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Assessing the resilience of electricity grid sectors to extreme weather disruptions

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MSc MADE

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Assessing the resilience of electricity grid sectors to extreme weather disruptions

by

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Abstract

Cities and regions around the world are experiencing an increase in extreme weather-related disruptions as a result of climate change. These disruptions are testing the integrity of energy systems including electricity grids. An emerging concept to assess the vulnerability of systems to disruptions is the concept of resilience. Resilience is used to assess the entire cycle of a disruptive event or specific phases such as the before, during, and after the event. In this thesis, a set of criteria to assess the resilience of the electricity grid is defined. Then the electricity grid sectors of Harris County, Texas are assessed by applying the developed and operationalized resilience criteria. This is done to understand the current resilience conditions of electricity grid sectors. The criteria are applied for assessment purposes by using the Multi-Attribute Value Theory (MAVT) method of Multi-Criteria Decision Analysis (MCDA). The results of this method are displayed using a series of maps. Results from the electricity grid sectors' assessment provide an understanding of the resilience of a city's electricity grid sectors, highlighting which low scoring sectors need more attention. In turn, having an overview of the resilience of electricity grid sectors can be used to plan or improve infrastructure including the integration of local renewable energy generation.

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1 Introduction

1.1. Context

Disruptions are increasing around the world and testing the ability of urban systems to continue providing their services. In 2021, extreme weather disruptions have had devastating impacts on basic services required to keep cities functioning. For example, the flooding event experienced in the western regions of Germany in the summer of 2021 resulted in severe damage to power and water utility infrastructure (Dumiak & Oirere, 2021). Besides flooding, a very extreme and rare winter storm caused 45 gigawatts of energy supply to freeze in Texas in early 2021 affecting 4.5 million people (Douglas & Ramsey, 2021). Because of the unpredictability of extreme weather-events, this type of disruption is the focus of the thesis.

These increasing occurrences can result in negative impacts to the energy system. Such impacts include increasing demand and threatening the security of generation, transmission, and distribution of energy (Charani Shandiz et al., 2020; Pasimeni et al., 2014). In addition to extreme weather-events, rapidly urbanizing cities account for 65% of global energy demand and 70% of energy-related carbon dioxide. This requires major changes if the world is to decarbonize. This change is coming through the form of an energy transition from non-renewable sources towards renewable sources in the building, transport, and industry sectors. As a result, the electricity grid that services urban centers is under pressure because of the intermittency of renewable energy sources and capacity limitations of the electricity grid (Dallinger & Wietschel, 2012). Therefore, the need for energy systems to be prepared for disruptions while integrating newer electricity generation technology must be met. The focus of this thesis is on the electricity grid and not the energy system at large.

However, planning the electricity grid to withstand any kind of disruption can quickly become expensive and unmanageable. This is because the possible sources of extreme weather-related disruptions are likely to increase due to climate change (Hanisch, 2016). Instead, it is more efficient for a system to ensure that it continues performing its function before and after a disruption (Jesse et al., 2019). Therefore, a concept that embodies such a notion is the one of resilience that can be used to plan the development and maintenance of the electricity grid. In short, the theory of resilience describes a system's ability to cope with change or disruptions (Jesse et al., 2019). Performing a resilience assessment gives an overview of the current conditions that a system has in dealing with disruptions.

1.2. Research objective

In this thesis, a novel way of assessing the resilience of specific urban electricity grid sectors is proposed. The goal is to provide an overview of the current resilience conditions of electricity grid sectors. As a solution, the direct connection of renewable energy generation to these vulnerable grid sectors is proposed. To do so, a thorough understanding of the concept of resilience needs to be accomplished first. This knowledge is then leveraged to develop criteria for the resilience assessment of electricity grid sectors. The criteria is then operationalized and applied to the context of a case study by August 2021.

1.3. Research questions

The main research question that will be answered in this thesis is the following:

How can the resilience of individual electricity grid sectors be assessed using standardized criteria?

This question is split into three sub-research questions as outlined:

1. What are the criteria that should be included to assess the resilience of electricity grid sectors?
2. How can the developed resilience criteria be operationalized to assess electricity grid sectors of a specific case study?
3. How can the developed and operationalized criteria be applied to compare the overall resilience of a case study's electricity grid sectors?

1.4. Research approach

From the research objective and questions, the research approach shows an overview of what needs to be completed to answer the research questions. In Figure 1.1, the objectives are divided by the expected result of each sub-research question. Methods used in each of these three milestones are discussed in Chapter 3.

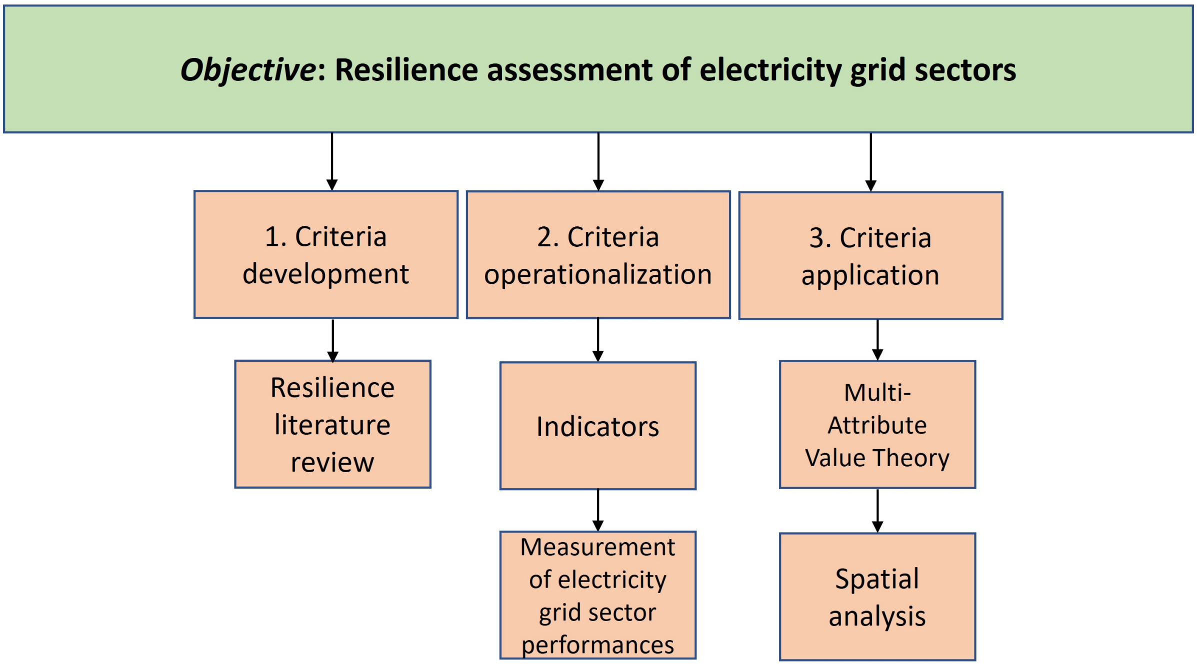


Figure 1.1: *Research framework*

1.5. Thesis outline

In Chapter 2, literature on resilience is reviewed. Resilience characteristics will be discussed in this chapter. Chapter 3 describes the methods used for development, operationalization, and application of resilience criteria. In this chapter, a background on the case study is also included. Chapter 4, describes the development and operationalization of criteria by discussing the approach taken. In Chapter 5, the case study is analyzed by applying the criteria using Multi-Attribute Value Theory and spatial analysis. Results from the case study chapter are then discussed in Chapter 6 by identifying the main findings of the process and reflecting on the methods used in this thesis to develop, operationalize, and apply resilience criteria. The limitations of the study are also discussed in Chapter 6 including contributions to policy and research. Finally, the thesis is concluded through summarizing the research done, answering the research questions, and providing recommendations for future research in Chapter 7.

2

Literature review

For the development of resilience criteria, a literature review on resilience is warranted. This literature review is the first milestone in achieving the objective of assessing the resilience of electricity grid sectors.

The aim of the resilience literature review is to gain a thorough understanding of the concept of resilience. This will be used to develop criteria for the assessment of the resilience of electricity grid sectors. For this, definitions of resilience in different disciplines are reviewed as well as resilience approaches and capacities. Then, by using the analytical questions posed in Henly-Shepard et al. (2018) as seen in Figure 2.1, the focus is narrowed down to energy resilience. Although energy resilience focuses on the overall energy system, papers on this give an indication on what principles and characteristics should be included for assessment purposes. In turn, this serves as guidance to concentrate the development of criteria on electricity grid sectors.

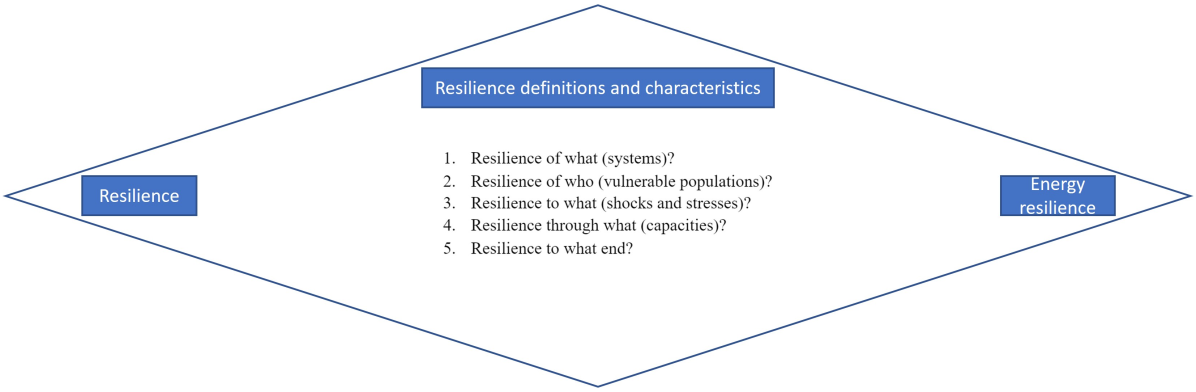


Figure 2.1: *Conceptualization or resilience review*

2.1. Resilience

Disruptions such as extreme weather-events have become more frequent and unpredictable. The type of disruption refers to shocks and sudden events like conflict, disasters, or long-term trends such as resource degradation, urbanization, or climate change (Brunetta & Caldarice, 2020). Systems affected by different disruptions require specific approaches to handle specific disruptions. Infrastructure systems must be equipped to handle such disruptions to ensure that cities and regions are supported through services and connectivity (Guy et al., 2011).

For example, the energy system is considered one of the most complex and important critical infrastructure systems that provides modern society with essential services (Gasser et al., 2019). Therefore, this support system must be secured throughout its life cycle. For the electricity grid, power grid disruptions cause imbalances in the supply and demand of electricity impacting residential, commercial, and industrial activities (Tennet, n.d.). In reviewing literature, several power grid related disruptions associated with infrastructure, urban areas, and energy systems are identified as seen in Table 2.1. In addition, the impact that the disruption creates is categorized into system complexity, pressure, and failure. System complexity is regarded as dealing with the interconnected functions of energy systems whereas system pressure deals with surpluses or shortages that need to be balanced. System failure has to do with disruptions that can lead to blackouts or the total failure of the electricity grid system.

Table 2.1: *Disruptions that potentially impact electricity grid infrastructure*

Type of disruption	**Definition**	**Impact to system**
Deteriorating infrastructure	Aging infrastructure needs continuous follow-up and maintenance (Sjögren, n.d.)	Failure
New, disruptive technologies	A disruptive technology supersedes an older process, product, or habit (Smith, 2020).	Complexity
Interconnected systems	Complex, long-distance energy systems (Sharifi & Yamagata, 2014)	Complexity
Cyber-security threats	Threats such as data theft, billing fraud, and ransomware (Baily et al., 2020)	Failure
Climate change	Impacts of climate change include sea level rise, drought, and more frequent and severe weather (C2ES, 2019)	Failure
Natural disasters	A serious disruption causing widespread human, material, economic or environmental losses ((UNISDR, 2009)	Failure
Resource degradation	Depletion of resources such as air, water, and soil (Jouanjean et al., 2014).	Pressure
Urbanization	Rapid and unforeseen expansion of territorial systems (Brunetta & Caldarice, 2020)	Pressure

In dealing with disruptions, current approaches such as risk assessment are not enough to prepare systems to withstand and recover from disruptions. Risk assessment identifies hazards and the potential risk of disruptive events (Heinimann, 2016). Therefore, the aim of risk assessment is to minimize the impact of a disruption. This is not sufficient as systems should be assessed for the whole life cycle of a disruption. An emerging approach to assess a system's interaction with a disruption is resilience. Resilience assessment covers the whole life cycle of a system as it analyses potential disruptive events and pre, during, and post-event phases (Gasser et al., 2019). From the different power grid disruptions listed in Table 2.1, the focus of this thesis is on the pre-event phase and climate change induced extreme weather-events.

Generally, resilience is a relative term that describes something or someone being resilient to a circumstance (C2ES, 2019). The term resilience was first introduced in scientific research through ecological systems as the interactions within a system and a measure of the ability of these systems to absorb changes and persist (Holling, 1973). Thus, the theory of resilience is one way of describing a system's ability to cope with changing factors or disruptions (Jesse et al., 2019).

Furthermore, resilience is a multidimensional concept, which cuts across many different fields (Alessi et al., 2020). For example, in economics, resilience is defined as enabling the speed of recovery from a shock through the efficient utilization of resources for repair and reconstruction (Rose & Krausmann, 2013). Resilience in infrastructure systems is defined as the ability to reduce the magnitude or the duration of disruptive events (US National Infrastructure Advisory Council, 2009). Other fields that define resilience include ecology, material science, organizational science, psychology, and sociology.

Resilience can be described using both socio-ecological and socio-technical systems. However, socio-technical systems are more relevant to the topic of this thesis as it can be used to explain the impact of interconnected technologies on the population serviced by the grid. Socio-technical systems make the fabric of industrialized societies more tightly coupled and more complex (Eljaoued et al., 2020). Furthermore, because socio-technical systems are complex and multidimensional, resilience can be analyzed using socio-technical systems. The relation between these two concepts is relevant as methods that can support decision making related to resilience management of these systems are called for (Bellini et al., 2020).

As the goal of this section is to gain an understanding of how resilience can be used to develop resilience criteria, the broader scope of resilience needs to be narrowed down to a more focus specific application. Selecting the resilience approach and capacities based on the objective enables the selection of a more focused resilience approach.

2.1.1. Resilience approaches

In contrast to the definitions of the resilience disciplines mentioned, the types of resilience describe the approach to analyse a system undergoing a disruption. The main difference between the approaches is the point of equilibrium that a system should reach after a disruption. Based on Holling's work, many authors have contributed to the definition of resilience and its approaches. Among the approaches are engineering and ecological resilience which were first introduced by Holling. Engineering resilience describes the ability of a system to return to a previous stable point after a shock (Gunderson & Holling, 2002). Unlike engineering resilience, in the ecological resilience approach, the system returns to one of the multiple possible equilibrium states (Sharifi & Yamagata, 2016). Another resilience approach is adaptive resilience, but this was not considered as it describes socio-ecological systems.

Unlike ecological resilience returning to one of many possible equilibriums, engineering resilience is most suitable as the electricity grid needs to reach a specific point of equilibrium. The point of equilibrium for electricity grid systems is when supply is equal to demand. Therefore, the electricity grid must return to its previous stable point. Some example measures for engineering resilience include redundant capacities, storage, and physical protective measures (Charani Shandiz et al., 2020). Along with the most suitable resilience approach mentioned, resilience capacities are discussed to further narrow the scope down.

2.1.2. Resilience capacities

Resilience capacities describe how a system copes with disruptions throughout its life cycle and enables resilience to be quantified (Linkov & Palma-Oliveira, 2017). Gasser et al. (2019) identified capacities that can be developed for dealing with disruptions per phase. The disruption trajectory is divided in four phases namely the pre-event, draw-down, draw-up, and post-event as seen in Figure 2.2. However, depending on the scope and application, it is not always suitable to measure the overall resilience of a system with a single, aggregated system performance indicator (Gasser et al., 2019). The focus of this thesis will be on the pre-event phase which includes the anticipate, prepare, and avoid capacities. These capacities all address a different way of dealing with a disruption meaning that they cannot be used in combination. Therefore, to describe how a system can prepare for a disruption, capacities in the draw-down phase were also chosen. This is because the same methods used to describe the pre-event phase capacity cover some of the draw-down phase capacities (Gasser et al., 2019). Out of these capacities, absorption, robustness and redundancy are reviewed in depth as these align with the engineering resilience definition that emphasizes that a system must restore its balance after a disruption.

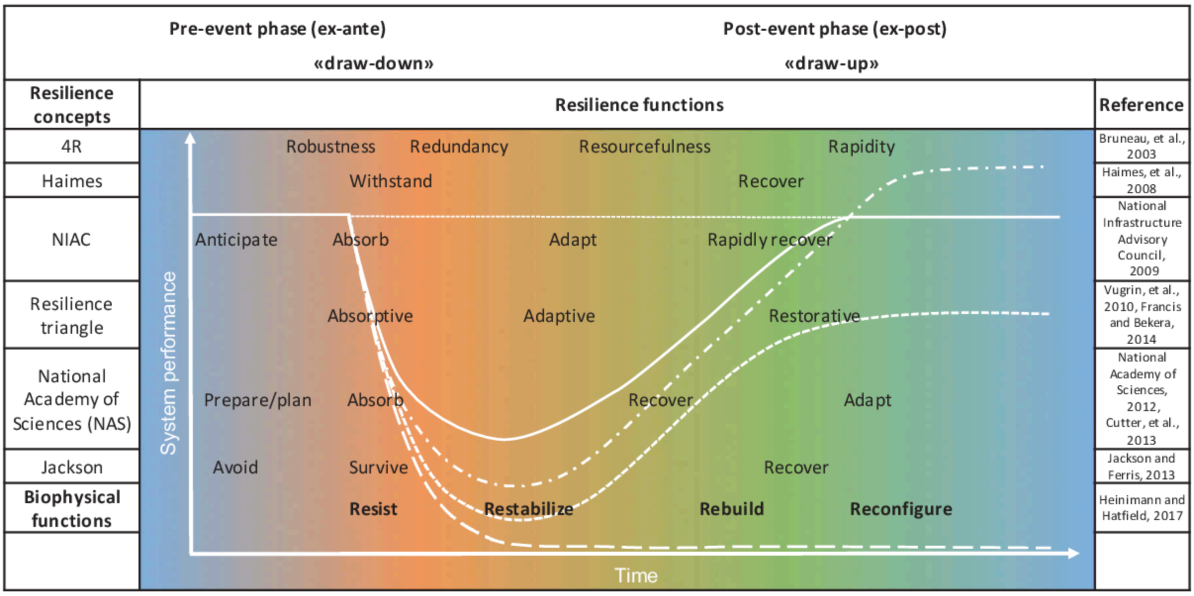


Figure 2.2: *Disruption event recovery trajectory (Gasser et al., 2019)*

Absorptive capacity is the degree to which a system can absorb the impacts of system perturbations with little effort (Francis & Bekera, 2014; National Research Council, 2012). Absorption enables the system to minimize the potential overall impacts of the disruption, however, the potential impact may surpass the resistance threshold of a system (Sharifi & Yamagata, 2016).

Robustness capacity has to do with absorbing shocks without failing (Seager et al., 2017). In contrast with the absorption capacity, robustness aims at reducing the initial shock (Rose & Krausmann, 2013). Robust energy systems are built on well-designed, constructed, and managed physical infrastructure. This enables them to withstand hazardous events without significant damage or loss of function (ARUP International, 2019).

Redundancy capacity refers to spare capacity or repeated infrastructure to accommodate disruptions that create an imbalance between demand and supply (ARUP International, 2019). The ARUP International (2019) resilience report also states that systems with redundancy can normally tolerate some infrastructure failures without affecting the overall function. Redundancy also refers to the availability of replaceable components with similar functions to enhance the system's adaptive capacity and ability to absorb shocks (Roege et al., 2014; Sharifi & Yamagata, 2014).

2.1.3. Energy resilience

From the different disruptions, discipline definitions, approaches, and capacities reviewed, a decision on the scope that resilience is applied can be made. This decision is made to directly address the objective. Literature found on the specific scope can be then used as reference for the development of criteria. Therefore, it is paramount to decide on the resilience of what, to what and over what period (Carpenter et al., 2001) it will be applied. To apply resilience in a way that addresses electricity grid sectors, five analytical questions posed by Henly-Shepard et al. (2018) are answered:

1. Resilience of what : Electricity grid sectors
2. Resilience of who : Population served by the electricity grid
3. Resilience to what : Extreme weather event related power-grid disruptions
4. Resilience through what : Absorption, robustness, and redundancy capacities
5. Resilience to what end: Better prepare electricity grid sectors for extreme weather-events

Through answering these questions, the application of resilience is focused on energy resilience. Energy resilience is described as its ability to reduce the impact of disruptions through the capacity to anticipate, absorb, adapt to, and rapidly recover from disruptive events (ARUP International, 2019). This means that resilience in energy systems is a complex challenge as an energy system is resilient to a specific disruption instead of many (Molyneaux et al., 2016). For the purposes of this thesis, the following definition of energy resilience is used:

The ability of a system to provide and maintain an accepted level of service even in the event of failure (Afgan & Veziroglu, 2012).

This definition of energy resilience is most applicable as it relates to the engineering resilience approach of reaching the previous state of equilibrium (Jesse et al., 2019). Although energy resilience addresses the energy system as a whole, reviewing energy resilience literature can be used to assess electricity grid sectors. This is briefly described in Sub-section 2.1.4 and further detailed in Chapter 4.

2.1.4. Energy resilience criteria

Criteria for the resilience planning of energy systems is proposed by Sharifi and Yamagata (2016). Along with the process, the criteria are also described through the relationship of sustainability dimensions and resilience capacities. These criteria were developed by synthesizing the concept of sustainability and resilience by using the preparation, absorption, recovery, and adaptation resilience capacities. Along with the four mentioned resilience abilities, 17 principles of a resilient urban energy system (robustness, stability, flexibility, resourcefulness, coordination capacity, redundancy, diversity, foresight capacity, independence, interdependence, collaboration, agility, adaptability, self-organization, creativity, efficiency, and equity) were used. The criteria are then categorized into urban infrastructure, resources, land use, urban governance and socio-demographic aspects that characterize urban energy resilience. In total, 196 criteria were developed.

The Sharifi and Yamagata (2016) paper is mainly reviewed to choose criteria that can be developed for the purposes of assessing the resilience of electricity grid sectors. Although the proposed criteria in this paper addresses the energy system as a whole, criteria for this thesis is developed by adjusting relevant criteria dealing with the supply, transmission, and distribution of electricity. In Chapter 4, the development and operationalization of the criteria is discussed.

2.2. Research gaps

Two research gaps were identified through the literature review on resilience. They are briefly discussed below:

- Energy resilience criteria proposed has not been applied for the assessment of electricity grid sectors.

Literature on energy resilience focuses on principles and the need for assessing energy systems using the concept of resilience. Gasser et al. (2019) and Sharifi and Yamagata (2016) outline how resilience principles can be used to assess energy systems. Sharifi and Yamagata (2016) also proposed criteria that can be used to assess the resilience of energy systems. However, these papers describe the overall energy system without focusing on certain parts of the energy system such as the electricity grid. This means that criteria developed from these papers must be re-focused to assess the resilience of electricity grid sectors.

- Resilience of energy systems is not approached through spatial analysis

The application of resilience is mainly focused on analyzing the phases of a disruption but the method of analysis is not specified in the papers reviewed. Therefore, there is no emphasis on performing spatial analysis for the phases of resilience. Analyzing resilience on a spatial level is valuable as the spatial perspective is relevant to simulate local and regional diversification of the energy system (Zuidema & de Boer, 2017).

3

Methodology

Based on the research questions and research approach discussed in the introduction, the methods that address the questions and approach are presented in this chapter. Background on the selected case study and the spatial level of the assessment is also discussed in this chapter.

3.1. Methods

The different methods used throughout this thesis are outlined in this section.

3.1.1. Criteria development and operationalization

Having a thorough understanding of resilience is required for the development of criteria for assessment purposes. Therefore, the literature review discussed in the previous chapter guides the development and operationalization of these criteria. The criteria were obtained through two approaches. First, the development of criteria is done by reviewing proposed criteria from the Sharifi and Yamagata (2016) paper through the lens of resilience approaches and capacities that were identified. Second, the criteria were also developed from expert interviews in the form of validation and suggestions of new criteria.

Operationalization of criteria is done to measure the performance of electricity grid sectors. This is needed for the purposes of applying the criteria to quantify the resilience of electricity grid sectors. To do so, indicators are set that give options for to measure electricity grid sectors in a wide range of contexts. The development and operationalization of resilience criteria sets a precedent for what data needs to be collected and how it should be processed, handled, and visualized.

3.1.2. Data collection and processing

Data was collected through desk research by accessing open data from:

- Electric Reliability Council of Texas (ERCOT): general facts about ERCOT and supply data;
- Houston Advanced Research Center (HARC): geospatial data on electricity grid components;
- City of Houston (COH): geospatial data on flood plain maps, emergency services;
- National Renewable Energy Laboratory (NREL): geospatial data on wind resources

- and the American Community Survey (ACS): geospatial data on population census

Data collection is done to be able to measure the performance of electricity grid sectors with respect to each criterion and ultimately handle the criteria. The performance measurement requires the data collected to be processed at the spatial level of electricity grid sectors to be able to compare the data measured at the same level. All data except for data collected from ERCOT already contained geospatial attributes ready to be processed.

3.1.3. Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis (MCDA) is commonly used when there is a need to handle multiple and conflicting criteria. To simultaneously handle such criteria, MCDA is be used because it enables for the different measurement ranges of criteria to be compared on an uniform scale. This uniform scale gives an indication of how each electricity grid sector ranks in terms of resilience. Furthermore, Geographical Information Systems (GIS) can be combined with MCDA to display the results of the chosen MCDA method spatially (Cradden et al., 2016).

MCDA determines an optimal decision based on a finite set of available decision alternatives with multiple and potentially conflicting criteria (Wang et al., 2020). MCDA is subdivided in two sub-classes: multi-attribute decision making (MADM) and multi-objective decision making (MODM) (Aydin et al., 2009). MADM is associated with problems where the number of alternatives is predetermined whereas MODM is associated with problems with non-predetermined alternatives (Zavadskas et al., 2019). Therefore, the main difference between the two MCDA sub-classes is the degree of certainty involved in the problem statement. Based on Table 3.1, the Multi-Attribute Value Theory (MAVT) is chosen to handle the developed and operationalized criteria. Table 3.1 gives examples of each sub-class but are not limited to the types listed. Further discussion on why this method was chosen and what steps are followed is discussed in Section 4.3.

Table 3.1: *MCDA methods*

Method	**Description**	**MCDA type**
ELECTRE	Preference aggregation-based methods that work on pairwise comparisons of the criteria alternatives (Greco et al., 2016).	MODM
PROMETHEE	Requires information between and within the criteria (Cinelli et al., 2014).	MODM
AHP	Requires the identification of a set of alternatives and a hierarchy of evaluation criteria (Belton & Stewart, 2002).	MADM
MAUT	Suitable for decision making under risk which requires the identification of utility functions and weights for each attribute that leads to a probability distribution (Comes et al., 2011; Figueira et al., 2005; Keeney et al., 1993).	MADM
MAVT	Targeted at decision making under certainty, where each alternative leads to a specific result (Bottero et al., 2014; Comes et al., 2011).	MADM

An important part of most MCDA methods is conducting expert or stakeholder interviews. This is done to place the different measurements on an uniform scale and assign weights to the criteria (elicitation of preferences and weights). As the case study is based in Texas, interviewees with experience in the energy grid, resilience, and energy industry were contacted. Diana Wallison from the Smart Energy Grid Center and Dr. Ali Mostafavi from the Urban Resilience.AI Lab, both at Texas A&M University, were interviewed about the relevance of the criteria developed and to inquire about case study specific data. To elicit the preferences and weights, energy industry experts Christian Cuellar, Jose Joaquin Dueñas, and Mike Mason P.E. were contacted. The interview process is discussed in Chapter 5. but an outline of how the interviews were conducted can be found in A.

3.1.4. Spatial analysis

All of the analysis outlined above is done through a spatial analysis lens. The boundary of the spatial analysis is at the electricity grid sector level. Spatial analysis is used to display the results of both the performances and overall scores of the electricity grid sectors trough a series of maps. Using spatial analysis software such as Geographic Information Systems (GIS) for spatial planning and vulnerability assessments could be better integrated to find site-specific solutions for objectives regarding resilience (Greenwalt et al., 2018).

3.2. Case study: Harris County, Texas

The described methods are applied for the purposes of assessing electricity grid sectors in Harris County, Texas. This case study was chosen due to this area's vulnerability to extreme weather-related events, especially flooding events. However, the electricity grid in Harris County is not only prone to flooding. In addition to the winter storm experienced in February, in the summer of 2021, electricity demand hit an all time record high during a heatwave putting pressure on the grid (DiSavino et al., 2021). To first describe the case study, the current conditions of the energy system in Texas are looked at to gain a general understanding of how the state provides its citizens with electricity.

3.2.1. Texas energy system characteristics

The United States Energy Information Administration (EIA) states that Texas is the top U.S. producer of both crude oil and natural gas accounting for 41% of crude oil and 25% of gas production. However, in a push for more renewable energy generation, Texas also leads the U.S. in wind power generation producing about 28% of all the U.S. wind-powered electricity in 2019 (United States Energy Information Administration, 2021).

The Electric Reliability Council of Texas (ERCOT) is an independent organization responsible for overseeing the reliable and safe transmission of electricity over the power grid that serves 90% of Texas' electricity demand (Electric Reliability Council of Texas, 2018). Per the Long-Term Assessment report by Electric Reliability Council of Texas (2018), the energy operator manages the flow of electric power to more than 26 million Texas customers with an available generation capacity of over 82,000 MW. ERCOT schedules power on an electric grid that connects over 46,500 miles of transmission lines and more than 680 generation units as seen in Figure 3.1. This map was made using data from Houston Advanced Research Center (2021).

The majority of Texas' renewable energy sources are in the western part of the state. So, as a need to alleviate grid congestion, the state government introduced measures in the form of the concept of Competitive Renewable Energy Zones (CREZs) in 2005 (Powering Texas, 2018). The five CREZs are designated geographical areas in western Texas where the wind resource is the strongest, however, most of the energy demand comes from central and eastern parts of the state as seen in Figure 3.2 (Orrell et al., 2016). This map was created using data from the National Renewable Energy Laboratory (2021). The CREZ transmission project

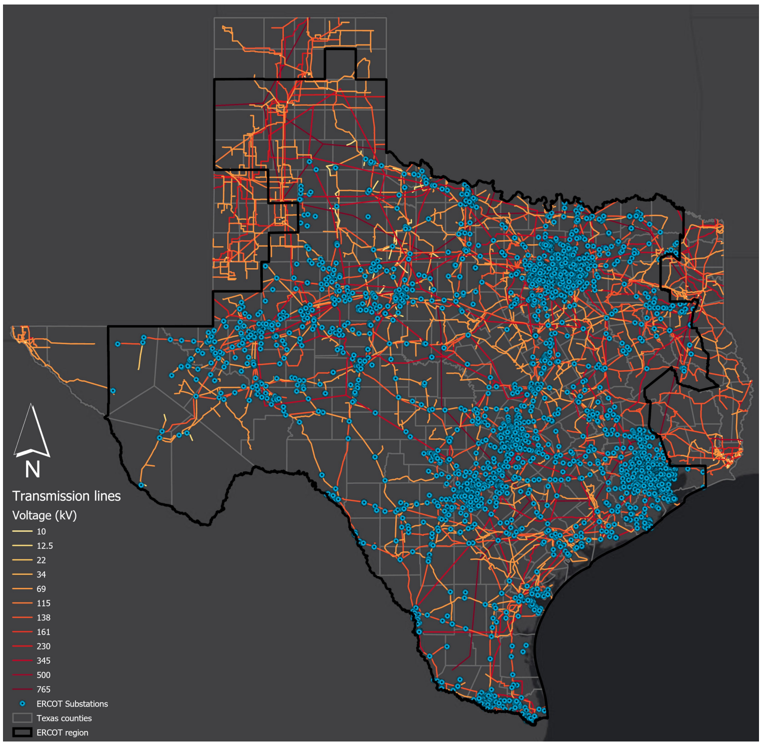


Figure 3.1: *Transmission lines and ERCOT substations*

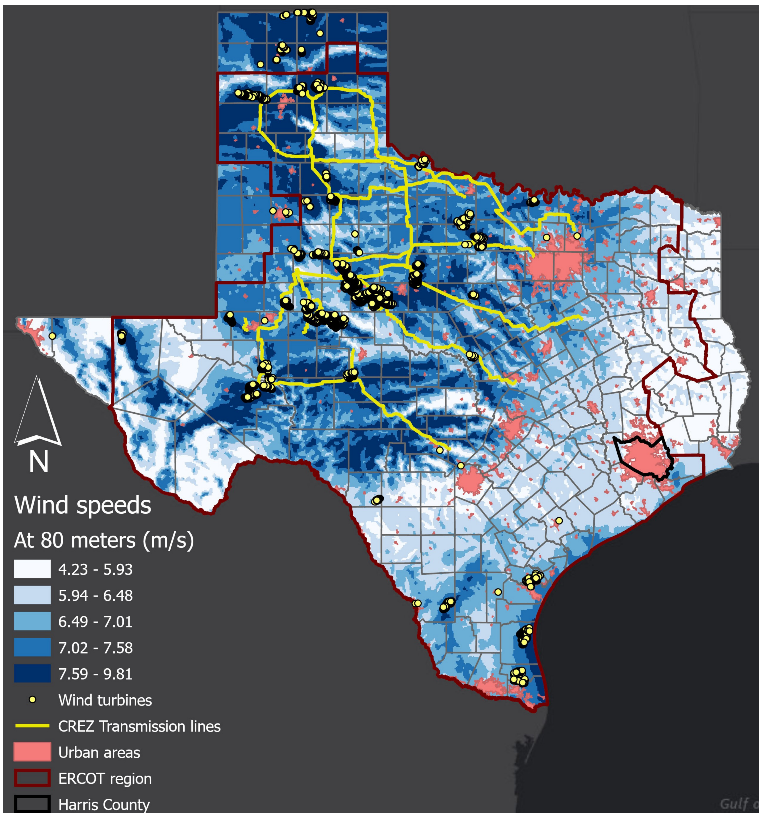


Figure 3.2: *Wind energy resources in comparison to urban areas*

enabled an increase of wind energy generation of 750% from 2005 to 2015 (1,854 MW to 15,764 MW) (Electric Reliability Council Of Texas, 2016). The success of this project had to do with the fact that there are few land development barriers in west Texas because the population is sparse and the geographic scope of ERCOT enables easier regional planning (Lasher, 2014). Due to the increased production of renewable energy resources through CREZs, there has been development of new standards and requirements in the last five years with a special focus given to wind energy (Nimmagadda et al., 2014).

3.2.2. Harris County

In addition to the extreme weather-related risk, the electricity grid in Harris County is chosen as it represents one of the major load centers in Texas. Harris County forms part of the greater Houston area which represents more than 25% of the entire load in the ERCOT system (Boyd et al., 2014). Furthermore, Boyd et al. (2014) noted that as the load continues to grow, it is expected that either forced or planned outages will cause significant reliability issues and become increasingly more costly.

Harris County is located in the flat Gulf Coastal Plain, at an elevation of about 17 meters above sea level and has a humid subtropical climate characterized by springtime thunderstorms, hot humid summers, and temperate winters (Britannica, 2020). Extreme weather-events, especially flooding, are common. For example, Harris County has experienced six federally declared flooding disasters in the form of 100- and 500-year return period flooding events from 2015 to 2020 (Barone et al., 2020). Flooding in the Houston area is not only confined to extreme single events, but also occurs with heavy rainfall whose frequency is increasing (Rappenglueck et al., 2021). Therefore, increasingly intense and frequent extreme weather-events pose a challenge on electricity demand when it comes to daily or hourly response (Gabriel & Nathwani, 2018).

Harris County is the third most populous county in the United States with around 4.7 million people in 2019 in 4600 square kilometers (Balderrama et al., 2020). The electricity grid is composed of transmission and distribution lines as well as substations (Majithia, 2014). Substations transform the high voltage carried by transmission lines (138 kV-765 kV) to low voltage levels for distribution lines (≤69 kV) to distribute electricity to consumption points (Federal Energy Regulatory Commission and North American Electric Reliability Corporation, 2011). The transmission and distribution of electricity is handled by the CenterPoint Energy utility company. CenterPoint Energy's service area serves more than 2.2 million customers in a 5,000 square-mile area (CenterPoint Energy, n.d.). As mentioned, the boundaries of the spatial analysis conducted in this study is at the electricity grid level.

However, data on the distribution grid was not found. So to work at the electricity grid sector level, treating the county's neighborhoods or zip codes as service areas was looked into. As seen in Figure 3.3, not all neighborhoods are represented by a substation meaning that they cannot be treated as service areas of the electricity grid. Therefore, service areas were drawn for each of the 365 substations using a Voronoi diagram as seen in Figure 3.4. 11 substations were left out as the data indicated that they are not in service.

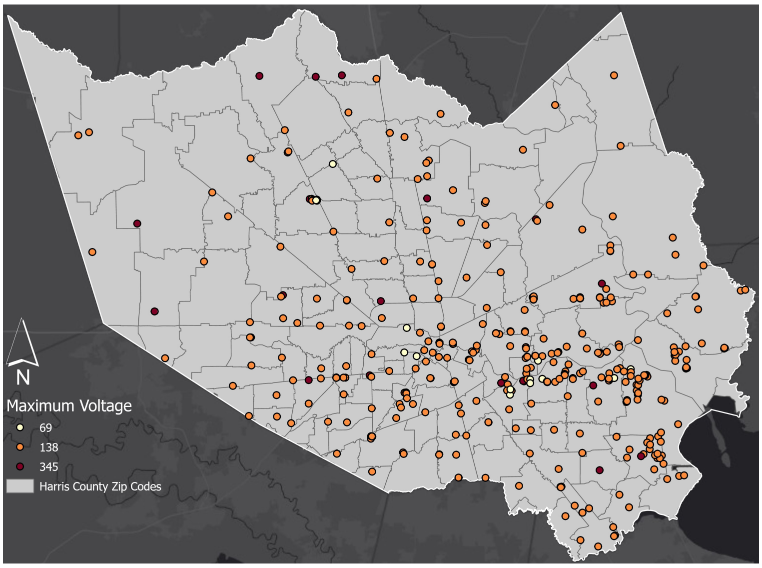


Figure 3.3: *Neighborhoods as service areas*

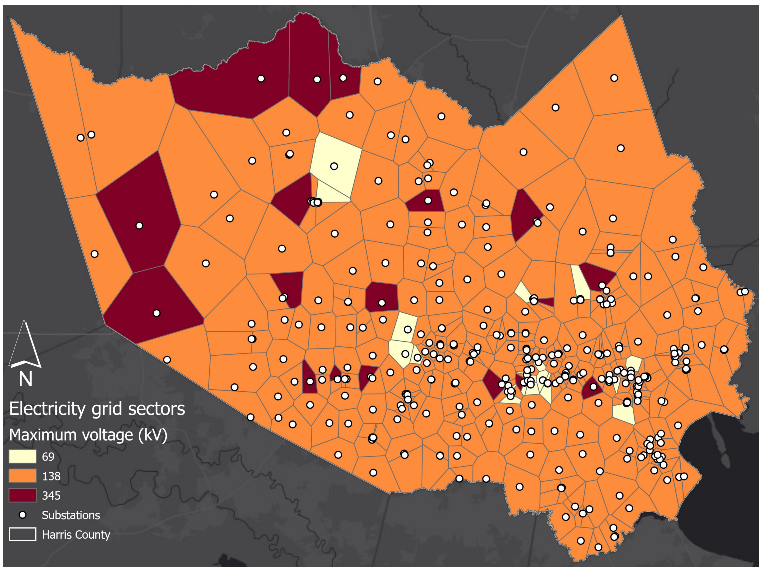


Figure 3.4: *Voronoi diagram of substations*

4

Criteria development and operationalization

The literature review provided an understanding of resilience through disruptions, approaches, and capacities. This combination enables the development and operationalization of criteria with respect to the resilience assessment of electricity grid sectors. This is a crucial step for the objective of the thesis as insights gained from resilience literature will be applied to a case study. However, criteria developed in this chapter have a general application for assessing the resilience of electricity grid sectors to extreme weather-events. In Section 4.2 the criteria is made suitable for the context of Harris County.

4.1. Criteria development

The following resilience criteria is derived from the literature review and expert interviews. The development of criteria is done by incorporating knowledge gained from the literature review to assess the resilience of electricity grid sectors. The developed criteria in this thesis are divided into technical and socio-demographic categories.

196 proposed criteria from Sharifi and Yamagata (2016) are reviewed using the knowledge gained from resilience approaches and capacities. These criteria are categorized into five aspects of energy resilience. The urban infrastructure and socio-demographic categories were considered for the development of criteria for this thesis:

- Urban infrastructure

64 criteria are subdivided into supply, transmission, and distribution; backup and storage; green infrastructure; blue infrastructure; buildings and neighborhoods; transportation; and innovative technology. Out of these criteria, 10 were selected as they directly deal with supply, transmission, distribution, and storage capabilities of the energy system.

Criteria related to storage was ultimately left out as the objective is not focused on the challenges of incorporating renewable energy sources into the electricity grid. Furthermore, criteria from the green infrastructure, blue infrastructure, building and neighborhoods, transportation and innovative technology were also not chosen as they focus on the end users or demand side of the energy system.

- Resources

This category contains 33 criteria that mainly have to do with other resources such as water and food and their relationship with energy. Therefore, these criteria focus on reducing energy consumption as well as conserving and optimizing water and food processes. None of the criteria were chosen as they are more focused on the nexus between energy, water, and food systems. However, assessing this nexus could be more applicable using urban resilience as it integrates the analysis of governance networks, networked material and energy flows, urban infrastructure, and form and socio-economic dynamics (Meerow et al., 2016).

- Land use

28 criteria are proposed for this category which address the spatial factor and built environment focused approaches. For example, this category emphasizes the design aspects of a city and its buildings with respect to creating a functional and energy efficient mix. The only criteria considered here had to do with population density. However, population density is used to measure the electricity grid sectors criterion. This is described in Section 4.2

- Urban governance

With 50 criteria proposed in the urban governance category, the focus mainly has to do with policy, incentives, planning, and management of the urban energy system. This category was not considered as the focus of this category is beyond the scope of assessing the resilience of electricity grid sectors. However, visualizing the assessment results through maps should be considered as a tool to enable more energy resilient planning. Policies and incentives will play an important role in securing the integrity of energy systems in specific regions or countries.

- Socio-demographic aspects

Lastly, 21 criteria provide an approach for analyzing human and social behavior. No criteria were directly selected from this category. However, socio-demographic characteristics such as social vulnerability is considered as resilience can be described through a socio-technical lens. This means that resilience does not only have to do with the technical aspects of a system but also should consider impact on the community.

Criteria chosen from the Sharifi and Yamagata (2016) paper were to assess the resilience of electricity grid sectors. This is done by combining some of the criteria and relating back to the absorptive, robustness and redundancy capacities reviewed in the Chapter 2. The following paragraphs discuss the criteria chosen from the urban infrastructure and socio-demographic categories that can be categorized into technical and socio-demographic aspects of resilience:

Technical criteria:

Fortification is an engineering-based measure to strengthen the generation, transmission and distribution of an electricity grid (Arghandeh et al., 2014). For this criterion, extreme weather-related disruptions to electricity system infrastructure are considered. This measure is important as countries around the world are dealing with extreme weather-events that affect the provision of electricity to cities (Greenwalt et al., 2018).

Based on the resilience capacities identified in Chapter 2, fortification in this thesis is used to analyze the robustness capacity of the electricity grid. To account for disruptions, regular maintenance and upgrading of infrastructure is needed to maintain the system's function when facing more frequent and intense extreme weather-events (Willis & Loa, 2015). For example, the disruption of above ground transmission lines following severe rainfall or wind accounts for the majority of vulnerabilities that can result in system-wide blackouts (Sharifi & Yamagata, 2016). Therefore, upgrades such as undergrounding distribution lines creates benefits such as securing supply during extreme weather and lower transmission losses among other benefits (Ritchie et al., 2013).

Energy diversification is one of the most important measures that can enhance the resilience of an electricity system (Mola et al., 2018)). Diversification is chosen as it describes the supply source mix that supplies an electricity grid.

Energy diversification is used to analyze the redundancy capacity of an electricity grid. This is aimed at ensuring continuous supply in the case of replacing a disrupted energy source with another (Sharifi & Yamagata, 2016). For example, the benefits of a diverse generation portfolio include having a reliable source of supply in the form of gas while producing cheap and clean electricity such as wind energy (Leibowicz, 2021). Given the uncertainty involved with predicting the occurrence and impacts of extreme events, diversification is a good option for dispersing the risk (Månsson et al., 2014). However, capacity generated in a diverse energy portfolio should be substantial across electricity source types. For example, France has nine electricity source types but heavily depends on nuclear energy representing around 90% of electricity generated in the country (International Energy Agency, 2020).

Distributed generation in an electricity grid describes system diversity and ensures a continued flow of energy (Sharifi & Yamagata, 2016). This criterion is considered in order to see the distribution of electricity generated with respect to the grid.

Distributed generation is used to analyze the redundancy and robustness capacities of an electricity grid. However, the high level of integration of centralized generation makes it vulnerable to disruptions that affect the energy system's supply chain (Sharifi & Yamagata, 2016). Therefore, connecting energy generation at one specific level of the grid can be problematic during disruptions as the electricity grid is only being fed at one point. Exploring more and various connection points creates redundancy in supply input to the grid reducing the shock of a disruption. This enables flexibility which helps increase the reliability and resilience of the electricity grid by making it less vulnerable to disruptions caused by extreme weather-events (International Renewables Energy Agency, 2016). Therefore, it is necessary to develop appropriate infrastructure that will be flexible and diverse to facilitate the distribution of various energy types to consumption points (Ritchie et al., 2013).

Socio-demographic criteria:

Electricity grid sectors criterion serves to distinguish the different sectors of the electricity grid. This is needed as each electricity grid sector's characteristics need to be known. In turn, this allows for decisions to be made on how to prioritize sectors.

Understanding an area's electricity grid sectors helps analyze the robustness capacity as this knowledge can result in finding solutions to better prepare the population and infrastructure serviced by each grid sector.

Social vulnerability is included to further detail the socio-demographic conditions of a study area. This criterion takes variations of disaster experience and disproportionately affected socially vulnerable groups into account (Coleman et al., 2020). Social vulnerability is considered as a criterion resulting from an interview with Dr. Mostafavi as he noted the importance of including the level to which a community is prepared to face a disruption. This criterion indicates the degree to which a community exhibits certain social conditions, such as high poverty, low percentage of vehicle access, or crowded households. The extent of said social conditions may affect a community's ability to prevent impacts caused in the event of disaster (Center for Disease Control, 2020).

Considering the vulnerabilities of a study area based on social conditions can contribute to analyzing the absorptive and robustness capacities. This way, areas with high social vulnerability are known. This results in an overview of vulnerability in an area in terms of preparedness and what needs to be improved so that such areas can better face a disruption to the electricity grid. Therefore, robustness can be achieved by better equipping the most vulnerable areas so that they are more prepared in the event of a disruption.

Emergency services such as hospitals and fire stations must be continuously supplied with electricity especially during extreme weather-related disruptions. Knowing the locations and number of emergency services allows for electricity supply to be better connected to a grid sector with a high number of emergency services.

Having critical services locations is used to analyze the absorptive capacity as such sectors with critical services can be given priority when choosing supply connection points. Additionally, priority given to emergency services such as hospitals also benefits its surrounding area. Maliszewski and Perrings (2012) investigated the spatial dependence between blackouts and land use types and found that functions closer to hospitals are likely to have their power restored faster than functions farther away from hospitals. However, the proximity to police stations, fire stations and schools turned out to either be insignificant or to have a negative relation to outage duration.

4.2. Criteria operationalization

Criteria has been developed to assess the resilience of electricity grid sectors. For these criteria to be applied, it is first operationalized by setting indicators. The indicators give options on what the criteria can be measured on. This gives the ability to apply the criteria to many different case studies. Therefore, the criteria is then measured to calculate the performance of each electricity grid sector with respect to the criteria. Table 4.1 gives an overview of each criterion and its corresponding indicators and measurement examples.

Fortification is explained through the weatherized infrastructure indicator. As fortification has to do with the maintenance and upgrading of infrastructure, weatherization indicates the extreme weather-related hazard that an electricity grid component is exposed to. However, weatherization is done for a specific type of extreme weather-event. For example, weatherization measures considered after superstorm Sandy included undergrounding overhead distribution lines, safeguarding substations, and strengthening the pole distribution system (Van Nostrand, 2015). On the other hand, winter storm related measures include insulating natural-gas compression stations and equipping wind turbines with heating elements to de-ice their blades and gearboxes (John, 2021; Krane et al., 2021). Other potential extreme weather-related risks to the energy system include heat waves, summer drought, flooding, sea level rise, coastal erosion, river erosion, vegetation changes, lightning, and combined events (Majithia, 2014).

As the chosen extreme weather-event is based on flooding, this measurement identifies substations in danger that would most likely need to be upgraded through safeguarding. The length of above ground transmission and distribution lines can also be measured for the weatherization of flood-prone infrastructure depending on the availability of data. Weatherization measures could also be focused on heat waves due to the increase in energy demand required to cool water and indoor temperatures (Beersma et al., 2015) as is happening in Northern European countries such as the Netherlands.

Energy diversification is explained through the supply mix indicator. Knowing what the energy supply mix of an energy system gives an idea of what the availability of energy is and whether an energy system is dependent on one or more types of energy generation. However, energy generation is area-based meaning that some regions or areas may be specialized in a specific energy generation form (Zuidema & de Boer, 2017). Because of this, the way of measuring the supply mix can be done through the number of sources, power generated, or using percentages per supply to see how diverse the supply mix in an area of interest already is.

However, measuring the supply mix indicator at a specific spatial level such as electricity grid sectors is not easily be compared as supply differs more at a regional scale. Although diversification cannot be compared at this spatial level, it is still considered due to the importance of having a diverse energy mix to create redundancy in the electricity grid. This provides information on the availability of energy and whether the study area is dependent on limited supply sources.

Distributed generation is explained through the transmission line connections indicator. This gives an indication of how supply carried in transmission lines is distributed within an electricity grid. This is an important factor as connections to multiple levels of the electricity grid contributes to building a redundancy capacity as stated in the previous section.

For the measurement of the distributed transmission criterion, the number of lines connected to each substation are counted. This is done for the purposes of displaying how each electricity grid sector is connected to the transmission of energy supply. Another way of measuring this criterion is by calculating the cost or distance of transmission from generation facilities to the grid's substations.

Electricity grid sectors are explained through the distinction of electricity grid sectors indicator. Making such a distinction is needed to understand the layout of the electricity grid in a specific area. Each sector can then be characterized to gain a better understanding of the difference between sectors. This can be done by measuring socio-demographic or technical characteristics such as supply and demand per sector.

Social vulnerability is explained through the community preparedness indicator. To understand preparedness, the vulnerability of a community needs to be known. Coming up with a vulnerability measurement is done with the socio-demographic characteristics known in the study area. Therefore, there are no options for this indicator other than determining the vulnerability of communities using local characteristics.

As the chosen study area is in the United States, the CDC (Center for Disease Control) created a social vulnerability index (SVI) to help public officials and planners better prepare communities for disruptions. This index is the aggregation of estimates regarding socio-economic status, household composition, minority status, and housing type and transportation.

Emergency services are explained through the locations of emergency services such as hospitals. Knowing these locations are needed as these services are essential response mechanisms in the event of disruptions. The Maliszewski and Perrings (2012) stated that police stations, fire stations and schools do not contribute to helping their surrounding area to recover from a blackout. However, they should be considered as these services need a continuous supply to provide safety, emergency response, and shelter respectively to citizens during and after a disruption.

4.3. Multi-Attribute Value Theory

For this thesis, the Multi-Attribute Value Theory is used. This method can deal with a large number of alternatives without increasing the need for experts to assign preferences and weights compared to a study with a smaller number of alternatives (Schuwirth et al., 2012). MAVT can be used to address problems involving a set of alternative options that have to be evaluated based on conflicting objectives.The following steps explained in Bottero et al. (2014) and Ferretti (2016) are used. The first two steps have already been defined. The remaining four steps are described and will be fulfilled in the following chapter. Step four is a crucial step as it involves conducting interviews with experts to translate the different alternative performances into an uniform scale for the comparison of sector resilience.

Table 4.1: *Criteria indicators and measurements*

Criteria	**Indicators**	**Measurement examples**
Fortification (Sharifi & Yamagata, 2016)	Weatherized infrastructure	• Distance of electricity grid component to extreme weather-related risk • Length of transmission and distribution lines above ground
Energy diversification (Sharifi & Yamagata, 2016)	Supply mix	Percent, number, or amount of supply
Distributed generation (Sharifi & Yamagata, 2016)	Transmission line connections	• Number of transmission lines connected to each substation • Locations of generation facilities
Electricity grid sectors (Sharifi & Yamagata, 2016)	Distinction of electricity grid sectors	• Population density per sector • Demand per sector • Supply per sector
Social vulnerability (Center for Disease Control, 2020)	Community preparedness	Degree of a community's social conditions (indices from the Center for Disease Control)
Emergency services (Maliszewski & Perrings, 2012)	Locations of critical services	Number of critical services per grid sector used for emergency response in the study area

1. Definition of the problem, objectives, and criteria

   This first step is crucial since it concerns the definition of the problem, which implies identifying and structuring objectives and criteria. In this thesis, the problem identified has to do with cities being unprepared for extreme weather-event disruptions to their electricity grid. The problem is addressed through the objective of assessing the resilience of the electricity grid sectors of a case study. Criteria to assess the resilience of electricity grid sectors has been developed and operationalized in the previous sections of this chapter.

2. Identification and creation of alternative options

   The assessment of criteria based on the identified problem and objectives is done by evaluating different options or alternatives. These alternatives are the potential solutions to the decision problem. Based on the decision problem, potential solutions may be used to choose the best option or to identify the worst performing options. As mentioned in the methodology chapter, the spatial scale of the assessment is on the electricity grid sectors. The performance of these alternatives are measured in terms of each criterion as specified in the next step.

3. Determining levels for each alternative with respect to each criterion

   Once the alternative options have been identified, the performance of each alternative is measured. This measurement specifies how the alternatives perform in each of the stated criteria. The level of each alternative is referred to by the term performance in this thesis.

4. Modelling of preferences and weights

   In this step, expert interviews are conducted to obtain their preferences and weights based on their judgement. The collection of preferences and weights from experts is referred to as elicitation in this thesis as well as in MCDA papers. Before the preferences and weights can be collected from expert interviews, an appropriate aggregation technique has to be determined. Aggregation techniques deal with translating the alternative's performance into a single scale to compare overall scores of alternatives.

   Several aggregation techniques can be used for the elicitation process. In this thesis, the decomposed scaling technique is used. This technique involves identifying marginal value functions and weights. Marginal value functions are mathematical representations of human judgments that translate the performances of the alternatives into a value score. The value score represents the degree to which a performance satisfies the criterion. There are several options for both marginal value functions and weights which both require relevant stakeholders or experts to assign preferences and weights.

   Applying the marginal value function translates each performance measured into an individual value score given from expert preferences. Among the curve fitting, bisection, standard differences, parameter estimation, and semantic judgment techniques, the approach chosen is the direct rating technique. Through this technique, the expert is asked to score the minimum and maximum performance levels from 0 to 1. The rest of the levels are scored within the range of the minimum and maximum preferences given. After preferences are elicited, marginal value function graphs are made which represent how each electricity grid sector satisfies the criteria.

   Eliciting weights has to do with giving priority to certain criteria. Weights are scaling constants, which allow marginal value functions to take on values in the same interval. To bring attribute preferences onto the same scale so they may be aggregated, weights need to be assigned for the criteria (French et al., 2003). The elicitation of weights is stated as the value improvement obtained by switching an attribute from its worst to its best score corresponds to the attribute weight (Beinat, 1997). Among the rating, pairwise comparison, trade-off and qualitative translation techniques, the swing-weighting approach is used. The swing-weighting procedure is based on the process done in French et al. (2003) in pages 40-41. Through this process, the expert is asked to choose the criterion that can best improve the score of a newly introduced alternative that scores poorly on all criteria. This means that each point on the chosen criterion scale is worth more than a point on the scales of the other criteria. After choosing the criterion with maximum points (1), the expert is asked to proceed in assigning points for the other criteria by translating maximum points into the scale of the initially chosen criterion.

5. Aggregation model to calculate the overall value of each alternative

   After applying the marginal value function and eliciting weights, overall scores for each alternative need to be calculated. There are different aggregation models, but the simplest and most used is the additive model (Belton & Stewart, 2002) which requires for the swing-weighting procedure to be done:

$$V(a) = \sum_{i=1}^{n} w_i * v_i(a_i) \tag{4.1}$$

Where:

- $V(a)$ is the overall score of alternative a;
- $v_i(a_i)$ is the single attribute value function reflecting alternative a's performance on criteria i;
- and w_i is the weight reflecting the importance of criteria i.

6. Sensitivity analysis

   This final step is done to test the stability of the obtained results with regards to variations of the weights. As a result, a final recommendation can be obtained and further discussed with the decision makers and stakeholders. The procedure is also based on French et al. (2003) in pages 41-42 which used the following formula. In this procedure, the criterion identified in step four that can best improve the score of an alternative is used to see how varying the weight of the chosen criterion influences the overall scores of the alternatives. The following equation was used to calculate how the most important identified weights influenced the overall scores of the alternatives:

$$V(a) = w_c * v_c(a_c) + (1 - w_c)(w_i * v_i(a_i) + \ldots) \tag{4.2}$$

Where:

- $V(a)$ is the overall score of alternative a;
- w_c is the weight percentage that the chosen criterion contributes to the overall weight
- $v_c(a_c)$ is the individual score of alternative c with respect to the chosen criterion
- $v_i(a_i)$ is the individual score reflecting alternative a 's performance on criteria i;
- and w_i is the weight reflecting the importance of criteria i.

Steps three to six are followed in Section 5.1 through Section 5.4. while discussing the results obtained in each step.

5

Case study approach and results

In the previous chapter six criteria were developed and operationalized. This chapter addresses steps three to six of the MAVT method which are used to generate results and discussion. Step three, discussed in Section 5.1, is about measuring the performance of electricity grid sectors using the options from the indicators for the context of Harris County. By doing so, step four (Section 5.2) can be carried out to model preferences and weights elicited from expert interviews. To be able to compare the resilience of electricity grid sectors, step five (Section 5.3) is about aggregating the modelled preferences and weights. To wrap up the MAVT method, sensitivity analysis (Section 5.4) is conducted to see how the most important criteria chosen by the experts influence electricity grid sector scores. To finalize the chapter, a conclusion in Section 5.5 discusses what information the maps display and how they can be used.

5.1. Electricity grid sector performances

In the following paragraphs, the measured performances of the electricity grid sectors with respect to each criterion are explained. The data collected for each measurement is processed, handled, and visualized through a series of maps. This step of the MAVT process is crucial as the maps shown in this section are used in step four for the elicitation of preferences and weights through expert interviews.

Fortification: The distance from substations to 500-year return period flood plains are measured to see the severity of flooding risk. In Figure 5.1 all distances to flood plains from 365 substations in Harris County were measured. Out of these 365 substations, 15% of substations are located inside a 500-year return period flood plain. However, 37% of substations are within 100 meters from a 500-year return period flood plain. This is alarming as depending on the topography, close to half of the county's substations are prone to flooding which can disrupt the distribution of electricity. This means that close to the majority of substations in Harris County are flood prone. Data used for this map includes flood plains from City of Houston (2021) and substations from the Houston Advanced Research Center (2021) open data portal.

Energy diversification: Data on the supply mix for Harris County was not obtained. However, it is known that Harris county's energy supply is heavily dependent on the import of electricity (Electric Reliability Council of Texas, 2020) from gas fields and wind farms located across the state. This means that Harris County is not fed through local supply making it vulnerable to power outages if the generation capacity is hindered or the transmission of electricity is interrupted. For measurement purposes, the energy supply mix for the state of Texas is used. The energy generation mix up until April 2021 in the ERCOT region is seen below in Figure 5.2. where the ‘under 2%’ category represents biomass and hydro. Data used for displaying the energy supply mix was retrieved from the Electricity Reliability Council of Texas (2021) open data portal.

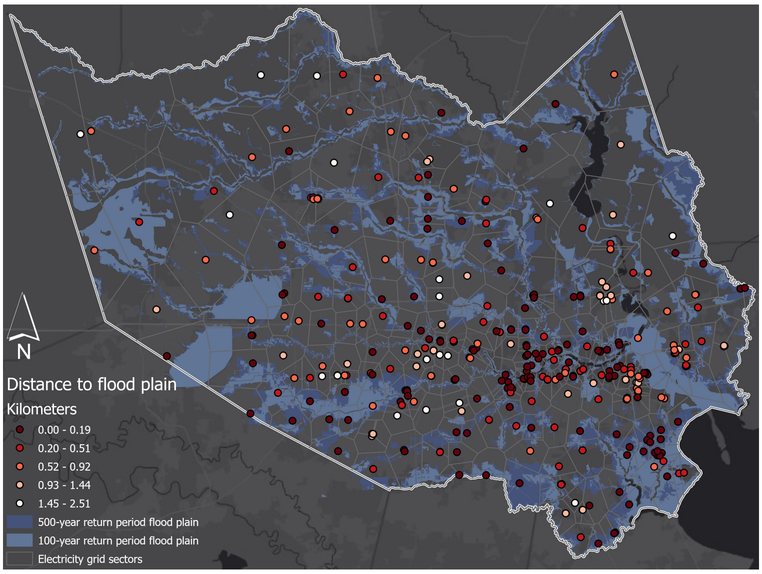


Figure 5.1: *Distances from substations to flood plains*

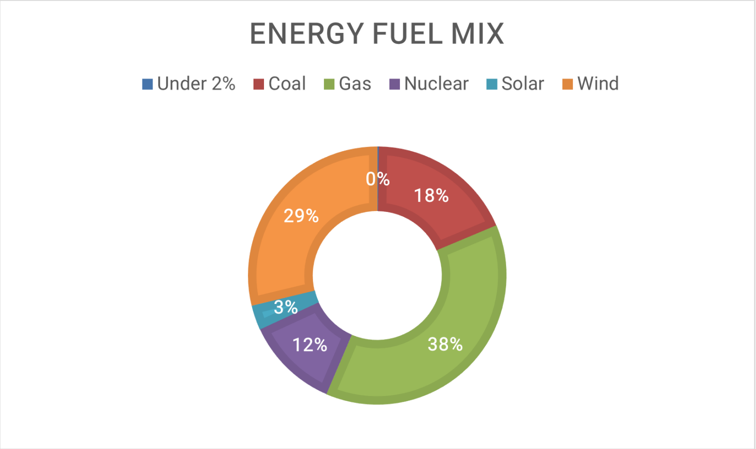


Figure 5.2: *Supply mix in the ERCOT region*

Distributed generation: Transmission lines connected to each substation are counted to see how much supply is being converted from high to low voltages for consumption in each of the electricity grid sectors. Substations in Harris County have a minimum of 1 line and a maximum of 20 transmission lines connected to them. In Figure 5.3 the map demonstrates how electricity is distributed within the county. It can be denoted that a large part of the electricity delivered from transmission lines is converted to lower levels in substations located close to the outer parts of the county (substations with more than eight connected lines). From this, the lower voltage electricity is distributed to around 90% of substations that have less than or equal to four transmission lines connected. Data used for this map includes substations and transmission lines from was retrieved from the Houston Advanced Research Center (2021) open data portal.

Electricity grid sectors: Population density is measured for this criterion to understand the demographic characteristics of electricity grid sectors. From the electricity grid sectors defined, the population density is calculated by using population data per zip code areas or neighborhoods. Since the electricity grid sector areas are not the same as zip code areas, the population was re-calculated to fit the electricity grid sector's spatial level. The density was then calculated by dividing the population sum by electricity grid sector areas. The most dense areas are in the south central portion of Harris County as seen in Figure 5.4, while the surrounding areas such as suburbs, farmland, and industry are of lower density. Population data used for this map was retrieved from the American Community Survey (2021) open data portal.

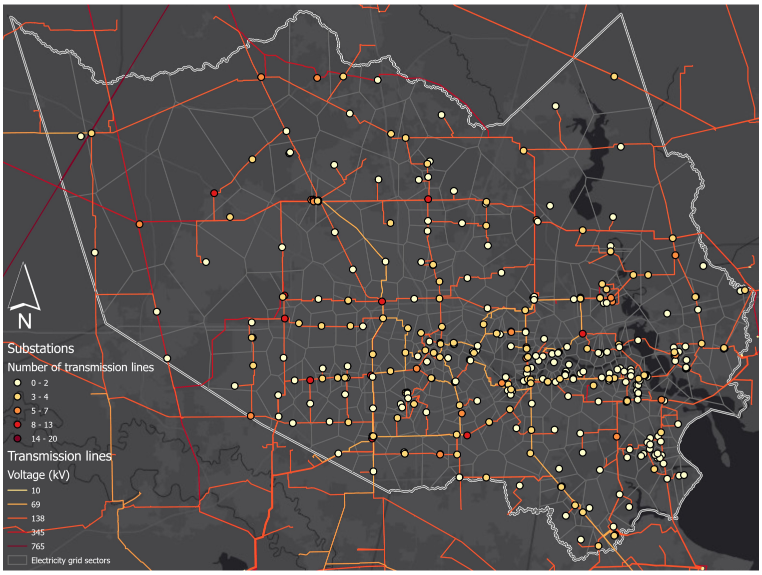


Figure 5.3: *Number of transmission lines connected to each substation*

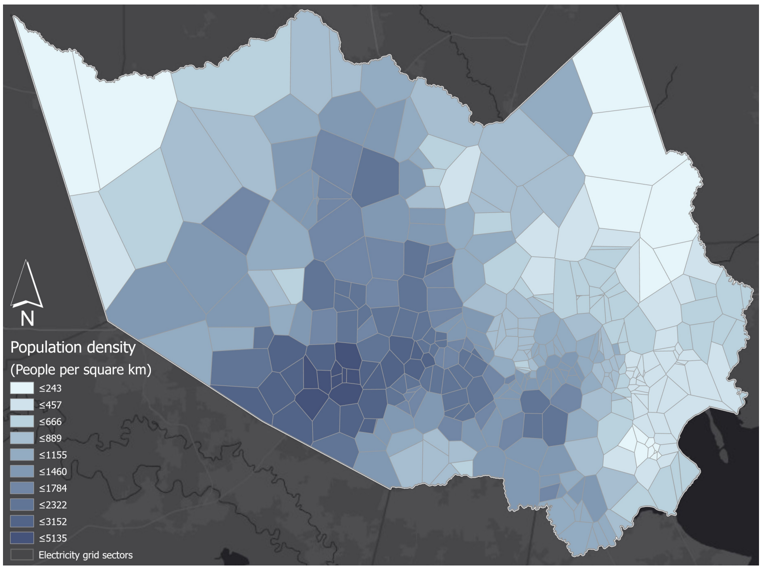


Figure 5.4: *Electricity grid sector population densities*

Social vulnerability: To further describe the socio-demographic characteristic of electricity grid sectors, social vulnerability is displayed. This is done to gain an overview of how well prepared communities in each electricity grid sector are to a disruption. The indices from the CDC are calculated per census tracts or areas that are defined for the purposes of recording population. Therefore, the indices were fitted to the spatial level of electricity grid sectors. The more central areas of Harris County, have a higher vulnerability than .6 as seen in Figure 5.5 representing close to 70% of the county. This is problematic as the higher the index, the more vulnerable an area is. Data used for this map includes the social vulnerability indices retrieved from the Center for Disease Control (2020) open data portal.

Emergency services: Displaying the number of emergency services per sector can show the distribution of services within the county and whether an electricity grid sector with many services needs more electricity backup. Close to 40% of the emergency services are located in the less-dense suburban areas of the counties as seen in Figure 5.6. This means that there is more priority for these areas which is part of the reason why close to 70% of the sectors have a high vulnerability. The transparent sectors represent areas where there are no hospitals, fire stations, police stations, or schools. Data used for this map included locations of hospitals, fire stations, police stations, and was retrieved from the City of Houston (2021).

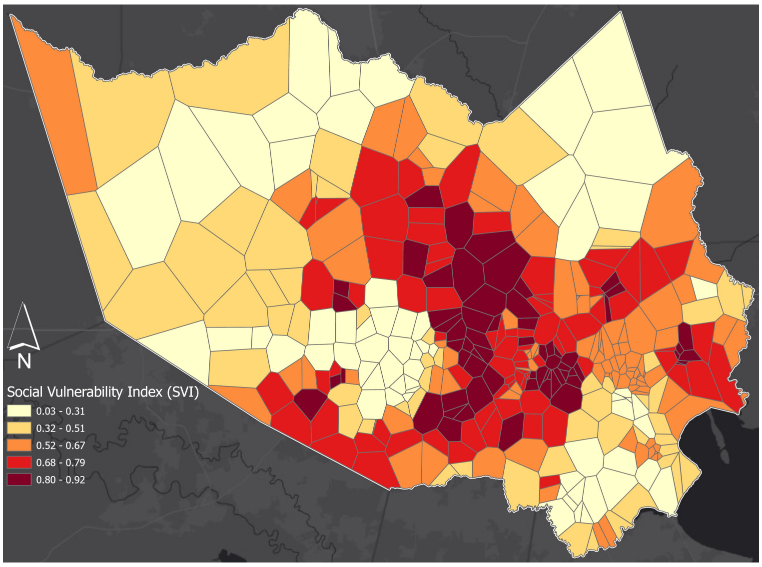


Figure 5.5: *Social vulnerability index*

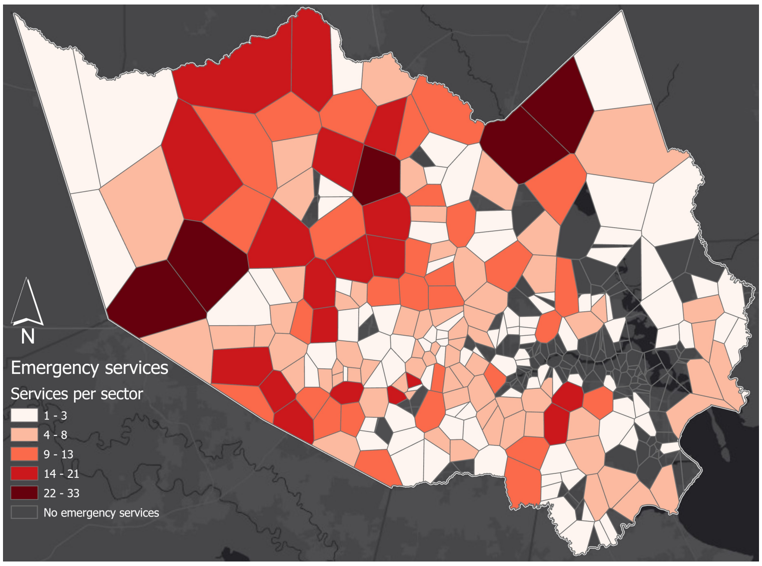


Figure 5.6: *Emergency services per electricity grid sector*

5.2. Modeling of preferences and weights

Using the performance maps discussed in the previous section, the direct rating technique and swing weighting approach were used for conducting expert interviews for the elicitation of preferences and weights.

For experts to give their preferences, they were asked to score the lowest and highest performance measurement in the scale of 0 to 1. These preferences represent an individual electricity grid sector's score for each criterion. After doing so, experts were asked to score the median performance instead of scoring the 363 leftover sectors. The difference in expert judgments is indicated through calculating the standard deviation. Standard deviations show how much variation exists from the average value. Because of the difference in expert judgements, the minimum, average, and maximum expert preferences are used in the making of marginal value functions, aggregating preferences and weights, and conducting sensitivity analysis. To make the marginal value function graphs, interpolation was done between the lowest and median and the median and highest values for each of the minimum, average, and maximum scenarios.

After presenting the maps to the experts and eliciting preferences from them, the criteria was weighted by giving the experts a scenario where a new electricity grid sector was introduced but it scored badly in all criteria. With this scenario, the experts were asked to choose one criterion that they thought could increase the sector's score to maximum points. After choosing the most important criteria, the rest of the criteria are asked to be weighed by asking the experts to transfer full points of the other criteria into the scale of the most important criterion chosen. However, the process used in French et al. (2003) was not fully followed for the interviews of Expert 1 and 2. This was mainly because time was running out as interviews were only scheduled for an hour. However, for Expert 3, the preference elicitation went faster which allowed for a more detailed explanation on how to follow the weighting process.

Fortification preferences: The lowest, median, and highest performances for this criterion are 0, 0.28, and 2.51 kilometers from a flood plain respectively. The differences in lowest, median, and highest expert judgement are shown through the standard deviations of 0, 0.25, and 0.16. The subjectivity of the elicitation process is first present in this criterion as the median performance of the distance of substations to 500-year return period flood plains are very different. Expert 2 considered 0.28 kilometers to be sufficient to avoid flooding risk unlike Expert 1 and Expert 3. Expert 3 noted that because of Harris County's topography, one of the main fortification measures is to raise or find higher elevations to place the substations.

The x-axis of Figure 5.7 is represented by the measured performances done in Section 5.1. while the y-axis represents expert judgements. For example, if a substation is located 1 kilometer away from a 500-year return period flood plain, the minimum, average, and maximum scenario score for this substation would be around 0.32, 0.58, and 0.88 respectively.

Energy diversification preferences: All energy industry experts except Expert 3, expressed their concern that Harris County receives supply from a limited number of sources meaning that the county lacks in energy diversification. For the overall energy diversification conditions of Harris County, the preferences given were 0.3, 0.2, and 0.6 for Experts 1, 2, and 3 respectively. Because of Expert 3's preference, the difference of judgement is described through the standard deviation of 0.17. Expert 3 did not think the supply mix was a major problem. However, did think that because Texas does not import supply it can cause pressure during extreme weather-related events like the recent winter freeze.

Unlike the rest of the criteria that is assessed at the electricity grid sector level, the experts were asked to score diversification based on their knowledge of the current supply delivered to Harris County. This was done as specific data for Harris County was not obtained. Therefore, the lower, higher, and median performances are not given preferences by the experts.

Distributed generation preferences: The lowest, median, and highest performances for this criterion are 1, 4, and 20 transmission lines connected respectively. The differences in lowest, median, and highest expert judgement are shown through the standard deviations of 0.39, 0.29, and 0.24. This criterion is considered to build the redundant and robust capacities of an electricity grid sector by arguing that more connection points gives a sector more flexibility. However, it was noted by Expert 2 that having too many lines connected can be counterproductive. This is based on the reasoning that the more lines connected, the less reliable it is as a substation can be overwhelmed by the amount of energy being transmitted to its connection point. In addition, Expert 3 also noted that it is more difficult to manage substations as more lines means more congestion in the substations. As a result, this criterion has the biggest differences in preferences due to the different approaches taken to give judgments on the performance measurements.

Because of the difference in judgments, the median performance is not within the range of the lower and higher performances for the average and maximum scenarios as seen in Figure 5.8. This means that the marginal value function results for the distributed generation criterion are inaccurate. This error resulted from the interview questions as the experts were given the choice on how to approach this criterion. However, this was not the case for the minimum preference.

Electricity grid sectors preferences: The lowest, median, and highest performances for this criterion are 54, 955, and 5135 people per square kilometer respectively. The differences in lowest, median, and highest expert judgement are shown through the standard deviations of 0.28, 0.08, and 0.36. Expert preferences are very different for the lowest and highest preferences. This is due to experts approaching the scoring of performances differently. Unlike Expert 1, Expert 2 scored the lowest performance higher as areas with lower population density require less energy supply than heavily populated sectors. Similarly to Expert 2, Expert 3 used the reasoning that the less dense a sector is, the less competition for energy demand is created meaning these sectors put less pressure on the grid. Furthermore, Expert 2 suggested combining this criterion with the fortification and energy generation criteria as the minimum population density can be compared to the highest distances and number of connected lines.

Differences in scoring were also noticeable for this criterion as seen in Figure 5.9. Expert

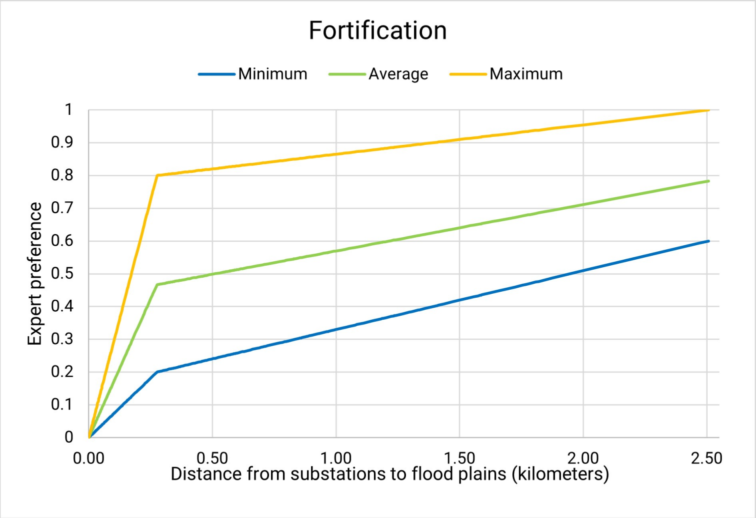


Figure 5.7: *Minimum, average, and maximum marginal value function for the fortification criterion*

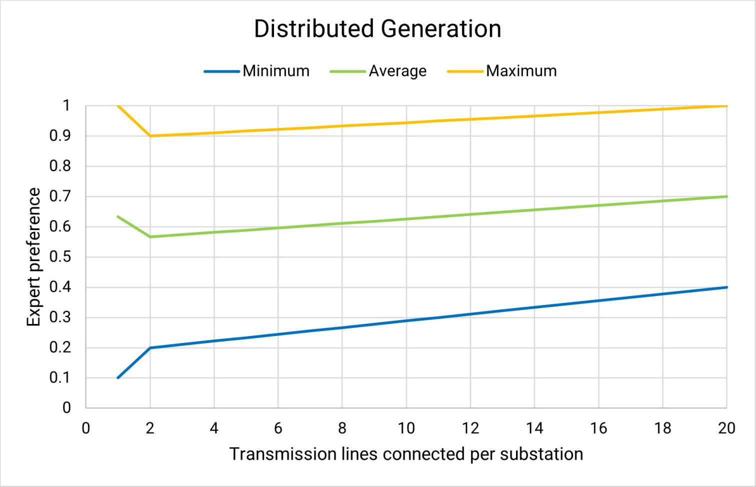


Figure 5.8: *Minimum, average, and maximum marginal value function for the distributed generation criterion*

2 in addition to scoring areas with lower population densities higher, also approached the scoring through comparing the fortification, distributed generation, and electricity grid sectors criteria. For this criterion, only the average marginal value function is correct as the other median preferences do not fall within the lower and higher preference range.

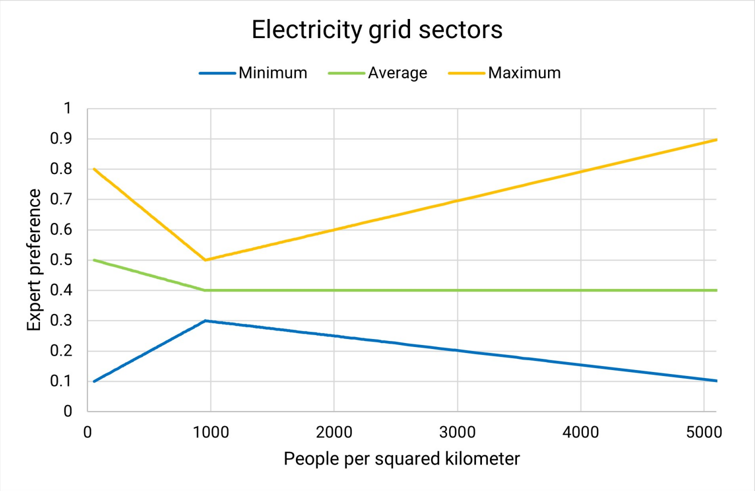


Figure 5.9: *Minimum, average, and maximum marginal value function for the electricity grid sectors criterion*

Social vulnerability preferences: The lowest, median, and highest performances for this criterion are 0.03, 0.62, and 0.92 respectively in the social vulnerability index scale respectively. The differences in lowest, median, and highest expert judgement are shown through the standard deviations of 0.08, 0.11, and 0.12. For this criterion, experts were mostly in agreement of the importance of considering social vulnerability when planning improvements to the electricity grid. Although there is consensus between the experts, Expert 1 took a different approach in comparing this map with the maps created for the electricity grid sectors (population density) and emergency services criteria (number of services per area).

Figure 5.10 show a negative trend as the lower the vulnerability, the higher the score the electricity grid sector is given. This is because higher vulnerability indices indicate that the population served by an electricity grid sector is not as well prepared for a disruption compared to an electricity grid sector with a lower index.

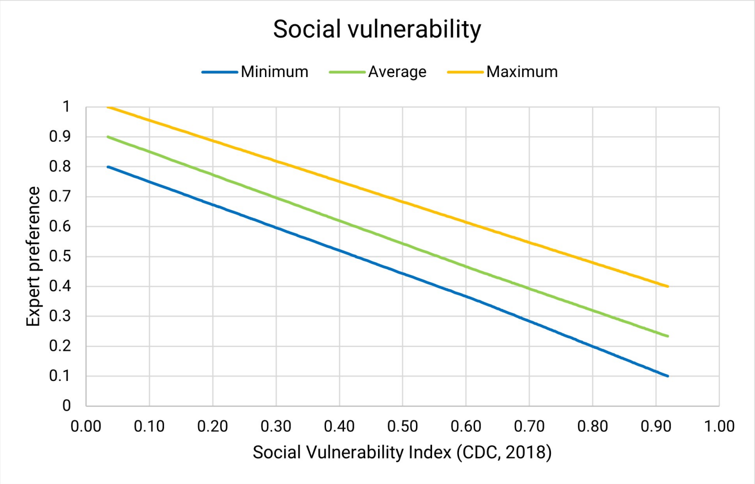


Figure 5.10: *Minimum, average, and maximum marginal value function for the social vulnerability criterion*

Emergency services preferences: The lowest, median, and highest performances for this criterion are 1, 4, and 33 emergency services per electricity grid sector respectively. The differences in lowest, median, and highest expert judgement are shown through the standard deviations of 0, 0.05, and 0.03. As noted in the (Maliszewski & Perrings, 2012) paper, experts also mentioned that during the record low temperatures that happened in February of 2021, areas near hospitals did not experience the blackouts that the majority of Harris County did.

The positive trend in Figure 5.11 for the final marginal value function indicates that sectors with more emergency services fare better. This is because said services are closer meaning it is more accessible. In addition, sectors with hospitals are more likely to avoid experiencing blackouts as such sectors are given priority and have backup generators.

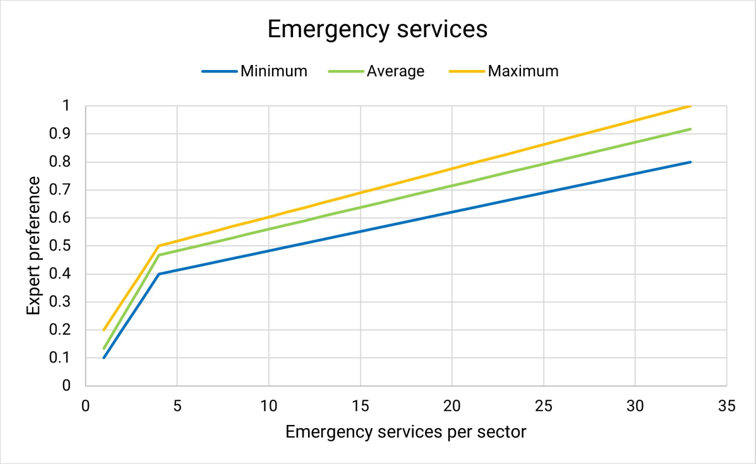


Figure 5.11: *Minimum, average, and maximum marginal value function for the emergency services criterion*

Weights: Based on the knowledge from their areas of expertise, the experts identified what criterion they thought would increase the resilience score of the imaginary electricity grid sector. Expert 1 identified fortification while Expert 2 identified energy diversification and Expert 3 distributed generation. Expert 1 identified fortification as most important because flooding can disrupt a substation's capability to distribute electricity within its service area. Expert 2 identified energy diversification as most important as reliable supply must be ensured especially during flooding events. Expert 3 identified distributed generation as most important as the number of transmission lines connected to a substation reflect the intensity of demand needed. After choosing the highest weighted criterion, the rest of the criteria weights were determined by transferring full points for the criterion on the scale of the most important criterion. In the first two interviews, the lack of time to thoroughly explain the elicitation of weights caused experts to not completely grasp the process. In contrast, there was more time after the elicitation of preferences to better explain the process to Expert 3. Therefore, because of the faulty first two interviews, the difference in weights is significant.

5.3. Aggregation

Step five is about using the elicited preferences and weights to calculate the overall scores of each of the 365 electricity grid sectors. Using the additive model Equation 4.1 the scores were aggregated. However, since the weights elicited do not sum up to 1, normalization was done by dividing the aggregated overall score by the sum of the minimum, average, and maximum weights (2.20, 3.43, 4.20). The lighter colors indicate low scoring electricity grid sectors while darker colors indicate high scoring electricity grid sectors. The range for the minimum overall

Table 5.1: *Elicited weights per expert*

Criteria	**Expert 1**	**Expert 2**	**Expert 3**	**Average**	**Average standard deviation**
Fortification	**1.00**	0.50	0.40	0.63	0.26
Energy diversification	0.30	0.90	0.50	0.57	0.25
Distributed generation	0.60	0.50	**1.00**	0.70	0.22
Electricity grid sectors	0.50	0.50	0.10	0.37	0.19
Social vulnerability	0.50	0.70	0.20	0.47	0.21
Emergency services	0.80	**1.00**	0.30	0.79	0.29

scores is from 0.18 to 0.46 while the range for the maximum is from 0.46 to 0.88 The average range is from 0.32 to 0.64. The average scenario is highlighted in this section as it is most representative of expert judgements (Figure 5.12). The minimum and maximum scenarios represent the extremes of expert judgements which can be seen in Appendix B.

Regardless of the minimum, average, and maximum scenarios, the relationship of these sectors stays the same. This positive trend relationship can be seen in Figure 5.13. meaning that electricity grid sectors will score just as poorly or just as well in any of the three scenarios. However, the purpose of this assessment is to identify underperforming sectors. By identifying them, decision makers can enact measures to improve the resilience of these sectors.

For example, close to 40% of these sectors are underperforming in all scenarios. Not only the underperforming sectors were identified but the relationship seen in Figure 5.13 can also be noticed spatially as denoted in Figure 5.14. To further describe this relationship, the lower 20th percentile of the scores was used to display how most sectors perform at the same level regardless of the scenario. The lowest scoring electricity grid sectors are located in the eastern portion of the county where the main port and refineries are located. However, there are some low scoring areas in residential areas near the eastern central parts of the county. Based on this identification, connecting local renewable energy generation directly to the substation servicing the sector is recommended. This is because renewable energy sources contribute to the diversification of energy production which increases the energy system resilience (Mola et al., 2018). In turn this makes these sectors less reliable on the transmission of electricity from far distances. Furthermore, placing power plants closer to urban areas decreases the distance required for transmission and distribution contributing to lower costs and network losses (Yousefi et al., 2018).

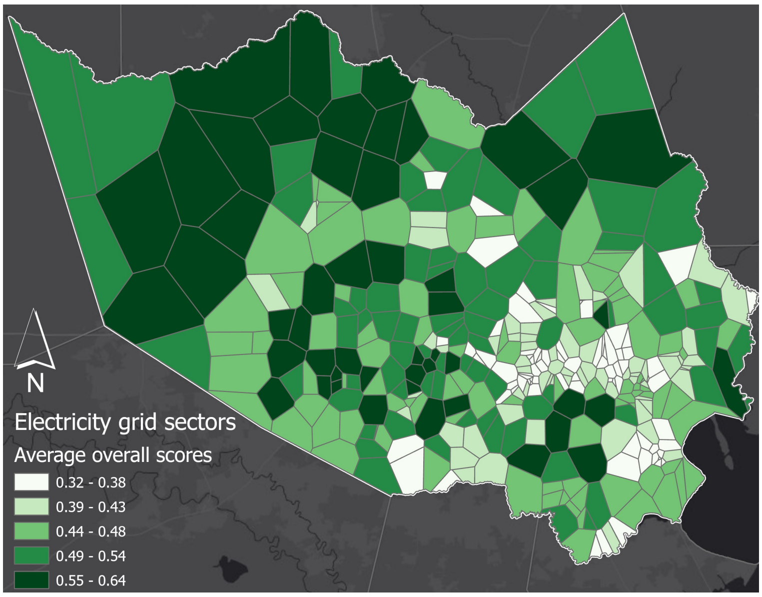


Figure 5.12: *Average overall scores by electricity grid sector*

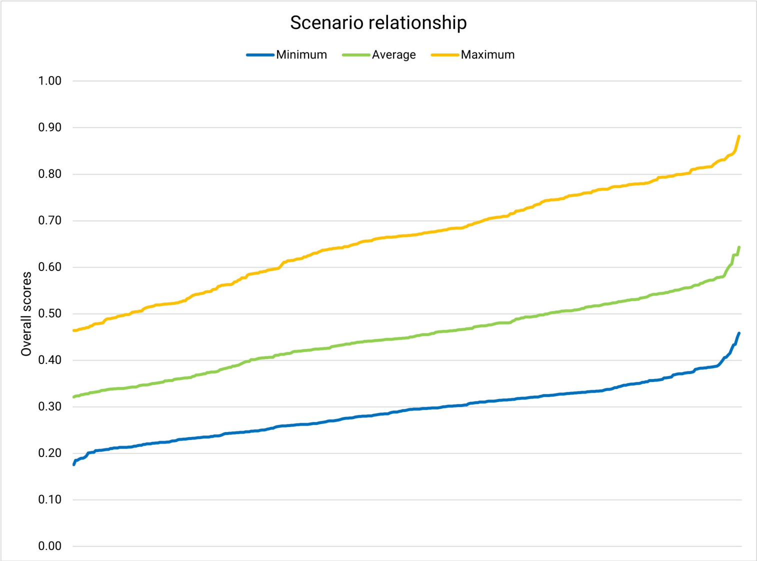


Figure 5.13: *Scenario relationship*

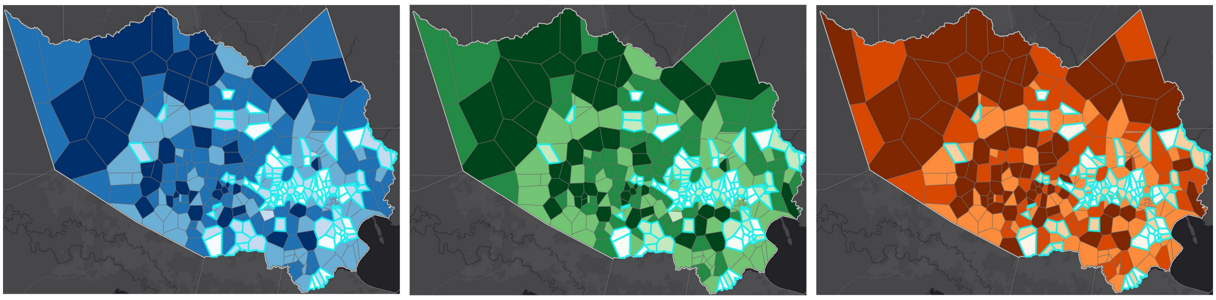


Figure 5.14: *Underperforming sectors*

5.4. Sensitivity analysis

Sensitivity analysis is conducted by using the three different criteria identified by experts that can best improve the overall score of an electricity grid sector from Table 5.1. This was done by using Equation 4.2 to alter the weights of the identified criteria. Sensitivity analysis is used to understand how these three differently chosen criteria affect the scores calculated in the previous step.

Again, the average scenario maps will be shown in this section for each of the three criteria. The minimum and maximum scenario maps can be found in Appendix B along with the respective aggregated overall scores maps.

Without sensitivity analysis, the weights of the selected criteria already indicate how overall scores can change to some extent. Fortification contributes to 27% of the total weight. Emergency services contribute to 24% of the total weight. Distributed generation contributes to 40% of the total weight. After conducting the analysis, the resulting maps are displayed by using the range of the corresponding minimum, average, and maximum overall score maps created in Section 5.3. This is done to compare the sensitivity analysis maps to the aggregation map (top left) in Figure 5.15. The scores that are most negatively impacted are through the distributed generation criterion. With this, planners and policy makers can start by considering how distributed generation in this county can be improved.

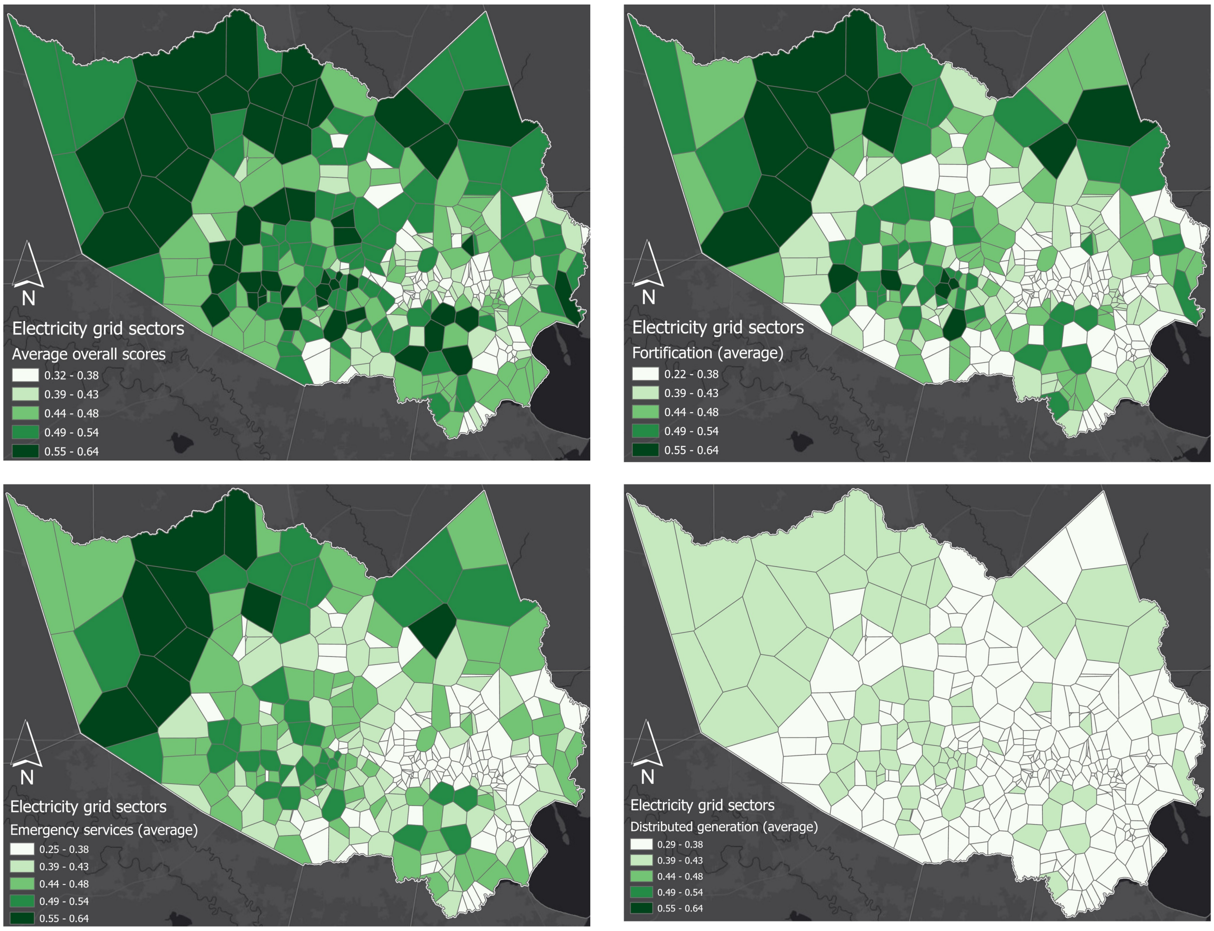


Figure 5.15: *Sensitivity analysis comparison*

5.5. Conclusion

In this section, an overview of what the maps say and how they can be used is described.

The maps in Section 5.1 display the measured performance of the electricity grid sectors with respect to each of the criteria. These measurements give an indication of the risk, infrastructure capacity, and socio-demographic conditions present in Harris County. Maps in Section 5.3 are the result of aggregating the expert preferences of the performances measured in Section 5.1 and the weighting of criteria. The overall scores displayed in the maps indicate the resilience of each of the electricity grid sectors from 0-1. Finally, maps made in Section 5.4 display how the criteria chosen in the three expert interviews impact the overall scores of the electricity grid sectors.

The maps produced in Section 5.1 provide both technical and socio-demographic characteristics that can be used to conduct a resilience assessment. These maps can be used to understand the technical and socio-demographic preparedness of Harris County's electricity grid sectors to flooding events. By using the maps in Section 5.3, an overview of the current resilience situation of Harris County is gained. In turn, this can be used to initiate the planning and policy process to better prepare sectors that are more vulnerable to blackouts during flooding events. To better understand what criteria have a greater influence in the overall scores displayed in the maps from Section 5.3, maps in Section 5.4 can be used to focus the improvement of electricity grid sectors based on the most impacting criterion. The resulting maps in Section 5.3 and Section 5.4 can also be used in combination with the maps in 5.1. Doing so, gives planners and policy makers more detail on why the chosen sector's overall score performed better or worse than other sectors.

6

Discussion

After extensive research on how electricity grid sectors can be assessed using resilience, a reflection on the methods and approach used in this thesis is discussed. The main findings are explained along with the advantages and disadvantages that can be identified including contribution to scientific research. In addition, the contribution to policy is discussed in Section 6.3.

6.1. Main findings

In this section the main findings along with this thesis' contribution to scientific research is highlighted. The main findings include the development of resilience criteria, the application of the criteria for assessment purposes, and the use of the assessment results for planning and policy purposes through spatial analysis. This section is concluded with a discussion on how the main findings are contributions to scientific research.

The development of resilience criteria is a valuable tool in assessing electricity systems. This is especially important as a system's ability to maintain its function is tested by many types of disruptions. In Chapter 4, criteria were developed from a review on resilience literature and expert interviews. The literature review and expert interviews contributed to a more complete and consistent list of criteria. This is because the literature review was used to gain a thorough understanding of resilience. In turn, the created criteria addresses the resilience of electricity grid sectors to extreme weather-event disruptions. However, criteria should not be case specific as it limits the scalability of criteria developed for other contexts.

Another result of the literature review was identifying the gap of how energy resilience criteria proposed by Sharifi and Yamagata (2016) have not been applied for the assessment of electricity grid sectors. This influenced the operationalization of the criteria to then apply it to assess the electricity grid sectors of Harris County. This assessment approach is important as policy makers have initiated significant infrastructure improvements as a response to the increasing trend in grid disruption frequency and severity (Roege et al., 2014). Therefore, an overview of the current resilience of the electricity grid can influence the implementation of appropriate improvements. In addition, the results of the operationalization and application of criteria was done through spatial analysis. This addressed the second research gap identified of how energy resilience is not approached enough times through a spatial lens.

Planners and policy makers alike work to address the needs of communities living in their jurisdiction. Using assessment results for planning and policy through maps gives decision makers a more tangible approach to employ strategies and plans to safeguard their communities from electricity grid disruptions. This way, decision makers are able to compare the conditions of each electricity grid sector side by side through a series of maps.

The main findings are contributions to scientific research as an approach to assess the resilience of electricity grid sectors regardless of the context was created. This is a comprehensive approach as it complements the development of resilience criteria by applying it through Multi-Criteria Decision Analysis and displaying the assessment results through a spatial lens. With this approach, scientific research can be directly interpreted by planners and policy makers. This is because complex concepts such as resilience can be explained and applied through the development, operationalization, and application of criteria visualized with maps.

6.2. Limitations

The limitations identified in the approach and throughout the thesis include the lack of specific data, difficulties with MCDA, and difficulties experienced in the interview process. The data collection process enabled for the assessment to be completed. However, key data such as information on the distribution grid and supply mix of Harris County could not be collected. This means that the assessment results are not the most accurate representation of the resilience conditions of electricity grid sectors in Harris County. Data on the distribution grid and supply mix was not able to be collected through open data portals. It was noted in the expert interviews that this data is not publicly available due to the sensitivity of the data. Although this is a limitation in this work, it could be fixed if an entity like CenterPoint Energy performed the same analysis for example. They would have the data not available to the public, helping bridge the inaccuracies that might be present in this work.

Choosing a MCDA method is an extensive process as there are many methods to choose from. The methods depend on the number of variables and level of uncertainty. Therefore, a good understanding of MCDA in general is needed for the correct method to be chosen. However, a sufficient time frame for getting familiar with the process can also be used to choose the most appropriate method. Moreover, a central part of the method is involving stakeholders and experts to reflect their opinions and integrate the different options (Bottero et al., 2014). This notion adds to the complexity of MCDA as on top of choosing a method, the interview process requires time to prepare and conduct in a clear manner.

The subjectivity of the process can be questioned as differences in expert judgement can create ambivalence in creating adequate results. This was apparent in Section 5.1. as experts took different approaches to scoring the performances. Furthermore, the interview process taken was confusing to experts as the protocol for elicitation of preferences and weights was not thoroughly explained. The direct rating technique chosen to elicit preferences does not include consistency checks (Schuwirth et al., 2012) meaning the difference in judgements is not controlled. Additionally, weights for criteria are usually the hardest parameters to elicit in MADM problems (Roy & Mousseau, 1996). Furthermore, in eliciting preferences and weights, the expert might not feel confident about giving precise information to translate performances into preferences and assigning weights for criteria (Aguayo et al., 2014). Therefore, eliciting preferences and especially weights is a cognitive demanding process that can result in substantial difference between expert judgements creating imprecise information. Because of this, the expert interviews should be more than an hour in length especially to take the time to explain the weighting process clearly for the expert to base their judgment on.

The subjectivity of the interviews is stated as a disadvantage for this thesis, methods for dealing with the subjectivity have been proposed by Aguayo et al. (2014), Erol et al. (2011), and Chang and Yeh (2009) using fuzzy membership functions. However, due to the limited time frame of this thesis and the focus on resilience, it was not possible to thoroughly review these methods.

6.3. Contribution to policy

The main two contributions to policy identified in this thesis are the assessment results of the electricity grid resilience and the visualization of results through maps to facilitate the decision making process.

The results from the assessment conducted in Chapter 5, provides an overview of the current situation of electricity grid sectors with respect to technical and socio-demographic characteristics. In addition, the assessment gives an indication of what can be done to improve the resilience of certain low scoring sectors. This is possible through the sensitivity analysis conducted in Section 5.4. Criteria that negatively affects sector scores can be given a focus when implementing plans and strategies to improve the resilience of low scoring sectors.

The results of the resilience assessment are amplified by displaying the scores through maps. Having this visual representation of the results facilitates the communication of resilience scores with a broad range of stakeholders and decision makers. This is useful for the policy making process as the results of the assessment are given an overview of what locations should be looked into first and how improvements to low scoring sectors can impact its surroundings.

7

Conclusion

In this chapter, final remarks are made on the previous chapters. In addition, the the main research questions are answered through the results of the three sub research questions. This is followed by criteria, data, and method related recommendations.

7.1. Summary

The problem of the increase in frequent and intense extreme weather-events creating pressure on the functional integrity of electricity grids was highlighted in Chapter 1. Extreme weather-related disruptions are the motivation for using resilience to assess the preparedness of electricity grid sectors to extreme weather-events. Therefore, the objective stated was to develop resilience criteria, operationalize it, and apply it to a case study specific context.

The literature review in Chapter 2 contributed to the first part of the objective of developing criteria. Through this review a thorough understanding of the concept of resilience was gained. Gaining this knowledge was important for reaching the first part of the objective as resilience characteristics were reviewed to decide on the focus that resilience was to be applied. In turn, energy resilience was identified as the focus for which provided guidance on what energy resilience principles and criteria could be used for the assessment of electricity grid sectors.

In Chapter 3, the methods used and background of the case study was discussed. The methods used to reach the objective included the literature review, operationalizing criteria, applying criteria through choosing a MCDA method, and visualizing the results through spatial analysis. The Harris County case study was first introduced by giving context of the energy system conditions present in Texas. Harris County was chosen as it represents 25% of the load serviced by ERCOT in Texas and because it is prone to different extreme weather-related events.

In Chapter 4 a discussion on how the criteria were developed and operationalized was explained. Criteria were developed by reviewing the Sharifi and Yamagata (2016) paper and through expert interviews. However, criteria in Sharifi and Yamagata (2016) address the energy system as a whole. Therefore, criteria that were chosen from this paper were selected based on whether they could be adjusted to address electricity grid characteristics specifically. Criteria developed includes fortification, energy diversification, distributed generation, electricity grid sectors, social vulnerability, and emergency services. In addition, the specific steps of MAVT were outlined in this chapter.

In Chapter 5, steps three to six of the MAVT method were applied to the Harris County case study. Steps one to two had to do with identifying the problem, objective, alternatives, and criteria. The results of steps three, five, and six were visualized through a series of maps.

These maps show the performance measurements, overall scores, and sensitivity analysis scores for each electricity grid sector. Step four results were displayed through graphs that showed how the experts gave preference to the performance measurements. Because of the difference in expert preferences and weights, the graphs and resulting maps display the minimum, average, and maximum expert judgements. Although these three scenarios are displayed, they all demonstrate a positive trend. This means that regardless of which scenario the sector is analyzed in, it will perform at the same level. The sensitivity analysis demonstrated that the criterion that most affected the overall scores was the distributed generation criterion. Through this, decision makers can focus planning and improvements of low scoring electricity grid sectors by first addressing the distributed generation situation of said sectors.

In Chapter 6, the main findings, limitations, and contribution to policy were discussed. The main findings include the development of resilience criteria, applying the criteria for assessment purposes, and using the assessment results for planning and policy purposes through spatial analysis. These main findings were then discussed on how they are contributions to scientific research. Limitations identified include the lack of specific data, difficulties of MCDA, and difficulties experienced in the interview process. Contributions to policy identified in this thesis was the assessment of electricity grid resilience and integrating spatial analysis into the approach to facilitate the decision-making process.

7.2. Research questions

Answers to the research questions provided in the introduction chapter are discussed in this section.

MRQ: *How can the resilience of individual electricity grid sectors be assessed using standardized criteria?*

SRQ1: What are the criteria that should be included to assess the resilience of electricity grid sectors?

A literature review on resilience was done to answer this question. The thorough understanding of resilience gained helped in developing and operationalizing a set of criteria. In addition, research gaps resulting from the literature review helped structure the assessment approach. Criteria that were included to assess the resilience of electricity grid sectors are categorized into technical and socio-demographic characteristics. The technical criteria included fortification, energy diversification, and distributed generation which address the robustness and redundancy capacities of grid infrastructure. The socio-demographic criteria included electricity grid sectors, social vulnerability, and emergency services to address the absorptive capacity of the social component of electricity grid sectors. Four out of the six criteria were developed to fit the thesis objective using the criteria proposed in the Sharifi and Yamagata (2016) paper. One criterion, social vulnerability, resulted from the expert interview with Dr. Mostafavi. The emergency services criterion was influenced by the Maliszewski and Perrings (2012) paper.

SRQ2: How can the developed resilience criteria be operationalized to assess electricity grid sectors of a specific case study?

From the literature review, the criteria was operationalized using measurement indicators. These measurement indicators give options on what criteria can be measured on. Measurement options are identified to operationalize and apply the criteria to any other context regarding the resilience of electricity grid sectors to extreme weather-events. Therefore, depending on the context, electricity grid sector performances are measured with respect to each criterion by choosing a measurement option.

SRQ3: How can the developed and operationalized criteria be applied to compare the overall resilience of a case study's electricity grid sectors?

Developed and operationalized criteria was applied through the MCDA method of MAVT. MAVT was chosen as it can handle a large number of alternatives and conflicting objectives. So, the criteria was applied by measuring the performance of each electricity grid sector, eliciting preferences and weights from expert interviews, aggregating the preferences (individual scores) with the weights, and conducting a sensitivity analysis on the aggregation results. The results of this method were displayed using a series of maps to visualize an overview of the electricity grid sectors conditions to flooding-related disruptions.

7.3. Recommendations

The current results provide a general overview of the resilience conditions. Therefore, to create a more accurate and detailed representation of the resilience of electricity grid sectors, data on the distribution grid and more specific supply mix data needs to be collected. Doing so requires more human and capital resources as this data is either protected by grid companies and institutions or can only be purchased. However, open data should still be collected as that can be done rather quickly and can be used to create preliminary results before the more detailed and specific data can be gathered.

As mentioned in Section 5.3, a measure to improve the resilience of certain electricity grid sectors is to introduce local electricity generation and directly connect it to the distribution grid. As the energy transition is unfolding, renewable energy sources should be considered over other generation methods. However, this requires an additional method to be used. After performing an MCDA method and obtaining the resilience assessment results, the research can go a step further by performing a site selection analysis. A MCDA method can also be applied to the site selection analysis but will require a new objective, alternatives, and criteria to be specified. Site selection analysis is done to produce options on where renewable energy generation can be placed. Several criteria should be considered in this analysis including technical, environmental, economic, and land use characteristics. After site selection is performed, the grid level that the electricity plant should be connected to needs to be decided. This can be done by considering transmission and distribution costs along with distance from a power plant to an existing substation. However, this decision can also be integrated in the site selection process.

A

Appendix

Interview process and questions

The interview process for the elicitation of preferences and weights is as follows including the questions asked:

- Provide a general overview of the criteria
- Explain criteria using maps of measured performances of electricity grid sectors displayed in Section 5.3
- Explain the eliciting procedure:
  To be able to compare the criteria on the same scale, I am going to ask you to score the measurements from 0 to 1 with 0 being the worst score and 1 the best score. To be able to aggregate the scores of sectors per criteria, I will ask you to give points to the criteria based on a scenario. This will allow me to then calculate the overall score for each electricity grid sector.
- Elicit scores for all criteria:
  Question: As there are 365 electricity grid sectors, what score will you give to the minimum and maximum measurements and within the minimum and maximum range what score will give to the median? Question: Can you explain why you scored the measurements for this criteria like this?
- Elicit weights for criteria:
  Question: Now let us assume that we introduce a new sector but it turns out that it scores badly for all criteria. What criteria would you choose to increase the score of the sector to full points? Question: Why do you think this criterion would increase the score of the sector to full points? Question: What would full points of the other criteria translate to in the scale of the chosen criterion? The weights do not have to add up to 1 as will normalize it after the interview.

The interview process about the relevance of the criteria developed and additional data:

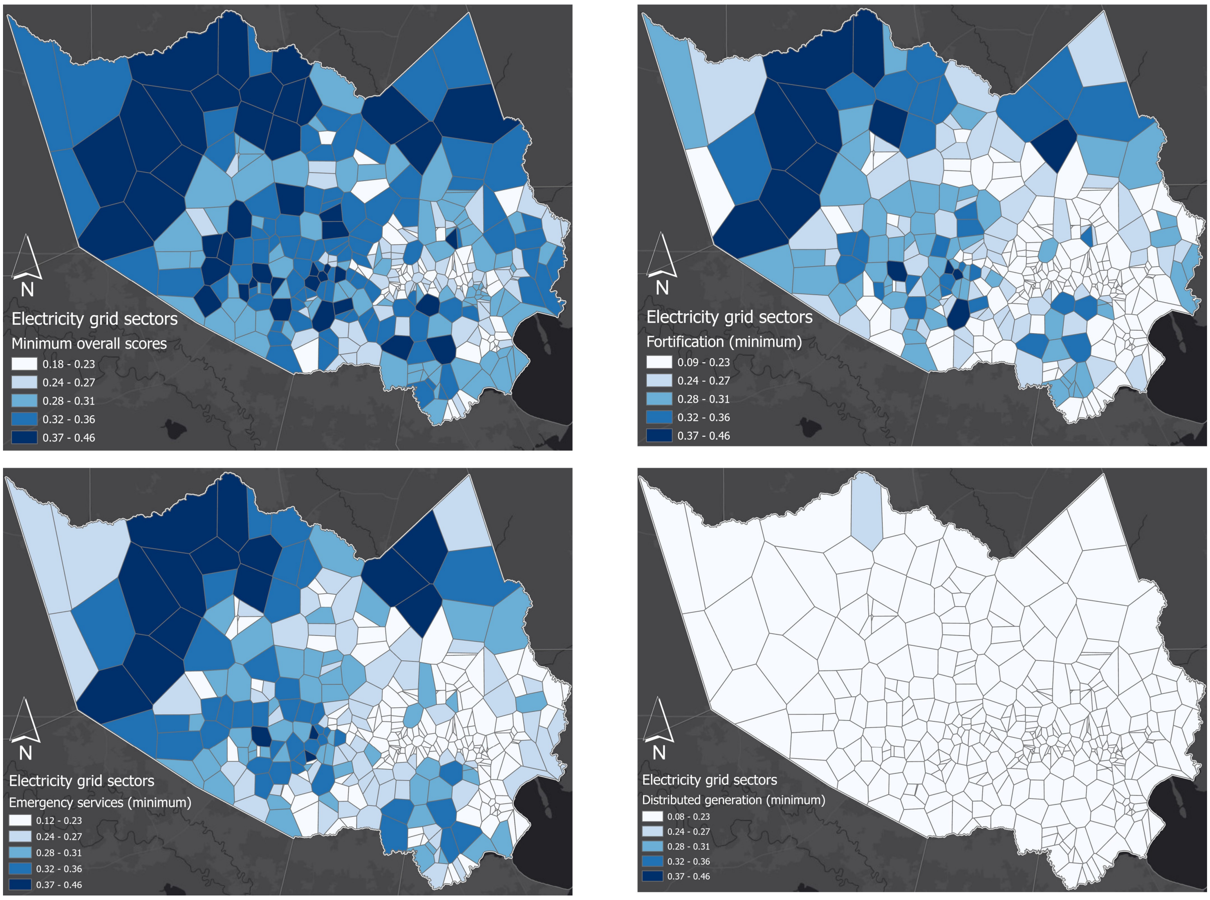
- Provide a general overview of the criteria
- Explain criteria using maps of measured performances of electricity grid sectors Section 5.3

- Questions about specific data on Harris County:
  How can I access data on the distribution network of the county? If that is not possible, can you give me your opinion on the Voronoi diagram drawn to represent the electricity grid sectors? I have been able to access supply data for ERCOT but have not found the supply mix for Harris County specifically. What open data can I use to calculate the supply mix?
- Question about the criteria:
  Do the criteria make sense in how they are operationalized to assess electricity grid sectors? Based on your field of expertise, is there a criterion missing that you feel should be added?

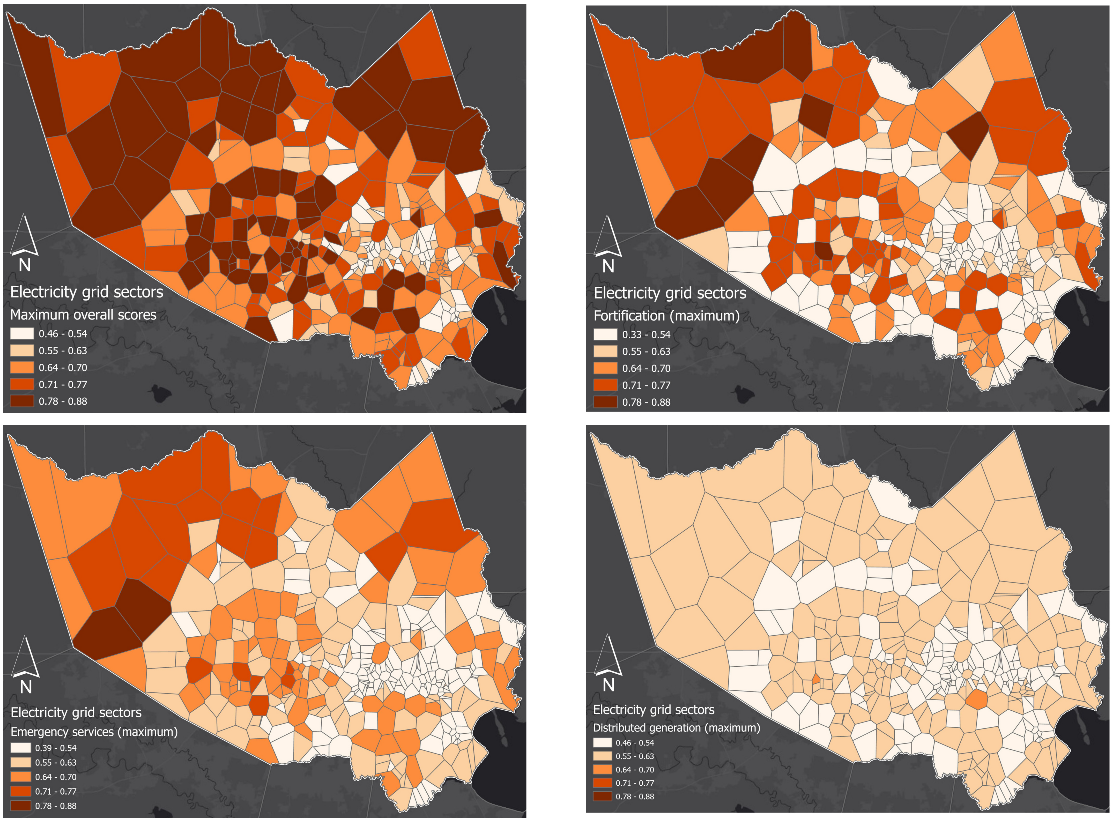
B

Appendix

Minimum scenario (top left) and sensitivity analysis comparison



Maximum scenario (top left) and sensitivity analysis comparison



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