SECURITY AND SUSTAINABILITY FOR THE U.S. INFRASTRUCTURE BY PROVIDING INCREMENTAL ELECTRICAL RESTORATION AFTER BLACKOUT

by

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Dedication

To my wife, Christine - for her unwavering love, support
and strength to support my academic efforts.

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To my wife and best friend, Christine. I have become a better person because of your love and support. I look forward to spending the next chapter in life together.

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GLOSSARY

Control – Boundaries or requirements a system uses to define interactions of a systems interface (SEBok website, n.d.).

Design – Preliminary activity that has the purpose of satisfying the needs of stakeholders that must be transformed into models employing visual formats (Buede, 2009, p.477).

Function – Transformation process that changes inputs into outputs (Buede, 2009, p. 478).

Inputs – A command, element, item, method or process enters a method to be transformed by a function (SEBok website, n.d.).

Integration – Process of testing (or qualification) to achieve a valid system for meeting the needs of stakeholders (SEBok website, n.d.).

Life-cycle – Phases of a product or model that persist from inception, conceptualization and design a model, process or operation of a device through the final validation of operation thorough the need or usefulness of the model, process or device. (SEBok website, n.d.)

MBSE – Formalized application of modeling to support requirements, design, analysis, verification and validation activities beginning in the conceptual design phase throughout development and later life-cycle phases (SEBok website, n.d.).

Outputs – The transformation of an input by a function producing a result (Kenley, 2016).

Recovery - The phase of the emergency management cycle that begins with the stabilization of the incident and ends when the community has recovered from the disaster’s impacts (Homeland Security, 2008).

Reliability – The definition of reliability can be derived from the IEEE 1366 indices describing the duration an electric utility requires to restore consumers from total loss of electrical power, or interruption beyond 5 minutes, to normal electrical operations (IEEE Std. 1366-2012,).

Resiliency - Ability of systems, infrastructures, government, business, and citizenry to resist, absorb recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance (Homeland Security, 2008)

System - A collection of hardware, software, people, facilities, and procedures organized to accomplish some common objective (Kenley, 2016).

Stakeholder - People or operators that determine the methodologies, practices and processes required for reliable operation of various types of critical infrastructure (Homeland Security, 2008).

SysML – A graphical language to provide visualization and communication of a system's design among stakeholders (Friedenthal, Moore, Steiner, 2014).

LIST OF ABBREVIATIONS

AC	Alternating current
ANSI	American National Standards Institute
APPA	American Public Power Association
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
CHP	Combined heat and power
COU	Customer-owned utility
CI	Critical infrastructure
DG	Distributed generation
DMS	Distribution management system
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DHS	U.S. Department of Homeland Security
DR	Demand response
DRMS	Demand response management system
DRP	Distribution resources plan
DS	Distributed storage
D-SCADA	Distribution system supervisory control and data acquisition system
DSM	Demand-side management
DSO	Distribution system operator
EE	Energy efficiency
EEI	Edison Electric Institute

EIA	U.S. Energy Information Agency
EMP	Electromagnetic Pulse
ESP	Energy service provider
FFBD	Functional flow block diagram
FDIR	Fault detection, isolation, and recovery
FERC	Federal Energy Regulatory Commission
FIT	Feed-in tariff
G&A	General and administrative
GIS	Geographic information system
GMI	Grid Modernization Index
GWh	Gigawatt-hours
ICOM	Input control output mechanism
IDEF	Integrated definition for functional modeling
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
IOU	Investor-owned utility
Kcmil	Abbreviation for thousands of circular mils, an old measurement of wire gauge. 1 MCM = 1 kcmil = 0.5067 square millimeters.
kV	Kilovolts
LDHS	Local department of Homeland Security
MBSE	Model based system engineering
MWh	Megawatt-hour
NAP	National Academies Press

NERC	North American Electric Corporation
O&M	Operations and maintenance
OMS	Outage management system
PUC	Public utilities commission
RTO	Regional transmission operators
SAIDI	System Average Interruption Duration Index
SCADA	Supervisory control and data acquisition
SHAPE file	Data format for geographic information system (GIS) software
T&D	Transmission and Distribution
TSO	Transmission system operator
U.S.	United States

ABSTRACT

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Is North America vulnerable to widespread electrical blackout from natural or man-made disasters? Yes. Are electric utilities and critical infrastructure (CI) operators prepared to maintain CI operations such as, hospitals, sewage lift stations, food, water, police stations etc., after electrical blackout to maintain National security and sustainability? No. Why? Requirements to prioritize electrical restoration to CI do not exist as a requirement or regulation for electrical distribution operators. Thus, the CI operators cannot maintain services to the public without electricity that provides power for the critical services to function. The problem is that electric utilities are not required to develop or deploy a prioritized systematic plan or procedure to decrease the duration of electrical outage, commonly referred to as blackout. The consequence of local blackout to CI can be multi-billion-dollar financial losses and loss of life for a single outage event attributed to the duration of blackout. This study utilized the review of authoritative literature to answer the question: “Can a plan be developed to decrease the duration of electrical outage to critical infrastructure”. The literature revealed that electric utilities are not required to prioritize electrical restoration efforts and do not have plans available to deploy minimizing the duration of blackout to CI. Thus, this study developed a plan and subsequent model using Model Based System Engineering (MBSE) to decrease the duration of blackout by providing incremental electrical service to CI.

CHAPTER 1. INTRODUCTION – COMMON RECOVERY SYSTEM

Electricity has become a necessity to provide power for the infrastructure that has been developed to sustain the systems that support the growing global population. Transportation, communication, health care, food, clean water, waste removal, security and other systems utilize electricity for daily operations to provide services to the population. “Thus, modern societies have become totally dependent on an abundant electricity supply.” (Rudnick, Rivier, & Perez-Arriaga, 2008, p. 3). The dependence upon electricity results from electricity providing the impetus for innovative technological advancement in all areas of society. The growth of global population creates the demand for an increase in services. The demand for increased services requires the expansion of electrical infrastructure. As the global population grows, the increase in growth and dependence upon the electrical infrastructure necessitates the need to maintain electrical operation. Electrical blackouts cease operation of essential services creating socioeconomic chaos.

The result of blackouts caused by weather related events and man-made attacks globally has increased the awareness of the devastating effects of electrical blackout upon modern societies (Castellano, 2010). The devastating effects of electrical system blackout has caused the technical industries and governmental authorities to prioritize emergency technology as a research area in power grid security to prevent or mitigate the negative impacts upon modern societies (Chen, Deng, Chen, & Li, 2007). This study investigated the literature describing historical blackout events in the electrical system serving North America to provide a path to produce an emergency restoration model producing incremental electrical restoration to distribution systems serving consumers. In addition, the model created by this study can be used to produce a resiliency index for the distribution system in the U.S. as further research providing a measure of an electric utility's resiliency.

Examination of the U.S. electrical system, commonly referred to as *The Grid*, was conducted by surveying and collecting technical and legislative knowledge from literature available in the form of technical reports and government documents. The literature provides the historical knowledge detailing the technical and regulatory evolution of how electricity is delivered in North America.

The common phrase used as a generalization of the transmission and distribution of electricity is *The Grid.* The phrase implies that North America is served by one electrical system. In actuality, the electrical system in North America is divided into two distinct systems; (1) the high voltage Bulk Electric Transmission System (BETS), which transmits wholesale electricity from generation plant to regional or local retail providers, and (2) the lower voltage distribution systems, which distributes retail electricity (National Academies of Sciences, Engineering, and Medicine., 2017) to businesses and households.

Figure 1. Source: www.netl.doe.gov diagram of power production sources feeding the interconnected BETS and substations to transform electricity for distribution to consumers.

The purpose of the BETS is to transport electricity at high voltages between electrical production facilities, power plants, in different states to be transformed into a lower voltage electricity ultimately being distributed to various types of consumers. Consumers are typically categorized as industrial, commercial and residential. The BETS is physically and electrically interconnected among states and is transmitted between utilities via physically interconnected electrical conductors as a system resulting in financial transactions between electric utilities.

The BETS prov ides long distance, thousands of miles, connection between utilities to transmit high voltage electricity that is transformed into lower voltage electricity for distribution. The electrical distribution system, tens of miles, provides electrical service for consumption to critical infrastructure (CI) that the general population have become dependent upon. The lower voltage distribution system is at risk of disruption from natural disasters, extreme weather events, human error and mischievous acts, animals, equipment or software failure, space weather, and various disruptions that have caused widespread blackout. The incremental functional loss of the BETS may not have a significant impact upon the general population such as blackout in the electrical distribution system which has become common for the electrical consumer.

Two words that are commonly interchanged describing the operation of the two electrical systems are actually distinctive by definition. Reliability and resiliency have variations in definition depending upon the application. When the words are applied to the electrical system the federal government defines them as follows: Reliability: “the ability of the system or its components to withstand instability, uncontrolled events, cascading failures, or unanticipated loss of system components” and “The traditional definition of reliability—based on the frequency, duration, and extent of power outages” (U.S. Department of Energy [DOE], 2017). When applying resiliency to the electrical system, Presidential Policy Directive-21 dictates the definition as: “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents” (PPD-21: Critical Infrastructure Security and Resilience). The distinction between reliability and resiliency can be summarized as the ability to withstand instability and the ability to recover respectively. Typically, resiliency is applied to the operation of the BETS (Government Accountability Office [GAO], 2018, p. 2) and reliability is applied to the distribution system (Sarma & Madhusudhan, 2016). A report issued by the National Academies of Science (National Academies Press [NAP], 2012) delineates the various functions between the two electrical systems, discusses the vulnerabilities and provides recommendations how to mitigate the vulnerabilities that can cause blackout. The report provides the following recommendation as an application specific to the distribution system. “without some numerical basis for assessing resilience, it would be impossible to monitor changes or show that community resilience has improved. At present, no consistent basis for such measurement exists. We recommend therefore that a National Resilience Scorecard be established” (National Academies Press [NAP], 2012, p. 112).

The technical research reports identify the differences in function between the BETS and the distribution system. The vulnerability of the distribution system necessitates the development of a resiliency index as a method to measure a community’s resiliency to blackout. The technical function of the BETS creates financial transactions between utilities which are managed and regulated by various federal and state government agencies ultimately measured by resiliency to blackout. Federal agencies develop rules that compel electric utilities to develop and simulate plans for recovery in preparation of the BETS to recover from blackout. (North American Electric Reliability Corporation, December 9, 2017). The purpose of the rules and regulations are to make the BETS resilient to blackout and/or provide methods to recover from blackout. The goal of mitigating or eliminating BETS blackout is to minimize the negative effects within the technical transactions thereby decreasing the negative effects upon the financial markets. However, the system that provides power to consumer services is not regulated and is vulnerable to failure causing widespread blackout among the general population.

> There is no single organization responsible for establishing or enforcing mandatory reliability standards in distribution systems, although state utility regulators and boards of publicly or customer-owned utilities often assess performance using quantitative reliability metrics and set goals for the allowable frequency and duration of system and customer outages. (National Academies of Sciences, Engineering, and Medicine., 2017, p. 28).

1.1 Statement of the Problem

Electric utilities are not required to develop or deploy a prioritized systematic plan or procedure to decrease the duration of electrical outage to CI after blackout within the electric distribution system. The absence of a systematic plan for electrical restoration within the electrical distribution system after blackout has caused significant financial losses and sociological harm (National Institute of Building Sciences [NIBS], 2018). The operation of the electrical distribution system, or retail electric sales, is not managed, regulated and or governed by national or federal resiliency or operational rules. Thus, the electrical distribution system is vulnerable to widespread blackout causing socioeconomic harm to the general population.

The literature identifies regulations aimed at the complexities involved to defend against blackout in the BETS, but regulations and standards are not applied to the electrical distribution system. The new and complex methods of digital technology, commonly described as *Smart Grid,* (Litos Strategic Communication [DOE], 2011, p. 4) are designed to reroute or switch electrical transmission and distribution systems utilizing the internet or WIFI systems, when electricity is present and operating, to alternate feeds or alternate locations of power production.

Indeed, digital infrastructure can provide operational advantages, however, digital infrastructure cannot function properly after blackout occurs negating all operational advantages. The inclusion of digital infrastructure provides operational advantages. However, the inclusion of digital infrastructure without a procedure designed to bypass inoperable functionality can exacerbate the blackout when the intention was to decrease the duration of the blackout. The absence of a compelling reason for an electric utility to develop a plan to provide incremental electrical restoration increases the negative impact of blackout upon society.

1.2 Research Questions

The research questions central to this research were:

1. Can a plan be developed that will provide electric utility owners and CI operators with a method to plan for and to provide incremental electrical recovery decreasing the duration of blackout to CI?
2. Can Model Based System Engineering (MBSE) be utilized to develop a universal model to support planning for incremental recovery to electrical distribution systems after widespread electrical blackout mitigating the negative socioeconomic effects?

1.3 Significance of the Problem

The delay in restoration to CI as a result of blackout causes significant increase in insurance premiums and financial losses, mortality and morbidity. Extreme financial losses and the loss of life resulting from blackout is a significant negative impact upon society that should not be ignored. The issue is that widespread electrical distribution blackout causing socioeconomic chaos is a historical fact in which the socioeconomic costs have been well documented. The impact from the loss of electricity is estimated by the national insurance agency to be $79 Billion annually (LaCommare & Eto, 2006, p. 16). Some estimates increase the losses to $209 billion (Executive Office of the President, 2016, p. 2). These estimates account for numerous costs associated with power outages including lost output and wages, spoiled inventory, inconvenience and the cost of restarting industrial operations. Loss of retail electricity to the U.S. population has caused significant financial and physical loss to the U.S. population.

In addition to financial estimates and losses in the U.S., "electricity was recognized by the UK Department of Health as the 'most vital of all infrastructure services' because 'without it most other services will not function'" (Department of Health, UK, 2014, p. 29). The study of New York City power outages published in the Journal Environmental Health Perspectives suggests "'that localized power outages may adversely affect health' in addition to 'cold-weather outages were associated with all-cause mortality and cardiovascular disease hospitalizations'" (Dominianni, Lane, Johnson, Ito, & Matte, 2018, p. 11). Several documents in the literature, (Campbell, 2012), (Townsend, 2006), (NAP, 2012) identify the significant consequences upon heavily populated locations as a result of blackouts. The significance of blackout is summarized by the following statement: "Since all parts of the economy, as well as human health and welfare, depend on electricity, the results [of blackout] could be devastating" (National Research Council [NRC], 2012, p. 1).

The literature documents the vulnerability and significant threat of blackout to the electrical system resulting from a lack of oversight. "More than 90 percent of the U.S. power grid is privately owned and regulated by the states, making it challenging for the federal government to address potential vulnerabilities to its operation, and perhaps especially its vulnerability to terrorist attack" (National Academy of Sciences [NAS], 2012, expression vii). Despite the various Presidential Policy Directives and congressional reports ordering, authorizing and recommending the creation and deployment of methods to produce recovery, plans and procedures have not been developed. The absence of execution procedures to develop a plan is perplexing especially when the literature identifies two issues: 1. Federal, State, Local and technical organizations continue to order recommendations for *the national grid.* The electrical distribution system is not an integrated national system or national grid, but the distribution system is independently owned and operated within defined territories. Blackout within the local and individually owned electrical distribution system causes significant socioeconomic chaos. The second perplexing issue, State and local regulators have not required solutions or compelled electrical distribution owners to develop and develop plans to create models for recovery from distribution blackout. “There is no “one-size-fits-all” solution to avoiding, planning for, coping with, and recovering from major outages” (National Academies of Sciences, Engineering, and Medicine., 2017, p. 1). “Large-scale disruption caused by damage to the high voltage transmission system garners wide attention, but widespread damage in the distribution system, such as that caused by recent Florida and Gulf Coast hurricanes, can be more expensive” (Schuler, 2005, p. 115).

The management and monitoring of the BETS reside within the owners of the BETS and is governed by federal agencies. State and local regulators provide a framework for the retail price of electrical distribution but do not require electric utility distribution owners to develop and simulate plans for recovery from blackout. Thus, the problem of blackout is compounded by the absence of a planning approach that can be readily replicated across the many distribution systems to provide incremental recovery to reduce the duration of blackout in distribution systems. Therefore, the impact of blackout upon society will continue until utility owners are compelled to adopt and implement an approach to planning that can be used to create modeling and simulations to reduce the duration of blackout.

The 2017 Hurricane's Harvey, Irma and Maria caused billions of dollars in damage to Texas, Florida and Puerto Rico and the Caribbean. (Weatherbug, Hurricane Season by the Numbers website, 2018). More than 400 deaths are attributed to the hurricanes and the number of deaths continues to grow because of exacerbated health conditions resulting from the impact created by various hurricanes causing disruptions and/or loss of electricity powering essential services. (Centers for Disease Control and Prevention MMWR website, 2017). Weather related events that damage electrical infrastructure place the U.S. population is at risk of harm resulting from widespread long-term distribution blackout. The aforementioned reports from Weatherbug and the CDC provide the significance of the financial impact in addition to the morbidity and mortality resulting from hurricanes and natural disasters causing blackout. The literature from the Congressional Research Service (Parfomark, 2014, p. 2) reveals the disruptions and/or loss of distribution, or retail electricity, resulting from various types of disasters have caused and will continue to cause the loss of essential public services or CI causing significant financial losses.

"Electrical power outages, surges and spikes are estimated to ring up more than $150 billion in annual damages to the U.S. economy. Downtime costs vary not only by industry, but by the scale of business operations" (Eaton, 2013, p. 3). Loss of retail electricity has created significant exposure to insurance companies creating policy revisions and extensions. "Optional policy extensions such as "Contingent Business Interruption", "Spoilage", or "Utility Services Disruption" can expand coverage to events occurring within a specified distance from the insured property. Insurance products are emerging that cover disruptions in distant supply chains, with waiting periods of 30 days or more" (Marsh 2012). Financial losses from loss of retail electricity extend to small and large business and the residential consumer causing increased financial losses each year.

1.4 Statement of Purpose

The purpose of this research is to provide a model to support planning to provide incremental electrical restoration to CI after blackout. The impetus for the development of a model to support planning for incremental restoration to CI emerges from observational experience and a philosophical premise. Observation from 28 years' experience as an electric utility engineer observing empirical results from restoration efforts initiated the paraphrase of an often-quoted muse from H.L. Mencken "there is always a well-known solution to every human problem – neat, plausible and wrong" (Mencken, 1920, p. 158). Paraphrasing and adding additional rumination; the solution to a complex problem is usually simple. However, arriving at a *simple* solution can be a *complex* process. Thus, observing and developing strategies for blackout recovery provides the premise that *low-tech rules*. In other words, utilizing analog manual operations, *simple and low-tech*, to provide incremental electrical recovery will provide a systematic electrical recovery process, *complex*, to the distribution system. Although the systematic process developed is simple in methodology, defining the priority location (PL) to begin incremental electrical recovery is complex.

The existing independent electric distribution systems in the United States are vulnerable to attack because the system is highly distributed geographically, independently owned and not an integrated national system. The huge investment already made in individual electric distribution systems makes significant structural changes both expensive and long term. Consequently, efforts must focus on maintaining the health and robustness of distribution with an emphasis on restoring power after outages and maintaining the continuity of electric service to critical customers. (NAS, 2012, p. 64). This study created a planning methodology applying architectural concepts, tools and techniques from Model Based System Engineering (MBSE) to electric utilities with the goal of utilizing existing infrastructure and not disrupting the existing facility investment while decreasing the duration of blackout to prioritized locations of CI. The deliverable is a working MBSE model to maintain the robustness of the existing distribution system. The process can be described as decomposing the existing distribution system into a single system capable of supplying electricity to specific entities. The regular or traditional methods of blackout restoration will continue simultaneously until the blackout has been restored. Subsequent to the complete restoration, the prioritized locations where the Common Recovery System (CRS) was applied can be restored to electrical service as emergency operation.

The model for incremental restoration has three distinct functions. One, the operation or process of identifying priority locations of CI. Two, isolating the distribution electrical system, decomposition, to specific electrical substations and circuits in proximity to prioritized CI. Three, the use of an external power source, apropos to individual electric utilities, at identified substations to decrease the duration of electrical outage to prioritized CI. Upon completion of blackout restoration, the system customers other than the prioritized CI can be restored to normal operation. This study does not provide the methods of restoring the system to normal operation after blackout restoration at the identified substations associated with the prioritized CI. Each utility will develop individual methods and plans to restore the system to normal operation after the blackout has been restored. The model created in this study utilizes manual methods of isolating specific circuits to provide electricity to specific locations of CI.

Blackout causes loss of electricity including the loss of functionality to digital devices installed within the distribution system. Therefore, analog manual methods (*low tech)* must be utilized to provide incremental electrical restoration. The development of a system model using digital tools, software and System Engineering tools and techniques (*complex*) prior to a crisis or catastrophic event provides the plans and procedures necessary to provide incremental electrical restoration to CI.

1.5 Assumptions

Presidential directives, congressional reports and technical recommendations identify the need for appropriations to provide resources for the development of plans and procedures to provide electric distribution resiliency for CI. PPD-5 directed Homeland Security, FEMA and the DOE to develop the National Incident Management System which, in part, established the concept of appropriations to develop mechanisms, models and systems to produce resiliency in the CI to protect the public (HSPD-5, 2003). Without appropriations, electric utilities will not and have not voluntarily budgeted resources for the adoption or development of plans and procedures to produce incremental electrical recovery to CI. Blackout in the electrical distribution system does not represent a significant amount of lost revenue for the utility when comparing the losses that can be incurred from a blackout in the BETS. However, blackout in the distribution system does cause socioeconomic loss. The appropriations coupled with accompanying legislation will provide a compelling reason for the electric utility to adopt the CRS to provide a measure of resiliency to mitigate future losses.

PPD's 5 -21 dictate the need for policies to be created for the protection of the electric system. However, actions based on the PPD's have not been delineated and or detailed into plans for federal, state and local decision makers. Appropriations for the design efforts and decisions necessary to determine the sophistication required to protect the electrical system from a man-made or natural disaster have not been developed, which leaves the electrical system vulnerable to various threats. The need for the design and application of a recovery system that supports the planning needed to provide security of the electrical system have been well documented in the briefing provided by Dr. Peter Vincent Pry (Pry, 2015). The CRS provides an algorithm for prioritization and an executable operational concept using MBSE diagrams that can be simulated to support a recovery methodology for the electrical distribution system to provide incremental recovery from blackout.

1.6 Limitations

The deployment of the CRS is limited by two factors. 1. Application of data specific to the operation, engineering and construction of electric utility distribution facilities is considered proprietary and not available for application for general research. 2. The application of a method for recovery after an event causes blackout has been recommended and ordered by federal and state policies, but the appropriations to develop a method have not been delivered. Therefore, the delivery and application of the CRS to a local community is limited by specific data and available funds with compelling legislation for the development and application process. Open source data limits the CRS to a general design or application. However, the CRS can be customized and applied to specific electric distribution territory. Without compelling reasons for an electric utility to deploy the CRS, CI operators and electric utilities will not voluntarily provide the necessary resources to deploy the CRS.

The model developed in this research originally utilized existing data specific to an electric utility blackout event. The data specific to a historic weather-related blackout within the territory of an electric utility is proprietary and cannot be utilized for research and development of the CRS in this study. Therefore, open source public data was used to develop the CRS model. The public ‘generic’ data does not provide specific electric utility component information, blackout and restoration time, specific location of blackout relative to electric utility components limiting the ability to validate the restoration capability of the model. In addition, the public data only identifies 5 (electrical substations, hospitals, fire stations, police stations and trauma centers) of the 16 CI sectors defined by DHS/FEMA.

The open source public data used to develop the CRS model provides validation of the concept of incremental electrical recovery. The validation process provides confidence that the CRS is applicable to any electric utility. In addition, applicability of the model is not dependent upon specific software, equipment or the adoption of specific hardware or electrical infrastructure to develop an incremental recovery model.

The application of the data to the CRS in this research utilized general engineering practices and requirements to define technical aspects and requirements providing parameters for application. The electric utility territory utilized for this research has a requirement of 5% maximum voltage drop or under voltage from the source, electrical substation, imposed upon the electric utilities by the Public Utility Commission of Texas (PUCT) (Public Utility Commission of Texas, n.d.). The construction and conductor standards for Ocnor, the utility serving Houston, are not published to provide specific information regarding conductor and equipment sizes. Therefore, parameters from the rural electric association standards published by the National Rural Electric Cooperatives (National Rural Electric Cooperative Association International [NRECA], 2018) will serve as the guidelines for conductors serving residential and commercial electric consumers.

Various electrical engineering calculations are typically utilized for the design of an electrical distribution circuit providing service for residential, commercial and industrial customers. The calculations are specific to the conductors and equipment used providing service to consumers. This study used open source public data available from various government organizations describing one blackout event allowing the application of the CRS models. The information for this study relative to CI within the described territory was obtained from public sources. Specific information relative to CI location and operation is proprietary to specific regions and could not be utilized for this study to describe the specific duration relative to location of electrical outage and subsequent restoration to specific CI. Future accurate application of the CRS is dependent upon the aggregation and knowledge obtained from electric utility and CI operators.

The literature review identifies Presidential Policy Directives (PPD), Congressional Research Reports, technical papers and legislative materials detailing the funding mechanisms and compelling reasons to aggregate knowledge of operators from each CI to assist in the development and deployment of a system to produce recovery to CI. The success of the the CRS is dependent upon acceptance, deployment and refinement of the CRS by CI operators through the funding efforts as described in various Presidential Policy Directives. An exhaustive review and discussion of the evolving electrical system regulations are beyond the scope of this study. However, a perfunctory review of the regulatory process, beginning in chapter 2, provides the general structure of the regulatory framework.

Federal regulations created through Presidential Policy Directives provide the framework for appropriations to fund the application of the organization and development of methods and processes to create an emergency response plan to blackout. Appropriations for methods of preparation have not been delivered to local DHS and/or emergency responders in the 50 states and 6 territories. The application of the CRS to communities is limited due to the dependency upon the federal, state and local political processes to compel electric utilities to develop a recovery method.

1.7 Delimitations

The development of the CRS occurs prior to an event but application of the CRS begins after a widespread disaster has caused blackout. The development and subsequent application of the CRS is not limited by public sourced data but will be customized to each electric utility within the parameters prescribed by the CI data. Data specific to an electric utility that provides details for electrical outage and the standards and engineering practices specific to an electric utility could not be used due to the proprietary nature of the data. This study did not address specific blackout data that may have occurred within a specific territory since proprietary data was not available. The researcher used data available to the public that is published by various federal or state agencies.

This study did not address any existing methodologies for blackout restoration used by electric utilities due to the proprietary nature of the plans, procedures and proprietary outage management and customer system software used by electric utilities.

This study developed the CRS with open source software, QGIS (QGIS Version 3.8.0), to overlay GIS map layers to develop priority locations (PL) as a layer relative to the position of the electrical substations contained in a different layer. The PL are used as inputs to develop a model using a SysML-compliant modeling language. SysML modeling is adaptable to various engineering analysis models and tools that are compliant with the SysML standard (Walden, Roedler, Forsberg, Hamelin, & Shortell, 2015). The model developed using the SysML-compliant MBSE diagrams provided by Vitech. Genesys (Vitech Genesys Version 6.0) is not limited in design as a result of using open source data. The open source data and SysML-compliant modeling approach provides the opportunity for the CRS to be customized to any electric utility and community to provide confidence that preparations have been developed to mitigate and/or prevent loss of CI services.

The research and subsequent development of the system engineering model is in response to literature that defines the necessity for the development of a process to provide electrical distribution restoration. The model created using SysML defines the process required to isolate the electrical system and the process necessary to begin incremental electrical distribution restoration to CI. However, the electric utility engineers and operators will have to determine if an alternate power source is necessary and the requirements necessary to provide an alternative power source to a specified substation. The CRS model is not limited by the type of alternate power source designed and recommended by the electric utility but provides the process and procedures to decompose and isolate the existing electrical system identified to provide electricity to CI. The standard utility storm restoration operating procedures are not limited the CRS. The process of decomposing and isolating the existing electrical system to apply the CRS is not limited by other activities required to restore the electrical system to its original state prior to an event. Normal crisis or emergency procedures of electrical restoration can proceed simultaneously with the CRS model to continue the process of electrical facility restoration within the utility’s territory.

CHAPTER 2. LITERATURE REVIEW

The research study proposal was utilizing mixed methods research to identify qualitative and quantitative literature discussing electrical blackout. Indeed, blackout causes qualitative societal issues affecting the health and welfare of the population. However, the development of a plan to provide incremental electrical restoration to CI focuses upon the quantitative literature identifying the technical and legislative structure of the electrical system. Literature identifying the technical and legislative structure reveals the necessity of a method for recovery in the electrical distribution system. Thus, the application of a model producing incremental electrical restoration to CI provides positive affects for the socioeconomic aspects typically impacted by blackout. Therefore, the literature reviewed for the completion of the research focused upon the quantitative research from the positivism paradigm by reviewing authoritative literature. The application of the CRS will fulfill the directives and recommendations identified in the literature by providing incremental electrical restoration to CI.

The authoritative literature reviewed for this study are divided into three groups. 1. Documents providing details of the regulatory bodies that manage and regulate the electrical system. 2. Literature identifying the results of blackout. 3. Literature from local, state and federal documents advocating and authorizing the development of a solution to blackout.

During the beginning of the 20th century, industrial companies started creating electric utilities to begin the transmission of electrical power across state lines. The U.S. government identified the need to manage, monitor and regulate the transmission and distribution of electricity. The following sections discuss the evolution of the regulations and the technical structure of the electrical system.

The electrical system comprises two distinct systems consisting of electrical transmission and distribution. The context of this research is focused upon the electrical distribution system. Thus, decomposing the electrical system will identify the distinction between the two electrical systems. Decomposition of the electrical system begins with the evolving regulatory process providing the distinction between regulations of the transmission and distribution systems. Additional clarification is provided through technical literature describing the differences between the transmission and distribution systems. The third section of the review will provide a brief discussion of Model Based System Engineering (MBSE) with additional clarification of MBSE in chapter 3. The review will begin by providing a brief description of the historical technical structure of the electric utility system providing context to the decomposition of the evolving regulation of the transmission and distribution systems. The literature review of the regulatory structure is not an exhaustive review but will provide the framework and basic structure of the federal state and local regulatory entities.

2.1 History of the Electrical Industry Regulation

The review of literature begins by providing an overview of how the electrical system is structured, resulting from increased consumer demand, providing context to the national electrical system commonly referred to as *the grid.* The following review begins with a delineation of the technical structure and will continue by describing the role of federal, state and local regulatory entities.

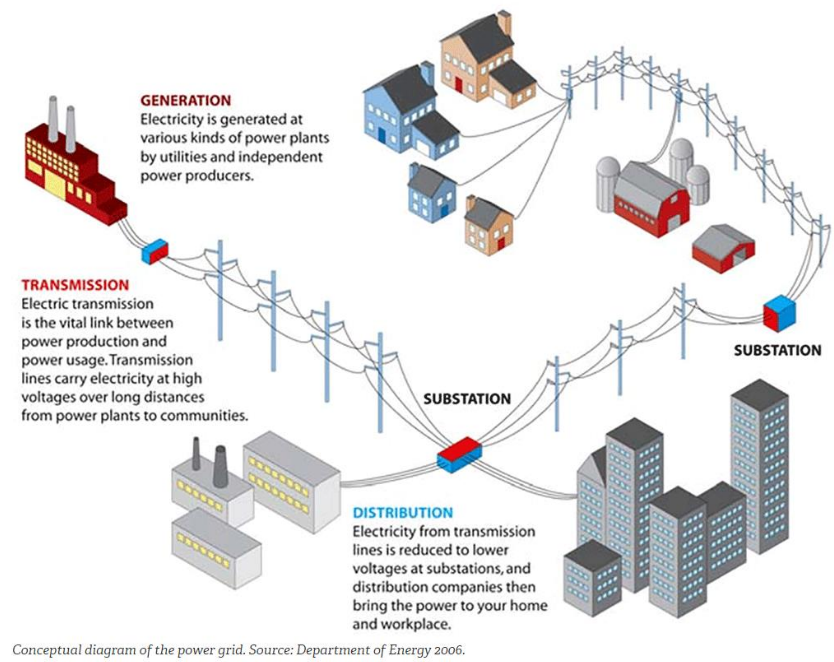


Figure 2. Conceptual diagram of city / state power grid identifying power production (generation), transmission to substations and distribution of electricity.

"The structure of electricity delivery can be categorized into three functions: generation, transmission, and distribution, all of which are linked through key assets known as substations." (Office of Electricity Delivery and Energy Reliability [DOE], 2015, p. 6).

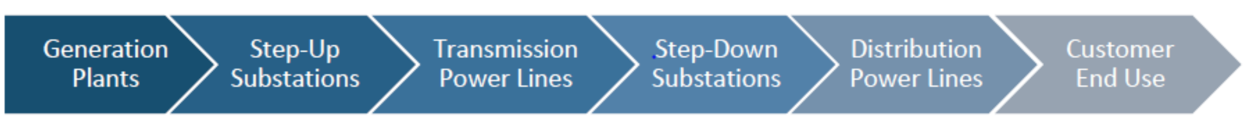


Figure 3. Diagram of electricity delivery retrieved from www.energy.gov

The electrical system consisting of steel towers and/or wood poles and wires in North America are divided into two distinct systems; the high voltage BETS consists of high and medium voltages while the lower voltages are confined to distribution systems. Transmission and distribution voltages are divided by the voltage class as shown in table 1.

Table 1 Description of transmission and distribution voltage classes

Power Line Classification	Voltage Range (kV)	Purpose
Ultra High Voltage (UHV)	>765kV BETS	High Voltage Transmission > 765kV
Extra High Voltage (EHV)	345, 500, 765	High Voltage Transmission or BETS
High Voltage (HV)	115,138,161,230	
Medium Voltage (MV)	34, 46, 69	Sub-transmission
Low Voltage (LV)	< 34	Distribution for residential or small commercial customers, and utilities

Note. Source: U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, July 2015 (p.15)

The table above defines the electoral system by voltage class. The following diagram, Figure 4, identifies the voltage class and / or transmission and distribution of electrical service.

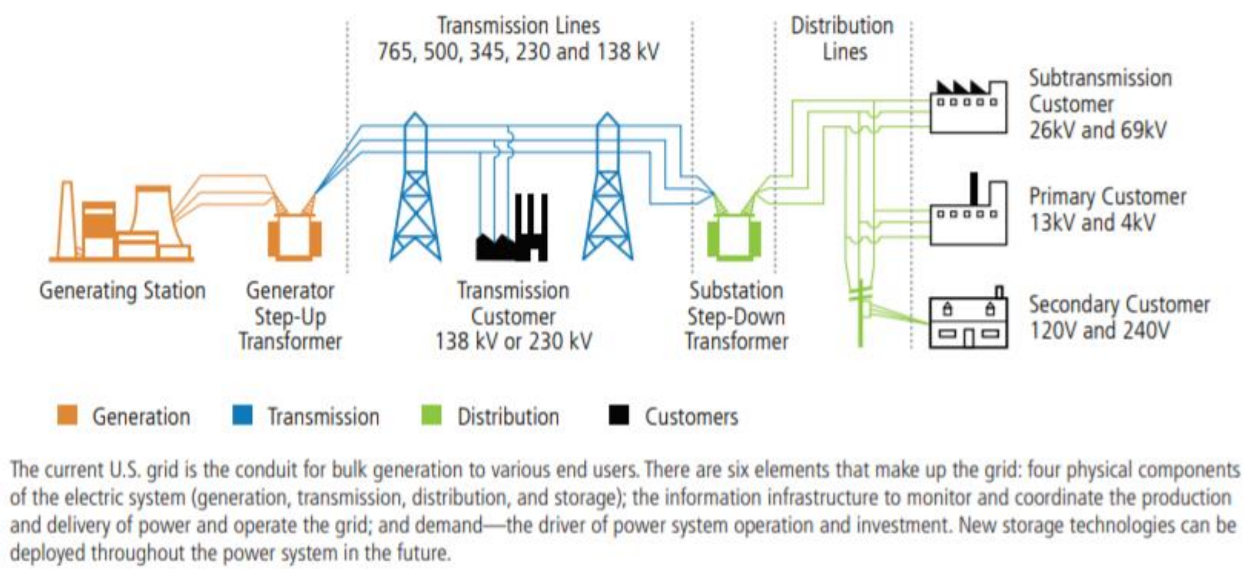


Figure 4. Existing electrical system from power production to end users through the bulk electric transmission system (BETS) to substation step down transformers to distribute electricity to consumers.

The purpose of the BETS is to transport electricity at ultra-high, extra high and high voltages (765kV to 115kV), between power plants, large industrial consumers, and/or electric utilities in different locations or states to be transformed into different types of lower voltage electricity. Sub-transmission, or medium voltage (34kV to 69kV), is transmitted interstate or inter territorial between utilities or substations. Lower voltage (<34kV) distribution is distributed to various types of consumers of electricity for customer end use described as retail sale of electricity. However, some large industrial customers consume electricity at a transmission voltage with a corresponding financial transaction through a rate structure managed through metering activities. The BETS is electrically interconnected among states transmitting high voltage electricity, > 69kV, between electric utilities via physically interconnected conductors and sold as a commodity resulting in financial transactions between electric utilities.

2.1.1 Regulation of the BETS

The federal government started regulating financial transactions of the BETS through actions by the Supreme Court of the United States in 1920 (Vann, 2010). The U.S. Supreme Court identified the Commerce Clause in the U.S. Constitution (U.S. Const. art. I, § 8, cl. 3) as the legal justification to regulate the energy industry. The growth of the electrical transmission industry during the 20th century necessitated the creation of various federal agencies whose responsibilities are to direct, monitor and regulate the technical aspects and wholesale sale and purchase of electricity within the BETS (FERC webpage, n.d.).

In 1920 congress established the Federal Power Commission (FPC) first enacted as the Federal Power Water Act to coordinate the purchase of power among the federal hydropower projects (Vann, 2010). The Federal Power Act was amended in 1935 to give the FPC specific power to regulate the sale and transmission of electricity (Vann, 2010). The growth of the BETS resulting from consumer demand and in response to the 1973 oil crisis, initiated legislation evolving the FPC into the Federal Energy Regulatory Commission (FERC) (Department of Energy Organization Act, 1977) designed to monitor and regulate the BETS.

The electrical industry identified a need for the creation of an informal, voluntary organization to facilitate coordination of the BETS by creating the formation of the not for profit North American Power Systems Interconnection Committee (NAPSIC) ("History of NERC," 2018). NAPSIC was eventually renamed the North American Electric Reliability Corporation (NERC) to include the transmission connections between the United States and Canada ("History of NERC," 2018). NERC is a not-for-profit international regulatory authority whose mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid (NERC website, n.d.).

FERC issued Order 888 in 1996 creating Regional Transmission Organizations and Independent System Operators (RTO/ISO) tasked with managing, monitoring and regulating the BETS and other energy transmission organizations (FERC Wholesale Open Access, 1996). Ultimately the DOE is responsible to monitor, oversee & regulate interstate commerce and technical requirements of the BETS. The expanding requirements and responsibilities of the DOE necessitated the expansion of FERC and NERC and the creation of the RTO/ISO. The three federal agencies FERC, NERC, and the RTO/ISO regions in Figure 5 below provide oversight of the BETS by monitoring the transport of electricity for the purpose of ensuring adequate supply is available for transformation into usable power for consumers.

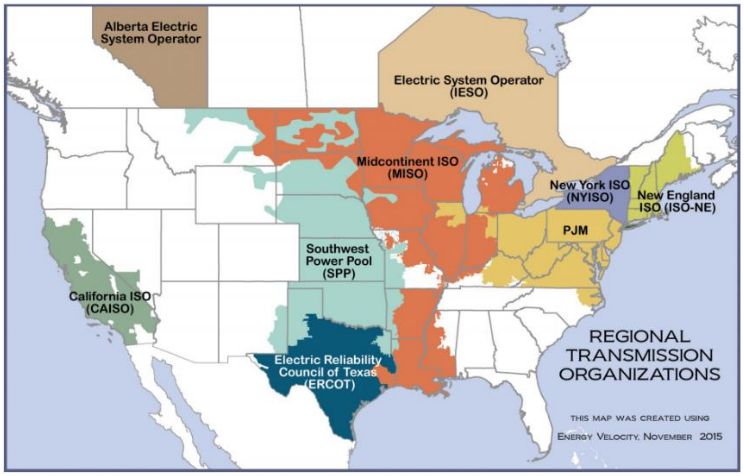


Figure 5. FERC map showing Regional Transmission Organizations (RTO). Retrieved from https://www.ferc.gov/industries/electric

NERC develops rules that compel electric utilities to create and simulate plans for recovery in the event that portions of the BETS experience outage or blackout. (North American Electric Reliability Corporation, December 9, 2017). The rules developed by NERC provide assurance of operations, reliability and resiliency through yearly simulations of outage and blackout restoration in the electrical system. NERC requires yearly verification and testing of electrical system comprised of electrical generating facilities that produce electricity to be transmitted over high voltage transmission lines (NERC, 2016). The transmission interconnection is divided into regions and managed by NERC as shown in Figure 6 below. The Reliability Guideline developed by NERC is applied to each interconnection within the NERC regions.

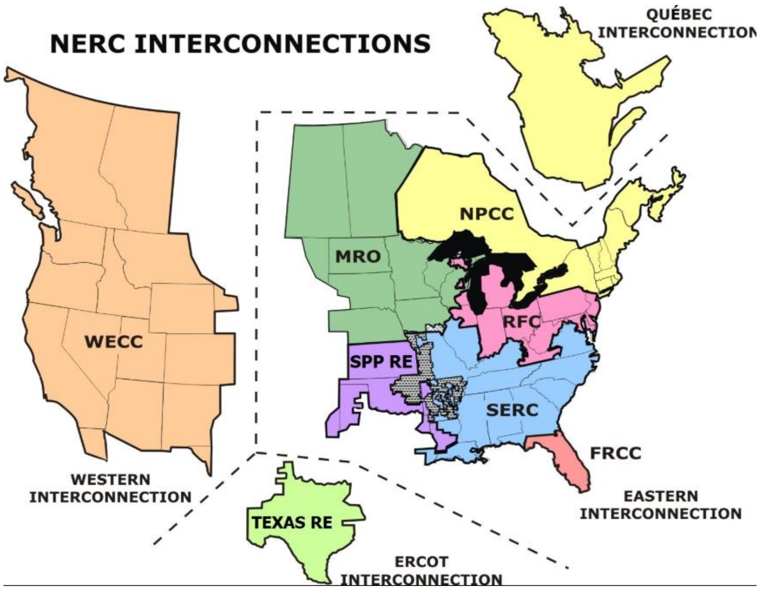
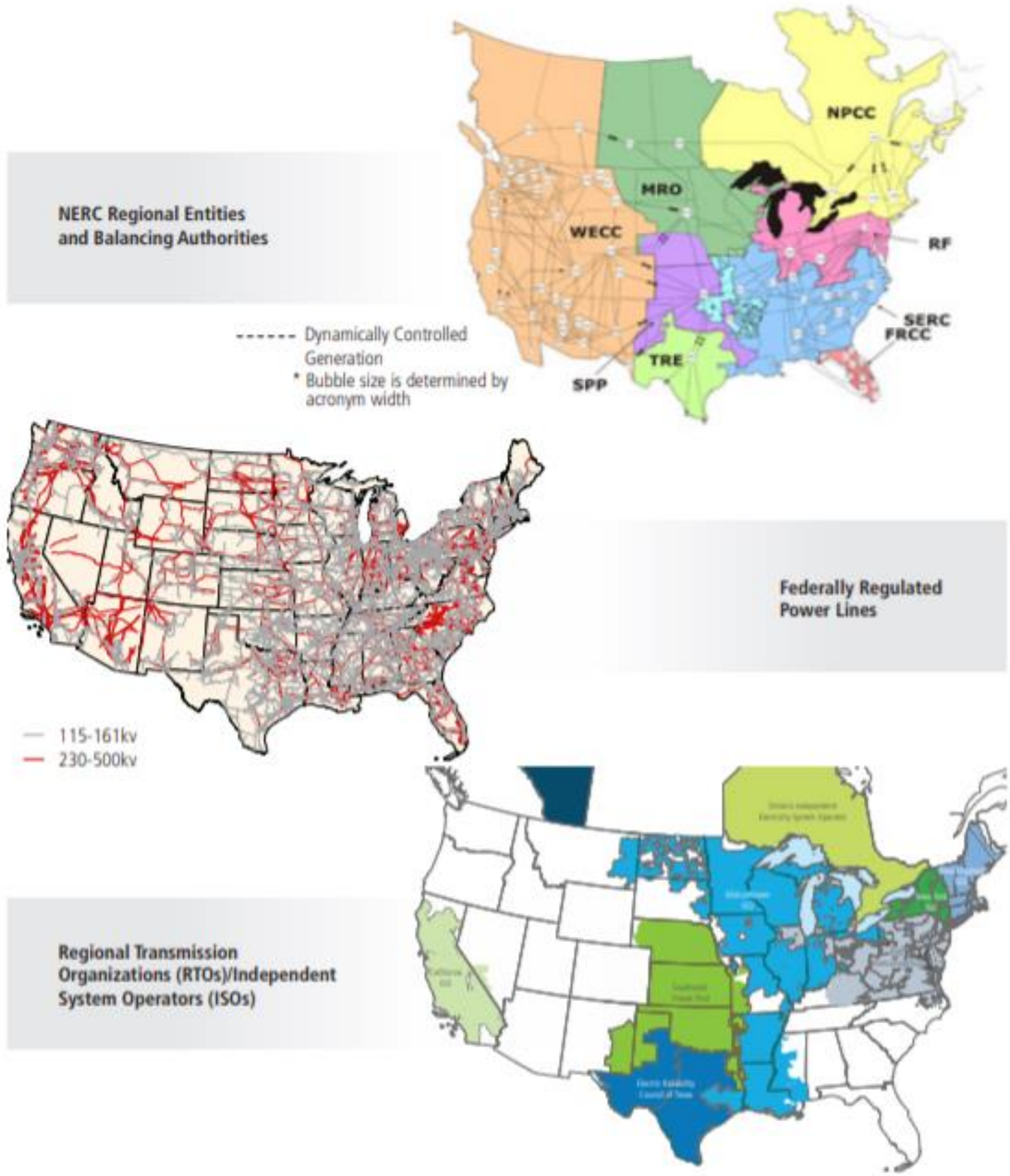


Figure 6. NERC map showing electrical transmission interconnections between regional entities. Retrieved from https://www.nerc.com/AboutNERC

FERC and NERC provide the regulations for the BETS throughout North America to ensure that reliability, resiliency and market consistency is maintained between electrical power producers. The maps below show an aggregated view of the divisions between regions and the interconnection of transmission lines in North America. The map in the middle shows' interconnectedness of the federally regulated BETS throughout the U.S.



Transmission lines are regulated at the Federal level with regard to their rates, terms, and conditions of service. In contrast, states regulate the distribution of electricity to end-use customers for entities under their jurisdiction, as well as the siting of transmission on non-Federal lands by non-Federal entities. Further, in most states, local appointed or elected governing boards handle the regulation of distribution for their publicly or cooperatively owned electric utility. This diversity of institutions and differences in jurisdictional boundaries create challenges in grid governance (given that changing the grid in one location can alter electricity dynamics over a large area).

Figure 7. Maps of federally regulated transmission lines jurisdictions

U.S. electricity trade with Mexico is minimal and the operation is not regulated by any of the U.S. federal agencies. The interconnection with Mexico provides an opportunity for wholesale sales between the U.S. and Mexico during peak demand in either country. Figure 8 below shows the location and voltage class of the interconnections.

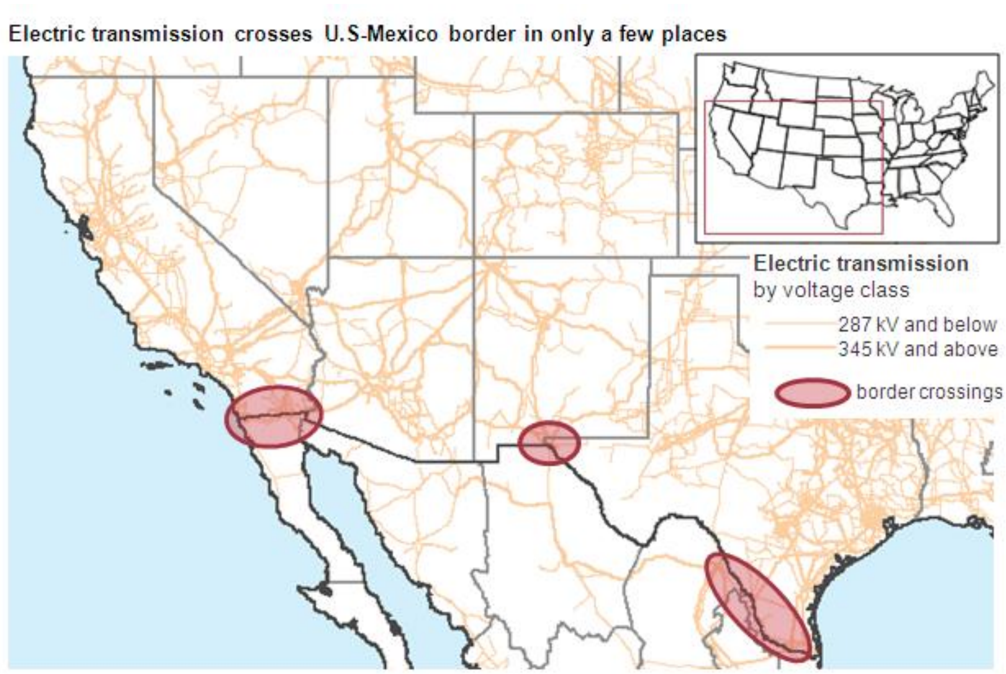


Figure 8. Locations of electrical transmission interconnection between the U.S. and Mexico.
Source: U.S. Energy Information Administration retrieved from:
https://www.eia.gov/todayinenergy

The evolution of the electrical regulatory structure is complex and complicated. The federal regulatory agencies manage and monitor the BETS while the functionality and operation of the distribution system relies upon the distribution system owners. See map in Figure 9 below.

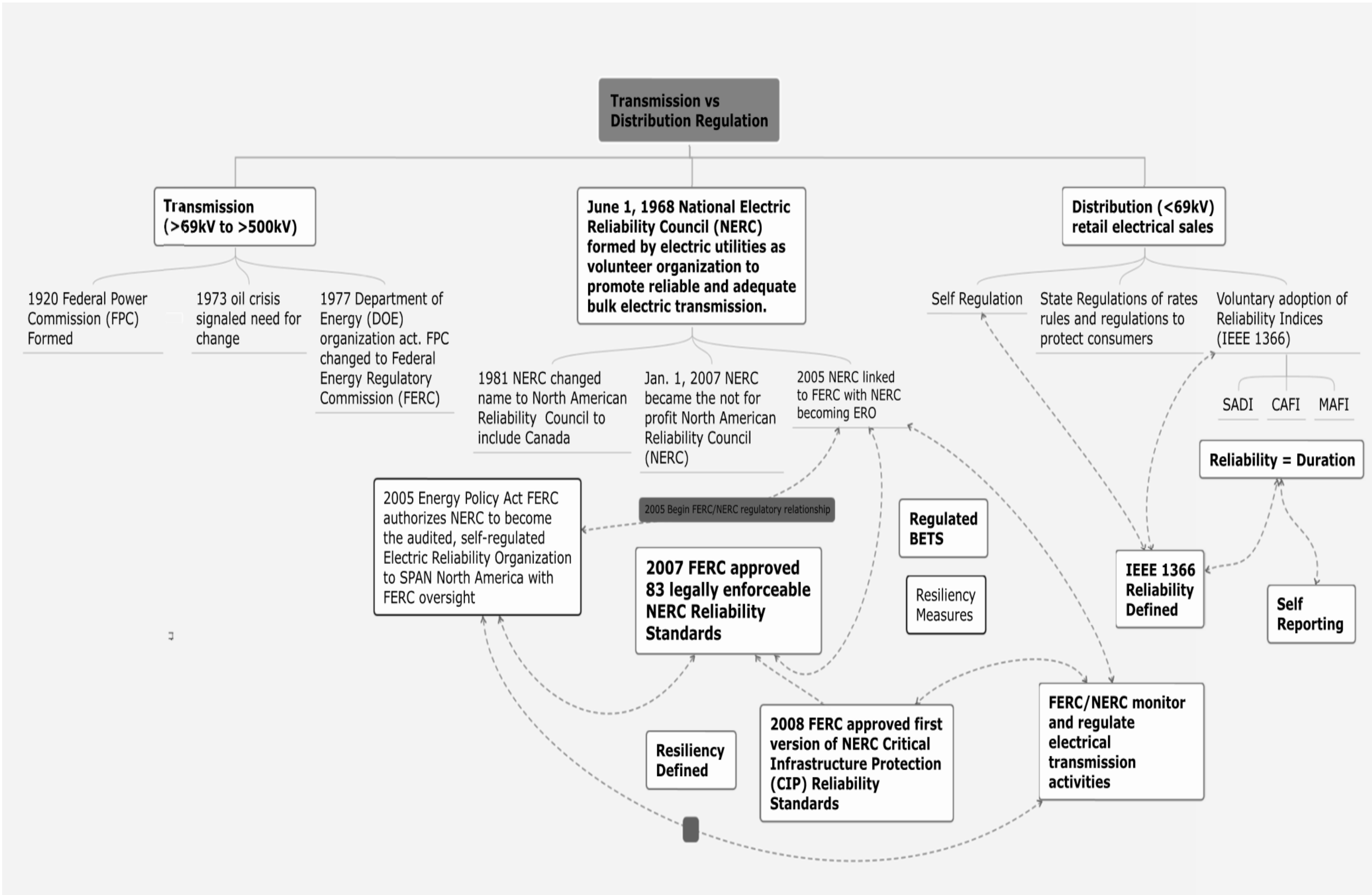


Figure 9. Map of regulations imposed upon transmission and distribution systems

The BETS have inputs from multiple generation sources with transmission interconnections nationally through thousands of miles of high voltage transmission conductors providing the ability to transmit electricity to multiple regions. The high voltage transmission is transformed into lower voltage, referred to as electrical distribution. “Data indicates that 90% of customer outage-minutes are due to events that affect local distribution systems.” (Folga, McLarmore, Talaber, & Tompkins, 2016, p. 16). Therefore, the majority of blackout occur in the distribution system. The distribution system supplies retail electricity to CI. Thus, an incremental model for electrical recovery should be applied to the electrical distribution system.

The power production facilities create and provide electricity to the BETS. Electricity from the BETS is transformed and distributed to consumers through distribution facilities. The common term, *the grid*, consists of two distinct systems. 1., The BETS which transports electricity to distribution facilities from power production facilities through the high voltage electrical transmission system. 2., The transmission electricity is transformed into retail electricity and distributed to consumers. The distinction between the BETS and the lower voltage distribution system is within the voltage class and regulations applied to the two systems. The BETS is regulated by federal agencies that impose penalties upon the owners of the BETS when failure to comply with rules and regulations imposed by NERC. The regulation of the operational activities of the BETS, discussed previously, is monitored and managed by federal regulatory agencies while the operations of individual distribution systems are not regulated but the rates are regulated by state agencies.

2.1.2 Regulation of the Distribution System

Considering the BETS is monitored and/or governed by federal agencies, how is the lower voltage distribution system monitored and managed? The short answer is that the operation of the distribution system is managed by the utility owners while the retail price of electricity is regulated by local and state authorities. The federal, state and local regulators realized the dependence upon electricity necessitated the need for regulation of the distribution system rates to ensure the reliable cost, rates, and technical aspects, rules, required to efficiently deliver electricity to consumers (U.S. DOE, 2015). The federal regulations provide monitoring of the BETS while the state and local regulations monitor and manage the rates and rules electricity is sold as a retail product. Local and state regulations require the electric utility to adhere to specific rates, rules and regulation standards developed by the state and/or local regulatory commission. There are no requirements, standards or imposed penalties for failure to maintain a specific distribution reliability or resiliency measure.

> There is no single organization responsible for establishing or enforcing mandatory reliability standards in distribution systems, although state utility regulators and boards of publicly or customer-owned utilities often assess performance using quantitative metrics and set goals for the allowable frequency and duration of system and customer outages. (National Academies of Sciences, Engineering, and Medicine., 2017, p. 28).

The electrical distribution systems are typically owned and managed by Investor Owned Utilities (IOU) and the reliability is self-managed by the entities or electric utilities that own the distribution systems. Rates, rules and regulations are imposed by the various state regulatory commissions. Typically, Public Utility Commissions (PUC) do not monitor, enforce or compel electric utilities to maintain or adhere to operational standards of reliability or resiliency. “The majority of PUC adopted service quality indices (SQI) based on specific indicators to measure the quality of utility service, such as the frequency and duration of outages” (Lazar, 2016, p. 34).

"Most PUC only monitor and regulate the retail price of electricity while other PUS provides some regulation but, in general, some utilities self-regulate their cost" (U.S. DOE, 2015, p. 30).

2.2 Blackouts and Disasters

The electrical distribution system typically experiences blackout due to natural and /or manmade events. Natural disasters such as hurricanes, tornados and/or winter weather disasters and the affect upon the population have been well documented. However, manmade events, whether nefarious or accidental, do not garner the same media coverage. For example, The Metcalf event in 2013, believed to be a terrorist attack, upon substations in the Silicon Valley area of California caused multiple days of electrical outage and millions of dollars in infrastructure damage (Homeland security news wire website, 2014). Jon Wellinghoff, former Chairman of FERC, described the attack as "the most significant incident of domestic terrorism involving the U.S. power grid that has ever occurred" (Homeland security news wire website, 2014). The general population did not suffer physical loss from the event, however, the financial losses although not reported most likely exceeded hundreds of millions of dollars (Homeland security news wire website, 2014).

Widespread electrical outage caused by an event that cannot be controlled and or defended against, such as a large man-made blackout, is described as a Major Event Day (MED) and is excluded from the indices to normalize the indices among electric utilities (Islam, Hofmann, & Hyland, 2014). Therefore, the IEEE 1366 reliability indices describe a utilities ability to maintain electrical service on a bright sunny day or during minimal intermittent blackout. Events causing long duration widespread blackout are usually removed from the indices by describing the event as an MED. The indices reported are derived from formulas identified in the IEEE 1366 Reliability Indices standard (IEEE Std. 1366-2012,). Indeed, the

IEEE 1366 standard provides a measure of an electric utilities ability to maintain the duration of electrical service to consumers but does not provide details of the electric utilities actual measure of consistent electrical service. The IEEE 1366 does not provide a measure for any occurrence of outage less than a 5-minute duration or large territorial outage.

2.2.1 Cause of Blackouts

Blackouts can result from natural or manmade events. Natural events can be weather or terrestrial. Manmade blackout can result from operational error, unanticipated high electrical demand or events from nefarious groups wanting to cause chaos and harm (Office of Cybersecurity, Energy Security, and Emergency Response [Energy.gov], n.d.). Considering the variations in the weather-related causes of blackout. The purpose of the IEEE 1366 is to provide indices for blackout while retaining uniformity among all utilities reporting reliability indices. Some areas of the country incur weather related events not experienced in other parts of the country. For example. Outage in Wisconsin, usually winter weather, is significantly different than the cause of blackout in Arizona. Large blackout events, regardless of the cause, are removed from the reliability indices as allowed in the IEEE 1366 guidelines. Large blackout events, typically 10% of the total number of meters, are described as MED for the purpose of removing the data from the reliability reports to normalize outage events between utilities. Currently there seems to be no uniformity describing the methods used to remove the MED from the indices being reported (Eto & LaCommare, 2012). However, the IEEE 1366 indices have been used for reporting the indices of the distribution system, regardless of the cause of the event, vaguely describing the true reliability for most electric utility distribution systems.

Electric system failure caused by natural or manmade events are allowed to be removed from the indices if the electric utility can justify the event as a MED (Eto & LaCommare, 2012).

The various events causing outage, natural or manmade, have become well documented and identify the vulnerability of the complex and evolving electrical system. Blackout has become an accepted issue among the general population, however, long term blackout to CI can be mitigated to reduce the socioeconomic impacts. However, reducing the impact of blackout requires investment in planning, engineering and development of methods to strengthen the infrastructure producing a resilient system.

The reiteration of definitions mentioned previously will provide context to the subsequent discussion. The definitions of resilience and reliability as defined by the DHS: Resilience is the "ability to resist, absorb, recover from or successfully adapt to adversity" (Homeland Security [DHS], 2008, p. 23). Resilience is commonly used as a requirement imposed by federal and state organizations compelling electrical transmission owners to develop and simulate plans for recovery for the BETS. "Reliability is the ability of the system or its components to withstand instability, uncontrolled events, cascading failures, or unanticipated loss of system components." (U.S. Department of Energy [DOE], 2017, Chapter 4-3). The DOE (2017) further described reliability "The traditional definition of reliability—based on the frequency, duration, and extent of power outages." Hence, the IEEE 1366 indices provide an electric utility the opportunity to self-report the ability to withstand instability and/or the ability to resist cascading failures. "Metrics for generation and transmission are used by FERC and NERC, whereas oversight of reliability at the distribution level is left to state regulatory agencies." (National Academies of Sciences, Engineering, and Medicine., 2017, p. 31).

2.2.2 Measuring the Success of Blackout Restoration

The electric distribution blackout restoration process is planned and executed, and the success is reported by the electric utility. The indices measuring success are a function of the number of customers affected and the duration the customers were out of service (IEEE Std. 1366-2012,). Specifically, the measure of success is in customer minutes of outage avoided. The state agencies document the indices provided by each electric utility providing a measure of an electric utility's ability to decrease the duration of blackout to the largest group of retail consumers. Therefore, restoring power to the largest number of customers encourages improvement to the reliability indices. Restoration to the single CI retail meter that provides service to one of the 16 CI sectors (Exec. Order No. PPD-21, 2013) may be necessary to avert socioeconomic harm. However, the electric utility's measure of perceived reliability is developed through the self-reporting of the reliability indices. Thus, some of the CI experiencing may be inoperable for an extended period of time resulting from the unintended consequences of the electric utility striving to improve upon reliability indices.

The current methods of electrical distribution restoration do not have and/or require models for recovery and "recovery does not begin until the disaster has ceased and the assessment of repair, models and plans for recovery can begin" (National Academy of Sciences [NAS], 2012, p. 4). State regulators provide a review of distribution reliability and regulate the distribution rates that can be charged to consumers. Regardless of the event causing the blackout, recovery procedures are similar and can be developed in advance of an event. Blackout recovery procedures and processes developed by electric utilities are not monitored or managed by federal or state regulators. Blackout recovery performed by electric utilities has developed through alliances between utilities through a network of "mutual assistance from other electric utility resources to respond to large natural disaster to restore damaged facilities and areas devastated by a disaster" (Folga, McLarmore, Talaber, & Tompkins, 2016, p. 21). The restoration process requires days, weeks and in some cases months of reconstructing wood poles, installation of electrical wires and facilities, as opposed to "adapt to adversity" (DHS, 2008, p. 23), before normal consumer activities can resume.

The IEEE 1366 reliability indices allows the electric utility to self-report the total minutes of customer outage (Islam et al., 2014), or duration of outage within the distribution system, defining the duration of the restoration process. State regulators provide review and recommendations of recovery operations and do not manage, monitor or compel electric utilities to perform recovery operations utilizing any specific plan or procedure (U.S. DOE, 2015, p. 30). Thus, CI could be one of the last retail consumers restored from blackout exacerbating the negative effects of the blackout.

2.3 Critical Infrastructure

What services or assets can be identified as CI? "High-value assets of a community are those for which continued operation is essential and urgent for the entire community (e.g., water and power utilities, fuel systems, transportation facilities and systems, communication systems, first responder operations centers, and hospitals)." (National Academies Press [NAP], 2012, p. 69). Indeed, the current method of restoring damaged and devastated electrical facilities must continue in response to natural or manmade disasters. However, the development of a model to provide procedures and processes for incremental restoration also known as "adapt to adversity" (DHS, 2008, p. 23), decreasing the electrical outage duration to CI will reduce an increase in financial losses and will mitigate an increase in rates of morbidity and mortality.

2.4 Literature Describing the need for a Blackout Recovery System

> Lecomte (1998) estimated that the 1998 ice storm that disrupted power to 1,673,000 customers, of whom 1,393,000 were in Quebec, resulted in economic losses of $1.6 billion in Canada and $1 billion in repair costs to the Hydro-Quebec

> and Ontario Hydro systems. A significant fraction of the 28 deaths in Canada and 17 deaths in the United States also resulted from the lack of power (Lecomte, Pang, & Russell, 1998, p. 17); (National Academy of Sciences [NAS], 2012, p. 16).

DHS/FEMA and the DOE identified the need to provide high voltage equipment reserves, non-distribution voltage > 69kV, as a reaction to natural and man-made disasters causing widespread blackout. Natural and man-made disasters have cost the United States billions of dollars in lost revenue and the loss of life. “FERC analysis identified 30 critical substation transformers; in FERC’s simulation, losing nine of these substations (in various combinations) as the result of a coordinated attack reportedly was found to cause a nationwide blackout for an extended time” (Parfomak, 2008, p. 45).

The DOE released a report to congress identifying the need to develop a program and provide spare high voltage transformers to protect the U.S. against widespread cascading failure within the BETS (Department of Energy [DOE], 2017). The concept is to avoid national blackout from cascading transmission failure in the event a high voltage electrical transformer fails unexpectedly. The DOE recommends providing spare high voltage transformers stored in a strategic location to be available as an emergency replacement in the event one of the existing high voltage transformers fails. The Strategic Transformer Reserve (STR) program developed and implemented by the DOE as a solution to the potential of national blackout mitigating socioeconomic chaos. The implementation of the STR developed by the DOE is problematic and complex to implement.

Indeed, the STR program is necessary if one of the high voltage transformers is incapacitated. However, the design and location of the high voltage transformers create significant complexities to the deployment of the STR if needed. High voltage transformers are customized for each installation, are not universal or generic in their construction, thus, providing a spare transformer that is universal in design allowing installation at various locations is very problematic (Parfomark, 2014, p. 5). In addition, the design, availability, long lead times for manufacturing, transportation and specialized requirements for installation create significant challenges that could eliminate the possibility of success (Parfomark, 2014). To illustrate one of the complexities, the image in figure 5 is an actual photo of a high voltage transformer weighing in excess of 500 tons being transported using specialized equipment.

Figure 10. Image of high-voltage transformer being transported in 2008 for Consumers Power using one of only 30 Schnabel rail cars available in the U.S. to transport high-voltage transformers. Retrieved from https://www.powermag.com

The STR developed by the DOE as a method to secure the U.S. electrical system is the primary program for recovery discovered during the literature review process. Blackout in the BETS garners widespread attention (Schuler, 2005) and, in theory, the spare high-voltage replacement program provides a measure of security.

If a catastrophic event disables high voltage transformers, the STR program will, eventually, provide relief from the blackout event. However, the literature review identified that 90% of blackout occurs in the electrical distribution system (Folga et al., 2016), thus, the application of the STR program will not provide blackout restoration to the distribution system. Therefore, dependence upon the STR program to provide relief from blackout, or outage within the distribution system, creates a false sense of security. Thus, a method for incremental recovery from blackout in the electrical distribution system in conjunction with the STR program are necessary and will provide resilience and security against socioeconomic chaos.

> "Assuring that we have reliable, accessible, sustainable, and affordable electric power is a national security imperative. Our increased reliance on electric power in every sector of our lives, including communications, commerce, transportation, health and emergency services, in addition to homeland and national defense, means that large-scale disruptions of electrical power will have immediate costs to our economy and can place our security at risk. Whether it is the ability of first responders to answer the call to emergencies here in the United States, or the readiness and capability of our military service members to operate effectively in the U.S. or deployed in theater, these missions are directly linked to assured domestic electric power" (*CNA Military Advisory Board*, 2015, p. 1).

2.4.1 Presidential and Congressional Directives

Presidential Lessons Learned document from Hurricane Katrina in 2005 identifies the impact on multiple states and was the first widespread disaster that impacted the U.S. after the creation of the Department of Homeland Security (H.R. Res. H.R. 5005, 2002). DHS developed and administered the National Incident Management System (NIMS) and the National Response Plan (NRP) according to the Homeland Security Presidential Directive-5 (HSPD-5, 2003) revised in 2011 (PPD-8, 2011) after the Hurricane Katrina Lessons Learned Report. The report disclosed the affect upon the population and the need to provide additional national assistance from the various federal agencies which resulted in additional Presidential Directives (Townsend, 2006). The lessons learned report from Hurricane Katrina provides identification of critical infrastructures and the emergency support functions necessary, but not readily available after a disaster, to provide critical elements for life sustaining infrastructure for the human population. The report listed the emergency support functions needed for future planning and future proactive federal response to widespread natural disasters. Electricity is the primary critical infrastructure necessary for the operation of emergency support functions. (Townsend, 2006).

"Today when the power goes out, individual customers are essentially on their own until service is restored." (National Academies of Sciences, Engineering, and Medicine., 2017, p. 107). "The analysis of threats and hazards impacting the electric sector is conducted on a national level as well as on a regional level using NERC regional entities." (Risk and Infrastructure Science Center Global Security Sciences Division Argonne National Laboratory [AGNL], 2016, p. 14). However, the impact is only analyzed at the BETS or "grid" and not the distribution system which is the area most vulnerable to electrical outage. "The Department of Homeland Security coordinates security information and preparedness for the nation's critical infrastructure, while the Department of Energy serves as the sector specific lead agency for grid security" (Center for The Study of The Presidency & Congress [CSPC], 2014, p. 19).

Under Homeland Security Presidential Directives HSPD-5 and HSPD-7, the President of the United States charged the Department of Homeland Security (DHS) with developing and implementing plans to create a framework through which the plans and activities of the federal government, state and local governments, the private sector, and nongovernmental entities could be aligned for the purpose of identifying critical infrastructure priorities and developing strategies to protect and restore critical infrastructure and preserve public safety

The literature reviewed from sources that focus on recovery from natural or man-made disasters where there is a wide spread loss of electricity focus on the recovery of the BETS and do not provide an analysis of recovery models necessary for decreasing the duration of power outage to CI that are served from the distribution electrical system. Indeed, widespread loss of the BETS would have a larger impact upon consumers considering the BETS is interconnected throughout North America and supplies electricity between states and electric utilities. However, an attack disrupting the BETS on a national scale would require significant effort and planning to create a national disruption or blackout from an attack on the BETS. 90% of consumers receive their electrical service from the local distribution system. (NAS, 2012, p. 63). Therefore, a coordinated attack upon strategic distribution systems will cause widespread electrical outage to consumers in which the U.S. and local operators are not required and do not have the necessary plans and procedures available to recover from blackout.

Concern has been expressed that private power utilities are not truly prepared to handle a catastrophic loss of electric power event, and that the effects of such an event would be profound on the entire national grid system. (Electric Grid Security, 2012). The federal, state and local regulators and operators are not prepared for a wide scale outage event currently characterized by the Electric Infrastructure Security Council (EIS) as a black sky event. (Electric Infrastructure Security Council website, 2017)

The BETS is a system of financial transactions selling and purchasing high voltage electricity transported over thousands of miles of transmission conductors constructed using steel structures to deliver electricity for use by consumers through the local distribution facilities. The federal and state regulatory agencies require a simulated plan for recovery for a blackout from an attack on the BETS (North American Electric Reliability Corporation, n.d.) but a recovery plan for the distribution system is not required by federal or state regulators. (National Academies of Sciences, Engineering, and Medicine., 2017, p. 107). Indeed, the BETS provides interstate transport of electricity to territorial distribution systems, but the interconnected system of the BETS provides stability to the electrical system nationally. However, small coordinated attacks with multiple EMP devices upon the distribution system will cause widespread blackout. The problem is the lack of planning or regulation requiring electric utilities to integrate plans and methods for recovery after widespread electrical outage caused by the coordinated attacks using multiple EMP devices. (NAS, 2012). Therefore, widespread outage at the distribution level of electrical delivery comprises the greatest risk to the population. Thus, the necessity for the Common Recovery System to provide a model detailing processes and procedures for electric utility operators to provide incremental electrical recovery decreasing the duration of electrical outage to specific CI.

2.5 Literature Review Summary

Society has become dependent upon CI services such as water, storm and sanitary pumps, health care, transportation, commination systems etc. for routine activities (Rudnick et al., 2008). Electric utilities have developed plans and methods for electrical distribution recovery from localized weather-related outage which can be measured using reliability indices. But, reliability of a distribution system defines the utilities ability to maintain the duration and/or delivery of electricity to consumers (IEEE Std. 1366-2012,). Resilience is defined differently by various organizations which have goals that differ in scale, scope and context and typically used as the term to describe protection of the BETS. This study utilizes the following definition to provide an adequate description of resilience commonly used at the BETS level of electrical delivery. Resilience is the “ability to resist, absorb, recover from or successfully adapt to adversity or a change in conditions.” (Homeland Security [DHS], 2008, p. 23). The extended definition provides additional clarity that should be applied to the electrical distribution system. DHS (2008) resilience is the “ability of systems, infrastructures, government, business, and citizenry to resist, absorb recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance." (DHS, 2008, p. 24). For the purposes of this study, the definition of resilience can be extrapolated to define a utilities ability to recover from outages caused by various natural or manmade events providing consumers access to CI services. The term resilience has not been applied to the electric utility distribution system in a manner that will provide a compelling reason for an electric utility to develop or adopt a common model for incremental restoration.

Widespread electrical distribution blackout disrupts and or eliminates the operation of CI ultimately disrupting routine activities of the population affected by the electrical blackout. Wide spread distribution electrical outage from natural events or man-made attacks can cause socioeconomic chaos in densely populated areas "A systematically designed and executed terrorist attack could cause disruptions considerably more widespread and of much longer duration than the largest power system disruptions experienced to date" (National Research Council [NRC], 2012, p. 16). Texas, Florida, Puerto Rico and the Caribbean endured significant economic, health and welfare losses resulting from hurricanes. Currently, federal and state regulators compel electric utilities to produce and simulate restoration activities for the BETS and power plant facilities but do not require restoration plans for electrical distribution blackout. However, the electrical distribution system serves more than 90% of all consumers in the U.S. (National Academy of Sciences [NAS], 2012, p. 63) and is the most vulnerable to attack causing long term electrical outage.

Review of historical literature describing the impact of natural and manmade disasters upon the delivery of electricity to communities identified the significant impact upon populated areas. The communities affected have suffered economic losses resulting from loss of routine services and witnessed an increase in the morbidity and mortality rates resulting from the loss of routine access to CI. Indeed, the study and recommendations to defend against electrical outage and/or increase the robustness of the BETS should be pursued. However, the review of 72 reports from organizations including DOE, DHS/FEMA, FERC/NERC, NAP reports, Presidential Directives, Congressional Testimony, Technical Reports commissioned by the U.S. Congress, White House Lessons Learned of Hurricane Katrina, IEEE Technical Briefs, EEI Technical Reports all provide the same basic recommendation: Develop and disseminate a model to support the planning needed to provide electrical distribution recovery after electrical blackout to mitigate the loss of CI. The recommendation from the most recent report discusses the need for the development of a model to support planning needed to provide electrical distribution recovery at the state or local level of critical infrastructure and should be coordinated by the Department of Homeland Security. The perplexing issue is that despite federal and academic literature identifying the need to develop a model for electrical recovery to mitigate loss of CI, a model to recover from blackout has not been developed or deployed. The significance of not developing a model for electrical distribution recovery has been and will continue to be an increase in disaster related expense and/or the increase in the rate of mortality resulting from losing access to life sustaining facilities.

The importance of functioning heating and cooling systems is forcefully demonstrated by the deaths that occurred from prolonged exposure to cold in the aftermath of the 1998 ice storm in Quebec, and from prolonged exposure to heat in the aftermath of Hurricane Katrina.

Reviewing the literature identified various reports from the NAP suggesting the establishment of a committee to review the existing BETS identifying weaknesses and vulnerabilities in the BETS and electrical distribution system to make recommendations that will strengthen and/or mitigate the impending socioeconomic losses resulting from electrical outage.

Most recently, the NAP published a Consensus Study Report by the Committee on Enhancing the Resilience of the Nation's Electric Power Transmission and Distribution System to identify weaknesses and vulnerabilities in both power systems and in part summarized the following recommendations directed to the Department of Homeland Security and the Department of Energy:

> **Recommendation 7** to DHS and DOE: DHS and DOE should work collaboratively to improve preparation for, emergency response to, and recovery from large-area, long-duration blackouts by doing the following:
>
> - Working with state and local authorities and electricity system operators to undertake an "all hazards" assessment of the natural hazards faced by power systems on a periodic basis (e.g., every 5 years). Local utilities should customize those assessments to their local conditions. (Recommendation 3.2)
> - Developing and overseeing a process to help regional and local planners envision potential system-wide effects of long-duration loss of grid power. (Recommendation 5.3)
> - Evaluating and recommending the best approach for getting critical facility managers to pre-register information about emergency power needs and available resources. (Recommendation 5.5) Renewing efforts to work with utilities and national, state, and local law enforcement to develop formal arrangements (such as designating selected utility personnel as "first responders") that credential selected utility personnel to allow prompt utility access to damaged facilities across jurisdictional boundaries. (Recommendation 6.1)
> - Building off of existing efforts to manufacture and stockpile flexible, high-voltage replacement transformers, in collaboration with electricity system operators and asset owners and with support from the U.S. Congress. (Recommendation 6.6)
> - Developing a model for large-scale cyber restoration of electricity infrastructure. (Recommendation 6.9) (National Academies of Sciences, Engineering, and Medicine., 2017, p. 139)

Historical literature identified three primary types of disasters causing electrical distribution blackout: natural related catastrophes, operational errors or terrorist attack. The type of disaster causing electrical outage does not necessitate customized solutions for incremental electrical recovery to CI, but can utilize the same logic, methods and procedures for recovery regardless of the cause of the outage. Therefore, the type of event, natural or manmade disaster, does not require a specific description of the event to develop a model to support the planning for recovery. The process and procedures developed by the CRS for recovery are applicable, with minor modifications, to any electrical distribution system.

CHAPTER 3. METHODS & PROCEDURES

The author developed CRS from 28 years as a utility engineer observing the methods of crisis and outage restoration. Current methods and procedures for restoration do not prioritize critical locations needing electrical restoration. The author identified areas of improvement for electrical restoration to CI and developed an algorithm to provide process and procedures for incremental electrical restoration to CI.

The literature identified the problem of not having electrical power to critical infrastructure during blackout. The significance of blackout is the financial impact estimated to be more than $150 billion per year in addition to the negative impact upon the health and welfare of the population. Presidential Policy Directives, Congressional Reports, technical papers have all identified the need for a method, process or plan to provide restoration to the electrical system providing power to CI. However, a system to provide incremental electrical restoration to CI has not been deployed. Is the development of a model possible? The short answer is Yes.

Research question 1: Can a plan be developed that will provide electric utility owners with a method or plan to provide incremental recovery decreasing the duration of blackout to critical infrastructure? This research developed a model to satisfy the research question and satisfy the demands and recommendations identified in the literature. The method used in this research to develop a model for incremental restoration is Model Based System Engineering (MBSE).

MBSE is a standard by which systems are detailed prior to design commences. IEEE Std 15288-2004 (Adoption of ISO/IEC Std 15288:2002): Adoption of ISO/IEC 15288:2002 Systems Engineering-System Life Cycle Processes. 2005. Engineering of a system begins by representing all of the external entities that may interact with the system (Wymore, 1993, p. 5). The System

Context Diagram is a block diagram representing all of the inputs and outputs at the highest level of the process that can interact with the system. The system hierarchy begins by defining the context where the system will operate or function. Diagrams were developed with data from the review of literature and the experience from 28 years of engineering observational experience in the management of blackout restoration. 28 years of blackout restoration provided the foundation to create an algorithm for restoration. The literature and algorithm provided the knowledge to begin development of a method and diagrams to isolate the electrical system ultimately allowing incremental electrical restoration to CI.

3.1 Method

The process of decomposing the existing transmission and distribution electrical system employed a middle-out approach involving a multistep iterative process. “Middle-out engineering is generally implemented on projects that require system improvement” (Vitechcorp webpage, n.d.). The methods employed to develop an MBSE process evolves from a flow chart, or block diagram, to MBSE diagrams divided into key diagram types. Structure, behavior, requirements and parametric diagram types identify the process and procedures, customized to individual systems, to begin the process of decomposing the electrical system.

The first step to define the existing system is to define the electrical system that will be decomposed. Defining the system requires collaboration with the electric utility operators and engineers will identify the basic process, specific to their utility, necessary to isolate the electrical system to develop a detailed requirements diagram. This study utilized public data; thus, a detailed requirements diagram could not be developed. The next step is to develop a flow chart or block diagram that provides a universal decomposition depiction of the electrical system with respect to the generic requirement: isolate the electrical system. The flow chart in Figure 11 below depicts the basic process of isolating the electrical system after blackout.

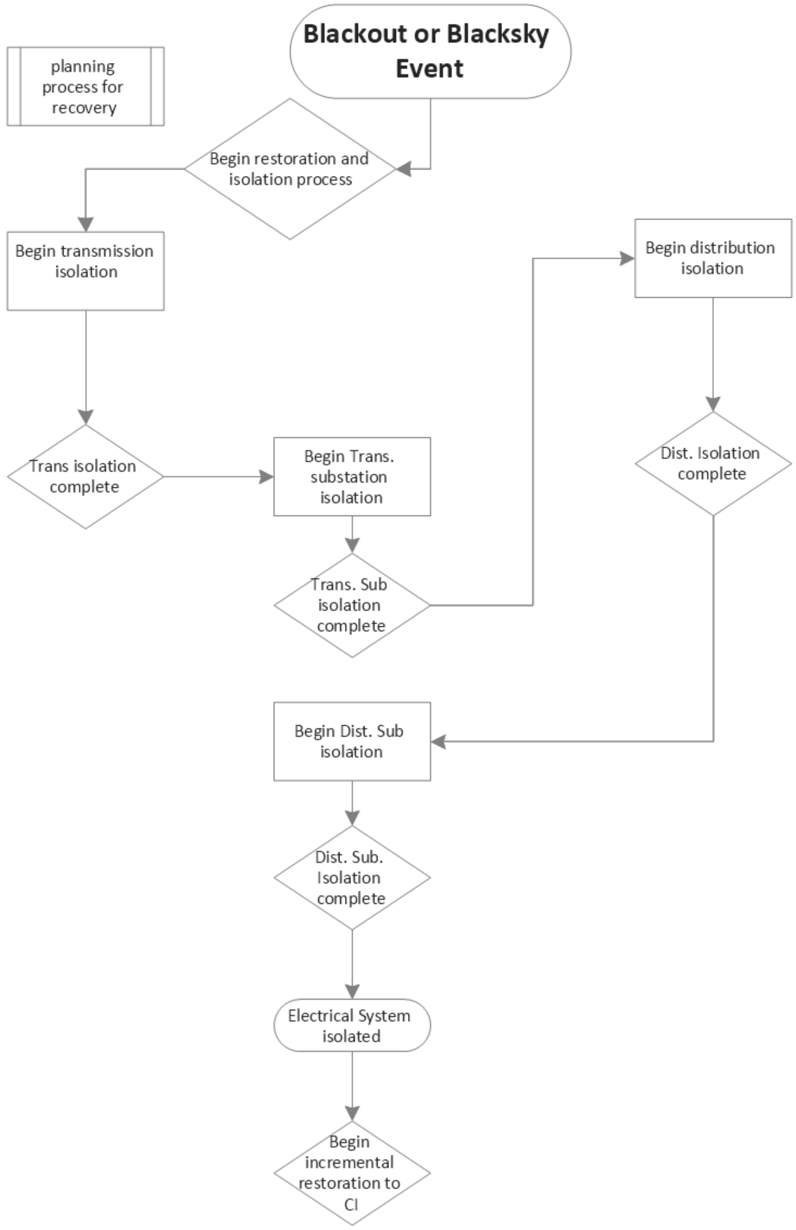


Figure 11. Basic flow chart of process to isolate electrical system after blackout.

The flow chart or logic diagram in Figure 11 provides the foundation to develop the CRS algorithm. The basic logic of the algorithm is to isolate the electrical transmission through the distribution system serving the identified CI. Requirements for the model are simple: isolate the electrical system to allow application of incremental electrical restoration. The CRS Algorithm in Figure 12 below shows the logical process of isolating the electrical system after blackout and prior to the application of incremental electrical restoration. Basic process and procedures for isolation are common to all electrical utilities receiving transmission into a substation transformer to transform the high voltage to lower voltage for distribution to retail customers (Energy Information Administration, n.d.). Figure 2 on page 24 provides a simple representation of electricity production and delivery process. Requirements for isolation in a specific electric utility system are proprietary and will be detailed during the CRS design process.

The algorithm begins by isolating the transmission system that enters the substation identified as a distribution substation in Figure 2. Generally, the transmission isolation process begins outside of the substation until all electrical connections have been disabled and concludes by disabling all electrical connections inside the substation with respect to specific specifications. Regardless, the logic of isolation requires the same basic methods while accounting for any procedural sequencing to satisfy stakeholders.

Isolating the transmission system can proceed in parallel with isolating the distribution system from the substation transformer through the identified distribution locations to be isolated. The basic manual process and procedures for isolation are common to all electric utilities. Applying the logic of the algorithm to any electrical system employs the basic requirements: isolate the electrical system, then apply incremental electrical restoration as depicted in Figure 12 below.

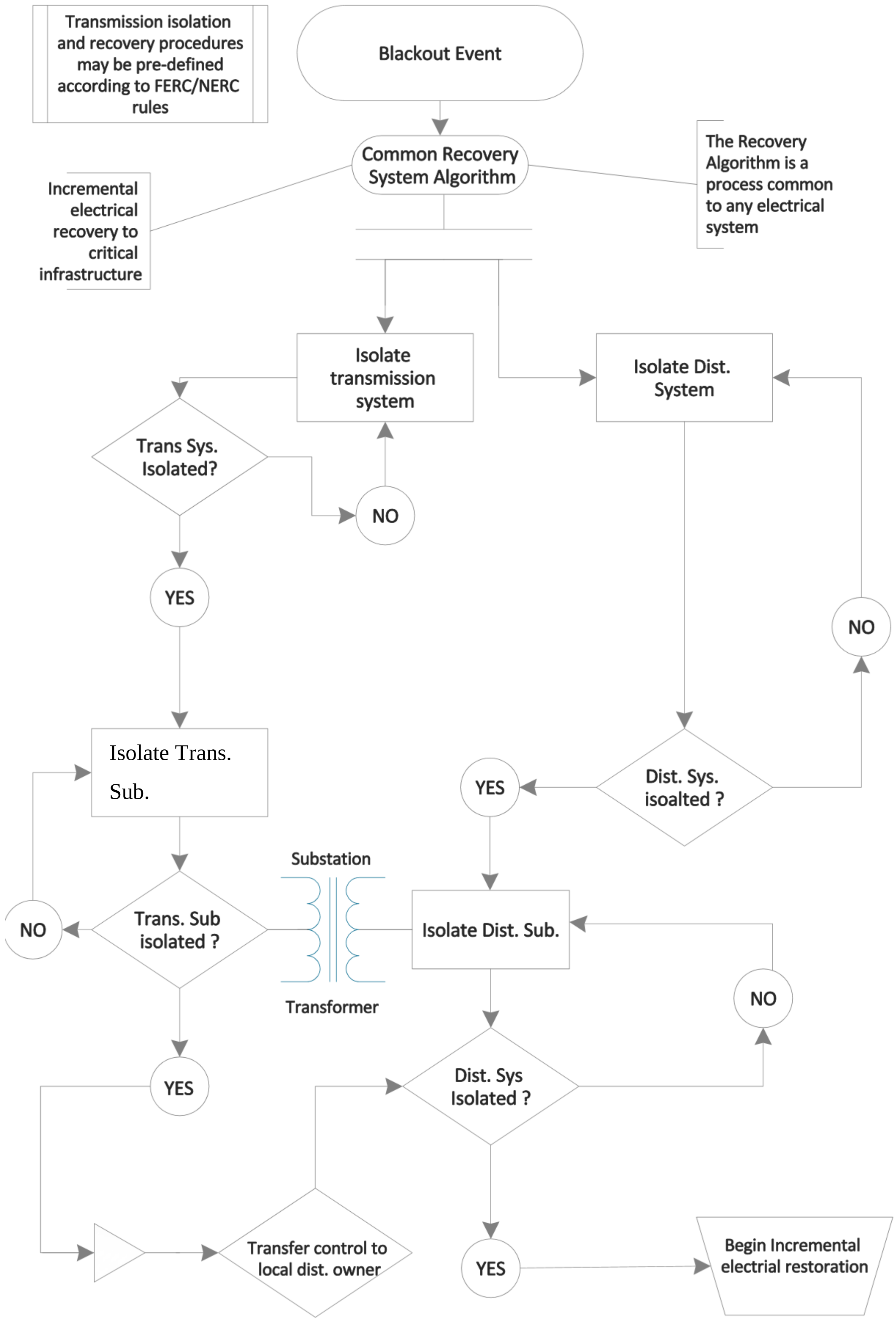


Figure 12. CRS Algorithm depicting the process of isolating the electrical system after blackout allowing the application of incremental electrical restoration to CI

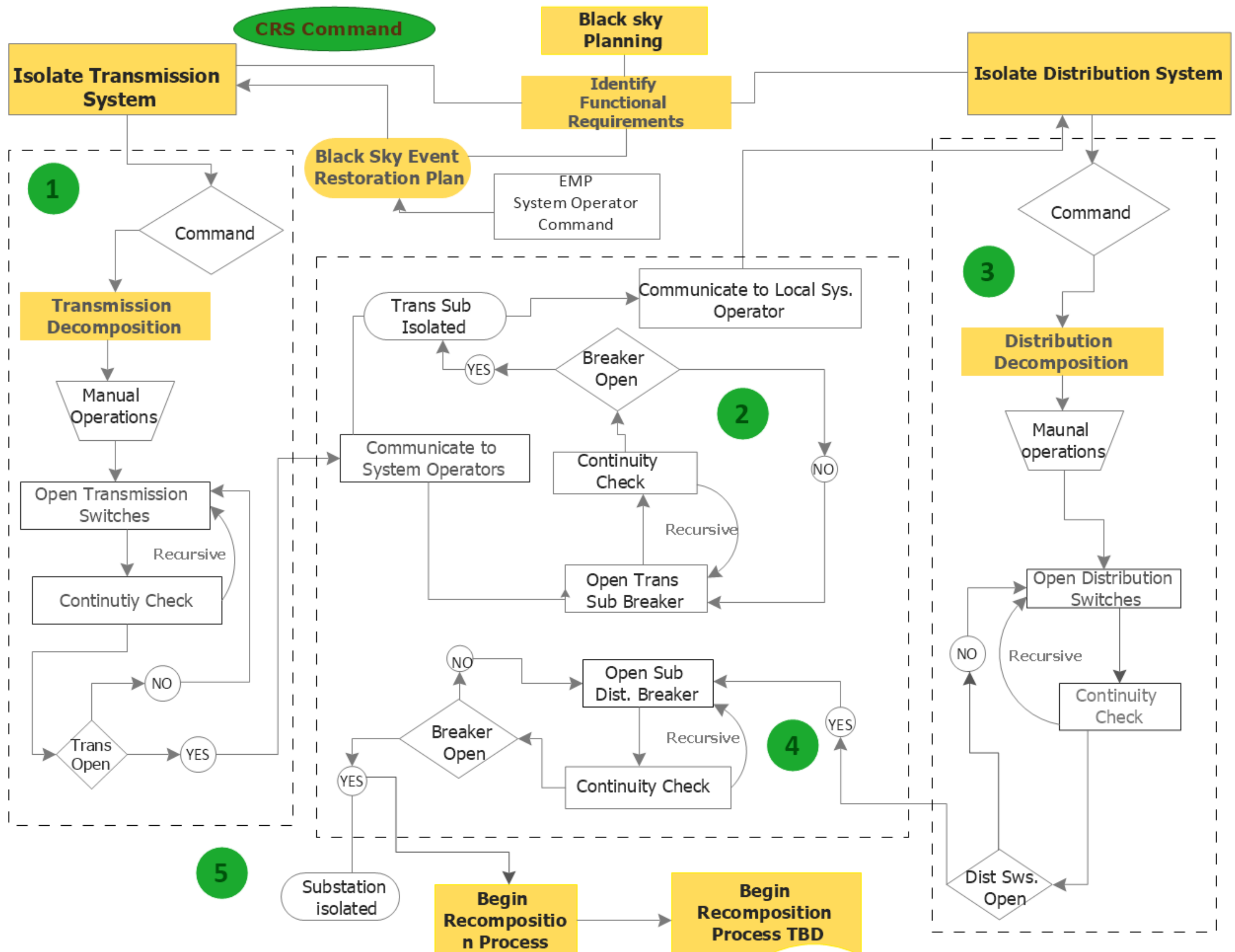


Figure 13. Block diagram created by referencing the algorithm to group the activities in sequential procedures to begin process of isolating the electrical system.

This study utilizes behavior and structure diagram types. Decomposing the system to develop MBSE diagrams can be achieved by referring to the algorithm block diagram to define additional activities within the context of the structured language and diagrams of MBSE. Each diagram created is a layer decomposing the structure and behavior of the electrical system. The Electric utility operators and engineers can provide specific information to decompose the system to develop requirements and parametric MBSE diagrams specific to an existing electric utility's system. The first diagram created using Genesys is the IDEF diagram. The basic function of an IDEF is displayed in Figure 14.

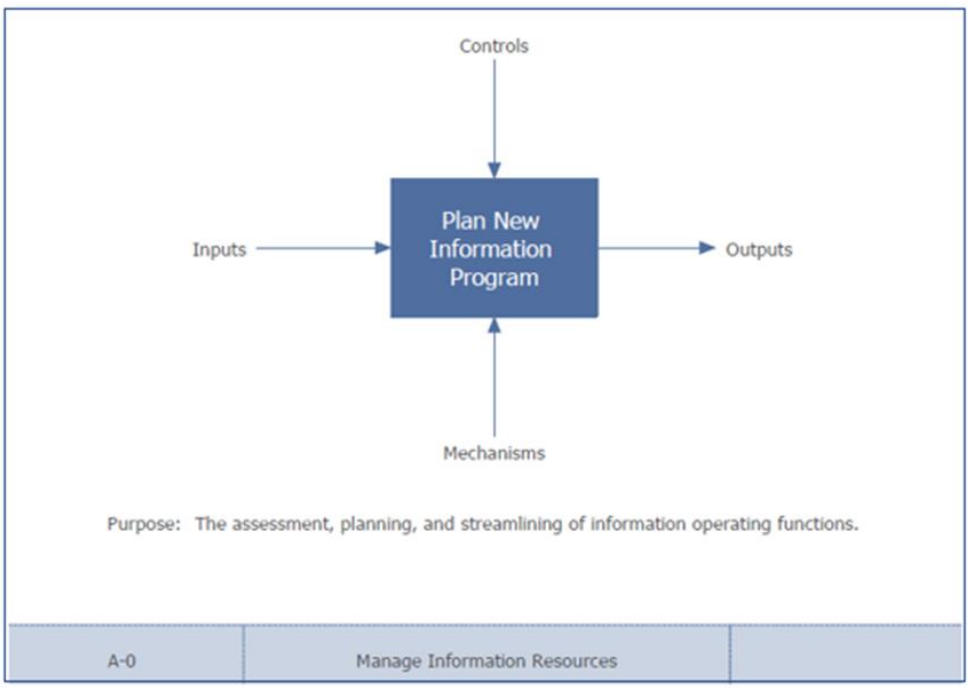


Figure 14. Basic IDEF0 diagram showing inputs transformed into outputs

"IDEF0 is not included in SysML as a modeling technique, However, IDEF0 has gained wide acceptance and standardization and used successfully for decades as an approach to start the modeling process" (Buede, 2009, p. 85). Genesys is an integrated modeling platform that provides end to end generation of structure and behavior diagrams (Vitech Corp website, n.d.). Creating the IDEF0 simultaneously created the EFFBD diagram in addition to other diagrams within the MBSE methodology. The design and creation of an IDEF0 diagram shown in Figure 15 allowed automatic creation of the EFFBD.

IDEF0 provides the first step in the modeling process to identify inputs being transformed by functions to produce outputs. IDEF0 provides the logical process of decomposing the electrical system with respect to various transmission and distribution stakeholders to create diagrams detailing the structure and behavior of a system.

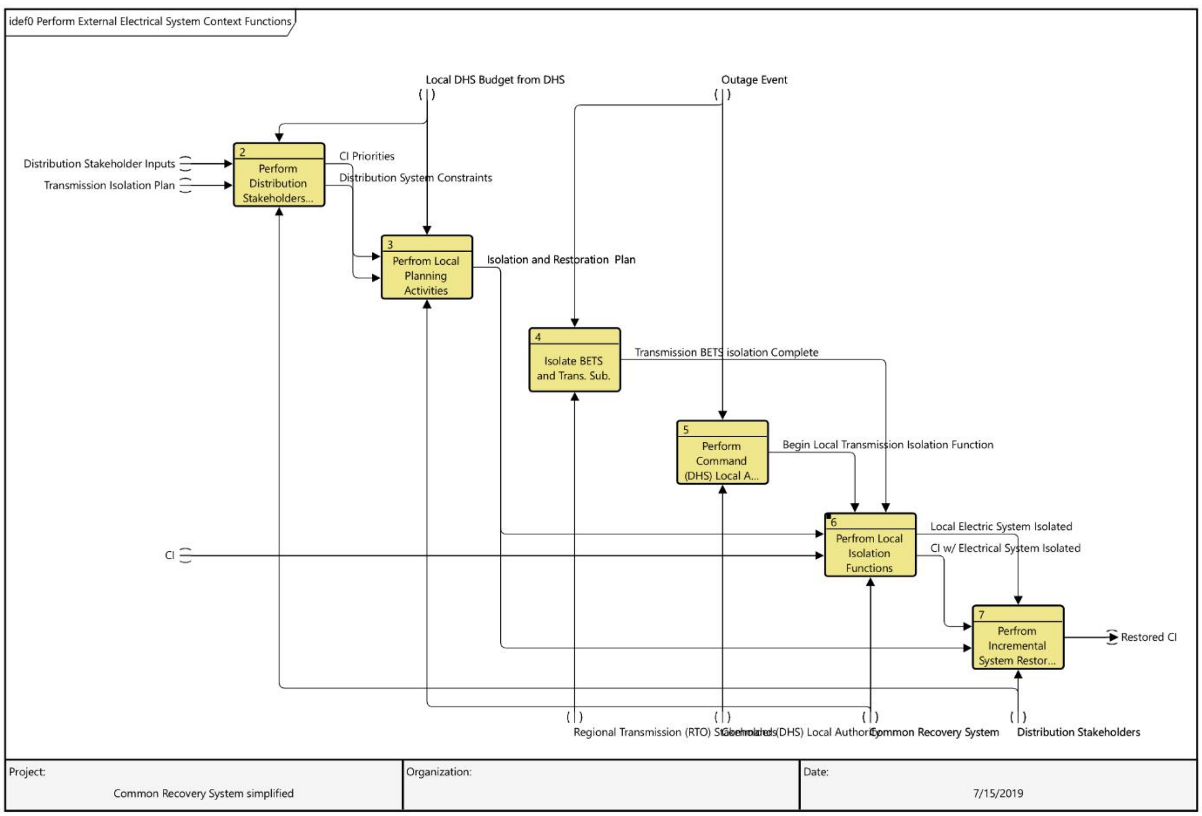


Figure 15. IDEF diagram decomposing the electrical system showing inputs to functions to produce outputs

Utilizing the modeling capabilities of Genesys provides the ability to create an IDEF0 as the foundation for creating additional diagrams. MBSE diagrams are created from the IDEF0 refining CRS to allow additional definition of the process. Diagrams of the electrical system specific to each utility can be created showing specific detail within the specifications and standards relative to individual electric utilities. The block diagram in Figure 10 provided the logic necessary to create the IDEF0. Genesys automatically created the EFFBD shown in Figure 16 below.

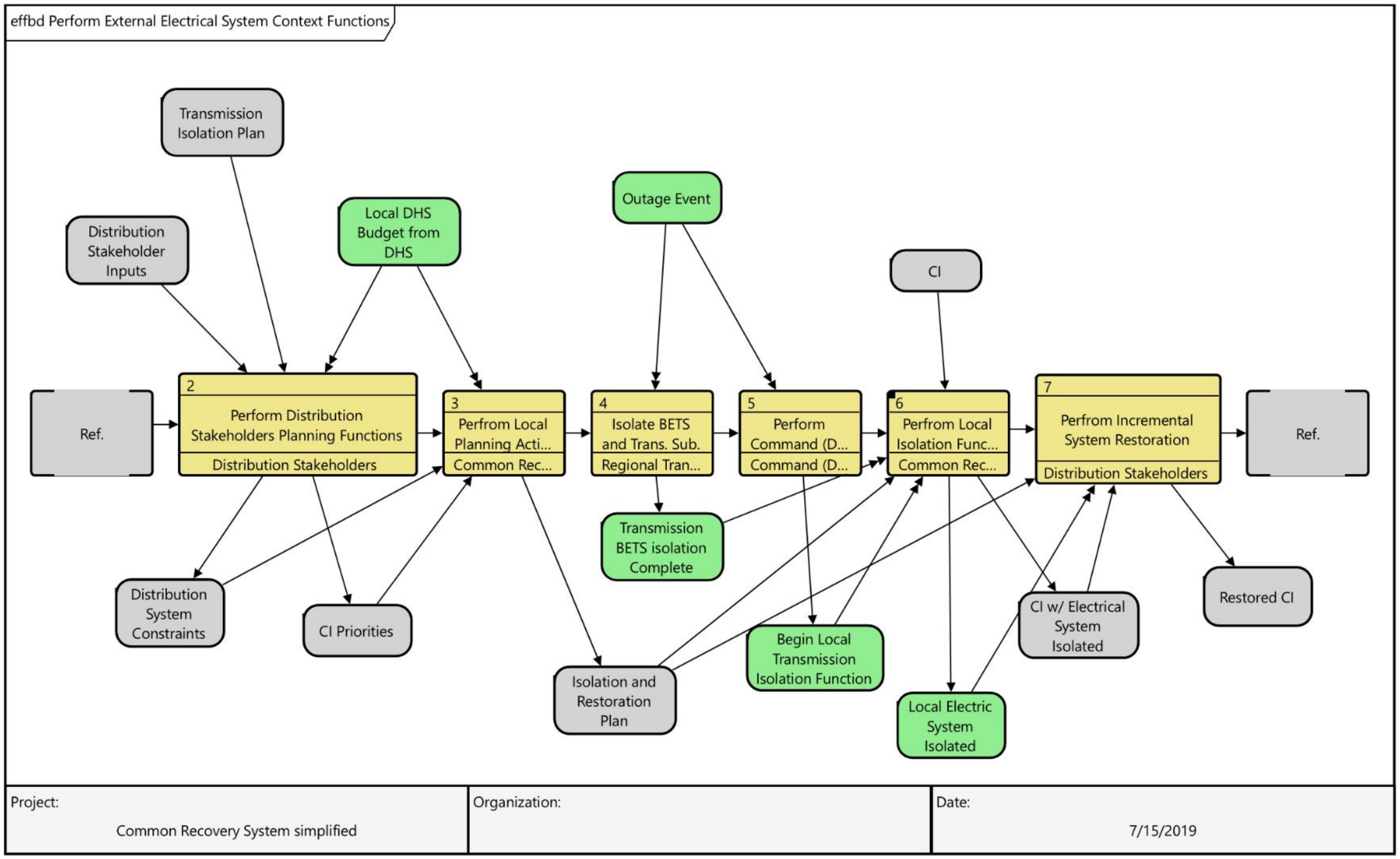


Figure 16. EFFBD diagram created from the IDEF0 showing the functional activities to isolate the electrical system

Block diagrams depicting the CRS algorithm provide the information necessary to begin the design of the IDEF0 and EFFBD diagrams. Additional diagrams are automatically generated in Genesys providing additional decomposition of the isolation process. The activity diagram in Figure 17 decomposes the inputs, outputs and elements into the activities required to isolate the electrical system.

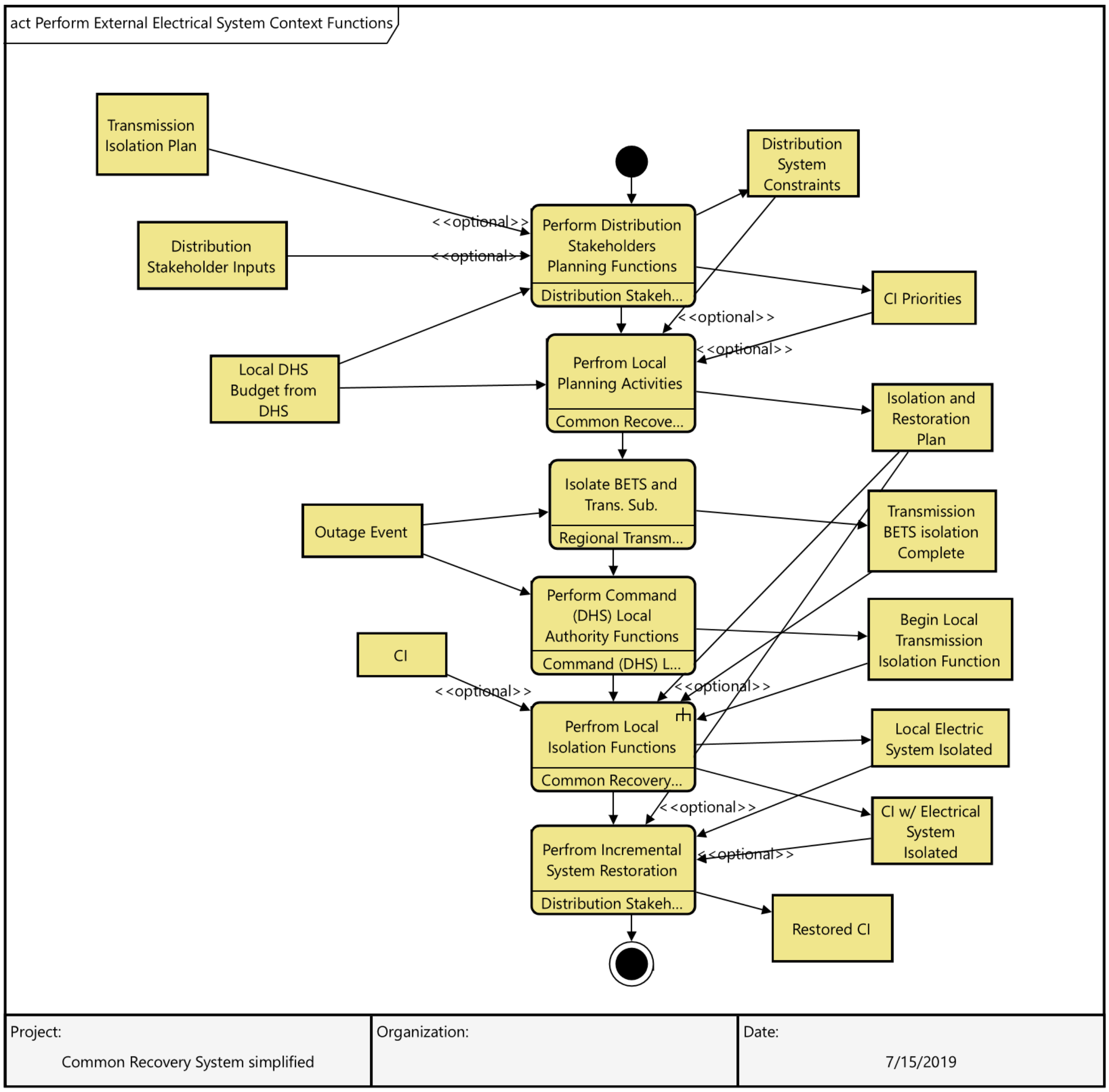


Figure 17. Activity diagram decomposing electrical system isolation process

IDEF0 diagram provides an overview of the system processes and procedures necessary to isolate the electrical distribution system serving CI. The IDEF0 diagram provides the foundation to define the system of process and procedures necessary to isolate the electrical structure to provide incremental electrical recovery to specific CI.

The development of an IDEF0, EFFBD and activity diagrams provide graphical representation of the process to isolate a basic electrical system. The IDEF0 diagram defines functions of components with inputs and outputs identifying the decomposition of the electrical system. Defining the electrical distribution system with MBSE diagrams provides an architecture and functionality of an existing system.

Genesys provides fully integrated diagrams providing functional simulation of the logic defined in the system model. Genesys simulation process provides traceability sequence of functions in the model to identify any conflicts between functions. Simulation of the model is dependent upon specific requirements for each electric utility. Validation through simulating functional flow provides traceability through the isolation process to verify the operation of the model.

3.2 Theoretical Framework

The literature review established the need for a systematic plan or model to provide incremental electrical recovery to power CI after a blackout event. The absence of a model for incremental electrical recovery can cause significant socioeconomical harm. Theoretically a model can be developed to provide incremental restoration to CI mitigating socioeconomic harm. Thus, the development and application of a model for incremental recovery will provide relief from potential harm caused by blackout.

3.3 Conceptual Framework

The development of a model to provide incremental electrical restoration is conceptually simple; model the procedures necessary to isolate the electrical system between the source and load allowing for subsequent electrical restoration to specific CI. The concept utilizes three steps necessary to develop a conceptual framework for incremental recovery: 1. Identify the components of the system necessary for electrical delivery; 2. Develop a process to isolate the electrical delivery components serving specific CI; 3. Provide locations where electrical recovery can be established providing power to CI. The three steps required to develop the model are conceptually simple. However, each individual electric utility may require specific methods and procedures to establish isolation and subsequent incremental restoration can be complex. The utilization of an established method to develop the model reduced the complexity into structured diagrams using a structured language to describe the logical and progressive model of decomposition.

The logical progression of decomposing the electrical system into individual components and requirements can be achieved by using the principals of system engineering. Wayne Wymore, considered the father of Model-Based System Engineering, defined system engineering as “the intellectual, academic, and professional discipline the principal concern of which is the responsibility to ensure that all requirements of a bioware/hardware/software system are satisfied throughout the life cycle of the system” (Wymore, 1993, p. 5). The academic work by Wayne Wymore established MBSE as a discipline that can be used to define a new system or provide system improvement to an existing system. The technical structure and operation of the electrical system was designed and implemented in response to growing consumer demand. The system was developed prior to the application of system engineering tools and techniques. Therefore, the system is decomposed, or reverse engineered, from the middle out to define the components and functions of the existing system using MBSE.

3.4 Data Collection

The data collected for this study was adopted from a historical blackout event in Texas. Specifically, the data collected from the USGS map in Figure 18 identifying the impact and consequences from hurricane Harvey in Houston Texas (Urban Data Platform Kinder Institute for Urban Research [Kinderudp], 2017) were used as inputs to validate the model.

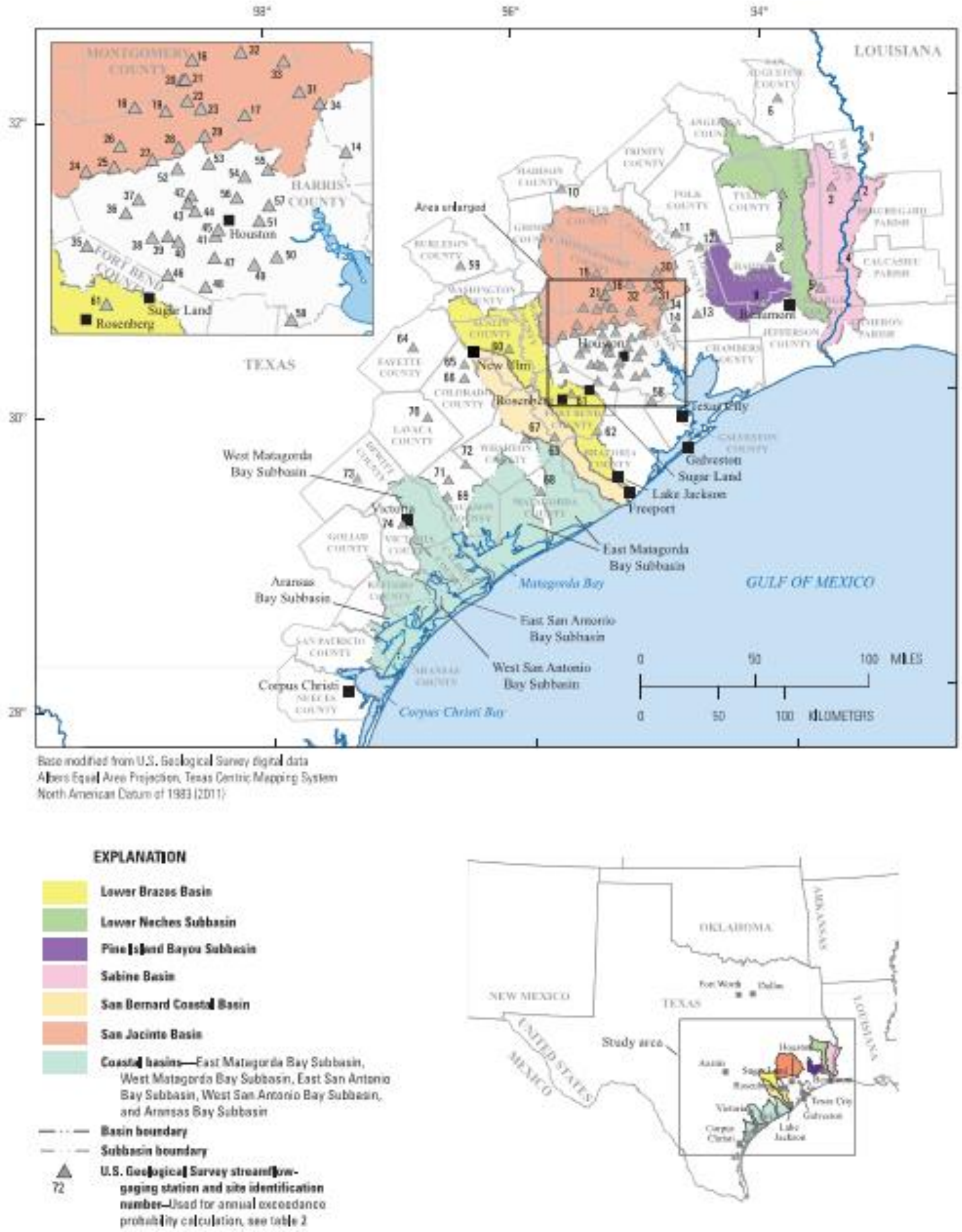


Figure 18. Area of flood inundation in Houston Texas are from hurricane Harvey. Retrieved from https://pubs.usgs.gov, Report 2018-5070 6-17-2019

The CRS prioritizes substation location(s) by aggregating the prioritized CI in closest proximity to an electrical substation as the method inferred from the literature.

“Recommendation 6 (DHS) Take the lead in initiating planning at the state and local level to reduce the vulnerability of critical services in the event of disruption of conventional power supplies and offer pilot and incremental funding to implement these activities where appropriate." (National Research Council [NRC], 2012, p. 109).

This validation of the CRS was achieved by identifying specific CI locations in storm inundated areas and prioritizing the locations to a geographic boundary in close proximity to specific substations. The GIS locations were uploaded into QGIS mapping and spatial tools defining priority locations. Priority locations were determined from the proximity of CI to a distribution substation. Proximity is determined by distance between load and source within voltage drop criteria. The aggregation of CI to substations are collected into an area defined by a polyline in QGIS and labeled as PL. The PL are weighted according to severity of the events within each location and weighted using Rank Sum methodology to determine the location or substation where incremental electrical restoration to CI should begin.

The geographic boundaries must contain various CI and be within a reasonable proximity, defined by electric utility engineering standards, to an electrical substation. The reasonable proximity will ultimately be determined by CI operators and electric utility managers based upon specific criteria of the electric utility and operating characteristics of the CI. The electric utility territory utilized for this research has a requirement of 5% maximum voltage drop or under voltage from the source to the load imposed upon the electric utilities by the Public Utility Commission of Texas (PUCT) (Public Utility Commission of Texas, n.d.). The construction and conductor standards for Center Point Energy, the utility serving Houston, are not published to provide specific information regarding conductor sizes. Therefore, the rural electric association standards published by the National Rural Electric Cooperatives (National Rural Electric Cooperative Association International [NRECA], 2018) will serve as the guidelines for conductors serving residential and commercial electric consumers. Various electrical engineering calculations are typically utilized for the design of an electrical distribution circuit providing service for residential, commercial and industrial customers. Voltage drop calculations provide the information necessary to determine proximity of CI to substations.

This study utilized a proximity between CI of a one-mile radius from the electrical substation. One mile of three phase conductor, or one circuit mile, was chosen to provide an established industry standard method of determining distance of conductor from a substation to consumer loads. For the purpose of this study, 1.0 circuit mile (1 mile per conductor) of electrical conductor size 334.6 kcmil Al is the common size of conductor in general use by electric utilities serving residential and commercial facilities in Texas (National Rural Electric Cooperative Association International [NRECA], 2018). The distance and conductor size provide appropriate under voltage tolerance abiding by the PUCT rules. The voltage drop calculation formula does not account for the various complexities in impedance, power factor and relaying calculations that can be implemented by various utilities. For the purpose of this study:

Basic voltage drop equation for a single-phase conductor for one mile =

DeltaV=2I(k-factor) L (Warne, 2005, p. 266)

I = current (amps)

k-factor = factor for aluminum conductor

L = length of circuit (ft.)

336.4kcmil = 336,400 mils

I=513 maximum operating amps for 336.4kcmil ("Conductor handbook," 2018)

Use 513 amps for total load at end of circuit.

1.0 miles = 5280Ft./mi. *(1.0mi) = 5,280ft.

DeltaV = [2*513amps *(21.2)*5,280]/336400 mils = 341.4 volts

5% of 7,200 volts = 360 volts Therefore, the calculated voltage drop, 341.4 volts, does not exceed the 5% allowable, 360 volts, imposed by the PUCT and IEEE 1453-2015 standard recommendations.

The CI locations were identified using public data from the City of Houston as inputs to QGIS to provide point data locations of electrical substations around the city of Houston Texas. Each electrical substation is within 1-mile radius to locations described by DOH/FEMA (Department of Homeland Security, n.d.) representing CI such as, hospitals, trauma centers, police stations and fire stations. The CI locations are available through public accessible SHAPE files from the City of Houston (City of Houston Geographic Information System [COHGIS], 2018).

The electrical substations were selected using public data file identifying transmission lines in Texas allowing magnification of the Houston area to identify the convergence of electrical transmission lines (FEMA, 2017). High voltage transmission lines provide electricity to electrical substations ultimately providing service to various types of consumers. Electrical substations must have high voltage transmission lines entering the substation to transform the electricity into usable power to serve downstream consumers. Thus, transmission lines typically converge at substation locations.

The transmission line data file was opened in QGIS to identify the convergence of transmission lines at a substation indicating the transformation of electricity providing service to the Houston Texas area to four types of consumers: residential, commercial, lite industrial and heavy industrial. The electrical substations may provide electrical service to heavy industrial customers, transmission voltage, and not have the capability to provide electrical service, distribution voltage, to the other three types of consumers. Therefore, substations perceived to provide service to heavy industrial customers were not utilized as PL. Thus, in some instances the electrical substations appear to provide heavy industrial customers, such as oil refineries, with service and may not provide electrical service to the surrounding area.

CenterPoint Energy electric utility territory has multiple PL that are ranked by assigning a weight or importance of each PL. The development of PL within the territory of the electric utility are ranked from 1 to 5 based upon the proximity of CI to an electrical substation. Figure 19 below shows the QGIS map with identified PL.

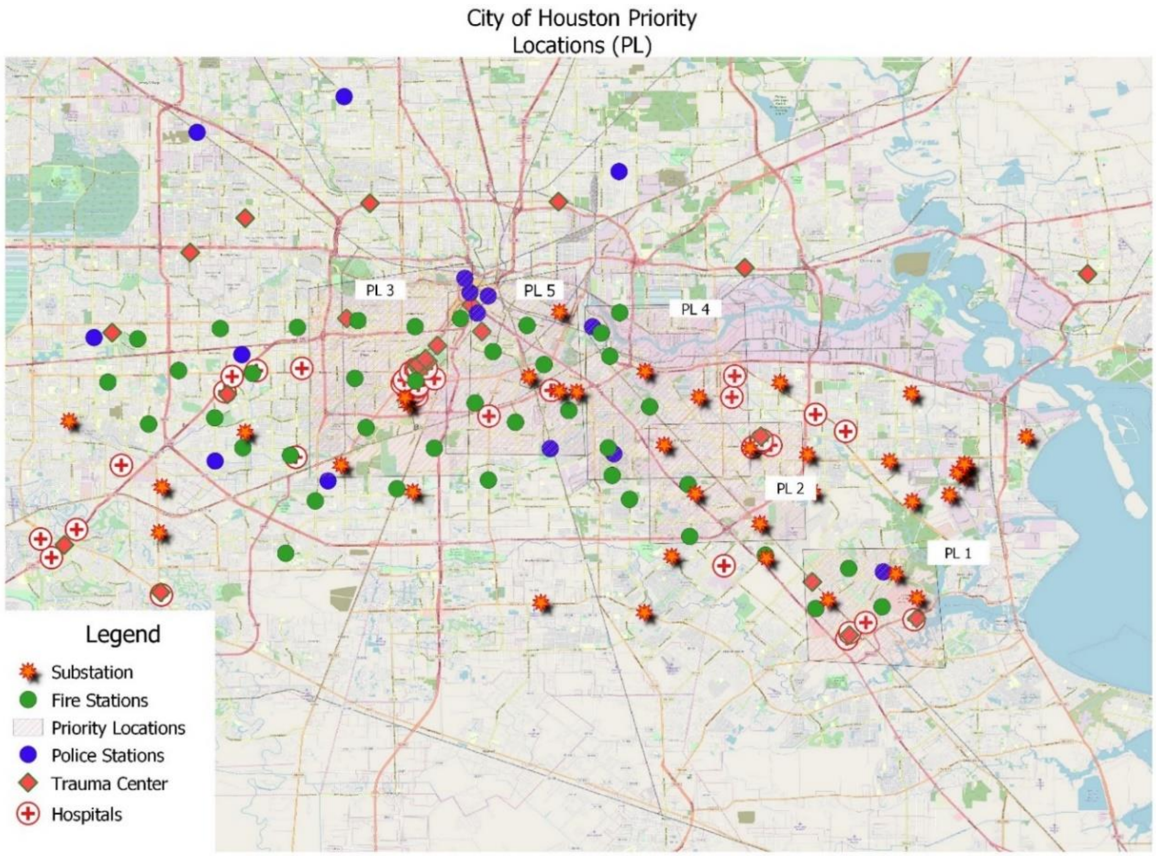


Figure 19. QGIS map showing PL within the 2017 flood inundated areas in the city of Houston

CRS developed in this study can be customized for each electric utility prior to an event causing blackout. During actual blackout events, the rank for each PL will be determined based upon the location of the blackout and the impact upon the population. Thus, an event in a specific quadrant of an electric utility territory might be weighted differently depending upon the location of the blackout. During real time blackout restoration, the application of the CRS will be specific to the weighting process described above.

Genesys software was utilized to develop a system model identifying the process necessary for an electric utility to isolate the electrical system around PL allowing incremental electrification to CI. The method to provide incremental electrical power from the prioritized substation is determined by the individual electric utility. The Common Recovery System (CRS) utilizes MBSE diagrams while using QGIS data to determine PL as inputs into the electric utilities proprietary outage management software detailing the recovery location. The PL inputs to the model provide the utility locations for the application of incremental electrical power to specific CI. Electric utilities will dispatch lineman and technicians to specific PL to begin incremental electrical restoration.

The recommendation emphasizes that DHS develop a committee utilizing the resources of the local DHS in each community to determine different high-value assets or CI that will be included in the priority locations. Each community may require specific power requirements dependent upon variable weather conditions. For example, Arizona may have different needs in February compared to Minnesota in February.

3.4.1 Data Manipulation

The public data collected for each CI consists of latitude and longitude geographical information. Spreadsheets were created for each CI to sort the GIS information numerically. The

GIS information for each CI was copied into a single spreadsheet labeled PL to group the GIS locations by proximity to one another and proximity to a substation. 5 PL locations were identified by aggregating the latitude and longitude of each CI in close proximity to a substation. PL 4 and 5 locations were weighted the lowest since the data available did not indicate the presence of a police station in proximity to the other CI locations. The PL locations are identified on a QGIS map using a polyline, see Figure 19, to identify the aggregated CI.

3.5 Method Summary

The following are the steps used to develop CRS from the algorithm:

1. Create an abstract logic diagram or flowchart of the components in a basic electrical system see Figure 11.
2. Develop a logic diagram or flowchart depicting the steps necessary to isolate an electrical system see Figure 13.
3. Using the algorithm, Figure 12, and logic block diagram, Figure 13, create an IDEF0 diagram, Figure 15, depicting the process necessary to isolate the distribution circuit to begin application of incremental electrical restoration.
    a. The IDEF0 diagram provides the data and logic flow necessary to automatically create the EFFBD in Figure 16.
4. Using QGIS and open source data, identify CI locations by latitude and longitude within the city of Houston, see Appendix A.
5. Create table of locations for CI using latitude and longitude from public data, see Appendix A.
6. Define latitude and longitude of CI locations to determine proximity locations, see Appendix B.

7. Create map of CI locations in QGIS, see Figure 19.
8. Develop map of PL for the city of Houston, see Figure 19, from open source data to prioritize aggregated CI relative to locations of severe damage.

The electric system was first modeled with respect to the algorithm in Figure 12 using an abstract model or diagram in Figure 13 as a mock-up or flow chart to depict three systems, transmission, substations and distribution, within the single system context referred to as the electrical system. An abstract model based upon the City of Houston public data was used as a reference to create MBSE diagrams using the SysML-compliant modeling software Genesys. The MBSE model created using Genesys provides graphical representations of inputs transformed into outputs by functions that can be simulated within diagrams to validate the function of the model. The IDEF0 diagram, identifies controls, inputs, outputs, and mechanisms of the electrical system. IDEF0 "provides a very useful graphical representation of the interaction of the functional and physical elements of a system." (Buede, 2009, p. 85). The IDEF0 diagram in Figure 15 represents the electrical system context with the transmission system and the distribution sub-system. Controls come into the top, inputs enter on the left side being transformed into outputs by a function inside the box with data, and a mechanism that performs the function entering from the bottom allowing outputs coming out on the left.

The MBSE software Genesys provides automatic generation or vertical integration of diagrams with the completion of a single functional diagram. The development of an EFFBD, see Figure 16, provides details of the basic functions required to isolate the electrical system. Genesys was utilized to refine and simulate the electrical distribution system context as the system is transformed from a functioning electrical system into electrical isolation allowing the process of incremental restoration to CI. Traceability of the model is demonstrated through the simulation activities provided within Genesys.

CI identified within a boundary in close proximity to an electrical substation were aggregated to develop a PL. The data, or PL, were conditioned using a weighing method to provide inputs to an accepted weighting technique. The PL were weighted by the author and refined by ROC to identify the locations where the CRS should be applied. Thus, incremental electrical restoration is achieved using the CRS to provide CI for the affected population.

Three functions were employed to develop a model for electrical distribution recovery: 1. Analysis of historical literature to identify CI necessary for the affected social structure. 2. Spatial analytics software, QGIS using public GIS data to identify the CI items of priority in develop priority locations. QGIS will use ESRI mapping structure to identify CI relative to electrical substations as priority locations where the CRS can be applied. 3. MBSE using system engineering software tools Genesys from Vitech (Genesys 6.0) using the priority locations as inputs into functions to develop outputs to decrease the duration of outage to CI. MBSE utilizes blueprint graphical representations with structured analysis to describe or depict a scenario. "Structured analysis (SA) combines blueprint-like graphic language with the nouns and verbs of any other language to provide a hierarchic, top-down, gradual exposition of detail in the form of an SA model." (Ross, 1977, p. 1). Genesys provides vertically integrated graphical models and SysML-compliant language allowing ease of integration into other MBSE software.

The need for a method to restore electrical service to CI is becoming increasingly necessary. Literature identifies past natural disasters and thwarted threats that could have caused significant harm without the inclusion of a model to restore electricity. "Many threats to critical electricity infrastructure are universal (e.g., physical attacks), while others vary by geographic location and time of year (e.g., natural disasters). Threats also range in frequency of occurrence, from highly likely (e.g., weather-related events) to less likely (e.g., electromagnetic pulse).” (The White House, 2014, Chapter 4-25). “Public threats from Russia, China, North Korea and Iran in their military doctrines advocate using combined attacks by EMP, cyber and sabotage against electric grids and other civilian infrastructures” (Pry, 2015, p. 49). “The freighter, Chong Chon Gang, owned by North Korea was captured in panama heading into the Gulf of Mexico with two nuclear-capable SA-2 missiles hidden under 10,000 tons of sugar.” (Pry, 2015, p. 45).

This study distilled the cause of electrical outage as natural or manmade disasters that cause electrical distribution blackout creating socioeconomic chaos. Loss of electrical power to critical infrastructure has caused increase in damages to commercial and residential structures in addition to increase in mortality and morbidity rates among the affected population. Future disasters have been estimated to exceed $150 billion in damages. The losses from man-made or natural events impact the financial markets, insurance companies and negatively impact mortality and morbidity rates. The development of the CRS and application of the CRS to the impact of Hurricane Harvey in Houston provides relief to the community affected by the disaster.

CHAPTER 4. PRESENTATION OF DATA AND FINDINGS

The application of the CRS to the areas affected by blackout caused by hurricane Harvey in Houston provide the opportunity for the electric utility to provide incremental electrical restoration to CI. QGIS was used to develop maps showing the aggregated CI within 1 mile to electrical substations. Applying the CRS to the areas in Houston affected by hurricane Harvey would have decreased the socioeconomic losses by providing incremental electrical power to CI to provide resources for the population and emergency responders. Specific data, location, duration, severity etc., of the blackout to specific locations are not available, thus results specific to incremental restoration cannot be ascertained. However, incremental electrical restoration would have been available providing the CRS could have been developed prior to the weather-related event and applied to the electrical system subsequent to the event.

4.1 Data

The development of the CRS requires geographical boundaries containing various CI be within a reasonable proximity, defined by electric utility engineering standards, to an electrical substation. The reasonable proximity of CI will be determined by CI operators and electric utility managers and operators based upon specific criteria of the electric utility standards and operating characteristics serving CI. The electric utility territory utilized for this research has standards and operating requirements of 5% maximum voltage drop dictating the proximity of CI to electrical substations. The construction and conductor standards for Center Point Energy, the utility serving Houston, are not published to provide specific information regarding electrical components, equipment and conductor sizes. The availability of standards and operating procedures do not negate the effect CRS would provide the surrounding community. Public data identifying CI by latitude and longitude was utilized to apply CRS based upon assumptions about the electrical facilities serving CI. Assumptions included the type of electrical conductor and designation of such conductor as a main distribution feeder between the substation and specific hospitals. PL were identified based upon the location of CI and the areas with the largest inundation of water or the largest crisis. The main electrical distribution feeder is placed in service providing power to hospitals located with the PL to provide power for hospital operations. Furthermore, the public data validates incremental electrification to specific hospitals and electrical service to other CI items such as, water and sewer lift stations, storm water pumps that would mitigate or prevent water from inundating hospitals.

Data was obtained by prioritizing GIS locations from public data utilizing a subjective weighting method for ranking and measuring criteria values as inputs into Rank Order Centroid to assign true swing weights (Barron & Barrett, 1996). Each CI is weighted differently according to a value assigned to the CI by the author. The weights assigned to each CI are normalized using Rank Order Centroid (ROC).

(1)

$$wt_i = \left(\frac{1}{K}\right)\sum_{j=1}^{K}\left(\frac{1}{r_j}\right)$$

$$wt_1 = \left(1+\frac{1}{2}+\frac{1}{3}+\ldots\frac{1}{K}\right)/K$$

$$wt_K = \left(0+0+0+\ldots\frac{1}{K}\right)/K$$

wt_i = The original assigned weight

K = The total number of objectives or CI

The first CI wt_1 = (1+1/2+1/3+1/4+1/5) / 6 = .4083

The second CI $wt_2 = (0+1/2+1/3+1/4+1/5+1/6) / 6 = .2417$ The ROC method continues for each CI until all CI have been calculated using the ROC method. The results are in Table 2 below.

Table 2 Rank Order Centroid weighting of CI retrieved from Barron and Barrett (1996)

CI W_t	ASSIGNED WEIGHT VALUE	ROC Value
Substation	1	0.4083
Crisis Location	2	0.2417
Hospital	3	0.1583
Trauma Center	4	0.1028
Fire Station /Rescue	5	0.0611
Police Station	6	0.02728
Total		1.0000

The highest-ranking CI are substations followed by the location of the worst crisis, hospitals etc. Table 2 shows each CI by name and the ranking assigned to each item with the ranking of one as the highest ranking. The rankings are normalized Normalizing the rankings required since the quantity of each critical infrastructure will be different in each PL. Some PL will have a significantly larger number of one specific CI compared to the number of the same CI in another PL. For example: Public data obtained for this study indicate 6 police stations located in the PL 3 and 4. Police stations are ranked 5 on the raking list in Table 2. Using the actual number of police stations in this example would indicate PL3 and PL4 are the locations where incremental electrical recovery should be applied first as opposed to the locations with the largest crisis. Thus, a method of subjective weighting is necessary when some PL will have larger number of CI than locations higher in rank. Criteria weights were developed using a subjective weighting method (Toloie-Eshlaghy, Homayonfar, Aghaziarati, & Arbabium, 2011):

(2)

$$CIw = \frac{Vx}{SUMVx}$$

CIw = Critical Infrastructure weights

Vx = Priority Locations with weights assigned to each CI

Data in table three contains the actual number each CI item identified using public data that are located in each PL.

Table 3 Number of CI in each PL to calculated Standardized weighting of CI

CIw	PL1 V_{x1}	PL2 V_{x2}	PL3 V_{x3}	PL4 V_{x4}	PL5 V_{x5}	V_{xt} Total
Substation	3	4	2	3	3	15
Crisis Location	1	0.5	0.25	0.125	0.125	2
Hospital	4	3	2	9	2	20
Trauma Center	3	1	7	0	2	13
Fire Station / Rescue	3	2	6	6	3	20
Police Station	1	0	2	2	4	9
Total						79

Crisis location is weighted based upon the most severely affected location ranked as 1. Other CI Crisis locations were assigned a weight value assigned by the author based upon the severity of the storm in the affected area available from public data from USGS. The most severe area was ranked 1 indicating the need for immediate response.

Data in Table 3 was refined to determine criteria weights taking into account the large number of CI in some of the PL. Large numbers of CI in some of the PL locations will skew the results in reference to the large numbers of specific CI. Thus, scaling the data in table 3 to scale each CI to equal 1 provides a consistent comparison of weights. Table 4 below contains the results from the subjective weighting formula.

Table 4 Subjective Weighting

PL1	PL2	PL3	PL4	PL5	TOTAL
0.2000	0.2667	0.1333	0.2000	0.2000	1.0000
0.5000	0.2500	0.1250	0.0625	0.0625	1.0000
0.2000	0.1500	0.1000	0.4500	0.1000	1.0000
0.2308	0.0769	0.5385	0.0000	0.1538	1.0000
0.1500	0.1000	0.3000	0.3000	0.1500	1.0000
0.1111	0.0000	0.2222	0.2222	0.4444	1.0000

Subjective weighting data was multiplied by ROC swing weights to develop surrogate weights to represent an approximation of unbiased true weights (Roberts & Goodwin, 2003).

PL need to be translated into surrogate weights with respect to the CI data aggregated within each PL. Results from the subjective weighting data were multiplied by the PL ROC results to define the locations where CRS can be applied after PL1. The results of multiplying the subjective weights by the ROC are in Table 5.

Table 5 ROC X Subjective weights

PL1	PL2	PL3	PL4	PL5	Total
0.0817	0.1089	0.0544	0.0817	0.0817	0.4083
0.1208	0.0604	0.0302	0.0151	0.0151	0.2417
0.0317	0.0238	0.0158	0.0713	0.0158	0.1583
0.0237	0.0079	0.0553	0.0000	0.0158	0.1028
0.0092	0.0061	0.0183	0.0183	0.0092	0.0611
0.0031	0.0000	0.0062	0.0062	0.0123	0.0278
0.2701	**0.2071**	**0.1803**	**0.1925**	**0.1499**	**1.0000**

Total of each PL represents the weighting of PL within the identified PL of the crisis event.

4.2 Findings

Hurricane Harvey caused significant damage to the Center Point Energy territory in the Houston area due to flooding and high winds. The Center Point Energy territory in Figure 20 below shows the confined area of electrical service and the electric utilities adjacent to the Center Point Energy territory. Generally, the standards and specifications for the distribution of electricity are proprietary to each electric utility. The proprietary nature of the voltage, Center Point Energy utilizes 7,200 V, and the different voltages of the adjacent electric utilities prevents electrical connections from adjacent electric utility from providing incremental electrical service to areas of blackout. Thus, the need to customize CRS to each individual electric utility for application to specific electrical systems to provide incremental electrical recovery to CI.

The development of the CRS requires geographical boundaries containing various CI be within a reasonable proximity, defined by electric utility engineering standards, to an electrical substation. The reasonable proximity of CI and weighting of CI will be determined by CI operators and electric utility managers and operators based upon specific criteria. The electric utility territory utilized for this research has utility standards and operating requirements of 5% maximum voltage drop dictating the proximity of CI to electrical substations. The construction and conductor standards for Center Point Energy, the utility serving Houston, are not published to provide specific information regarding electrical components, equipment and conductor sizes. The availability of standards and operating procedures do not negate the effect of the CRS but provide the Various electrical engineering calculations are typically utilized for the design of an electrical distribution circuit providing service for residential, commercial and industrial customers. Voltage drop calculations provide the information necessary to determine proximity of CI to substations.

Public data identifying CI by GIS location was used to provide results using ROC and subjective weighting techniques. The results indicate CR should be applied to the substation in PL1 that will provide incremental electrical service to the affected CI. CRS can be applied during normal restoration efforts by the affected utility to provide electrical restoration to other areas affected by the crisis.

Hurricane Harvey caused significant damage to the Center Point Energy territory in the Houston area due to flooding and high winds. The Center Point Energy territory in figure 8 below shows the confined area of electrical service.

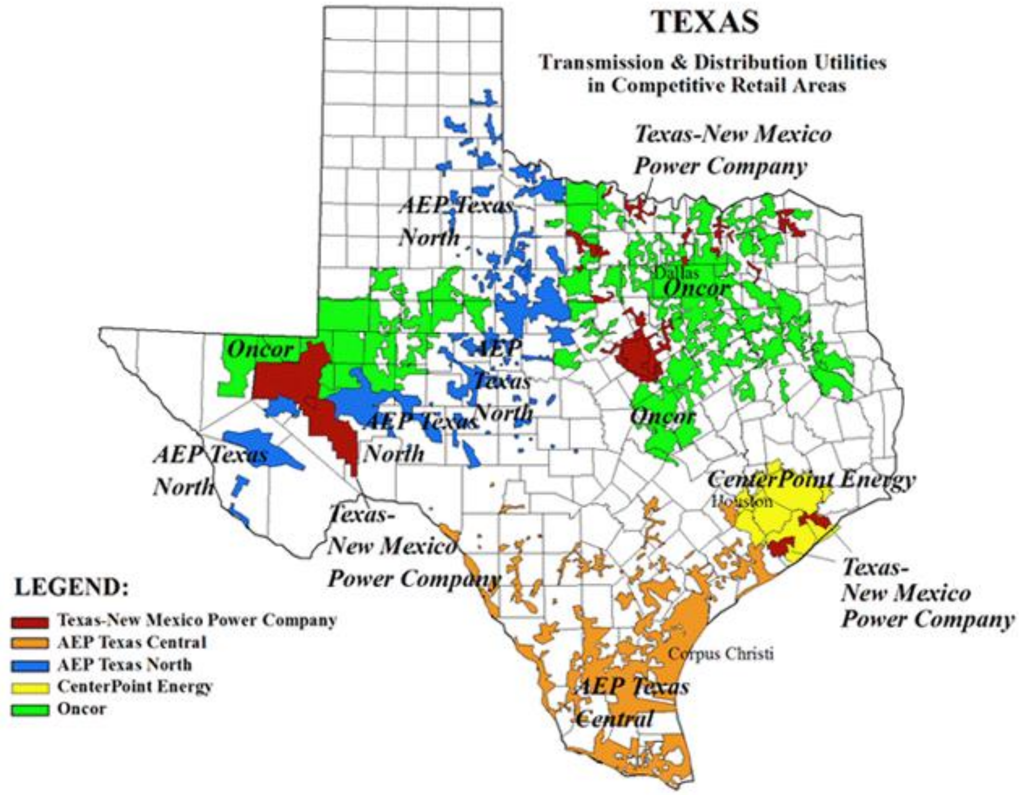


Figure 20. Center Point Energy service territory serving Houston Texas adjacent to electric utilities serving other areas of Texas. Retrieved from https://callmepower.com

Generally, the standards and specifications for the distribution of electricity are proprietary to each electric utility. The proprietary nature of the voltage, Center Point Energy utilizes 7,200 V, and type of electrical components prevent one electric utility, adjacent utility's use 7,620 volts which prevents electrical connections from adjacent electric utility from providing incremental electrical service to areas of blackout. Thus, the development of CRS prior to blackout needs to be developed. Therefore, the need for the application of the CRS to provide incremental electrical recovery to CI.

The CI used for this study included electrical substations, fire stations, hospitals, police stations and trauma centers available from public GIS data. The CI GIS point data obtained from the City of Houston GIS Open Data Portal was downloaded into Microsoft Excel (Microsoft Excel). The latitude and longitude for each CI were copied into one single cell using the concatenate function in excel. Copying the data into one cell allowed for a method to easily sort numerically. The point data, latitude and longitude, for each CI was sorted sequentially, lowest number latitude and longitude, to largest and compared across each spreadsheet containing point data for each CI to compare latitude and longitude locations of each CI. The point data for each CI was aggregated into a new spreadsheet titled PL, see appendix A, to identify proximity of substations to CI locations. The PL locations were grouped by selecting one or two substations within 1.5 miles to various CI locations. The resulting PL locations, see Figure 19, were prioritized by the location of the damage and proximity of a distribution substation to the CI.

CRS is an algorithm that is a direct response to the literature review describing the need to develop an electrical recovery procedure. Legislation compelling electric utilities to develop and apply CRS and appropriations to fund the activities required to develop CRS. MBSE provides the method to develop a recovery model that is applicable to every electric utility without the need to purchase and apply specialized software. Electric utility operators and engineers will collaborate with operators of the CI sectors identified by FEMA to determine locations of CI that can be aggregated into a PL allowing deployment of CRS.

Ultimately each electric utility will divide the territory into PL based upon the PL weighting criteria. Each PL will be ranked or weighted based upon the swing weights calculated using ROC. Some utilities with small territories will have a small number of PL while other utilities with large territories will have a large number of PL. ROC provides a method to normalize the relative importance into weights allowing determination of an electric utility's preparation for a future disaster. If a utility has applied CRS across the territory, the PL locations will be represented by a weighted average that total 1 or 100%.

Applying CRS to Houston Texas using public data identified 5 PL in the Houston area. The normalized weights of the PL with the CI swing weights indicate the 5 PL added to 1 or 100%. If CRS is applied to the Center Point Energy territory, the PL ROC for the swing weighted CI will total to 100% indicating Center Point Energy has a 100% resiliency rating.

The CRS method was applied to historical data from hurricane Harvey to provide an example of the positive impact the CRS would have had by applying the method of incremental recovery after the impact of hurricane Harvey. The application of CRS to Houston after the blackout event would have decreased the duration of the blackout to Memorial Herman-Fortbend Hospital and Memorial Sugarland Hospital decreasing the financial cost associated with damage from hurricane Harvey. Specifically, damage was caused from loss of electricity to water pumps allowing flood water into the hospital and the loss of ability to condition or filter the air system due to blackout (Beckers hospital review web site, 2017).

Applying the CRS to an electric utility prior to an event allowing incremental electrical recovery after blackout will produce data identifying the socioeconomic mitigating factors produced by the application of the CRS. The comparison and contrast of specific data from the application of the CRS to areas of blackout would demonstrate the effect of the CRS.

CHAPTER 5. CONCLUSIONS

Blackout caused by natural or manmade events inflicts the U.S. with an estimated $150 billion in damages each year. Blackouts create exacerbated health conditions and/or loss of life for the population with compromised health conditions. The losses in commercial and residential structures are primarily the result of extreme weather-related and or man-made events in addition to loss of power to CI causing loss of power to storm water pumps, sewage pumps, HVAC in commercial buildings, cooling or heating systems in addition to storage of food, water and health care pharmaceuticals. The perplexing issue is: Why have the operators of electric utility infrastructure not heeded the directives and recommendations of the federal government to develop a process or plan for electrical recovery to CI? Electric utility executives will continue to ignore recommendations unless corresponding legislation compel electric utilities to develop the CRS methods and practices to provide incremental electrical recovery to CI.

The purpose of the study was to answer two research questions: 1. Can a plan be developed that will provide electric utility owners and CI operators with a method to plan for and to provide incremental electrical recovery decreasing the duration of blackout to CI? And 2. Can Model Based System Engineering (MBSE) be utilized to develop a universal model to support planning for incremental recovery to electrical distribution systems after widespread electrical blackout mitigating the negative socioeconomic effects? This study affirmed that a plan and subsequent model can be developed to provide incremental electrical recovery to CI. The algorithm in Figure 12 on pg. 55 provides the logic necessary to develop a plan. The method to develop the model in Chapter 3 follows the logic in the algorithm and can be applied to any electric utility with modifications. The modification of data in Chapter 4, although the data used is public data, applied to the algorithm provides evidence that CRS will provide incremental electrical restoration to CI. The model developed from the algorithm is a simple solution to a complex problem. The study affirmed both research questions by creating a model for recovery using public data as inputs to the model to define locations for incremental electrical restoration.

5.1 Recommendations for Practice

The literature review provides compelling arguments for an electric utility to provide a community with resiliency against blackout. The development and application of CRS to an electric utility territory to simulate incremental electrical recovery will provide data to further validate the efficacy of CRS. Identifying the location of CI within the prescribed distance from a substation to simulate the operational ability of CRS will provide duration of the CRS operation as an additional input to provide empirical evidence for the application of CRS. Furthermore, the simulation activities will provide hospital operators and managers with evidence of sustainability during crisis and blackout events. The application of CRS to the Houston Texas locations after hurricane Harvey would have decreased the duration of blackout to Memorial Herman-Fortbend Hospital and Memorial Sugarland Hospital reducing the financial impact due to damage caused by hurricane Harvey (Beckers hospital review web site, 2017).

5.1.1 Opportunities for Practice

The application of CRS as a simulated activity upon an existing electric utility infrastructure will provide DHS/FEMA and federal legislators with evidence that CRS offers a solution to providing sustainability and protects national security. Electric utility operators moving forward with activities to satisfy the recommendations in the literature (*CNA Military Advisory Board*, 2015), (NAP, 2012) by developing CRS as an application for recovery will

5.1.2 Recommendations for Research

The development and application of the CRS provides the data necessary to create a resiliency index to ascertain the ability of a specific electric utility's ability to adapt to a blackout. "without some numerical basis for assessing resilience, it would be impossible to monitor changes or show that community resilience has improved. At present, no consistent basis for such measurement exists. We recommend therefore that a National Resilience Scorecard be established." (-Disaster Resilience: A National Imperative, National Academy of Sciences)

The process of applying the algorithm to develop CRS to an electric utility territory produces the PL data necessary to create an index or scorecard. ROC calculations can be used to ascertain an electric utilities ability to withstand a disaster by providing incremental electric al restoration to CI. The ROC results will provide an index identifying the percentage of PL areas that have been developed to provide incremental electrical restoration. Using ROC eliminates the differences in geographic territorial size by rendering the number of PL to an index.

(1)

$$wt_i = \left(\frac{1}{K}\right)\sum_{j=1}^{K}\left(\frac{1}{r_j}\right)$$

$$wt_1 = \left(1 + \frac{1}{2} + \frac{1}{3} + \dots \frac{1}{K}\right) / K$$

$$wt_K = \left(0 + 0 + 0 + \dots \frac{1}{K}\right) / K$$

The number of PL used in this study is 5. The 5 PL are weighted by engineers, operators and emergency responders. The weights of each PL are normalized using ROC. The ROC weighting for each of the 5 PL in this study:

PL1 = .2701

PL2 = .2701

PL3 = .1803

PL4 = .1925

PL5 = .1499

The ROC weights indicate that PL1 and PL2 have the largest normalized weighted result. CRS can be applied in descending numerical order considering the larger number indicates the location where CRS should be applied first. ROC weights can be used as a resiliency index if the ROC weights are transformed into percentages. The total of the ROC weights equal 1 or 100%.

Assume the electrical territory had a maximum of 5 PL with the ROC results from the previous calculations. The ROC weights add to 1, therefore the resiliency index would be 100%. The number of PL is dependent upon the geographic size of the utility territory. Regardless of the size, 5 or 100 PL, the ROC normalizes the weights and the sum of all the weights add to 1 or 100%. Thus, a utility that has not developed and applied CRS to the system will have a resiliency index of 0. A utility that has developed and applied CRS to half of the existing system will have a resiliency index of 5 or 50% assuming the locations where CRS is applied will have results from ROC that total .5 or 50%.

Additional research should be conducted to develop the resiliency index to provide regulators and the general public with a measure of an electric utilities ability to adapt to a blackout. The identification of PL in each territory can weighted using ROC weighting procedure, see page 72. “ROC weights are useful, usable, efficacious weights whose average performance is excellent in absolute terms and is superior to that of previously proposed rank-based surrogate weights in the assessment of MAV” (Barron & Barrett, 1996).

5.2 Concluding Discussion

This study developed an algorithm that can be applied to any electric utility to develop a model to provide incremental electrical recovery to CI. Furthermore, the algorithm and subsequent MBSE method with corresponding ROC weighting method can be used to develop a resiliency index to provide rate payers and government regulatory groups with a measure of resiliency provided by individual electric utilities.

The study provides a solution to the literature identifying the need for a method of recovery for the distribution system (NAP, 2012), (*Presidential Policy Directive 21*, 2013). CRS provides the data necessary to produce a resiliency index satisfying the recommendations in the literature (Campbell, 2012), (National Academies of Sciences, Engineering, and Medicine., 2017), (National Academies of Sciences, Engineering, and Medicine., 2017).

The creation of the algorithm, see Figure 12 on page 55, provides the logical path to develop a plan and subsequent models for incremental electrical restoration. Legislative action is necessary to compel electric utility owners to adopt the algorithm to provide the necessary logic for the development of the CRS model that can be modified for each electric utility. Adoption and application of CRS nationally provide sustainability after blackout occurs and provide confidence in the protection of U.S. national security. Furthermore, adoption of CRS globally will provide sustainability and security for consumers of electricity globally.

APPENDIX A

Table A. 1 Table of substation locations with latitude and longitude required for identification of priority locations

Substations		
FID	latitude	longitude
13	28.93161694	-95.3169992
15	28.94033641	-95.3486891
14	28.95572191	-95.3167481
16	28.95894524	-95.3391863
17	28.98875637	-95.5734278
18	28.98904931	-95.5678601
20	29.00656936	-95.4052035
19	29.00968128	-95.4326234
21	29.2346986	-95.187393
53	29.26058161	-94.8534665
52	29.2963888	-94.8268943
51	29.30263153	-94.7975906
54	29.36216918	-94.9304935
55	29.37668907	-94.8976733
58	29.37861335	-94.9473745
59	29.37899637	-94.943879
60	29.37959827	-94.9345646
56	29.38281745	-94.8926498
57	29.38952905	-94.9501688
61	29.40899568	-94.9136334
62	29.42558724	-94.9638265
38	29.4561879	-95.3082918
41	29.46838003	-95.1790624
39	29.48319449	-95.252531
40	29.49920917	-95.2012914

Table A. 2 Table of fire station locations with latitude and longitude required for identification of priority locations

FIRE STATIONS		
ADDRESS	**LAT**	**LONG**
235 EL DORADO BLVD	29.556421	-95.149161
17401 SATURN LN	29.557516	-95.107266
15200 SPACE CENTER BLVD	29.581703	-95.128354
911 FM 1959	29.590172	-95.180910
16111 CHIMNEY ROCK RD	29.591278	-95.483847
11410 BEAMER RD	29.601966	-95.228676
13925 S POST OAK RD	29.624374	-95.465134
9726 MONROE RD	29.625365	-95.266750
2615 TIDEWATER	29.632012	-95.413539
10343 HARTSOOK	29.634736	-95.229706
11212 CULLEN BLVD	29.637590	-95.355843
7990 PAUL B KOONCE	29.640429	-95.277696
11616 CHIMNEY ROCK RD	29.653140	-95.480848
2625 REED RD	29.657653	-95.390010
7720 AIRPORT BLVD	29.657821	-95.280198
11250 BRAESRIDGE DR	29.657923	-95.510917
10515 MAIN	29.670649	-95.433086
9640 WILCREST DR	29.672858	-95.570369
5535 VAN FLEET	29.674047	-95.338759
8602 BISSONNET ST	29.676785	-95.528653
7111 DIXIE DR	29.681419	-95.305042
4831 GALVESTON RD	29.683797	-95.254007
3902 CORDER ST	29.686215	-95.364271
7200 COOK RD	29.699340	-95.596088
7117 FANNIN	29.700049	-95.401793

Table A. 3 Table of police station locations with latitude and longitude required for identification of priority locations

POLICE STATION	ADDRESS	AGENCY	latitude	longitude
Clear Lake	2855 Bay Area Blvd	HPD	29.57953958	-95.10646399
Southwest	13097 Nitida St	HPD	29.63704163	-95.45711234
South Gessner	8605 Westplace Dr	HPD	29.64954381	-95.528404
William P. Hobby Airport	7800 Airport Blvd	HPD	29.65408532	-95.27665426
Southeast	8300 Mykawa	HPD	29.65738445	-95.31681111
Midwest	7277 Regency Square Blvd	HPD	29.71667642	-95.51153145
Westside	3203 S Dairy Ashford	HPD	29.72747615	-95.60486678
Eastside	7525 Sherman	HPD	29.73430911	-95.29004564
South Central	2202 St. Emanuel	HPD	29.74287766	-95.36280999
Downtown	1900 Rusk St	HPD	29.75372519	-95.3560123
Police Headquarters	1200 Travis St	HPD	29.75577234	-95.3675137
Central	61 Riesner St	HPD	29.76487453	-95.37072535
Northeast	8301 Ley Rd	HPD	29.83226408	-95.27337679
Northwest	6000 Teague Road	HPD	29.85704177	-95.53980151
North	9455 W Montgomery Rd	HPD	29.87953416	-95.44693855
North Belt	100 Glenborough Dr	HPD	29.95147068	-95.4199242
Bush IAH Airport	3100 Terminal Road North	HPD	29.98726453	-95.34582612
Kingwood	3915 Rustic Woods Dr	HPD	30.05463728	-95.1882596

Table A. 4 Table of trauma center locations with latitude and longitude required for identification of priority locations

TRAUMA CENTERS				
OBJECTID_	**COMPANY**	**LevelClass**	**Lat**	**Long**
36	PALACIOS COMMUNITY MEDICAL		28.71748	-96.2136
31	MATAGORDA GENERAL HOSPITAL	Level III Trauma	28.99334	-95.9692
46	BRAZOSPORT MEMORIAL HOSPITAL	Active Pursuit of Level IV Trauma	29.0327	-95.4522
38	SWEENY COMMUNITY HOSPITAL	Active Pursuit of Level IV Trauma	29.0489	-95.6919
43	ANGLETON DANBURY MEDICAL CTR	Level IV Trauma	29.18517	-95.4056
34	EL CAMPO MEMORIAL HOSPITAL		29.22234	-96.2935
45	UTMB	Level I Trauma	29.3112	-94.7756
39	GULF COAST MEDICAL CTR	Active Pursuit of Level III Trauma	29.31733	-96.0522
48	MAINLAND MEDICAL CTR		29.39528	-94.9872
49	CLEAR LAKE REGIONAL MED CTR		29.53966	-95.1279
14	CHRISTUS ST JOHN HOSPITAL		29.55014	-95.0854
54	Memorial Hermann FortBend	Active Pursuit of Level IV Trauma	29.5667	-95.5628
50	MEMORIAL HERMANN SOUTHEAST	Level III Trauma	29.57326	-95.1514
53	Oak Bend Medical Center	Level III Trauma	29.57669	-95.7708
33	RICE MEDICAL ASSOC	Level IV Trauma	29.59172	-96.3434
37	METHODIST SUGAR LAND HOSPITAL		29.59658	-95.6236
41	BAYSHORE MEDICAL CTR		29.66511	-95.1838
17	MEMORIAL HERMANN SOUTHWEST	Level III Trauma	29.69164	-95.5206
56	COLORADO-FAYETTE MEDICAL CTR		29.6917	-96.7907
52	COLUMBUS COMMUNITY HOSPITAL	Level IV Trauma	29.69424	-96.5427
11	ST LUKE'S HOSPITAL		29.7071	-95.3991
12	TEXAS CHILDREN'S HOSPITAL	Active Pursuit of Level II Trauma	29.70944	-95.4011
10	METHODIST HOSP-NEUROSURGY DEPT		29.71077	-95.4001
9	BEN TAUB HOSPITAL	Level I Trauma	29.71236	-95.3939
55	Memorial Hermann Hospital	Level I Trauma	29.71399	-95.3957

Table A. 5 Table of hospital locations with latitude and longitude required for identification of priority locations

OBJECTID	HOSPITAL NAME	latitude	longitude
79	BAYWOOD HOSPITAL	29.53733	-95.1295
60	CLEAR LAKE REGIONAL MEDICAL CENTER	29.54121	-95.1277
48	CLEAR LAKE REHAB HOSPITAL	29.5476	-95.1176
106	CHRISTUS ST. JOHN HOSPITAL	29.54937	-95.0871
73	MEMORIAL HERMANN - FORT BEND HOSPITAL	29.565	-95.5623
103	POLLY RYON MEMORIAL HOSPITAL	29.57817	-95.7706
50	MEMORIAL HOSPITAL - SOUTHEAST	29.58343	-95.207
98	METHODIST SUGAR LAND HOSPITAL	29.58856	-95.6317
101	TRIUMPH HOSPITAL SOUTHWEST HOUSTON	29.60031	-95.6386
80	SUGAR LAND MEDICAL CENTER	29.60634	-95.6159
66	FOUNTAIN BROOK HOSPITAL	29.64686	-95.5876
36	SPECIALTY HOSPITAL OF HOUSTON	29.65195	-95.4775
81	SURGICAL OUTPATIENT HOSPITAL	29.65813	-95.1889
104	VISTA MEDICAL CENTER	29.65948	-95.1776
88	BAYSHORE SURGERY CENTER	29.6611	-95.1839
58	BAYSHORE MEDICAL CENTER	29.66271	-95.1831
53	HCA DEER PARK HOSPITAL	29.6682	-95.1303
42	CULLEN WOMENS CENTER HOSPITAL	29.67791	-95.3555
56	TRI CITY REGIONAL HOSPITAL	29.67898	-95.1493
75	MEMORIAL HERMANN - PASADENA	29.68981	-95.2021
24	INTRACARE HOSPITAL	29.69073	-95.4009
25	MEDICAL CENTER HOSPITAL	29.69255	-95.404
102	HCA WOMAN'S HOSPITAL OF TEXAS	29.69308	-95.4023
19	MEMORIAL HOSPITAL - SOUTHWEST	29.69336	-95.5222
35	I H S HOSPITAL	29.69408	-95.3162
34	CASA A SPECIAL HOSPITAL	29.6962	-95.4003

APPENDIX B

Table B. 1 Table of combined locations with latitude and longitude required identifying priority locations

Priority Location (PL) sheet										
PL are chosen by comparing critical infrastrucutre locations in close proximity to electrical substation locations.										
PL	Substation		Fire Station		Hospital		Police Station		Trauma Center	
1	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
	29.55402069	-95.2573086	29.55642124	-95.14916117	29.53732927	-95.12950375	29.57954	-95.1065	28.71747795	-96.21360917
	29.56022939	-95.3227187	29.55751632	-95.10726635	29.54120613	-95.12768857	29.63704	-95.4571	28.99333502	-95.96915013
	29.56190199	-95.1414228	29.58170289	-95.12835443	29.54759571	-95.11755514	29.64954	-95.5284	29.03269804	-95.45220099
	29.56309692	-95.0852067	29.59017196	-95.18090975	29.54937441	-95.0871108	29.65409	-95.2767	29.04889604	-95.69187705
	29.57842542	-95.0987283	29.59127847	-95.48384685	29.56500366	-95.56230386	29.65738	-95.3168	29.18516808	-95.40558199
2	29.58829124	-95.1803183	29.60196553	-95.22867559	29.57817068	-95.77055651	29.71668	-95.5115	29.22233706	-96.29347121
	29.58947434	-95.2401188	29.62437418	-95.46513368	29.58343175	-95.20699974	29.72748	-95.6049	29.31119712	-94.77561083
	29.60450766	-95.5637681	29.62536485	-95.26675007	29.58855552	-95.63174616	29.73431	-95.29	29.31732809	-96.05218316
	29.61006724	-95.184426	29.63201216	-95.41353874	29.60031091	-95.63859863	29.74288	-95.3628	29.39528114	-94.98720289
	29.62408766	-95.0881999	29.63473645	-95.22970566	29.60634478	-95.61590259	29.75373	-95.356	29.53965516	-95.12793193
3	29.62819971	-95.0646732	29.63758973	-95.35584271	29.64685529	-95.58757294	29.75577	-95.3675	29.55014116	-95.08535092
	29.62900936	-95.2251739	29.64042855	-95.2776959	29.65195222	-95.47746742	29.76487	-95.3707	29.56669924	-95.56277284
	29.63011921	-95.1510668	29.65313966	-95.48084841	29.65813344	-95.18892057	29.83226	-95.2734	29.57326317	-95.15136194
	29.6301556	-95.4035604	29.65765264	-95.39000992	29.65948332	-95.17755725	29.85704	-95.5398	29.57668721	-95.77084899
	29.63324856	-95.561947	29.6578207	-95.28019782	29.66110063	-95.1838684	29.87953	-95.4469	29.59171613	-96.34338325
4	29.6396616	-95.0552332	29.65792347	-95.51091746	29.66270645	-95.18313973	29.95147	-95.4199	29.59658416	-95.62358706
	29.64235404	-95.0595032	29.67064885	-95.4330859	29.66819862	-95.13026655	29.98726	-95.3458	29.66511118	-95.18379895
	29.64604694	-95.0536424	29.67285806	-95.57036867	29.67790572	-95.35548794	30.05464	-95.1883	29.69163918	-95.52060204
	29.64705655	-95.4489393	29.67404658	-95.33875889	29.67898454	-95.14933108	**There is no Police**		29.69170413	-96.79074936
	29.64768414	-95.0553378	29.6767854	-95.52865331	29.68981262	-95.2020877	**Station information**		29.69424114	-96.5427253
5	29.64947594	-95.1025901	29.68141887	-95.30504174	29.69073234	-95.40092702	**avaialble in the**		29.70709818	-95.39912401
	29.6536779	-95.1543478	29.68379656	-95.25400667	29.69254782	-95.40398271	**public data set in**		29.70944418	-95.40110501
	29.65780692	-95.1906635	29.68621492	-95.3642705	29.69308211	-95.40232346	**this area.**		29.71077118	-95.40006101
	29.65971677	-95.2448597	29.69934028	-95.59608793	29.69335864	-95.52221795			29.71235619	-95.393884
	29.66484182	-95.0161389	29.70004921	-95.40179255	29.69408296	-95.31624348			29.71399203	-95.39566533

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