NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Hurricane Harvey Event Analysis Report

March 2018

RELIABILITY | ACCOUNTABILITY




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Preface

The vision for the Electric Reliability Organization (ERO) Enterprise, which is comprised of the North American Electric Reliability Corporation (NERC) and the eight Regional Entities (REs), is a highly reliable and secure North American bulk power system (BPS). Our mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.

The North American BPS is divided into eight RE boundaries as shown in the map and corresponding table below.

The North American BPS is divided into eight RE boundaries. The highlighted areas denote overlap as some load-serving entities participate in one Region while associated Transmission Owners/Operators participate in another.

FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
SPP RE	Southwest Power Pool Regional Entity
Texas RE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Introduction

The purpose of this report is to provide an analysis of Hurricane Harvey's impact on the BPS to ensure a complete, coherent review and documentation of the event and restoration efforts. The report focuses on preparation before the storm, operations during the event, and restoration recovery efforts. The report is an independent assessment by ERO staff and summarizes the event for the entire storm area. For any questions about the contents of this report, including corrections, improvements, and any suggestions, please contact NERC.EventAnalysis@nerc.net.

Executive Summary

Hurricane Harvey made landfall as a Category 4 hurricane on August 25, 2017, at 10:00 p.m. Central with winds in excess of 130 MPH and a record-breaking storm surge. The storm inflicted massive disruptions on the electric power system in the Corpus Christi, Houston/Galveston, and Beaumont/Port Arthur areas of Texas. As Harvey moved inland, the storm stalled, causing excessive rain (40–50 inches) in parts of Southeastern Texas and flooding large areas of Houston and inland as far as Austin.

NERC REs, independent system operators (ISOs), and the potentially affected registered entities continually monitored weather developments and exchanged projections. Lines and generators on maintenance returned to service. Unit commitment and generator dispatch decisions postured the system to withstand the impact of the storm and recover promptly afterward. Equipment status and capabilities were confirmed. Transmission Owners (TOs) and Transmission Operators (TOPs) preemptively shut down several local load networks in a controlled fashion to prevent damage to equipment and speed restoration. Generator Owners (GOs) shut down or evacuated some fossil-fueled and wind generating units in the path of the storm.

The leading edge of the storm began to inflict transmission system outages on the BPS as early as 4:00 p.m. on August 25. As the main body of the storm progressed over the Texas power system from August 25 through August 30, approximately 225 transmission assets were impacted. These included 345, 138, and 69 kilovolt (kV) transmission lines and transformer banks. The TOs reported that several low-lying stations were flooded and became completely inoperable and that high winds had damaged transmission and substation equipment. Generating facilities over a very wide footprint were either forced or tripped off-line with some generators rendered unavailable due to the loss of interconnecting transmission. During the event, a maximum of 10,992 MW of generation capacity became unavailable. The distribution system also suffered severe damaged. By late Saturday, August 26, a peak 338,000 electric customer outages were reported across the impacted area. The total number of reported customer outages exceeded 1.67 million in the Electric Reliability Council of Texas (ERCOT) area.

In the SERC Region in the Midcontinent Independent System Operator (MISO) southern reliability area, Harvey impacted 37 230 kV and 138 kV transmission lines. Multiple substations and six generators flooded in Southeast Texas and Louisiana, totaling 2,285 MW. At the peak of this event within SERC's footprint, approximately 340,000 customers lost service in Texas (Entergy territory) and approximately 7,000 customers in Louisiana, mainly caused by outages on the distribution system.

Electricity demand in ERCOT was significantly lower than usual for the time of year mainly because of the cooler temperatures across much of the state as well as customer outages in storm-affected areas along the Texas Gulf Coast.

Transmission, distribution, and generation asset owners initiated the recovery effort once it was safe for crews to enter the impacted areas. The initial recovery consisted of inspections and asset assessments. Flooding and the unavailability of roads greatly hampered the equipment owners' initial assessments. The priority, as communicated by the utilities, was to the restore transmission assets to generating facilities needed for distribution load recovery. While there was sufficient generation capacity available to meet the load as restoration progressed, local area transmission outages hindered customer restoration in some cases. This included instances where severely damaged substations did not allow power to be delivered to the distribution system.

Most entities returned 95 percent or more of their customers to service between August 26, and September 2. Due to flooding in Houston, one of the hardest-hit areas, power restoration was not completed until September 8.

Hurricane Harvey Numbers

- **Rainfall:** 51.88 inches maximum rainfall recorded in Cedar Bayou near Highlands, Texas
- **Minimum surface pressure:** 938 millibars at landfall, tying for 16th lowest pressure hurricane on record
- **Multiple landfalls:**
  - Category 4 near Port Aransas, Texas
  - Tropical storm in Cameron, Louisiana
- **Top wind gust measured:** 132 mph near Port Aransas
- **Lightning strikes:** More than 42,000
- **Counties affected by flooding:** 50

Bulk Power System Damage

- **Customers affected:** over 2.02 million
- **Transmission structures downed or damaged:** over 850
- **Distribution poles downed or damaged:** over 6,200
- **Transmission and distribution conductor replaced:** over 800 miles
- **Substations damaged:** over 90
- **Employees and contractors involved in the restoration:** over 12,000

Chapter 1: Background

Pre-existing System Conditions

Pre-existing conditions for all areas were considered normal for late August, which is a peak season for the Texas RE Interconnection and the SERC Regions. During these times, TOs and GOs are typically restricted from taking facility outages due to high system demand.

Hurricane Harvey Recap[1]

Hurricane Harvey began as a tropical wave that emerged from the African coast in early August (see **Figure 1.1**). The disturbance formed into Tropical Storm Harvey east of the Lesser Antilles on August 17. Those islands experienced heavy rain and gusty winds as Harvey passed through. A couple of days later, Harvey weakened to a tropical wave due to dry air and unfavorable winds in the Eastern Caribbean, and the National Hurricane Center ceased advisories on August 19.

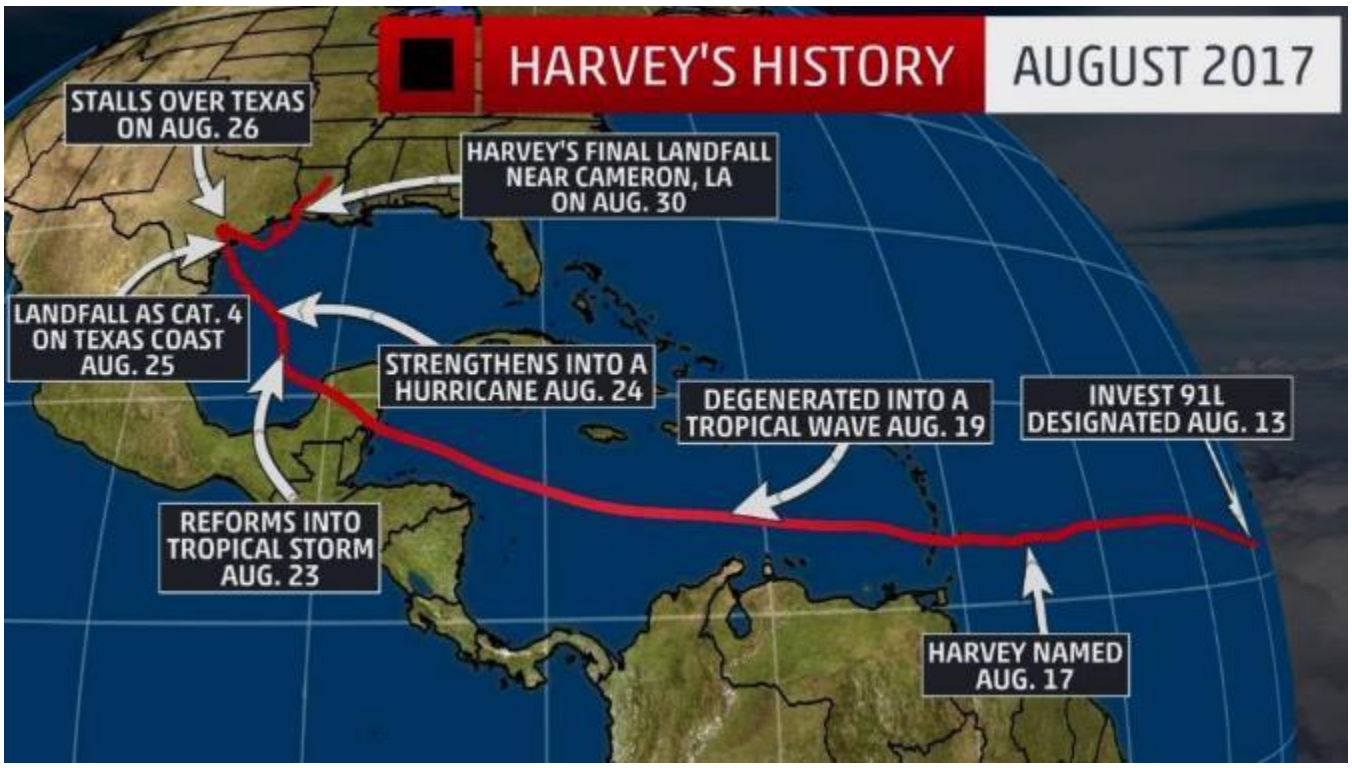

Figure 1.1: Hurricane Harvey Storm Track, August 2017

The remnants of Harvey continued to push northwest for several days and eventually crossed Mexico's Yucatan Peninsula. Once its remnants moved back over water in the Southwest Gulf of Mexico, Harvey reformed into a tropical depression on August 23. In just 56 hours, Harvey grew from a regenerated tropical depression over the Gulf of Mexico into a Category 4 hurricane as it made landfall near the Texas Gulf Coast late on August 25. Harvey's center of circulation stalled over Southern Texas on August 26 and then meandered slowly east into the Gulf of Mexico before making landfall near Cameron, Louisiana, on August 30. Still a named storm 117 hours after landfall, Harvey was the longest a Texas hurricane remained a named storm after landfall on record. It was the slow movement from August 26 to August 30 that led to the catastrophic flooding that was observed in Southeast Texas.

[1] Information and data from the National Weather Service

Harvey made landfall on the evening of August 25 near Rockport, a town of less than 10,000 people and about 30 miles up the Texas coast from Corpus Christi. Maximum sustained winds in Harvey's eyewall were 130 MPH at that time, making it a Category 4. With a diameter of approximately 280 miles, the effects of Harvey were felt from Brownsville, Texas to Lake Charles, Louisiana.

Harvey was the nation's first major hurricane (Category 3 or stronger) to make landfall since Hurricane Wilma struck South Florida in October 2005, an almost 12-year run. Harvey was the strongest storm to make a landfall in this area, known as the Texas Coastal Bend, since Hurricane Carla in September 1961.

According to the National Oceanic and Atmospheric Administration/Atlantic Oceanographic and Meteorological Laboratory (NOAA/AOML), Harvey's minimum surface pressure of 938 millibars at landfall tied it for the 16th lowest pressure hurricane on record to make landfall in the United States. Harvey was also the strongest hurricane by pressure to make landfall in the United States since Rita in 2005 (see **Figure 1.2** and **Figure 1.3**).

Figure 1.2: Hurricane Harvey at Landfall, August 25, 2017 at 10:00 p.m.

Top Wind Gust Reports (see **Figure 1.3**)

- **Port Aransas:** 132 MPH, sustained to 110 MPH
- **Near Copano Village:** 125 MPH
- **Near Lamar:** 110 MPH
- **Rockport:** 108 MPH
- **Near Taft:** 90 MPH
- **Near Magnolia Beach:** 79 MPH
- **Palacios:** 69 MPH
- **Corpus Christi Int'l Airport:** 63 MPH
- **Austin Bergstrom Int'l Airport:** 52 MPH

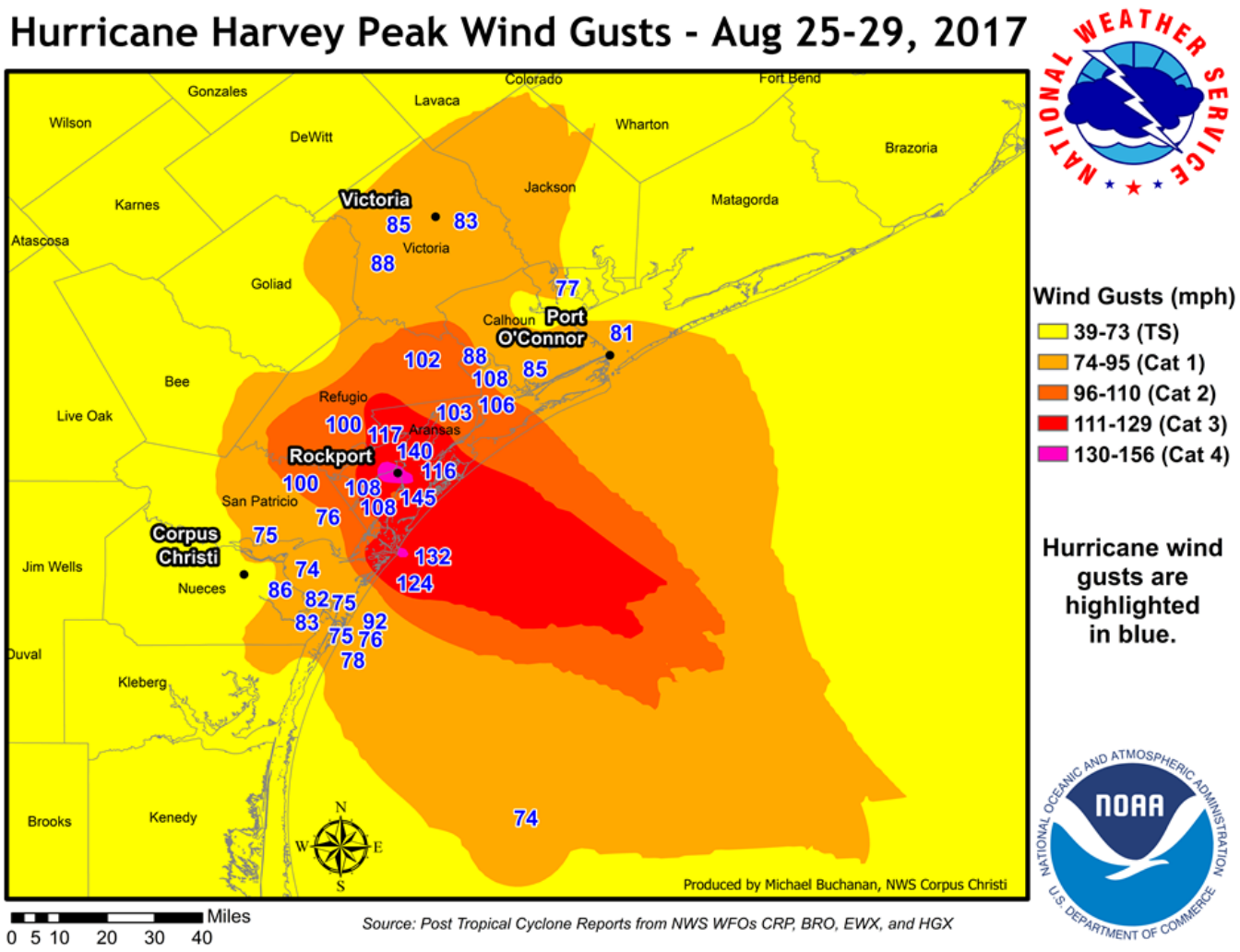

Figure 1.3: Hurricane Harvey Peak Wind Gust Profile

Harvey's slow movement from August 26 to August 30 resulted in catastrophic flooding. Numerous flash flood emergencies were issued for the Texas metropolitans areas of Houston and Beaumont and for Bastrop County and nearby communities. The area coverage of locations picking up at least 20 inches of rain was greater than the state of West Virginia while the 40-inch-plus zone was larger than Delaware (See **Figure 1.4**).

The top rainfall total was a preliminary 51.88 inches near Highlands, Texas, at the Cedar Bayou rain gauge.

Top Rainfall Reports

- 51.88 inches on Cedar Bayou near Highlands, Texas
- 49.40 inches on Clear Creek at Interstate 45 near League City, Texas
- 49.32 inches on Mary's Creek near Friendswood
- 49.23 inches near Dayton
- 49.20 inches on Mary's Creek at Winding Road
- 47.35 inches in Beaumont/Port Arthur, Texas
- 45.74 inches near Pasadena

- 44.91 inches near South Houston
- 43.38 inches at the NWS forecast office in Houston (League City)
- 37.01 inches at Houston Hobby Airport
- 31.26 inches at Houston Bush Intercontinental Airport
- 22.84 inches in Galveston
- 21.88 inches in Smithville
- 19.64 inches in College Station
- 15.60 inches near Victoria
- 15.41 inches near Lake Charles, Louisiana
- 12.33 inches near Hackberry, Louisiana

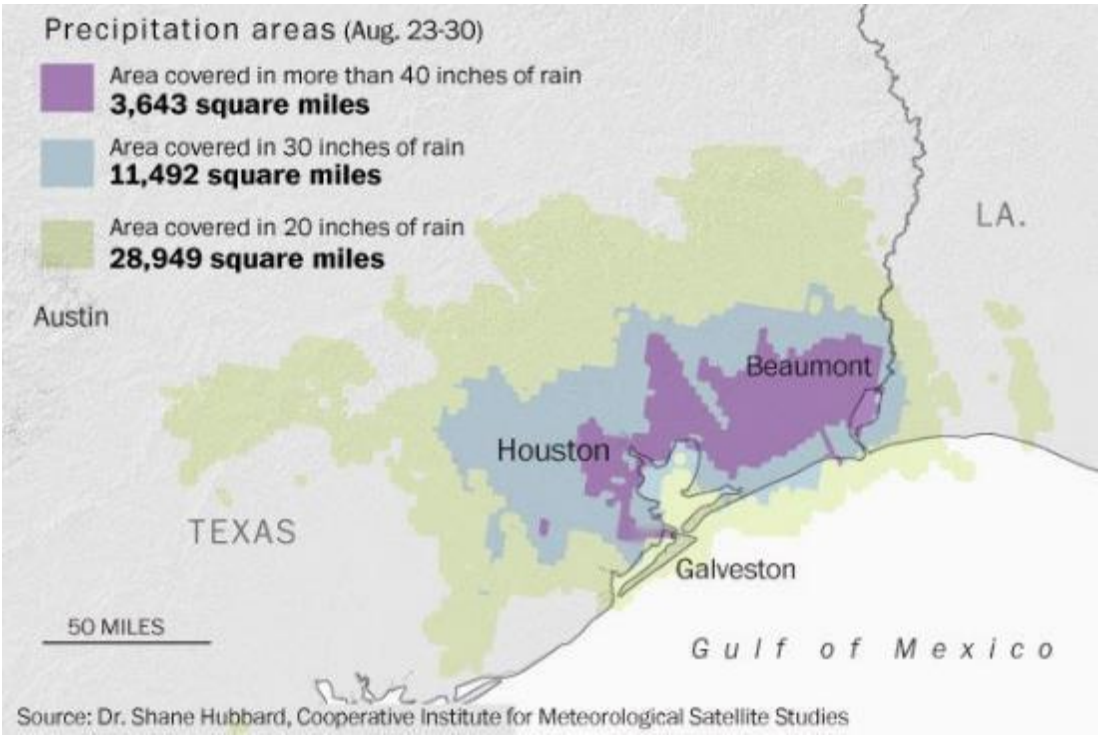

Figure 1.4: Hurricane Harvey Precipitation Area, August 23–30

Houston's Bush Intercontinental Airport exceeded its record-wettest calendar day Sunday, August 27 by over 5 inches, picking up 16.07 inches of rain, just under the five-day total of 16.48 inches from Tropical Storm Allison in 2001. Houston's Hobby Airport also exceeded a two-day rainfall record by almost 8 inches, picking up 23.06 inches of rain on August 26 and 27. The average rainfall within the Harris County Emergency Management network exceeded that of Tropical Storm Allison (2001) in almost half of the time (two to three days versus five days). The Harris County Flood Control District (HCFCD) estimated one trillion gallons of water was dumped on the county alone in four days. The HCFCD estimated 70 percent of Harris County was flooded by at least 1.5 feet of water with an estimated 136,000 flooded structures in the county alone as of August 31.

Thousands of water rescues occurred in the Houston metro area as many homes and businesses were swamped by floodwaters. Jack Brooks Regional Airport near Port Arthur, Texas picked up 26.03 inches of rain on August 29

alone, more than doubling the previous calendar-day rainfall record in Beaumont-Port Arthur set over 94 years ago. Its storm total from August 26 to August 30 was 47.35 inches of rain, almost 25 inches greater than its previous four-day rain record set in September 1980.

Serious flooding also occurred Southwest of Houston along the Brazos, Colorado, and Guadalupe Rivers. In total, 19 National Weather Service river gauges had observed record flooding as of August 31.

Harvey has also spawned numerous brief tornadoes in Southeast Texas, Louisiana, Alabama, Mississippi, Tennessee and North Carolina. Harvey is one of the most prolific tornado producers for a tropical cyclone.

Affected Areas

Hurricane Harvey affected many entities along the Texas coast and inland. These areas included the large coastal population centers of Corpus Christi, Victoria, Houston, Galveston, and Beaumont/Port Arthur, and areas further inland as far as San Antonio and Austin. The coastal areas impacted include the transmission and distribution service territories of American Electric Power, South Texas Electric Cooperative, Texas-New Mexico Power, and CenterPoint Energy. Inland areas impacted include the transmission and distribution service territories of Bryan Texas Utilities, Austin Energy, CPS Energy, Lower Colorado River Authority, Brazos Electric, and Oncor. In the SERC Region, Entergy customers in East Texas and Western Louisiana took the brunt of the storm along with cooperatives in that area.

Time Frame for Outage and Restoration

None of the generator or transmission losses required load curtailments to maintain BPS security. Despite the catastrophic nature of the storm and the high number of transmission line outages, utilities were able to operate within thermal and voltage system operating limits. See the reported restoration times in **Table 1.1**.

Table 1.1: Restoration Times Reported

Company	Restoration Start Date	Restoration End Date	Customers Impacted	Total Customer Outage-Hours
American Electric Power	8/26	9/2	220,400 (Maximum on 8/26) 304,728 (Total)	24,274,683
CenterPoint Energy	8/27	9/8	269,975 (Maximum on 8/26) 1,076,868 (Total)	~ 12,600,000
South Texas Electric Coop	8/26	9/3	29,735 (Maximum on 8/26) 31,950 (Total)	1,331,069
Texas-New Mexico Power	8/26	9/6	14,448 (Maximum on 8/28) 77,968 (Total)	n/a
Austin Energy	8/26	8/30	30,000 (Maximum on 8/27)	n/a
CPS Energy	8/26	8/28	231 (Maximum on 8/26) 149,136 (Total)	3,694
Bryan Texas Utilities	8/26	8/28	1,210 (Maximum)	11,889

Table 1.1: Restoration Times Reported				
Company	**Restoration Start Date**	**Restoration End Date**	**Customers Impacted**	**Total Customer Outage-Hours**
Brazos Electric	8/26	8/28	2,747 (Maximum on 8/27) 5,101 (Total)	6,720
Entergy Texas (MISO)	8/27	9/8	186,000	n/a
Other SERC entities	8/27	9/8	161,000	n/a

Chapter 2: Weather

Weather Systems and Notifications

Predicting the storm path for Hurricane Harvey proved to be difficult. Throughout much of the storm, the weather models used by ERCOT staff predicted varying outcomes as to the strength and path of the storm. For nearly the entirety of the storm, the various weather models could not agree with the expected movement of the hurricane once it reached the Western Gulf of Mexico. The models were in agreement that the storm would stall out somewhere north of the Corpus Christi area for a day or so before moving on.

Additionally, comparisons of the potential track areas from the National Hurricane Center were not consistent. As of 10:00 a.m. on August 25, the prediction was that Harvey would move east towards Louisiana, but by 4:00 a.m. on August 26, the prediction had Harvey potentially moving further west, possibly over the Texas Hill Country. The 4:00 a.m. update on August 27 then changed the model back towards Louisiana, possibly moving offshore and rebuilding first. After the 4:00 a.m. update, the storm future tracks began to be more consistent, moving the remnants of Harvey north and east; by then, significant damage and flooding had already been recognized along the coastal region of Texas.

The utilities of the Texas RE Region all use various weather tools to monitor current and forecast weather. The most often used tools or services are NOAA and staff meteorologists (see **Table 2.1**). Other weather services in use are WeatherSentry, MDA, StormGeo, Weather.gov, Intellicast, Weather Underground, and The Weather Channel. Virtually all control centers also use local and national television and radio forecasts.

Table 2.1: Weather Services Used by Utilities and ISOs

Entity	TELVENT	NOAA	AccuWeather	Staff Meteorologists	Private Vendor	Other[2]
ERCOT ISO		X		X		X
Registered entities	1	11	1	11	3	24

Timing of Warning Systems and Action Taken

On August 16, ERCOT began monitoring Harvey, using these weather systems/warnings to discuss operational preparations and staffing needs leading up to the event and to provide appropriate notice and warning to ERCOT market participants and other relevant entities. Harvey weakened to a tropical wave due to dry air and unfavorable winds in the Eastern Caribbean, and the National Hurricane Center ceased advisories on August 19. After the remnants of Harvey crossed Mexico's Yucatan Peninsula, Harvey quickly reformed into a tropical depression on August 23. In just 56 hours, Harvey grew from a regenerated tropical depression over the Gulf of Mexico into a Category 4 hurricane.

The majority of entities were actively monitoring the storm by August 23. As a result of these warnings, the following actions occurred:

- Senior management was informed and updated on the situation
- Facilities were secured for heavy weather
- The status and readiness of generation and transmission resources were determined

[2] Some companies use more than one "other" source for weather information. Services represented by "other" include WeatherSentry, StormGeo, Weather Underground, The Weather Channel, Intellicast, and MDA as well as local and national news services.

- Emergency response and incident command organizations were activated
- Employees were provided with the incoming weather and changes to daily schedules
- Plans for supplemental operations and support staffing were developed and/or implemented
- Predicted wind speeds and directions were monitored to determine most critical time frames
- Procedures and checklists were reviewed
- Outages were postponed or returned early
- Data were shared and regional mutual assistance groups were engaged

Entities continued to monitor the storm in the days leading up to landfall. ERCOT staff also took steps to prepare the system for the storm impact and the recovery effort that was sure to follow.

Benefits of On-Site Meteorologists

All entities that have on-site meteorologists reported it as beneficial because it allowed forecasts to be more narrowly tailored for the entity's particular areas of interest and to estimate resources needed for forecasted damage and post-storm recovery.

Storm Weather Updates during Event

ERCOT Disaster Management representatives were logged in and monitored National Weather Service briefings directly. System Operations representatives were on 9:00 a.m. WeatherSentry daily briefings via WebEx as well.

ERCOT System Operations conducted daily internal briefings at 8:00 a.m. and 5:00 p.m. to communicate storm weather updates between shifts, operation staff, and management staff. ERCOT's Senior Meteorologist also sent periodic emails with Hurricane Harvey updates. ERCOT System Operations also sent reports twice a day to the Public Utility Commission of Texas (PUCT).

Comparison of Harvey to Other Storms (Customer Outages, Extent of Outages)

The last two storms to hit the Corpus Christi and South Texas areas were Category 1 storms, and the extent of damage and length of outages on the transmission system were not comparable to Harvey. The last major hurricane to strike this area was Hurricane Celia in 1970.

In Houston, the lessons learned from Hurricane Ike were also not comparable to Harvey. Hurricane Ike caused large physical damage due to its storm surge and high winds. The Houston area did not experience any hurricane-force winds or storm surge with Harvey; it experienced unprecedented widespread flooding from the historic rainfall event (See **Table 2.2**).

Table 2.2: Storm Comparisons

Storm	Year	Landfall	Category (at landfall)	Customer Outages
Harvey	2017	Texas	4	2 million
Ike	2008	Texas	2	4.5 million
Rita	2005	Texas/Louisiana	3	2 million

Chapter 3: Maps of Impacted Areas

American Electric Power's impacted service area included Corpus Christi, Port Aransas, Aransas Pass, Rockport, Fulton, Refugio, Port Lavaca, Bay City, and Victoria. Dots represent broken or damaged poles (See **Figure 3.1**). **Figure 3.2** shows ERCOT transmission outages.

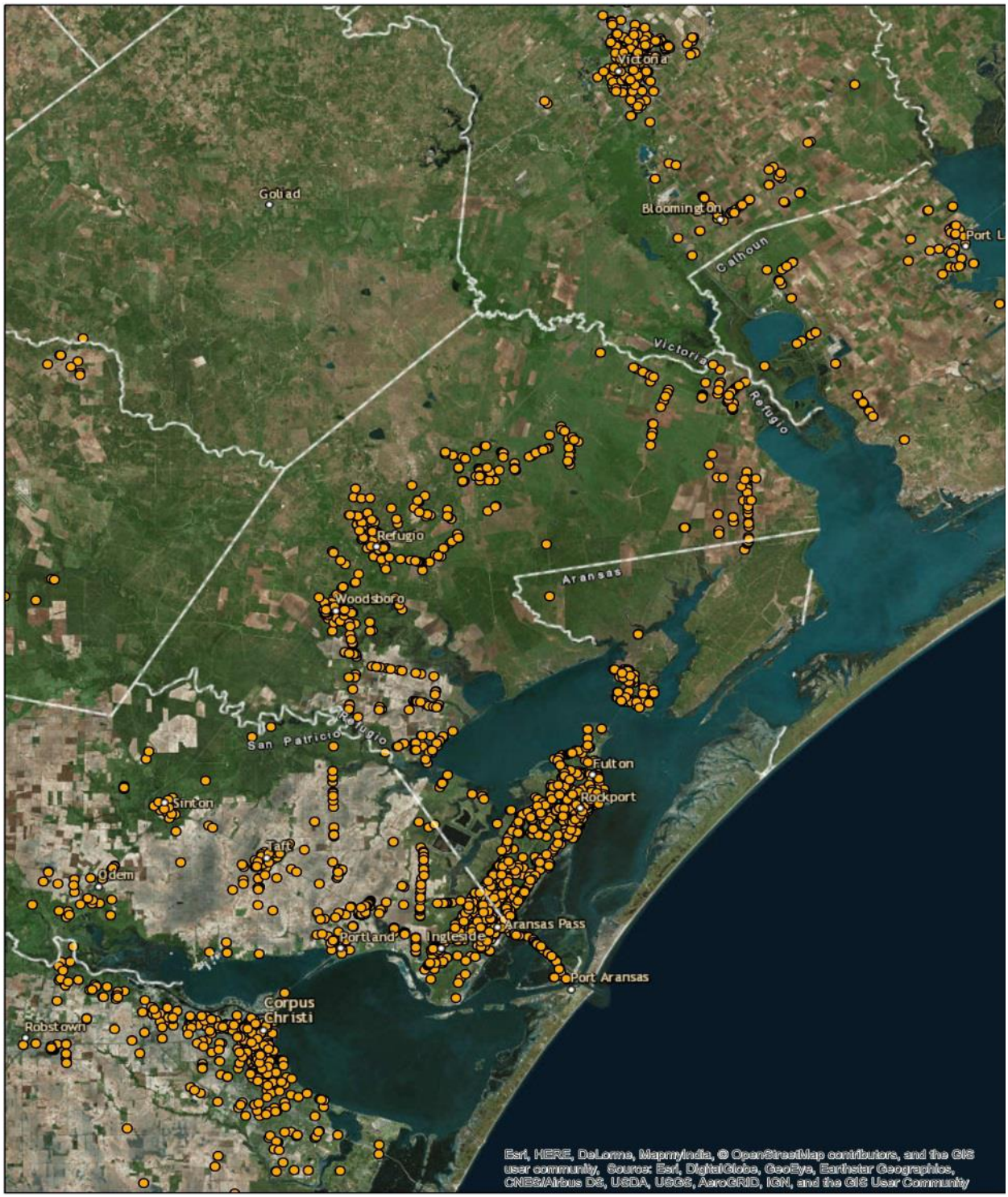

Figure 3.1: American Electric Power's Impacted Areas

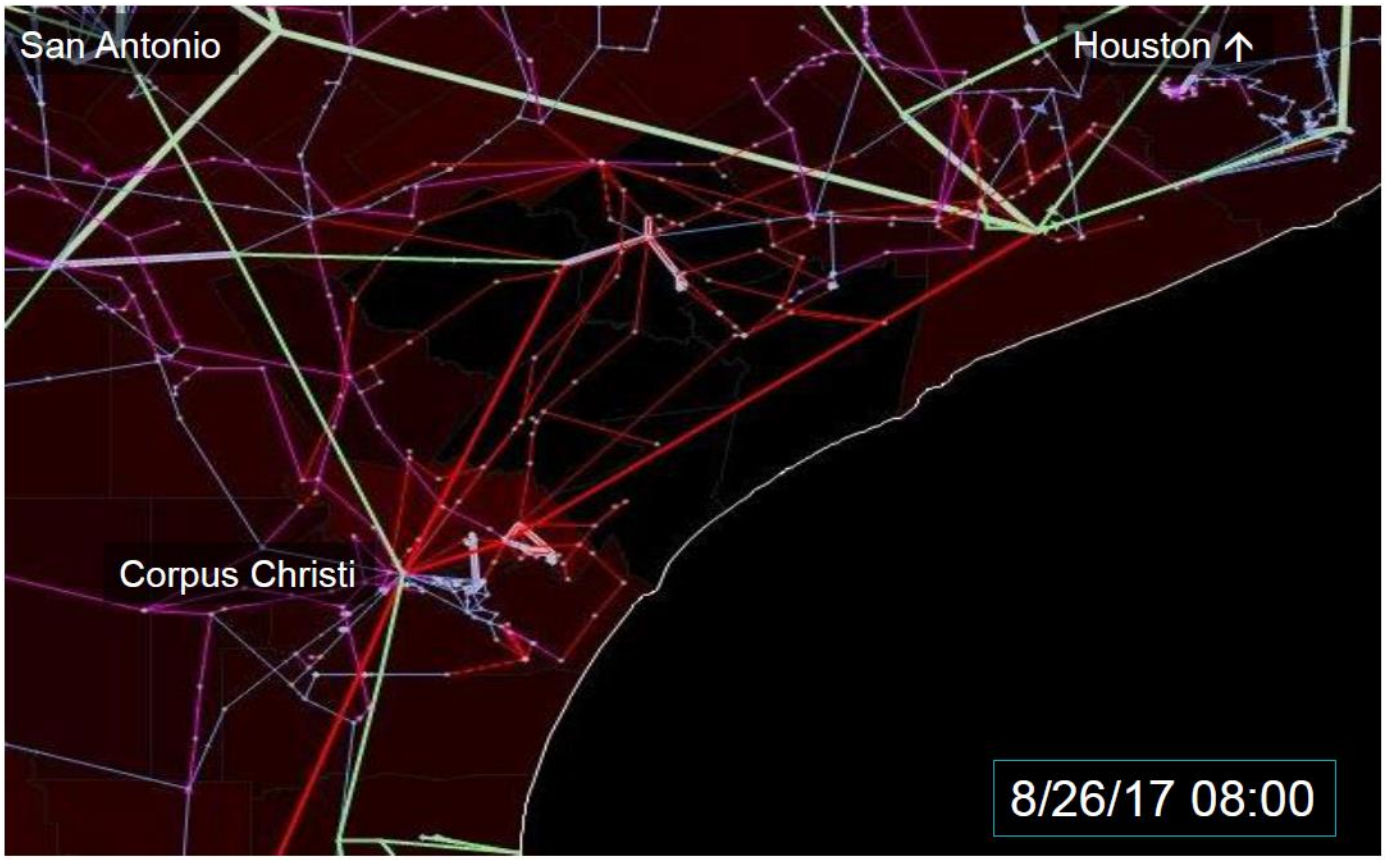

Figure 3.2: ERCOT Transmission Outages as of August 26 at 8:00 a.m.

Chapter 4: Preparation and Results Achieved

ERCOT contacted the TOs, TOPs, GOs, Generator Operators (GOPs), and other registered entities within the forecasted hurricane impact zone to discuss potential storm impacts and coordinate emergency plans. Entities worked to ensure that sufficient numbers of additional field operation crews were scheduled and available to respond to the expected storm disruptions.

Where possible, previously scheduled transmission and generation outages were restored or postponed to ensure that facilities would be available during the event. Transmission companies were advised of expectations during the storm, which included the testing of primary and backup communications, management of potential high voltage conditions, and communication of transmission outages to ERCOT. Generators were advised of expectations to be prepared to reduce output due to anticipated load loss and to respond to voltage support instructions. Gas pipeline companies were also contacted to review the potential for possible curtailments.

Concerns regarding potential impacts of the coming storm included the following:

- The unpredictable nature of the impending load loss
- The potential for high voltages due to the load loss
- The potential for substation flooding along the Texas coast
- The potential for gas curtailments to power plants
- The potential for reduction in generator output due to loss of load

Entities across the impacted area made the following special preparations:

- Existing storm preparation plans activated
- Loose equipment and materials in substations inspected, secured, or removed
- Retention ponds, basins, and sumps were pumped down to minimum levels
- Additional pumps and generators were secured
- Fuel storage tanks were topped off
- Labor, equipment, and materials staged to allow for a quicker start at restoration
- Critical mobile equipment moved to the mainland to protect against damage
- Service vendors and contractors contacted
- Additional transmission line and vegetation management resources scheduled
- All available transmission and generation outages returned to service
- Satellite and alternate communications paths were tested

While the above were for the most part effective, additional challenges were noted. For example, at several power plant facilities, employees were held in a “lockdown” status for extended periods. Food and medical supplies became an issue for sites held in “lockdown” for four to five days.

Communications

Entities convened or participated in numerous conference calls and broadcasts. They also communicated with the mutual assistance groups to which they belonged. These calls began August 23, 2017, and continued through the restoration effort.

Regional and Interregional Calls

On Wednesday, August 23, the first in a series of regional calls began. At 8:00 a.m., ERCOT contacted transmission entities in the hurricane impact zone to discuss potential storm impacts and requested that all outages that could be restored be put back into service prior to any impacts of the potential Hurricane. At 10:30 a.m., ERCOT issued an operating condition notice (OCN). GOPs were instructed to review fuel supplies and notify ERCOT of any known or anticipated fuel restrictions, review planned resource outages and consider delaying maintenance, and to review emergency operating procedures and notify ERCOT of any changes or conditions that could affect system reliability. TOPs were instructed to review planned and existing transmission outages to be canceled and/or restored and to review emergency operating procedures, evacuation plans, and the possible need to staff backup facilities.

On Thursday, August 24 at 7:50 a.m., ERCOT issued an Advisory for Tropical Storm Harvey. In addition to items listed under the OCN, GOPs were instructed to prepare for projected severe weather conditions and review procedures for operating in the lead due to possible high voltage concerns and to notify ERCOT if relocating personnel to backup control centers. TOPs were instructed to test communication with other TOPs and GOPs prior to the hurricane making landfall.

At 10:30 a.m., ERCOT contacted the MISO Reliability Coordinator (RC) to verified long distance numbers and discuss potential block load transfers if they were needed.

At 11:00 a.m., ERCOT issued a Watch due to Hurricane Harvey in Gulf of Mexico. In addition to the items listed under the OCN and Watch, GOPs were instructed to make any resources available that could be returned to service and to keep capacity telemetry and generation schedules updated. TOPs were instructed to be prepared to lose load and expect high voltage conditions and to keep ERCOT informed of transmission outages.

At 1:00 p.m., ERCOT System Operations, Operations Support, Outage Coordination, Operation Analysis, and Advanced Network Applications met to discuss Hurricane Harvey and the potential impacts on ERCOT systems.

At 4:00 p.m., ERCOT held an Electric/Gas coordination conference call with gas pipeline companies serving the coast and Lower Rio Grande Valley generation facilities to determine potential impacts on gas supply to those facilities. The gas companies indicated the potential for gas curtailments due to compressor stations and gas processing facility being shut down from the evacuations. One gas pipeline carrier reported it was blending raw gas to avoid curtailments and to allow continued gas delivery to generators in the Lower Rio Grande Valley.

On Friday, August 25 morning, SERC activated the SERC Incident Response Team (SIRT). The SIRT is designed to facilitate the gathering and sharing of data from and with SERC entities and to integrate with the NERC Crisis Action Plan. Texas RE and SERC worked closely with the affected entities, RCs, NERC, and several governmental agencies to gather and share information on the storm impact and restoration efforts. This information is vital to provide government stakeholders insight to the great work carried out across the BPS during major events and natural disasters.

On Friday, August 25 at 5:00 p.m., ERCOT issued an Emergency Notice for Hurricane Harvey.

Daily interregional government agency update calls were held between staff members from NERC Bulk Power Situational Awareness (BPSA), Texas RE, SERC, ERCOT, Federal Energy Regulatory Commission (FERC), Department of Energy (DOE), Department of Homeland Security (DHS), Nuclear Regulatory Commission (NRC), and Federal Energy Management Agency (FEMA).

Additional Staffing (RC, TOP, and TO Levels)

Entities resourced various staff to address additional requirements before, during, and after the storm. Some of these included the following:

- Assigning additional operators and supervisors to shifts
- Assigning director-level management to control locations
- Requesting and receiving assistance from mutual assistance crews
- Requesting and receiving substation support from various manufacturers and contractors

The majority of increased staffing was in the restoration area (i.e. vegetation management crews, substation crews, and line crews). Additional areas that received increased staffing were operations centers, primary control centers, backup control centers, and customer service centers.

ERCOT staffed both its primary and alternate control centers during the storm, including adding additional operators at the alternate control center and 24-hour on-site support to the control room over the weekend from Operations Support, EMMS Production Support, Facilities, and Advanced Network Applications. One TOP evacuated its backup control center since it was in the storm impact area. Another TOP moved its operations to its backup control center on August 27 due to flooding concerns at its primary location. All other TOPs operated out of their primary control centers and did not provide staffing at the alternate control center locations.

Manning Substations

Entities chose not to man substations during Hurricane Harvey due to safety concerns.

Sandbagging Facilities in Storm Surge Zone

Two substations were affected by storm surge, but it is unclear if sandbagging would have been effective.

Pre-positioning Storm Transmission System Equipment

In general, most utilities did not pre-positioned restoration equipment, other than to ensure it was located outside the anticipated storm impact area. Most entities also took stock of inventory, reviewed current materials designated to other projects, and determined which would be diverted for storm restoration. Substations were checked and secured before the storm. Material in the substations was secured, where possible, or removed from the station. The inventory of mobile substations and spare transformers was also verified.

Pre-positioning Storm Restoration Crews

Several entities pre-positioned transmission line crews in preparation for the storm. Substation crews in unaffected areas were also prepared to respond after the storm. Crews from mutual assistance companies were on alert and ready to respond. Mutual assistance was deployed after the storm passed to allow the impacted companies to complete their damage assessment

Chapter 5: Damage to Bulk Power System

Damage Due to Wind and Flooding

Several companies, including American Electric Power, CenterPoint Energy, Texas-New Mexico Power, and South Texas Electric Cooperative, reported significant damage to BPS facilities and subtransmission facilities. This damage also extended to the distribution level. Examples of the types of damage include the following:

- Conductor and static wire damage
- Broken poles and cross-arms
- Damage from trees being blown into the right-of-way
- Broken or damaged insulators
- Flooded substations
- Damaged/flooded substation control houses

Damage to BPS Reliability

ERCOT, as the RC, asserted that Harvey did not impact the overall reliability of the BPS at any time even though the damage caused by Harvey was significant.

Affected Transmission Facilities

Affected transmission facilities in ERCOT (by voltage class) are the following:

- 345 kV lines (7)
- 138 kV lines (99)
- 69 kV lines (119)
- 345/138 kV transformers (3)
- Substations reconfigured/bypassed due to flooding (6)
- Load-serving 138 kV and 69 kV substations (204)

One substation received substantial damage due to high winds. The utility contacted PUCT to receive permission to install temporary generators to restore service to the load in the area until the transmission line was restored and a temporary station installed.

Affected transmission facilities in Entergy's Texas area in the MISO footprint (**Figure 5.1**):

- Transmission lines segments impacted (111), including trip/reclose events
- Substations flooded (6)

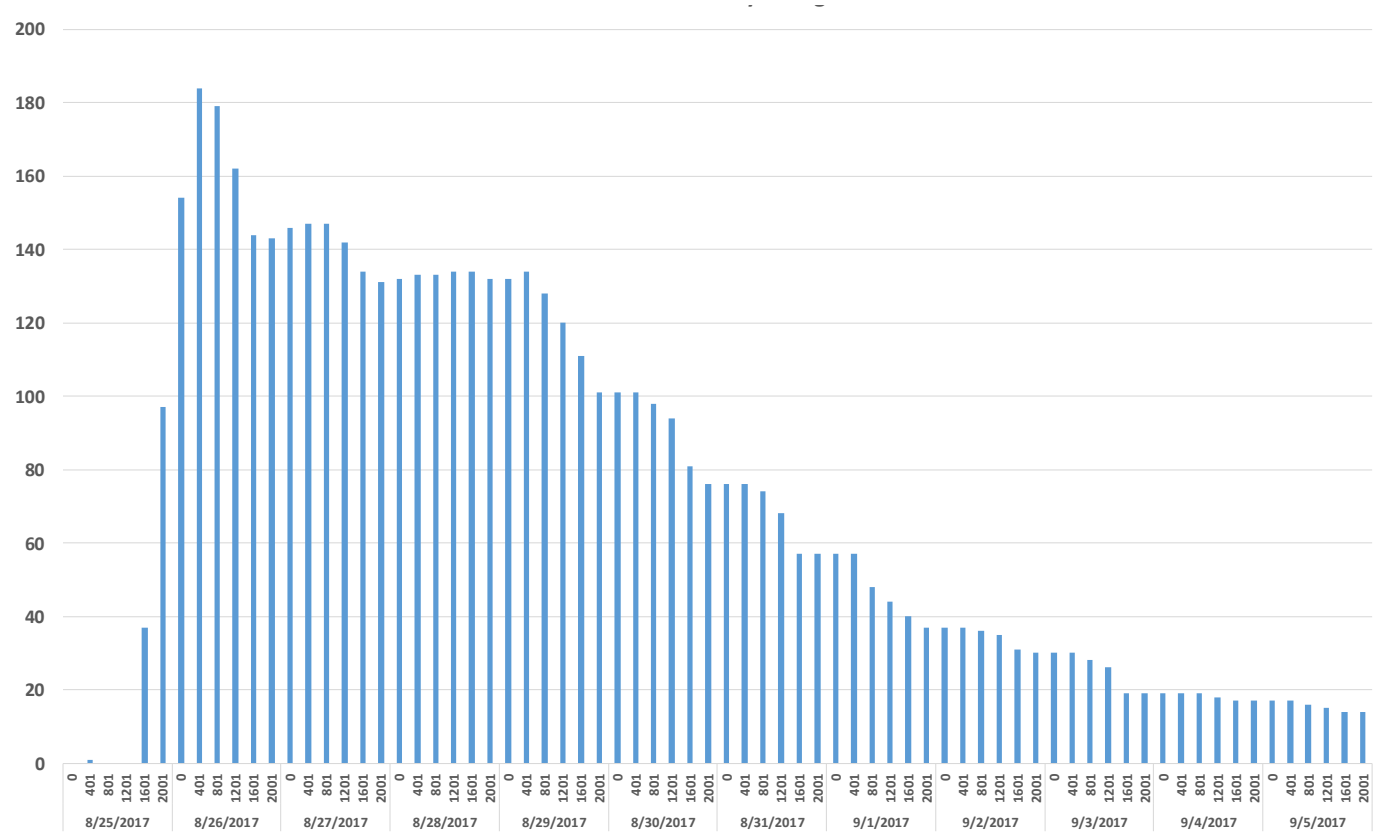

Figure 5.1: ERCOT Transmission Facility Outages

Affected Generation Facilities

The affected generation facilities in the storm are broken down by type here.

Nuclear Generation

The South Texas Project nuclear plant continued to operate at full power throughout the storm. The plant did experience the loss of one 345 kV transmission exit from the plant. The facility did not experience any storm damage from wind or rain with the highest sustained winds measuring 40 MPH. The plant sequestered a storm crew on site for emergency response if needed, including representatives from the NRC. Off-site power was maintained to the site.

Wind Generation

Only minimal damage was reported, but some wind units were taken off-line due to the high winds, resulting in 1,168 MW of unavailable wind capacity. One facility located near Corpus Christi, Texas was off-line for six days. Other wind facilities were returned between August 26 and August 27.

Wind turbines are commonly shut off at wind speeds of about 55 MPH and higher to protect them from damage, and several turbines in ERCOT's coastal area were shut off while high winds from the storm passed. ERCOT's southern region saw increased levels of wind generation during the four days after landfall when wind speeds were relatively high but below 55 MPH (**See Figure 5.2**).

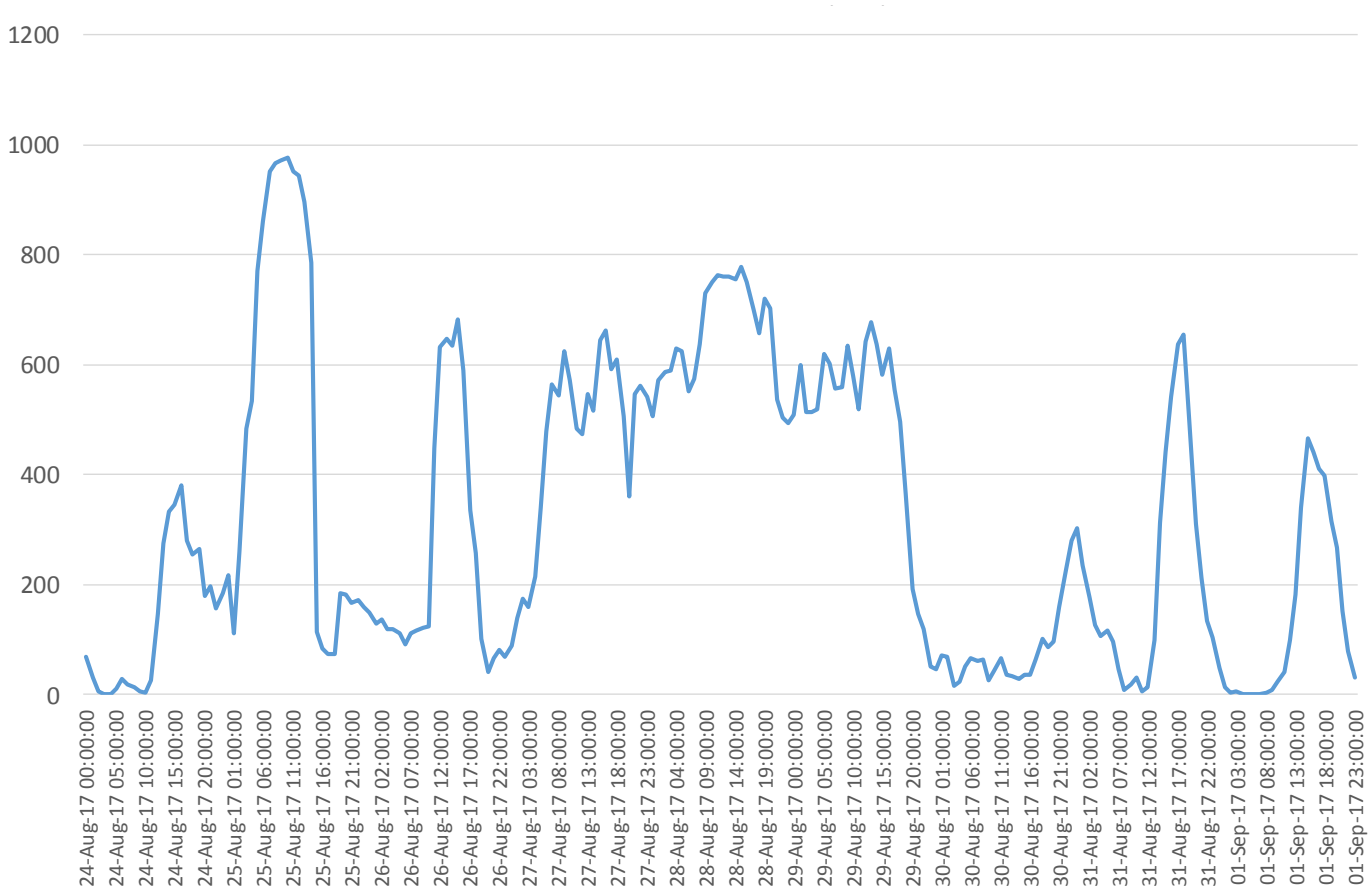

Figure 5.2: ERCOT Coastal Wind Generation, August 24 – September 1

Fossil Generation

Generation facilities in the hurricane impact area suffered the following damage:

- Flooding or water intrusion into administration buildings, storage facilities, and waste water treatment facilities
- Wind damage to building siding, windows, and roofs
- Wind damage to cooling tower housings and fans
- Flooding of substations
- Damage to substation equipment from wind-blown debris
- Water damage to protective relays, batteries, controls, motors and motor controls, and pumps
- Water intrusion into instrumentation enclosures

Generation Taken Off-line in Preparation of Storm

ERCOT did not instruct any generation to be taken off-line during the event; however, some entities chose to shut down and or evacuate in preparation of anticipated storm impact. A total of 3,043 MW of generation was shut down between August 24 and August 25 in anticipation of the storm.

Generation Capacity Unavailable during Storm

A peak of 10,992 MW of generation capacity in ERCOT became unavailable as a result of the storm (See **Figure 5.3**). In MISO, 2,285 MW of generation capacity was impacted. Total generation impact over the entire storm period

exceeded 21,435 MW. The lost generation, coupled with the reduced amount of load due to the continued rain and lower temperatures, allowed for load and reserves to be met with sufficient remaining capacity. Several blackstart units in ERCOT were impacted by the storm either due to flooding or forced outages on the transmission system (See **Table 5.1**).

Table 5.1: Blackstart Units Impacted

Outage Cause	Number of Units Impacted	Total MW Impact
Wind, Flooding	46	11,879
Evacuated, Site Shutdown prior to storm	21	3,043
Fuel	27	6,514

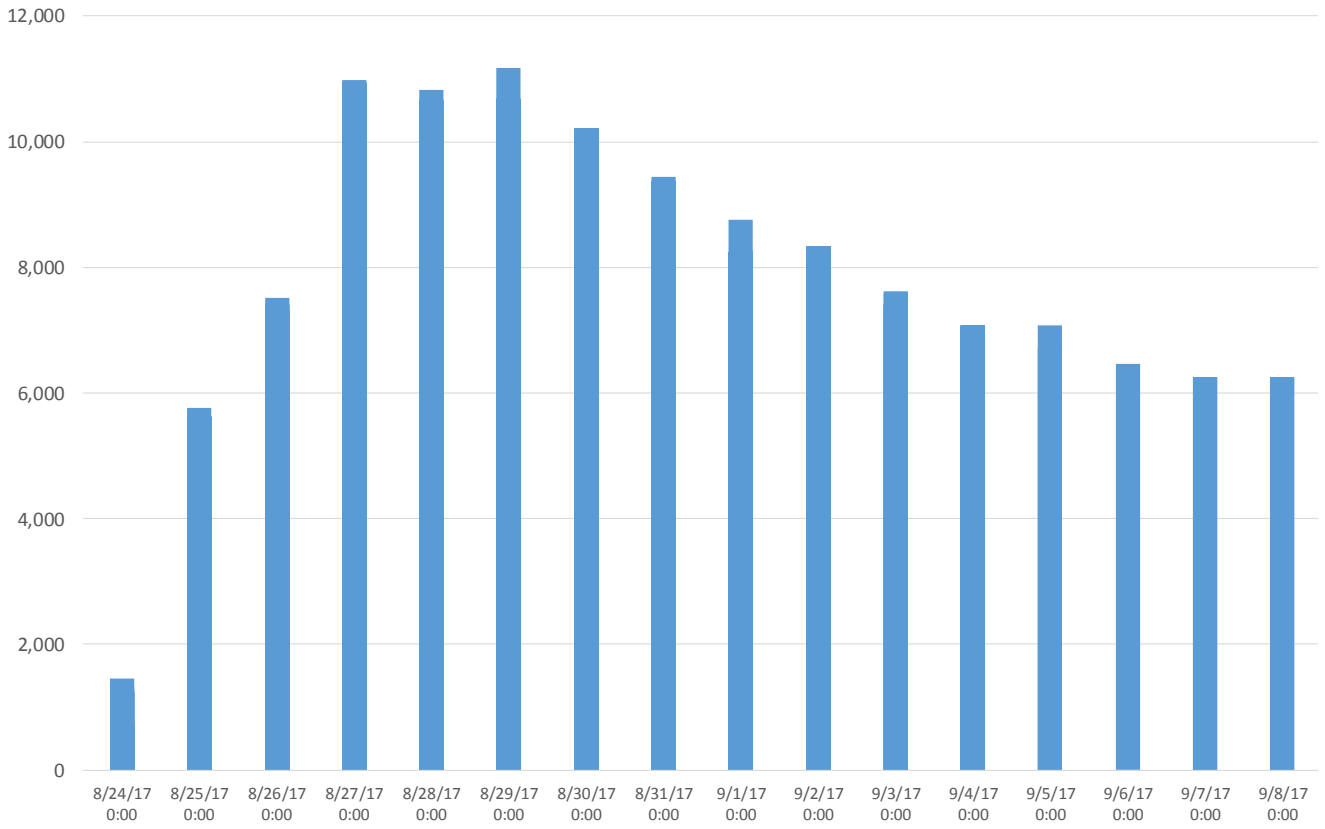

Figure 5.3 ERCOT Generation MW Unavailable, August 24 – September 8

Generation Fuel Issues

5,679 MW of generation capacity in ERCOT was derated between August 25 and August 29 due to fuel issues, such as wet coal, low gas pressure, and high wind. A generation entity reported that one of their natural gas suppliers shut down during storm, but the entity was able to receive gas from an alternate supplier. Pressure drops in natural gas supply lines resulted in temporary derates of units at three other sites. Wet coal issues resulted in derates at four sites.

Hydro Generation

There were no hydro generation issues related to the storm.

DCS Events Related to the Storm

There were no disturbance control standard criteria events related to the storm.

Generator Returns (Inhibition by Reduced Load, Transmission Damage)

On August 8, the loss of a 138 kV line created a 30 MW island for an industrial facility private use network (PUN). This island also carried 2 MW of ERCOT load in addition to the PUN load.

Generation was limited at a second facility due to damage to four transmission circuit breakers at the power plant switchyard.

Generation Operation Risks during the Storm

Several generation operation risks were identified during the storm. These include the following:

- Unavailability of three blackstart units as a result of the transmission system outages
- Increased potential for loss of off-site power to nuclear facilities
- Loss of generation due to switchyard damage
- Loss of generation due to damage to cooling towers
- Precipitator fly ash buildup and higher gas flow pressure due to operating without auxiliary feeds
- Curtailments due to wet coal
- Danger from the loss of building siding
- Potential lack of fuel due to damage to the fuel provider's facilities or loss or reduction of pressure in gas supply lines
- Impact to chemical deliveries due to flooded or impassable roadways

Chapter 6: Conservative Operations and Operational Challenges

Conservative Operations Mode or Emergency Procedures Implemented during Storm

Many of the entities affected by the storm implemented emergency procedures or entered a conservative operations mode sometime during the event. Entities implemented severe weather plans and incident command structures and continually reviewed conditions to determine if additional actions were necessary. Generation was committed in local areas to support load restoration or post-contingency voltage support issues.

Challenges Associated with High-Voltage Issues

High voltage challenges were the result of the following:

- Open-ended high-voltage transmission facilities
- Significant loss of distribution load
- Lightly loaded extremely 345 kV facilities

ERCOT did not experience challenges associated with high or low system voltage issues outside of typical real-time and post-contingency issues. TOPs developed temporary outage switching plans and took actions to mitigate voltage issues that manifested from multiple outages. Two voltage contingency issues of note were the following:

- **August 26:** Base case high voltage violations were noted on the 138 kV lines near a 345 kV substation on the coast due to the loss of the 345 kV circuit into the substation. Opening the radial 138 kV lines out of the substation resolved the issue.
- **August 29:** Multiple 345 kV contingencies showed overloads and possible localized voltage collapse on a portion of the 69 kV system south of San Antonio. Operating instructions were issued to perform transmission switching, which alleviated all post-contingency overloads greater than 120 percent. A temporary outage switching plan was developed to mitigate the remaining 69 kV overloads.

Challenges in Maintaining Load/Generation Balance during Storm

The largest challenge for ERCOT was coordinating load lost on the distribution systems with lost generation, the loss of entire generating stations or the loss of multiple units within close temporal proximity in particular. It was also challenging to maintain load/generation balance during restoration as generation and/or load was added back into the system.

ERCOT also experienced challenges with its short-term load forecasting due to load loss during the hurricane. ERCOT used manual intervention on the mid-term load forecast in order to have the forecast be more in-line with actual loads during the hurricane. This was necessary as the existing models were forecasting based on historical load levels that did not reflect the amount of outages that were present during the storm. For the short-term load forecast (STLF), ERCOT enabled purely autoregressive models, meaning that the forecasts are based on lagged actual load values. This allowed ERCOT to adjust the STLF rapidly to the actual five-minute loads during the storm.

ERCOT instructed one generator in the Rio Grande Valley to come on-line due to the loss of a 345 kV line between the valley and the Corpus Christi area and the likelihood of additional transmission outages in the area. An additional generator was made to stay on-line to provide generation to the local area in support of load restoration efforts in the Victoria area.

Frequency was maintained within the normal frequency bounds for the interconnection (See **Figure 6.1**).

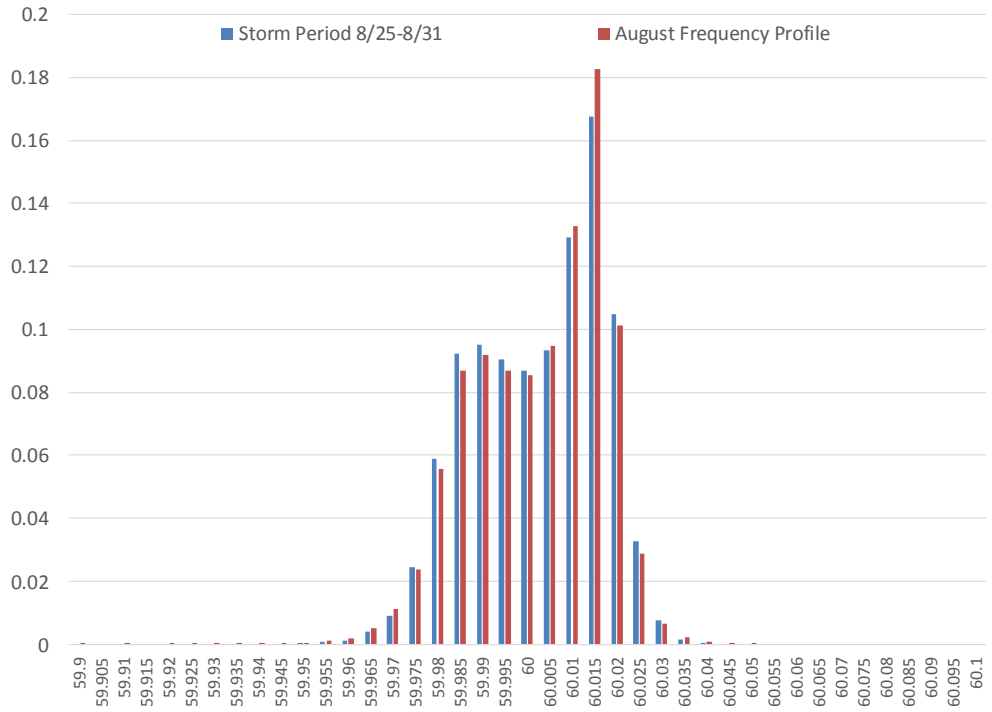

Figure 6.1: ERCOT Frequency Profile

Challenges Associated with Operational Assessment Tools

In general, the ERCOT operational assessment tools had minimal issues during the event. All of the energy management system (EMS) real-time assessment tools remained fully functional during Hurricane Harvey. The state estimator (SE) was able to continue solving during the loss of telemetry from multiple entities. On-site engineering support monitored the areas affected and watched for issues based on surrounding telemetry that remained available. SE solved with 100 percent convergence from 4:00 p.m. to midnight on August 25. The only time frames of note were on August 26 at 1:00 a.m. and 4:00 a.m. where SE solved with excessive mismatch around 1:00 a.m., which contributed to a 92.3 percent SE convergence for that hour due to growing telemetry failures.

For hour ending 04:00, the convergence performance reduced to approximately 85 percent. At this time, the Inter Control Center Communications Protocol (ICCP) link for one TOP went down. Discrepancies between out of service elements, telemetered MW generation, transmission flows and switching device status caused the SE to yield a "solved with Excessive Mismatch Solution" status. ERCOT Engineering Support personnel were able to utilize the State Estimator Statistical Application to quickly identify MW/Mvar mismatches and topology coherency issues in order to validate the system status. Staff could then manually replace the SCADA value or status in the ERCOT EMS with correct values as needed. This allowed for maximum continuity for SE convergence (See **Figure 6.2**).

Another TOP had intermittent ICCP issues on August 26 and 27 that did not cause any issues due to smaller footprint and actions taken to quickly identify and manage MW/Mvar mismatches and topology coherency issues.

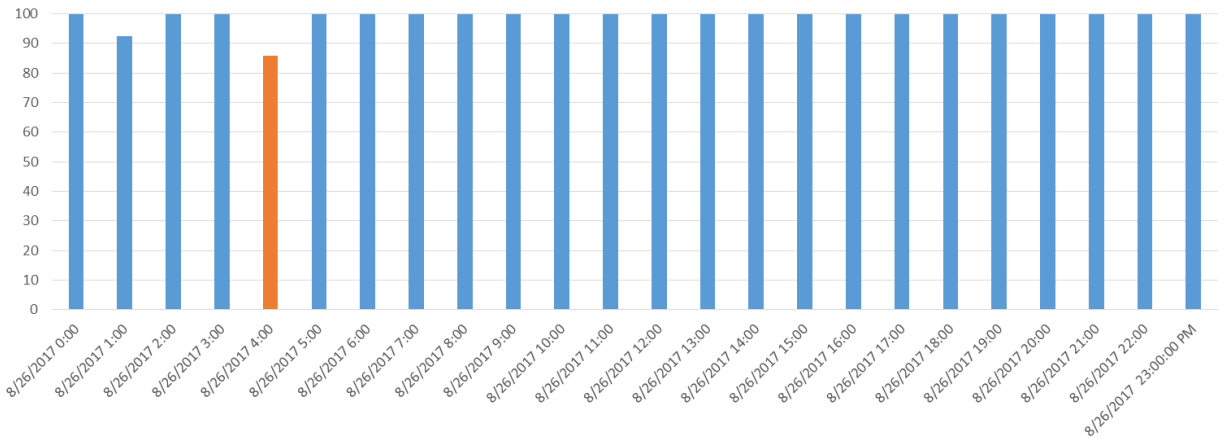

Figure 6.2: ERCOT SE Hourly Convergence Percentage, August 26

Challenges Associated with Loss of Telemetry and ICCP Data

Multiple entities experienced issues with loss of telemetry and ICCP data during the hurricane. These issues were caused by the following:

- Extended remote terminal unit outages at substations due to loss of battery backup power that was caused by extended station service outages
- Remote terminal unit outages due to lightning-induced surges causing circuit board failure
- Loss of ICCP links by external carriers that did not have sufficient backup power sources

To overcome these issues, utilities used multiple solutions, such as the following:

- Temporary cellular communications
- Portable generators for temporary station service for recharging substation batteries
- Monitoring substations from the remote ends of transmission circuits terminating at the substation
- Manually entering or replacing telemetry values

Challenges Associated with Loss of Voice Communications

There were no abnormal challenges associated with loss of voice communications. ERCOT utilized alternate communications (cell phones, satellite phones, UHF radios, etc.) when the primary communication channels were impacted between ERCOT and registered entities. Radio tower and cell coverage was affected in the Aransas Pass, Rockport, and Fulton areas. This was managed by installing a portable radio system and a satellite VPN router to allow communications with field personnel.

Long-Term Effects that Could Impact Serving Firm Load in 2017–2018 Winter

Several transmission and generation facilities suffered extensive damage due to the storm and remain out of service. None of these outages are expected to cause reliability issues with the operations of the system over Winter 2017–2018. Those damages are listed here:

- One generation facility suffered extensive damage to its cooling tower fan deck from high winds. All the fan cylinders, most of the fan blades and much of the decking and support for decking were damaged or destroyed. Units were returned to service on November 15.
- One generation facility suffered site-wide flooding damage to waste water treatment facilities, gas turbine controls, batteries, relays and administration building. Its expected return to service is the end of May 2018.

- One generation facility suffered extensive flooding of its control room, which damaged pumps, motors, protective relays, plant DCS, control valves, batteries, and other auxiliary equipment. Its expected return to service is the end of January 2018.
- One 345/138 kV autotransformer failed. Its expected return to service is the end of March 2018.
- One 345 kV line suffered heavy damage with approximately 25 miles of structures and conductor knocked down. Its expected return to service is the end of May 2018.
- One 138 kV line suffered heavy damage with over 90 structures knocked down. It was returned to service at the end of December 2017.
- In MISO, approximately 1,200 MW of generation remained out of service until mid-November 2017.

Chapter 7: Restoration

Amount of Load Lost (MW)

A peak of approximately 338,000 electric customer outages were reported across the impacted area of ERCOT, and the total number of reported customer outages exceeded 2.02 million in Texas, Louisiana, Mississippi, and Arkansas. All customer outages were restored by September 8.

Note: The gap in the customer outage data in **Figure 7.1** on August 30 between 2:00 p.m. and 11:00 p.m. was due to the loss of an entity website.

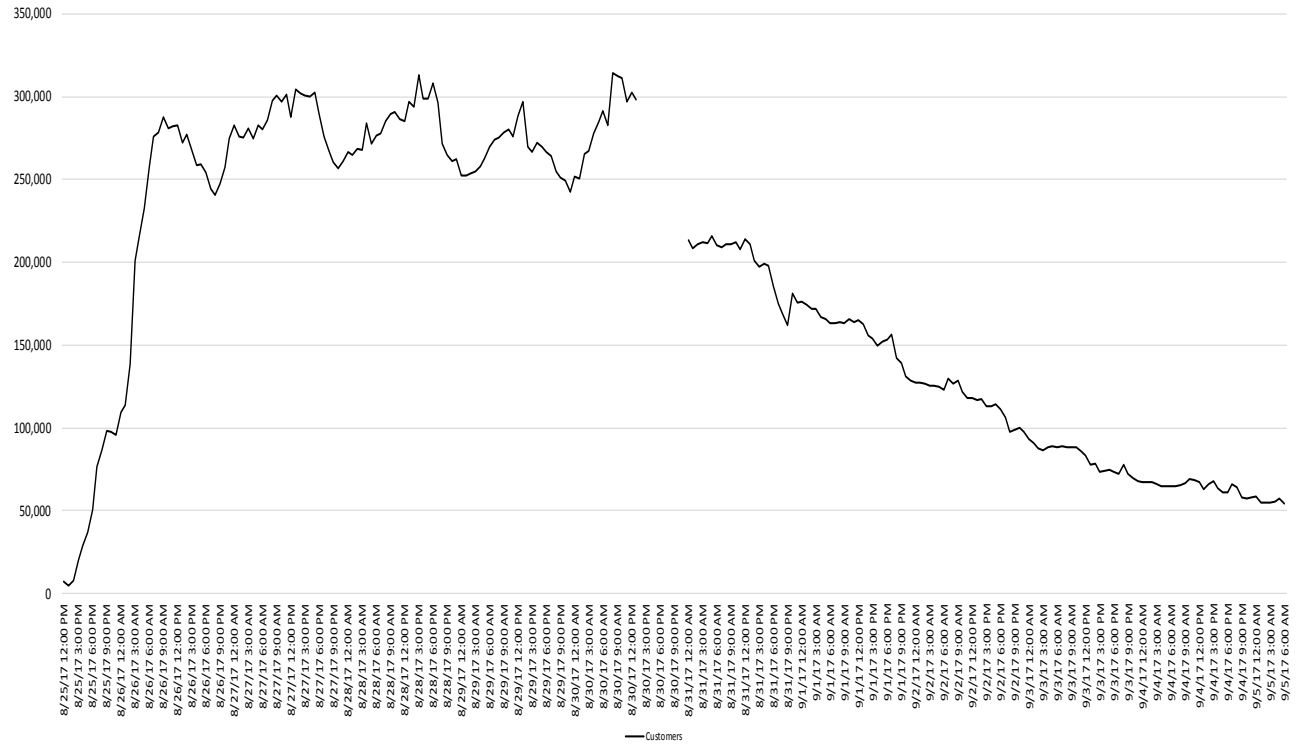

Figure 7.1: Hurricane Harvey Customers Out of Service

ERCOT demand during the storm period was approximately 15,000–20,000 MW lower than was typically observed during August due to the cloudy and cooler temperatures as well as the number of customer outages experienced in the storm impact areas (See **Figure 7.2**).

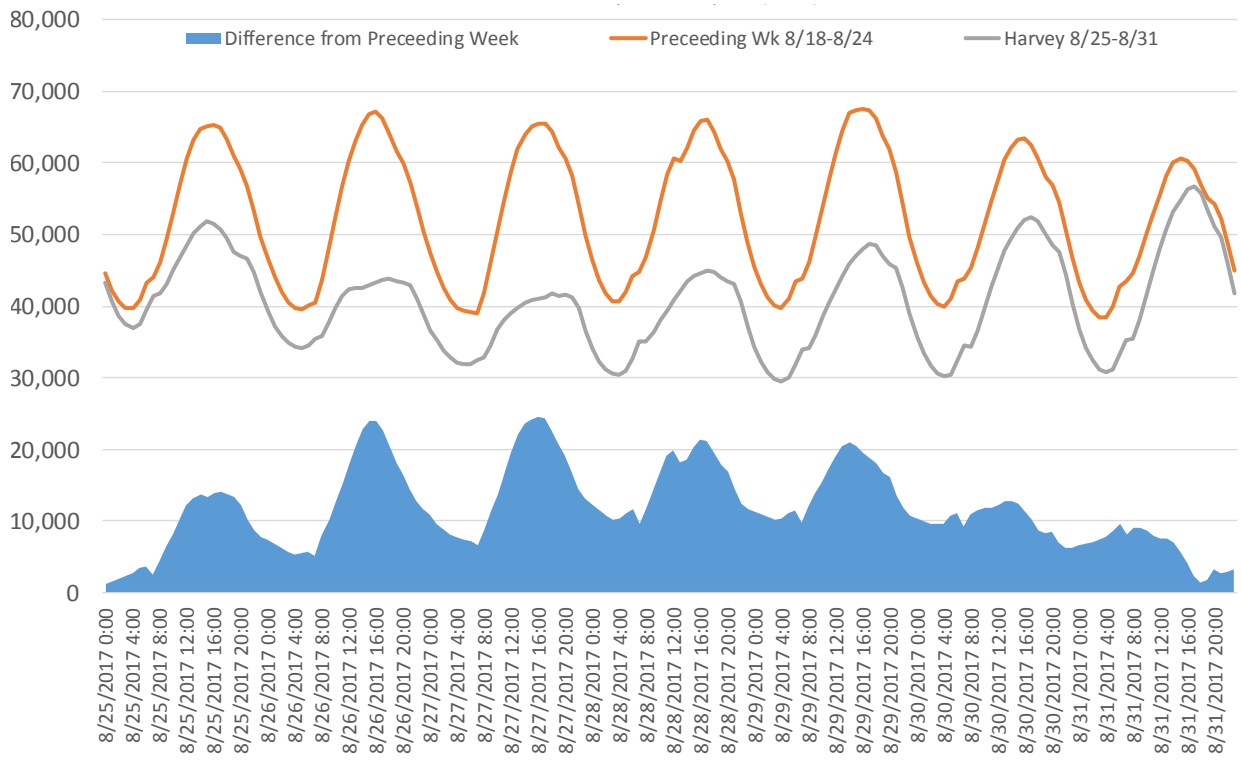

Figure 7.2: ERCOT System Load, August 25-31

Demand in the Houston area was 3,000–5,000 MW lower than normal (See **Figure 7.3**).

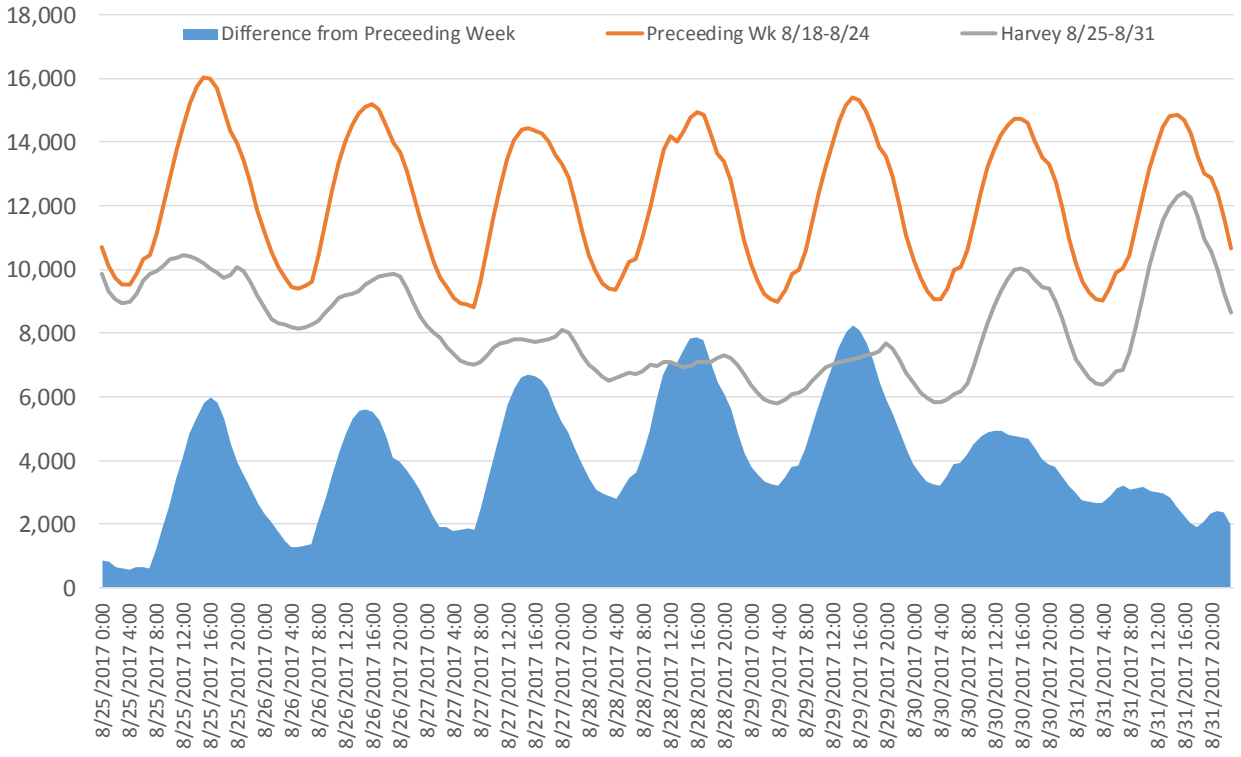

Figure 7.3: Houston Area Load, August 25-31

Duration Load Lost

Most entities returned 95 percent of their customers to service between August 27, and September 2. Several locations in the Houston area that were inaccessible due to severe flooding were not restored until September 8.

Challenges

Damage assessments were hampered due to flooding or by heavy debris on the roads in some areas. The slow forward speed of the storm also affected the ability to perform aerial patrols of transmission lines. Damage assessments were started in the areas that were accessible while other areas were delayed one to two days while hazards were cleared, weather abated, and the flooding subsided.

The challenges included the following:

- Road hazards
- Loss of station service ac power to the dc supply systems at the stations
- Wind damage to substation control buildings roofs and window and the failure of a substation control house
- Water damage to relay systems due to flooding or damaged control buildings
- Transmission line tower foundations washed out due to flooding
- Restoration personnel unable to use bucket trucks until wind speed reduced to safe levels

At several substations, the extended loss of station service power resulted in the loss of the backup dc battery power supply, which impacted the protective relaying and SCADA systems at those locations. Utilities used portable generators to power the charging of dc supply systems until station service could be re-established.

Additional challenges included the need to secure food, lodging, and fuel for the work crews. As is the case for many large events, management faced challenges in effectively utilizing resources needed to safely restore or maintain power.

Gasoline and diesel fuel availability was a significant challenge for utilities after Harvey made landfall. Harvey impacted several refineries in the Houston, Corpus Christi, and Victoria areas. Deliveries to gas stations were hindered by debris and flooded roadways. Local gas stations were without power.

Utilities overcame these issues by using approaches that have not been used in previous weather-related events, such as the following:

- Unmanned aerial drones were used to perform damage assessments on inaccessible transmission and distribution lines
- Amphibious vehicles and airboats were used to access flooded areas

ERCOT system operations and representatives of TOs and state government also held conference calls on priority loads, such as hydrogen gas facilities near the Gregory/Portland and Victoria areas and refineries in the Corpus Christi area.

Chapter 8: Considerations and Lessons Learned

Lessons Learned

The following good industry practices were identified by entities in the affected areas:

- Pre-staging of equipment outside of flood-prone areas made the restoration process more effective.
- Collaborative efforts with other Texas utilities, ERCOT, and regional mutual assistance groups worked well during this event. It is important to touch base with contract resources and adjacent utilities prior to the storm event to establish communication chains.
- Establishment of contacts with state and local emergency management coordinators and key stakeholders was key in maintaining continuity and prioritization of the recovery effort.
- The use of advanced meters and intelligent grid devices was effective to pinpoint outages, operate equipment remotely, and increase efficiency.
- The use of Facebook, Twitter, Power Alert Service, and text messages was effective in keeping customers informed.
- The use of aerial drones was effective to assess damage, evaluate work conditions, and enable real-time situational awareness. Infrared capabilities helped identify equipment that needed further inspection.
- Pausing wind turbines prior to experiencing high wind cut-out speeds helped avoid individual turbine faults, stop yawing, and allow the turbines to continuously pitch into the wind as long as possible.
- The use of detailed pictures of transmission structures facilitated a rapid design response, allowing materials to be marshalled and a high-level scope developed to mobilize construction resources.
- ERCOT's Forced Outage Detector application was instrumental in helping operators and support engineers identify undocumented outages.
- ERCOT's Grid Applications Support Operations engineers were able to utilize the State Estimator Statistical Application to quickly identify MW/Mvar mismatches and topology issues.
- Having on-site engineering support from the Advanced Network Analysis and Operations Support departments ensured quick evaluations of issues with ERCOT applications.

The following lessons learned were identified by entities in the affected areas:

- The following are steps entities could have followed to help mitigate fuel availability challenges after Harvey made landfall:
  - Evaluate back-up fuel supplies for primary and back-up control centers.
  - Evaluate coal yard fuel reserve supplies (diesel fuel for machinery to move coal to resources).
  - Implement diesel fuel conservation measures by limiting the number of start and stops of mills.
  - Consider developing power plant priority process for fuel availability/deliverability.
  - Raise re-order points for fuel at the beginning of hurricane season.
- Business continuity plans should be implemented seven days before the storm to allow employees ample time to take care of family matters before any travel that may be necessary.
- Ensure that plentiful wide-tracked equipment is engaged and available for the first day of restoration. Tracked diggers and buckets will speed the restoration process considerably over conventional transmission line equipment. Normal terrain equipment can be used, but each crew requires D6 or larger wide-tracked dozers to clear paths and pull the equipment in through the thoroughly soaked farm and pastureland.

- Entities should add tie down points for the fan blades of generation plant cooling towers.
- Transportation issues due to road closures posed a significant challenge to not only utility crews during the restoration process but also to suppliers and external restoration resources. Significant flooding, including road closures, should be included into future training exercises and mitigation during future events.

System Resiliency

BPS resiliency during major storm events can be evaluated in two ways: the ability of the BPS to withstand damage during the storm event and the ability of the BPS to quickly recover from the event.

Harvey's impact on the BPS can be separated into two distinct areas: flooding and major physical damage. Major damage to the transmission system was caused primarily by hurricane-force winds and tornados in the areas from Victoria, Port Aransas, to Corpus Christi and areas south. Flooding was the major impact in the Houston, Galveston, Beaumont, and Port Arthur areas.

In the Corpus Christi, Port Aransas, and Victoria areas, hurricane force winds and tornados damaged over 800 transmission line structures. The vast majority of these were wood poles. High winds also damaged cooling towers at several power plants. Utilities worked with federal and state agencies to prioritize the restoration of critical transmission facilities and feeds to refineries and petro-chemical plants in particular. Over 95 percent of the transmission lines and substations were returned to service by September 8.

In Houston and Southeast Texas areas, the unprecedented flooding created severe challenges. Substations and power plants experienced damaged equipment due to high flood waters. Several transmission line structure foundations were washed out. Substations had to be de-energized, reconfigured, or bypassed due to flooding. A mobile substation was used in one location when the existing substation was flooded. Areas were inaccessible for extended periods, delaying restoration activities. High water vehicles and boats were used to access some areas. All transmission lines and substations were returned to service by September 13.

Chapter 9: Summary of Findings and Conclusions

The coordination of preparations for the storm between ERCOT and the Region's TOs, GOs, TOPs, and GOPs all contributed to the BPS preparedness for this exceptional storm. Procedures and tools allowed the BPS to be operated in a secure state for all operating limits through the event and recovery.

From the day after Hurricane Harvey's landfall through Hurricane Irma's impacts, the Electricity Subsector Coordinating Council (ESCC) leadership held daily calls with senior leaders from the Department of Energy, Department of Homeland Security, Edison Electric Institute (EEI), American Public Power Association (APPA), National Rural Electric Cooperative Association (NRECA) and the CEOs of the impacted utilities to exchange information, synchronize government support to industry efforts, and harmonize messaging between industry and government. The focus of these calls was to support the ESCC's "unity of effort" and "unity of message" strategy. In parallel with these senior level engagements, NERC's Bulk Power System Awareness Group hosted daily updates for government partners including FERC, DOE, DHS, and FEMA, where staff from BPSA, ERCOT, and Texas RE provided more detailed updates and assessments on the storm's impacts and restoration efforts.

Chapter 10: Storm and Restoration Photos

Hurricane Harvey Path

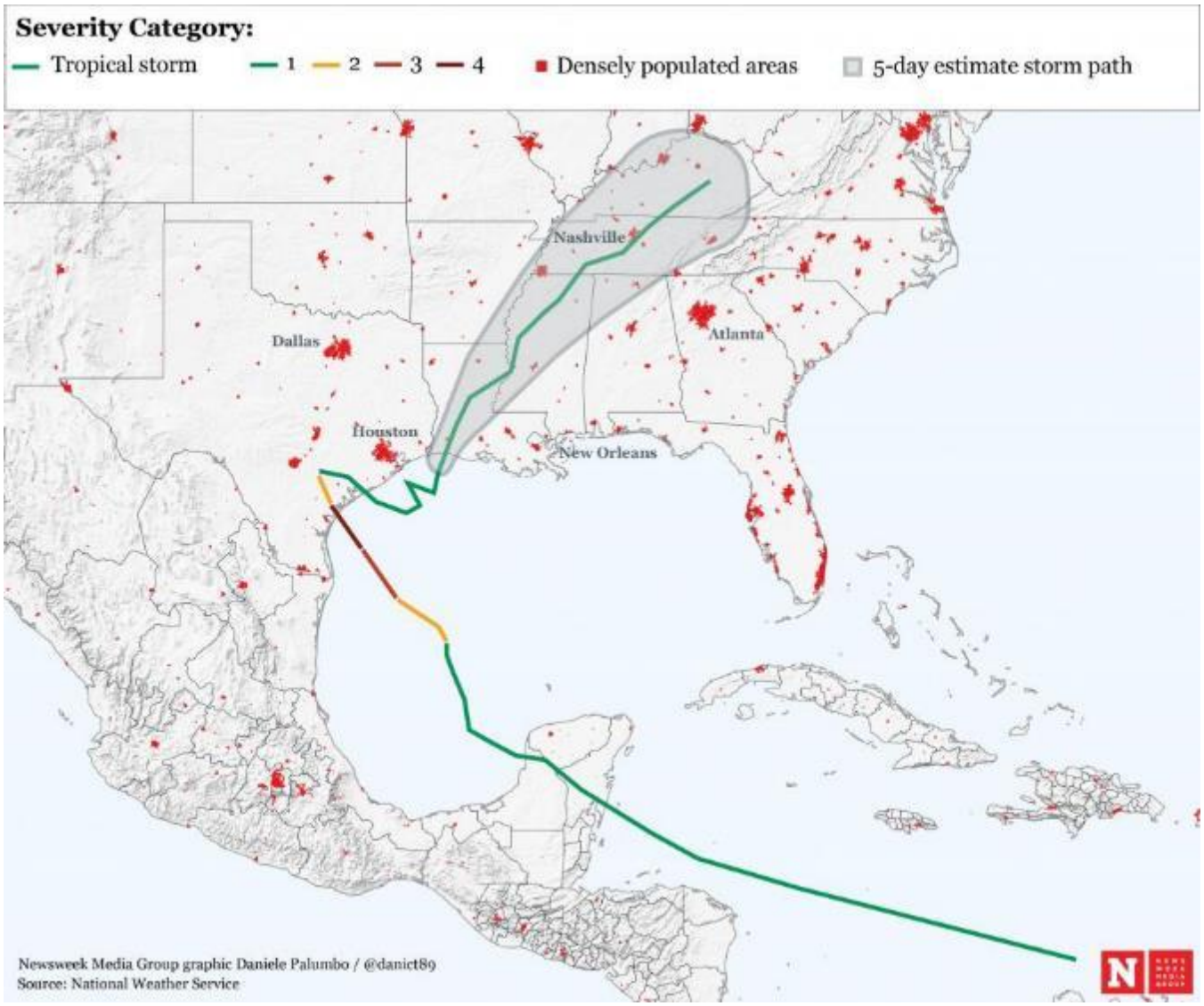

Figure 10.1: Path of Hurricane Harvey (Source: Newsweek)

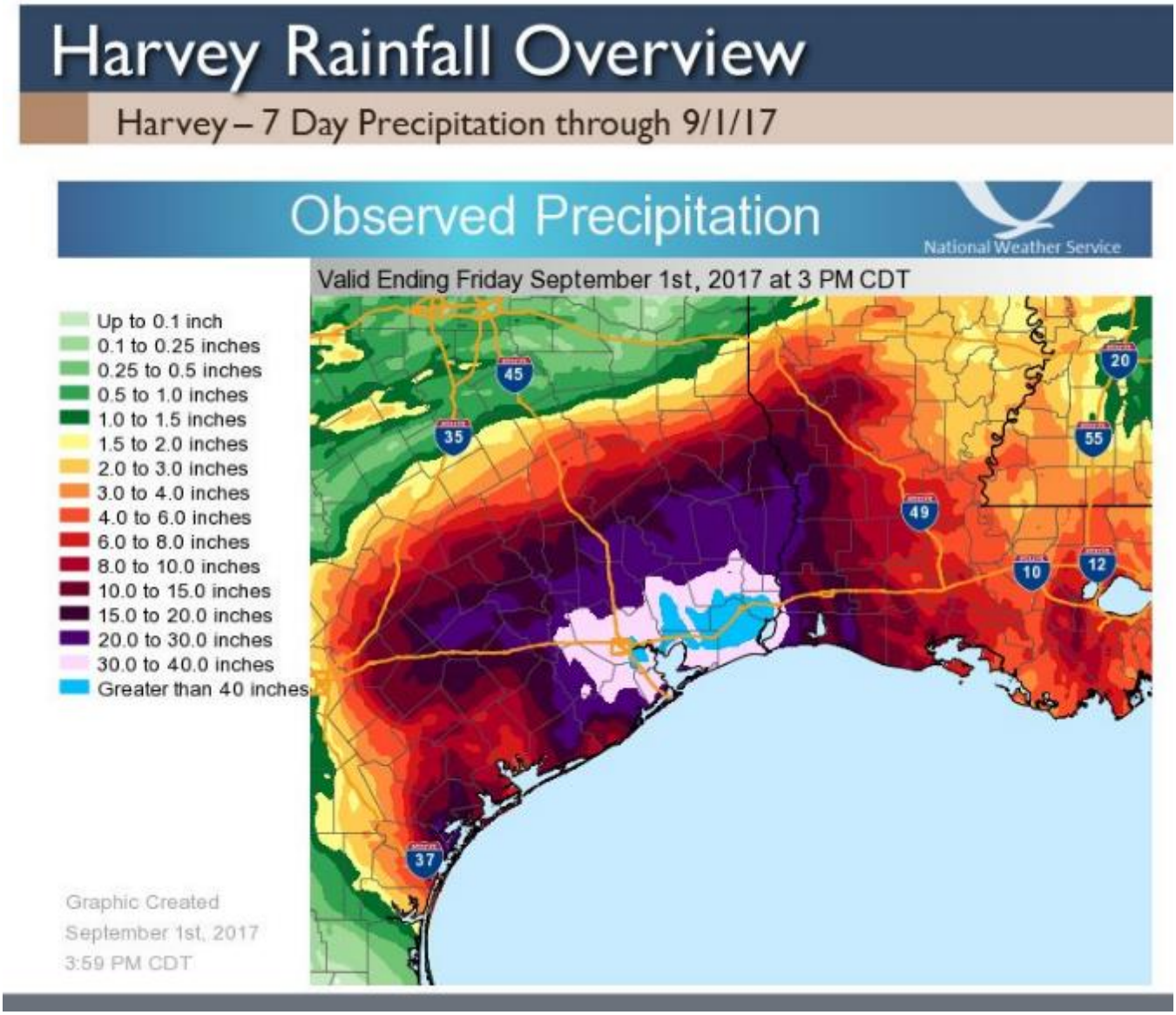

Figure 10.2: Hurricane Harvey rainfall (Source: National Weather Service)

Damage and Restoration Photos

Figure 10.3: 345 kV line structures down

Figure 10.4: 69 kV substation structure damage

Figure 10.5: Damaged power plant cooling tower fan deck

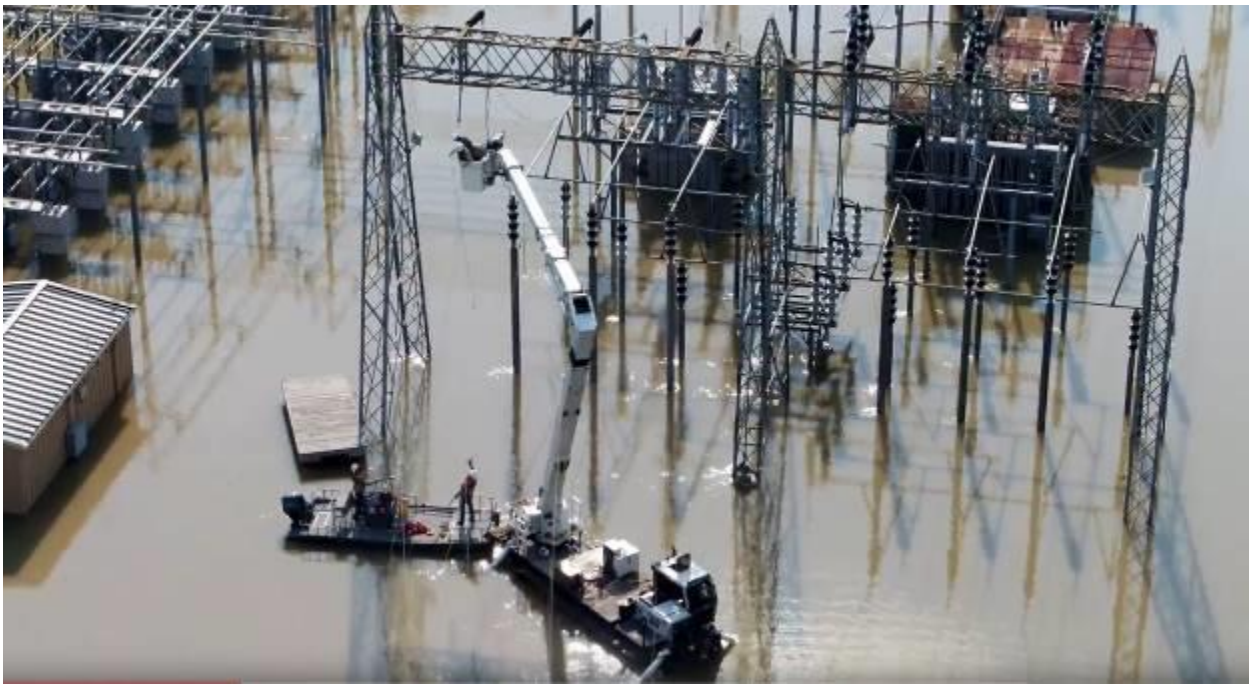

Figure 10.6: Flooded substation

Figure 10.7: Flooded power plant

Figure 10.8: Flooding, mosquitos, as well as windy and muddy conditions created special challenges for work crews.

Figure 10.9: Crew staging site

Figure 10.10: Use of drones to perform inspections.

Figure 10.11: Examples of the damage sustained by the distribution system

Figure 10.12: Examples of the damage sustained by the distribution system

Figure 10.13: Examples of the damage sustained by the distribution system

Figure 10.14: Examples of the damage sustained by the distribution system

Figure 10.15: Examples of the damage sustained by the distribution system

Figure 10.16: Examples of the damage sustained by the distribution system

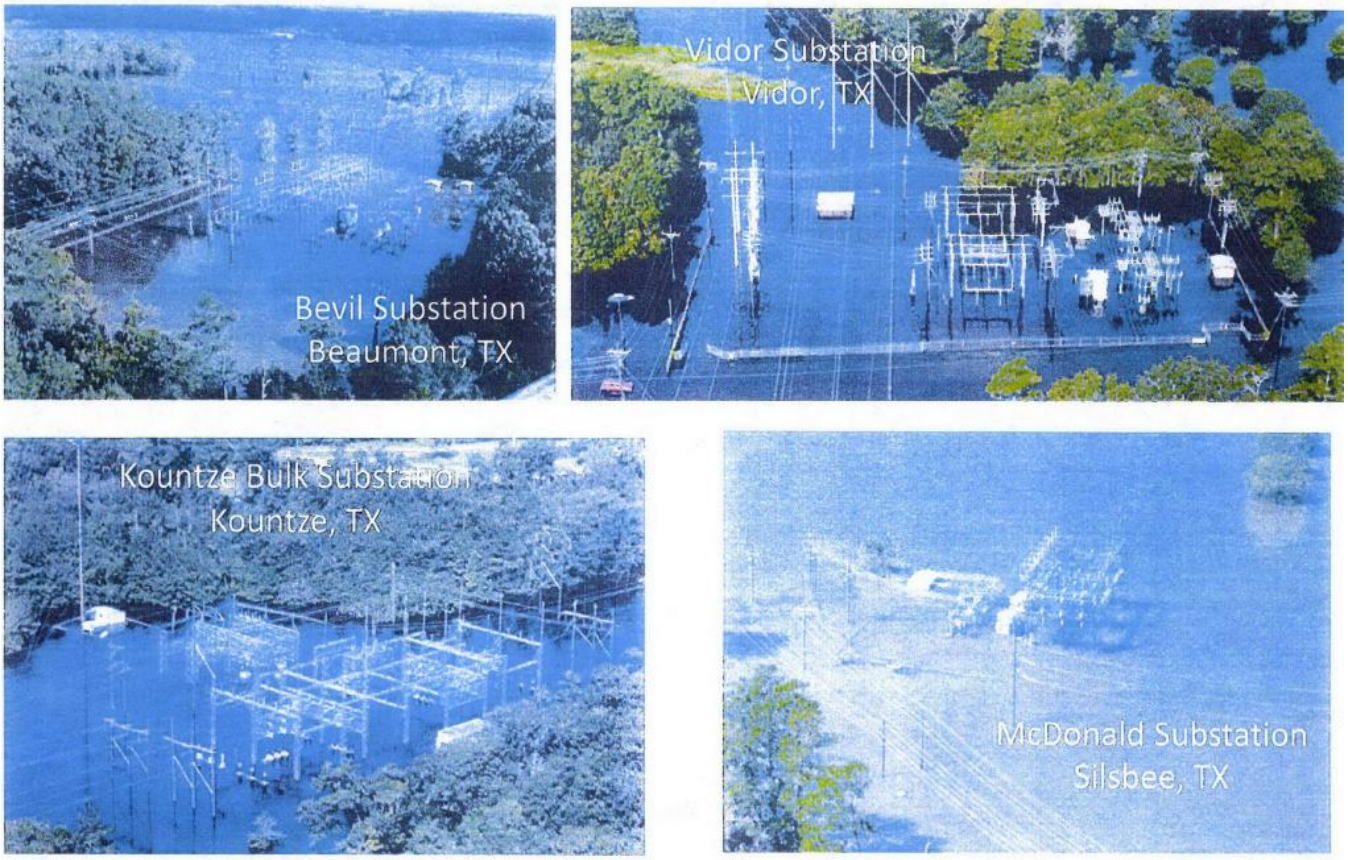

Figure 10.17: Examples of the damage sustained by the distribution system

Chapter 11: Follow-up Actions

The follow-up actions below are recommendations to improve reliability following the analysis of issues and challenges identified in this event:

- **System resiliency:** The vast majority of damaged transmission line structures were wood poles. Utilities should review design criteria and construction methods and consider "hardening" transmission lines in hurricane zones in order to reduce or limit the damage caused by hurricane-force winds.
- **Substation dc supply systems:** Monitoring and recovery was impacted by the loss of backup dc power supplies at multiple substations due to the loss of station service ac power sources. The loss of the dc supplies affected protection system equipment and remote terminal units providing telemetry. Utilities used portable generators to power the charging of dc supply systems until station service could be re-established. Consideration should be given to installing multiple station service sources or providing backup generators for station service to critical substation in hurricane zones.
- **Fuel shortages:** Gasoline and diesel fuel availability was a significant challenge for utilities after Harvey made landfall. Utilities should give consideration to back-up fuel supplies for primary and back-up control centers, fuel reserve supplies at power plants (e.g., diesel fuel for machinery to move coal to resources), etc.
- **Training:** Consideration should be given to providing enhanced training for system operators based on lessons learned from Harvey. This should include, but is not limited to, training for loss of telemetry and ICCP during hurricane drills and blackstart drills and training for response to loss of station dc supplies.

Chapter 12: Contributions

Acknowledgements
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