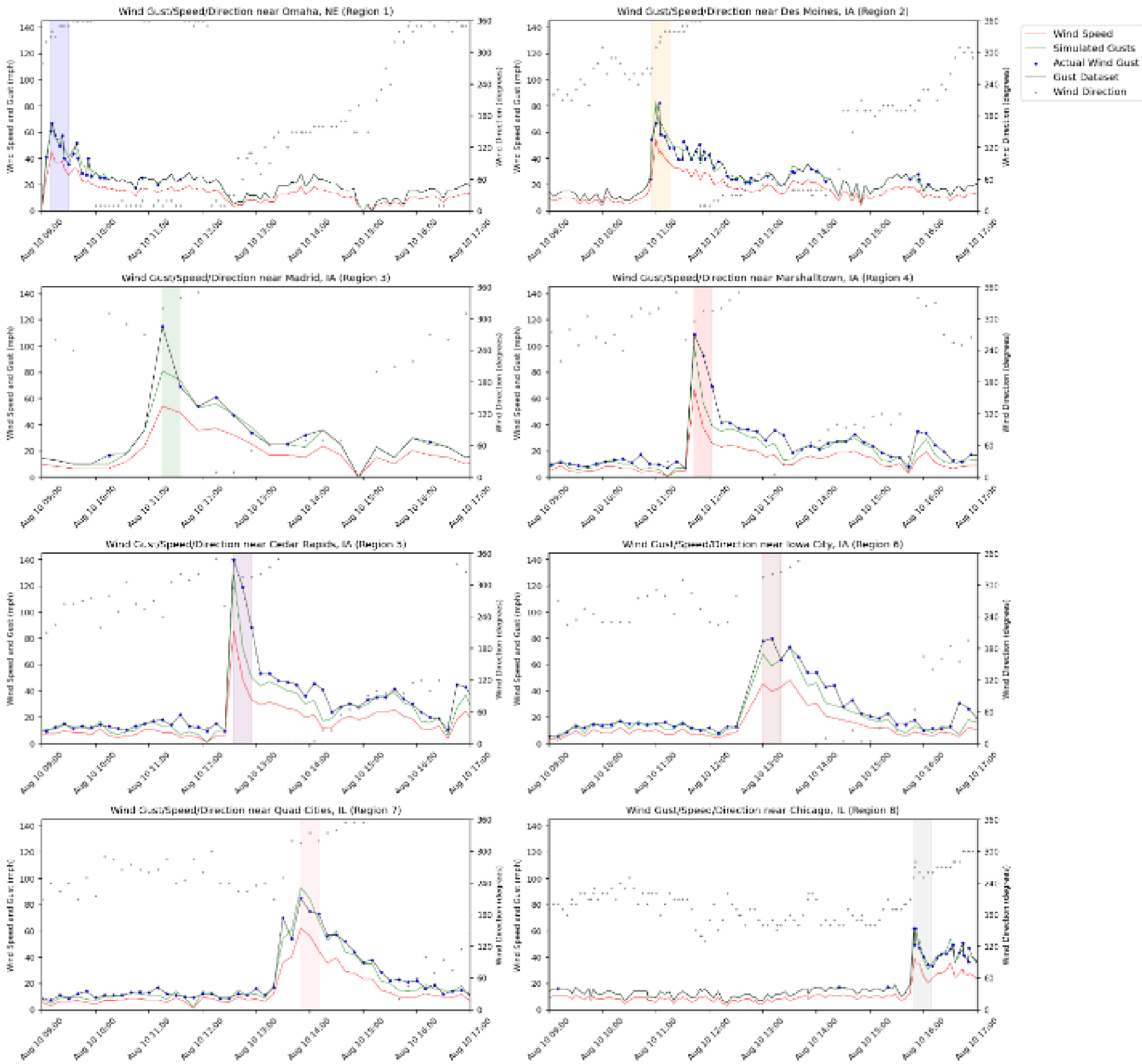


Figure 11: Wind profiles for each region (expanded)

The "simulated gust" represents the sustained wind speed multiplied by a factor of 'gust factor' of 1.5 and was used to estimate gusts when actual wind gust data was not available, as some ASOS/AWOS stations do not record maximum wind gusts during periods of lower wind speeds. This 1.5 "gust factor" was used based on the work by [53] for defining extreme convective wind gusts as having gusts 1.5 times or higher than the mean wind speed. Note that during the rolling 20-minute average period of highest winds, all weather regions recorded maximum gusts, but the ASOS/AWOS stations at regions 1, 2, 3, and 8 did not explicitly record gusts later in the day after the passage of the derecho. The "Gust Dataset" is the timeseries that was used for estimating failure probabilities, and it used "Actual Wind Gusts" by default and "Simulated Gusts" if an "Actual Wind Gust" data point was not available for that interval.

5.2 Fragility Curves and Regional Survival Probabilities

Resilience investments are generated in our model by derating the performance of transmission lines during/after the event and solving RCEP to find the optimal mix of resiliency investments. This model uses very similar fragility curves to [5], the first iteration of this model that was used for modeling hurricane resiliency in Puerto Rico. Fragility curves were discussed in depth in chapter 4, and have been used for derating electrical infrastructure due to extreme weather conditions in previous studies [5], [36], [41].

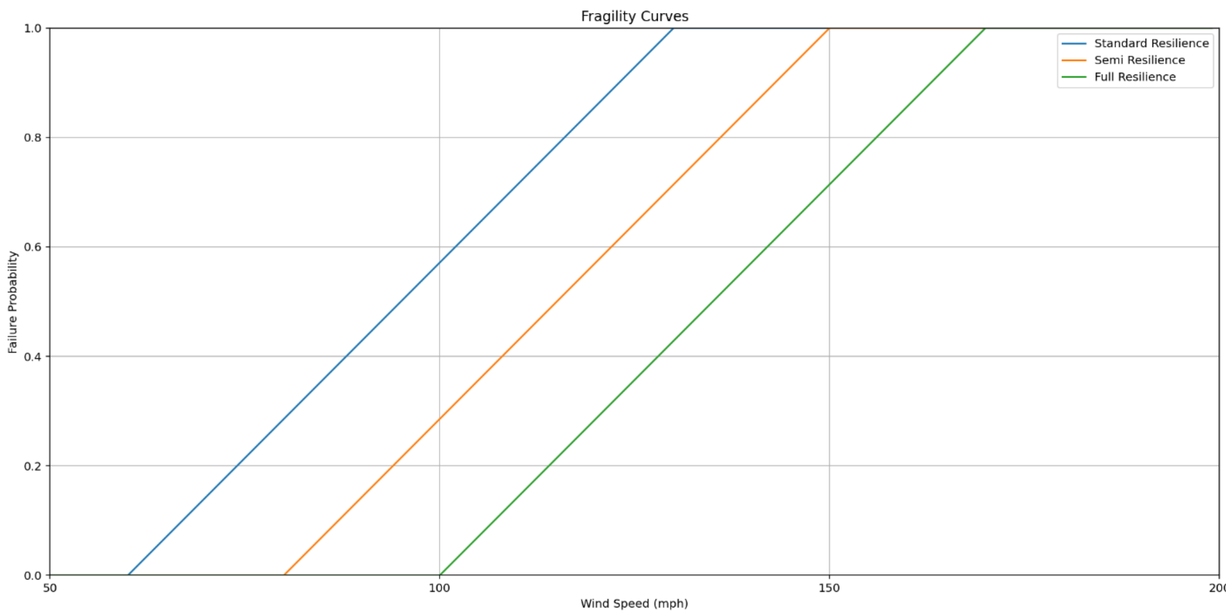


Figure 12: Fragility Curves for each resiliency level

By relating wind timeseries within each region to each fragility curve, we get a timeseries of line derates. Then, to reduce the timeseries to a single scalar, we took the 20-minute average of the highest derate in each region for each resiliency level.

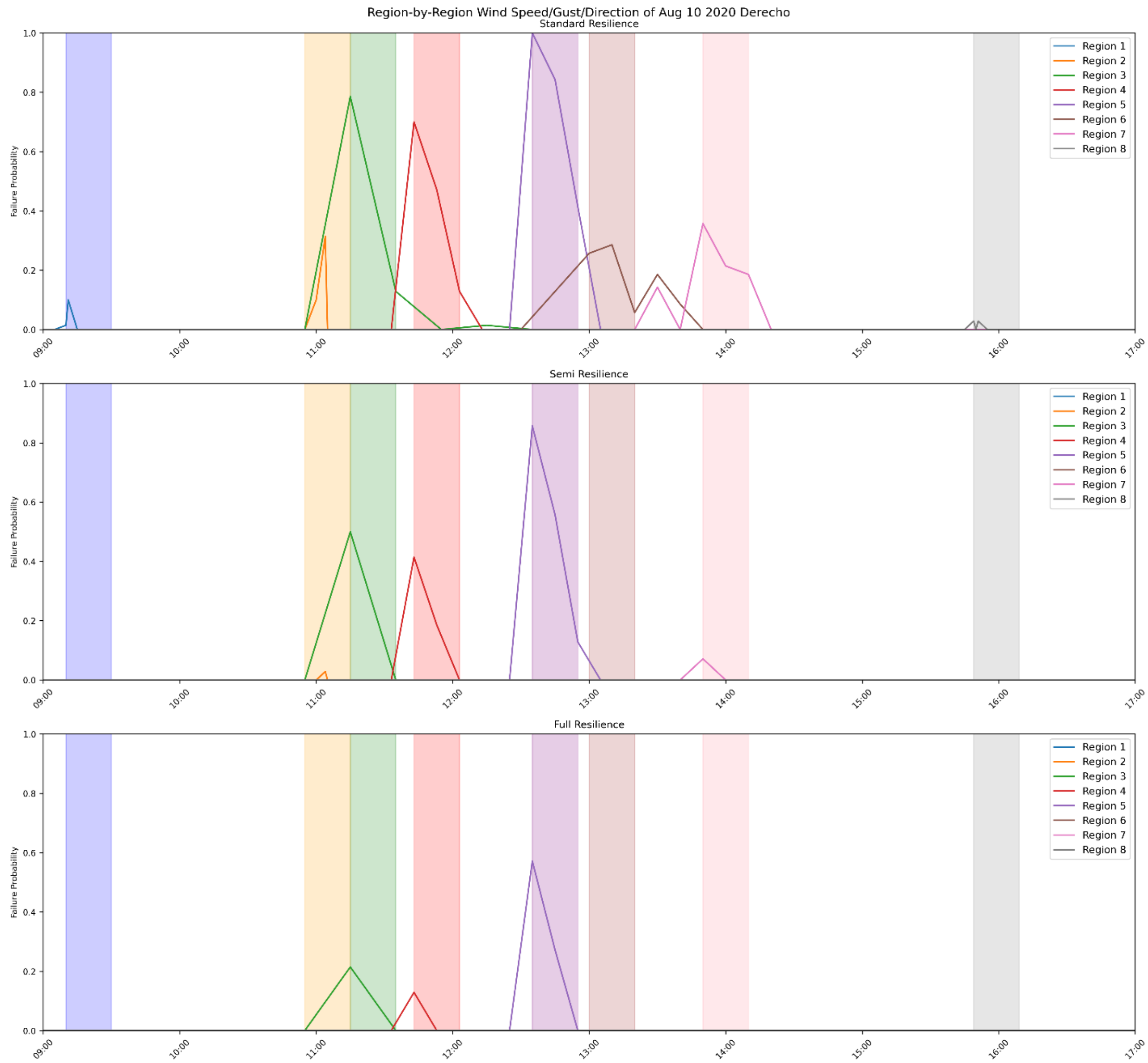


Figure 13: Failure probabilities of the 2020 derecho for each resilience level

This gave us two 3x8 tables, one for each event, shown below.

Table 4. Line Survival Probabilities for Each Weather Region

August 10, 2020 event

	R1	R2	R3	R4	R5	R6	R7	R8
Standard	0.98	0.93	0.54	0.57	0.25	0.80	0.75	0.99
Semi	1	1	0.75	0.80	0.49	1	0.98	1
Full	1	1	0.89	0.96	0.72	1	1	1

June 29, 1998 event

	R1	R2	R3	R4	R5	R6	R7	R8
Standard	0.99	0.90	0.69	0.25	0.75	0.44	0.89	0.99
Semi	1	1	0.94	0.53	0.94	0.70	1	1
Full	1	1	1	0.80	1	0.89	1	1

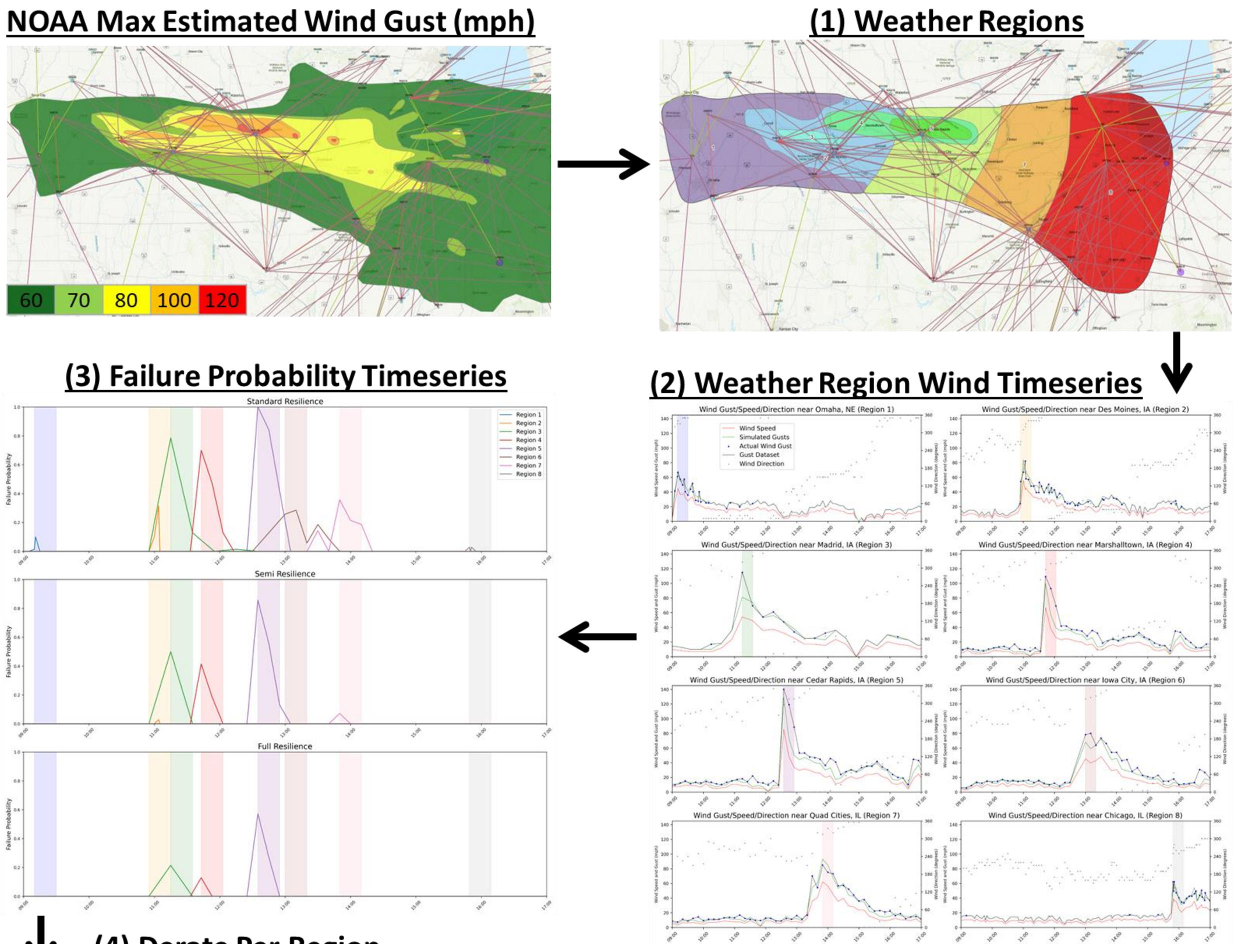
5.3 Derating Each Transmission Line

After calculating the "regional survival probabilities" above, we needed to calculate the derate for each transmission line in the 201-bus network. Lines that did not cross any regions were not derated. Lines that crossed one or more regions were derated according to the percentage of the line within each region, and any portion of the line outside the region was ignored in the calculation. This is because some of the longer lines that extended outside the weather regions would end up being less likely to fail than smaller lines that were wholly contained within any of the weather regions.

This equation was given as the following, where D_L = the derate of the line L, D_r = the derate of the weather region R, and L_r = the % of line in region R. This calculation was done for each resiliency level and for each weather event, meaning each line had six separate values of D_L.

$$D_L = 1 - \sum_{r=1}^{8} D_r \, L_r$$

The result was a set of derated lines over the reduced 201-bus network that corresponded to the observed meteorological conditions during each weather event. A summary of the entire process is given by fig. 11.



(4) Derate Per Region

	R1	R2	R3	R4	R5	R6	R7	R8
Standard	0.98	0.93	0.54	0.57	0.25	0.80	0.75	0.99
Semi	1	1	0.75	0.80	0.49	1	0.98	1
Full	1	1	0.89	0.96	0.72	1	1	1

(5) Derate Per Transmission Line

	Line % in Weather Region								Derate		
Line #	R1	R2	R3	R4	R5	R6	R7	R8	Standard	Semi	Full
396	0	19.13	0	15.26	57.01	8.60	0	0	52.38%	32.13%	16.57%
390	0	27.75	0	15.56	56.69	0	0	0	51.15%	32.02%	16.50%
401	0	13.23	0	14.43	56.72	15.62	0	0	52.79%	31.81%	16.46%
377	0	28.25	0	15.59	56.16	0	0	0	50.80%	31.76%	16.35%
378	0	0	0	11.23	56.54	32.23	0	0	53.68%	31.08%	16.28%
669	0	0	0	7.40	55.28	37.31	0	0	52.11%	29.67%	15.77%
n	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	$D_{n,standard}$	$D_{n,semi}$	$D_{n,full}$

Figure 14: Process for Derating Transmission Lines

5.4 Resilience-Based CEP Model Formulation

The RCEP model minimizes the following costs, subject to the following constraints. This is directly taken from [4], except that "hurricane conditions" are replaced with the two derecho events (1998 and 2020). A high-level formulation of the RCEP model structure is shown below, taken directly from [5].

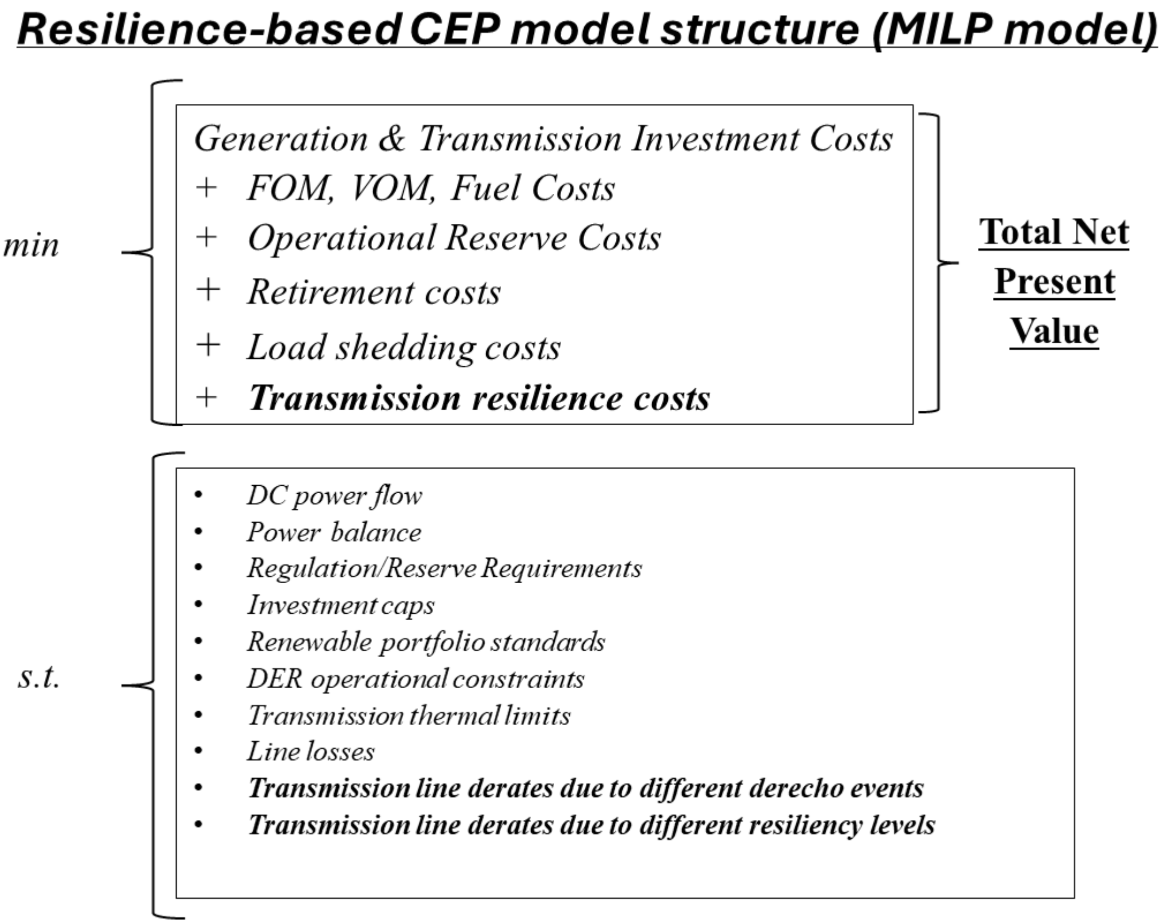


Figure 6: RCEP constraints and costs to minimize

5.5 RCEP Investment Technologies

The below diagram gives a sample, 3-bus power system that displays all of the possible transmission and distribution candidate technologies in the CEP model (NGCC, NGCT, and NGCC-CCS are all grouped as "NG"). The solid lines are existing transmission lines. The large, dashed lines represent "transmission line expansion" investments and the small dashed lines represent "distribution line expansion" investments. Note each bus can contain multiple investment decisions. In the "network reduction" example of the Eastern Interconnection above, this type of diagram would just be expanded to 201 buses.

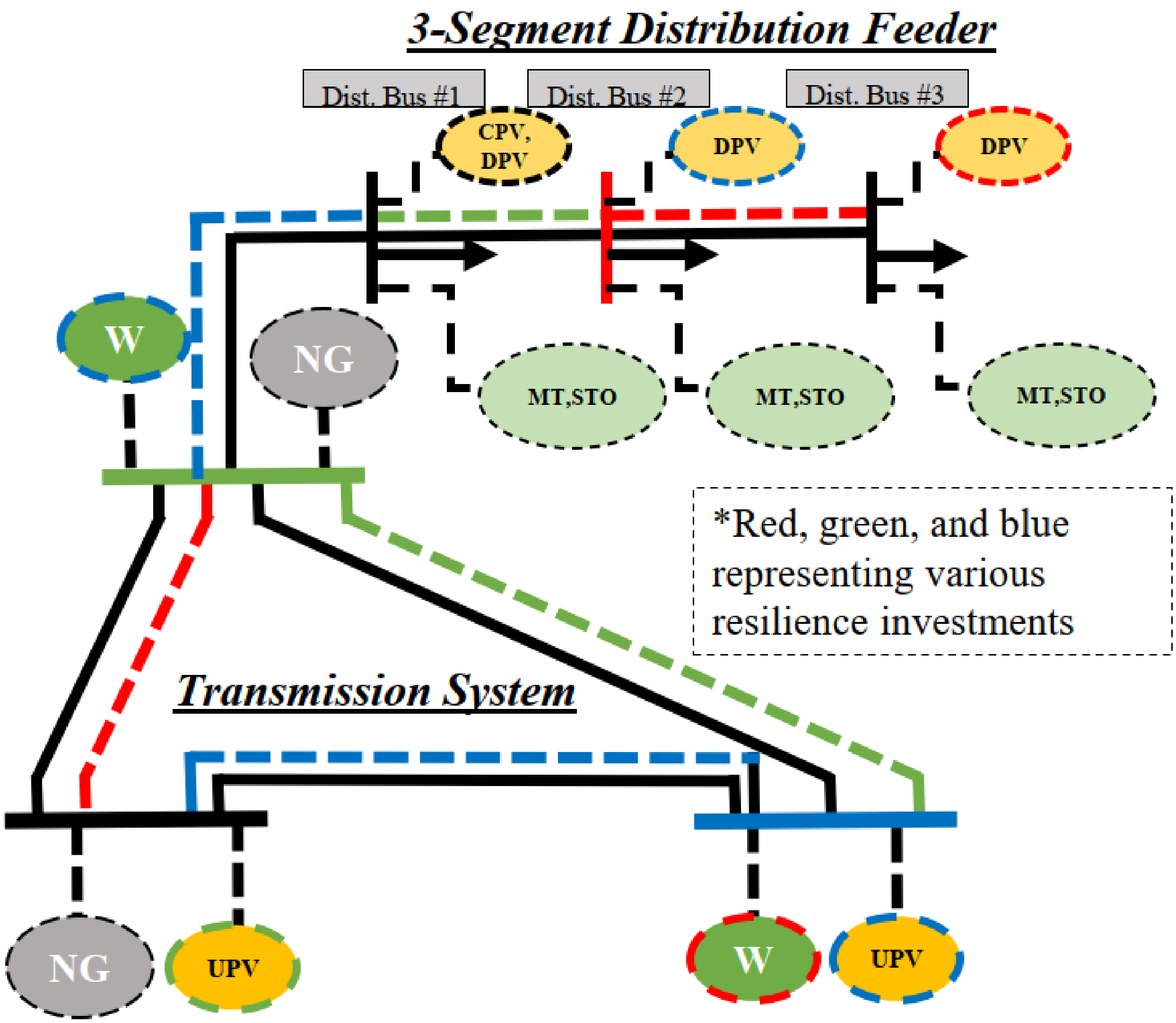


Figure 15. RCEP transmission & distribution-level investment technologies

There are 8 investment technologies at the transmission level and six at the distribution level. Technologies 1-7 are "capacity" investments that are motivated by long-term load growth and plant retirements, while (8) is the "resiliency" investment motivated by the occurrence of severe weather events and the desire to decrease the costs that the system incurs due to the derated transmission lines triggered by these weather events. Tables 5 and 6 display the candidate technologies for the transmission and distribution systems. [33]

Table 5. Transmission-level investments in RCEP

Transmission Level
Utility-scale photovoltaic (UPV)
Wind - 100m hub height (W)

Natural gas combined cycle (NGCC)
Natural gas combustion turbine (NGCT)
Natural gas CC carbon-capture sequestration (NGCC-CCS)
Utility-scale storage (STO)
Transmission line expansion
Transmission Resilience Upgrade

Table 6. Distribution-level investments in RCEP

Distribution Level
Commercial rooftop photovoltaic (CPV)
Distributed rooftop photovoltaic (DPV)
Distributed storage (STO)
Energy efficiency (EE)
Microturbine (MT)
Distribution segment expansion

The distribution system is modeled as a "3-segment distribution feeder." Using this terminology, the "segments" within a distribution line are analogous to "buses" in the transmission system, and multiple distribution-level investments can be made at each segment. Each distribution feeder can only have three segments. The radial feeders that represent the distribution feeders in the CEP model have variability in the number of buses and DER candidate technologies at the expense of extra computational complexity.

5.6 RCEP Investment Decisions

Tables 7-9 provides greater granularity into the factors that affect GTD investment decisions at each level (including the decision to "retire" an asset). The major factors affecting any investments within the power system expansion planning process are related to the investment and operational cost of that particular component, new environmental or regulation policies, and the feasibility of actually making that investment decision. [33]

Table 7. Factors impacting generation investment

Generation
Geographic location
Capacity expansion cost (CAPEX)
Maturation of CAPEX over time
Generator fuel type
Forced retirements

Policy constraints (RPS, Reduced carbon emissions
Derecho conditions (derating of generation at buses)
Derecho scenarios (variation in derecho locations, timeframes, and intensities)

Table 8. Factors impacting transmission investment

Transmission System
Capacity expansion cost (CAPEX)
Geographic location (line terrain)
Construction of new generation
Policy constraints
Derecho conditions (derating of transmission line capacity)
Derecho scenarios (variation in derecho locations, timeframes, and intensities)

Table 9. Factors impacting distribution investment

Distribution System
Capacity expansion cost (CAPEX)
Maturation of CAPEX over time
Geographic location
Construction of new distributed energy resources
Policy constraints
Minimum technical requirements for DER
Distribution feeder hosting capacity
Derecho conditions (derating of distributed energy resources & line capacity)
Derecho scenarios (variation in derecho locations, timeframes, and intensities)

5.7 Sample Resiliency Investments

RCEP does not specify *what types* of resiliency investments will be made. It only describes where the optimal resiliency investments would be in the reduced network. Resilience investments could range from strengthening overhead lines, to better vegetation management along transmission lines, to better preparation in advance of the derecho, with more resources on standby. The image below is taken from [24] and displays some of the investments that would be needed to harden the grid to a certain resilience level.

	Standard	Semi	Full
Transmission & Distribution Lines	❖ Significant repairs and reconstruction expected after event ❖ Susceptible to failure with next extreme event ❖ No major hardening investments made	❖ Adopt annual vegetation management program ❖ Smaller conductors used to reduce loads ❖ Replacing wood poles with steel or concrete ❖ Install modest amount of lattice structures for long transmission lines ❖ Flexible operations (switches) ❖ Pre-event preparation (develop plans for crews, pre-stage materials)	❖ Adopt semi-annual vegetation management program ❖ Smaller conductors used to reduce loads ❖ Replacing wood poles with steel or concrete ❖ Install modest amount of lattice structures for long lines ❖ Pre-event preparation (develop plans for crews, pre-stage materials) ❖ Reduction of spans in lines and feeders ❖ Underground lines where feasible/Flexible operations Pre-event preparation (develop plans for crews, pre-stage materials)
Wind & Solar Technologies	❖ Significant repairs and reconstruction expected after event ❖ Susceptible to failure with next extreme event ❖ No major hardening investments made	❖ Enhanced studies for site selection ❖ Annual maintenance of structures' components ❖ Enhanced foundation design ❖ Pre-event preparation (emergency reinforcements, crews on standby) ❖ Active yaw control for high winds ❖ Strengthen supporting towers (more steel and internal structure)	❖ Enhanced studies for site selection and wind load calculations made ❖ Semi-annual maintenance of structures' components ❖ Enhanced foundation design/larger, deeper foundations ❖ dual- post fixed tilt ground mounts only ❖ Pre-event preparation (emergency reinforcements, crews on standby) ❖ Active yaw control for high winds; high wind ride through capability ❖ Strengthen supporting towers (more steel and internal structure)
Substations	❖ Significant repairs and reconstruction expected after event ❖ Susceptible to failure with next extreme event ❖ No major hardening investments made	❖ Enhanced studies for site selection ❖ Annual maintenance of structures ❖ Construction of temporary/relocatable barriers ❖ Elevated platforms used when feasible ❖ Pre-even preparations	❖ Enhanced studies for site selection ❖ Semi-annual maintenance of structures ❖ Construction of permanent barriers (concrete wall) ❖ Elevated platforms used when feasible ❖ Control room protected and/or elevated ❖ Scaling and waterproofing components ❖ Pre-even preparations

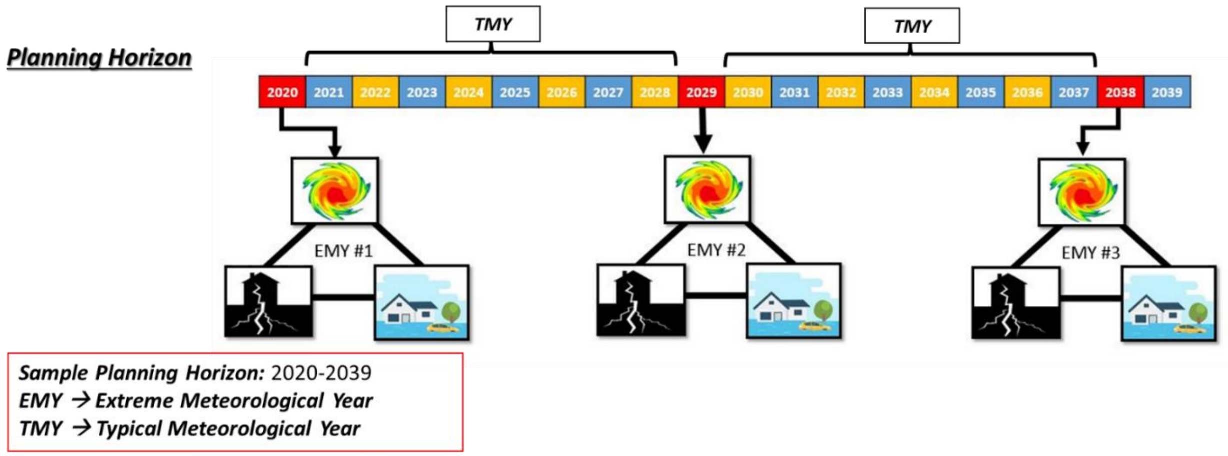
Figure 16: Sample investments for each resiliency level

Increasing the resilience level of a component in the RCEP model has two main impacts. First, it decreases the probability of that component failing (or mitigates the magnitude if it does fail), and second, it allows that component to be restored more quickly. Referring back to the "resilience trapezoid" discussed in chapter 4, the idea of a resilient system is to not only maintain operation during an event, but recover quickly from any damage sustained during that event. The image, taken from [33], shows the "resilience trapezoid" under "standard," "resilient," and "ideal" system configurations.

RCEP has the ability to invest in "standard resilience," "semi-resilience," or "full-resilience." Like the image above, stronger resilience investments have a (1) lesser probability/magnitude of failing and (2) recover sooner than non-resilient systems. We will address both components of resilience below. Different fragility levels have different fragility curves, bus multipliers, and restoration timelines. These are discussed in chapter 6, section (x)

5.8 RCEP Investment Years

RCEP is formulated over a multi-decadal planning horizon. Within this planning horizon, there are two types of years: "non-derecho years" (NDY) and "derecho years" (DY). Non-derecho years are split into "investment years" and "operational years," resulting in three 'categories' of years within the model. The below image is taken from [33] and shows the decisions made by the model for each of these years.



Model Feature	Investment EMY	Investment TMY	Operational TMY
Capacity Investments		x	
Resilience Investments	x		
Retirements	x	x	
Operational costs	x	x	x

Figure 17. Planning Horizon & Years in RCEP

5.9 RCEP Load Blocks

Expansion planning models model load growth by taking historical load hourly or subhourly load data, grouping it into load "blocks," and combining low-resolution load forecasts with these higher-resolution load "blocks" to create a high-resolution load forecast that must be satisfied by existing generation. These load "blocks" are used to make the expansion problem computationally tractable, as iteratively running the expansion planning model every hour over the course of 20 years (in that case, 175200 runs total) would be computationally infeasible.

The choice of load blocks is important for power system planning because planners want to capture load shapes while keeping the model computationally feasible. A poor choice of load blocks could result in the investment plan not being optimized for actual, hourly load patterns, and it could preclude the model from capturing all extreme events.

Typical Meteorological Year Load Blocks

In order for the model to be computationally tractable, load blocks need to be built to represent the load diversity in a more compact manner. Ideally, the model could handle all 8760 hours of each year within the long-term planning horizon. However, the computational time and memory necessary for such a problem is way too large to be handled by the resources available. To solve this problem, one method is the development of load blocks. For a "typical meteorological year," the load blocks are developed around seasons and the time of day. [33]

Table 10. Typical Meteorological Year Load Blocks in RCEP

Table 2.2: Breakdown of typical condition load blocks used for the Puerto Rico case study

Load Block	Season	Time of Day	# of hours
1	Rainy	11pm-6am	1712
2	Rainy	7am-1pm	1498
3	Rainy	2pm-6pm	1498
4	Rainy	7pm-10pm	1070
5	Dry	11pm-6am	1208
6	Dry	7am-1pm	1057
7	Dry	2pm-6pm	755
8	Dry	7pm-10pm	604
9	Peak	-	40

Extreme Meteorological Year Periods

A resilient system is one that both experiences minimal disruption during a severe weather event *and* recovers quickly after this event. In the RCEP model, resilience investments are quantified both by the fragility curves shown in section III, signaling decreased disruption during derechos, and a faster recovery to full system performance after the derecho has occurred [5]. This is illustrated by fig 14.

For an extreme meteorological year, the load blocks are instead developed around the occurrence of the event. This allows the user to analyze how the performance of the system improves during the recovery period of an event [33]. The restoration timeline was divided into 5 "EMY Periods," with each resiliency level having lines derated for a different total length. These periods were adopted from [5], [33] , but the timelines were decreased to reflect the greater speed of restoration of electrical systems over the Midwestern U.S. to Puerto Rico.

Table 11. Extreme Meteorological Year Periods in RCEP

EMY Period	Description	Standard Tech	Semi Tech	Full Tech
1	Extreme event occurring (4 hrs)	✓	✓	✓
2	24 hours after event	✓	✓	-
3	3 days after event	✓	-	-
4	1 week after event	✓	-	-
5	Remaining 51 weeks of year	-	-	-

Figure 14: Timeline for derate restoration

6. Results

Analysis results are forthcoming.

7. Conclusions

The goal of this report was to use the June 29, 1998 and August 10, 2020 derechos as a "proof of concept" to show how the RCEP model can find the least-cost combination of resiliency investments to minimize the combined costs from resiliency enhancement and storm-related infrastructure damage.

Areas for future work include modeling multiple, historical derecho events so that investments are optimized for an assortment of events instead of all being driven in response to one severe event. Additionally, the RCEP model could be extended to cover a variety of extreme weather events, such as winterization for arctic outbreaks, flooding, and more using the same paradigm of derating system components with fragility curves and/or bus multipliers. Lastly, a very important area of future work is incorporating "capacity shortage" weather events into the RCEP model, such as extended periods of low renewable generation.

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