

Power Resilience Assessment from Physical and Socio-Demographic Perspectives

Mehmet Baran Ulak

Postdoctoral Associate, Civil Eng. Department
Stony Brook University
Stony Brook, NY, USA
e-mail: mehmet.ulak@stonybrook.edu

Anil Yazici

Assistant Professor, Civil Eng. Department
Stony Brook University
Stony Brook, NY, USA
e-mail: anil.yazici@stonybrook.edu

Eren Erman Ozguven

Associate Professor, Civil & Env. Eng. Department
Florida State University
Tallahassee, FL, USA
e-mail: eoazguven@fsu.edu

Arda Vanli

Associate Professor, Ind. & Mfg. Eng. Department
Florida State University
Tallahassee, FL, USA
e-mail: avanli@fsu.edu

Reza Arghandeh

Professor, Comp. Sci. and Elect. Eng. Department
Western Norway University of Applied Sciences
Bergen, Norway
e-mail: arghandehr@gmail.com

Abstract—Urban resilience is a multifaceted concept including the recovery of the physical infrastructure and various urban activities that depend on that physical infrastructure. It is relatively straightforward to quantify infrastructure resilience by tracking the recovered facilities in time and marking the time that the infrastructure is fully functioning again. However, the physical infrastructure recovery does not necessarily indicate that the urban activities bounce back to the pre-disaster conditions. The restoration of urban activities depends on the areas that a particular infrastructure serves (e.g., residential, commercial) and the connections with other critical facilities (e.g., health, education). It is important to investigate the infrastructure recovery and “resilience divide” with respect to the enabled services and affected populations in order to achieve all-inclusive resilience. For this purpose, we examined the resilience of different physical elements such as power feeders (i.e., underground or overhead lines), critical facilities (e.g., fire and rescue services, hospitals) and different socio-demographic segments of the population (i.e., different age groups, ethnicities, and income levels) which constitute an urban environment. The analyses were conducted using the power outages experienced after Hurricane Hermine in Tallahassee, as a case study. The findings show that overall resilience performance can be distinct and/or not homogeneous for the resilience of different physical elements, urban services, and population groups.

Keywords—*infrastructure electric grid; resilience; critical facilities; socio-demographic groups*

I. INTRODUCTION

Resilience of power system infrastructure against disasters has been a pivotal concern especially as a result of the recent increase in both the number and the intensity of

the hurricanes battering the U.S. Gulf Coast in recent years. In the last decade, Florida Gulf Coast hit by three strong hurricanes: Hermine (2016), Irma (2017), and Michael (2018). These hurricanes, especially Hermine had a catastrophic impact on the City of Tallahassee, capital of Florida. Hermine revealed that the city’s power infrastructure is highly vulnerable as more than 65% of the city residents lost power for several hours and days [1].

The ability to withstand and cope with random and dynamic challenges that can potentially disturb the network is generally called resilience. Moreover, resilience also defined as the ability to recover and restore normal operating conditions rapidly and efficiently. Therefore, resilience reflects an urban system’s flexibility and adaptability to cope with the unexpected disturbances [2].

The resilience topic have been scrutinized by several studies focusing on the failure process of infrastructure systems such as power and transportation networks [3]–[7]. It was shown that it is absolutely critical to understand the circumstances that lead to disaster-induced disruptions, in order to enhance the resilience of infrastructure systems [8]. Furthermore, understanding the complex dynamics of infrastructure systems require an examination of the structural features of networks [3], [9], [10]. The estimation of network resilience also drew attention and several models were developed for this purpose [11], [12]. Findings of these studies showed that system resilience depends on the reliability of the critical elements of the network. Recent studies also focused on identifying the interdependencies between transportation and electricity networks [13]–[15], and evaluating the resilience and vulnerability of these networks [3]–[5], [16], [17]. Recently, the “co-resilience” concept was also proposed and studied [18], [19].

“Co-resilience” can be described as the joint resilience assessment of multiple networks in urban environments where co-dependent networks (e.g., transportation and power) are integrated to utilize the interdependencies of urban networks under extreme weather events.

Meanwhile, the resilience of the physical infrastructure do not tell the whole story about urban resilience. The urban networks have multiple layers, including public facilities that serve the communities from various socio-demographics groups. This helps building up the complexity of achieving resilience due to the physical, economical and demographical differences amongst the population [20]. In addition, depending on the dependency between the infrastructure, services and the community, the *bounce-back* implied by the term “resilience” may not be experienced homogeneously throughout the system. For instance, a study [21] interviewed 42 households in Florida following the Hurricane Irma. Results indicate that the resilience varies depending on the socio-demographics of the households. That is, for example, resilience of households with higher-income or without very young children were found to be higher compared to other households. Therefore, a thorough resilience assessment requires the analysis of affected facilities, population and groups, which may have different full recovery (i.e., resilience) points in time. In order to address this “*resilience divide*” problem, there is a need to understand the factors that foster and support the efficacy of all-inclusive hurricane resilience.

In this paper, we examined the resilience of different physical elements such as power feeders (i.e., underground or overhead lines), critical facilities (e.g., fire and rescue services, hospitals, etc.), as well as different socio-demographic groups (i.e., age groups, ethnicities, and income levels) which all together constitute an urban environment. The analyses were conducted using the power outages experienced after Hurricane Hermine in Tallahassee, as a case study. We argue that a system can be as resilient as the least resilient element. The proposed method is based on identifying the physical elements and socio-demographic groups with least resilience and focusing on those elements in the analyses. To assess the resilience of these elements and groups, power outages and restorations along the disaster timeline were extracted. For each failure event and the subsequent recovery, the affected services and populations were mapped based on the geographical location and duration of power outage for each customer. We plot the time-dependent resilience curves based on the data (i.e., the initial loss in capacity and the restoration along the timeline). The results show that certain services and/or population groups can have a distinct resilience performance compared to the overall population and/or services.

II. STUDY AREA, DATA, AND OUTAGES

A. Study Area

The study was conducted with the power infrastructure failures and recovery data obtained from the City of Tallahassee, the capital of Florida. Florida is very prone to hurricanes and has been impacted by severe hurricanes over

the last century, including the Hurricane Hermine that hit Tallahassee on September 2nd, 2016. It was the first hurricane to make landfall in Florida since Hurricane Wilma in 2005, and was the first hurricane to directly hit Apalachee Bay since Hurricane Alma in 1966 [1]. Hermine devastated the power infrastructure of the city and thousands of residents remained without power for several days. There are two major universities in Tallahassee and city has a total population of 190,894, making it a substantial urban region in the Northwestern Florida. Moreover, the City of Tallahassee is a full-service municipality and provides services such as electric, gas, water solid waste, sewer, public works, airport, and mass transit to the residents of the city.

B. Data

The study was conducted using data from three sources, namely: power infrastructure of the city; power system components failed during Hurricane Hermine; and socio-demographic structure of the city.

The power infrastructure was provided by the City of Tallahassee municipality and included power lines (feeders) as well as components such as circuit breakers, reclosers, sectionalizers, switches, fuses, and transformers. Moreover, the information (e.g., location, connected feeder, etc.) for all electricity customers (a total of 126,737 customers) of the city were also provided by the city government. Note that the city implemented a full-scale Automated Metering Infrastructure in 2009 making it one of the first public utilities in the U.S. to implement such a system. Therefore, information for all electricity customers is available.

The second source, which is the failed power system components, was also provided by the city. The outages occurred during the hurricane were identified through the “ping” operation in the aftermath of the hurricane. The “ping” operation identified the unresponsive components (e.g., switches, transformers, etc.) of the network, which are the sources of outages. Moreover, “ping” data provided information on the feeder group which failed component belongs to, date stamps of failure and restoration (e.g., 09/02/2016), duration that component remained failed (e.g., 2d 3hr 40 min, etc.), and number of customers who suffered from breakdown of that component. Note that system components have a hierarchical order and “ping” operation is only able to identify the highest hierarchy breakdown in the system. That is, for example, if a circuit breaker and a distribution transformer failed, “ping” operation would identify the circuit breaker first, and only identify distribution transformer breakdown after circuit breaker was fixed.

Finally, the third source is the 2010 Census data [22] which provides the socio-demographic information of the City of Tallahassee. Several socio-demographic indicators were used in the study including:

- Age groups (percentage of: aged 65 or over; aged 5 or under, aged 17 or under; aged 18-21; aged 22-64),
- Income levels (percentage of: income below \$24,000; income \$25,000-\$34,000; income \$35,000-\$49,000; income \$50,000-\$74,000; income \$75,000-\$99,000;

income \$100,000-\$124,000; income above \$124,000),

- Ethnicities (percentage of: African American; white American; Native American; Hispanic; Minority).

The socio-demographic data were used to illustrate restoration process based on the customers' socio-demographic features. Note that power infrastructure data do not include such personal information about the customers. Therefore, census blocks were used as proxies for customer socio-demographics. For this purpose, each customer was assigned the socio-demographic features of that census block to which that customer belongs. Eventually, customers were aggregated to evaluate the restoration process based on the socio-demographics.

C. Electricity Outages

Data indicates that 93,029 customers were affected by the outages and power restoration efforts continued until September 10th starting right after hurricane hit the city on September 2nd. The final group of customers suffering from outages were provided electricity after 207 hours from the time when the hurricane hit. The customers affected by the outages were identified using the failed power system components. Among the infrastructure components, "Fuses" experienced the highest number of breakdowns (304) and fuses were followed by "Distribution Transformers" (171), "Circuit Breakers" (93), "Switches" (38), "Reclosers" (29), and "Sectionalizers" (1) (Figure 1). The highest breakdown rate, on the other hand, was observed in "Reclosers" (34% failed) followed by "Circuit Breakers" (22%), "Fuses" (3.9%), "Sectionalizers" (3.8%), "Switches" (2.4%), and Transformers" (0.7%) (Figure 1).

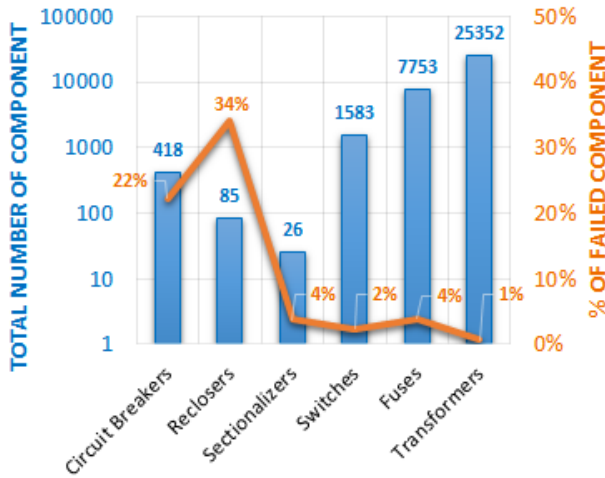


Figure 1. Number and percentage of failed power components

III. APPROACH

The approach consists of integrating multiple datasets to identify the location and duration of the power outages as well as the socio-demographic features of customers (residents).

The city government provided the spatial data of the power infrastructure of the city including customers

(electricity meters), power feeders, and components such as circuit breakers, distribution transformers, etc. Moreover, the failed infrastructure components during Hurricane Hermine and the restoration dates along with duration of outage were also provided by the city. The "customers" data include information about which feeder subnetwork each customer and power network component were connected. Therefore, we were able to calculate the power outage duration for each customer by tracking the failure and recovery of power components connected to the same feeder subnetwork. We define resilience as the percentage of the customers that received electric service as a function of time after the hurricane. We studied how the resilience profiles differ for different demographic groups.

As previously mentioned, the U.S. Census data [22] were used as the proxy of the customer characteristics. For this purpose, the socio-demographic characteristics of census blocks were assigned to the customers based on the geographic location of customers. That is, each customer was given the attributes of census block which customer is located in. For instance, if the census block has 25% aged 65 or over and 20% aged 17 or under population, the customer within that census block was given weights of 0.25 and 0.20 for those population groups, respectively. This was followed by the aggregation of all customers based on the socio-demographic characteristics and power restoration durations. Note that the assigned weight would sum up to the total number of customers and reflect the actual number of socio-demographic groups in both the census block and the city. Eventually, the power resilience plots were produced using the data that were processed as described above.

IV. RESULTS

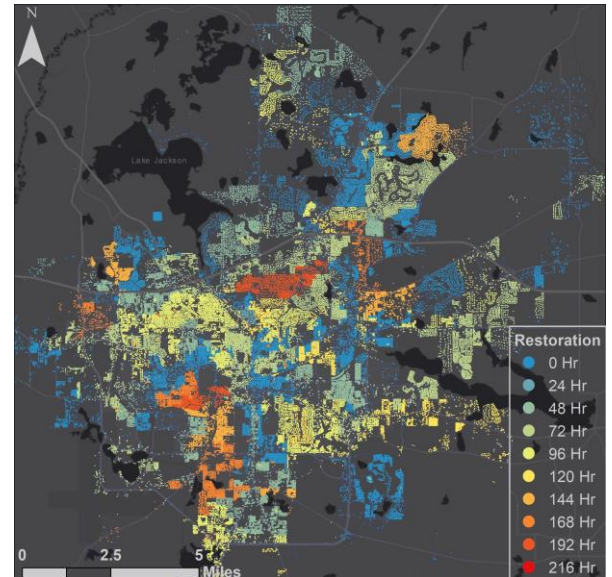


Figure 2. Restoration duration of customers in Tallahassee

The total power restoration process took 8 days after Hurricane Hermine hit Tallahassee. The last customer was provided electricity after 207 hours from the time when the hurricane impacted the city. Figure 2 illustrates the duration

of power restoration at different regions of Tallahassee while Figure 3 shows the progress of this restoration. The following subsections delve into the power restoration process, and hence evaluate the resilience of the power network from the *physical*, *customer*, *critical facility*, and *socio-demographic* perspectives.

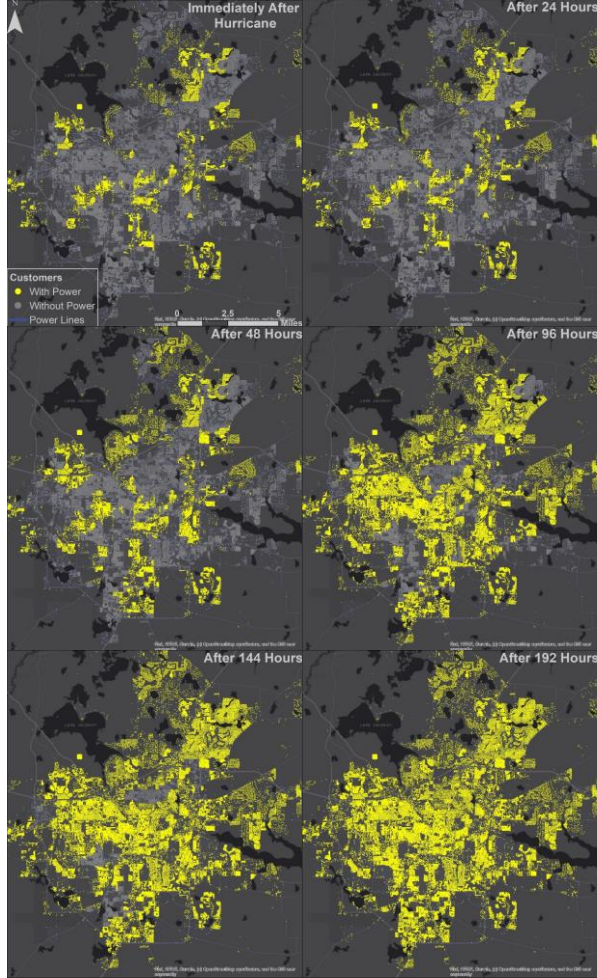


Figure 3. Power restoration process after hurricane Hermine

A. Resilience from the Physical Infrastructure Perspective

The resilience of the physical infrastructure was investigated through examining the outages experienced by customers connected to underground (65,406 customers) or overhead (59,779 customers) power lines. The resilience based on the feeder type was assessed in comparison with the resilience of the all customers aggregated. The results align with [23] and indicate that “underground” feeders are more resilient than “overhead” lines in terms of both the initial loss in capacity and the restoration speed (Figure 4). The difference between the initial losses in capacity indicate that overhead feeders lost 5.66% more capacity than underground feeders did, corresponding to 4,980 more customers with power. Furthermore, 75% of customers connected to underground feeders had power at the end of 78th hour while only 62% of customers connected to

overhead feeders had power (Figure 4). One important fact is that the underground and overhead lines are connected in the system and failures in the overhead feeders could also affect the underground feeders. Therefore, potentially higher resilience of underground feeders might be hampered by the overhead feeders. This means that underground feeder systems independent of overhead lines are needed to understand the actual resilience of underground feeders. It is also apparent that it is more expensive to deploy underground feeders compared to overhead feeders. Nevertheless, the benefits of underground feeders may overcome the investment costs in regard to efforts of establishing more resilient power systems and communities. This paper simply presents a real-life data-based resilience analysis to provide a better understanding of these benefits.

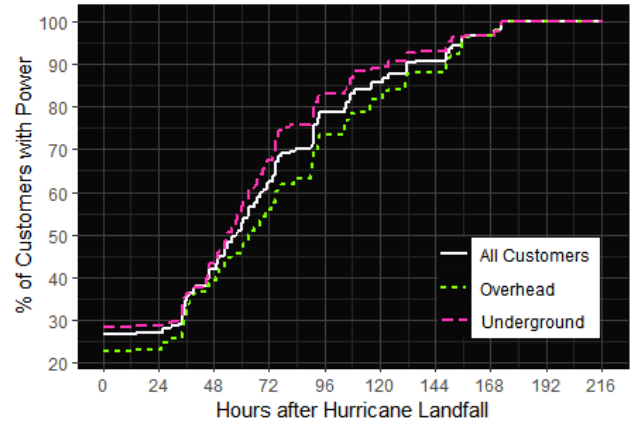


Figure 4. Resilience from the power feeder perspective

B. Resilience from the Customer Perspective

Within a broader layman context, the resilience implies the “return to the normal”, including the commercial activities. In that respect, two types of customers were examined in terms of power system resilience: 1) residential customers, and 2) commercial customers. Note that, majority of the city customers are residential (102,322) while there is still a considerable number of commercial customers (16,375). Figure 5 shows that only 25% of residential customers did not lose power whereas 35% of commercial customers maintained power immediately after the hurricane impact. Restoration speeds of residential and commercial customers, on the other hand, were very similar indicating that the recovery operations did not differentiate based on customer type.

C. Resilience from the Critical Facility Perspective

One of the most important aspect of system-wide resilience against disasters is emergency response operations and related critical facilities such as “fire and rescue” facilities and hospitals [24]. In this study, we investigated the power resilience of following critical facilities: 14 fire and rescue service facilities, 19 police stations, 5 hospitals, 174 health facilities, 20 assisted living and nursing facilities (that focus on elderly), 51 markets, 27 groceries (i.e., shops smaller than markets), and 149 schools

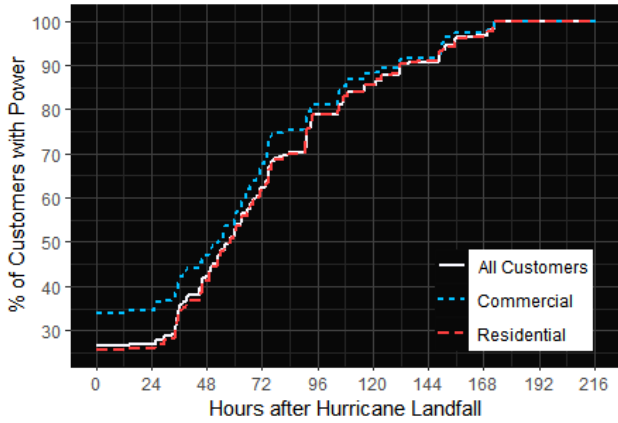


Figure 5. Resilience from the customer perspective

Among these critical facilities, hospitals are arguably the most crucial ones. The resilience plots in Figure 6 verify that 60% of hospitals maintained power. Arguably, even a 40% loss may not be desirable for hospitals. Nonetheless, the hospitals are the most “robust” in terms of initial loss in capacity compared to other facilities and customers. However, the power restoration rate was relatively slower considering that 2 hospitals (40%) remained without power until 100th hour, more than 4 days. This delay can be attributed to the fact that hospitals are generally equipped with multiple emergency power generators, and their operations may not be directly affected for prioritized recovery response. Health facilities (including local health centers and clinics) are less critical than hospitals but still have role in the process of returning to normal conditions in the city. The initial loss in capacity of health facilities (55%) was higher than hospitals and the power restoration speed is similar to the general trend of all customers (Figure 6).

Fire and rescue service facilities are also very important for both recovery efforts and emergency response following the disaster. However, 80% of fire and rescue facilities lost power, which was substantially high considering the role of fire and rescue in the aftermath of disasters. Power restoration speed, however, was higher than other facility types.

The city crews might have optimized and directed the recovery efforts in order to compensate high initial losses. Police stations performed better than fire and rescue service facilities but worse than hospitals in terms of initial loss in capacity. Accordingly, power restoration speed was better than hospitals and worse than fire and rescue service facilities.

The schools and particularly the assisted living and nursing facilities performed the worst in terms of power resilience. Figure 6 shows that the both schools and assisted living and nursing facilities suffered from high initial power losses, 80% and 85%, respectively (higher than general trend). Restoration speeds of both facilities, on the other hand, conform to the general trend of all customers. Schools are critical for two reasons: 1) schools are also used as shelters, and 2) recovery of schools is important to return to the normal conditions. When schools remain closed, the

parents of school children cannot go back to work and daily routines, which would further hamper the recovery of the day-to-day activities. Assisted living and nursing facilities, on the other hand, host elderly individuals who generally require special assistance such as medication or extensive care. Moreover, elderly individuals may also need continuous nursing and assistance due to their physical limitations especially during emergencies. Therefore, these assisted living and nursing facilities are particularly critical and they should be resilient against outages to save lives.

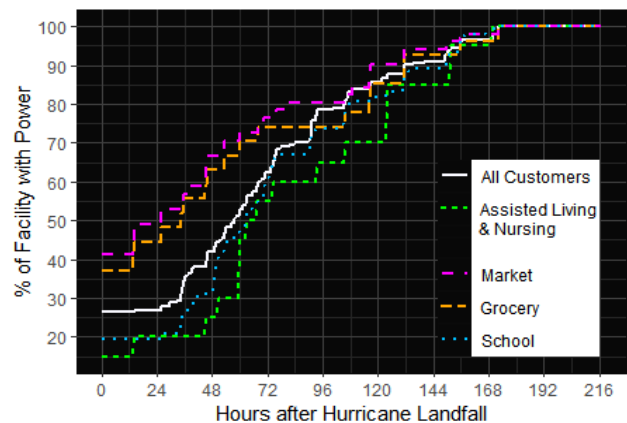
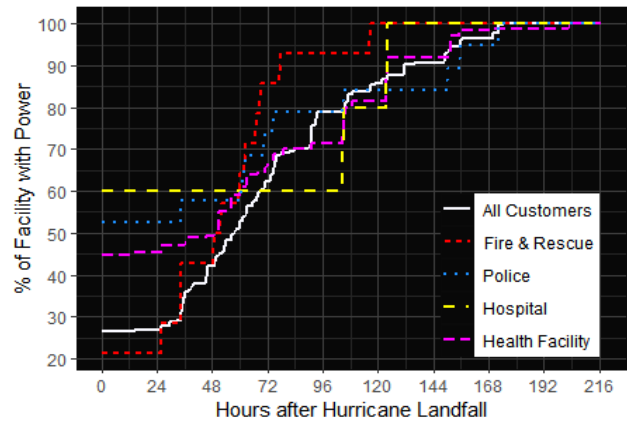


Figure 6. Resilience from the critical facility perspective

Markets and grocery stores are also very important to provide necessary goods such as food and supplies to communities impacted by a hurricane. Power outages also generally lead to the loss of water, sanitary services, and food since refrigerators would not work without electricity. As a result, impacted communities would need to access such goods and markets and groceries can provide these services. For instance, Walmart stores are shown to be effective in response and recovery during disasters [25]. Therefore, it is important to enhance the resilience of these facilities and maintain the power for these facilities to avoid any disruption.

D. Resilience from the Socio-demographic Perspective

The power resilience of different socio-demographic groups were examined in order to understand whether certain

socio-demographic groups face more problems related to resilience compared to other groups. For this purpose, census units were used as proxy of customers' socio-demographic features. Figure 7 shows the power resilience plots of different age groups and ethnicities. In general, there is no substantial difference between age groups except "Age 18-21", which corresponds to the age group of college students.

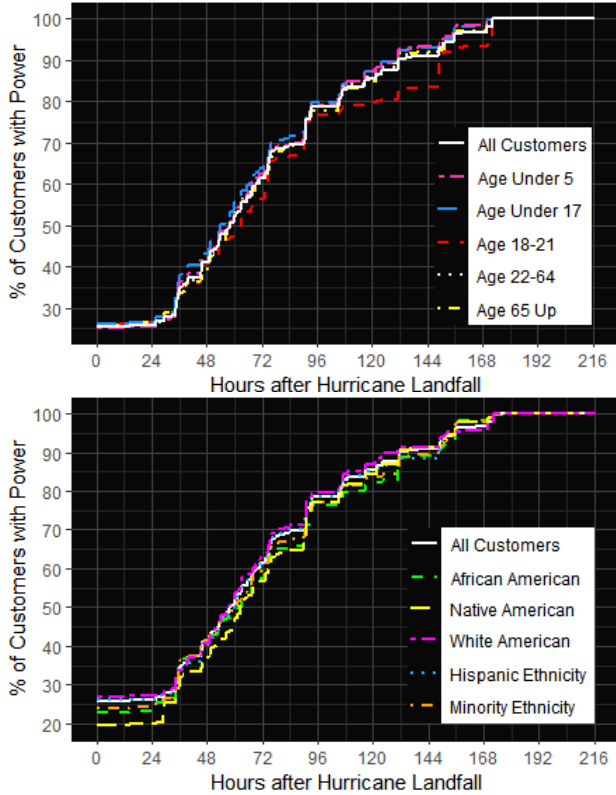


Figure 7. Resilience from the age groups and ethnicity perspectives

Note that Tallahassee is home to two major universities and one community college with more than 50,000 students. It is clear that 20% of customers from this age group were provided power later than other groups. Nevertheless, differences between age groups are negligible and it can be stated that it is a success for the city government in terms of maintaining social equity and fairness.

This is an important issue which other utility service providers should consider during recovery and restoration operations. Similar to age groups, there is not substantial differences between different ethnic groups as well. It can be argued that power resilience of White American customers is slightly better than other groups; however, power restoration progresses are comparable among groups.

E. Resilience from the Income Perspective

The power resilience from income perspective illustrates an anticipated but still interesting and striking result. The most power resilient group is the highest income customers who have a household income more than \$125,000 per year. The power resilience of households decrease in accordance with the income and the least resilient group is the customers

with less than \$25,000 income per year. However, it can be also argued that there is not a substantial difference between groups with income level below \$74,000 and above \$25,000 per year. Nevertheless, note that the restoration progresses are comparable among groups, even though power restoration of higher income groups is slightly faster than lower income groups. This finding is possibly associated with the locations where higher income groups live. That is, higher income groups generally live in recently developed regions with better and newer infrastructure (e.g., underground feeders instead of overhead ones). Therefore, higher income groups appear to be more resilient against disasters. That being said, this is a critical issue that requires scrutiny.

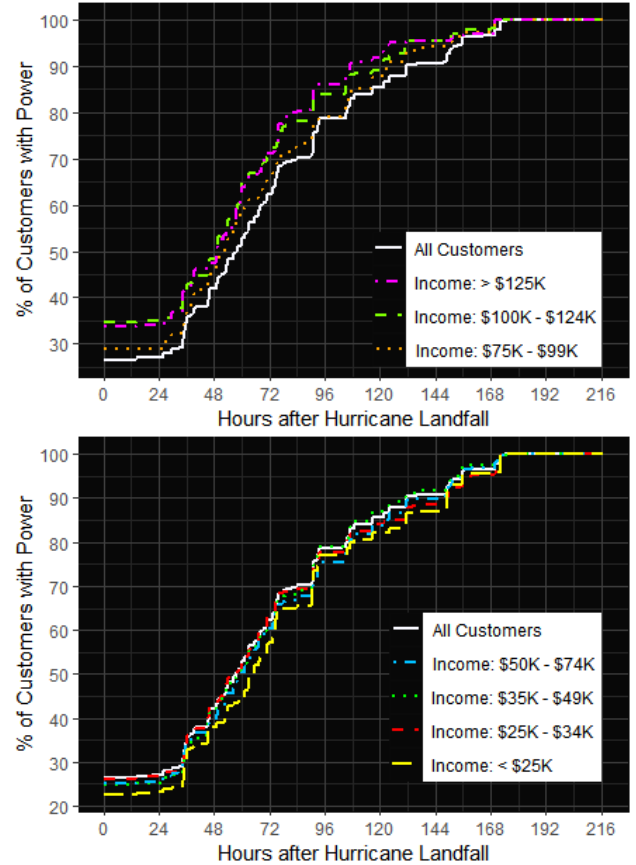


Figure 8. Resilience from the income perspective

Residents from lower income groups are also more vulnerable, not only due to the infrastructure problems associated with lower income neighborhoods, but also due to lack of financial sources that hamper preparation and response efforts of these residents before and after hurricanes. For instance, lower income residents are usually reluctant to evacuate since evacuation could place more monetary burdens such as accommodation (e.g., hotel, etc.) and travel (e.g., gas, etc.) costs [26]. Moreover, lower income individuals are less likely to have vehicles for evacuation, which also prevent these individuals from evacuating [27]. In other words, the low-income population are more likely to be home-bound after the hurricane, regardless of the power

service. On the contrary, the high-income populations have more means to arrange accommodation elsewhere if their homes do not have critical services such as power. Such issues intensify infrastructure problems and further hamper the efforts to enhance the resilience of cities. Therefore, special attention should be allocated to lower income groups and vulnerable infrastructure in the lower income neighborhoods to alleviate issues in the aftermath of such a hurricane.

V. CONCLUSION

This paper examines the resilience of different physical elements such as power feeders (i.e., underground or overhead lines), critical facilities (e.g., fire and rescue services, hospitals, etc.), as well as different socio-demographic groups (i.e., age groups, ethnicities, and income levels). The proposed analysis was conducted in order to identify physical elements and socio-demographic groups experiencing lack of resilience, considering that a system can be as resilient as the least resilient element in that system. The findings of the study show that resilience assessment should also focus on the individual resilience of elements or groups since resilience is generally not homogeneous throughout the whole system.

It is worth mentioning that there are certain limitations and caveats regarding the adopted approach. The socio-demographic characteristics of customers were identified using the census blocks as proxies since such information is not available in the customer data. Nevertheless, this is the most accurate approach considering that personal information about the customers is generally confidential and therefore not available. The power outage duration of each customer was calculated using the outages of the infrastructure components. However, for some components, it was not possible to identify exactly which customers were affected within the feeder subnetwork even though the number of affected customers was known. Therefore, for such cases, all customers were assumed to be affected if the component failure caused an outage for more than half of the customers within the feeder subnetwork. However, note that feeder subnetworks are relatively small with hundreds or occasionally a few thousands of customers connected to them. Therefore, the influence of this assumption on number of affected customers can be considered to be negligible. However, a more accurate analysis can be conducted with more detailed information on the power infrastructure, which can be a future extension of this study.

As a future direction, roadway closure data can also be temporally reconstructed to examine the effect of these closures on the restoration efforts. That is, public crews need to access failure locations in order to fix the components. However, roadway closures (due to fallen trees, poles, debris, etc.) prevent utility crews to reach to the power outage locations and restore the power. Therefore, we hypothesize that there would be a time-lagged relationship between roadway cleaning/opening and power restoration progress. Such analysis would help coordinating and planning the power restoration efforts together with roadway cleaning works. In addition, data collected from other hurricanes such

as Irma and Michael can be studied with the proposed approach.

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