Resilient Grid Operational Strategies Report: Phase 2

Presented to:
The Department of Energy
Office of Energy Policy and Systems Analysis

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TABLE OF CONTENTS

1 INTRODUCTION

Extreme weather-related disturbances, such as hurricanes, are a leading cause of grid outages historically. Although physical asset hardening is perhaps the most common way to mitigate the impacts of severe weather, operational strategies may be deployed to limit the extent of societal and economic losses associated with weather-related physical damage.[1] The purpose of this study is to examine bulk power-system operational strategies that can be deployed to mitigate the impact of severe weather disruptions caused by hurricanes, thereby increasing grid resilience to maintain continuity of critical infrastructure during extreme weather. To estimate the impacts of resilient grid operational strategies, Los Alamos National Laboratory (LANL) developed a framework for hurricane probabilistic risk analysis (PRA). The probabilistic nature of this framework allows us to estimate the probability distribution of likely impacts, as opposed to the worst-case impacts. The project scope does not include strategies that are not operations related, such as transmission system hardening (e.g., undergrounding, transmission tower reinforcement and substation flood protection) and solutions in the distribution network.

Figure 1 describes the potential impacts of a hurricane on the electrical power system. The power system is schematically represented by six transmission substations and three aggregate sources of electrical power interconnected by a simple transmission network topology and distributing power to aggregated loads in specific service areas. High winds and wind-driven storm surge are major hurricane hazards. Strong wind can damage the electrical distribution network, reducing the total load served in some service areas.

Surge inundation flooding impacts the transmission system by damaging electrical substations and, possibly, generator switch yards. The direct consequence is that the areas served by the inundated substations cannot be energized. In addition, power cannot flow though the lines connected to inundated substation. The topology of the remaining network may be significantly different than the "as-designed" network, which can potentially lead to power flow congestion that is not normally present in the as-designed network. To relieve this congestion, the power system operator may resort to shedding electrical load at substations that are still connected to the transmission network thereby increasing the extent of the electrical outage beyond the physically damaged components.

Using an optimal power flow model that includes line switching to control network topology, we calculate the maximum load that can be served in post-event power system and compare this to an optimal power flow model that considers optimal power flow without topology control. The difference in electrical load shedding between the two results is a measure of the efficacy of transmission topology control as a resilient grid operational strategy.

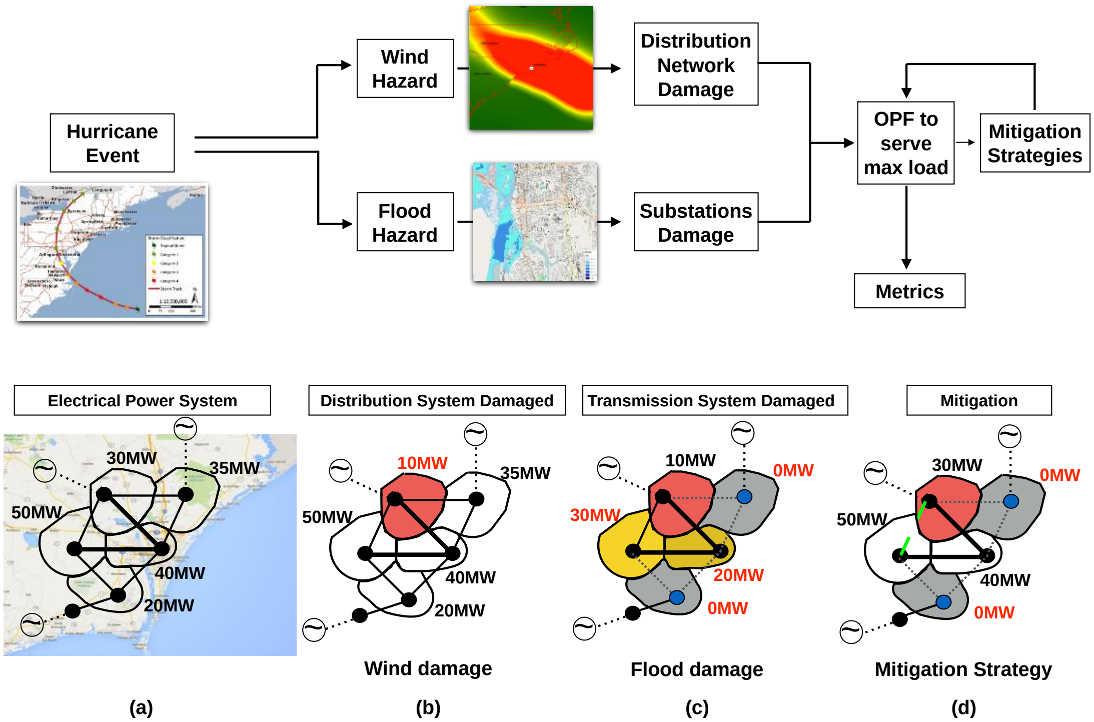

Figure 1 Description of hurricane impacts on electrical power. The power system is schematically represented by six substations (black dots) interconnected by a simple transmission network topology and distributing power to aggregated loads in specific service area (a). Wind and surge inundation caused by hurricanes are the major hazards for electrical power systems. High wind mostly impacts distribution networks reducing the total load served in some service area, red area in (b). Surge inundation mainly effects transmission substations (blue dots in (c)) and the connected transmission lines (dotted lines in (c)). The direct consequence is that the areas served by the inundated substations cannot be energized (gray service areas in (c)). In addition no power can flow though the lines connected to inundated substation (dotted lines in (c)) leading to potential power flow congestion in the available transmission lines and load shedding in service areas whose substations are connected with the inundated ones (yellow service areas in (c)). A change in the topology such as switching off lines (green line in (d)) could reroute the power to serve more load.

2 METHOD

LANL developed SynHurG, a synthetic hurricane generator tool, which draws hundreds of hurricane samples from a probability distribution based on historical data to reflect the historical distribution of hurricane physical characteristics—rate, track, intensity and winds. We evaluate the consequences of individual hurricane samples and aggregate the individual results to build a probability distribution of the impacts on the electrical power grid under different resilient bulk grid operational strategies. Figure 2 shows a schematic of the analysis workflow.

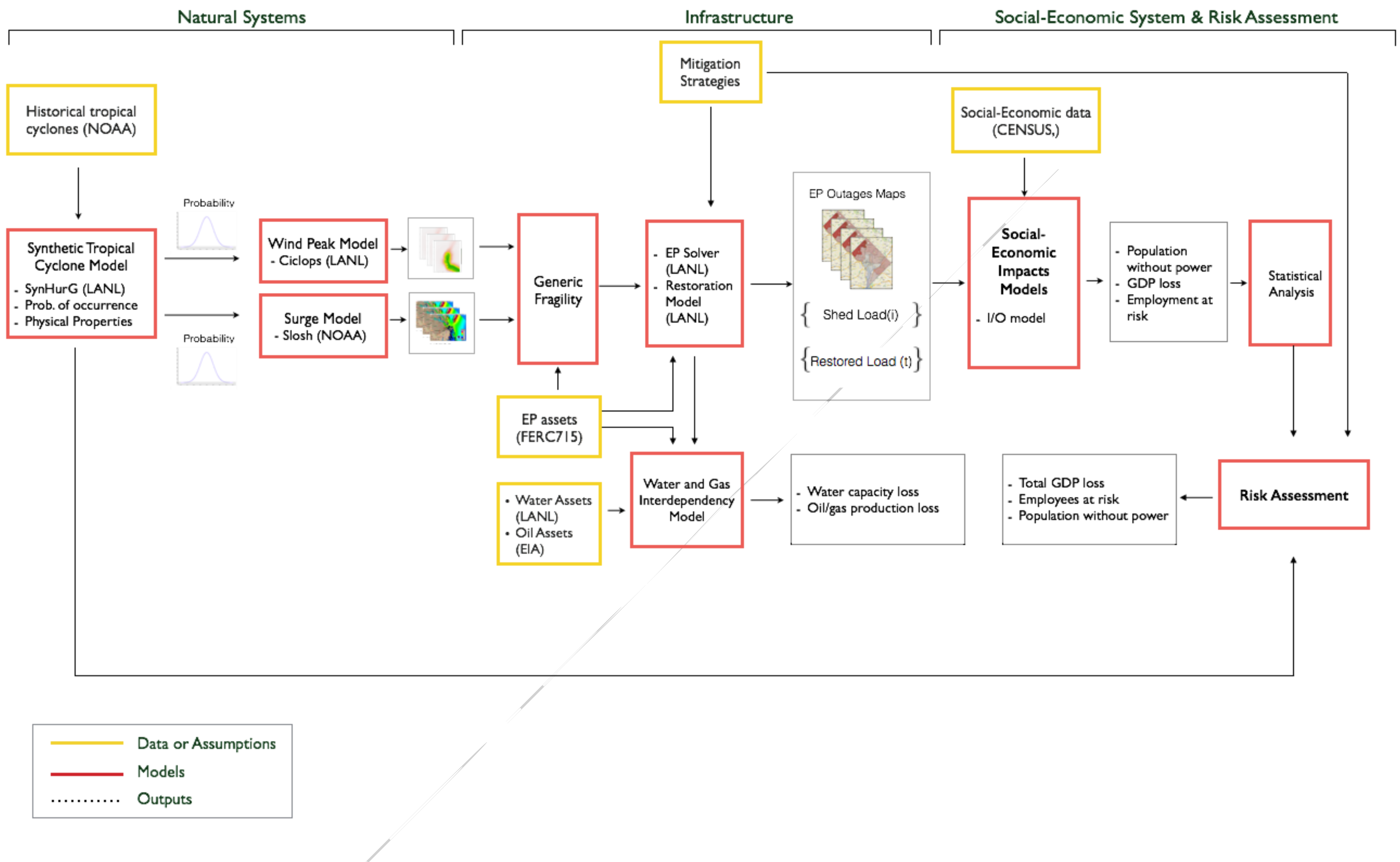

Figure 2. Analysis workflow that represents the integrated steps required for assessing the impacts on electrical power systems. The analysis integrates different models (red) whose inputs (yellow) are open source data with the exception of the electrical power (EP) assets, which are included in the proprietary Federal Energy Regulatory Commission bus data (FERC715).

The analysis uses the following modeling capabilities:

1. SynHurG
2. Cyclone-induced Commercial Loss of Power Simulator (CiCLOPS)
3. NOAA SLOSH
4. FloodFill
5. Generalized Fragility Model
6. Electric Power Restoration Model
7. Severe Contingency Electric Power Flow Solvers
8. Economic assessment: FastEcon

LANL developed these individual capabilities for a variety sponsors, as shown in Table 1.

Table 1 Sponsors for development of the models used in assessing hurricanes impacts

Model	DOE-EPSA	DHS/OCIA*	Other
SynHurG	x	x	
SLOSH			x
FloodFill		x	
CiCLOPS		x	x
Fragility		x	
Electric Power Restoration Model	x	x	x
FastEcon	x	x	
*Department of Homeland Security Office of Cyber & Infrastructure Analysis			

Steps for a single hurricane sample:

1. We use the hurricane samples from SynHurG as inputs into LANL's CiCLOPS, which produces maximum sustained wind speeds at any point in space over the entire duration of the storm based on the maximum storm intensity at landfall, the forward motion of the storm, and the size of the storm.[a]

2. We use the National Oceanic and Atmospheric Administration (NOAA) Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model[1] to calculate the surge depths for each hurricane sample. The coarse spatial resolution of SLOSH flood depths are refined using the LANL-developed FloodFill model.

3. We next use LANL's Generalized Fragility Model to estimate damage to the electric power system based on inland surge depth in the area of interest. This study does not consider wind impacts because wind mainly affects the

[a] CiCLOPS uses the same methodology presented in the Inland Wind Model developed by the Hurricane Research Division of the National Oceanic and Atmospheric Administration. See National Oceanic and Atmospheric Administration, Hurricane Research Division, www.aoml.noaa.gov/hrd/data_sub/wind.html and Kaplan, John, and Mark DeMaria. "A simple empirical model for predicting the decay of tropical cyclone winds after landfall." *Journal of applied meteorology* 34, no. 11 (1995): 2499-2512.

electric power distribution network, which is not included in the scope of this project.

4. We use the damaged transmission network and the remaining load on the substations in an AC Optimal Power Flow (AC-OPF) to optimally dispatch generation to serve the maximum remaining load. To ensure feasibility, the AC-OPF includes load shedding at the substations, which may result in unserved load in addition to that caused by the distribution network damage and the substation flooding. When assessing resilient operational strategies, the AC-OPF also includes transmission line switching to reduce additional load shedding due to transmission network congestion.
5. We run LANL's restoration model to estimate the restoration timeline for the flooded substations.
6. We estimate the population, total GDP loss, and jobs at risk as proportional to the total unserved energy over the entire restoration period.
7. In addition to the economic loss caused by the electric power outage, we assess potable water availability and the oil/gas sector. Oil and gas production and potable water supply and distribution generally depend on electrical power to function. Our analysis accounts for the dependence of these two infrastructures on electric power and quantifies the total amount of lost oil/gas production and potable water delivery due to the outage. Time and resources limitations preclude combining the electrical power restoration process with the potable water and oil/gas sector dependency so we use the maximum value of gallons of unmet drinking water and maximum reduction of oil and gas industry production as risk metrics.

2.1 IDENTIFYING INTERDEPENDENCY BETWEEN ELECTRIC POWER AND OTHER INFRASTRUCTURE

To identify interdependencies between electric power and other critical infrastructures, we use electric power service areas estimated from FERC 715 substation data to assess the cascading impacts of an electric power outage on other infrastructures, such as potable water distribution and oil and gas production. The analysis first identifies the electric power service area that supplies the critical infrastructure asset, i.e., water treatment plants, and oil/gas assets. If a substation is inundated or its associated load is not 100% served, the assessment assumes that an asset does not have electric power service. In reality, electric power utilities assign restoration priorities that direct the available load to critical assets. Without emergency operations procedures from the local utilities, the assessment cannot consider restoration priority. We do not perform a dynamic analysis of the water network or oil/gas systems to calculate the exact amount of unmet water demand or oil/gas production, respectively, but assume the unmet demand to be equal to the total asset capacity.

3 METRICS FOR EVALUATION

We run steps 1 through 7 for each sample from the hundreds of synthetic hurricanes to produce a probability distribution over a set of impact assessment metrics. Metrics include:

1. Electric power demand(MW-hours) not served
2. Total population without power
3. Total gross domestic product (GDP) loss
4. Total number of jobs at risk
5. Maximum unmet potable water demand
6. Maximum oil/gas production loss

Utilities or regulatory bodies can use these distributions as a metric for assessing current system resilience and to evaluate the efficacy of resilient operational strategies and also system hardening strategies. These metrics are consistent with the approach suggested by the Office of Energy Policy and Systems Analysis (EPSA).[2] We compute these distributions with and without the bulk grid resilient operational strategy, i.e., transmission line switching.

We also investigate other metrics, such as the expected GDP loss over the distributions or the effect on the tail events where the most extreme impacts occur. In this study, LANL did not conduct a hydraulic analysis of any potable water network or oil/gas systems, although this is possible in more detailed analyses. Instead, assessments of vulnerability and potential interruption of water infrastructure are based on the initial electric power outage and exposure of water and oil/gas assets to flood water.

Compared to transmission system hardening, bulk power operational strategies such as topology control are low cost actions and for this reason the metrics for evaluation do not account for the costs.

4 DATA SOURCES AND COLLECTION

LANL uses the following data to support various aspects of these analyses:

- NOAA historical hurricanes data base, HURDAT2[3]
- U.S. Geological Survey 10-meter National Elevation Dataset (NED)[4] supplemented with NOAA's Digital Coast Data (~1-meter) in the Norfolk area
- NOAA Tides and Currents gage data[5]
- Homeland Security Infrastructure Protection Gold substation data
- Federal Energy Regulatory Commission bus data (FERC715)
- LANL proprietary electric power service areas database
- LANL proprietary water asset database
- Population and business activity at tract level from 2010 Census
- Input-Output model input-data from Implan[6]

LANL uses the following assumptions to support this analysis:

- Population and economic activity remain constant at the 2010 levels
- The number and location of electric power, water, and wastewater infrastructure assets are the same as in 2015
- The geospatial location of infrastructure assets is an accurate representation of the asset and the underlying digital elevation model is representative of actual asset base elevation.
- Repairs to wind-damaged distribution networks are assumed to progress linearly over time.
- Analysts assume that the probability of hurricanes occurrence and the storms intensity does not change over the next 50 years in the studied area.
- This study does not include the effects of climate change on hurricane intensification and frequency over time.
- Water treatment plants are served by the substation within the treatment facility's service area.
- Business are closed if there is no electrical power service.

5 INTEGRATED MODELS

5.1 SYNHURG: SYNTHETIC TROPICAL STORM MODEL

LANL created its SynHurG model to develop probabilistic risk assessments of hurricanes in the United States. SynHurG identifies a sufficiently large region around the area of interest and extracts a statistically significant number of historical storms from the hurricane data provided by NOAA.[3] SynHurG estimates a probability distribution of physical hurricane properties (central pressure, maximum wind speed, and forward velocity, and heading) at landfall using an approach similar to the works of Torro and Blanton.[7] SynHurG also calculates the radius of the maximum wind speed as a function of central pressure and latitude and wind values at two different radii using a statistical model, as described in Vickery and Wadhera.[8] By sampling this distribution, SynHurG generates an ensemble of synthetic hurricanes for a specified area. Landfalls are placed randomly within a specific range of the coastline around the specified location.[9] Hurricane tracks are modeled as a spatial Markov chain[10] before and after landfall. A value for each physical variable is assigned to each point on the track using the time evolution profiles derived from historical data.

5.2 SURGE AND FLOODFILL MODELS

For hurricanes, wind and atmospheric pressure changes associated with a storm cause storm surge (the abnormal rise of water near the coast). Wind drives water inland, which inundates otherwise dry areas. The SLOSH model, developed by NOAA, is a simulation software package used to estimate storm surge depths resulting from hurricanes, parameterized by atmospheric pressure, wind speed, and other data typically associated with hurricane tracks. SLOSH also provides a number of basin configurations that specify features unique to specific shorelines, including topographic elevations, bridges, roads, flood barriers, and rivers.

The spatial resolution of SLOSH output data is too coarse to make determinations of the inundation effects on infrastructure. To overcome this limitation, LANL has developed FloodFill, a parallel post-processing algorithm used to estimate finer-scale flooding from a coarse inundation estimate. Figure 3 shows an example of FloodFill model output. By combining SLOSH and FloodFill with SynHurG, we provide probabilistic modeling of the inundation from an ensemble of synthetic hurricanes.

Figure 3 The NOAA's SLOSH surge model is used to estimate the surge storm depths caused by a hurricane. SLOSH spatial resolution is too coarse to accurately quantify the inundation effects on infrastructure. LANL developed FloodFill algorithm is used to improve SLOSH's output spatial resolution. The Figure shows an inundation map generated using SLOSH and FloodFill.

5.3 CICLOPS

CiCLOPS propagates a kinematic representation of a hurricane along the hurricane track. CiCLOPS uses the Kaplan and DeMaria model[11] to account for the decay of the hurricane wind speed over land. The maximum wind speed over the entire hurricane track is computed at each spatial location in the specified area. Figure 4 shows examples of CiCLOPS outputs for different storm track. By combining CiCLOPS with SynHurG, we provide probabilistic modeling of the maximum sustained winds from an ensemble of hypothetical hurricanes.

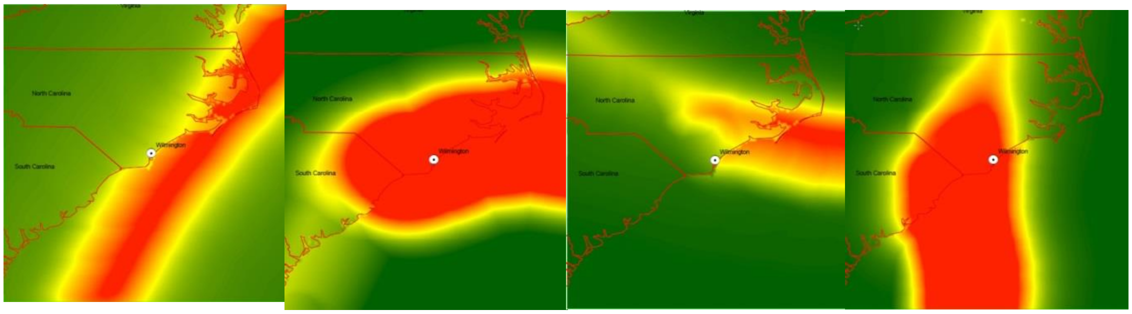

Figure 4 Effects of strong wind on infrastructures are estimated based on the maximum wind peak values in area of interest. Given a hurricane track, thevLANL CiCLOPS model calculates a wind field for each time step along the track and estimates the maximum wind speed over the entire hurricane track at each spatial location in the area of interest. As an example, the Figure shows four maximum wind maps estimated by CiCLOPS using four hurricanes, which generated by SynHurG have landfalls close to Wilmington, NC.

5.4 FRAGILITY

LANL fragility model estimates the impacts of storm surge inundation, which primarily affects substations and generators. The model is based on the assumption[b] that if the flood depth exceeds 4 feet, the substation and/or generator is removed from service and is de-energized by disconnecting the transmission power lines connecting to the substation.

5.5 ELECTRIC POWER RESTORATION ANALYSIS MODEL

LANL predicts the restoration timeline for flood-damaged substations. Based on discussions with electrical distribution utilities the time to repair a flooded substation is considered constant and equal to 240 hours.

5.6 SEVERE CONTINGENCY ELECTRIC POWER FLOW SOLVERS

Hurricane-driven inundation damage to electrical transmission substations can create severe contingencies to electrical transmission systems, well beyond the single bus contingencies considered by utilities. Under these conditions, commercial AC Optimal Power Flow (AC-OPF) solvers typically fail to converge and extensive analyst intervention is required to obtain a solution. Thus, current practices for severe contingency analysis are time consuming, difficult to repeat and replicate, and do not provide theoretical guarantees on solution quality. LANL's Severe Contingency Solver (SCS) fills these gaps.

In severe contingencies, the goal of the analysis is to calculate the minimum amount of load shed that will occur following the contingency. Under many conditions, the SCS finds the exact AC-OPF solution. When not exact, the constraint relaxation in the SCS is guaranteed to find a solution with a load shed equal to or less than the load shed found using a full AC-OPF solver. In either case, the relaxed solution from the SCS is a good initial solution for a commercial AC-OPF solver, helping to fill the gap

[b] Based on subject matter expert interview.

of finding good starting points for those tools and allowing them to converge rather than diverge when provided a severe contingency case. SCS approach combines generation dispatch with transmissions line switching. The basic workflow for the interaction between the SCS and a commercial AC-OPF solver is shown in Figure 5. In this study, PowerWorld[12] is used as the commercial AC-OPF solver that follows SCS.

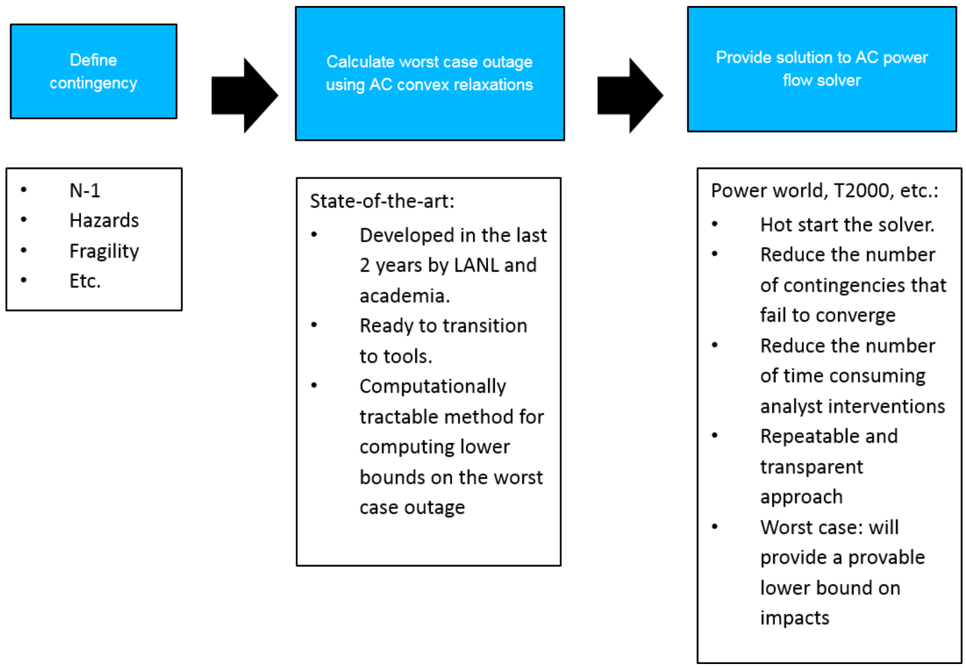

Figure 5. Process flow for the SCS tool. The process begins by defining the contingency. The worst case outage is calculated using AC convex relaxations and the solution is provided to the AC power flow solver.

5.7 ECONOMIC ASSESSMENT: FASTECON

FastEcon provides direct, indirect, and induced gross domestic product (GDP) at current prices at the spatial level of the 10 Federal Emergency Management Agency regions and individual states. The model uses the most recent available data (2014) for 20 industries corresponding to the North American Industry Classification System (NAICS) 2-digits industrial specification.

FastEcon estimates GDP values based on three components: 1) Number of jobs, 2) direct GDP per job, and 3) the multiplier that computes total GDP (i.e., the sum of direct, indirect and induced) per dollar of direct GDP. The workflow is explained in detail below. Figure 6 provides a diagram of the FastEcon workflow and inputs.

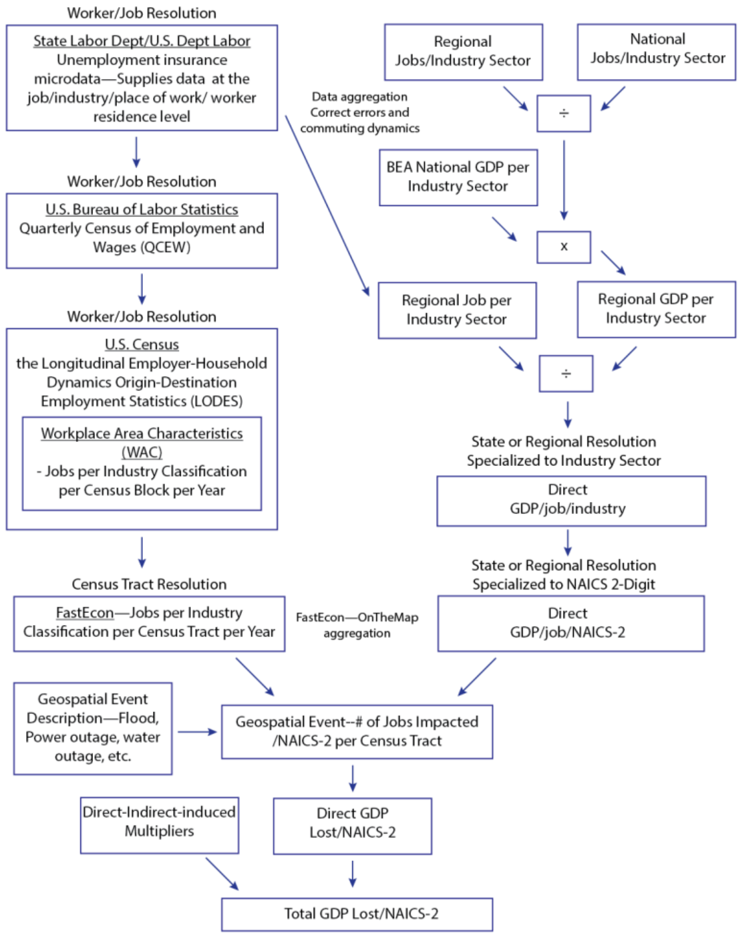

Figure 6. **Economic impacts of a hurricane are estimated using FastEcon model. FastEcon provides direct, indirect, and induced gross domestic product (GDP) at current prices. The Figure shows FastEcon workflow and its inputs.**

The Workplace Area Characteristics (WAC) data provide jobs quantities by industry sector. These data are contained in the Longitudinal Employer-Household Dynamics Origin-Destination Employment Statistics (LODES), published by the U.S. Census.[13] LODES data are derived from the Quarterly Census of Employment and Wages (QCEW) published by the Bureau of Labor Statistics. QCEW data are built on unemployment insurance micro data collected by state labor departments and validated by U.S. Department of Labor. These original microdata contain individual information for jobs, including the industry, establishment of work, and residence for each employee. QCEW data may be from 3% to 5% incomplete. The Census developed the LODES product to aggregate information about commuting dynamics and to fix small errors in the QCEW data by means of an algorithm that assigns employees with incomplete information to establishments that are spatially close within the state. The WAC dataset contains the number of jobs in a period and industry classification for each establishment. WAC data are estimated at the Census block level. FastEcon uses the Census Bureau's OnTheMap web service to aggregate data at the Census tract level.[14] The jobs reflected in the dataset are full or part time.

Direct GDP per job by industry is computed by dividing regional GDP by the number of jobs. Regional GDP by industry is derived by distributing Bureau of Economic Analysis (BEA) national GDP values to regions by multiplying national GDP by the ratio between the regional and national number of jobs by industry. The regional GDP values are at the BEA sector-level for 65 industries. These data are then aggregated at the NAICS 2-digits level. FastEcon estimates of direct GDP per job vary across regions because of regional industrial specialization.

Economic multipliers that provide direct, indirect, and induced GDP per dollar of GDP, are estimated using the standard procedure based on the Leontief inverse as it has been developed in the input-output literature and modeling approach.[c] LANL has developed regional input-output tables at the U.S. county level that simultaneously account for regional differences in both supply (as observed in QCEW data) and domestic trade flows (as estimated by transportation models and surveys).[d] FastEcon multipliers vary at the regional level because of differences in local economies and due to economic interdependencies within the nation.

Understanding the results: Direct GDP impacts result from an event. For example, if the event is a disruption of the electric grid, the direct GDP impact equals the consequent loss of production in the firms affected by the disruption. Indirect impacts are result from impacts along the supply chains of directly impacted firms. Induced impacts result from a loss of remuneration to production factors. In the previous example, direct impacts propagate to suppliers of directly affected firms, and iteratively to the suppliers of suppliers (indirect impacts are the sum of all these effects). Directly and indirectly affected firms then will have to reduce wages and dividends because of the production loss experienced. Because of that, consumers will have to reduce their consumption levels, which will represent a further loss of production for firms and that will iteratively propagate along supply chains (the impacts induced by loss in consumption constitute induced impacts).

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[c] The literature on input-output modeling is extensive. One source is Ronald E. Miller and Peter D. Blair, *Input-Output Analysis Foundations and Extensions*, Cambridge University Press, 2009.

[d] For example, *Computable General Equilibrium Model Fiscal Year 2014 Capability Development Report*, National Protection and Programs Directorate, Office of Cyber and Infrastructure Analysis, US Department of Homeland Security, May 2015, and *Computable General Equilibrium Model Fiscal Year 2013 Capability Development Report*, National Protection and Programs Directorate, Office of Cyber and Infrastructure Analysis, US Department of Homeland Security, April 2014.

6 ANALYSIS RESULTS

As describe in previous section, our analysis consists in performing a PRA of hurricanes in the Norfolk, VA, area. Instead of considering the worst case scenario for any hurricane analysis, a PRA considers many synthetic hurricanes sampled from a probability distribution over hurricane intensity and track. A PRA provides a better representation of the probabilistic risk to the Norfolk area when compared to a worst case analysis because many hurricanes will take different tracks, be more or less intense than the worst case scenario, generate more/less storm surge, and have more or less intense winds. Analyzing a distribution of hurricanes, rather than a single hurricane scenario, provides local stakeholders and policy makers with a quantified view of the risk to their infrastructure, population, and economy.

Because the electric power of the City of Norfolk is not an isolated network, we have to consider the hurricane impacts on a geographical extent larger than the City of Norfolk itself. The study area is the Hampton Roads, VA, a highly urbanized coastal area of southeastern Virginia that encompasses 18 cities, including Norfolk, Chesapeake, Newport News, Hampton, Portsmouth, Suffolk, Poquoson, Williamsburg, and Virginia Beach. The Hampton Roads area is important to the regional economy and has a strong tourism industry. In addition, the area is important from a national security perspective with the presence of several military installations, including the Naval Station Norfolk in Norfolk, VA, and Langley Air Force Base in Hampton, VA.

The area is low-lying, with a gentle increase in elevation moving inland and to the west. The low-lying nature of the area and its development around coastal waters, including the confluence of the Elizabeth, James, and Nansemond Rivers into Chesapeake Bay near the Atlantic Ocean, make the region electrical power system vulnerable to flooding from extreme storm events.

Figure 7 shows the load-serving electrical transmission buses and their associated service areas within the study area. Each substation service area is characterized by a population and business type density. The study area has a population of 1.6 million people and the main electrical power provider is the Dominion.

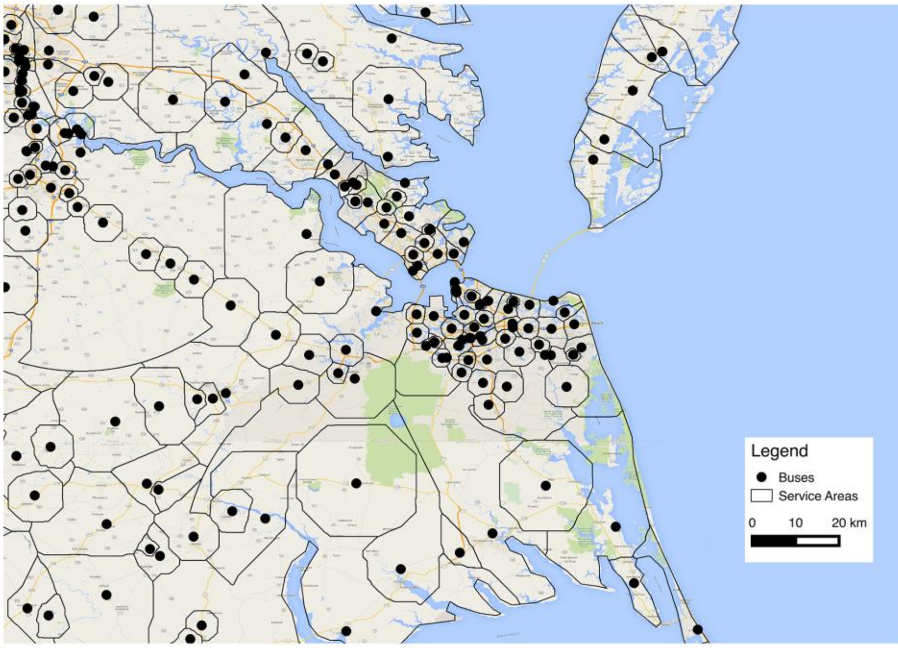

Figure 7. Electrical transmission power system: load-serving electrical transmission buses (black dots) and their associated service areas (polygons)

As described in Section 2, the first step of LANL's PRA generates an ensemble of several synthetic hurricanes whose physical characteristics are consistent with the characteristics of the historical storms occurred in the area. We generated a total of 100 storms whose landfall is on the coast close to the City of Norfolk, VA. Figure 8 shows the tracks simulated using SynHurG. Using these parameters as the inputs for the SLOSH model, we simulate the storm surge for each of the tracks obtaining 100 storm surge maps. Figure 9 illustrates the storm surge values averaged over the 100 generated storm surge maps.

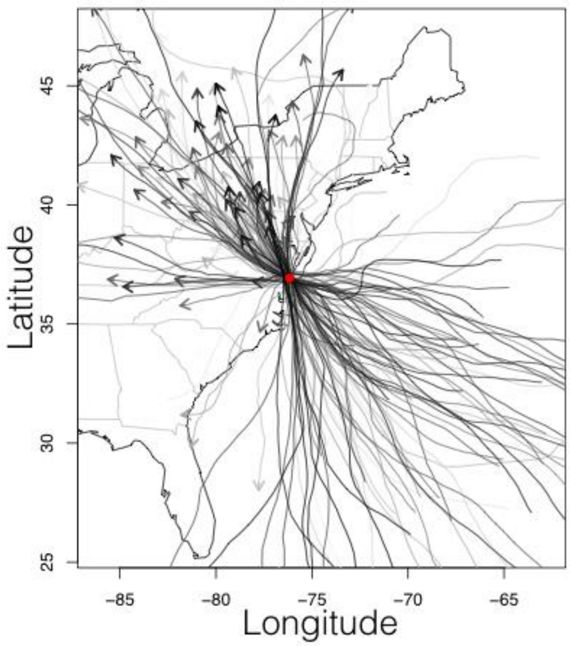

Figure 8 Synthetic historically-consistent tropical tracks with landfalls close to the City of Norfolk, VA (red dot).

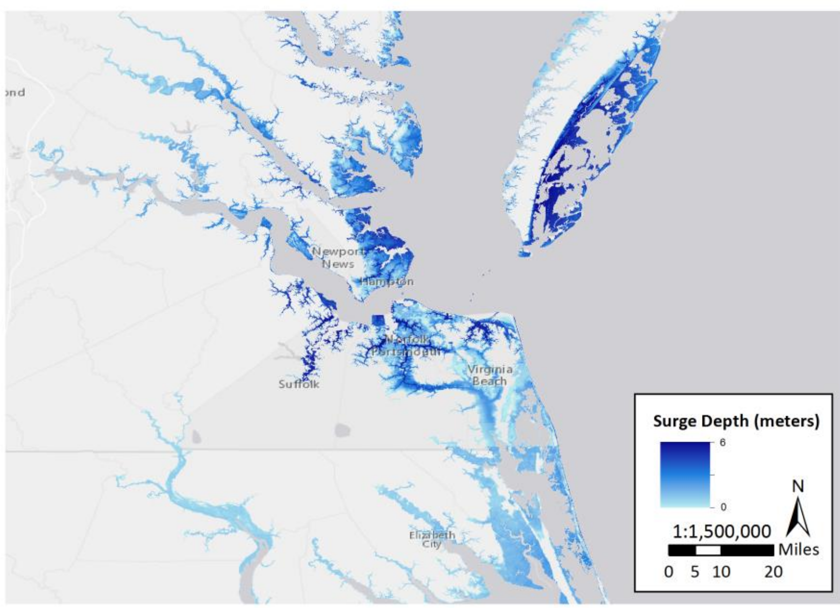

Figure 9 Storm surge water depth averaged over 100 storm surge maps

Our analysis identifies all buses in the expected surge storm surge inundation area at a flood depth of 4 feet or deeper and removes them and the attached transmission lines from service. The map on the bottom of Figure 11 shows the busses flooded (red dots) and the not flooded busses whose load was shed to relive transmission congestion (yellow dots) in at least one of the 100 synthetic hurricanes. Across all the generated storms, flood damage as a result of storm surge is expected to affect a maximum of 52 different load-serving electrical transmission busses. Figure 10 shows the frequency of flooding for each of the 52 affected buses across the synthetic hurricane scenarios.

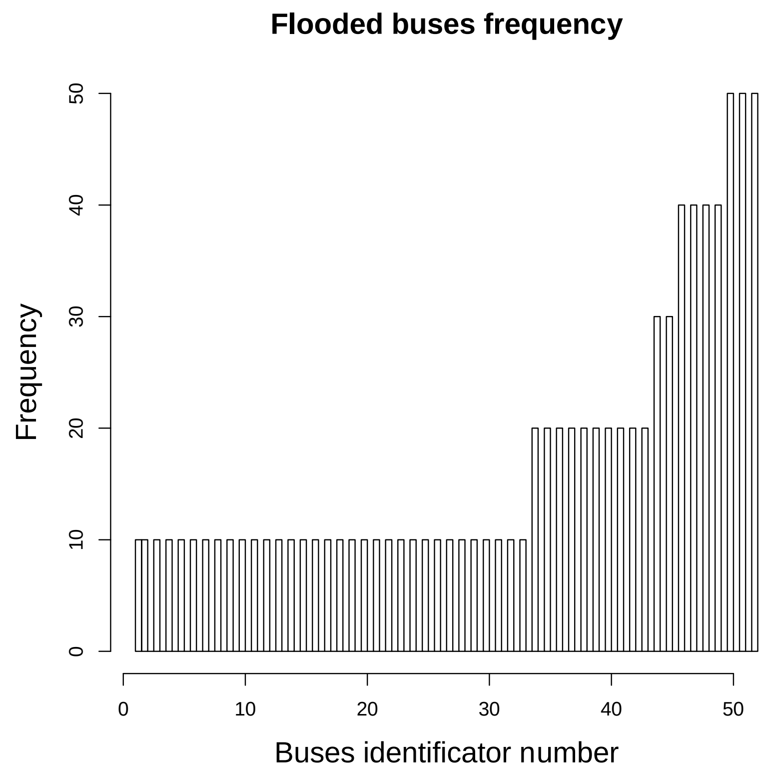

Figure 10 Frequency of inundation across scenarios: number of simulations where each bus is flooded

The resilient bulk power operational strategy analyzed in this study consists in generation dispatching combined with transmission line switching (LS) to affect network topology control. We want to understand if including topology control allows the system to serve more load, thereby increasing system resilience, than only using generation dispatching. We implemented an LS algorithm in the existing SCS electrical power solver allowing the closing and opening of lines in order to maximize load served. The LANL SCS solver can easily optimize on different parameters such as GDP, operational costs, or criticality of facilities served.

To evaluate the effectiveness of the LS strategy, we analyze a baseline scenario without transmission line switching to determine a probability distribution for each of the defined metrics noted previously. We then include LS and use the changes in these probability distributions as the metric for evaluating the efficacy of the resilient operational strategy.

Figure 11 shows one of the LS strategy improvements relative to the baseline. A substation that was not flooded in any of the synthetic hurricanes suffered load shedding to relieve transmission congestion in the baseline strategy. When the LS strategy was applied, this bus was able to completely energize its service area in at least one of the synthetic storms scenarios.

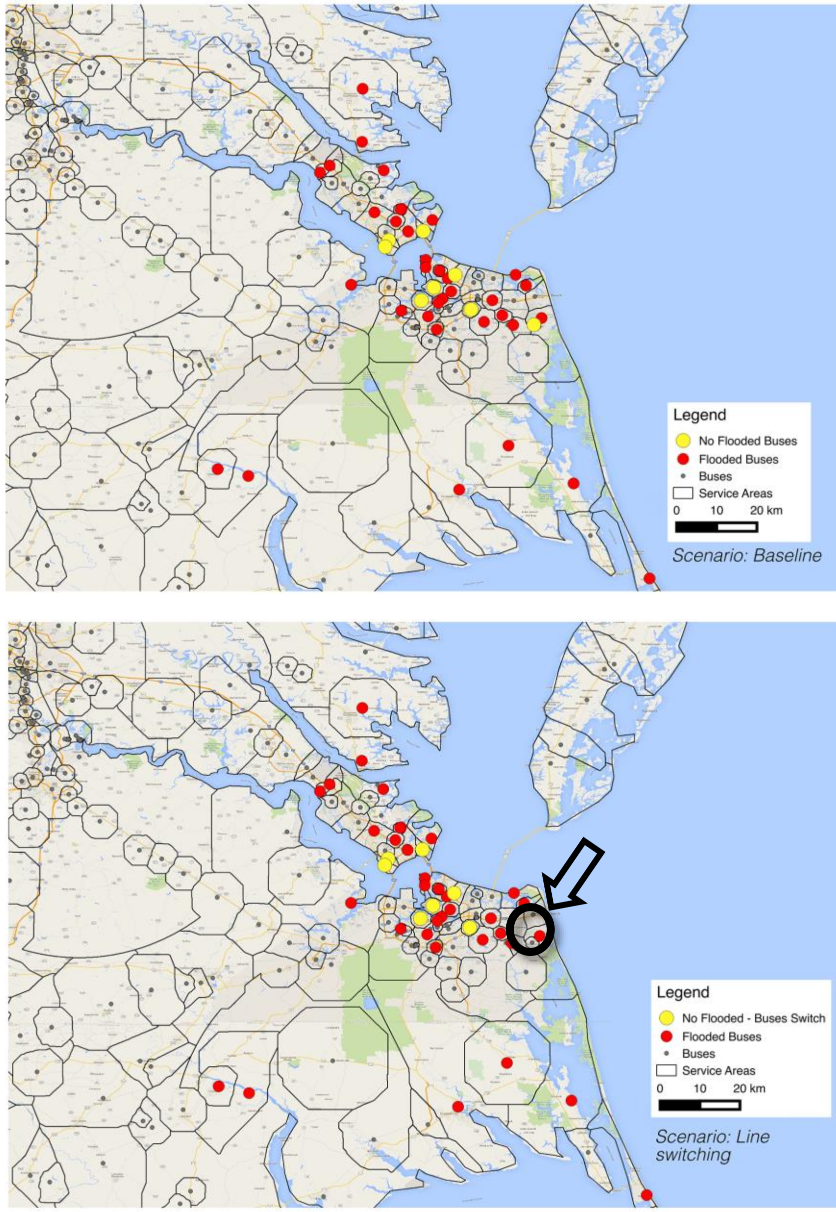

Figure 11 Baseline (top) and line switching (bottom) scenario comparison. Electrical power busses not able to completely energize their service area because they are flooded (red dots) or because load shedding is required (yellow dots) to relieve transmission network congestion. The black circle shows a bus that, in the baseline scenario, is not flooded but is unable to serve all of its load. In the LS scenario, this bus is able to completely energize its service area.

The following figures show a comparison of the baseline and resilient operational strategies by considering (1) the average value of a specific impact for each service area (Figure 12), and (2) for each impact the probability distribution (Figure 13 to Figure 16).

The results are similar for each impact:

1. For the majority of buses, the load shed, population without power and GDP/jobs loss result is less than or equal in the line switching scenario than in the baseline as shown in Figure 12**.**
2. For the study area and electrical power network, the LS strategy enhances the overall resilience of the electrical transmission network relative to the baseline: In many hurricane samples, LS lowers the amount of load shed and shifts the probability mass of the LS scenario distributions to lower impact relative to the baseline scenario distribution (Figure 13 to Figure 16).

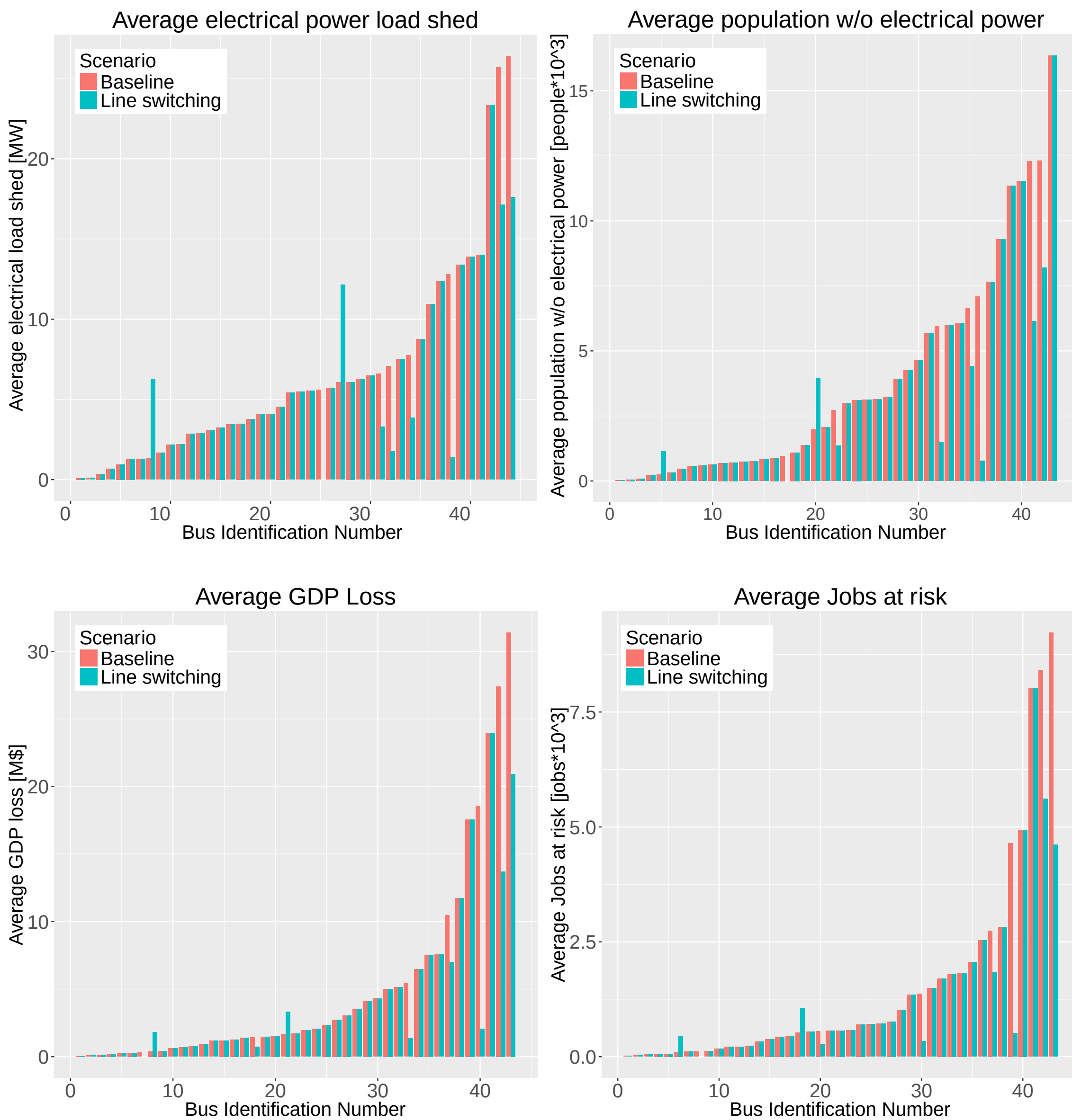

Figure 12 LS and baseline scenario comparison. Average impact (load shed, population without power, GDP loss, and jobs at risk) for each bus. X axes show the ID of the electrical power buses. For the majority of buses, the outage in the line switching scenario is less than or equal to the outage in the baseline.

Figure 13 shows that for hurricanes that generate large load shed, there is no significant difference between the two strategies: the high impact tails of the two distributions are similar. The extensive damage caused by these hurricanes leaves little room for topology control by the LS strategy. The majority of the difference is for storms that create moderate impact where there are still several topology options for the LS strategy to explore to reduce the load shedding caused by congestion in the baseline strategy.

In this initial application of the LS resilient strategy, we only considered minimizing load shed as the objective of the optimization, however, this also appears to benefit the social-economic impacts: population without power (Figure 14), GDP lost (Figure 15), and jobs at risk (Figure 16). As for the shed load, adopting the LS scenario results in a general shift of the distribution of each socio-economic metric toward lower impact in the LS scenario. This means that buses whose shed load was largely reduced served areas with high population and GDP.

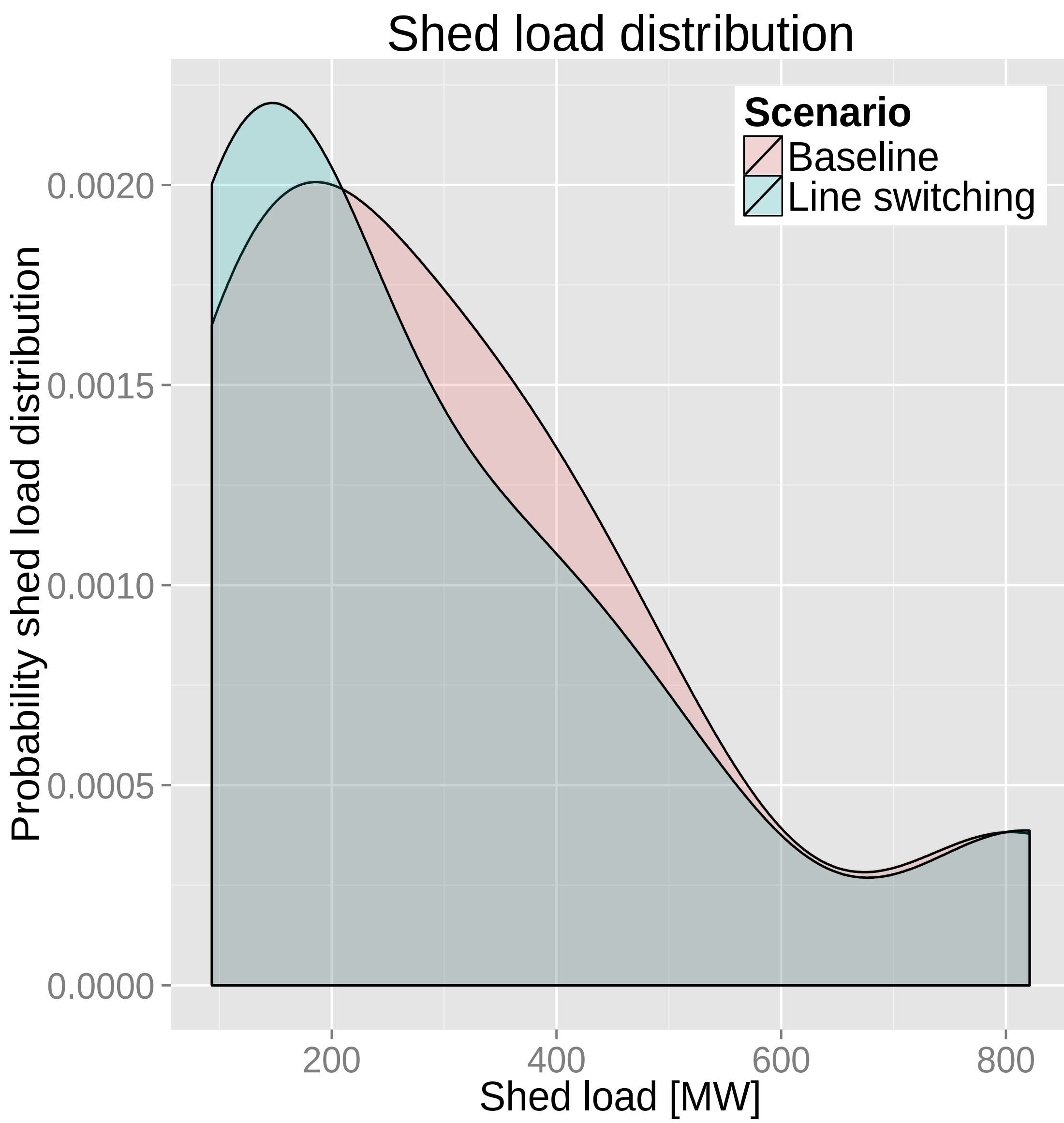

Figure 13 LS and baseline comparison: outage probability distribution. Overall, the line switching scenario enhances the resilience of the electrical transmission system: line switching produces a higher probability of small impact (the green shaded area on the top left). The majority of the difference is for storms that create moderate impact (200-500 MW of lost electrical load) in the baseline strategy where there are still several options for the LS strategy to explore to reduce load shedding. Very little difference is found for high impact storms, on the right side of the figure, because the extensive damage leaves little room for topology control by the LS strategy.

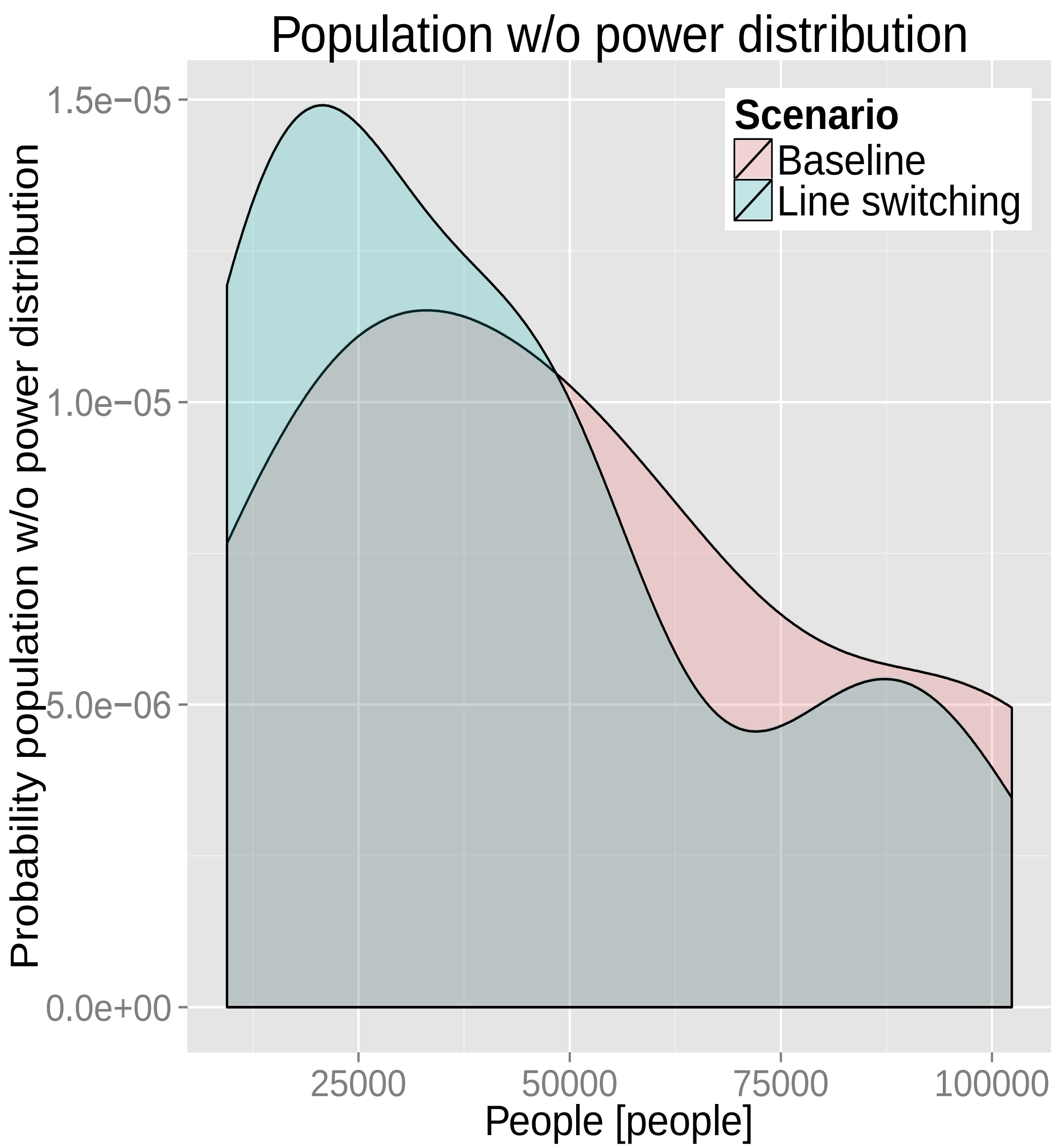

Figure 14 LS and baseline comparison: probability distribution of population without power. Overall the line switching strategy enhances the resilience of the electrical transmission system by reducing the impact on the population without power: the LS operational strategy produces a higher probability of small impact.

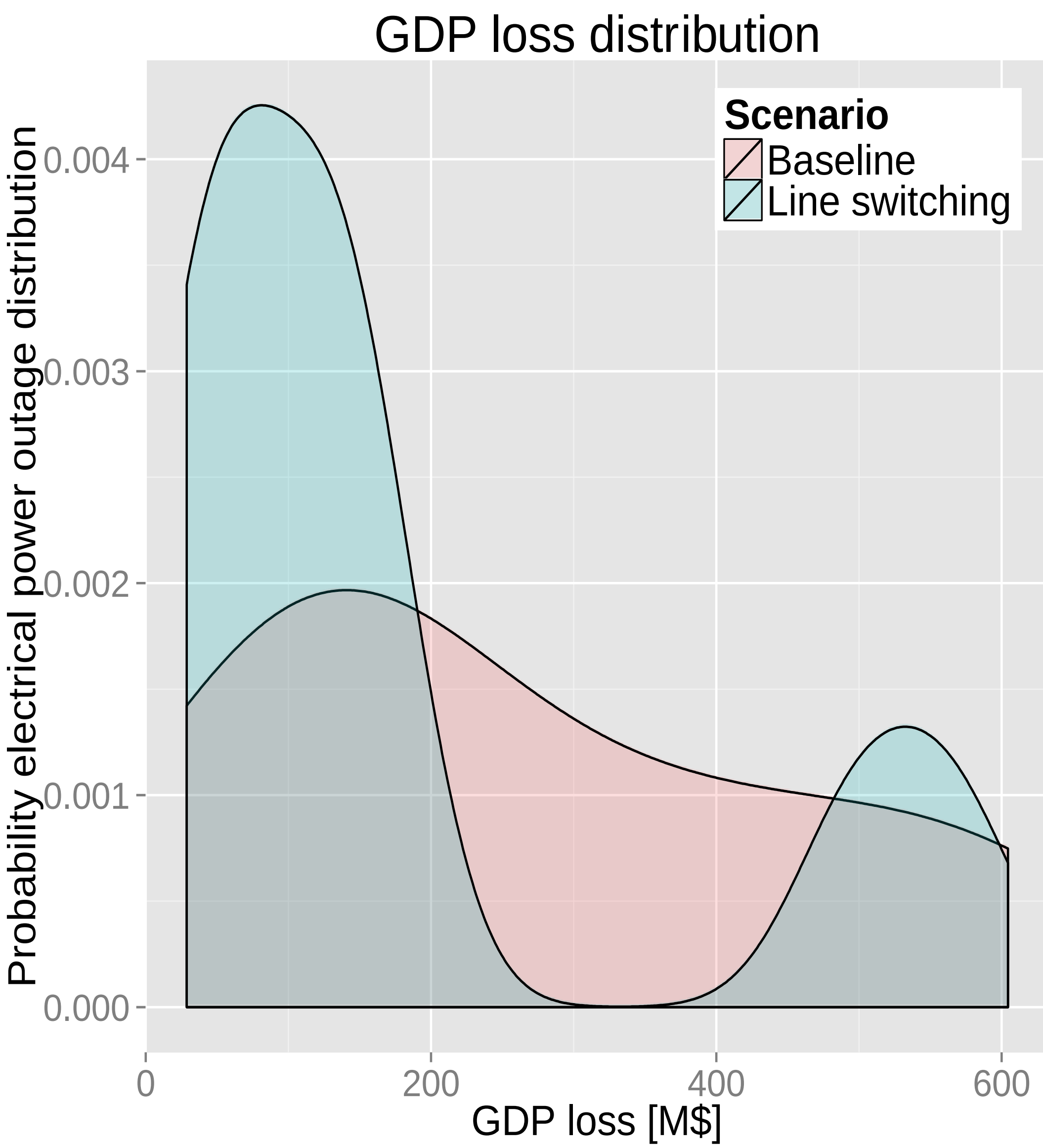

Figure 15 LS and baseline comparison. Probability distribution of GDP losses due to electrical power outages. Overall the line switching strategy enhances the resilience of the electrical transmission system by reducing lost GDP: the LS operational strategy produces a higher probability of small impact. We notice a slight increase of the probability of high GDP losses, which is the result of optimizing on served load and the difference between the spatial distribution of the GDP and the load served.

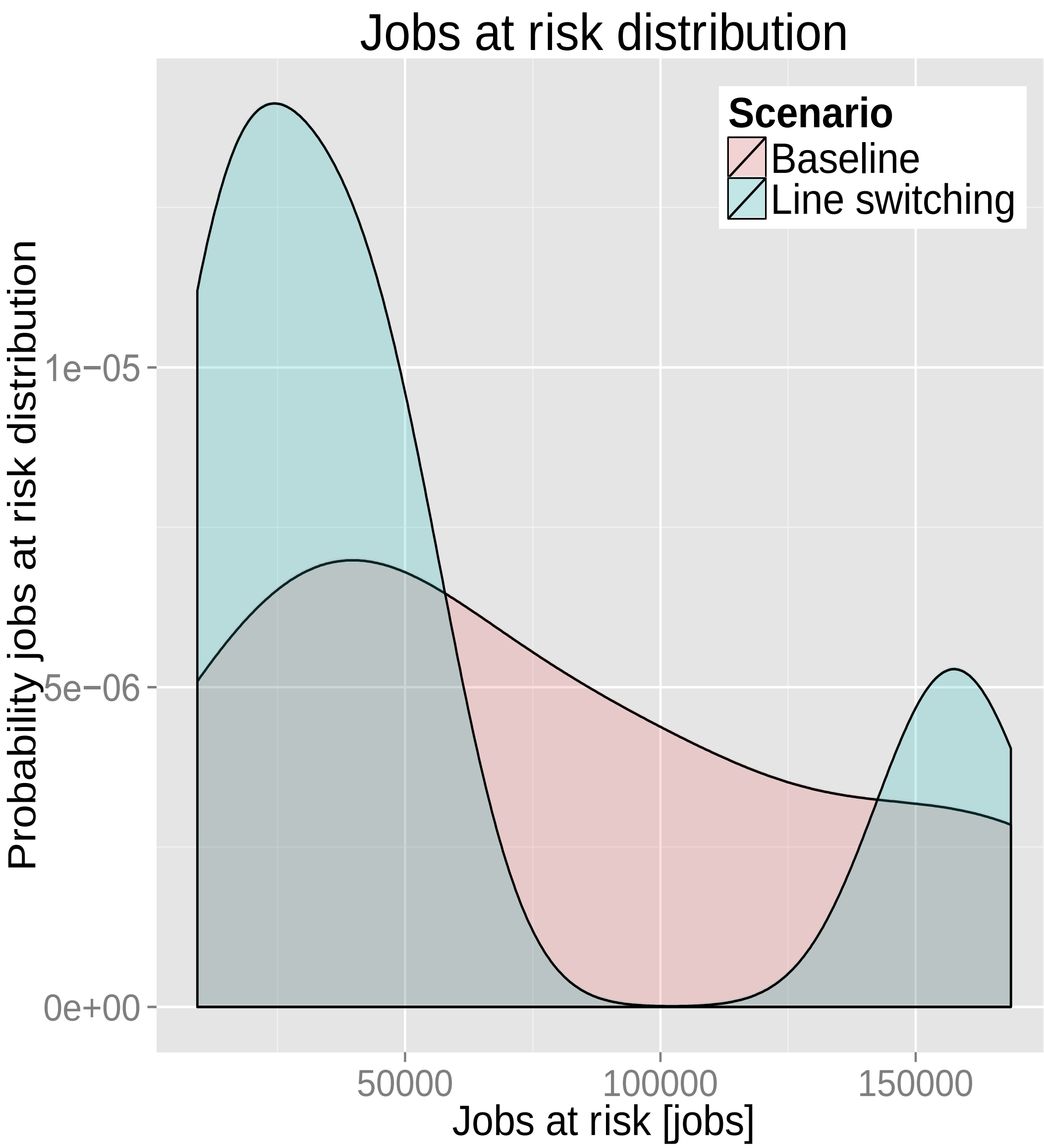

Figure 16 LS and baseline comparison: probability distribution of jobs at risk due to electrical power outages. Overall the line switching strategy enhances the resilience of the electrical transmission system by reducing the number of jobs at risk: the LS operational strategy produces a higher probability of small impact. As with the GDP loss, the results show a slight increase of the probability of many jobs at risk , which is the result of optimizing on served load and of the difference between the spatial distribution of the jobs and the load served.

6.1 ELECTRIC POWER DEPENDENCY

Disruption of the electrical power system can indirectly affect other critical infrastructures. Potable water treatment plants and water pump stations require electrical power to operate. Electrical power outage may have impacts on the oil and petroleum infrastructure asset operation including refineries and shipping terminals.

There are no operating refineries in the study area. The Yorktown Refinery shut down in 2010 and was converted to a rail/water/petroleum terminal. The only oil/petroleum infrastructure assets in the area are refined petroleum pipelines and refined product terminals. Current operating refined product terminals include: Allied Terminals, Apex Oil Company, Arc Terminals, CITGO, Hess, IMTT, Kinder Morgan, NuStar, PAPCO, Semmaterials, TransMontaigne, Western Refining, and Plains All American. Eight of these terminals are connected to the Colonial Refined Product Pipeline, which delivers refined product to the terminals. NuStar in Virginia Beach operates its own Terminal and Pipeline.

Figure 17 identifies the location of the refined product terminals operating in the area (orange triangles). If these terminals are not operable, local distribution of gasoline and other refined petroleum products will be interrupted. Five terminals are found to be without electrical power at least in one of the 100 simulations impacting the local distribution of gasoline (yellow triangles in Figure 17). These are Allied Terminals, PAPCO, Semmaterials, Western Refining, and Plains All American. The same result was found for both baseline and LS scenario. There is no difference in the electrical power outages to these plants between the baseline and LS strategies because the substations that provide power to those terminals were flooded. For each scenario the two PAPCO terminals were without power for 20 storms out of the 100 simulated, while the other three terminals were without power in 10 simulations.

The study area includes seven water treatment plants: Cheatham Annex Naval Supply, Fort Monroe, Lee Hall, Suffolk treatment plant, City of Williamsburg, G. Robert House Jr., 37th Street water treatment plant, and Harwood's Mill water treatment plant. Two treatment plants, the G. Robert House Jr. and the 37th Street water treatment plant, were without power for 10 simulations out of 100. The outage of these two facilities will affect potable water supply to approximately 78,600. As we found for the oil/petroleum terminals, the same two water treatment plants are without power in both the baseline and LS scenarios.

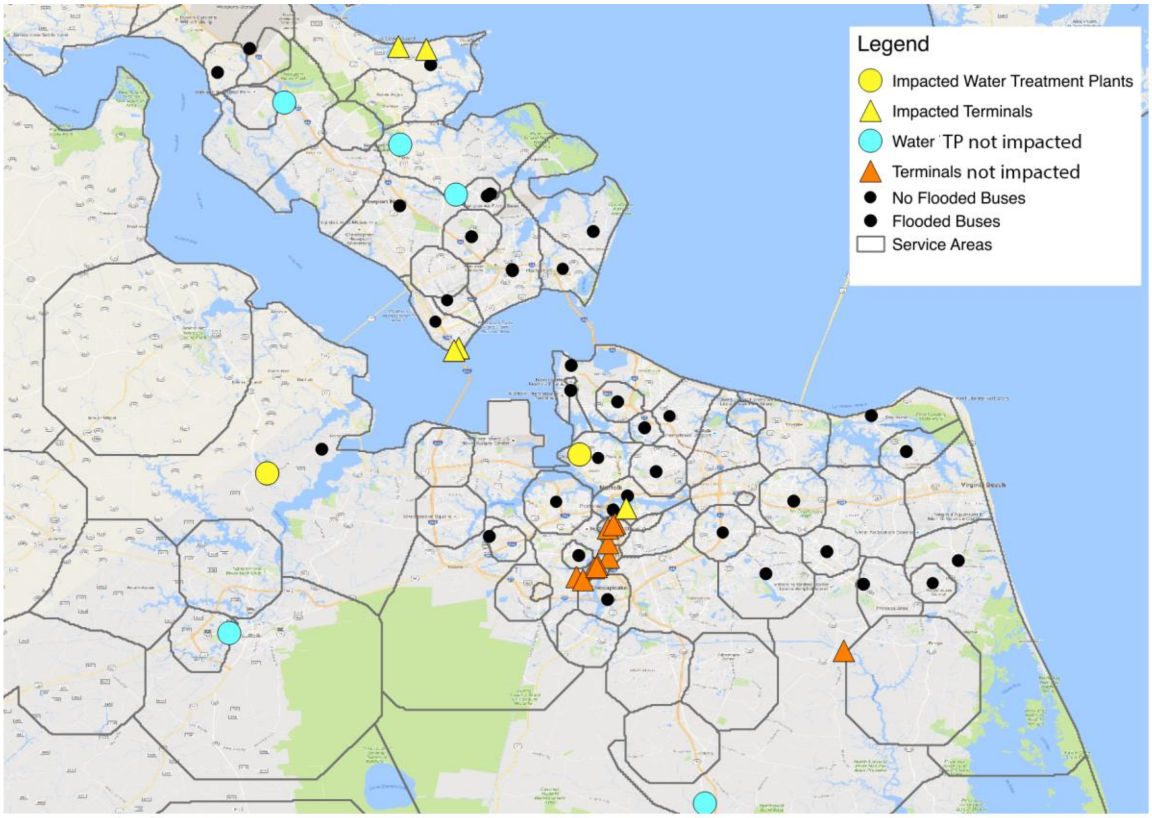

Figure 17 Baseline scenario impacts on water and petroleum infrastructures. The yellow circles and yellow triangles indicate water treatment plants and petroleum terminals, respectively, that are impacted by power outage in the baseline and line switching scenarios.

7 CONCLUSIONS

In this study, we developed a probabilistic approach to quantify the benefits of topology control as a resilient grid operational strategy and to evaluate the risk of asset damage given a suite of historically-consistent synthetic tropical storms. Our analysis showed that for an ensemble of historically-consistent storms, implementing transmission line switching strategy in the study area improves electrical transmission system resilience. When using load shed as a resilience metric, the line switching topology control strategy reduced the load shed for moderate impact hurricanes that leave some topology control degrees of freedom for the strategy to explore. In more severe impact hurricanes, there are fewer options for topology control, and the strategy show little or no improvement over the baseline. These results are expected to be qualitatively transferrable to other regions of the country that experience hurricanes, however, studies should be carried out in those regions to confirm this expectation.

Despite the fact our topology control resilient strategy seeks to minimize the amount of load shed, deploying the LS strategy also mitigates social-economic impacts. In addition, the topology control resilient strategy could evaluate the impacts of directly minimizing other metrics than load shed.

For the specific study area and the specific locations of the water and petroleum infrastructure in the electrical transmission grid, line switching does not enhance the resilience of the water and petroleum infrastructure. However, the probabilistic nature of our analysis allows identifying the frequency of power outage of the water and petroleum assets. The locations of key critical infrastructure in electrical transmission systems is typically specific to the study area. The configuration of these key electrical loads in other regions or areas may lead to entirely different results. We believe that location specific studies are required to accurately assess this metric.

There are several important paths to extend the present study:

- Perform a similar study in, e.g., the Gulf Coast to gain additional insight into which of the metric improvements are generically transferable

- Extend the approach to other resilience strategies beyond operational strategies. Examples include transmission grid hardening (e.g., undergrounding, transmission tower reinforcement, substation flood protection) or solutions in the distribution network (e.g., undergrounding, asset hardening, microgrids/distributed generation, distribution automation).

- In this study, the synthetic hurricanes are generated from a distribution that is consistent with historical storms. For an accurate risk analysis and resilience assessment, the physical properties of the hurricanes and their occurrence should include climate change. Considering climate correlations between climate variables (e.g., sea surface temperature) and the distributional parameters of hurricane physical properties within SynHurG would allow us to adapt this study to future climate projections to enable a forward looking risk analysis.

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