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Recovery Resiliency Characteristics of Interdependent Critical Infrastructures in Disaster-Prone Areas

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Abstract: When Hurricane Maria struck the island of Puerto Rico in September, 2017, it devastated the island's critical infrastructures, including the well-documented total loss of electric power systems. The strong interdependencies or associations among critical infrastructures in modern society meant that the failure of power systems propagated to and exacerbated the failure of other infrastructure systems. Moreover, these associations impact systems recovery just as they impact system failure. This study is a follow-up of previous research by the first author on Hurricane Maria. In this research authors extracted and quantified the recovery associations of Hurricane Fiona (September 2022) made landfall in Puerto Rico and inflicted considerable damage to its critical infrastructures. The recovery efforts following the disaster provided an opportunity to follow up on the previous research and examine the recovery associations. Significant money and efforts have gone into upgrading the infrastructures of Puerto Rico to make them more resilient to natural disasters such as hurricanes or tropical storms following Hurricane Maria. This paper explores the new recovery resiliency characteristics of Puerto Rico's critical infrastructure systems (CISs) that the recovery efforts following Hurricane Fiona illustrate. This research shows that the power systems and other CISs of Puerto Rico are much more resilient when compared to their state of resiliency in 2017. Moreover, examining the recovery interdependencies reveals that some of the CISs are strongly dependent on power systems recovery. Outcomes of this study suggest that CIS relationships based on recovery data from Puerto Rico, are transferable to similar disaster-prone areas such as the Caribbean islands or other island nations, as they have similar characteristics and challenges.

Keywords: critical infrastructure systems; power systems; critical infrastructure interdependencies; post-disaster recovery; Hurricane Fiona; Hurricane Maria; recovery resiliency; systems engineering

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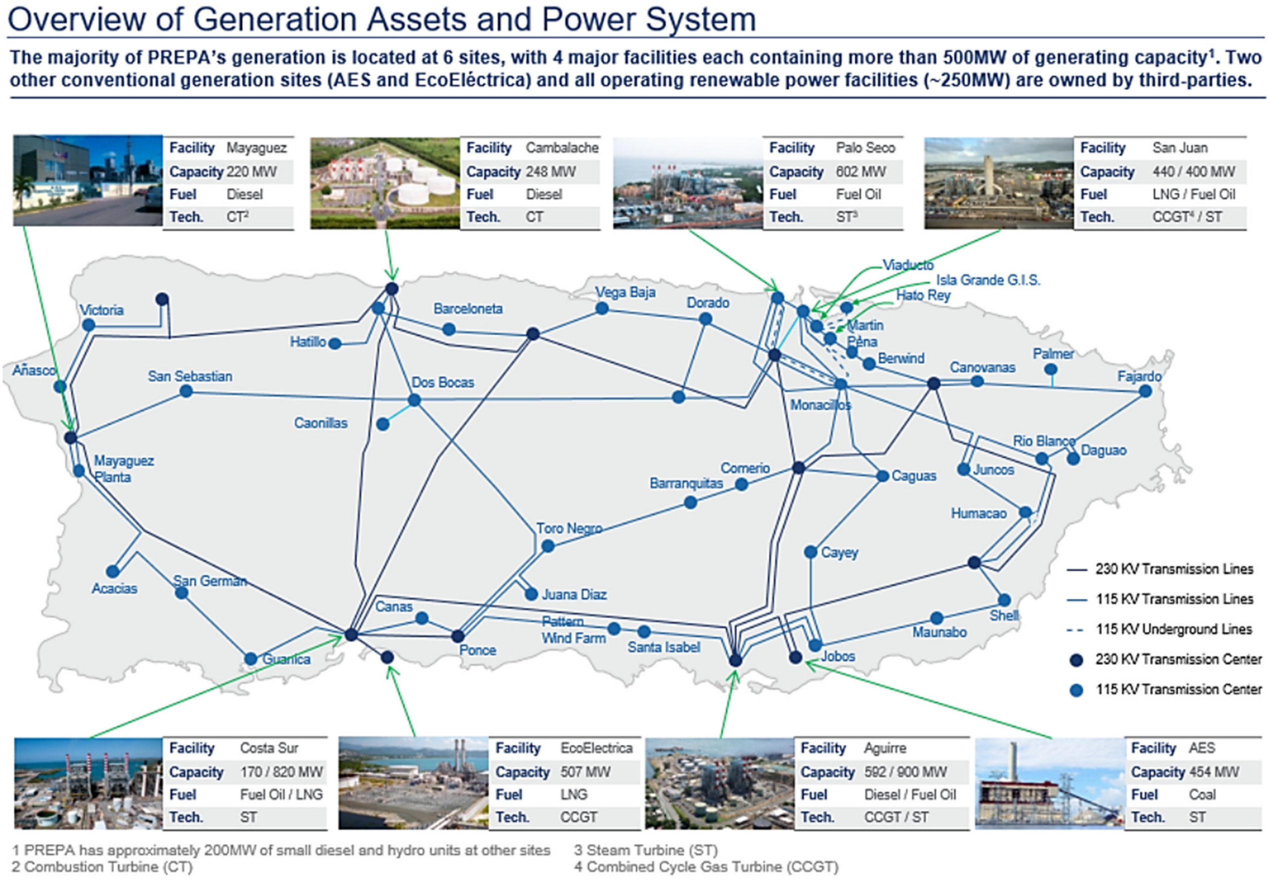
1. Introduction

Electricity and electrical system infrastructures are at the core of making and continuing the progress of modern society, so much so that other critical infrastructure systems are widely dependent on power systems in various degrees. These dependencies and interdependencies between the power system and other CISs were investigated, and their relationships were established, in a previous study [1] by examining the post-disaster recovery of these critical systems following Hurricane Maria. This paper presents a follow-up to this earlier research to examine how rigorous resiliency improvement measures by government and private agencies impact the recovery resiliency of critical infrastructure systems in disaster-prone areas. For this follow-up research, it is only appropriate to examine the same power systems and other CISs that were examined in the earlier work, and Hurricane Fiona provided that unique opportunity when it struck the island of Puerto Rico in 2022, bringing destruction to the island and its critical infrastructures. However, unlike during Hurricane Maria, the territorial and federal government, and other responsible parties of Puerto Rico, were comparatively well prepared to deal with Hurricane Fiona's destructive abilities. Plenty of money and labor had gone into greatly improving CISs by the relevant government and private agencies to prevent a repeat of the devastation caused by Hurricane Maria in 2017. Moreover, there has been a gradual privatization of the island's power systems. A private energy company named LUMA Energy has been in charge of operating the power transmission and distribution systems of Puerto Rico since 1 June 2021, after entering a 15-year agreement with PREPA (Puerto Rico Electrical Power Authority) [2]. PREPA still owns the island's power systems infrastructure, but the transmission and distribution network are now operated and maintained by LUMA Energy. The following year in July 2023, PREPA awarded a 10-year contract to another private energy company, Genera PR, an independently managed subsidiary of the New York-based energy company New Fortress Inc., to transfer the responsibilities of power generation, operations, and maintenance of the generation units of the island [3]. As with the transmission and distribution networks, PREPA still owns the generation units. PREPA still remains under bankruptcy as it focuses on restructuring its huge public debt of USD 9 billion [4]. Figure 1 shows Puerto Rico's power generation plants and some of the major high voltage transmission networks. Most of the island's power is generated in plants at the south side of the island and transmitted over challenging terrain to the north side, where the majority of the consumers are located. This setup adds to the vulnerability of the power infrastructure system. Cell towers or telecommunication antenna systems, hospitals, drinking water systems, etc., are also among the CISs of a community. Figure 2 shows the telecommunication antenna system of Puerto Rico (crosses and numbers indicate quantity) and Figure 3 shows the geographic locations of some of the other CISs of the island. The blue numbers on Figure 2 indicate the number of cell towers at the locations, and the white numbers are road numbers.



Overview of Generation Assets and Power System

The majority of PREPA's generation is located at 6 sites, with 4 major facilities each containing more than 500MW of generating capacity[1]. Two other conventional generation sites (AES and EcoEléctrica) and all operating renewable power facilities (~250MW) are owned by third-parties.

Facility	Mayaguez
Capacity	220 MW
Fuel	Diesel
Tech.	CT[2]

Facility	Cambalache
Capacity	248 MW
Fuel	Diesel
Tech.	CT

Facility	Palo Seco
Capacity	602 MW
Fuel	Fuel Oil
Tech.	ST[3]

Facility	San Juan
Capacity	440 / 400 MW
Fuel	LNG / Fuel Oil
Tech.	CCGT[4] / ST

Facility	Costa Sur
Capacity	170 / 820 MW
Fuel	Fuel Oil / LNG
Tech.	ST

Facility	EcoElectrica
Capacity	507 MW
Fuel	LNG
Tech.	CCGT

Facility	Aguirre
Capacity	592 / 900 MW
Fuel	Diesel / Fuel Oil
Tech.	CCGT / ST

Facility	AES
Capacity	454 MW
Fuel	Coal
Tech.	ST

1 PREPA has approximately 200MW of small diesel and hydro units at other sites
2 Combustion Turbine (CT)
3 Steam Turbine (ST)
4 Combined Cycle Gas Turbine (CCGT)

Figure 1. Puerto Rico's power generation and transmission system [5].

Figure 2. Puerto Rico's cell tower map (crosses and numbers indicate quantity) [6].

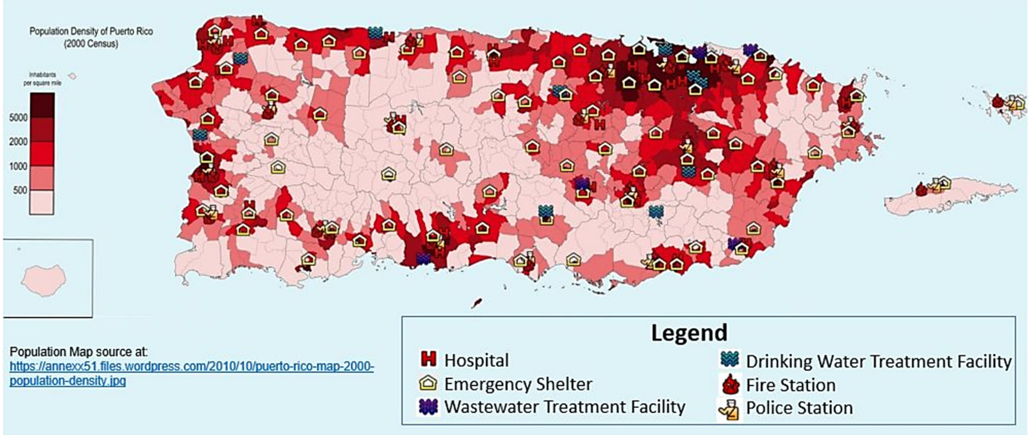


Figure 3. CIS of Puerto Rico [7].

One central aim of this research is to observe the updated state of resiliency of the CISs of Puerto Rico in addition to their updated states of interdependencies. Therefore, this research investigates the current state of research into CIS resiliency, particularly in disaster-prone areas. There are various ways of defining resilience depending on the context. In the context of critical infrastructure systems, resilience can be defined as the system's ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions such as deliberate attacks, accidents, or naturally occurring threats or incidents [1,8,9]. A survey of the literature includes several relevant and interesting research works in this category. For example, research by Forcellini et al. [10] proposes a model, labeled as loss model, for quantifying the resilience of CISs by conducting a case study into the damage caused by landslides in Sri Lanka, a natural-disaster-prone island nation. The paper investigates the disruptive phase of the resilience curve. The disruptive phase in a systems resilience curve also shows gradual system failure due to the disruptive event for a particular subsystem. The loss model proposed by the authors also factors in infrastructure interdependencies in the quantification of the disruptive phase and thus the resiliency. The paper therefore delves into the cascading failures of interdependent infrastructure systems in natural-disaster-prone areas. Other researchers have depicted resilience as a property of a system with three characteristics: absorption, adaptation, and recovery [11].

The concept of cascading failures is not new amongst complex systems. Cascading failures in electrical systems have been studied and modeled frequently by researchers. Valdez et al. [12] describe cascading failures as a "potentially devastating process that spreads on real-world complex networks and can impact the integrity of wide-ranging infrastructures, natural systems and societal cohesiveness". A current example of a cascading failure is the global information technology (IT) outage caused by a glitch in a software update from Microsoft in

July of 2024. The failure is now known as the Crowdstrike Glitch. In an article for CNN, Fung reports [13] that the glitch caused the largest IT failure in history. During the outage, a simple software update from Microsoft caused computer crashes, disrupted airlines, and affected hospitals around the world. In his writing, Fung reports that one insurer estimates the direct damage of the outage to Fortune 500 companies could exceed USD 5 billion. Another example of cascading failure is the statewide blackout or power outage in Texas in February 2021 due to extreme freezing conditions. The blackout was responsible for more than 4.5 million homes being without electricity during extremely cold weather, resulting in at least 57 deaths across 25 Texas counties and over USD 195 billion in property damage [14]. This almost total power outage also impacted critical infrastructures that depend on electricity to function, like natural gas, communication, and water systems [15].

Following the predecessor study [1], there have been similar investigations on CIS interdependencies in disaster-prone areas such as coastal communities. One such study focuses on links or associations among food, energy, and water infrastructure systems and proposes a food–energy–water (FEW) nexus approach that, when incorporated, can increase the resilience of coastal communities. The study also surmises that energy systems plays a central role in systems interdependencies and impacts all other linked systems, especially during a disaster event [16]. These findings are progressions of the predecessor study [1]. Another research that follows a similar pattern as the previous work [1] investigates a joint restoration strategy for the CISs of Saint Martin in the wake of Hurricane Irma in 2017. The research shows that identifying CIS interdependencies and incorporating them into a joint restoration strategy instead of CIS restoration in isolation, which is how this is typically performed, can lead to a more efficient recovery for the entire CIS network of networks (system of systems) [17].

The interdependencies among critical infrastructures have been considered to model a resilient smart city as a network of interconnected critical infrastructures that minimizes the effects of cascading failures and recover quickly following a disaster event. Research proposes a decision support system based on CIS interdependencies to enable the smart city to prepare for the disaster event and recover from it [18]. Keeping CIS interdependencies in focus, there is research that delves into the uncertainties associated with interdependency modeling. CIS interdependency modeling can include two main categories of uncertainties, namely system uncertainty and modeling uncertainty [19]. System uncertainties are further subdivided into physical and operational uncertainties and modeling uncertainties are subdivided into parameter and completeness uncertainties. Hence, the need for clearly stating the limitations of such an interdependency model is paramount. There are several research works that consider interdependencies between only two CISs, as it narrows the scope of research, allowing for a more thorough investigation into the dependency links between them. One such work [20] analyzes the interdependencies between a power system using gas-powered power generation units and natural gas systems. The authors model the two CISs as a system of nodes and buses and propose an optimization framework using a nested column-and-constraint generation (NC&CG) algorithm to formulate resilience enhancement pre- and post-disaster strategies for the two systems networks. Another such research study [21] on two system network, focuses on interdependencies between the water and transportation systems in Tampa, FL. The paper proposes a predictive socio-technical resilience assessment model that factors in the physical and spatial characteristics of the two CISs, the effects and propagation of cascading failures due to a natural disaster (Hurricane Irma), infrastructure aging, and social vulnerability elements. The results of their analysis show that in addition to the physical factors of the interdependent infrastructures, the social factors of the surrounding areas also play a key role in system resiliency. The interdependencies between a power system and water system were the subject of a doctoral research thesis [22] which tried to quantify the reliability of the interdependent power–water system network of the Phoenix metropolitan area using a mathematical model and a simulation of failures across the two-system network. The research also provides a framework for the contingency analysis of interdependent two-system networks.

Looking for ways to increase infrastructure resilience has been studied by several researchers. Truedinger et al. [23] have explored ways to identify and increase the resilience of sensitive healthcare infrastructures, particularly ones that focus on people with disabilities, following the Arh Valley flood disaster in Germany. Among other relevant studies, [24] uses an inoperability input–output model (IIM) to quantify CIS interdependencies and the effects of cascading failures through a case study of Hurricane Sandy's impact on the critical infrastructures of New York and New Jersey, and it proposes resilience improvement strategies targeted towards the system recovery process. Another research study [25] that focuses on strategies to improve CIS resiliency investigates a hypothetical integration of strategically located power systems microgrids into the power systems network of Puerto Rico. The research also factors in the CIS interdependencies of several other CISs of Puerto Rico, such as hospitals, fire stations, emergency shelters, communication towers, etc. The results show that adding microgrids to 30% of the island's CISs can keep the systems running even when most of the electrical grid systems are damaged [25].

As described above, the literature survey of relevant research shows that there have been some studies involving CIS interdependencies in disaster-prone areas, CIS interdependency modeling, and resilience improvement strategies of interdependent critical infrastructures. However, most of these studies involve simulated CIS failure and recovery scenarios of hypothetical critical infrastructures, and they do not involve a comparative analysis of CIS resiliency. The research presented in this paper is based on real recovery data of real CISs and a recovery resiliency comparison of the same CISs using data from disaster events occurring five years apart.

2. Materials and Methods

The earlier study [1] focused on establishing interdependency relationships between power systems and other critical systems infrastructures. For the purposes of this research, those relations discovered in the earlier research are synonymous with CIS recovery associations. This research examines those same CIS recovery associations and recovery interdependency relationships from available CIS recovery data following Hurricane Fiona, thus validating, or invalidating those associations. If new interdependency relationships are observed from Hurricane Fiona recovery data, these relationships are to be examined and possible causes explored. To establish the recovery associations, the same statistical method is implemented, primarily linear regression analysis, as was used in the previous research. Linear regression is a tried and tested and a very reliable method for establishing relationships between two quantitative variables. The details of regression analysis theory were presented in the earlier research [1] and are, therefore, not included here. Instead, focus is given here to the results of the regression analysis. As in the previous work, data on power systems recovery are used as the predictor variable and recovery data for other CISs are used as the response variables. Each of the other CISs is plotted against the power systems to model the regression lines. In addition, p-values and R^2 (coefficient of determination) values from the regression analysis are also observed and noted to examine the strengths of the recovery associations between the two CIS data sets. In this research, power systems infrastructure data were chosen to be the predictor variable due to their central role in CIS interdependencies. This central role of power systems can be depicted many ways [26,27]. Figure 4 below provides another such example.

In regression analysis between a bivariate data sets, a high R^2 value (>50%) is desired, as it indicates that the variability in the response variable is strongly dependent on the variability in the predictor variable. The p-value indicates whether the regression model is significant or not by testing the null hypothesis. A p-value of less than 0.05 is desired for the regression model to be significant.

For the validation efforts of the recovery associations, the hypothesis remains the same as in the earlier work. Therefore, in the context of the regression lines, the null hypothesis for interdependency relations between power systems and other CISs is

H0. *β1 = 0.*

and the alternative or research hypothesis is

H1. *β1 ≠ 0.*

Where β1 is the slope of the regression line [1].

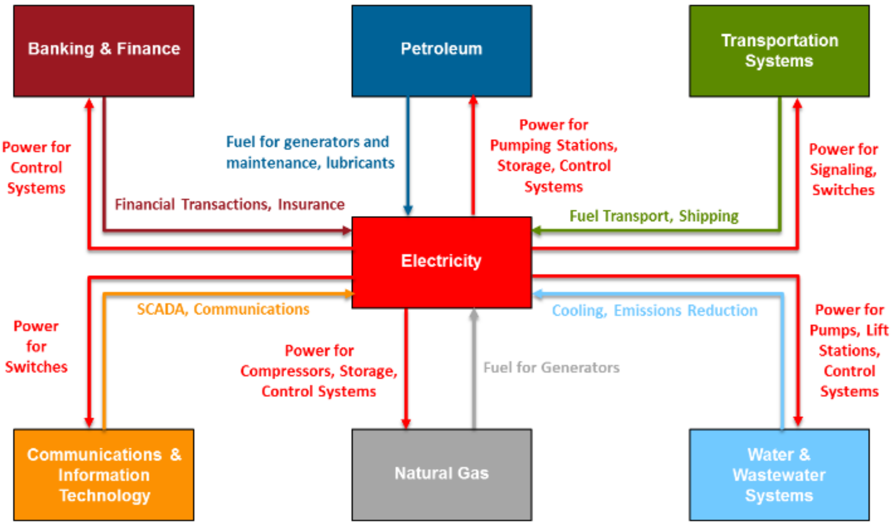


Figure 4. Power systems interdependencies [28].

The data of interest are the post-disaster recovery data for the various CISs of Puerto Rico following Hurricane Fiona. The targeted infrastructure systems are the same as the ones incorporated in the previous research, namely, power systems, water systems, telecommunications systems, hospitals, ports, airports, transportation systems, supermarkets, gas stations, banks, and automatic teller machines (ATMs). The primary source of Hurricane Fiona infrastructure recovery data is the Puerto Rico Emergency Portal System (PREPS) [29]. This site reported the recovery data for several CIS subsystems and other recovery and relief efforts and aided the local population immediately following the Hurricane. Screen captures of this webpage were collected multiple times a day and the information were tabulated to map the recovery of vital infrastructure systems in Puerto Rico and to provide transparency and accountability for the parties involved in the recovery efforts. Additionally, data from a few other sources [30,31] were used to fill in a few gaps found in the data reported by the PREPS.

The research encountered some of the similar challenges and issues while collecting data from the recovery efforts of Hurricane Fiona in 2022. The PREPS reported only partial updates on the recovery of some roads and transportation networks, and it only summarized data on the number of generators installed without specifications on how and where they were utilized. Moreover, a close examination of the collected CIS recovery data revealed that for several infrastructure systems, such as ports, airports, and transportation systems, the PREPS sometimes only reported whether these systems were active or suspended and sometimes only provided data on a part of a particular subsystem. In such cases, data from other sources, such as DOE (Department of Energy) Situation Reports, were used to fill in the gaps. Also, in the analysis, the "Active" status of a CIS was modeled as 100%, and a "Suspended" status was modeled as 0%. Additionally, unlike during the aftermath of Hurricane Maria, during Hurricane Fiona, the PREPS did not provide data on the progress of banks, ATMs, supermarkets/ grocery stores, and gas stations. Therefore, these CISs were also omitted from the CIS network considered in this study.

As in the earlier study [1] involving CIS recovery after Hurricane Maria, this study also implements the linear regression statistical analysis method to examine the relationships in bivariate quantitative data. After omitting unusable data, the CISs that are considered in the statistical analysis are power infrastructure systems, hospitals, water system infrastructures, and cell sites/antennas. Unlike in the first phase of the research, recovery data for banks, automatic teller machines (ATMs), supermarkets/grocery stores, and gas stations were not available, as they were not tracked or reported. One possible reason is the strong availability of emergency generators, including a reserve for generators. Unlike in the case of Hurricane Maria, in the case of Hurricane Fiona, data on generators were reported by the PREPS on a regular basis. Also, initial observation of the data reveals that relevant CIS recovery authorities planned and were better prepared when compared with the situation during Hurri-cane Maria. Since the recovery data were not archived by the reporting source (PREPS), the necessary data were collected daily and tabulated as they were being updated by the sources detailed in the Research Data section of this proposal.

3. Results

3.1. Daily Progress of CIS Recovery

The first analysis conducted is the generation of a plot showing the gradual recovery of the CISs, including power systems infrastructure. The plot includes available system recovery data starting from 17 September 2022, one day before the storm made landfall in Puerto Rico. On that day, most systems should be almost at a full system performance level, or 100% functionality. However, it is possible for some parts of a system to be in an offline state to prevent critical damage during a disaster event. The end date for the plotted CIS recovery data is 22 October 2012. By this date, the systems either reached a post-disaster steady-state system performance or all the data sources stopped reporting periodic system recovery data. The CIS recovery plot is shown in Figure 5 below.

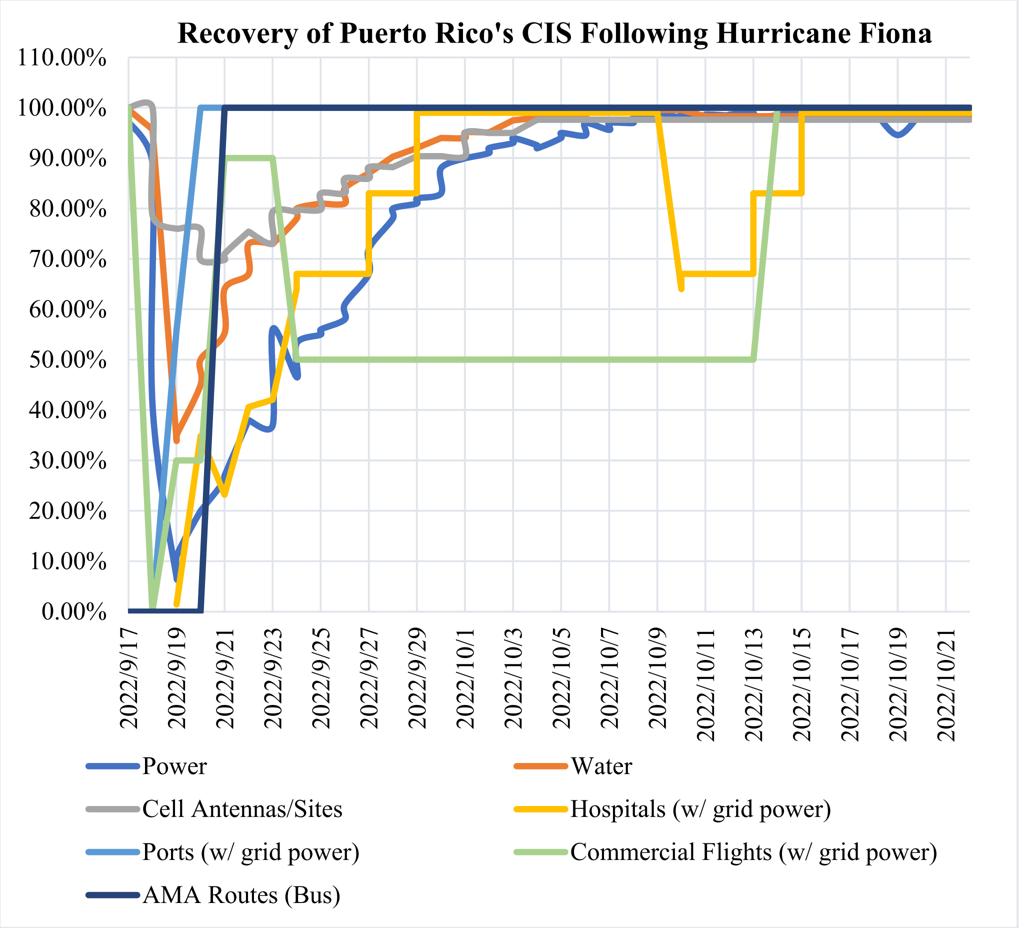


Figure 5. Daily progress of CIS recovery in Puerto Rico after Hurricane Fiona.

The recovery curves, also known as fragility curves, in Figure 5 directly correspond to the recovery phase of the CIS resilience curve. The CIS resilience curve is shown in Figure 6, with a circle drawn on the recovery phase to bring it to focus. The shorter the temporal distance of this recovery phase, the quicker the system recovers, as illustrated in Figure 6 curve (a), (b) and (c). The time begins when the system is at its lowest performance level and ends when the system reaches full performance level. For example, from the observations of the fragility curve of the power system, it appears that the system reaches almost full performance by 13 October 2022. The recovery fragility curves are also an indication of the disaster preparedness or readiness of the CIS.

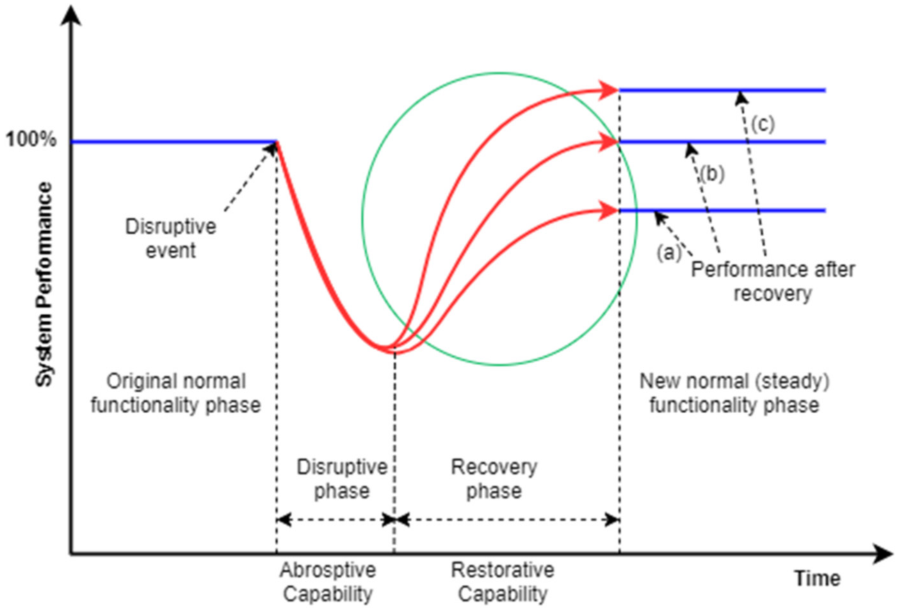


Figure 6. CIS resilience curves in terms of systems performance or functionality (adapted from [1,32,33]).

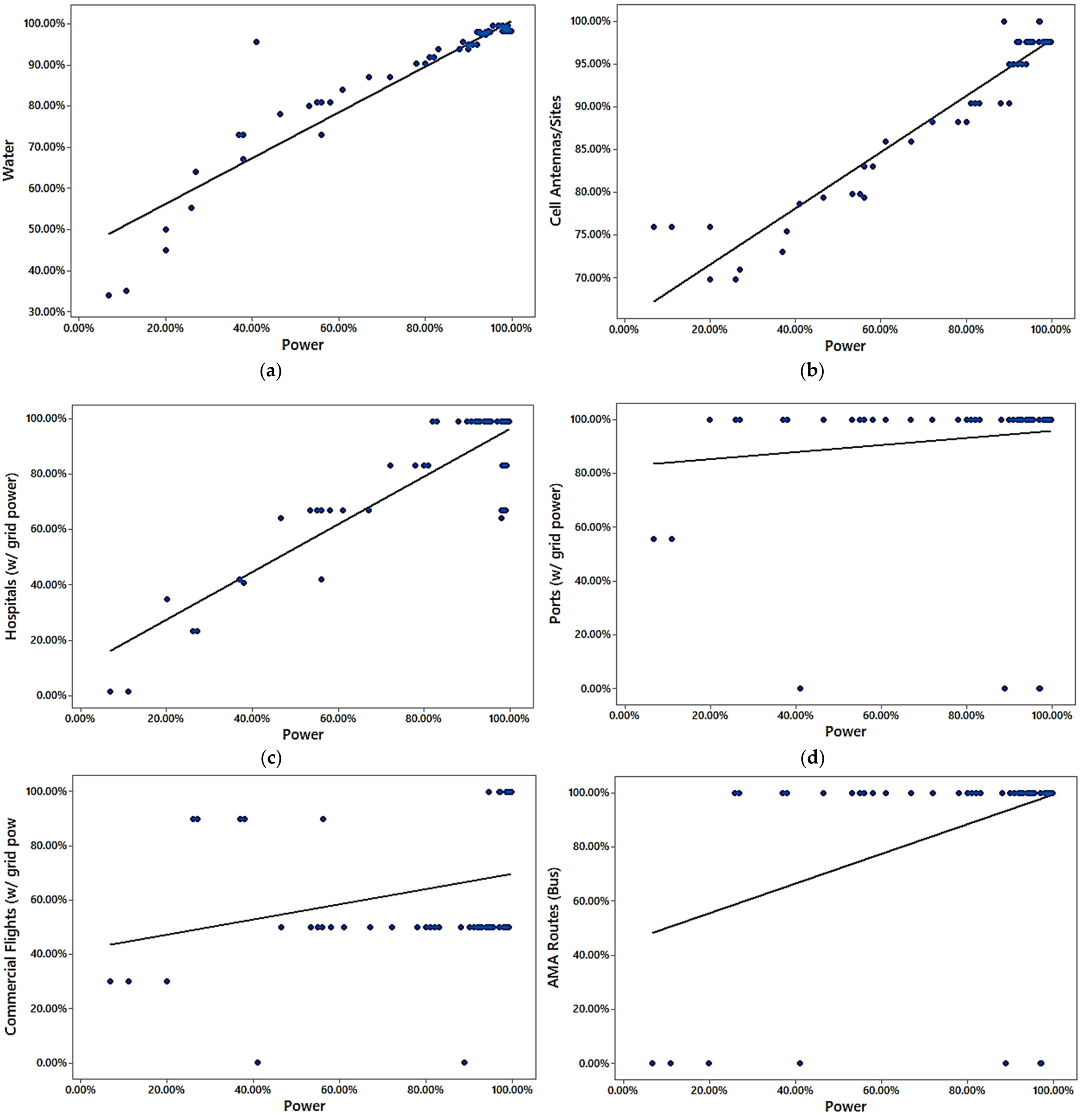
3.2. Interdependencies Between Power Systems and Other CISs

The interdependencies analysis between power systems and other CIS over the first 35 days recovery data, following Hurricane Fiona, is performed using a linear regression. Most of the CISs, including power systems, reached either full system functionality or a new steady-state system performance within this time. In cases where exact CIS recovery data were not reported by the PREPS, DOE Situation Reports, or other sources, this study assumed that these CISs had reached full system functionality and, therefore, the reporting sources had deemed it unnecessary to report on their recovery. Table 1 below shows the CIS interdependencies found in the examination of Hurricane Fiona data.

Table 1. Interdependency relations between power system (predictor variable, x) and other CISs (response variables, y).

Response Variable (y)	Interdependency Relationships (Linear Regression Fit)	R^2 Value (%)	S_e Value
Water	$y = 0.4500 + 0.5547x$	88.89	0.0520
Cell Antennas/Sites	$y = 0.6498 + 0.3290x$	93.36	0.0232
Hospitals	$y = 0.1039 + 0.8590x$	76.85	0.1253
Ports	$y = 0.8254 + 0.1310x$	2.03	0.2400
Commercial Flights/Airports	$y = 0.4158 + 0.2800x$	7.66	0.2569
AMA Routes	$y = 0.4430 + 0.5490x$	20.46	0.2861

The above regression analysis was performed in Minitab (17) software applications, and the analysis output showed that the *p*-values for all the bivariate relationships above were below 0.05, except for ports (*p*-value of 0.236). Therefore, the linear regression analysis method presented here can be used to identify the interdependency relations between power systems and other CISs, except for between power systems and ports. The curve fits for the linear regression analysis are shown in Figure 7.



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 7. Infrastructure interdependencies of (**a**) drinking water systems, (**b**) cell antenna sites, (**c**) hospitals, (**d**) ports, (**e**) commercial flights, and (**f**) AMA bus routes systems with power systems infrastructure based on post-disaster recovery data for Hurricane Fiona.

The standard error of estimate, Se, values in Table 1 show that there may be a very low degree of error in the results of the linear regression analysis, indicating that the interdependencies identified through the analysis are valid. This parameter provides a secondary check on the results of linear regression analysis, where the primary check is through the observation of the coefficient of determination, R^2 values. The Discussion section of this paper provides the interpretation of the values derived from the linear regression analysis presented in Table 1 and shown in Figure 7.

4. Discussion

An important observation on the collected data is that the duration of CIS recovery from Hurricane Fiona was much shorter compared to the data collection period (of almost a year) for recovery from Hurricane Maria, as the power systems and other CISs seem to have recovered much quicker following the storm in 2022 upon initial observations. The CIS recovery fragility curves in the earlier study [1] showed a very slow recovery phase. A month after the storm, the power system was able to provide power to only around 12% of its customers, and after 3 months, the power system recovery was around 65%. Even 6 months after the storm, the power systems had not recovered to 100% [1]. Figure 8 shows the fragility curves for the power systems and other CIS recoveries following Hurricane Maria. For Hurricane Fiona, the data were collected for the duration of a complete recovery of Puerto Rico's power systems. The analysis of the Hurricane Fiona data sheds light on these initial observations and is included in the Results section, earlier in this paper. One reason for the comparatively early recovery could be the efforts by various interested parties to upgrade the CISs and power systems, along with better preparations for the recovery by prepositioning necessary critical recovery resources prior to the storm. This new urgency of disaster recovery efforts owes its origin to the devastation of Hurricane Maria and the very slow recovery following the storm.

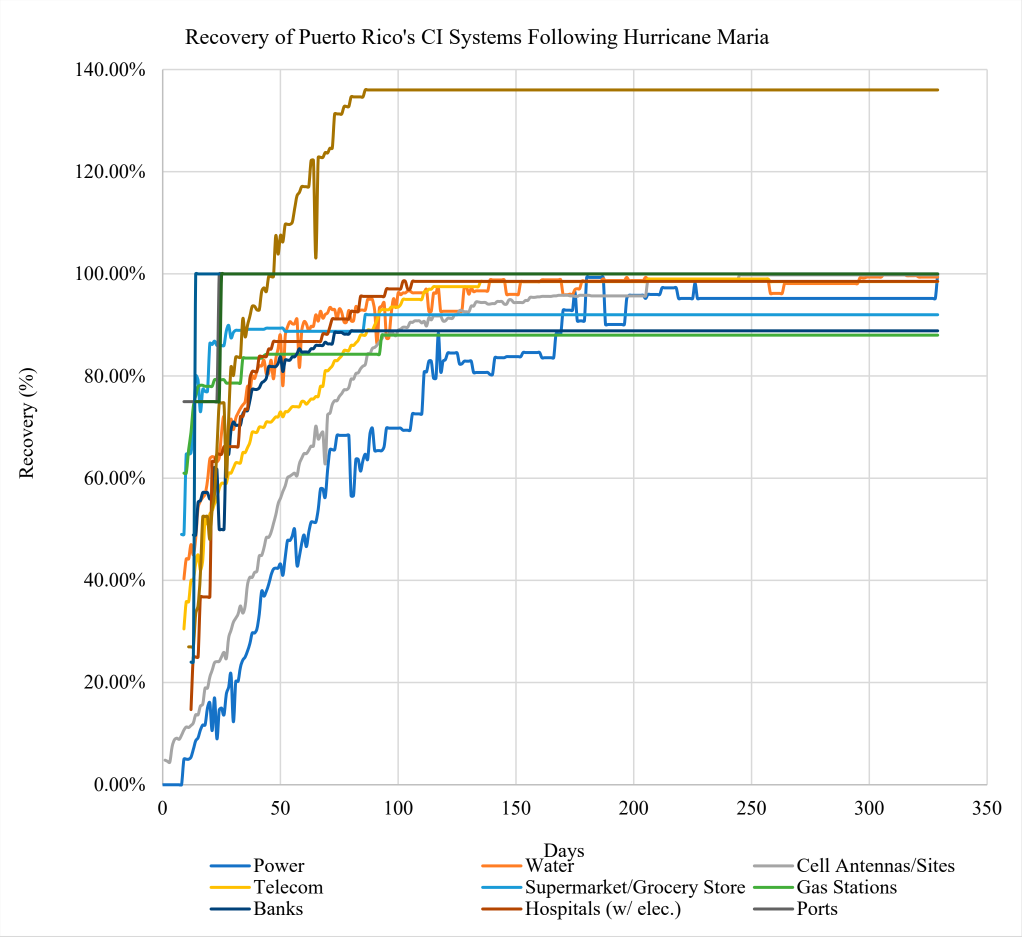


Figure 8. Daily progress of CIS recovery in Puerto Rico after Hurricane Maria.

As mentioned earlier, in addition to illustrating the recovery resiliency of critical infrastructures, the fragility curves in Figure 5 also portray the states of disaster readiness or preparedness of the CISs involved. The fragility curves indicate that the power systems, cell sites, water systems, ports, and AMA routes of Puerto Rico had a comparatively higher level of disaster preparedness or readiness, reflected by the exponential recovery curves. The sinusoidal recovery curves for airports and hospital systems indicate a comparatively lower level of disaster preparedness prior to the hurricane.

The coefficient of determination, R^2, between two variables in a linear regression analysis gives insight into the strength of the relationships or interdependencies between the variables. If the R^2 value for a particular relationship in a bivariate data set is higher than 50%, this indicates a significant interdependency between the variables, meaning the response variable is highly dependent on the values of the predictor variable. Based on the R^2 values listed in Table 1, this study finds that the response variables of drinking water systems, cell antennas/sites, and hospitals vs the predictor variable of the power system and coefficient of determination values are significantly higher than 50%. Therefore, this study finds that the water, cell antenna, and hospital infrastructure systems have strong associations or interdependencies with power systems infrastructure. The linear regression fits in Figure 7a–c also show these strong interdependencies diagrammatically. The regression lines in the figures show that the recovery data points are closely distributed around the lines and the lines fit the data points very well. This finding is consistent with the findings of the previous study on Hurricane Maria-induced recovery data [1] and therefore validates the earlier research. The research on Hurricane Maria data established some additional associations, which are between power and the ATM network, telecommunications (in terms of customers with service), banks, and gas stations. Unfortunately, due to lack of data availability, these CIS associations or interdependencies could not be examined and validated in this research.

The strong interdependencies observed in Figure 7 also seem to agree with the findings of existing research by other authors in this field, for example, with findings from a study by Raub et al. [16] based on an extensive literature survey focusing on interdependencies among energy, water, and food systems. The study discovered that in addition to water and food systems (supermarkets, food retailers, etc.), other CISs, such as telecommunications, healthcare, and transportation systems, are strongly interdependent with power systems infrastructures.

From observations of R2 values for commercial flights or airport network, ports and AMA or public bus transportation network, the research finds that the associations for these CIS with power systems infrastructure is weak (R2 values less than 50%) and cannot be examined through a linear regression analysis. This lack of recovery associations is also observed in Figure 7d–f in the poor fits of the regression lines with the given data points. This is to be expected, as the data points reflect whether these CISs were active or suspended as reported by the data source [29]. Moreover, the exact contribution of generators or emergency power systems into activating these systems could not be established based on the reported data. Therefore, the recovery data points for these CISs may have been distorted and do not reflect the actual recovery of these infrastructures on grid power. This finding is also consistent with the findings from the earlier study, which are thus validated. However, there may exist strong associations or interdependencies between these CISs and power systems, but they may not be identifiable using the data that were reported and using a regression model. These systems are highly critical to the initial recovery efforts of a community and, therefore, are typically brought online using temporary power or generators, immediately after a disaster event or as soon as possible.

5. Conclusions

This research establishes the recovery associations of CIS interdependencies between power systems and other CISs using infrastructure disaster recovery data reported from the recovery efforts of Hurricane Fiona. The findings validate the interdependencies established in the earlier research using CIS recovery data from Hurricane Maria. Moreover, this validation shows that CIS interdependencies remain after five years of significant efforts to improve critical infrastructures and their resiliency in a disaster-prone area such as Puerto Rico. This outcome indicates that recovery associations between power systems and other CISs may be a constant feature of these systems. In addition to examining and validating the CIS interdependencies discovered after Hurricane Maria, another purpose of this research was to examine the updated state of resiliency five years on. In this regard, this study shows that the power systems and other CISs of Puerto Rico were much more resilient, as demonstrated by their fragility curves, than during Hurricane Maria. This is due to these systems having a more robust disaster preparedness to prevent the catastrophic level of failure observed in the aftermath of Hurricane Maria. This research shows that strong interdependencies remain between power systems and some of the other CISs, such as water, telecommunications, and healthcare systems. And these critical infrastructures and their interconnecting components can be targeted to make these systems more resilient and thereby achieve the same for the communities that depend on them.

Even though many steps have been taken to improve the resilience of the power systems infrastructure in Puerto Rico, there still remains a lot of room for improvement to make the system truly resilient to natural disasters. As observed by [34], private and public stakeholders in Puerto Rico have focused on the resilience and transformation of the power systems infrastructure since the devastation of Hurricane Maria, but challenges remain, as the majority of the efforts have gone towards the stability of the system without actively working towards longer-term transformational changes. If long-term improvement of the energy system is not in serious consideration, Puerto Ricans are unlikely to experience a rapid transition toward a sustainable, inclusive energy system. However, the interdependencies between the power systems and some of the other critical infrastructure systems provide an opportunity to devise a resilience strategy that is suitable for a sustainable network of power systems and other CISs. This research can be improved upon by looking into the interdependent subsystems to identify the best possible areas to target to recover system performance quicker and thus improve the resilience of the systems and, in turn, that of the affected community. Moreover, given the push by many public and private institutions for a move away from fossil fuels and towards renewable energy sources, future CIS interdependency studies should look to integrate newer infrastructure systems such as Electric Vehicles (EVs) and EV charging stations, autonomous vehicles, and associated road networks, in addition to renewable power generation and transmission and distribution networks.

The authors suggest continuing this research and developing a Model-Based Patterns Library (MBPL) [35] for the identified CISs with a list of recommendations for disaster-prone areas, FEMA, state and local authorities, hospitals, ports, airports, and power plans to identify and strengthen CIS resiliencies. The pattern library will be like the space systems pattern library developed in [36], with a list of architectural patterns for individual CISs. The subject pattern library will articulate individual CIS architectures, starting from top-level systems to their smaller components, their relationships within the CIS as a system, and the interdependencies with other CISs. The subject patterns library will assist the users and stakeholders to select and customize their CISs per their interdependencies, characteristics, and challenges. This allows to identify the gaps, compare, and examine historical data to extract the minimum viable solutions to strengthen the identified resiliencies.

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