



Final Report

Undergrounding Assessment Phase 3 Report: *Ex Ante* Cost and Benefit Modeling



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Executive Summary

This report is the Phase 3 deliverable of a project awarded in response to RFP #U-1 issued by the Florida Electric Utilities. RFP #U-1 was a result of Florida Public Service Commission Order No. PSC-06-0351-PAA-EI, which directs each investor-owned electric utility in Florida to establish a plan that increases collaborative research to further the development of storm-resilient electric utility infrastructure and technologies that reduce storm restoration costs and interruptions to customers. Municipal electric and cooperative electric utilities are participating voluntarily.

The scope of the overall project (all three phases) is to investigate the implications of converting overhead electric distribution systems in Florida to underground (referred to as undergrounding). The primary focus of the project is the impact of undergrounding on the performance of the electric infrastructure during hurricanes, which is the ability of the local power system to withstand high winds, storm surges, and other damage from hurricanes and to minimize the number and duration of customer interruptions. This study also considers benefits and issues with regards to performance during non-storm situations.

The project is divided into three phases. Phase 1 is a meta-analysis of existing research, reports, methodologies, and case studies. The Phase 1 final report, *Undergrounding Assessment Phase 1 Final Report: Literature Review and Analysis of Electric Distribution Overhead to Underground Conversion*, was issued on February 28th 2007. Phase 2 examines specific undergrounding project case studies in Florida. The Phase 2 final report, *Undergrounding Assessment Phase 2 Final Report: Undergrounding Case Studies*, was issued on August 6th 2007.

Phase 3 develops and tests a methodology for analyzing the costs and benefits of specific undergrounding proposals in Florida. The methodology is separated into two basic components: normal weather assessment and hurricane assessment. The normal weather model includes the basic cost of utility capital and operational cost information. It also includes high-level reliability information that allows for the calculation of customer interruption information and related costs. A flowchart of the methodology is shown in Figure A-1.

The hurricane model determines infrastructure damage and related costs associated with tropical storms of hurricane strength when making landfall in Florida. To perform a cost and benefit analysis of sufficient detail to meet the objectives of this project, it is necessary to simulate hurricanes moving across Florida. Therefore, a large component of the hurricane model is dedicated to simulating hurricane years. For each year of simulation, the number of landfall hurricanes is randomly determined based on historical hurricane data. For each hurricane (if any), the landfall location, direction, speed, strength, and other parameters are also randomly determined based on historical hurricane data.

When a hurricane makes landfall, a storm surge model determines the amount of infrastructure damage that occurs in susceptible areas due to the wall of water (i.e., storm surge) that the hurricane pushes onto coastal areas.

As the hurricane travels over land, the simulation model keeps track of the fastest wind gusts to which each location is exposed. This determines the amount of wind damage that occurs during the hurricane. The model is flexible enough to consider many types of construction with many types of wind loading characteristics. This includes standard construction (e.g., Grade B, Grade C), “hardened” systems, and others.

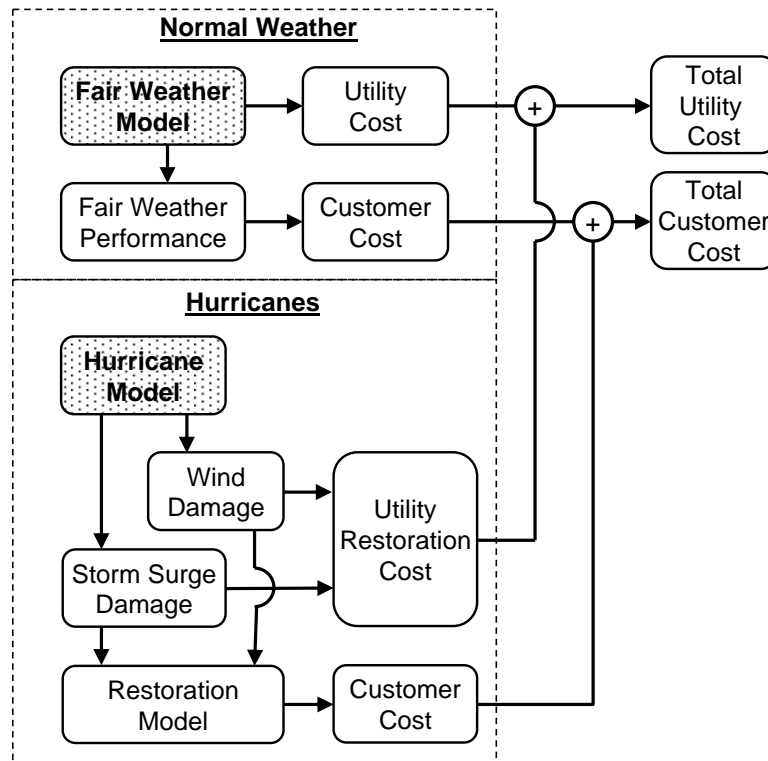


Figure A-1. Overview of Methodology

For each simulated hurricane, the model determines the amount of damage both for the proposed project area and for the entire service territory of the associated utility. Damage for the entire service territory is needed to determine the total utility restoration time, which then determines the restoration time for the proposed project area.

Once the total hurricane damage is determined for the entire project area, a restoration model is used to determine when repairs on the proposed project area begin and end. This restoration model includes factors such as startup inefficiencies (e.g., due to debris on roads), crew ramp up, and the difference between overhead crews and underground crews.

The hurricane damage and restoration models provide information that allows for the calculation of utility restoration costs, customer interruptions, and the customer costs associated with the interruptions. Taken together, the utility and customer costs constitute the total costs of the hurricane as it relates to electric utility infrastructure.

After simulating the costs and benefits of all hurricanes in a specific hurricane year, additional hurricane years can be simulated. Many simulated years will have no hurricanes and will therefore have no hurricane costs. Some simulated years will have a single weak hurricane and will therefore have small hurricane costs. Some simulated years will have multiple major hurricanes and will therefore have significant hurricane costs. Simulating many hurricane years allows the average hurricane cost to be computed.

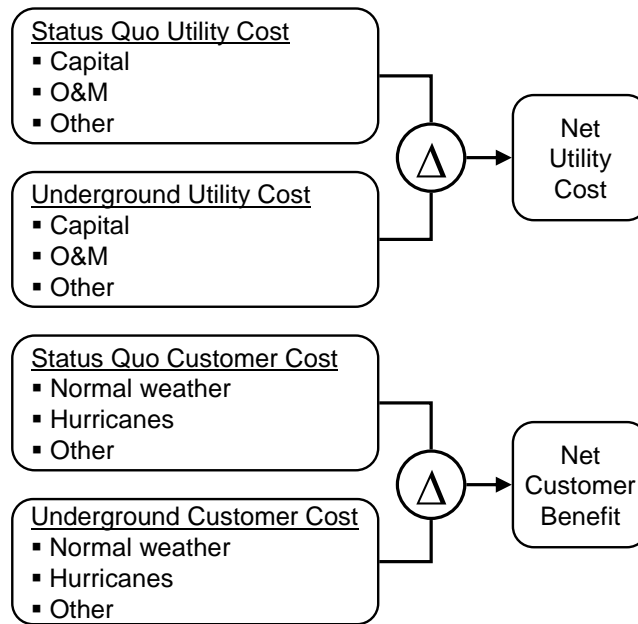


Figure A-2. Approach to Cost and Benefit Calculations

The output of the simulation is a list of initial utility costs, annual utility costs, customer interruption minutes during normal weather, and customer interruption minutes during hurricanes. The model is flexible enough to accommodate any cost category that can be characterized by initial cost and/or a recurring annual cost.

The model is designed to compare two cases. Typically, this will be the “status quo” case and a proposed undergrounding option. Hurricane simulations are performed automatically for both cases so that costs and reliability differences can be compared. This approach is shown in Figure A-2.

Consider a situation where a utility is considering an undergrounding project. When assessing this project, the utility will first enter information about the existing system. This allows the current utility costs, reliability performance, and customer costs to be calculated. The utility also enters information about the undergrounding project including the initial cost, annual costs, annual savings, and so forth. The assessment is then able to simulate the performance of the undergrounded system and compute associated utility costs, reliability performance, and customer costs. The difference in utility cost between the status quo and the proposed scenario is defined as the net utility cost. The difference in reliability performance is defined as net reliability benefit. When reliability benefit is translated into customer cost, it is defined as net customer cost. Net reliability benefit and net customer cost, taken together, constitute net customer benefit.

The scenario comparison in Figure A-2 is flexible and does not necessarily have to be used to compare the status quo to a proposed underground project. For example it could be used to compare the status quo to a proposed “hardened overhead” project where existing overhead structures are reinforced to better withstand wind damage. It could also be used to compare a proposed undergrounding project to a proposed hardened overhead project. Generally, the framework is suitable to compare any given “Scenario A” with another given “Scenario B.” This allows a range of options to be explored and compared based



on their incremental cost above the next least expensive option and their incremental benefit above the next least expensive option.

The methodology described above has been implemented in a Microsoft Excel (version 2003) spreadsheet with embedded computer programming. It can be run on any computer with Excel. A detailed user guide to this spreadsheet is provided in Section 2 in the body of this report, and the spreadsheet is applied to four Florida case studies in Section 8.

As concluded in Phase 2 report, there is not sufficient data for the four Florida case studies to compare the output of the *ex ante* model to historical realized benefits. There is not even enough data to determine upper and lower bounds of potential results. Analyzing the cases studies with the model is done to provide insights into how different variables affect costs and benefits of undergrounding; the purpose is not to replicate actual realized benefits or to anticipate future benefits.

It must be understood that the methodology requires the user to input many parameters and many assumptions. For many of these parameters and assumptions, there is little basis in historical data and expert judgment must be used. It is beyond the scope of this project to recommend parameters and assumptions. The spreadsheet should be viewed as a “calculator” and it is the responsibility of the user to make appropriate decisions about input parameters and assumptions.

The methodology and corresponding tool described in this report should be viewed as a “calculator.” It is the responsibility of the user to make appropriate decisions about input parameters.

Even if utilities do not have a large amount of data from which to base assumptions and parameter selections, much insight can be gained by using the tool. In fact, the tool can be used to determine the sensitivity of results to certain assumptions and certain parameters.

The conversion of overhead electric power distribution facilities to underground has been a topic of discussion in Florida for more than twenty years. The topic has been studied, discussed, and debated many times at the state, municipal, and local levels. Overhead construction is generally the standard for new construction, with developers or customers typically paying for any incremental cost for underground construction. However, all investor-owned utilities are required to have a process where customers can opt to underground existing overhead service by paying the incremental cost. For municipals and cooperatives, the decision to underground is left to local citizen boards.

It is well-known that the conversion of overhead electric distribution systems to underground is costly, and these costs almost always exceed quantifiable benefits. This conclusion is reached consistently in many reports that range from state-wide studies to very small projects. However, there is no consistent approach has been used to compute the costs and benefits of proposed undergrounding projects, making studies difficult to interpret and use for making decisions.

As more areas in Florida begin to explore the possibility of underground conversion, it becomes increasingly desirable to have a consistent methodology to assess the associated costs and benefits. Results from a trusted approach can provide insight, lead to better projects, aid in customers communicating with utilities, and potentially help guide certain regulatory approaches.

This report has presented a methodology capable of computing the costs and benefits of potential undergrounding projects. The methodology can also be used to compute the costs and benefits of other activi-



ties that have an impact on hurricane performance such as the hardening of overhead systems. The methodology used a detailed simulation with the following components: hurricane module, equipment damage module, restoration module, and cost-benefit module. This methodology has been implemented in a spreadsheet application so that it can be easily used by interested parties.

The conversion of overhead electric infrastructure to underground is of interest around the country and around the world. Often times underground conversion proposals are either pursued or rejected without a systematic analysis of costs and benefits. The methodology presented in this report is an attempt to add consistency, rigor, and thoroughness to these types of analyses. At present, the methodology is specific to the state of Florida, but the general approach is valid wherever extreme weather events have the potential to wreck havoc on electricity infrastructure.



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1 Introduction

This report is the Phase 3 deliverable of a project awarded in response to RFP #U-1 issued by the Florida Electric Utilities. RFP #U-1 was a result of Florida Public Service Commission Order No. PSC-06-0351-PAA-EI, which directs each investor-owned electric utility in Florida to establish a plan that increases collaborative research to further the development of storm-resilient electric utility infrastructure and technologies that reduce storm restoration costs and interruptions to customers. Municipal electric and cooperative electric utilities are participating voluntarily. In an effort to comply with this order, the following utilities (referred to collectively as the Project Sponsors) are joint sponsors and are coordinating their efforts through the Public Utility Research Center (PURC) at the University of Florida:

Investor-Owned Utilities

- Florida Power & Light Company
- Progress Energy Florida, Inc.
- Tampa Electric Company
- Gulf Power Company
- Florida Public Utilities Company

Publicly-Owned Entities

- Florida Municipal Electric Association
- Florida Electric Cooperatives Association
- Lee County Electric Cooperative, Inc.

The scope of the overall project (all three phases) is to investigate the implications of converting overhead electric distribution systems in Florida to underground (referred to as undergrounding). The primary focus of the project is the impact of undergrounding on the performance of the electric infrastructure during hurricanes, which is the ability of the local power system to withstand high winds, storm surges, and other damage from hurricanes and to minimize the number and duration of customer interruptions. This study also considers benefits and issues with regards to performance during non-storm situations.

The project is divided into three phases. Phase 1 is a meta-analysis of existing research, reports, methodologies, and case studies. The Phase 1 final report, *Undergrounding Assessment Phase 1 Final Report: Literature Review and Analysis of Electric Distribution Overhead to Underground Conversion*, was issued on February 28th 2007. Phase 2 examines specific undergrounding project case studies in Florida. The Phase 2 final report, *Undergrounding Assessment Phase 2 Final Report: Undergrounding Case Studies*, was issued on August 6th 2007¹. Phase 3 develops and tests a methodology to evaluate the costs and benefits of proposed undergrounding projects in Florida. This report presents the results of Phase 3.

The goal of Phase 3 is to develop and test a methodology for analyzing the costs and benefits of specific undergrounding proposals in Florida. The methodology builds upon well-designed features of existing research, including but not limited to meteorological study, structural research, and utility studies on costs

¹ The Phase 1 and Phase 2 reports are available on the Florida Public Service Commission web site www.floridapsc.com and the PURC web site www.purc.ufl.edu.



and benefits of undergrounding, upon which a general consensus is found, while compensating for omissions and unsuitable features not applicable to the situation in Florida.

As mentioned previously, the costs and benefits analyses of this project primarily focus on electric distribution infrastructure performance during hurricanes. *Ex ante* distribution reliability analyses² typically assume that all faults are mutually exclusive. This means that (1) faults occur independently of one another, and (2) the occurrence of one fault does not change the impact or operation response related to any other fault. The mutually exclusive assumption is reasonable in non-storm conditions, but is not true during adverse weather situations such as hurricanes in which a common mode failure³ results in many overlapping fault events. Therefore, existing predictive reliability models are not suitable for this project and a new model must be developed. The model described in this report includes a hurricane simulation module, an infrastructure damage module, a system restoration module, and a cost-benefit analysis module.

The models developed in Phase 3 have been implemented in an Excel spreadsheet application using embedded VBA programming⁴ for most of the calculations and simulations. The application has been applied to the four Phase 2 case studies in Section 8.

It must be understood that the model requires many parameters and many assumptions. For many of these parameters and assumptions, there is little basis in historical data and expert judgment must be used. It is beyond the scope of this project to recommend parameters and assumptions. Throughout this report, parameters and assumptions appear. In addition, parameters and assumptions are embedded in the spreadsheet application. Neither the authors nor the utility sponsors of this project endorse these assumptions as appropriate for any particular analysis. The tool should be viewed as a “calculator” and it is the responsibility of the user to make appropriate decisions about input parameters and assumptions. Further, utilities are encouraged to collect data that will increase the accuracy and confidence of input parameters and assumptions.

The methodology and corresponding tool described in this report should be viewed as a “calculator.” It is the responsibility of the user to make appropriate decisions about input parameters.

This report begins with a user guide explaining the step-by-step operation of a tool representing the *ex ante* methodology. Next, the report describes the model structure and general approach. The report continues with the analytical explanations of individual modules including hurricanes simulation module, infrastructure damage and system restoration module, and costs and benefits analysis module. After the discussion of the model applications, the report ends with conclusions.

² *Ex ante* is Latin for “before the fact.” It refers to analyses based on predictions. This is opposed to *ex post* modeling (Latin for “after the fact”), which refers to analyses based on historical data.

³ A *common mode failure* refers to a condition in which multiple failures are caused by the same physical root cause. For example, if a hurricane results in the failure of many utility structures, the hurricane is referred to as the *root cause* of all the failures. Since the root cause is the same for all failures, they are referred to as *common mode*.

⁴ The Microsoft spreadsheet application Excel has an embedded programming language called Visual Basic for Applications (VBA). Any computer with Excel is able to support spreadsheets with embedded VBA code as long as the security settings allow macros to be run.

2 User Guide

This chapter serves as a step-by-step instruction for using the toolkit as a result of the *ex ante* methodology, which will be presented in detail in the following chapters.

The use of this toolkit is fairly straightforward. For general use, five spreadsheets are involved:

Main Spreadsheets

- General Project Data (sheet name: “General_Data”)
- Equipment Data (sheet name: “Equipment_Data”)
- Non-Equipment Cost Data (sheet name: “Cost_Data”)
- Dash Board (sheet name: “Dash_Board”)
- Parameter Setting (sheet name: “Parameter”)

The user provides project information in first three data sheets and then uses dash board to run the simulation and get the statistical results. The parameter setting sheet mainly serves as a guide to determine the model parameters.

The information shown in the tables in this chapter are for demonstration purposes only. It is the responsibility of the user to make appropriate decisions when making assumptions and selecting model parameters.

2.1 Excel Macro Settings

This toolkit is implemented in Microsoft Excel with extensive use of VBA programming. In order to run this application, users need to set the Excel macro security properly. This instruction⁵ is based on Microsoft Office 2003, it may be different for other versions; please refer to Microsoft Office help if needed.

When the macro security level in Excel is set to Low (not recommended), macros can be run without prompting. When macro security is set to Medium, Excel displays a dialog box asking if you want to enable macros. When macro security is set to High (the recommended macro security setting for all users by Microsoft), Excel allows you to run only those macros that are digitally signed.

1. On the Tools menu, point to Macro, and then click Security.

⁵ This part of instruction is mainly from Microsoft Office Online

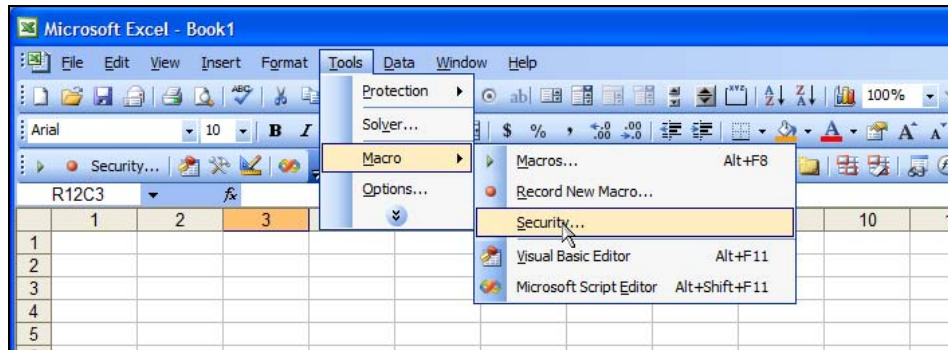


Figure 2-1. Macro Security Setting

2. On the Security Level tab, select the Medium check box.

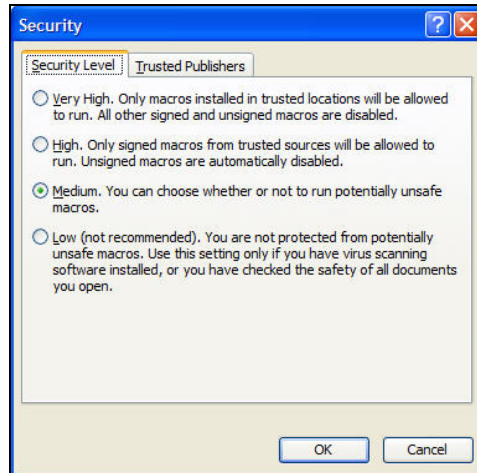


Figure 2-2. Macro Security Setting

3. If the security level is set at medium, every time the tool is opened, a dialogue is prompted as shown below, click Enable Macros button. If the security level is set at low (not recommended), no prompt will be seen.

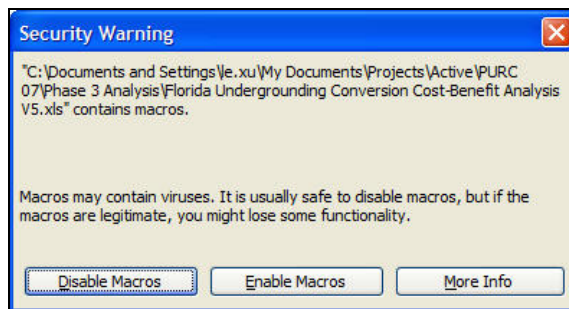
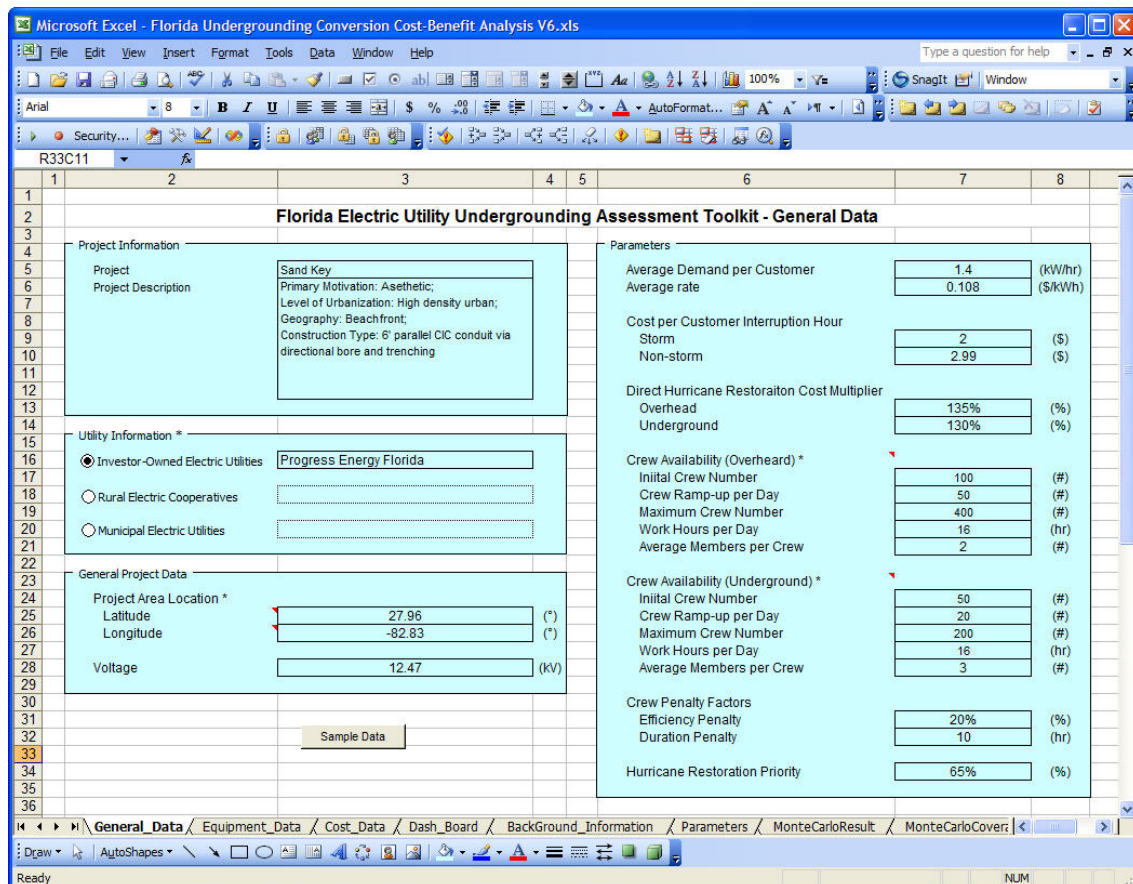


Figure 2-3. Macro Security Warning

2.2 Project General Data Input

The *ex ante* methodology is developed to analyze the costs and benefits of specific undergrounding proposals in Florida; this toolkit requires a significant amount of data from the user in order to produce a customized report. The sheet “*General_Data*” is the section where users input general project information and necessary algorithm parameters.



Florida Electric Utility Undergrounding Assessment Toolkit - General Data							
Project Information				Parameters			
Project				Average Demand per Customer			
Project Description				Average rate			
Project Key				Cost per Customer Interruption Hour			
Primary Motivation: Aesthetic;				Storm			
Level of Urbanization: High density urban;				Non-storm			
Geography: Beachfront;				Direct Hurricane Restoration Cost Multiplier			
Construction Type: 6" parallel CIC conduit via				Overhead			
directional bore and trenching				Underground			
Utility Information *				Crew Availability (Overhead) *			
<input checked="" type="radio"/> Investor-Owned Electric Utilities				Initial Crew Number			
Progress Energy Florida				Crew Ramp-up per Day			
<input type="radio"/> Rural Electric Cooperatives				Maximum Crew Number			
<input type="radio"/> Municipal Electric Utilities				Work Hours per Day			
General Project Data				Average Members per Crew			
Project Area Location *				Crew Availability (Underground) *			
Latitude				Initial Crew Number			
Longitude				Crew Ramp-up per Day			
Voltage				Maximum Crew Number			
				Work Hours per Day			
				Average Members per Crew			
				Crew Penalty Factors			
				Efficiency Penalty			
				Duration Penalty			
				Hurricane Restoration Priority			

Figure 2-4. General Data Sheet

- **Project Information:** the user provides project name and a brief description here. This information is for reference purpose.
- **Utility Information:** the user is *required* to specify the project sponsoring utility:
 1. Select a radio button for the utility type
 2. Select the utility name from the corresponding pull down menu
- **General Project Data:**
 - **Project Area Location:** the user is *required* to provide the project location in terms of **Latitude** and **Longitude**.



Positive latitude is generally considered as "N" of the equator (negative is "S") and positive longitude is generally considered as "E" of the Greenwich Meridian in England (negative is "W"). Florida is located in the northern latitude and western longitude region, so the latitude is always a positive number and the longitude is always a negative number. For example, 25.2°N is expressed as 25.2° and 81.7° W is expressed as -81.7°.

- **Voltage (kV):** the voltage level for the project related feeders; it is for reference purpose.
- **Total Customers:** the number of customers in the project area.
- **Parameters:**
 - **Average Demand per Customer:** the average demand (kW/hr) for the customers in the project area; it is *not* a system-wide average value. There is no distinction between different customer types; the average demand per customer is based on all residential, commercial, and industrial customers in the project area.
 - **Average Rate:** generally this value will be the average electricity rate, in \$/kWh, for customers in the project area. Using this value will compute lost revenue due to customer interruptions. The user can also subtract average fuel costs from the average electricity rate. Using this value will compute lost pre-tax earnings due to customer interruptions. This value should be based on the project area and not on the entire utility service territory.
 - **Cost per Customer Interruption Hour:** this value is used to reflect the average hourly loss to the customers due to sustained power interruptions. For residential customers, it includes the out-of-pocket costs for consumable goods such as candles and food spoilage; it can also include the “costs” related to inconveniences such as resetting clocks and changing plans. For non-residential customers, it includes, but not limited to, labor and materials costs and the lost revenue. The user provides the hourly customer interruption cost for both storm condition and non-storm condition.
 - **Direct Hurricane Restoration Cost Multiplier:** a scalar to adjust the total restoration cost.

In the *ex ante* methodology, the total hurricane induced overhead electric facility damage is approximated by pole damage and span damage; the total underground electric facility damage is approximated by pad-mount device damage and underground cable damage. It is recognized that hurricanes cause damage to other system components. In order to alleviate the underestimate due to the approximation approach, users can provide a cost multiplier such that the total estimated cost can be adjusted to closely represent the actual restoration cost. Please refer to *Chapter 3.2* for detailed discussion. The overhead restoration cost multiplier and the underground restoration cost multiplier are needed for calculation.
 - **Crew Availability:** both overhead system crew availability and underground system crew availability are *required* for modeling the system restoration process.

The *ex ante* methodology models the general hurricane restoration process as: a certain number of crews are available immediately after the hurricane passes; additional crews are typically added until a maximum number of crews are reached. Please refer to *Chapter 3.3* for detailed discussion.
 - **Initial Crew Number:** the crew resources available for immediate hurricane restoration.



- **Crew Ramp-up per Day:** the average number of additional crew added each day for hurricane restoration.
- **Maximum Crew Number:** the maximum number of crew that the project sponsoring utility has for hurricane restoration, including both internal and external resources.
- **Work Hours per Day:** the average number of hours crews work during the hurricane restoration.

It is recognized that the number of available crew is dynamic from hurricane to hurricane. The user can provide a best estimate of the average value.

Some utilities may call in external crews for an approaching hurricane that ends up not hitting its service territory. In most cases, the associated costs of this action will occur whether a project is performed or not. Therefore, this issue will not affect the costs and benefits of a particular undergrounding conversion project and is not modeled in this algorithm.

- **Crew Penalty Factor:** two penalty factors are designed to account for initial restoration inefficiencies arising from a variety of factors such as road accessibility, availability of materials, having the right crew skill sets in the right locations, and so forth.
 - **Efficiency Penalty Factor (%):** a scalar for crew efficiency
 - **Duration Penalty Factor (hr):** a scalar for duration of inefficiency

Penalty factors are scalars proportional to hurricane category. Consider the following example. After a Category 4 hurricane, many roadways are blocked by trees and debris. This severely limits the ability for damage to be assessed and for crews to be efficiently dispatched. There are 1000 crews available, but many crew hours are not initially spent on effective restoration activities. By using penalty factors, extra repair time can be added to account for these inefficiencies. Assume that the efficiency penalty factor is set at 25% and the duration penalty factor is set at 10 hours. For the Category 4 hurricane, this means that each initial repair will require $4 \times 25\% = 100\%$ more crew hours to complete. This inefficiency persists for the first $4 \times 10 = 40$ hours of restoration. After this time, it is assumed that crews are able to work at full efficiency for the remainder of the restoration effort. Please refer to *Chapter 6* for detailed discussion.

- **Hurricane Restoration Priority:** is a percentage number (between 0% and 100%) representing the hurricane restoration priority ranking of the project area. This priority number indicates the number of system-wide crew hours that must be expended before restoration work on the project area is initiated. For example, if the all hurricane damage requires 1000 crew hours to restore, and a project area is assigned a post-hurricane restoration priority of 30%, then the repair work for the project area starts after 300 crew hours have been expended.

Users can click the **Sample Data** button to see the automatically filled parameters, which serves as a template or reference.

2.3 Equipment Information Input

The sheet “*Equipment Data*” is the section where users input equipment related information such as the quantity, failure rate, repair cost, associated customer number, and so on.



Figure 2-5. Equipment Data Sheet

Four buttons in the top section allow users to add or delete a record, clear all records, or fill in the sample data.

- **Add a Record:** a new record will be added at the end of table. The user can add as many records as needed.

Please do not manually add records by inserting rows!

- **Delete a Record:** the **last** record will be deleted from the table.

If the user wants to delete a record in the middle of the table, you can:

- Change the existing record to a new record.
- Specify the equipment type category as “Not Used” (more on this in the later section).

Please do not manually delete records by deleting rows!

- **Clear Records:** all the records in the table will be cleared.

Please do not manually delete records by deleting rows!

- **Sample Data:** a sample set of data will be automatically filled in.

The field called “**# of Equipment Entries**” above the main table will be filled in by the tool. It is for reference purpose only. *Please do not manually change this value!*

Each row in the equipment data table corresponds to one record. Each record includes many data fields, all of which are **required** information unless stated otherwise.

- **Equipment:** the description of different equipments.
- **Category:** The user selects an equipment type category from the pull down menu, which forms only when the new record is generated by clicking the *Add a Record* button.

Since the tool only allows deleting a record at the end of the table, if users do not want to keep a record in the middle of the table, the category of “Not Used” can be selected.



- **Unit:** the unit of different equipment types.
- **Quantity:**
 - **System Wide:** the number of a particular type of equipment currently in service throughout the entire service territory.
 - **Project Area:**
 - **Before Project:** the number of a particular type of equipment currently in service, i.e., before the undergrounding conversion occurs, in the project area.
 - **After Project:** the number of a particular type of equipment that will be in service after the undergrounding conversion occurs, in the project area.

Note: this toolkit requires the user to provide underground equipment related information in all categories of storm surge zones even though the project area is located in one of the storm surge zones; it is because the algorithm need to estimate the restoration time required for then entire service territory.⁶ The user provides only the system wide quantity and the storm condition damage model parameters for those categories of storm surge zones where the project area is not in, but the user needs to provide all the required information for those categories of storm surge zones where the project area is in (more on this in the later section).

- **Initial Cost:**
 - **Removing Existing:** the **total** initial costs associated with removing existing equipments, including materials, labor, and others.
 - **Hardening:** the **total** initial costs associated with hardening existing equipments if applicable, including materials, labor, and others.
 - **Installation:** the **total** initial costs associated with installing new equipments, including materials, labor, and others.
 - **Miscellaneous:** the **total** initial costs associated with other equipment related expenditures.
- **Annual Cost:** the annual operation and maintenance (O&M) cost for equipment. The value is provided as the cost per unit per year.
- **Reliability Data:**
 - **Customers:** the **average** customer count associated with equipment in the project area.
 - **Non-Storm Condition:**
 - **Failure Rate:** the equipment failure rate under non-storm condition. It generally measured as number of failures per year per unit.
 - **Repair Cost:** the **total** repair cost associated with a single equipment failure, including materials, labor, and others.

⁶ Please refer to *Chapter 5.3* for detailed discussion.



- **Outage Time:** the average outage time for a single equipment failure. It can be considered as the corresponding mean time to repair (MTTR).
- **Storm Condition:**
 - **Storm Condition Damage Model Parameters:** the damage models for different types of equipments are all modeled as two-parameter functions (detailed description of each damage model is included in *Chapter 5*):
 - Exponential function for pole damage
 - Power function for span damage
 - Linear function for underground equipment damage

It is recommended that utilities generate damage model parameters based on their own historical data if applicable. Users can also use the parameter setting guide introduced in *Chapter 2.6* to estimate model parameters.

Note: For a type of underground equipment, the damage model parameters will be all the same for different storm surge zones. It does **NOT** mean that the equipment failure rate in different storm surge zones under storm condition will be same. Since underground failure rate of a piece of equipment is a function of its storm surge zone category, the algorithm is able to estimate the corresponding failure accordingly given the storm surge zone category. The design of this layout is to collect the quantity information. Please refer to *Chapter 5.3* for detailed algorithm discussion.

- **Crew Hours to Repair:** the average crew hours required to repair a type of equipment during the storm restoration.
- **Repair Cost:** the average repair cost for a type of equipment during the storm restoration.

Among different equipment related cost data fields, the *storm condition damage model parameters* and *the crew hours to repair* under storm condition (other than the system wide equipment quantity) also refer to system average values. The remaining fields refer to the values for the project area only.

2.4 Non-Equipment Related Cost Information Input

The sheet “*Cost_Data*” is the section where users input non-equipment related cost information including project initial cost, annual cost, and intangible cost if applicable.



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Figure 2-6. Cost Data Sheet

The layout of this sheet is similar to the “*Equipment_Data*” sheet.

- The user clicks buttons to add a record, delete a record, clear all records, and fill in sample data. ***Please do not manually add or delete records by inserting or deleting rows in the spreadsheet!***
- The field of “# of Cost Data Entries” is filled by program. ***Please do not manually change this value!***

Three cost categories are included in the cost data table:

Cost Categories

- Initial Costs
- Recurring Costs
- Intangible Costs

The user only needs to fill in the applicable cells. If a cost item is only associated with project initial costs, the user does not have to provide cost information from column E to H. If a cost item is only associated with recurring costs, the user only needs to provide cost information from column E to G. If a cost item is only associated with intangible costs, the user doesn’t need to provide initial and recurrent cost information.

- **Cost Item:** this field is for a brief description of an expenditure item.



The project initial cost breaks down to three sub-categories: undergrounding costs, hardening costs, and miscellaneous costs. In order to correctly classify them:

- If an initial expenditure item is related with undergrounding, add a “(U)” anywhere in this field. It can be in the front or end, and it is NOT case sensitive.
 - If an initial expenditure item is related with hardening, add “(H)” anywhere in this field. It can be in the front or end, and it is NOT case sensitive.
 - If an initial expenditure item is related with other categories, add nothing.
 - If an expenditure item is not related with initial cost categories, add nothing.
 - Do not add both “(U)” and “(H)” in one field.
- **Unit:** the unit of different expenditure items.
 - **Initial Costs:** the non-equipment related undergrounding project initial cost.
 - **Quantity:**
 - **Before Project:** the expenditure item quantity before the undergrounding conversion project (or the hardening project if applicable).
 - **After Project:** the expenditure item quantity after the undergrounding conversion project (or the hardening project if applicable).
 - **Recurring Costs:** the annual operation and maintenance (O&M) cost for non-equipment related expenditures such as the vegetation management and pole attachment revenue. The value is provided as the cost per unit per year.
 - **Intangible Costs:** the categories that are intangible, such as the aesthetic benefits associated with the projects or the improved property values. The user can type in their expected value per unit per year. For example, the user can define a cost category of “improved aesthetics” and assign a value of \$100 million after a project is completed.

2.5 Dashboard

After providing project information, the user runs the *ex ante* algorithm and examines the statistical results in this “*Dash Board*” sheet.

The user needs to identify the number of hurricane years to be simulated:

- **Number of Hurricane Years:** this number determines how many simulation years the algorithm is going to run. It takes longer computing time for a larger number of simulations. The results are not statistically representative of expected hurricane impacts if too few simulations are used, so it is recommended that users set a value near 10,000⁷.

⁷ Authors do not have a determined upper limit on this value, but experience shows that the value of 15,000 will cause memory overflow. The default value of 10,000 is set in the tool.

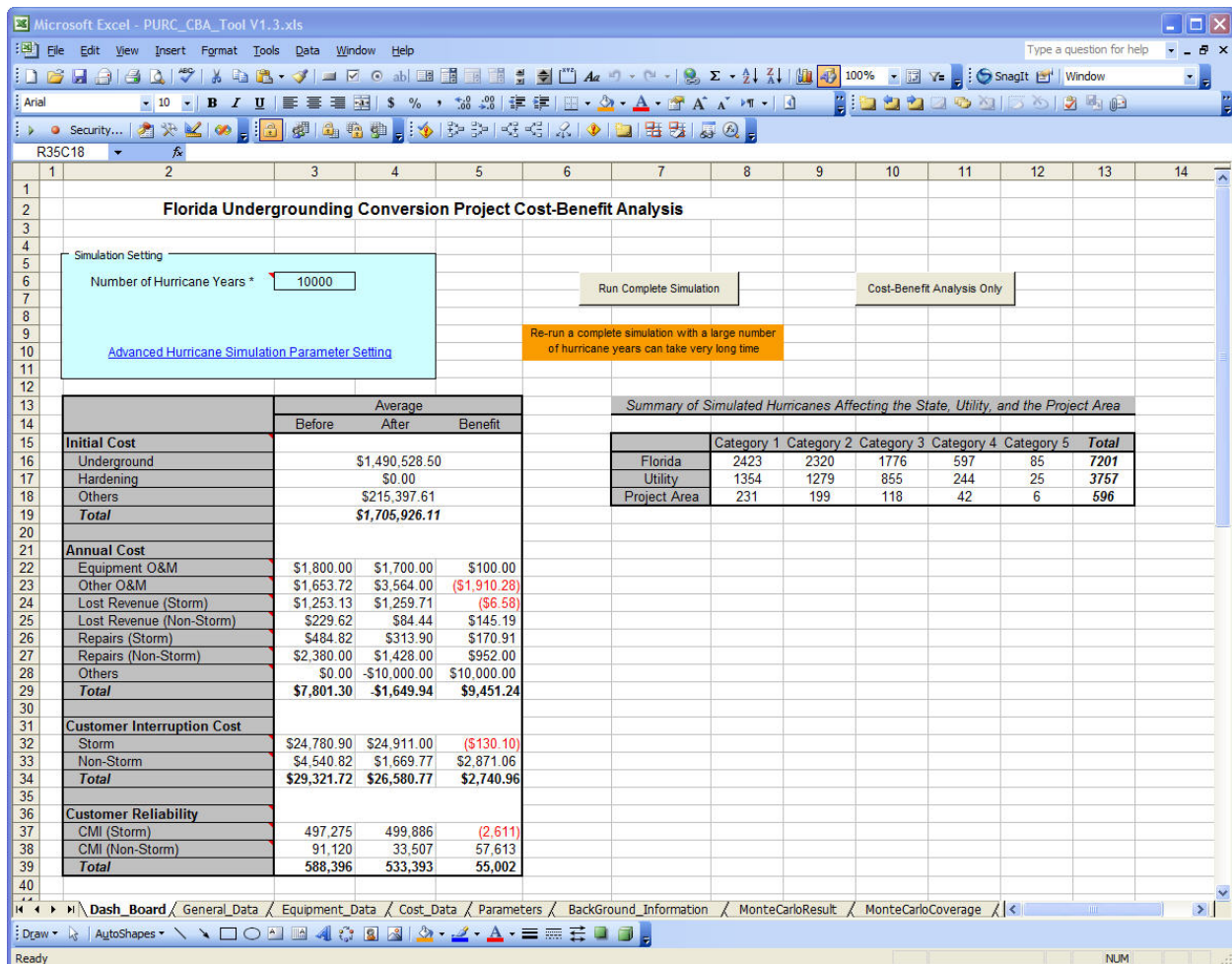


Figure 2-7. Dash Board

“Run Complete Simulations” and “Cost-Benefit Analysis Only” buttons allow the user to either run the complete Monte Carlo simulation or perform the costs and benefits analyses based on previously simulated hurricanes. The entire Monte Carlo simulation is needed if the project location is changed. It is recommended that the user run only the costs and benefits analysis if the simulation parameters or costs data are changed. It will not only require significantly less computing time but also provide a consistent basis (the same set of hurricane simulations) to compare the benefits and costs with different algorithm parameters and cost data.

After a designated time of hurricane years have been simulated, the costs and benefits analysis for an undergrounding project will be presented in the tabular format. The initial project costs are generally one time costs. The system (project area) performance under non-storm conditions keeps the same from simulation to simulation since the algorithm is designed to simulate the hurricane scenarios. The system (project area) performance under storm condition varies depending upon the hurricane characteristics of different hurricane years. The expected values are presented in the table.

- **Initial Cost:** the initial cost of the undergrounding or hardening project, which is incurred once. Three sub-categories of initial cost are provided, and the user can use discretion as to where ini-



tial costs are assigned. For example, landscaping costs can be included in either “undergrounding” or “others”.

- Undergrounding
- Hardening
- Others
- **Annual Cost:**
 - **Equipment O&M:** the annual equipment operation & maintenance cost before and after the undergrounding or hardening project. This set of values will not change from simulation year to simulation year.
 - **Other O&M:** the annual non-equipment related operation & maintenance cost before and after the undergrounding or hardening project. This set of values will not change from simulation year to simulation year.
 - **Lost Revenue (Storm):** the lost revenue due to hurricane induced interruptions in a simulation year.
 - **Lost Revenue (Non-Storm):** the annual lost revenue due to interruptions in non-storm weather. This value will not change from simulation year to simulation year.
 - **Repairs (Storm):** the cost of repairing hurricane damaged equipments in a simulation year.
 - **Repairs (Non-Storm):** the annual cost of repairing damaged equipments under non-storm condition. This value will not change from simulation year to simulation year.
 - **Others:** this category includes the annual costs not covered before, including the intangible costs.
- **Customer Interruption Cost:**
 - **Storm:** the customer interruption loss in a simulation year.
 - **Non-Storm:** the annual customer interruption loss in non-storm weather. This value will not change from simulation year to simulation year.
- **Customer Reliability:**
 - **CMI (Storm):** the customer minute interruption caused by hurricanes in a simulation year.
 - **CMI (Non-Storm):** the annual customer minute interruption during the non-storm weather condition. This value will not change from simulation year to simulation year.

The summary of simulated hurricanes is also provided as supporting information. In the summary, the number of hurricanes, in different categories, affecting Florida, the project affiliated utility, and the project area are presented. It helps the user to understand how likely the project area is affected by a certain category of hurricanes.



2.6 Parameter Settings

2.6.1 Hurricane Simulation Parameter Setting

A set of calibrated hurricane parameters are embedded in the algorithm. The user is allowed to modify the major hurricane parameters if more historical data becomes available. The hyperlink embedded in “*Advanced Hurricane Simulation Parameter Setting*” in the dash board sheet will bring the user to the hurricane parameter setting section as shown in Figure 4-2. Please refer to *Appendix A* for detailed discussion on determining the parameters.

2.6.2 Equipment Damage Model Parameter Setting

This toolkit provides a parameter setting guide to help users determine the equipment damage model parameters. In the *ex ante* algorithm, all the equipment damage models are modeled as two-parameter functions whose parameters generally depend on historical data⁸. If there is no sufficient historical data to extract the model parameters; the user can utilize the damage model parameter setting guide to estimate a set of parameters.

The hyperlink embedded in “*Storm Condition Damage Model Parameter*” in the “*Equipment_Data*” sheet will bring the user to the damage model parameter setting section in the sheet “*Parameter*”. Please refer to *Chapter 5* for detailed model description and equations. Since all the equipment damage model are two-parameter functions, the user can change the parameter *a* and *b* to see how the function changes. The user can select a set of parameters best describing its own utility practice and input the parameters in the “*Equipment_Data*” sheet.

⁸ Please refer to Chapter 5 for detailed explanation

3 Methodology Overview

The term *ex ante* refers to analyses based on predictions. The goal of the *ex ante* methodology presented in this report is to estimate the costs and benefits of specific undergrounding project proposals. The focus is on hurricane performance, but normal weather performance is considered as well. The approach taken to cost and benefit modeling is shown in Figure 3-1.

The methodology is separated into two basic components: normal weather assessment and hurricane assessment. The normal weather model includes the basic utility capital and operational cost information. It also includes high-level reliability information that allows for the calculation of customer interruption information and related costs.

The hurricane model determines infrastructure damage and related costs associated with tropical storms of hurricane strength when making landfall in Florida. To perform a cost and benefit analysis of sufficient detail to meet the objectives of this project, it is necessary to simulate hurricanes moving across Florida. Therefore, a large component of the hurricane model is dedicated to simulating hurricane years. For each year of simulation, the number of landfall hurricanes is randomly determined based on historical hurricane data. For each hurricane (if any), the landfall location, direction, speed, strength, and other parameters are also randomly determined based on historical hurricane data.

When a hurricane makes landfall, a storm surge model determines the amount of infrastructure damage that occurs in susceptible areas due to the wall of water (i.e., storm surge) that the hurricane pushes onto coastal areas.

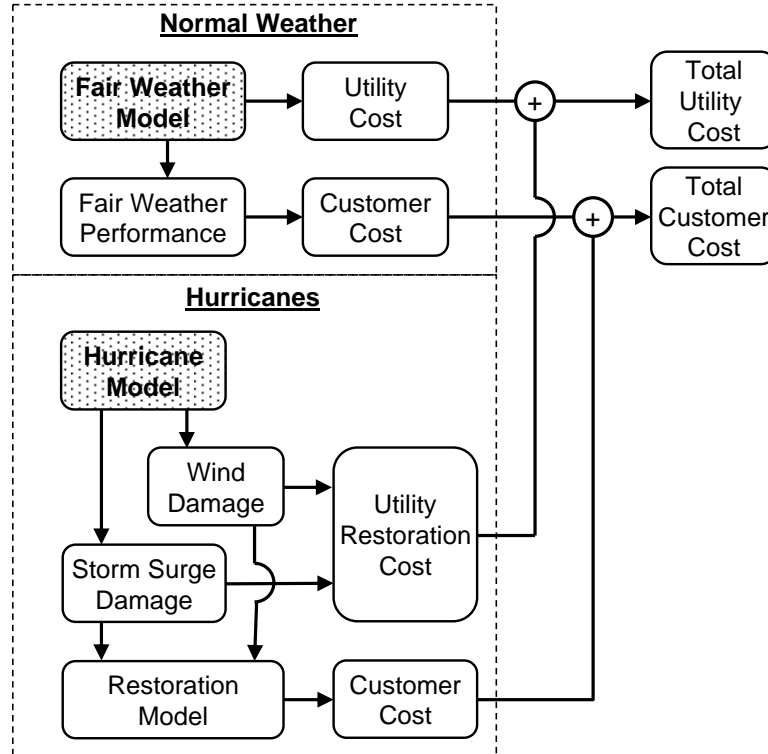


Figure 3-1. Overview of Methodology



As the hurricane travels over land, the simulation model keeps track of the fastest wind gusts to which each location is exposed. This determines the amount of wind damage that occurs during the hurricane. The model is flexible enough to consider many types of construction with many types of wind loading characteristics. This includes standard construction, sub-standard construction, “hardened” systems, and others.

For each simulated hurricane, the model determines the amount of damage both for the proposed project area and for the entire service territory of the associated utility. Damage for the entire service territory is needed to determine the total utility restoration time, which then determines the restoration time for the proposed project area.

Once the total hurricane damage is determined for the entire project area, a restoration model is used to determine when repairs on the proposed project area begin and end. This restoration model includes factors such as startup inefficiencies (e.g., due to debris on roads), crew ramp up, and the difference between overhead crews and underground crews.

The hurricane damage and restoration models provide information that allows for the calculation of utility restoration costs, customer interruptions, and the customer costs associated with the interruptions. Taken together, the utility and customer costs constitute the total costs of the hurricane as it relates to electric utility infrastructure.

After simulating the costs and benefits of all hurricanes in a specific hurricane year, additional hurricane years can be simulated. Many simulated years will have no hurricanes and will therefore have no hurricane costs. Some simulated years will have a single weak hurricane and will therefore have small hurricane costs. Some simulated years will have multiple major hurricanes and will therefore have significant hurricane costs. Simulating many hurricane years allows the average hurricane cost to be computed. It also allows for the assessment of risk levels such as the worst one-in-ten year outcome or the worst one-in-fifty year outcomes.

The output of the simulation is a list of initial utility costs, annual utility costs, a list of reliability performance, and a list of customer costs. Some of these costs are related to hurricane and normal weather reliability, but the model is flexible enough to accommodate any cost category that has an initial cost and/or a recurring annual cost.

The model is designed to compare two cases. Typically, this will be the “status quo” case and a proposed undergrounding option. Hurricane simulations are performed automatically for both cases so that costs and reliability differences can be compared. This approach is shown in Figure 3-2.

Consider a situation where a utility is considering an undergrounding project. When assessing this project, the utility will first enter information about the existing system. This allows the current utility costs, reliability performance, and customer costs to be calculated. The utility also enters information about the undergrounding project including the initial cost, annual costs, annual savings, and so forth. The assessment is then able to simulate the performance of the undergrounded system and compute associated utility costs, reliability performance, and customer costs. The difference in utility cost between the status quo and the proposed scenario is defined as the net utility cost. The difference in reliability performance is defined as net reliability benefit. When reliability benefit is translated into customer cost, it is defined as net customer cost. Net reliability benefit and net customer cost, taken together, constitute net customer benefit.

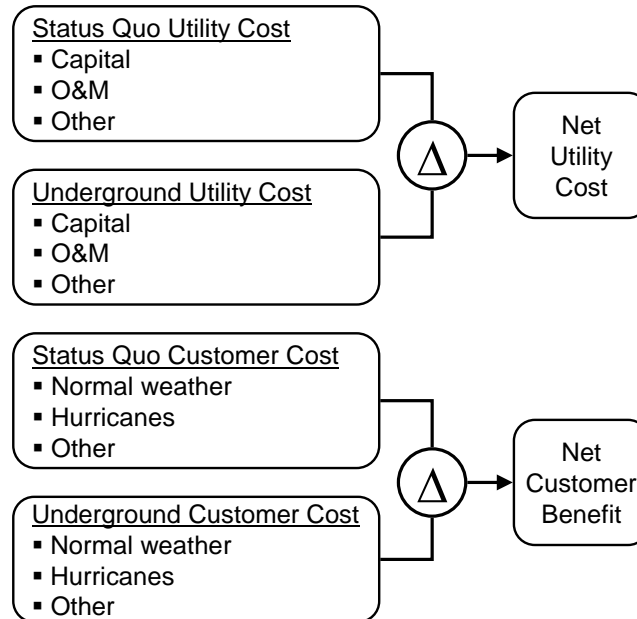


Figure 3-2. Approach to Cost and Benefit Calculations

The scenario comparison in Figure 3-2 is flexible and does not necessarily have to be used to compare the status quo to a proposed underground project. For example it could be used to compare the status quo to a proposed “hardened overhead” project where existing overhead structures are reinforced to better withstand wind damage. It could also be used to compare a proposed undergrounding project to a proposed hardened overhead project. Generally, the framework is suitable to compare any given “Scenario A” with another given “Scenario B.” This allows a range of options to be explored and compared based on their incremental cost above the next least expensive option and their incremental benefit above the next least expensive option.

3.1 Hurricane Simulation Module

Since the primary focus of the cost to benefit analysis is on electric infrastructure performance during hurricanes, it is critical to correctly model different hurricane characteristics. Because hurricanes are driven by complex natural mechanisms and their developments involve a large number of uncertainties, it is not feasible to deterministically model hurricane features, so a probabilistic approach is required.

Probabilistic modeling is the most widely used analysis technique for handling uncertainties [1]. The hurricane simulation model therefore begins by probabilistically modeling adverse storm characteristics; most of the hurricane characteristics are modeled as probability distribution functions. Instead of a determinate value, each parameter is assigned a probability of being a range of values. As a result, the wide variances of hurricane characteristics (which may due to mechanisms that have not been well understood by researchers or due to complex meteorological phenomena) are taken into consideration. Because a single hurricane (or a hurricane year) may not be representative of a typical hurricane (or a typical hurricane year), many Monte Carlo simulations are needed in order to generate statistically representative results.



A Monte Carlo simulation uses repeated random sampling to compute the results when it is infeasible or impossible to compute an exact result with a deterministic algorithm [2]. For each individual hurricane simulation, a random set of characteristics are sampled from the modeled probability distribution functions to form a complete hurricane simulation. Given the simulated hurricane information, the corresponding costs and benefits of undergrounding for this particular hurricane are then estimated using the infrastructure damage module, the system restoration module, and then cost-benefit analysis module (these are introduced later). This particular simulated hurricane is one case out of all possible scenarios; by performing this procedure many times, the Monte Carlo simulation generates a large set of possible cost and benefit pairs. This allows for the calculation of expected output in the long run, how the output is distributed, and what the worst outcome is over a given number of years.

The intent of this hurricane simulation modeling method is to track the average effect of a large group of simulations. The goal is not to precisely reproduce a specific hurricane that has occurred in the past or may occur in the future. Therefore, certain characteristics can be omitted as long as the impact of these characteristics on cost and benefit averages out over a large number of simulations (e.g., tidal influences on storm surge damage). Figure 3-3 shows the flow chart of one hurricane year simulation (the Monte Carlo simulation is composed of many years of simulation).

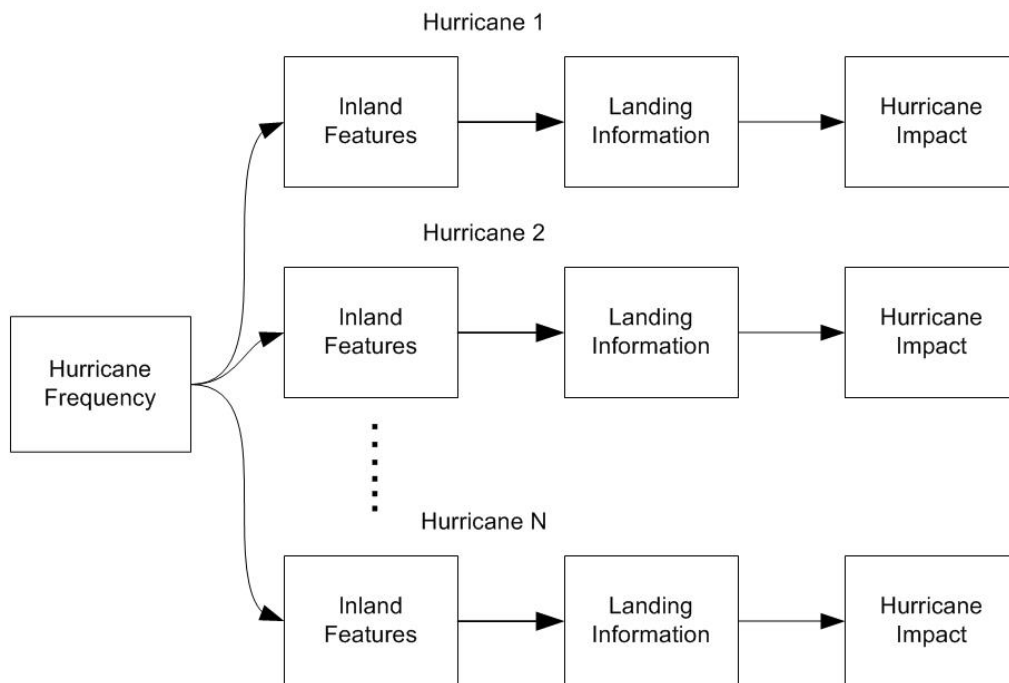


Figure 3-3. Hurricane Simulation Module Flow Chart



The first step is to simulate the annual frequency of hurricane landfall in Florida. The landing information for each simulated hurricane is then probabilistically determined. The modeled hurricane landing information includes the following:

Hurricane Landing Information⁹

- Landfall position expressed in latitude and longitude
- Approach angle (based on compass direction) at landfall
- Translation velocity (i.e., forward speed)
- Central pressure difference
- Maximum wind speed
- Radius to maximum wind

Most of the hurricane characteristics are modeled by probability distribution functions.¹⁰ The selection of the functions is based on meteorological research publications. The selection of function parameters, if applicable, is extracted from historical hurricane information recorded in the North Atlantic Hurricane Data Base (HURDAT) compiled by the Atlantic Oceanographic and Meteorological Laboratory at National Oceanic & Atmospheric Administration (NOAA) [3]. Although not perfect, HURDAT is presently the most complete and reliable source of data for North Atlantic hurricanes.

For each simulated hurricane, a random number generator is used to determine landing characteristics. Starting with these landing characteristics, the hurricane is then simulated as it moves inland across Florida. Simulated inland hurricane features include the following:

Hurricane Inland Features¹¹

- Decay of maximum wind speed along the path
- Central pressure differences along the path
- Radial wind field profile
- Hurricane duration in Florida

The inland simulation tracks the storm as it crosses Florida. When the maximum wind speed drops below hurricane strength, the simulation for this particular storm is complete. Locational wind speed data produced by the simulation is recorded and used to determine the impact of the Hurricane. This includes the following:

⁹ Some factors, such as tidal effects, will influence the actual impact of a specific hurricane, but are not considered in the model. These factors are assumed to average out over a large number of simulations. Storm surge is considered in the underground equipment damage model (see Chapter 5.3 for detailed discussion).

¹⁰ Please refer to Appendix A for the detailed explanations of modeling each characteristic.

¹¹ Microclimate factors such as inland tornados and microburst are not considered in the model. These factors are assumed to average out over a large number of simulations.



Hurricane Impact

- Percentage a utility service territory affected by the hurricane
- Average sustained wind speed and 3-second gust speed in the affected service territory¹²
- Sustained wind speed and 3-second gust wind speed experienced at the location of the proposed project area

The impacts of each hurricane as described above are used as inputs to the infrastructure damage module and the system restoration module. In addition, the complete hurricane simulation results are used to calibrate the simulation assumptions so that simulated Florida hurricanes reflect historical hurricane data.

¹² The algorithm uses a root-mean-squared calculation for both sustained wind speed and 3-second gust speed. The term “average” is used here for readability.



3.2 Infrastructure Damage Module

The infrastructure damage module determines equipment failure rates based on hurricane simulation results. This allows for the amount of hurricane infrastructure damage (and corresponding costs) to be calculated. Damage models for overhead and underground equipment are treated separately, with overhead equipment damage based on wind gust speed and underground equipment damage based on storm surge severity.

3.2.1 Overhead Equipment Damage

The overhead infrastructure damage estimation uses pole damage and span damage as a proxy to determine the extent of hurricane induced primary distribution equipment damage. It is recognized that hurricanes cause damage to system components other than poles and spans. It is also recognized that there are significant other costs related to hurricane restoration that are not directly related to pole and span damage (e.g., staging costs, material availability). However, due to the limitation of available historical data, it is not possible to directly model hurricane induced equipment damage other than with poles and spans. This damage is then used as a proxy for total damage and total restoration cost. Using historical data, a utility can determine the percentage of total overhead restoration costs typically made up of pole and span repair. This can then be used to determine an appropriate hurricane cost restoration multipliers so that the total estimated overhead cost is close to the expected overall overhead restoration cost.

Curve fitting is the most extensively used method for modeling structural damage during strong wind events [4, 5, 6]. This approach is used to find a curve that best describes the relationship between equipment failure rates and wind speed. It is recognized that wind blown debris may be a key driver for the equipment damage. Since the amount of debris largely depends on wind speed, it is reasonable to include this effect in a single failure rate function. Both surveyed literature [4, 5, 6] and historical data from FPL (which is the only usable data at the time of this report) have demonstrated that this approach results in a good representation of hurricane induced damage.

FPL historical data has been utilized to develop the both pole damage model and span damage model. According to the FPL historical data (shown in Table 5.1), the pole damage model is best described as an exponential function, and the span damage model is best presented as a power function. The basic equation is encoded in the model, but the parameters of the equation can be modified by the user. Detailed descriptions of these equations and parameters are shown in Chapter 5. When further data become available, parameters can be updated such that the models can more accurately represent the actual situation for a particular utility.

3.2.2 Underground Equipment Damage

Underground equipment damage is a key consideration in undergrounding, especially for coastal areas subject to storm surges. However, there is currently not sufficient historical data to support a curve fitting approach to underground equipment failure rate modeling. Therefore, the damage model for underground equipment is based on hurricane category instead of wind speed. This approach is a tradeoff between the model accuracy and data requirements. As further data becomes available, the parameters (and possibly the model itself) can be updated to better reflect an individual utility's actual condition.



The commonly used Saffir-Simpson scale [7] divides hurricane intensity into five categories. The relatively weak hurricanes are classified as Category 1 and the strongest ones as Category 5. The definition of storm surge zone category implies that flooding is possible for this zone with a storm of that category or higher [8]. For instance, a Category 3 storm surge zone would be most vulnerable to hurricanes of Category 3 and higher, but relatively safe to hurricanes of Category 1 or 2. According to this concept, the difference between an incoming hurricane category and the storm surge zone category plays a critical role in estimating the failure rates of the underground equipment located in that storm surge zone.

It is assumed that underground equipment in a storm surge zone has the non-storm condition failure rates for a hurricane of category lower than the storm surge zone category. For a storm surge zone hit by a hurricane of that category or higher, underground equipment within the zone will experience higher failure rates; failure rates increase as the difference between the hurricane category and storm surge zone category increases. Since there is insufficient data to justify a more complicated model, a linear relationship between the underground equipment failure rate and the difference of hurricane category and storm surge zone category is assumed. Please refer to Chapter 5 for detailed description of the underground equipment damage model. As further data becomes available this relationship can be updated.

Similar to the approximation approach for overhead system damage assessment, pad-mount equipment (e.g., pad mount transformer and switchgear) and underground cable damage is used as a proxy to total underground damage and total underground restoration cost. Using historical data, a utility can determine the percentage of total underground restoration costs typically made up of pad mount equipment and cable damage. This can then be used to determine an appropriate hurricane cost restoration multipliers so that the total estimated underground cost is close to the expected overall underground restoration cost.

The preceding hurricane simulation module calculates the average wind speed experienced at each point in a utility service territory and percentage of the service territory that is exposed to hurricane-force winds. Failure rates of each equipment class at this average wind speed are estimated using the damage models. In addition, the hurricane simulation module determines the local wind speed at a specified project location. This allows equipment failure rates at the project location to be determined. Equipment failure rate are then used to determine the amount of damaged equipment. Using this approach, the amount and type of equipment to be repaired after a hurricane is estimated both system-wide and for the project area. The outputs of the infrastructure damage module include the following:

Infrastructure Damage Module Outputs

- Total amount of overhead infrastructure damage in the utility service territory
- Total amount of underground infrastructure damage in the utility service territory
- Total amount of overhead infrastructure damage in the project area
- Total amount of underground infrastructure damage in the project area

3.3 System Restoration Module

The system restoration module models the post-hurricane system restoration progress and then estimates the restoration duration at a project area for a simulated hurricane. This is based on the estimated overhead and underground equipment damage for both the affected utility service territory and the project location. Figure 3-4 shows a flow chart of the system restoration module.

Given necessary equipments available, the restoration time is based on two factors, (1) the number of crew hours required to repair damaged equipment, and (2) the number of crews available to perform repair work. The number of crew hours required to repair damaged equipment is based on the amount of damaged equipment along with the required number of crew hours needed to repair each class of equipment. For example, if 1000 poles are damaged, and poles require an average of 10 crew hours to repair, then complete pole repair requires 10,000 crew hours. Now assume that all repairs require a total of 20,000 crew hours. If 2,000 crews are available each day, then total system repair will take $20,000 \div 2,000 = 10$ hours.

When a hurricane causes widespread damage to a utility service territory, restoration can take many days. Therefore, utilities need to prioritize their restoration efforts, typically by focusing first on facilities that provide electricity to critical services such as hospitals, police stations, and fire stations [9]. After the initial critical services are restored, restoration activities are often focused on major thoroughfares consisting of gas stations, grocery stores, restaurants, and home improvement stores. The remaining main feeder trunks will typically receive the next priority, followed by lateral taps and finally secondary service drops.

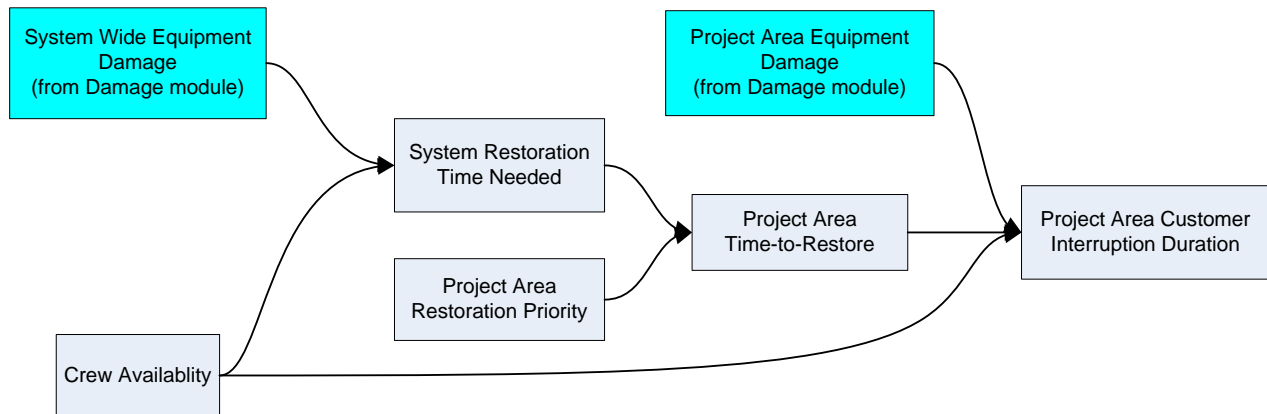


Figure 3-4. System Restoration Modeling Flow Chart



In order to compute the benefit of an undergrounding or hardening project, the restoration priority of the project area is needed. If a project area has high restoration priority, the benefits of undergrounding are lower since interruption time will be lower. This may seem counter-intuitive, but consider the following. When a critical facility such as a hospital is interrupted during a hurricane, crews are forced to focus on the critical facility. This highly constrains the early restoration effort. If critical facilities do not sustain major damage, the utility can be much more flexible and efficient in system-wide restoration efforts. Therefore, the benefit of undergrounding a critical facility is primarily for overall restoration effort.

The restoration priority of a project area is represented by a percentage between 0% and 100%. This priority number indicates the number of system-wide crew hours that must be expended before restoration work on the project area is initiated. For example, if all the hurricane damage requires 1000 crew hours to restore, and a project area is assigned a post-hurricane restoration priority of 30%, then the repair work for the project area starts after 300 crew hours have been expended. Depending on the available crew resources, the actual number of days passed before the restoration starts can vary. If more crews are available, restoration of the project area can begin sooner.

Crew availability varies from utility to utility, and the number of crew dispatched also varies from hurricane to hurricane. Generally, a certain number of crews are available immediately after the hurricane passes. Additional crews are typically added until a maximum number of crews are reached. When the restoration work comes close to being finished, crew resources will typically ramp down. The ramp-down period typically occurs at the clean-up stage when most customers have been restored. Therefore, crew ramp-down is not simulated in this model. This general dynamic pattern of crew resource throughout the restoration process is modeled by the following variables:

Crew Availability Variables

- Initial overhead crews
- Initial underground crews
- Overhead crew ramp-up per day
- Underground crew ramp-up per day
- Maximum overhead crew number
- Maximum underground crew number
- Overhead crew work hours per day
- Underground crew work hours per day

In the early days following a major hurricane, it is often times difficult to utilize crews with maximum effectiveness. This initial inefficiency can be due to a variety of factors such as road accessibility, availability of materials, having the right crew skill sets in the right locations, and so forth. To account for these initial inefficiencies, the model allows for early repairs to require additional man-hours. The amount of increase and the duration of the inefficiencies are both a function of hurricane severity. A detailed explanation of efficiency factors is presented in Chapter 6.



The outputs of system restoration module include the following:

System Restoration Module Outputs

- Total required overhead crew hours
- Total required underground crew hours
- Total required days for restoration
- Start and end restoration time for the project area
- Customer interruptions hours in project area

3.4 Costs and Benefits of Undergrounding Conversions

The model is flexible in its treatment of costs and benefits. The user can assign both initial and/or annual costs to equipment classes. The user can also assign initial and/or annual costs to categories other than equipment. The tool will summarize all of these costs in the output results, including the incremental and avoided costs associated with the proposed project.

The model also estimates the total number of customer interruptions hours during hurricanes. This allows the hurricane reliability benefits of a project to be computed. In addition, any reduction in customer interruptions hours is used to compute utility lost revenue benefits, reductions in storm restoration cost, and customer interruption cost benefits.

Finally, the model predicts the total number of customer interruptions hours during normal weather. This allows the normal weather reliability benefits of a project to be computed. Similar to hurricane reliability, any reduction in customer interruptions hours is used to compute utility lost revenue benefits, reductions in outage repair costs, and customer interruption cost benefits.

The cost and benefit framework is flexible. It allows for an examination of initial costs, savings in annual costs, savings in forced outage repair, and savings in lost revenue. The focus is on the comparison of costs before and after the conversion, and is addressed in two ways. The first are costs associated with equipment. Costs associated with equipment are computed based on equipment quantities both before and after the project. The second are general costs that are incurred before and after the project. These can represent a wide variety of costs such as attachment revenue; underground locate costs, and accident-related costs. Examples of costs and benefits that can be considered in the model are now provided.

Reliability Calculations

- Normal weather customer interruptions and customer interruption hours
- Hurricane customer interruptions and customer interruption hours



Initial Costs

- The retrofit cost of placing facilities underground
- The retrofit cost of hardening facilities
- Direct financing costs
- Land acquisition and easements
- Third party facilities, such as street lightning, telephone, cable TV, broadband fiber, etc
- Customer facilities, such as service entrance and other customer-owned equipments
- Landscaping

Annual Recurring Costs

- Cost of normal weather outage restoration
- Cost of hurricane outage restoration
- Lost revenue due to normal weather interruptions
- Lost revenue due to hurricane interruptions
- Loss of pole attachment revenue
- Vegetation management
- Vehicular accidents (lawsuit costs)
- Employee accidents
- Public accidents
- Underground locates
- Avoided economic and business losses

Some benefit categories are intangible, such as the aesthetic benefits associated with the projects and the improved property values. They are conceptually valid, and are often the main project driving force behind undergrounding. It is typically infeasible to meaningfully quantify them in engineering or economic terms, but the model does allow these classes of costs and benefits to be included along with other costs and benefits. For example, the user can define a cost category of “improved aesthetics” and assign a value of \$100 million after a project is completed. The model will keep track of these costs, but it is simply reflecting the value inputted by the user¹³. Examples of intangible benefits that can be treated in this manner include the following:

Intangible Benefit/Costs Types

- Aesthetic benefits such as elimination of overhead facilities, improved landscaping, etc.
- Property values
- Operational flexibility (reduced flexibility for both operations and system expansion)
- Business impact
- Environmental impact such as damage including soil erosion, and disruption of ecologically-sensitive habitat

¹³ There are no studies that provide guidance on determining the magnitudes of these intangibles found at current stage.



4 Hurricane Simulation Module

As discussed in previous chapter, the various uncertainties involved in hurricane systems make it necessary to model hurricanes probabilistically. A review of hurricane modeling literature shows that there are three basic approaches to modeling hurricane characteristics:

Hurricane Modeling Approaches

- Statistical models using probability distribution functions
- Empirical models
- Sampling approach

To achieve the cost and benefit analysis goals of this project, it is necessary to use a mix of the three modeling approaches. The following hurricane characteristics are modeled statistically:

Modeled Hurricane Characteristics

- Hurricane occurrence
- Landing position
- Approach angle
- Translation velocity
- Central pressure difference
- Maximum wind speed
- Radius to maximum wind
- Gust factor
- Wind speed decay rate
- Central pressure filling rate
- Radial wind field profile

Table 4-1 summarizes the probabilistic models for hurricane landing characteristics. Most of the models have a standard form of corresponding probability distribution functions, as the detailed description explained in Appendix A. For each simulated hurricane, a random number is used to determine the value for each of these characteristics. These define the initial state of the hurricane as it makes landfall on the Florida coast. The hurricane is then simulated as it travels across Florida. There are no random factors involved; the initial state of the hurricane determines its characteristics as it travels across Florida.

The remainder of this section describes how the spreadsheet tool presents hurricane simulation results. Users interested in the technical details of the hurricane simulation algorithm are referred to Appendix A.

Table 4-1. Hurricane Landing Characteristics

Feature	Model	Probability Distribution Function
Annual Occurrence (h)	Poisson [10, 11, 12]	$f(h) = \frac{e^{-\lambda} \lambda^h}{h!}$
Approach Angle (θ)	Bi-normal [13, 14]	$f(\theta) = \frac{a_1}{\sqrt{2\pi}\sigma_{x1}} \exp\left[-\frac{1}{2}\left(\frac{\theta - m_{x1}}{\sigma_{x1}}\right)^2\right]$ $+ \frac{(1-a_1)}{\sqrt{2\pi}\sigma_{x2}} \exp\left[-\frac{1}{2}\left(\frac{\theta - m_{x2}}{\sigma_{x2}}\right)^2\right]$
Translation Velocity (c)	Lognormal [15, 16]	$f(c) = \frac{1}{c\sqrt{2\pi}\sigma_{\ln c}} \exp\left[-\frac{1}{2}\left(\frac{\ln c - m_{\ln c}}{\sigma_{\ln c}}\right)^2\right]$
Central Pressure Difference (Δp)	Weibull [14, 17]	$f(\Delta p) = \frac{k}{C} \left(\frac{\Delta p}{C}\right)^{k-1} \exp\left[-\left(\frac{\Delta p}{C}\right)^k\right]$
Feature	Model	Empirical Models
Radius to Maximum Wind (R_{\max})	Empirical [18]	$\ln R_{\max} = 2.556 - 0.000050255\Delta p^2 + 0.042243032\psi$
Wind Speed Decay Rate	Empirical [19]	$V(t) = V_b + (RV_0 - V_b)e^{-at}$
Central Pressure Filling Rate	Empirical [20]	$\Delta p(t) = \Delta p_0 e^{-at}$

4.1 Single Hurricane Year Simulation¹⁴

For each hurricane year, the tool first determines the number of hurricane landings in Florida. For each landed hurricane, landfall parameters are probabilistically determined and then the hurricane is simulated as it moves across Florida. Figure 4-1 presents an interface listing basic information about the simulated hurricanes, most of which are related to the hurricane landing characteristics.

¹⁴ This section, which focuses on an individual hurricane simulation, is arranged to provide a basis for the following Monte Carlo simulation section. Some of the screenshots in this section are not seen in the actual tool; they are provided to help explain how each individual hurricane is simulated.



Number of Hurricanes:

No.	Landing Position		Approach Angle	Central Pressure Difference	Translation Velocity	3 s Gust Speed	Maximum Wind Speed	Category	Radius to Maximum Wind	Duration	Region	Leaving Position	
	Latitude	Longitude										Latitude	Longitude
1	29.97	-83.95	65	31.71	13.38	41.42	33.45	1	43.44	1.58	NW	30.60	-83.65
2	26.20	-81.89	70	78.92	12.96	79.45	64.53	4	28.49	7.16	SW	29.07	-80.85
3	29.48	-80.98	120	18.32	12.49	45.85	37.06	1	44.00	3.65	SE	30.80	-81.74

Figure 4-1. Interface for Single Hurricane Year Simulation in Florida¹⁵

As shown in Table 4-1, three of the parameters (radius to maximum wind, wind speed decay rate, and central pressure filling rate) use empirical models of which parameters have been provided, while the remaining four parameters (hurricane occurrence, approach angle, central pressure difference, and translation velocity) use probability distribution functions, whose parameters are chosen based on historical hurricane data from HURDAT and calibrated using ASCE (American Society of Civil Engineering) 7 wind map [21].

The currently used parameters are embedded in the hurricane simulation model as defaults. With more historical data available, the parameters for these probability distribution functions can be updated; users can use the interface shown in Figure 4-2 to manually change the parameters. The hurricane characteristics not included in Table 4-1 are modeled through sampling approaches or complicated iterative algorithms in which there is less opportunity for parameter adjustment. The reader is referred to Appendix A for a more detailed treatment of model parameters and default values.

Hurricane Parameter Setting					
<input checked="" type="radio"/> Use Default Parameters <input type="radio"/> User Defined Parameters					
Hurricane Aspects		NorthWest	SouthWest	SouthEast	NorthEast
Frequency	λ	0.29677	0.1871	0.2	0.03871
	μ_1	35	40	310	345
	μ_2	295	300	30	285
	σ_1	25	25	30	5
	σ_2	40	30	15	10
Approach Angle	σ	0.5	0.63	0.9	0.5
	a_0	2.3	2.3	2.3	2.3
	a_1	-0.00275	-0.00275	-0.00275	-0.00275
	σ_{mc}	0.3	0.3	0.3	0.3
	a_2	42	51	53	51
Translation Velocity	a_3	-0.02	-0.02	-0.02	-0.02
	k	2.5	1.9	2.8	2.5

Figure 4-2. Parameter Setting Interface¹⁶

Figure 4-3 shows the interface in which users can select a hurricane from the simulated hurricanes listed in the table in Figure 4-1 by the index number. For this hurricane, the model can estimate the hurricane

¹⁵ Most of the fields shown in the figure 4-1 are self-explained. The field “No.” is the hurricane index number. The field “Region” refers to region where the hurricane made landfall.
¹⁶ Please refer to Appendix A for regionalized parameter settings.



coverage for different utilities¹⁷, the average sustained wind speed, and the average 3-second gust speed. The average wind speed is measured as a root mean square (RMS) value. The calculations performed in this interface provide the basis for further infrastructure damage and system restoration simulation.

Select A Hurricane:

IOU

	FPL	PEF	TEC	GPC	FPUC
Coverage	16.4%	56.6%	96.8%	0.0%	0.0%
Wind Speed	23.12	32.36	33.94	0.00	0.00
Gust Speed	28.69	40.04	41.99	0.00	0.00

COOP

	CFEC	CEC (Choctawhatchee)	CEC (Clay)	EREC	FKEC	GEC	GCEC	LCEC	OREMC
Coverage	100.0%	0.0%	74.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Wind Speed	35.92	0.00	26.83	0.00	0.00	0.00	0.00	0.00	0.00
Gust Speed	44.42	0.00	33.26	0.00	0.00	0.00	0.00	0.00	0.00

	PREC	SEC (Seminole)	SEC (Sumter)	SVEC	TEC	TCEC	WFEC	WREC	
Coverage	36.1%	0.0%	98.1%	20.7%	0.0%	16.7%	0.0%	100.0%	
Wind Speed	20.90	0.00	33.99	20.31	0.00	23.11	0.00	46.31	
Gust Speed	25.95	0.00	42.05	25.24	0.00	28.69	0.00	57.18	

Figure 4-3. Interface for Hurricane Effects to Different Utilities¹⁸

For a specific location such as an undergrounding project area, the hurricane simulation can trace the local wind speed at different time steps. The interface shown in Figure 4-4 allows users to provide location information in terms of latitude and longitude; by identifying a particular simulated hurricane using the index number, the program can track the sustained wind speed and peak gust speed this inputted location experiences over time.

Select A Hurricane:

Select A Location:

Latitude

Longitude

Figure 4-4. Interface for Hurricane Effects to Specific Location

4.2 Monte Carlo Simulation

The single hurricane year simulation records the hurricane information for that year only. Many years must be simulated in order to take uncertainties into consideration and generate statistically representative results of the undergrounding cost-benefit analysis. A Monte Carlo simulation repeats the single hurricane year simulation multiple times. Some of the interfaces designed for single hurricane simulation need to be modified to accommodate the multiple hurricane simulation results from the Monte Carlo simulation.

The Monte Carlo simulation runs the designated number of single hurricane year simulations and records hurricane information, the hurricane coverage in different utilities, and the average sustained wind speed across the affected service territory for each utility. This information is stored in different worksheets; the

¹⁷ Hurricane coverage is the percent of a utility's service territory that is exposed to hurricane-force winds. This can be computed for investor-owned utilities (IOUs) and cooperative utilities (co-ops). Municipal utilities are considered a spot location instead of a distributed area due to their small service territory.

¹⁸ The abbreviations of different utility names listed the table may be different from the ones that are commonly used.



information is for reference purpose only, and is not used directly in calculating costs and benefits. Figure 4-5a-c presents the screenshots for one example with 50 hurricane years simulated.

Landing Position		Approach	Central Pressure	Translation	3 second Gust	Maximum Wind	Category	Radius to Maximum	Duration	Region	Leaving Position	
Latitude	Longitude	Angle	Difference	Velocity (m/s)	Speed (m/s)	Speed (m/s)		Wind (km)	(hr)		Latitude	Longitude
25.10000038	-81.229492	70	34.11970901	10.0145825	54.76057434	42.54900742	2	35.08576584	2.690634966	SW	25.4241848	-80.338806
28.82666397	-80.773544	295	71.55471802	8.548726082	76.57190704	59.49642944	4	33.66356659	13.54977703	NE	30.60000038	-84.576477
26.33139992	-80.168594	305	57.98174667	12.62214756	69.02148438	53.62974548	3	33.09448624	7.152330875	SE	28.13704491	-82.747322
30.41056442	-87.5	35	28.20616722	13.12805176	52.39006042	40.70711899	1	44.73034668	1.608091712	NW	31	-87.087273
28.51150322	-82.664108	60	106.0668564	6.838687897	95.76531982	74.409729	5	24.41102028	7.961241245	SW	29.48276901	-80.981827
26.42214203	-82.011841	50	92.51291656	10.6175642	88.90254211	69.0773468	4	25.58578491	5.624851704	SW	27.74842262	-80.431244
28.45210075	-80.654633	340	52.46261215	10.52453327	66.00263977	51.28409958	3	37.32207108	7.205386639	SE	30.79999924	-81.509193
30.03031158	-86.179688	360	39.68954086	6.71061039	58.27538681	45.28002167	2	42.32621765	4.470532417	NW	31	-86.179688
40.0584183	-83.305565	315	35.14764023	9.034287453	55.40926361	43.05303955	2	41.93450928	3.13620019	NW	28.71840668	-82.618134
29.95944786	-83.941895	320	11.39263344	14.13236523	46.55408859	36.17256165	1	45.37926102	1.729678273	NW	30.60000038	-84.479378
26.04800415	-80.221764	285	23.78458977	6.351810455	50.85533905	39.51463699	1	37.63434601	8.440288544	SE	26.54530144	-82.077705
29.84876442	-85.531303	45	70.2148819	6.840651989	75.78365326	58.88395691	4	35.48601532	4.466760635	NW	30.60000038	-84.780067
29.26671219	-83.145641	15	47.1614151	8.319019318	62.99050522	48.94367218	2	39.66770935	5.075384617	NW	30.60000038	-82.788399
30.45487404	-87.5	295	9.409593582	9.579116821	45.86577225	35.63774109	1	46.43514633	12.88974667	NW	30.92498016	-88.508148
26.59792519	-80.118591	285	22.15019798	8.974827766	50.28804016	39.07384491	1	38.66444016	7.459134102	SE	27.21946716	-82.438217
29.1490612	-83.010414	60	28.89564514	14.02125168	52.62937164	40.89306259	1	42.32525253	4.140540123	NW	30.19053841	-81.20652
29.90485382	-83.879143	80	33.40722656	9.887350082	54.31097794	42.1996727	2	43.08543396	3.034179926	NW	29.71204376	-84.972626
30.24562836	-86.948669	330	43.7473793	16.7293396	60.83607864	47.26968002	2	41.99234772	1.560797453	NW	31	-87.384209
26.11348534	-80.20948	230	23.62858391	9.935622215	50.80118561	39.47256088	1	37.7526207	4.333453178	SE	25.16515541	-81.339653
29.70713997	-84.983772	310	25.40607834	10.88534164	51.41814423	39.95193863	1	43.74956131	5.25681448	NW	31	-86.524544
25.54446793	-81.542496	40	40.60890961	10.60986614	58.85554886	45.73080826	2	34.89002991	5.707476139	SW	27.11024857	-80.228645
27.06372643	-80.213882	320	42.57158279	7.161436558	60.09410858	46.69316864	2	36.89863968	16.5548439	SE	27.88191986	-80.900429
29.23220253	-83.10598	70	67.06265259	7.830486774	73.98848724	57.48911285	3	35.33380127	7.343093872	NW	29.95120621	-81.130539
29.75944138	-85.212288	300	55.75027466	11.82042885	67.80090332	52.68135452	3	38.7422905	5.827951908	NW	31	-87.361
29.80410194	-85.371796	25	28.25480461	11.41544819	52.4069519	40.72024155	1	43.5929451	2.944353104	NW	30.81586456	-84.900002
25.10000038	-80.744141	0	65.2516098	14.01105785	72.99790192	56.7194252	3	30.0338707	7.989721298	SW	28.73404312	-80.744141
26.15089798	-80.202461	285	43.97803497	6.59996748	60.98163223	47.38277435	2	35.28636551	8.501725197	SE	26.67144203	-82.145157
29.00948524	-82.849983	30	38.11450577	11.98349953	57.2814827	44.50775528	2	40.79022217	5.145964622	NW	30.79999924	-81.816231
28.98450089	-82.821266	10	12.83588123	10.0884037	47.05503464	36.5617981	1	43.47183228	4.983719826	NW	30.60000038	-82.536407
29.83888245	-85.49601	70	16.07607841	7.769254684	48.17969513	37.43566132	1	44.85777664	7.794255257	NW	30.60000038	-83.404854
30.43960762	-87.5	65	42.15984726	12.82409668	59.83428192	46.49128342	2	42.62902832	2.83754015	NW	31	-86.298241
30.21530914	-86.840393	45	27.06160736	9.795124054	51.99277496	40.39842606	1	44.50417328	3.261259794	NW	31	-86.055702
25.39685822	-80.343925	285	14.05256939	5.351148605	47.4773407	36.88993073	1	37.29712296	7.11660957	SE	25.7470417	-81.650826
29.95586967	-85.913818	300	23.33926392	11.69414139	50.70074844	39.39451981	1	44.43608093	4.346906185	NW	30.8716526	-87.5
25.10000038	-80.934044	60	34.83311462	19.14724922	55.21078873	42.8988266	2	34.99913788	1.044536471	SW	25.44602966	-80.334709
25.10000038	-81.176918	325	15.94049358	11.02295494	48.13264465	37.39910126	1	36.72766876	2.570393562	SW	25.87301254	-81.718193
25.10000038	-81.184299	20	42.01888275	6.797754288	59.74530792	46.42214966	2	34.04116821	11.15564537	SW	27.4398613	-80.33329
29.78550148	-84.805679	360	63.21781921	6.830219746	71.88549042	55.85507965	3	37.09143829	3.660204411	NW	30.60000038	-84.805679
25.10000038	-81.214325	360	50.68099213	7.490844727	65.02813721	50.52691269	3	32.69483185	17.52448654	SW	26.28264236	-81.214325

Figure 4-5a. Screenshot of Hurricane Static Information Record

The layout of this result table is almost identical to the one shown in Figure 4-1. Most of the fields are identical except the leftmost column labeled as “No.”. This field indicates the simulation year of the hurricane instead of the hurricane index as in single hurricane year simulation. For example, it is shown in the tables that there is one landfall hurricane in Florida in year 5 and two landfall hurricanes in Florida in year 4. There are no landfall hurricanes in years 1, 2, 3, or 6.



No						CEC		CEC								SEC		SEC							
	FPL	PEF	TEC	GPC	FPUC	AEC	CFEC	(Choctawhatchee)	(Clay)	EREC	FKEC	GEC	GCEC	LCEC	OREMC	PREC	(Seminole)	(Sumter)	SVEC	TEC	TCEC	WFEC	WREC		
4	26%	0%	0%	0%	0%	0%	0%	0%	0%	0%	75%	11%	0%	73%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
4	20%	8%	0%	0%	0%	0%	0%	0%	0%	3%	0%	0%	2%	0%	0%	10%	0%	8%	0%	0%	0%	0%	0%	0%	0%
5	11%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10	0%	0%	0%	59%	0%	0%	0%	74%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	6%	0%	0%
10	21%	28%	31%	0%	20%	0%	67%	0%	93%	0%	0%	0%	0%	0%	69%	0%	0%	58%	3%	0%	0%	0%	0%	88%	0%
10	29%	14%	3%	0%	0%	0%	0%	0%	0%	0%	82%	0%	32%	0%	59%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10	7%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
13	21%	12%	0%	0%	10%	0%	29%	0%	78%	0%	0%	0%	0%	0%	81%	0%	0%	0%	60%	0%	0%	0%	0%	0%	0%
14	0%	32%	44%	0%	0%	0%	100%	0%	11%	0%	0%	0%	0%	0%	0%	0%	0%	56%	31%	0%	36%	0%	97%	0%	0%
19	0%	32%	0%	0%	0%	0%	92%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	29%	42%	85%	0%	0%	0%	0%	0%
20	12%	0%	0%	0%	0%	0%	0%	0%	0%	25%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
23	0%	17%	0%	30%	62%	0%	0%	16%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	100%	0%	66%	0%	0%	0%	0%
25	20%	33%	0%	0%	0%	0%	100%	0%	99%	0%	0%	0%	0%	0%	0%	0%	27%	31%	0%	21%	0%	19%	0%	0%	0%
27	0%	0%	0%	28%	0%	0%	0%	4%	0%	79%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
27	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
28	19%	31%	0%	0%	38%	0%	100%	0%	68%	0%	0%	0%	0%	96%	0%	0%	12%	100%	0%	27%	0%	28%	0%	0%	0%
29	1%	28%	0%	0%	0%	0%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	43%	63%	100%	0%	0%	0%	0%	0%
29	0%	2%	0%	65%	0%	0%	0%	74%	0%	72%	0%	0%	34%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
29	22%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
32	0%	12%	0%	4%	18%	0%	0%	0%	0%	0%	0%	55%	0%	0%	0%	0%	0%	0%	46%	0%	0%	0%	0%	0%	0%
32	34%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	20%	0%	78%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
32	11%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
33	12%	31%	0%	0%	16%	0%	100%	0%	41%	0%	0%	0%	0%	96%	0%	0%	6%	100%	0%	56%	0%	6%	0%	0%	0%
35	0%	10%	0%	9%	22%	0%	0%	0%	0%	0%	0%	72%	0%	0%	0%	0%	0%	0%	35%	0%	0%	0%	0%	0%	0%
38	0%	25%	0%	16%	52%	0%	0%	7%	0%	0%	0%	91%	0%	0%	0%	0%	0%	100%	45%	23%	0%	0%	0%	0%	0%
38	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
38	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%	25%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
40	21%	33%	2%	0%	2%	0%	100%	0%	98%	0%	0%	0%	0%	0%	0%	0%	0%	52%	7%	0%	3%	0%	53%	0%	0%
41	12%	35%	3%	0%	0%	0%	85%	0%	60%	0%	0%	0%	0%	0%	0%	0%	0%	85%	0%	0%	0%	0%	59%	0%	0%
42	0%	12%	0%	41%	62%	0%	0%	26%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	65%	0%	96%	0%	0%	0%	0%
43	0%	0%	0%	41%	0%	0%	0%	34%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
43	0%	0%	0%	88%	2%	0%	0%	100%	0%	79%	0%	0%	28%	0%	0%	0%	0%	0%	0%	0%	68%	0%	0%	0%	0%
45	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
46	0%	5%	0%	35%	12%	0%	0%	45%	0%	0%	0%	83%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%
46	21%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	31%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
48	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
48	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
49	17%	15%	0%	0%	0%	0%	46%	0%	87%	0%	0%	0%	0%	35%	0%	0%	10%	33%	0%	0%	0%	0%	0%	0%	0%
49	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 4-5b. Screenshot of Hurricane Coverage Record

No						CEC		CEC								SEC		SEC							
	FPL	PEF	TEC	GPC	FPUC	AEC	CFEC	(Choctawhatchee)	(Clay)	EREC	FKEC	GEC	GCEC	LCEC	OREMC	PREC	(Seminole)	(Sumter)	SVEC	TEC	TCEC	WFEC	WREC		
4	28.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.9	21.8	0.0	28.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	35.2	31.8	0.0	0.0	0.0	0.0	0.0	0.0	18.9	0.0	0.0	15.4	0.0	0.0	0.0	20.8	0.0	19.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	34.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	30.7	0.0	0.0	0.0	27.2	0.0	34.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.8	0.0	0.0	0.0
10	30.9	44.0	40.4	0.0	18.1	0.0	37.4	0.0	37.0	0.0	0.0	0.0	0.0	0.0	22.6	0.0	0.0	41.2	15.2	0.0	0.0	0.0	54.3	0.0	0.0
10	42.3	34.2	41.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	44.1	0.0	47.0	0.0	35.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	34.5	30.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	33.1	24.5	0.0	0.0	18.0	0.0	21.1	0.0	34.1	0.0	0.0	0.0	0.0	0.0	32.4	0.0	0.0	0.0	25.7	0.0	0.0	0.0	0.0	0.0	0.0
14	15.4	29.3	22.3	0.0	0.0	0.0	34.0	0.0	17.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.7	27.4	0.0	29.4	0.0	28.3	0.0	0.0
19	16.7	26.0	0.0	0.0	0.0	0.0	24.9	0.0	14.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.2	22.8	28.1	0.0	0.0	0.0	0.0
20	27.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.1	0.0	0.0	14.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	39.0	0.0	34.2	41.1	0.0	0.0	23.6	0.0	0.0	0.0	0.0	44.3	0.0	0.0	0.0	0.0	0.0	0.0	35.0	0.0	31.4	0.0	0.0	0.0
25	25.9	33.4	0.0	0.0	0.0	0.0	41.5	0.0	30.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.4	26.7	0.0	29.0	0.0	20.5	0.0	0.0
27	0.0	0.0	0.0	24.7	0.0	0.0	0.0	17.5	0.0	24.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	27.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	27.8	29.2	0.0	0.0	25.5	0.0	35.4	0.0	28.1	0.0	0.0	0.0	0.0	0.0	29.0	0.0	0.0	23.6	28.7	0.0	21.2	0.0	21.2	0.0	0.0
29	18.6	30.7	0.0	0.0	0.0	0.0	17.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.0	27.2	34.5	0.0	0.0	0.0	0.0
29	0.0	23.7	0.0	32.0	0.0	0.0	0.0	31.4	0.0	23.5	0.0	0.0	23.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	28.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.5	0.0	0.0	21.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	0.0	29.6	0.0	19.0	18.1	0.0	0.0	0.0	0.0	0.0	0.0	26.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.2	0.0	0.0	0.0	0.0	0.0
32	30.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0	0.0	34.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	32.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33	32.7	37.7	0.0	0.0	19.2	0.0	46.1	0.0	30.7	0.0	0.0	0.0	0.0	0.0	27.2	0.0	0.0	18.3	39.7	0.0	29.6	0.0	18.4	0.0	0.0
35	0.0	39.2	0.0	27.9	23.3	0.0	0.0	0.0	0.0	0.0	0.0	34.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.7	0.0	0.0	0.0	0.0	0.0
38	0.0	30.5	0.0	26.6	26.4	0.0	0.0	18.9	0.0	0.0	0.0	0.0	30.7	0.0	0.0	0.0	0.0	0.0	0.0	31.6	22.9	21.0	0.0	0.0	0.0
38	38.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	49.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
38	31.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.2	0.0	0.0	14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
40	27.1	31.6	16.4	0.0	15.9	0.0	34.6	0.0	29.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.9	16.0	0.0	15.5	0.0	29.4	0.0	0.0
41	22.2	27.1	14.6	0.0	0.0	0.0	28.3	0.0	25.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.2	0.0	0.0	0.0	0.0	26.1	0.0	0.0
42	0.0	27.6	0.0	26.7	29.6	0.0	0.0	20.3	0.0	0.0	0.0	0.0	31.5	0.0	0.0	0.0	0.0	0.0	0.0	24.0	0.0	26.1	0.0	0.0	0.0
43	0.0	0.0	0.0	34.4	0.0	0.0	0.0	22.6	0.0	39.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43	0.0	0.0	0.0	29.4	15.7	0.0	0.0	32.2	0.0	23.4	0.0	0.0	20.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.7	0.0	0.0	0.0
45	27.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
46	0.0	26.0	0.0	28.8	18.8	0.0	0.0	27.7	0.0	0.0	0.0	0.0	26.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.7	0.0	0.0	0.0
46	31.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.5	0.0	0.0	23.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
48	26.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
48	32.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.6	0.0	0.0	16.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
49	37.2	32.3	0.0	0.0	0.0	0.0	28.5	0.0	41.8	0.0	0.0	0.0	0.0	0.0	25.1	0.0	0.0	0.0	18.4	21.2	0.0	0.0	0.0	0.0	0.0
49	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0



These two result tables listed the hurricane coverage and average sustained wind speed in hurricane affected service territories for IOUs and Co-ops. The field headers stand for the abbreviations of different utilities. The sequence of simulated hurricane is consistent with the result table shown in Figure 4-5a.

The outputs of hurricane simulation module are not presented as a part of the tool final outputs; but users are still able to examine them as they are recorded in spreadsheets.



5 Infrastructure Damage Module

Infrastructure damage models estimate equipment failure rates under certain hurricane conditions. This section develops two classes of damage models: overhead equipments damage model and underground equipment damage models. As discussed in Chapter 3, pole damage and span damage are used as a proxy for total overhead damage. Pad-mount device damage and underground cable damage are used as a proxy for total underground damage. Taken together, these infrastructure damage models compute total infrastructure damage given the hurricane intensity simulated by the hurricane model.

A default set of parameters for each damage model is embedded in the spreadsheet application. These parameters are either determined from currently available data from a particular utility or theoretically designed. Utilities are able to change model parameters so that equipment failure rates best match historical data.

5.1 Pole Damage Model

As discussed in Chapter 3, overhead damage models are developed via a curve fitting approach. Historical data from FPL is currently the only available usable data for this approach. Both the pole damage model and the span damage model are developed based on this FPL data. Other utilities may find different curves as the best fit for their particular situations; the model can be updated as further data becomes available.

FPL recorded the pole failure rates it experienced during a number of hurricanes going back to Hurricane Andrew in 1992. Pole failure rate is calculated by dividing the number of poles issued during storm restoration by the total number of poles exposed to hurricane force wind.¹⁹ Table 5-1 lists the actual FPL pole failure rates for different hurricanes and the corresponding average sustained wind speed in the affected area, which is estimated from HURDAT and Tropical Cyclone Report issued by NOAA.

It is found based on this set of historical data that an exponential function can well represent the relationship between the pole failure rate and wind speed as shown in Figure 5-1 (dots represent historical data and the curve represents the fitted model).

Table 5-1. Failure Rate vs. Average Wind Speed

Year	Hurricane	% of Exposed Poles ²⁰ that Failed	Hurricane Category	Average Sustained Wind Speed in Affected Service Territory (mph)
1992	Andrew	10.1%	5	160
2004	Charley	3.1%	3-4	135
2004	Frances	0.9%	2	100
2004	Jeanne	0.5%	2-3	100
2005	Katrina	0.3%	1	75
2005	Wilma	1.5%	2-3	115

¹⁹ Poles include both FPL poles and third party poles with FPL equipment. Most FPL poles are designed to Grade B construction.

²⁰ Poles exposed refer to the poles exposed to 74+ mph wind speeds, which is the lower boundary of the category 1 hurricane wind speed according to Saffir-Simpson scale.



$$\lambda_p = a \cdot e^{bW} \quad ; \text{ pole failure rate model}$$

where λ_p is the pole failure rate, W is the sustained wind speed, and a and b are tuning parameters. Using the FPL historical data results in $a=0.0001$ and $b=0.0421$.

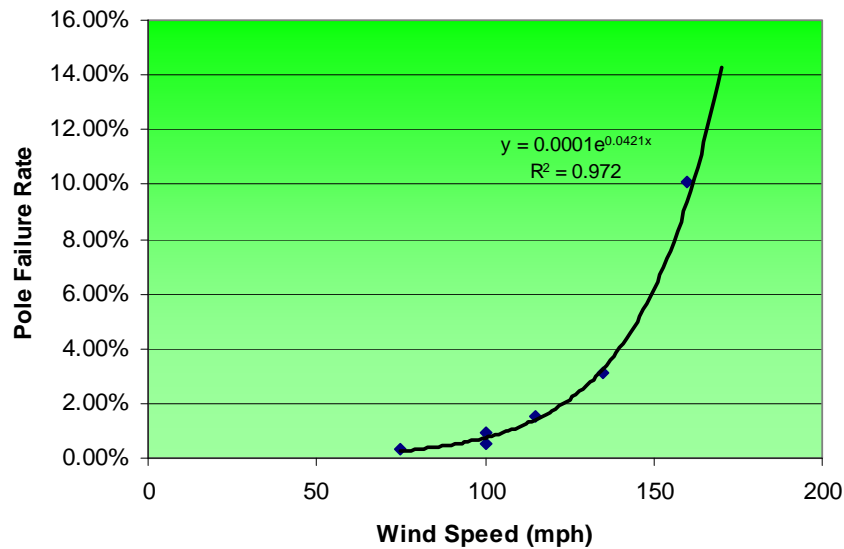


Figure 5-1. Pole Failure Rate vs. Average Wind Speed in Affected Area

The pole damage model describes the relationship between pole failure rates and the wind speeds. This failure rate includes all factors that may lead to a structural pole failure such as extreme wind speed and microclimate effects such as tornadic activity and microbursts. Again, the current model parameters are based on FPL data, which will not be appropriate for all categories of equipment, especially when equipment categories become more granular. For example, Grade B poles could be segmented for modeling purposes into “overloaded Grade B” and “lightly loaded Grade B”. This type of classification can potentially give more precise insight into the potential costs and benefits of undergrounding. Each category requires its own failure rate parameters which ideally will be derived from historical data.

To reiterate, the default model parameters should be used with caution, and will not appropriate for all utilities in all situation. Therefore, utilities are strongly encouraged to collect as much failure data as possible after each hurricane.

5.2 Span Damage Model

Like the pole damage model, the span damage model computes span failure rates as a function of wind speed. It is recognized that span damage often occurs due to many factors such as falling trees and flying debris. However, each of these factors is a strong function of wind speed, and wind speed is therefore used as the primary determinant of span damage.

FPL data is also the only available resource for fitting a representative curve of span failure rate with respect to wind speed. Figure 5-2 presents the FPL data series.

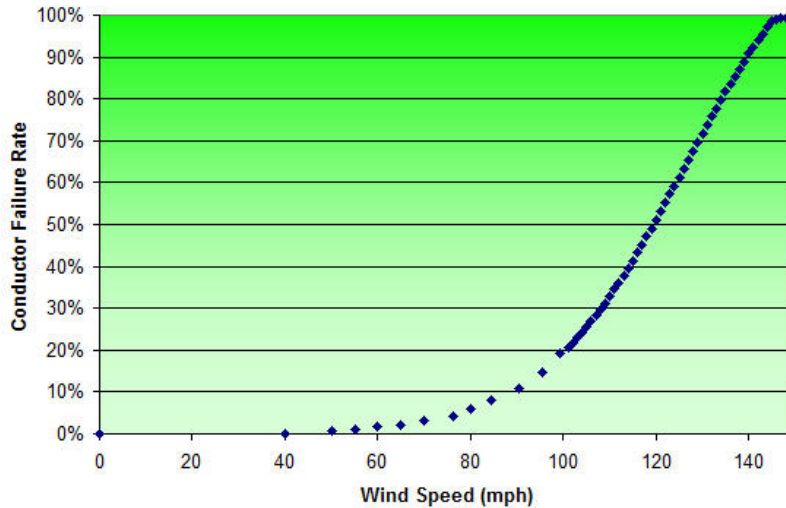


Figure 5-2. Florida Power & Light Span Failure Rate Data

Although an exponential function best fit the FPL pole failure rate data, a power function has a better fit for span failure rate. This fit is shown in Figure 5-3, with the dots representing FPL data points and the solid line representing the best fit power function. The power function is represented as follows:

$$\lambda_c = a \cdot W^b \quad ; \text{ span failure rate model}$$

where λ_c is the span failure rate, W is the sustained wind speed, and a and b are tuning parameters. Using the FPL historical data results in $a=8 \times 10^{-12}$ and $b = 5.1731$.

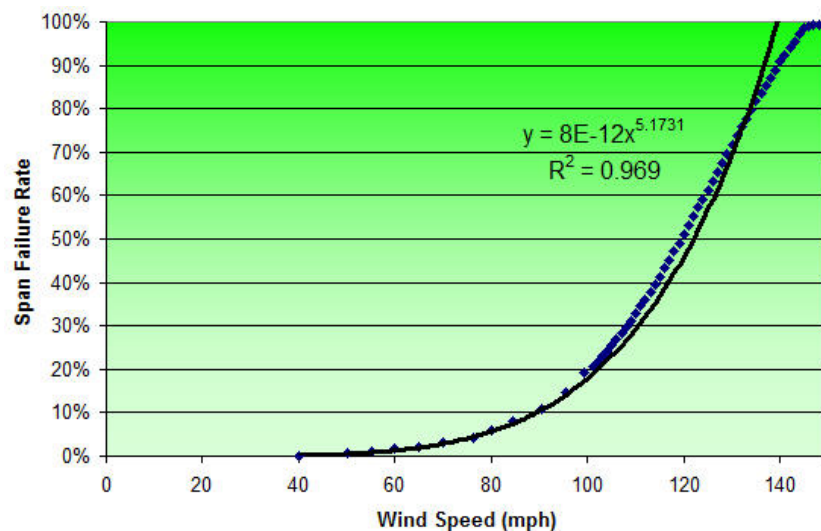


Figure 5-3. Span Failure Rate vs. Average Wind Speed across Affected Area



Like the overhead model, the span damage model default parameters are based on FPL data, which will certainly not be appropriate for all categories of spans, especially when categories become increasingly more specific. Even in the case of FPL, spans could be segmented for modeling purposes into “big wire with dense trees,” “big wire with sparse trees,” “small wire with dense trees,” and “small wire with sparse trees.” This type of classification can potentially give more precise insight into the potential costs and benefits of undergrounding. Of course, each category requires its own failure rate parameters which ideally will be derived from historical data.

5.3 Underground Equipment Damage Model

When a hurricane approaches land, it blows a wall of water onto shore called a storm surge. A storm surge tends to pick up a large amount of sand and debris. The sand can bury and contaminate pad-mounted equipment, and the debris can damage and dislodge pad-mounted equipment. When the storm surge recedes, it can carry away sand and dirt, leaving formerly underground cables, vaults, and manholes exposed.

When a storm surge floods coastal areas, salt water immerses all of the pad-mounted and sub-surface electrical equipment in the storm surge area. When the storm surge recedes, a salt residue can be left on insulators, bushings, and other components. This contamination can result in an immediate failure when the equipment is energized, or can result in a future failure when the contamination is exposed to moisture.

Clearly, underground equipment failures are a critical aspect of hurricane reliability, especially in coastal areas. Underground equipment is not only prone to damage, but repair times are often long when compared to overhead, and the specialized crews needed for underground repairs are often scarce during restoration. In fact, it is quite possible that undergrounding an existing overhead system in a coastal area may result in *more* hurricane damage and *longer* restoration times for customers. In any case, the intent of the underground equipment damage model is to account for these issues.

Presently there is not sufficient data to determine the best mathematical model for storm surge damage. Therefore, a simple approach is presented that estimates underground equipment damage based on hurricane category and storm surge zone category rather than wind speed. As more data becomes available, users can replace this simplified model with more complex models. The selected damage model for underground equipment is proposed as the following linear relationship:

$$\lambda_u = [a + b(H - S)] \cdot I(H - S) \quad ; \text{ underground equipment failure rate model}$$

$$I(H - S) = \begin{cases} 1 & H - S \geq 0 \\ 0 & H - S < 0 \end{cases}$$

where λ_u is equipment failure rate, H is the hurricane category (1-5), S is the storm surge zone category (1-5), and a and b are tuning parameters. $I(H-S)$ is an indicator function showing whether the area is affected by an incoming hurricane.

Consider the following example. If $a = 0.01$ and $b = 0.06$, the failure rate λ_u under different combinations of hurricane categories and storm surge zones is shown in Table 5-2 and graphically represented in Figure 5-4.

Table 5-2. Underground Equipment Failure Rate Example

		Storm Surge Zone Category				
		1	2	3	4	5
Hurricane Category	1	1%	0%	0%	0%	0%
	2	7%	1%	0%	0%	0%
	3	13%	7%	1%	0%	0%
	4	19%	13%	7%	1%	0%
	5	25%	19%	13%	7%	1%

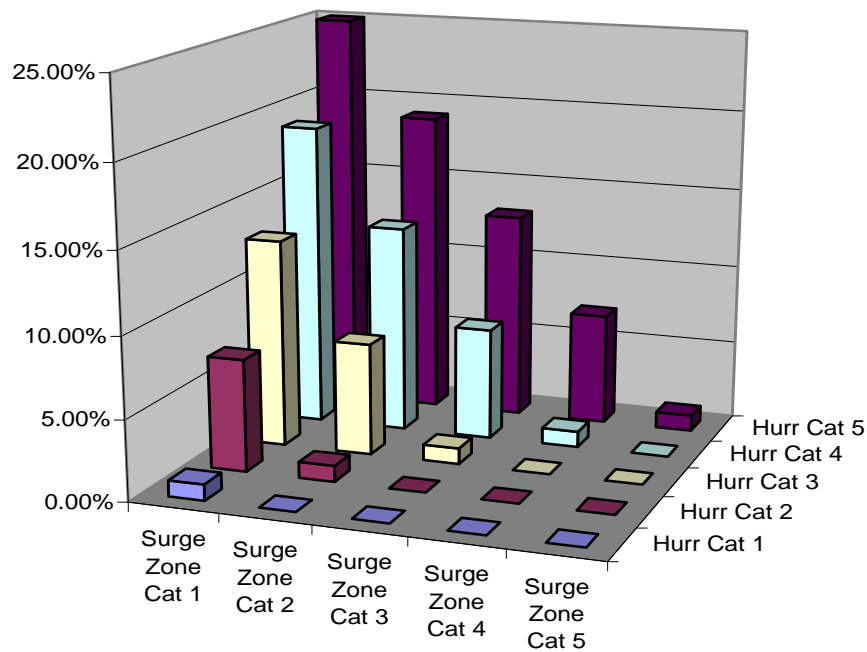


Figure 5-4. Underground Failure Rate Example

This model, though simple, is able to consider the effects of both vulnerability to storm surges (storm surge zone category) and hurricane strength (category). The parameters for this model can be determined with a minimum amount of data, and it is possible that utilities may be able to find historical hurricane damage information that allows parameter selection to be based on data rather than estimates.

5.4 Final Thoughts on Damage Models

Hurricane reliability calculations are strongly influenced by the choice of parameter for damage models. As stated previously, it is beyond the scope of this project to recommend parameters and assumptions beyond the basic form of the equations. In this section and in the spreadsheet model, default parameters appear. Neither the authors nor the utility sponsors of this project endorse these parameters as appropriate for any particular analysis. The tool should be viewed as a “calculator” and it is the responsibility of the user to make appropriate decisions about input parameters and assumptions. Further, utilities are encouraged to collect data that will increase the accuracy and confidence of input parameters and assumptions.

The damage model parameters shown in this section and in the spreadsheet application are for illustrative purposes only. It is the responsibility of the user to make appropriate decisions about damage model input parameters.

Since all three damage models are described by two parameters, the damage model interface only requires users to input the “a” and “b” parameters for each equipment type; the algorithm will automatically select the appropriate damage model. Figure 5-5 shows a screenshot of the form where users input damage model parameters.

Equipment	Category	Unit	Associate Custom	Damage Model Parameter	
				A	B
Grade B Poles	Poles			0.0001	0.0421
Grade C Poles	Poles			0.00008	0.04
Span	Spans	Miles		8E-12	5.1731
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 1)			0.1	0.3
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 2)			0.1	0.3
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 3)		100	0.1	0.3
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 4)		100	0.1	0.3
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 5)		100	0.1	0.3
Cable	Cables (surge Zone Cat 1)	Miles	80	0.08	0.28
Cable	Cables (surge Zone Cat 2)	Miles	80	0.08	0.28
Cable	Cables (surge Zone Cat 3)	Miles	80	0.08	0.28
Cable	Cables (surge Zone Cat 4)	Miles	80	0.08	0.28
Cable	Cables (surge Zone Cat 5)	Miles	80	0.08	0.28

Figure 5-5. Screenshot of Equipment Damage Model Parameter Input

As shown in Figure 5-5, multiple equipment types can be assigned to the same model category but use different “a” and “b” model parameters. For example, the first two types of equipment are both in the category “poles,” but use different parameters.

Since underground failure rate of a piece of equipment is a function of its storm surge zone category, the model needs to know the amount of equipment in each storm surge zone category. The input parameters are the same, but failure rates will be higher for equipment in lower storm surge zone categories. For example, the last five rows in Figure 5-5 all represent underground cable failure rates with the same model parameters. Having five categories allow the user to specify how much cable is located in each zone. This results in cables located in lower zones having higher failure rates.

6 System Restoration Module

The system restoration module estimates the total system restoration time, the start time for restoration in the project area, and the end time for restoration in the project area. This also allows for the calculation of customer interruptions hours, which can be used to compute the associated customer interruption costs.

The system restoration module is based on output from the hurricane simulation and damage models, which provides information about damaged overhead and underground equipment. This calculation requires additional information such as available crew resources, the project area restoration priority, and the number of crew hours required to repair damaged equipment.

Given the necessary equipment resources available²¹, the restoration time is based on two factors, (1) the number of crew hours required to repair damaged equipment, and (2) the number of crews available to perform repair work. The number of crew hours required to repair damaged equipment is based on the amount of damaged equipment along with the required number of crew hours needed to repair each class of equipment. For example, if 1000 poles are damaged, and poles require an average of 10 crew hours to repair, then complete pole repair requires 10,000 crew hours. Now assume that all repairs require a total of 20,000 crew hours. If 2,000 crews are available each day, then total system repair will take $20,000 \div 2,000 = 10$ hours.

Figures 6-1 and 6-2 show the interface where users provide the quantity and repair time (under storm condition) of different types of equipment. This information forms the foundation for simulating the restoration process.

Equipment	Category	Unit	Associated Customers/Unit	Quantity		
				System wide	Project Area	
					Before Project	After Project
Grade B Poles	Poles		50	5000	30	5
Grade C Poles	Poles		80	100	10	0
Span	Spans	Miles	300	400	1	0
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 1)		100	40	0	2
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 2)		100	50	0	3
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 3)		100	60	0	4
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 4)		100	70	0	0
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 5)		100	80	0	0
Cable	Cables (surge Zone Cat 1)	Miles	80	6	0	0.5
Cable	Cables (surge Zone Cat 2)	Miles	80	8	0	0.6
Cable	Cables (surge Zone Cat 3)	Miles	80	10	0	0.7
Cable	Cables (surge Zone Cat 4)	Miles	80	12	0	0
Cable	Cables (surge Zone Cat 5)	Miles	80	15	0	0

Figure 6-1. Screenshot of Equipment Quantity Input

Equipment	Category	Unit		Storm
				Crewhours to Repair (hr/Unit)
Grade B Poles	Poles	#		5
Grade C Poles	Poles	#		5
Span	Spans	Miles		4
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 1)	#		5.5
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 2)	#		5.5
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 3)	#		5.5
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 4)	#		5.5
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 5)	#		5.5
Pad-mount Transformer	Underground Equipments (Out of Surge Zones)	#		5.5
Underground Cable	Underground Equipments (Storm Surge Zone Cat 1)	Miles		8
Underground Cable	Underground Equipments (Storm Surge Zone Cat 2)	Miles		8
Underground Cable	Underground Equipments (Storm Surge Zone Cat 3)	Miles		8
Underground Cable	Underground Equipments (Storm Surge Zone Cat 4)	Miles		8
Underground Cable	Underground Equipments (Storm Surge Zone Cat 5)	Miles		8
Underground Cable	Underground Equipments (Out of Surge Zones)	Miles		8

Figure 6-2. Screenshot of Equipment Repair Time Input

²¹ Penalty factors introduced in a later section are included to account for the material availability issue.



When a hurricane causes widespread damage to a utility service territory, restoration can take many days. Therefore, utilities need to prioritize their restoration efforts, typically by focusing first on facilities that provide electricity to critical services such as hospitals, police stations, and fire stations. After the initial critical services are restored, restoration activities are often focused on major thoroughfares consisting of gas stations, grocery stores, restaurants, and home improvement stores. The remaining main feeder trunks will typically receive the next priority, followed by lateral taps and finally secondary service drops.

In order to compute the benefit of an undergrounding or hardening project, the restoration priority of the project area is needed. If a project area has high restoration priority, the benefits of undergrounding are lower since interruption time will be lower. This may seem counter-intuitive, but consider the following. When a critical facility such as a hospital is interrupted during a hurricane, crews are forced to focus on the critical facility. This highly constrains the early restoration effort. If critical facilities do not sustain major damage, the utility can be much more flexible and efficient in system-wide restoration efforts. Therefore, the benefit of undergrounding a critical facility is primarily for overall restoration effort.

The restoration priority of a project area is represented by a percentage between 0% and 100%. This priority number indicates the number of system-wide crew hours that must be expended before restoration work on the project area is initiated. For example, if all the hurricane damage requires 1000 crew hours to restore, and a project area is assigned a post-hurricane restoration priority of 30%, then the repair work for the project area starts after 300 crew hours have been expended. Depending on the available crew resources, the actual number of days passed before the restoration starts can vary. If more crews are available, restoration of the project area can begin sooner.

Crew availability varies from utility to utility, and the number of crew dispatched also varies from hurricane to hurricane. Generally, a certain number of crews are available immediately after the hurricane passes. Additional crews are typically added until a maximum number of crews are reached. When the restoration work comes close to being finished, crew resources will typically ramp down. The ramp-down period typically occurs at the clean-up stage when most customers have been restored. Therefore, crew ramp-down is not simulated in this model.

The restoration process is modeled by having initial available crews (C_{initial}), daily ramp-up crews (ΔC), and the maximum available crews (C_{max}). In this way, the available crews in any particular day can be calculated, and the algorithm can estimate the daily completed work and work remaining. Each day is sequentially simulated until all restoration tasks are complete. Since different crew types work on overhead and underground damage, two sets of crew related variables are used. One set of crew parameters is used for overhead restoration and separate set of parameters is used for underground restoration. Figure 6-3 presents the spreadsheet interface where users provide crew information.

Crew Availability (Overhead)		
Initial Crew Number	100	(#)
Crew Ramp-up per Day	50	(#)
Maximum Crew Number	400	(#)
Work Hours per Day	16	(hr)
Crew Availability (Underground)		
Initial Crew Number	50	(#)
Crew Ramp-up per Day	20	(#)
Maximum Crew Number	200	(#)
Work Hours per Day	16	(hr)

Figure 6-3. Screenshot of Crew Availability Input



In the early days following a major hurricane, it is often times difficult to utilize crews with maximum effectiveness. This initial inefficiency can be due to a variety of factors such as road accessibility, availability of materials, having the right crew skill sets in the right locations, and so forth. To account for these initial inefficiencies, the restoration model allows for early repairs to require additional crew hours. The amount of increase and the duration of the inefficiencies are both a function of hurricane severity. This aspect of restoration is modeled by the use of two penalty factors, one relating to crew efficiency and one relating to the duration of the inefficiency.

Penalty Factors:

- Efficiency penalty factor
- Duration penalty factor

Penalty factors are scales proportionally to hurricanes category. Category 1 storms will be assigned the base efficiency and duration penalty factors. Category 2 storms will be assigned twice the base efficiency and duration penalty factors. This continues up to Category 5 storms, which will be assigned five times the base efficiency and duration penalty factors.

Consider the following example. After a Category 4 hurricane, many roadways are blocked by trees and debris. This severely limits the ability for damage to be assessed and for crews to be efficiently dispatched. There are 1000 crews available, but many crew hours are not initially spent on effective restoration activities. By using penalty factors, extra repair time can be added to account for these inefficiencies. Assume that the efficiency penalty factor is set at 25% and the duration penalty factor is set at 10 hours. For the Category 4 hurricane, this means that each initial repair will require $4 \times 25\% = 100\%$ more crew hours to complete. This inefficiency persists for the first $4 \times 10 = 40$ hours of restoration. After this time, it is assumed that crews are able to work at full efficiency for the remainder of the restoration effort.

Figure 6-4 shows the interface for the input of penalty factors as well as the restoration priority factor.

Crew Penalty Factors		
Efficiency Penalty	<input type="text" value="20%"/>	(%)
Duration Penalty	<input type="text" value="10"/>	(hr)
Hurricane Restoration Priority	<input type="text" value="65%"/>	(%)

Figure 6-4. Screenshot of Penal Factor and Priority Factor Input

7 Costs and Benefits Analysis Module

The cost and benefits analysis module computes cost and reliability results for two cases (e.g., the status quo and a proposed undergrounding project) and allows these costs and reliability results to be compared. The user is able to compare the results in various ways, assuming the “status quo” case is both lower cost and lower reliability than the proposed project case, this allows the incremental costs to perform the project to be compared with the incremental reliability benefits; given additional necessary information such as discount rate, the net present value or the benefit cost ratio of the project (with or without considering intangible benefits and costs) can be assessed from the simulation results. In reality, there will typically be a variety of cost and reliability differences; the cost and benefits analysis module is designed to easily examine these differences.

The costs and benefits analysis module requires a significant amount of data from the user, with data organized into the following three categories:

Data Categories

- Initial costs and recurring annual spending
- Reliability performance during non-storm and storm conditions
- Intangible benefits

7.1 Initial Costs and Recurring Annual Spending

Each defined equipment class has the ability to be assigned both an initial cost and an annual recurring cost. The spreadsheet interface where this data is entered is shown in Figure 7-1.

Equipment	Category	Unit	Initial Cost (\$)				
			Project	Remove Existing	Hardening	Installation	Miscellaneous
Grade B Poles	Poles		0				
Grade C Poles	Poles		0				
Span	Spans		0	-\$55,062.71			
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 1)		15			\$4,927.87	
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 2)		2				
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 3)	#	0				
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 4)	#					
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 5)	#					
Pad-mount Transformer	Underground Equipments (Out of Surge Zones)	#					
Underground Cable	Underground Equipments (Storm Surge Zone Cat 1)	Miles				\$1,435,959.15	
Underground Cable	Underground Equipments (Storm Surge Zone Cat 2)	Miles					
Underground Cable	Underground Equipments (Storm Surge Zone Cat 3)	Miles					
Underground Cable	Underground Equipments (Storm Surge Zone Cat 4)	Miles					
Underground Cable	Underground Equipments (Storm Surge Zone Cat 5)	Miles					
Underground Cable	Underground Equipments (Out of Surge Zones)	Miles					

Figure 7-1. Screenshot of Equipment Related Initial Cost Input Section

The interface shown above only deals with the equipment related costs. Non-equipment related costs are entered in a separate worksheet as shown in Figure 7-2.



Cost Item	Unit	Initial Costs (\$)	Quantity		Recurring Costs (\$/Unit/Year)	Intangible Costs (\$/Unit/Year)
			Before Project	After Project		
Install Street Light (U)	#	\$53,551.31	0	1		
Locate & Verify (U)	#	\$7,255.06	0	1		
Vegetation Management	Miles		1.7	0	\$1,233.00	
Pole Attachment Revenue	#		101	0	-\$4.38	
Survey Work (U)	#	\$43,898.00	0	1		
Sidewalk Fix	Miles	\$560.00	0	1		
Locates	Miles	\$1,575.00	0	1		
Survey	Miles	\$951.72	0	1		
Bores	#	\$159,291.60	0	1		
Hand Trench	#	\$36,125.60	0	1		
Machine Trench	#	\$16,893.70	0	1		
Underground Locates	#		0	396	\$9.00	

Figure 7-2. Screenshot of Non Equipment Cost Input Section

Three categories are allowed when entering a non-equipment related cost. The categories are the following:

Cost Category

- Initial Cost
- Recurrent Cost
- Intangible Cost

The user provides the best estimate of different initial costs and annual recurrent costs. It is usually difficult to quantify the intangible costs in engineering or economic terms; the user may provide the intangible costs if he chooses to. After the user provides all necessary cost information, the application sums up the initial costs and then calculates the annually recurring cost both before and after the undergrounding project.

7.2 Reliability Performance

As discussed previously, the hurricane simulation helps to estimate the total amount of damaged equipment and the total number of customer interruption hours. To perform a cost and benefit analysis, it is useful to translate both of these values into dollars. Figure 7-3 shows the interface where users can provide the cost information related with storm restoration. The amount of equipment damage in each category is multiplied by its unit repair cost to estimate the cost required to fix damaged equipment in this category. The costs associated with all categories are then summed to obtain the total restoration cost. Similarly, the total amount of customer interruption hours is multiplied by the customer cost of reliability to obtain the total cost of customer interruptions. These calculations are performed for both the before and after conversion scenarios.



Equipment	Category	Unit	Repair Cost (\$/Unit)
Grade B Poles	Poles		\$2,500.00
Grade C Poles	Poles		\$2,500.00
Span	Spans		\$1,500.00
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 1)		\$5,000.00
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 2)		\$4,500.00
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 3)		
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 4)		
Pad-mount Transformer	Underground Equipments (Storm Surge Zone Cat 5)		
Pad-mount Transformer	Underground Equipments (Out of Surge Zones)		
Underground Cable	Underground Equipments (Storm Surge Zone Cat 1)		\$11,000.00
Underground Cable	Underground Equipments (Storm Surge Zone Cat 2)		\$11,000.00
Underground Cable	Underground Equipments (Storm Surge Zone Cat 3)		
Underground Cable	Underground Equipments (Storm Surge Zone Cat 4)		
Underground Cable	Underground Equipments (Storm Surge Zone Cat 5)		
Underground Cable	Underground Equipments (Out of Surge Zones)		

Figure 7-3. Screenshot of Storm Reliability Related Cost Input Section

Similarly, the cost information associated with the reliability under non-storm conditions is needed. Figure 7-4 shows the interface for this task. This information allows for non-hurricane outage restoration costs to be computed for both the before and after conversion scenarios.

Equipment	Category	Unit	C	Reliability Data			
				Failure Rate (λ)	Average Outage Time	Cost/Failure	Crew
Grade B Poles	Poles			0.02	5	500	
Grade C Poles	Poles			0.01	5	600	
Span	Spans	Miles		0.015	4	300	
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 1)			0.05	6	1000	
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 2)			0.05	6	1000	
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 3)			0.05	6	1000	
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 4)			0.05	6	1000	
Pad-Mount Transformer	Pad-mount Transformers (Surge Zone Cat 5)			0.05	6	1000	
Cable	Cables (surge Zone Cat 1)	Miles		0.05	10	2000	
Cable	Cables (surge Zone Cat 2)	Miles		0.05	10	2000	
Cable	Cables (surge Zone Cat 3)	Miles		0.05	10	2000	
Cable	Cables (surge Zone Cat 4)	Miles		0.05	10	2000	
Cable	Cables (surge Zone Cat 5)	Miles		0.05	10	2000	

Figure 7-4. Screenshot of Non-storm Reliability Related Cost Input Section

7.3 Intangible Benefits

Some benefit categories are intangible, such as the aesthetic benefits associated with the projects and the improved property values. They are conceptually valid, and are often the main project driving force behind undergrounding. It is typically infeasible to meaningfully quantify them in engineering or economic terms, but the model allows these classes of costs and benefits to be included along with other costs and benefits. For example, the user can define a cost category of “improved aesthetics” and assign a value of \$100 million after a project is completed. The model will keep track of these costs, but it is simply reflecting the value inputted by the user. If users decide to include these factors, they can provide the best estimates for their individual cases in the interface shown in Figure 7-2.

In summary, the *ex ante* methodology utilizes the user provided cost information along with the results from its hurricane simulation module, infrastructure damage model, and system restoration model to analyze the costs and benefits of a particular undergrounding project.

8 Model Applications

The developed *ex ante* methodology is applied to the four case studies developed in Phase 2. These four recent projects where significant portions of overhead facilities have been moved underground were selected by the Steering Committee with input from Quanta Technology. To ensure that the results of the studies can be applied in different settings, the projects were selected in an attempt to represent different regions of the state, topography, urbanization (city versus rural), type of utility (investor-owned, co-op, or municipal-owned), and other factors. The geographic locations of the selected case studies are shown in Figure 8-1, and a summary of the selected case studies is shown in Table 8-1.



Figure 8-1. Location of Case Studies

Table 8-1. Summary of Case Studies

Project	Utility	Year of Conversion	Circuit Miles of New Underground
Sand Key	Progress Energy Florida	1996	3.4
Allison Island	Florida Power & Light	2000	1.0
County Road 30A	CHELCO	2006	0.8
Pensacola Beach	Gulf Power	2007	6.8

As concluded in Phase 2 report, there is not sufficient data to compare the output of the *ex ante* model to historical realized benefits. There is not even enough data to determine upper and lower bounds of poten-

tial results. This study of model applications aims to provide insights into how different variables might affect costs and benefits of undergrounding instead of trying to replicate realized benefits from any of these case studies.

8.1 General Parameter Settings

It must be understood that the methodology requires many parameters and many assumptions. For many of these parameters and assumptions, there is little basis in historical data and expert judgment must be used. It is beyond the scope of this project to recommend parameters and assumptions. The tool should be viewed as a “calculator” and it is the responsibility of the user to make appropriate decisions about input parameters and assumptions. In order to apply the *ex ante* methodology to the projects, a set of parameters have been selected and a set of assumptions have been made. These parameters and assumptions do not indicate the actual system performance and utility practice.

The costs and benefits analysis of an undergrounding project examines the system incremental costs (or benefits) after the overhead systems are converted to underground. In other words, the analysis investigates if a system gains any benefits by the conversion and how much the benefits (or costs) are if any. Therefore, a set of fixed overhead system parameters is used as a benchmark and the underground system parameters are varied in an attempt to provide insights into how these variables might affect costs and benefits of undergrounding.

- **Failure Rate and Repair Time**

Table 8-2 lists the typical failure rate and repair time of different equipments [31] under non-storm conditions.

Table 8-2. Summary of Equipment Failure Rate and Repair Time

	Failure Rate (failures/year/circuit mile)	Repair Time (hours)
Overhead Lines (Primary Trunk)	0.10	4.0
Overhead Lines (Lateral Tap)	0.16	4.0
Underground Cable (Primary Cable)	0.07	10.0
Underground Cable (Secondary Cable)	0.10	10.0
Pad-mount Transformers	0.01	6.5

The overhead equipment failure rates under storm condition are modeled as described in Chapter 5.1 and 5.2. The underground equipment failure rates are roughly estimated using linear functions as described in Chapter 5.3 with the magnitude approximately half of the overhead equipment failure rates. Equal equipment repair times under non-storm conditions and storm conditions are assumed.

- **O&M Costs**

An underground feasibility study [37] shows that the O&M costs (per mile) for overhead and direct-buried underground distribution systems are comparable (the duct bank underground systems cost more). These costs include maintenance, repair, preventive maintenance, and service restoration, not including the costs related with tree trimming, wildlife protection, and line patrolling for overhead systems and the costs related with cable locating for underground systems. Parameters based on this study are used in case studies; they are listed in Table 8-3.



Table 8-3. O&M Costs

	Overhead System (\$/mile)	Direct-buried Underground (\$/mile)	Duct Bank Urban Underground (\$/mile)
Typical Value	1000	1000	4000

- **Repair Costs**

There is no document that provides guidance on determining the typical value of equipment repair costs found. It is assumed that the equipment repair costs are identical for both storm conditions and non-storm conditions²². It is also assumed that different overhead equipments have the same repair costs. Typically underground equipments cost more; it is assumed that underground equipments repair costs are twice as the overhead equipments repair costs, unless indicated otherwise; different underground equipments have the same repair costs.

- **Equipment Quantity**

The equipment quantity in the project area can be estimated from the general project information such as the length of the overhead feeder. However, the accurate system-wide equipment quantity is not directly available at current stage. It is assumed that the system-wide overhead equipment quantity is proportional to the project area overhead equipment quantity. The proportion of the project area equipments to the system-wide equipments may affect the starting of the local restoration process given a certain local restoration priority. A scalar number is assigned to each project as shown in Table 8-4. These scalar numbers are chosen with distinguishable disparities in an attempt to provide insights into how this variable might affect costs and benefits of undergrounding. These numbers do not indicate actual utility service territory sizes.

Table 8-4. Assumed System-wide Equipment Quantity Scale

Project	Utility	Scale (system wide : project area)
Allison Island	Florida Power & Light	10,000:1
Sand Key	Progress Energy Florida	5,000:1
Pensacola Beach	Gulf Power	1,000:1
County Road 30A	CHELCO	100:1

It is also assumed that the overhead distribution lines are three times the underground distribution lines [32], so are the related equipment quantities. Among all the underground equipments, it is assumed that half of them locate out of any storm surge zone, and the other half equally distribute among different storm surge zones.

²² In actual applications, the repair costs in storm condition may be significantly higher than non-storm condition due to the crew overtime costs. Since the focus of the comparison is the costs before and after the project instead of costs in non-storm and storm condition, the assumption that the repair cost is the same for storm condition and non-storm condition will not affect the analysis of the test cases.



- **Algorithm parameters**

Most of the customers involved in these projects are residential customers; therefore, many algorithm parameters are estimated based on the residential customer type, unless indicated otherwise.

- **Average Demand per Customer:** 1.4 kW/hr [33]
- **Average Rate:** 0.108\$/kWh [34, 35]

The average demand per customer and average rate are multipliers used to compute the lost revenue for the project area before and after the conversion. Changing these parameters will proportionally change the computed lost revenue, but will not change the ratio of lost revenue before and after the conversion. Therefore, the same parameters are used in all case studies instead of the utility specific values. In an actual application, the actual values for the project area should be used.

- **Cost per Customer Interruption Hour:** \$2.99 for residential customers and \$ 1,000 for commercial customers [36].

Similarly, the same set of cost per customer interruption hour values is used for each case study. In an actual application, the actual values for the project area should be estimated and used.

- **Crew Availability:** It is assumed, unless indicated otherwise, that overhead crew number is twice as the underground crew number; it is also assumed that the maximum crew number is four times as the initial crew number, with 40% of the initial crew as the daily ramp-up crew.
- **Penalty Factors:** An efficiency penalty factor of 50% and a duration penalty factor of 20 (hr) are used in the algorithm, unless indicated otherwise.
- **Hurricane Restoration Priority:** It is set at a medium level of 50%, unless indicated otherwise.

8.2 Sand Key (Progress Energy)

Sand Key project converted approximately 9,500 circuit feet three-phase overhead feeder to 9,000 circuit feet three-phase underground cable. This project involved 3,375 customers of which 94.5% are residential customers. According to the Pinellas County Surge Zones map, majority of the Sand Key project is located in category-1 storm surge zone.

A Monte Carlo simulation of 10,000 hurricane years has been run. This simulation generates 7,077 land-falling hurricanes in Florida²³; 3,104 of them affect the Progress Energy service territory and 591 affect the Sand Key project area. Table 8-5 summarizes the hurricane simulation results in terms of hurricane years.

²³ 2413 category 1 hurricanes, 2221 category 2 hurricanes, 1782 category 3 hurricanes, 579 category 4 hurricanes, and 82 category 5 hurricanes



Table 8-5. Hurricane Simulation Summary

# of Hurricanes (per year)	Years (Affect Florida)	Years (Affect Progress Energy)	Years (Affect Sand Key)
0	4,918	6,896	9,409
1	3,533	2,569	559
2	1,185	459	32
3	293	66	0
4	60	10	0
5	11	0	0
<i>Total</i>	<i>10,000</i>	<i>10,000</i>	<i>10,000</i>

It shows that the project area is not affected by hurricanes most of the time. Therefore, the system performance under non-storm condition is a major component of the costs and benefits analysis. The simulated system annual costs under non-storm condition are listed in Table 8-6.

Table 8-6. System Annual Costs (Non-Storm Condition)

	Before Conversion (Overhead)	After Conversion (Underground)
Equipment O&M	\$1,800.00	\$1,700.00
Other O&M	\$1,653.72	\$3,564.00
Repairs	\$2,380.00	\$1,836.00
Lost Revenue	\$229.62	\$390.57
Total	\$6,063.34	\$7,490.57
Customer Interruption Cost	\$4,540.82	\$7,723.62
Total	\$10,604.16	\$15,214.19
CMI (min)	91,120	154,989

Since the overhead facility O&M costs (per circuit mile) and underground facility O&M costs are comparable and the circuit length is similar before and after the conversion, the equipment O&M costs are also comparable.

Table 8-7 lists the utility provided O&M cost data; in this category (other O&M), the underground system costs more than the overhead systems.

Table 8-7. Sand Key Recurring Cost Data

Category	Units	Quantity Before	Quantity After	\$/yr per Unit
Vegetation Management	Miles	1.7	0	\$1,233.00
Pole Attachment Revenue	#	101	0	-\$4.38
Underground Locates	#	0	396	\$9.00

The total non-storm condition equipment repair costs is a function of the equipment failure rate and the equipment repair costs. The low underground cable failure rate leads to a lower repair cost for the underground system as shown in the simulation results.



If the underground equipment repair cost is changed with other parameter unchanged, the total repair costs can either go higher or stay lower than the overhead system cost, as shown in Figure 8-2.

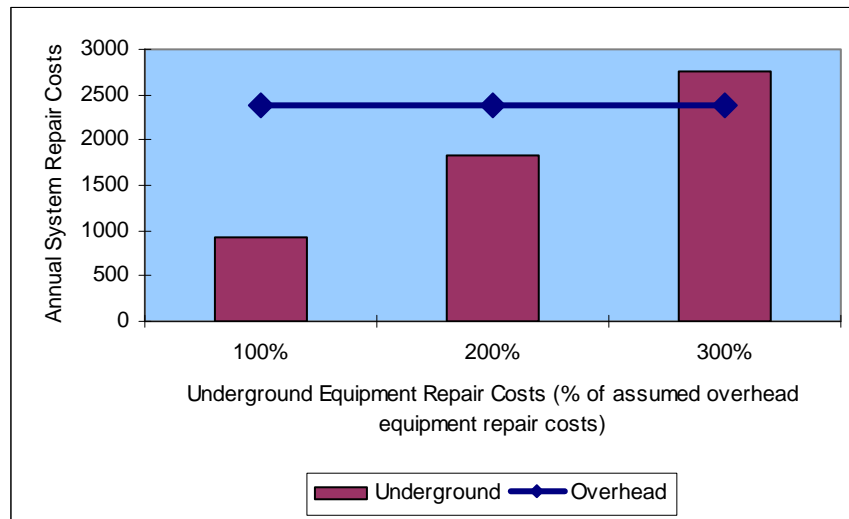


Figure 8-2. System Repair Costs vs. Equipment Costs (Underground)

The lost revenue and customer interruption costs depend on the CMI (customer minutes interrupted) under non-storm condition, which is a function of the equipment failure rate and repair time. It is well known that underground equipments generally have smaller failure rates but longer repair time. This simulation shows that the CMI for underground systems is 70% higher than the overhead systems. If the underground system includes a redundancy mechanism such as a spare run of cable or a loop design to increase the reliability, then the CMI for underground systems can be reduced to about 1/3 of the overhead systems.

System performance under hurricane conditions is the main focus of the costs and benefits analysis. Table 8-8 lists the simulation results, with a 20th, 50th, and 80th percentile level. A 20th percentile indicates the simulated costs and benefits will reflect values where 80% of simulated years with hurricanes affecting the project area are higher and 20% are lower; a 50th percentile indicates the simulated costs and benefits will reflect values where 50% of simulated years with hurricanes affecting the project area are higher and 50% are lower (it is a median value instead of an average value); an 80th percentile indicates the simulated costs and benefits will reflect values where 20% of simulated years with hurricanes affecting the project area are higher and 80% are lower.

Table 8-8. System Annual Costs (Storm Condition)

	20%		50%		80%	
	Before	After	Before	After	Before	After
Repairs	\$806.81	\$885.33	\$3,845.09	\$6,333.60	\$9,562.46	\$9,118.20
Lost Revenue	\$4,233.43	\$2,342.23	\$10,153.13	\$9,144.73	\$31,371.13	\$30,676.49
Customer Interruption Cost	\$83,716.56	\$46,317.86	\$200,779.52	\$180,838.30	\$620,368.28	\$606,631.61
CMI (min)	1,679,931	929,455	4,029,021	3,628,862	12,448,861	12,173,209

Similar to the non-storm condition, the system repair costs under storm condition depend on the number of equipments damaged in the project area. According to the results shown in Table 8-8, the underground system cost is significantly more than the overhead system cost at the 50th percentile; but comparable with the overhead system cost at both the 20th and 80th percentiles. It can be explained by the distribution of hurricane induced equipment repair costs as show in Figure 8-3. The overhead equipment repair costs concentrate at the lower end with a long tail while the underground equipment repair costs spread out with more costly events²⁴, especially in the mid-range of the cost scale. When the project area is affected by a strong hurricane, the current adopted linear damage model generates a smaller underground equipment failure rate compared to the exponential-like functions for overhead equipments, so the underground system repair costs at 80th percentiles are smaller than the overhead system.

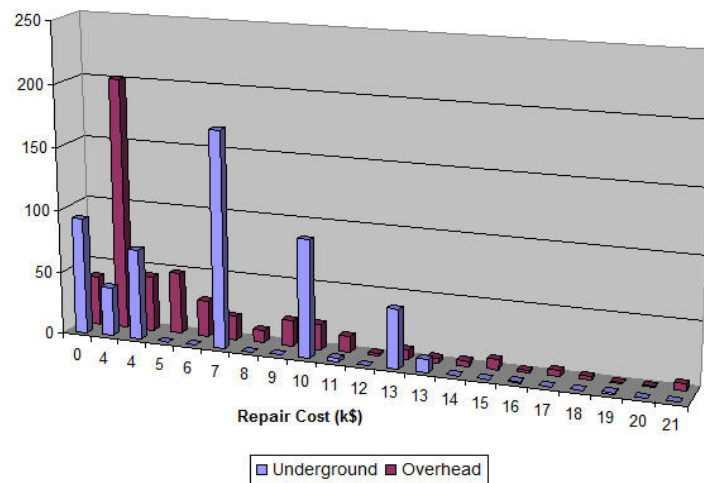


Figure 8-3. Distribution of Hurricane Induced System Repair Costs

All the lost revenue, customer interruption costs, and CMI are closely related with the interruption duration. When the project area is affected by a weak hurricane, less underground equipments are damaged due to their low equipment failure rates so the interruption duration is relatively short. When the project area is affected by a strong hurricane and more underground equipments are damaged, the long underground equipment repair time becomes a key factor to delay the restoration and cause longer interruption duration. As shown in Table 8-8, underground systems have smaller lost revenue, customer interruption costs, and CMI at all three (20th, 50th, and 80th) percentiles, but the advantage of the underground system over the overhead system is less prominent when stronger hurricanes hit the project area.

8.3 Allison Island (Florida Power & Light)

The underground conversion for Allison Island was completed in November of 2000. Allison Island used to be served by a 0.5 mile-long two-phase radial tap from a primary main trunk. The new underground system loops to the end of Allison Island and back, and is therefore 1.0 miles in length. The project in-

²⁴ Because the current underground equipment failure rates under hurricanes are discrete function, there are spikes, with a continuous function developed when more data is available, it can be smoothed.



volves 45 residential customers. According to the Dade County Surge Zones map, the Allison Island is located in category-1 storm surge zone.

Allison Island is located in the southeast region of Florida which is more likely to be hit by a strong hurricane (category 4 or 5)²⁵. A Monte Carlo simulation of 10,000 hurricane years generates 7,089 landfalling hurricanes in Florida²⁶; 5,283 of them affect the Florida Power & Light and 2,003 affect Allison Island project area.

Table 8-9. Hurricane Simulation Summary

# of Hurricanes (per year)	Years (Affect Florida)	Years (Affect Florida Power & Light)	Years (Affect Allison Island)
0	4961	5934	8200
1	3402	3033	1610
2	1294	874	178
3	281	138	11
4	54	17	1
5	8	4	0
Total	10000	10000	10000

The system performances under non-storm conditions are listed in Table 8-10. Same as the Sand Key project study, the lost revenues and the customer interruption costs of the underground system are significantly lower than the overhead system owe to the low equipment failure rate. But the underground system repair costs are slightly higher than the overhead systems due to the high repair costs.

Table 8-10. System Annual Costs (Non-Storm Condition)

	Before Conversion (Overhead)	After Conversion (Underground)
Equipment O&M	\$500.00	\$1,000
Other O&M	N/A	N/A
Repairs	\$960.00	\$1,040.00
Lost Revenue	\$4.69	\$1.12
Total	\$1,464.69	\$2,041.12
Customer Interruption Cost	\$92.84	\$22.20
Total	\$1,557.53	\$2,063.32
CMI (min)	1,863	446

Allison Island area is affected by more hurricanes and especially category 4 or 5 hurricanes due to its geographic location. Table 8-11 shows that the underground system costs more than the overhead system under the storm condition, except the repair costs at 20th percentile, which is because less underground equipments are damaged during weak hurricanes. When a strong hurricane hits the area and causes catastrophic damages, the high repair costs of underground equipment significantly increase the system repair costs.

²⁵ Please refer to Appendix A for detailed discussion.

²⁶ 2317 category 1 hurricanes, 2300 category 2 hurricanes, 1792 category 3 hurricanes, 587 category 4 hurricanes, and 93 category 5 hurricanes

One possible reason for the high interruption-duration-related costs of the underground system might be the crew availability since it is assumed that the underground crew availability is only half of the overhead crew availability. Figure 8-4 shows the change of the average lost revenue with the increase of underground crew availability. It shows that the average lost revenue becomes less when more underground crews are available for restoration, but when more crews are available for restoration, the initial inefficiency such as the road accessibility becomes the key factor to delay the restoration for both the overhead and underground systems. The long underground equipment repair time results in long interruption duration of the underground system, it further leads to higher lost revenue and customer interruption costs.

The same conclusion can be drawn by examining the scenarios with different penalty factors (the underground crew availability is 50% of the overhead crew availability). As shown in Figure 8-5, when the penalty factor increases, the initial inefficiency plays a more critical role in determining the restoration duration, the difference between overhead system and underground system get smaller. After the initial period, the longer restoration time of underground equipments keep the associated costs higher.

Table 8-11. System Annual Costs (Storm Condition)

	20%		50%		80%	
	Before	After	Before	After	Before	After
Repairs	\$142.34	\$112.67	\$584.84	\$788.67	\$2,194.88	\$4,732.00
Lost Revenue	\$12.64	\$13.66	\$61.54	\$80.42	\$291.79	\$417.05
Customer Interruption Cost	\$249.99	\$270.18	\$1,216.92	\$1,590.29	\$5,770.09	\$8,247.27
CMI (min)	5,017	5,422	24,420	31,912	115,788	165,497

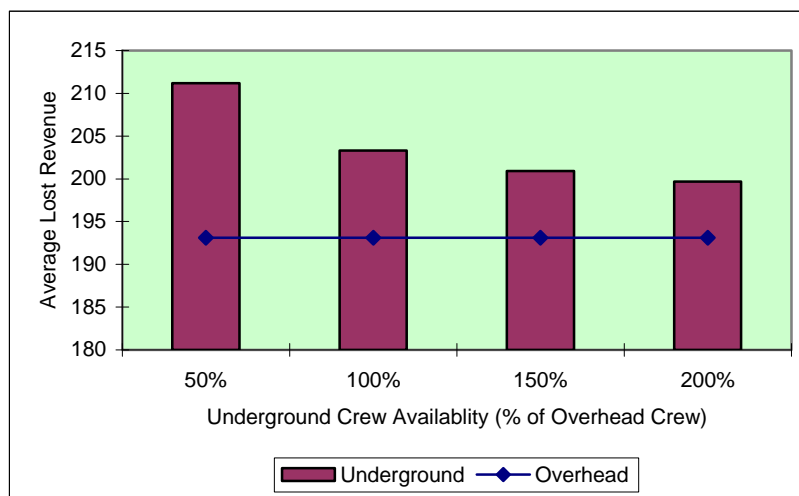


Figure 8-4. Average Lost Revenue vs. Crew Availability (Underground)

Assuming there is a scenario in which equal numbers of overhead crews and underground crews are available and the repair time for overhead equipments and underground equipments are the same. The system performance under storm condition is listed in Table 8-12 (excluding the repair costs which depend on the equipment repair cost instead of restoration duration). The results show that the underground system and



the overhead system have comparable performance with slightly less costs from the underground system at 20th and 50th percentiles.

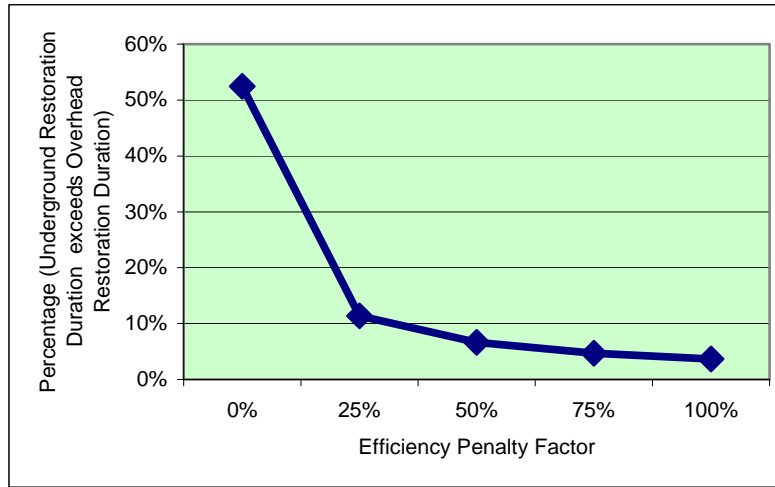


Figure 8-5. Effect of Efficiency Penalty Factor on Underground System Restoration Duration

Table 8-12. System Annual Costs (Storm Condition)

	20%		50%		80%	
	Before	After	Before	After	Before	After
Lost Revenue	\$12.64	\$11.16	\$61.54	\$61.39	\$291.79	\$398.29
Customer Interruption Cost	\$249.99	\$220.64	\$1,216.92	\$1,214.05	\$5,770.09	\$7,876.20

8.4 County Road 30A (CHELCO)

The underground conversion for County Road 30A project was completed in July of 2006. County Road 30A project converted 4,400 feet of three-phase overhead lines to underground cable. The project involves 1200 residential customers. The County Road 30A project area is considered to be located in category-3 storm surge zone according to the Walton County Surge Zones map.

A Monte Carlo simulation of 10,000 hurricane years generates 7317 landfalling hurricanes in Florida²⁷; 1484 of them affect the CHELCO and 1150 affect the County Road 30A project area.

²⁷ 2328 category 1 hurricanes, 2323 category 2 hurricanes, 1807 category 3 hurricanes, 5951 category 4 hurricanes, and 88 category 5 hurricanes



Table 8-13. Hurricane Simulation Summary

# of Hurricanes (per year)	Years (Affect Florida)	Years (Affect CHELCO)	Years (Affect County Road 30A)
0	4899	8624	8913
1	3488	1270	1021
2	1254	104	65
3	298	2	1
4	58	0	0
5	3	0	0
Total	10000	10000	10000

Table 8-14 lists the system performance under non-storm conditions. Different from previous cases, the underground system causes more costs than the overhead system in all the categories other than the *other O&M* calculated from utility provided information as shown in Table 8-15. It is because this project does not include redundant mechanisms to improve the underground system reliability. A larger non-storm underground cable failure rate causes more failures and then results in more annual costs and customer minutes interrupted.

Table 8-16 shows the system performance under storm conditions. Different from previous cases, the underground system significantly outperforms the overhead system because of the small underground equipment failure rate (the project area is located in a category-3 storm surge zone; hurricanes of category 1 and 2 have small impact on the underground system).

Table 8-14. System Annual Costs (Non-Storm Condition)

	Before Conversion (Overhead)	After Conversion (Underground)
Equipment O&M	\$800.00	\$800.00
Other O&M	\$120.00	\$0.00
Repairs	\$1,480.00	\$1,824.00
Lost Revenue	\$81.56	\$138.80
Total	\$2,481.56	\$2,762.8
Customer Interruption Cost	\$1,612.81	\$2,744.82
Total	\$4,094.37	\$5507.62
CMI (min)	32,364	55,080

Table 8-15. County Road Recurring Cost Data

Category	Units	Quantity Before	Quantity After	\$/yr per Unit
Vegetation Management	Miles	0.8	0	\$500
Pole Attachment Revenue	#	16	0	-\$17.50



Table 8-16. System Annual Costs (Storm Condition)

	20%		50%		80%	
	Before	After	Before	After	Before	After
Repairs	\$293.00	\$197.60	\$1,281.02	\$197.60	\$3,323.58	\$1060.80
Lost Revenue	\$517.44	\$116.06	\$1,691.10	\$319.99	\$7,258.08	\$1,781.47
Customer Interruption Cost	\$10,232.44	\$2,295.14	\$33,441.79	\$6,327.94	\$143,529.50	\$35,228.88
CMI (min)	205,333	46,056	671,073	126,982	2,880,191	706,934

8.5 Pensacola Beach (Gulf Power)

Pensacola Beach project converted approximately 2.25 miles of three-phase overhead feeders to 6.84 miles of underground cables, with 1,251 customers involved. The project is constructed in a high density urban area with high rise condos using concrete duct bank with below grade submersible switchgear in vaults which causes the annual operation & maintenance costs about 4 times as the costs of a direct buried underground system as shown in Table 8-3. According to the Escambia County Surge Zones map, the Pensacola Beach is located in category-3 storm surge zone, which is relatively less vulnerable for storm surges.

The project area is a portion of the business core area with both residential customers (about 2/3) and commercial customers (about 1/3). It will increase the cost per customer interruption hour. Since this change affects both overhead and underground system, the simulation still uses the typical value for residential customers.

A Monte Carlo simulation of 10,000 hurricane years generates 6941 landfalling hurricanes in Florida²⁸; 1765 of them affect the Gulf Power and 997 affect Pensacola Beach project area.

Table 8-17. Hurricane Simulation Summary

# of Hurricanes (per year)	Years (Affect Florida)	Years (Affect Gulf Power)	Years (Affect Pensacola Beach)
0	4997	8395	9058
1	3442	1453	888
2	1226	144	53
3	296	8	1
4	36	0	0
5	3	0	0
Total	10000	10000	10000

Table 8-18 lists the system performance under non-storm conditions. The long underground circuit (6.8 miles) causes a significant increase in equipment O&M costs and repair costs. However, the reliability related performance such as lost revenue and customer interruption costs still benefit from the low equipment failure rate.

²⁸ 2297 category 1 hurricanes, 2266 category 2 hurricanes, 1739 category 3 hurricanes, 551 category 4 hurricanes, and 88 category 5 hurricanes



Table 8-18. System Annual Costs (Non-Storm Condition)

	Before Conversion (Overhead)	After Conversion (Underground)
Equipment O&M	\$2,550.00	\$27,360.00
Other O&M	N/A	N/A
Repairs	\$6,040.00	\$12,273.60
Lost Revenue	\$311.35	\$139.71
Total	\$8,901.35	\$39,773.31
Customer Interruption Cost	\$6,157.01	\$2,762.72
Total	\$15,058.36	\$42,536.03
CMI (min)	123,552	55,439

Table 8-19 lists the system performance under storm conditions. The underground system outperforms the overhead system in general. However, the advantage of the underground system over the overhead system is not as significant, because this project has a long underground circuit (about three times as the overhead feeder length).

Since the storm surge has been a major concern for Gulf Power service territories, the underground equipment failure rates are set as 150% of their typical values to further examine their impact on the costs and benefits analysis. The results in Table 8-20 show that the underground system further loses its current advantage over the overhead system.

Table 8-19. System Annual Costs (Storm Condition)

	20%		50%		80%	
	Before	After	Before	After	Before	After
Repairs	\$3,203.74	\$1,329.64	\$8,132.56	\$7,977.84	\$19,848.42	\$31,911.36
Lost Revenue	\$2,824.74	\$947.70	\$8,353.11	\$7,780.53	\$17,928.74	\$16,123.05
Customer Interruption Cost	\$55,859.52	\$18,740.91	\$165,183.78	\$153,860.92	\$354,543.31	\$318,835.51
CMI (min)	1,120,927	376,072	3,314,725	3,087,510	7,114,581	6,398,037

Table 8-20. System Annual Costs (Storm Condition) with Higher Equipment Failure Rates

	20%		50%		80%	
	Before	After	Before	After	Before	After
Repairs	\$3,203.74	\$1,329.64	\$8,132.56	\$11,966.76	\$19,848.42	\$47,867.04
Lost Revenue	\$2,824.74	\$983.93	\$8,353.11	\$9,184.87	\$17,928.74	\$20,102.18
Customer Interruption Cost	\$55,859.52	\$19,457.28	\$165,183.78	\$181,632.09	\$354,543.31	\$397,523.27
CMI (min)	1,120,927	390,447	3,314,725	3,644,791	7,114,581	7,977,056



8.6 Case Study Summary

Analyzing the cases studies with the model is done to provide insights into how different variables affect costs and benefits of undergrounding; the purpose is not to replicate actual realized benefits or to anticipate future benefits. The algorithm parameters used in the case studies do not represent the actual practice of individual cases; the user may draw a different conclusion about the benefits and costs of a specific undergrounding conversion project when a set of parameters and cost data representing the actual situation are used.

From the studies of these four case projects, an undergrounding project can either gain benefits or induce more costs, depending on the feeder design (e.g., feeder length), geographic location (e.g., different storm surge zones), and actual system restoration practice (e.g., crew availability). However, this analysis is based on assumed parameters. When actual utility-provided parameters are provided, the *ex ante* methodology is able to generate an analysis representing actual scenarios.

A user can use this “calculator” to analyze the costs and benefits of different project design plans. For example, it can help to determine if a project should include a redundancy feeder to improve the feeder reliability. A user can also use this “calculator” to plan the hurricane restoration operations in order to maximize the benefits from an undergrounding conversion. For example, it can provide useful information in determining how to arrange the available crew resource and planning the restoration practice accordingly.



9 Conclusions

The conversion of overhead electric power distribution facilities to underground has been a topic of discussion in Florida for more than twenty years. The topic has been studied, discussed, and debated many times at the state, municipal, and local levels. Overhead construction is the standard in Florida, but all investor-owned utilities are required to have a process where customers can opt to underground existing overhead service by paying the incremental cost. For municipals and cooperatives, the decision to underground is left to local citizen boards.

It is well-known that the conversion of overhead electric distribution systems to underground is costly, and these costs almost always exceed quantifiable benefits. This conclusion is reached consistently in many reports that range from state-wide studies to very small projects. However, no consistent approach has been used to compute the costs and benefits of proposed undergrounding projects, making studies difficult to interpret and use for making decisions.

As more areas in Florida begin to explore the possibility of underground conversion, it becomes increasingly desirable to have a consistent methodology to assess the associated costs and benefits. Results from a trusted approach can provide insight, lead to better projects, aid in customers communicating with utilities, and potentially help guide certain regulatory approaches.

This report has presented a methodology capable of estimating the costs and benefits of potential undergrounding projects. The methodology can also be used to compute the costs and benefits of other activities that have an impact on hurricane performance such as the hardening of overhead systems. The methodology used a detailed simulation with the following components: hurricane model, equipment damage model, restoration model, cost model, and benefit model. This methodology has been implemented in a spreadsheet application.

It must be understood that the methodology requires many parameters and many assumptions. For many of these parameters and assumptions, there is little basis in historical data and expert judgment must be used. It is beyond the scope of this project to recommend parameters and assumptions. The tool should be viewed as a “calculator” and it is the responsibility of the user to make appropriate decisions about input parameters and assumptions.

<p>The methodology and corresponding tool described in this report should be viewed as a “calculator.” It is the responsibility of the user to make appropriate decisions about input parameters.</p>

Even if utilities do not have a large amount of data from which to base assumptions and parameter selections, much insight can be gained by using the tool. In fact, the tool can be used to determine the sensitivity of results to certain assumptions and certain parameters.

The conversion of overhead electric infrastructure to underground is of interest around the country and around the world. Often times underground conversion proposals are either pursued or rejected without a systematic analysis of costs and benefits. The methodology presented in this report is an attempt to add consistency and thoroughness to these types of analyses. At present, the methodology is specific to the state of Florida, but the general approach is valid wherever extreme weather events have the potential to wreck havoc on electricity infrastructure.



Appendix A: Hurricane Modeling

A.1 Introduction

Appendix A outlines the development of a probabilistic hurricane simulation module, which is customized specifically for Florida. This proposed probabilistic hurricane simulation module is able to determine the number of hurricanes landed in Florida in a simulated year. For each simulated hurricane, the landfall characteristics are assigned; these features include: landing positions, approach angle or direction, translation velocity or forward speed, central pressure difference, maximum wind speed, radius of maximum wind, as well as the gust factor used to estimate the peak gust speed. While the simulated hurricane moves across Florida, its inland features such as the maximum wind speed decay rate, the central pressure difference filling rate, and the radial wind field profile are also modeled. Although this module can generate all the detailed information aforementioned for each simulated hurricane, it is designed to generate an expected effect which is derived from the average effect of a large number of simulations as opposed to reproducing the effects of a specific hurricane from the historical database.

Besides simulating the hurricane characteristics, the module also tracks the percentage of service territory impacted for both Investor-Owned Utilities (IOUs) and Cooperative Utilities (Co-ops) and the average wind speed experienced within the affected areas for different utilities. Furthermore, this module can track the wind speed at a given location for any simulated hurricane. These functions allow the hurricane simulation module to be linked with infrastructure damage module in order to estimate the expected hurricane damage.

This hurricane simulation module is developed in Microsoft Excel with the extensive use of VBA programming.



A.2 Available Data

The development, especially the parameter calibration, of individual hurricane characteristic modules heavily relies on the information extracted from historical data provided by North Atlantic Hurricane Data Base (HURDAT). HURDAT, compiled by the Atlantic Oceanographic and Meteorological Laboratory at National Oceanic & Atmospheric Administration (NOAA), is the most complete and reliable source of data for North Atlantic hurricanes available²⁹. This database has been widely employed by hurricane researches and cited in many meteorological publications.

HURDAT consists of position and intensity estimates at six hour intervals for tropical cyclones (including hurricane, tropical storms, and subtropical storms) dating back to 1851. The data and records in HURDAT are less reliable during the nineteenth and early twentieth centuries, and are increasingly reliable from the early twentieth century to present day. Key hurricane features recorded in HURDAT are central position (to the nearest 0.1 degree latitude and longitude), direction (to the nearest 5 degree with North), translation speed (or forward speed), maximum sustained wind speed (1-minute at 10-m height) as well as the Saffir-Simpson category, and central pressure for some latest hurricanes. The Saffir-Simpson scale is shown in Table A1.

Table A1. Saffir-Simpson Scale

<i>Category</i>	<i>Minimum Central Pressure (mb)</i>	<i>Maximum Sustained Wind Speed (mph)</i>	<i>Storm Surge (ft)</i>
5	<920	≥155	≥18
4	920-944	130-155	13-18
3	945-964	110-130	9-12
2	965-979	94-110	6-8
1	≥980	74-94	4-5
Tropical Storm	-	39-74	0-3
Tropical Depression	-	0-39	0

The average number of landfall hurricanes in Florida in one decade is 7. Figure A1 presents the hurricane frequency by decade. It shows that the hurricane occurrence during the period from 1871 to 1950 is more frequent than the period from 1951 to 2000. From 2001 to 2005, which is only half a decade, there are already 7 hurricanes in record (all the 7 hurricanes occurred in 2004 and 2005).

²⁹ HURDAT is currently undergoing re-analysis in order to improve the data quality, but it still is the best available data source so far

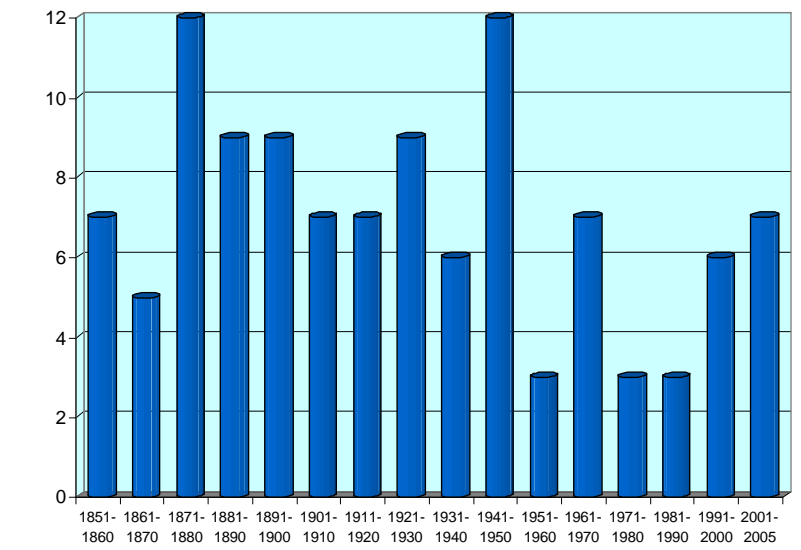


Figure A1. Histogram of Hurricane Frequency (by Decade)

Since HURDAT records the storm information every 6 hours, it usually does not contain the exact landing information such as time and positions (in terms of latitude and longitude) for hurricanes³⁰ landed in the U.S., but the states where hurricanes landed are recorded. For those hurricanes landed in Texas or Florida, their landing areas are further narrowed down to different regions of that state. Florida is divided into four regions: northwest, northeast, southwest, and southeast, as the approximate Florida coastline shown in Figure A2. The north-south dividing line is from Cape Canaveral to Tarpon Springs, and the dividing line between west-east Florida goes from 82.69°W at the north Florida border with Georgia and due south along longitude 80.85°W.

³⁰ Only the landing information of hurricane is included in HURDAT, the landing information of tropical storms and subtropical storms is not included.



Figure A2. Approximate Florida Coastline

There are 112 hurricanes which made landfall in Florida during the period from 1851 to 2005 recorded in HURDAT. The summary statistics of the hurricane occurrence in different regions of Florida are presented in Table A2.

Table A2. Hurricane Occurrence in Different Regions of Florida

	<i>Category 1</i>	<i>Category 2</i>	<i>Category 3</i>	<i>Category 4</i>	<i>Category 5</i>	<i>Total</i>
<i>Northwest</i>	20	13	13	0	0	46
<i>Southwest</i>	12	7	6	3	1	29
<i>Southeast</i>	8	9	10	3	1	31
<i>Northeast</i>	3	3	0	0	0	6
<i>Total</i>	43	32	29	6	2	112

As shown in the table, the northwest region has experienced the most landfall hurricanes and the northeast region has experienced the fewest. Neither of the southern regions has seen as many landfall hurricanes as the northwest region, but southern regions are more likely to be hit by Category 4 or 5 storms: both the southwest region and the southeast region have three Category 4 hurricanes and one Category 5 hurricane on record, while northern regions have none.

HURDAT doesn't contain accurate hurricane landing information; a possible alternative way to directly get this set of information is to collect from the Tropical Cyclone Report for each hurricane published by NOAA. However, even these reports only provide estimates; and some do not have landfall information included, such as the report for hurricane IVAN. As a result, instead of manually collecting available landfall information from all the NOAA reports (only dating back to 1958), the hurricane landing parameters are estimated based on an approximate Florida coastline as shown in Figure A2.



Among the central positions recorded on six-hour interval for any landfall hurricane, the one closest to the approximated Florida coastline is identified as the landfall position; the corresponding record is considered as the one containing the landfall information so that other features including approach angle, translation velocity, and maximum wind speed can be identified.

Table A3 uses landfall hurricanes in 2004 as examples to compare the estimates based on six-hour interval data with the estimates reported in Tropical Cyclone Reports. It can be seen that the difference between two sets of landfall information is statistically insignificant.

Table A3. Comparisons of Reported Landfall Information and the Estimates

		<i>Latitude</i>	<i>Longitude</i>	<i>Central Pressure</i>	<i>Wind Speed</i>	<i>Comment</i>
Frances	<i>Estimate</i>	27.2	80.2	960	105	
	<i>Report</i>	27.1	80.2	960	103.5	“landfall at southern end of Hutchinson Island, FL”
Charley	<i>Estimate</i>	26.1	82.4	947	145	
	<i>Report</i>	26.6	82.2	941	149.5	“landfall near CayoCosta, FL”
Ivan	<i>Estimate</i>	30	87.9	943	120	
	<i>Report</i>	N/A	N/A	N/A	N/A	N/A
Jeanne	<i>Estimate</i>	27.3	80.6	953	110	
	<i>Report</i>	27.2	80.2	950	126.5	landfall at southern end of Hutchinson Island just east of Stuart, Florida



A.3 Probabilistic Hurricane Modeling

- **Method Selection**

Only few complete hurricane models such as HAZUS-MH hurricane model developed by Federal Emergency Management Agency (FEMA) are available in public domain. HAZUS-MH hurricane model is currently designed for potential residential structural damage estimation. Because the tool aims to assess the economic loss instead of simulating hurricane information, the hurricane model in HAZUS-MH is embedded with limited intermediate results such as sustained and peak gust wind speed presented to users. The lack of full control of the hurricane simulation inevitably causes certain difficulties in applying the HAZUS-MH to assess hurricane damage to utility infrastructures, which is not its original target population.

The proposed probabilistic hurricane simulation module is based on the same historical hurricane database HURDAT as in the HAZUS-MH hurricane model, uses similar assumptions as HAZUS-MH, and adopts the same equations as HAZUS-MH for a large portion of hurricane characteristics. But this module also has several differences from the HAZUS-MH hurricane model in order to better serve the purpose of this specific project and to reduce the computational demand (the detailed technical difference between these two models will be presented in the subsequent sections of this appendix). This said, this hurricane module is customized for the specific purpose of evaluating the costs and benefits of distribution underground conversion and offers more flexibility since all the features can be modified or adjusted by the users as needed.

- **Probabilistic Modeling**

Various probabilistic models have been developed to model different hurricane characteristics in order to simulate a complete hurricane. The modeled characteristics include:

Modeled Hurricane Characteristics

- Annual hurricane frequency by region
- Landfall position expressed in latitude and longitude
- Approach angle at landfall (forward direction)
- Translation velocity (forward speed)
- Central pressure difference at landfall and its filling
- Maximum wind speed at landfall and its decay
- Gust factor
- Radius of maximum wind
- Radial wind field profile

Hurricane features and effects may be highly idiosyncratic. For example, the center of a hurricane may not make landfall but it can still affect the state with its outer cloud cluster, the trajectory may not follow a straight line path through land, or some hurricanes come back to the state after they leave. However, this probabilistic hurricane module is designed to simulate a statistically general hurricane year for Florida; in other words, it is designed to simulate expected effects based on the average impact of a large number of simulations rather than track every single possible hurricane scenario.

Currently there are only 112 historical landfall hurricanes in Florida; it is not feasible to extract statistically representative information for many different scenarios. Therefore, the following assumptions are made for the modeling:

1. When extracting information from HURDAT, only the hurricanes landed in Florida are included. It has been observed that HURDAT already includes some “near-miss hurricanes” such as Ivan (2004) and Elena (1985) whose center did not land in Florida but their outer cloud clusters did. For these near-miss hurricanes and those hurricanes landing in neighboring states such as Alabama, Mississippi, the module can incorporate their effects by tuning the parameter for hurricane occurrence in the northwest regions.
2. Only one landfall is considered for each hurricane; this is generally true for Florida. For rare cases in which a hurricane makes more than one landfalls, it will be considered as separate hurricanes in simulation.
3. The hurricane wind speed is assumed constant until landfall since only the hurricane intensity after its landfall is of interest; in other words, the wind speed before landfall is always the same as when it lands. The wind speed decays after its landfall due to frictions and insufficient continuous moisture.
4. The hurricane translation speed is held constant for each simulated storm.
5. A hurricane generally follows a curvature. However, it is observed that the duration of a hurricane in Florida is usually short because of its narrow shape and most of the historical hurricane tracks are straight lines (Figure A3 shows the 2004-2005 season Florida hurricane tracks). The authors believe that it is reasonable to assume that storms travel along a straight path when they move across Florida.

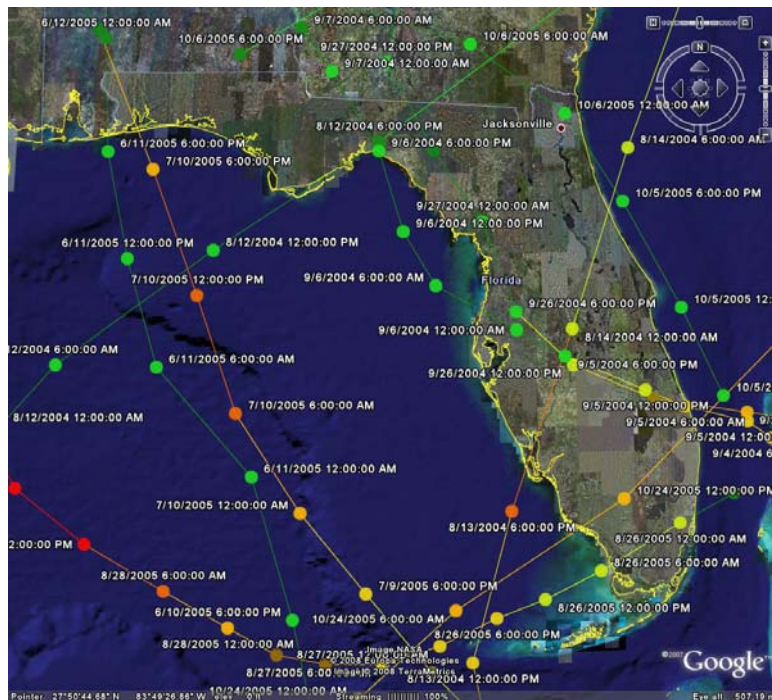


Figure A3. Tracks of Charley (2004), Hermine (2004), Jeanne (2004), Frances (2004), Bonnie (2004), Tammy (2005), Wilma (2005), Katrina (2005), Arlene (2005), and Dennis (2005).

A major difference between this simulation approach and HAZUS-MH hurricane model is the simulation starting point. HAZUS-MH model starts from sampling the historical hurricane originating positions while this hurricane module starts from modeling the landfall position in Florida. HAZUS-MH is designed for the entire North Atlantic coastal region instead of specifically for Florida, so many of its simulated hurricanes may not affect Florida at all; which significantly increases its computational demands. In addition, the simulated landfall rate in different regions of Florida may deviate from the actual historical information as explained in the HAZUS-MH technical manual [18]. The proposed simulation module starts directly from the historical data related to Florida alone, which not only reduces the computational time but also fits the local landfall patterns better. This makes the module “customized” for Florida only, while HAZUS-MH is a very good tool for the entire coastal region.

- **Occurrence**

Annual hurricane frequency has been successfully modeled parametrically using Poisson distribution and negative binominal distributions [10, 11, 12, 15]; the difference between Poisson distribution and negative binominal distribution in modeling annual hurricane frequency is negligible [10]. The Poisson distribution is chosen due to its simplicity.

The Poisson distribution expresses the probability of a number of events occurring in a fixed period of time if these events occur with a known average rate and independently of the time since the last event; it is modeled as:

$$f(h) = \frac{e^{-\lambda} \lambda^h}{h!}; \quad h = 0, 1, 2, \dots,$$

where h is the number of landfall hurricanes per year, λ equals to the expected (average) number of hurricanes that land in Florida during a given year, and $f(h)$ is the probability of h hurricanes landed in Florida in a given year. The probability mass function is shown in Figure A3, where the horizontal axis is h . The function is discrete, the connecting lines are only guides for the eye and do not indicate continuity.

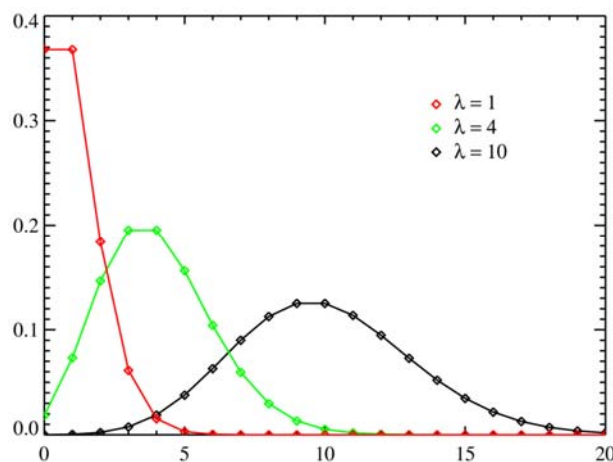


Figure A3. Probability Mass Function of Poisson Distribution

There are several ways to estimate the parameter λ ; the maximum likelihood estimator (best estimate) of λ is simply the mean value of the sample data. The statistics of hurricane frequency in each region are listed in Table A4.

Table A4. Hurricane Occurrence Statistics in Different Regions of Florida

Region	Northwest	Southwest	Southeast	Northeast
Mean	0.29677	0.18710	0.20000	0.03871

- **Landing Position**

The hurricane occurrence is modeled on a regional basis; it does not make sense for a hurricane simulated to occur in northwest region of Florida has a landfall position in the northeast or southeast region. So the hurricane landing positions are also modeled individually in different regions.

The landing position of a simulated hurricane is statistically assigned according to the distribution of historical hurricane landing position in the corresponding region. The coastline of each region of Florida is divided into a certain number of bins. The bins are equally sized in terms of the range of latitude or longitude. The distribution of historical hurricane landing positions among those bins forms the base for assigning the landfall location for each simulated hurricane so that the simulated landing positions is consistent with the probability distribution of historical data.

The choice of the bin number can affect the accuracy of simulation: it may be too coarse to include enough details if too few bins are assigned, but it may be too sensitive to data noise if too many bins are assigned, since the historical landing information is estimated from the six-hour interval records and the approximated Florida coastline. In this module, 15 bins are selected for each region. The histogram of landing latitudes in the southwest region of Florida is shown as an example in Figure A4, in which the entire latitude range of a given region is divided into 15 bins, and the distribution of the range of simulated hurricane landing latitudes is proportional to the historical distribution; the range without any historical records is assigned a small probability to avoid absolute safe zone. When the latitude range is determined, a uniform distribution is applied to determine the exact landing location within the range, and to further determine the corresponding landing longitude.

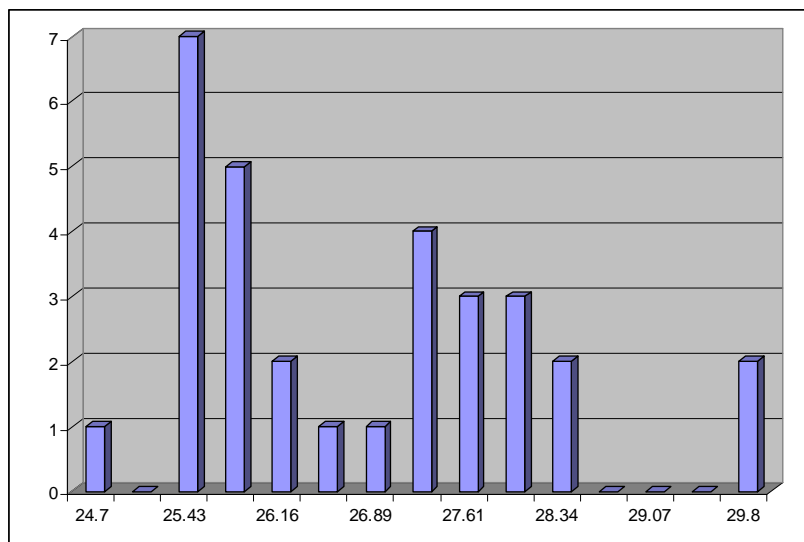


Figure A4. Histogram of Landing Latitude in Southwest Region of Florida

Since many historical landing positions are estimated from the 6-hour interval HURDAT data instead of actual observations; this estimation may cause misclassification of the landing region when a hurricane lands in the boundary area of two adjacent regions. As a result, certain degree of overlap among landing positions in two adjacent regions is allowed to avoid discontinuity.

- **Approach Angle**

The approach angle indicates the heading direction of a hurricane when it comes ashore; it is expressed to the nearest 5 degrees with North as 0 degree, as shown in Figure A5.

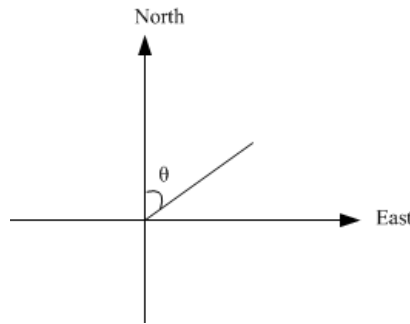


Figure A5. Approach Angle

The approach angle is modeled as a bi-normal distribution [13, 14], which is a weighted sum of two normal distributions as shown:

$$f(\theta) = \frac{a_1}{\sqrt{2\pi}\sigma_{x1}} \exp\left[-\frac{1}{2}\left(\frac{\theta - m_{x1}}{\sigma_{x1}}\right)^2\right] + \frac{(1-a_1)}{\sqrt{2\pi}\sigma_{x2}} \exp\left[-\frac{1}{2}\left(\frac{\theta - m_{x2}}{\sigma_{x2}}\right)^2\right]$$

where m_{x1} and m_{x2} are means for two normal distributions, respectively; σ_{x1} and σ_{x2} are their standard deviations, and a_1 is the weighting factor, these parameters are to be identified from historical data.

Since the trajectory of a hurricane in Florida is assumed to be a straight line, it can be described as

$$y = kx + b$$

with x denoted as the hurricane longitude at any time and y denoted as the latitude of the hurricane at the same time. Once the landing position (*landing_latitude* and *landing_longitude*) and the approach angle θ are determined, both k and b can be calculated to determine the hurricane trajectory:

$$k = \tan(\theta)$$

$$b = \frac{\text{landing_latitude}}{\tan(\theta) * \text{landing_longitude}}$$

- **Translation Velocity**

The translation velocity of a hurricane (m/s) upon landfall can be modeled as a lognormal distribution [15, 16]:

$$f(c) = \frac{1}{c\sqrt{2\pi}\sigma_{\ln c}} \exp\left[-\frac{1}{2}\left(\frac{\ln c - m_{\ln c}}{\sigma_{\ln c}}\right)^2\right]$$

where c is the translation velocity, $m_{\ln c}$ is the logarithmic mean, and $\sigma_{\ln c}$ is the logarithmic standard deviation; both $m_{\ln c}$ and $\sigma_{\ln c}$ are to be identified from historical data.

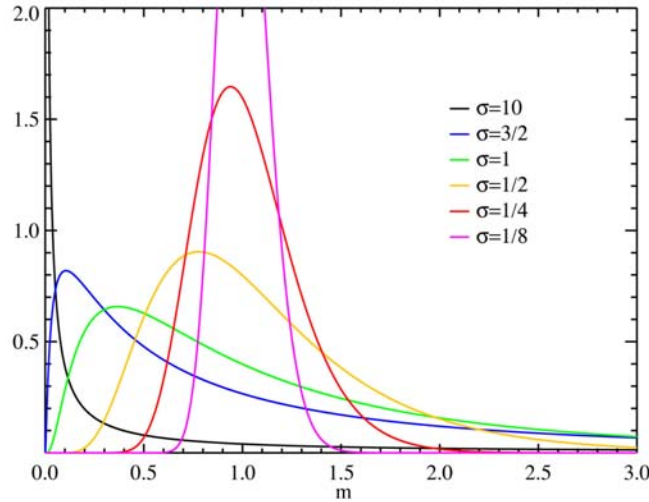


Figure A6. Probability Distribution Function of Lognormal Distribution

It is found that there is a positive correlation between the translation velocity and the storm approach angle along the Gulf Coast and South Atlantic coasts [16]; in order to take into account this correlation, the logarithmic mean of the translation velocity is modeled as: $m_{\ln c} = a_0 + a_1\theta$ in which a_0 and a_1 are to be identified from historical data, and the logarithmic standard deviation $\sigma_{\ln c}$ is treated as a constant.

- **Central Pressure Difference**

The difference between atmospheric pressures at the center and at the periphery of a hurricane, denoted as Δp , plays a very important role in determining the maximum wind speed. The central pressure difference (millibar) is modeled as the Weibull distribution [15, 16]:

$$f(\Delta p) = \frac{k}{C} \left(\frac{\Delta p}{C} \right)^{k-1} \exp \left[- \left(\frac{\Delta p}{C} \right)^k \right]$$

where k and C are parameters to be identified from historical data.

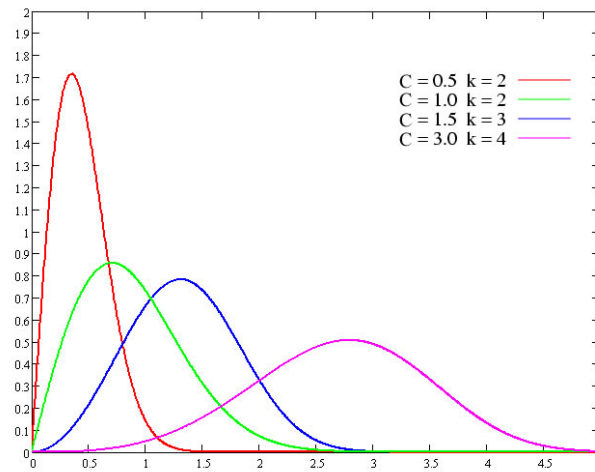


Figure A7. Probability Distribution Function of Weibull Distribution

A statistically significant correlation between central pressure difference and the approach angle is also found in certain locations such as south Florida [16], the effect of the correlation is included by modeling the scale parameter C in the Weibull distribution as a linear function of the storm heading:

$$C = a_2 + a_3\theta$$

where a_2 and a_3 are constants to be identified from historical data.

Instead of recording the central pressure difference Δp , HURDAT records the central pressure p . The conversion from the central pressure p to the central pressure difference Δp is fairly straightforward given the atmospheric pressure at a distance beyond the effect of the hurricanes having a typical value of 1,013 millibars [17]:

- **Maximum Wind Speed**

The maximum wind speed models in recent meteorological researches are usually complicated and involve sensitive and difficult-to-determine parameters. In this work, the maximum wind speed is roughly modeled based on its minimum central pressure p at its landfall.

The simulated minimum central pressure p at landfall determines the Saffir-Simpson category of the corresponding hurricane (it has been investigated that using minimum central pressure to categorize a hurricane leads to fewer errors than using wind speed [18]). Then the maximum wind speed is proportionally calculated in that specific Saffir-Simpson category.

For instance, the central pressure difference for a simulated hurricane is 45mb at its landfall, i.e., the minimum central pressure is 968mb. According to the Saffir-Simpson scale shown in Table A1, it is a Category 2 hurricane; and then the maximum sustained wind speed for this hurricane upon landfall is calculated as 106.6mph (47.4m/s) proportionally in the range from 94mph (41.8m/s) to 110mph (48.9m/s).

- **Gust Factor**

The wind speed produced in hurricane simulations are maximum sustained wind speed based on 1-minute duration. However, the structural damage is closely related with peak gust speed, which is the highest “instantaneous” wind speed during a specified period (usually 3 seconds). The gust factor can be used to estimate the most likely peak gust speed from sustained wind speed. It is demonstrated that ESDU³¹ model [38, 39] provides an adequate model for hurricane gust factors, both over water and over land.

In the ESDU approach, the peak wind speed at height z averaged over time period τ occurring over an observation time of 3600s (1 hour) is given as:

$$\hat{U}(\tau, z) = U(3600, z)[1 + g(\nu, \tau, z)I_u(z)]$$

where $U(3600, z) = 2.5u_* \ln(z/z_0)$;

$I_u(z) = \frac{\sigma_u(z)}{U(3600, z)}$ is longitudinal turbulence intensity, in which $\sigma_u(z)$ is the standard deviation of wind

speed, calculated as $\sigma_u(z) = \frac{u_* 7.5\eta[0.538 + 0.09 \ln(z/z_0)]^{\eta^{16}}}{[1 + 0.156 \ln(u_*/fz_0)]}$, $\eta = 1 - 6fz/u_*$, f is the Coriolis pa-

rameter $f = 2\Omega \sin \phi$, Ω is the Earth's angular velocity, whose value is $7.292 \times 10^{-5} \text{ rad/s}$ [22], ϕ is the local latitude, z_0 is the terrain roughness (a value of 0.05 is used in this work [23]);

$g(\nu, \tau, z)$ is the peak factors, calculated as $g(\nu, \tau, z) = \left[\sqrt{2 \ln(T_0 \nu)} + \frac{0.557}{\sqrt{2 \ln(T_0 \nu)}} \right] \frac{\sigma_u(z, \tau)}{\sigma_u(z)}$, in which

T_0 is observation period which is set to 3600s, $\nu = \frac{0.007 + 0.213(3.13z^{0.2}/\tau)^{0.654}}{3.13z^{0.2}}$, $T_u = 3.13z^{0.2}$,
 $\sigma_u(z, \tau) = \sigma_u(z) \left[1 - 0.913(T_u/\tau + 0.1)^{-0.68} \right]$.

Given the simulated maximum sustained wind speed as well as the values of $\hat{U}(\tau, z)$, τ , z , f , and z_0 , the value of friction velocity u_* can be determined using iterative approaches. The Newton-Raphson method [24] is used in this work.

Based on 1000-year simulation (for 3-s peak gust at roughness length of 0.05m) using Newton-Raphson method, it is observed that the distribution of the calculated values of the gust factor is highly concentrated around 1.287 with standard deviation of 0.002. In this work, the value of 1.287 is used to replace the ESDU model in order to reduce the computational intensity, especially for Monte Carlo simulation.

- **Radius to Maximum Winds**

Radius to maximum winds describes the range of most intensive hurricane wind speed. The radius of maximum winds R_{\max} is empirically modeled in [18] as:

$$\ln R_{\max} = 2.556 - 0.000050255\Delta p^2 + 0.042243032\psi$$

³¹ ESDU is an acronym of “Engineering Sciences Data Unit”, which is an engineering advisory organization based in the United Kingdom.

where ψ is the storm latitude, Δp is the center pressure difference.

- **Maximum Wind Speed Decay Rate**

Hurricanes' intensity decays and dissipates after their landfall because large land mass causes frictions and the terrain cuts off hurricanes' circulation and squeezes out the storm's moistures. There are two widely accepted models to model the decay of hurricanes: one estimates the decayed wind speed, and the other model is for estimating the change in minimum central pressure.

KD95³² [13, 19] is the most widely used model for simulating the decay of hurricane maximum wind speed inland, it has been used in many real-time forecasting and emergency preparedness scenarios. KD95 is for storms south of 37°N (Florida is located south of 31°N). KD95 model is based on the assumption that hurricanes decay at a rate proportional to their landfall intensity and decay exponentially with time after landfall.

$$V(t) = V_b + (RV_0 - V_b)e^{-\alpha t}$$

where $R=0.9$ is a factor used to account for the sea-land wind speed reduction, $V_b=13.75\text{m/s}$, $\alpha=0.095h^{-1}$, V_0 is the maximum sustained 1-min surface wind speed at the time of landfall.

- **Central Pressure Filling Rate**

The filling rate module for evolvement of the minimum central pressure [26] is modeled as following:

$$\Delta p(t) = \Delta p_0 e^{-at}$$

where the filling constant a is defined as:

$$a = a_4 + a_5 \Delta p_0 + \varepsilon$$

The values of parameters for Florida peninsula are defined in [26]: $a_4=0.006$, $a_5=0.00046$, and ε is a normally distributed error term with a mean of zero and a standard deviation of 0.025.

Both the maximum wind speed decay module and the central pressure filling module will be used since the direct link between the central pressure difference and the maximum sustained wind speed is not available.

- **Wind Field Profile**

The most intensive wind of a hurricane generally occurs at the eye wall; wind speed decreases as the location moves away from hurricane center. The wind field model developed by Holland [27] describes the radial profile of winds in a hurricane.

$$V_g = \left[\frac{AB(p_n - p)e^{-A/r^B}}{\rho r^B} + \frac{r^2 f^2}{4} \right]^{1/2} - \frac{rf}{2}$$

where V_g is the gradient wind at radius r , $\rho=1.15\text{kg/m}^3$ is the air density, p is the central pressure, p_n is the ambient pressure (with typical value of 1013mbars), and f is the Coriolis parameter:

$$f = 2\Omega \sin \phi$$

³² KD95 is named after the authors John Kaplan and Mark Demaria, the related paper was published in 1995.



where $\Omega=7.292 \times 10^{-5}$ rad/s is the Earth's angular velocity [25], and \varnothing is the local latitude.

The parameters A and B in the model are scaling parameters. For actual hurricanes, they are empirically estimated from observations; while for a simulated hurricane, A and B can be determined climatologically as:

$$V_m = \sqrt{\frac{B}{\rho e} (p_n - p)}$$
$$R_{\max} = A^{1/B}$$

where V_m is the maximum wind speed, e is the base of natural logarithm with a value of 2.718, and R_{\max} is the radius to maximum wind.

This calculated gradient wind is considered as the upper level wind, needs to be adjusted to surface level (10m) in order to assess the distribution infrastructural damage caused by hurricanes. A simple approach in [26] applies a 17.5% reduction for $r < 2R_{\max}$ and a 25% reduction for $r > 4R_{\max}$ with a smooth transition curve used for intermediate values of r . These parameters are for wind speed adjustment over water; the reduction of wind speed is larger over land. This approach is utilized, while the parameters are calibrated towards the ASCE 7 wind map.

- **Complete Hurricane Simulation**

Individual hurricane characteristics have been modeled either statistically or empirically, a complete hurricane and then a general hurricane year for Florida can be simulated by combining those components together.

The first step is to simulate the annual hurricane frequency in different regions of Florida. Then, the landing features including landfall position, approach angle, translation velocity, central pressure difference, maximum wind speed, and radius to maximum wind, are probabilistically generated for each simulated hurricane using corresponding modules. The hurricane landing information further determines its inland movement. Since the trajectory of a hurricane landed in Florida is assumed as a straight line, the landing position and the approach angle determine its inland path. As the translation velocity is considered as constant, the duration of hurricane in Florida is calculated as the time elapsed before the simulated hurricane leaves the state or the time elapsed before it decays to a tropical depression, whichever comes earlier.

One example of the trajectory of a simulated hurricane central movement is shown in Figure A8. It is implemented in Microsoft MapPoint using the simulation data from the proposed module. The color scheme is in accordance with the hurricane intensity. The lighter the color is, the lower the wind speeds are.

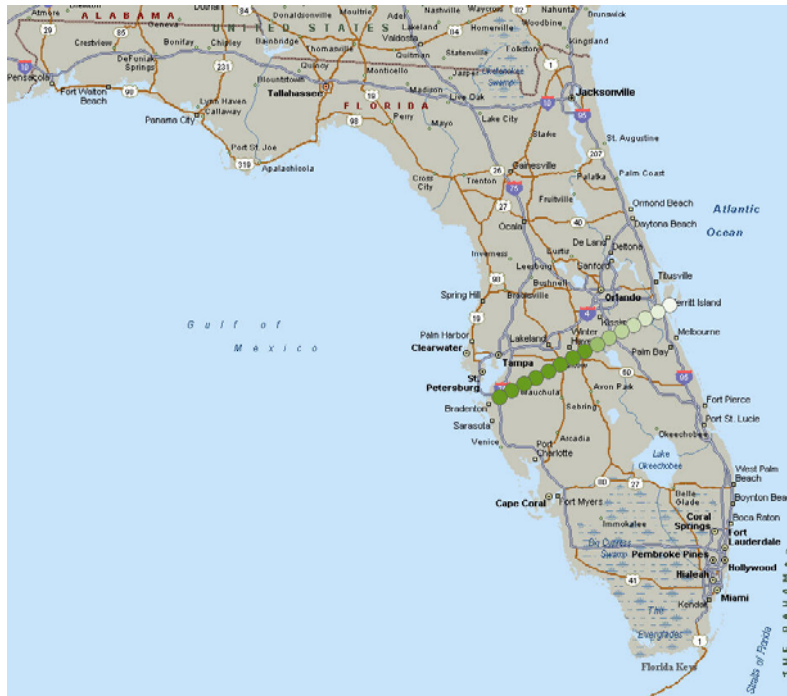


Figure A8. Sample Hurricane Track in Florida

The central pressure filling rate module updates the central pressure difference at any location along the hurricane path, and then the corresponding radius to maximum wind speed is calculated. On the other hand, KD95 model tracks the maximum wind speed at any point along the hurricane path. With the maximum wind speed and the radius to maximum wind speed updated along the hurricane path, parameters A and B for the radial wind field model are calculated so that the current radial profile of hurricane wind can be described.

Given the wind speed in any specific location, the gust factor is applied to convert the sustained wind speed to the most likely 3-second peak gust in order to help assess the hurricane induced utility structural damage.

A.4 Parameter Estimation

In order for the proposed probabilistic hurricane simulation module to represent the actual hurricane characteristics shown in historical data, the module parameters should be carefully calibrated. However, the insufficient historical data may cause difficulties in getting an accurate parameter set. For instance, there are only 6 landfall hurricanes recorded for northeast Florida; central pressure data was not recorded until recently due to the technology limitation.

The patterns of some hurricane characteristics such as landfall frequency, approach angle vary among different regions, so the corresponding module parameters are extracted and calibrated based at the regional level whenever possible. Sometimes it is impossible to get statistically representative localized parameter estimates due to the limitation of the available historical data, a general set of parameters, under this circumstance, is assigned to match the overall hurricane pattern in Florida.

Among various models for all the hurricane characteristics, some are empirical models with parameter provided such as the model for the radius to maximum winds, the maximum wind decay rate, and central pressure filling rate, some are well-developed models with parameters easily determined from historical data such as the Poisson distribution for the hurricane frequency, some models use sampling approach so that the parameter extraction is avoided such as the approach for getting landing position and maximum wind speed at landfall, while others have parameters that are not fully determinable, such as translation velocity and central pressure difference at landfall, either because of the insufficient historical data or due to the lack of theoretical support.

The parameters of the models for hurricane occurrence and approach angle are individually estimated in different regions as listed in Table A6.

Table A6. Region-Specific Parameters

		<i>Northwest</i>	<i>Southwest</i>	<i>Southeast</i>	<i>Northeast</i>
<i>Occurrence</i>	λ	0.297	0.187	0.200	0.039
<i>Approach Angle</i>	m_{x1}	35	40	310	345
	m_{x2}	295	300	35	285
	σ_{x1}	25	25	30	5
	σ_{x2}	40	30	15	10
	a_1	0.5	0.63	0.9	0.5

The parameters of the models for the central pressure difference at landfall and translation velocity are estimated for the entire state instead of each individual region, with reference to recommended values published in various research documentations such as [16]. Table A7 lists the set of estimated parameters.



Table A7. State-Wide Parameters

<i>Translation Velocity</i>	a_0	2.3
	a_1	-0.00275
	σ	0.3
<i>Central Pressure Difference</i>	a	35
	b	-1
	k	1.8

Due to the fact that there is insufficient historical data to generate statistically representative parameters for many weather characteristics, those estimated parameters during the calibration process are allowed to be slightly changed in order to better represent the actual hurricane patterns. The calibration is based at the regional level; in other words, even though the parameters for translation velocity and central pressure difference at landfall are initially estimated for the entire state, the calibration process may generate a different set of parameters for different regions according to the local hurricane patterns. Appendix B introduces the parameter calibration in detail.



A.5 Hurricane Impact Estimation

Since this hurricane simulation module is linked with infrastructure damage module and system restoration module to support the benefit and cost analysis of undergrounding conversion, there is some utility related hurricane impact information required in addition to the hurricane simulation itself. This set of information includes the hurricane duration in Florida, hurricane coverage for different utilities, and the wind speed track for a given location.

- **Duration**

The duration of a hurricane in Florida is defined in this work as the time elapsed between hurricane landfall and when it degrades to a tropical depression or its leaves Florida. The hurricane duration obviously has an impact on the equipment damage and the restoration time; a hurricane with shorter duration causes less damage and faster restoration while a hurricane with longer duration causes more damage and longer restoration.

The duration of a hurricane in Florida is estimated using the translation velocity and the approximate Florida coastline as well as its trajectory. Once a hurricane makes landfall in Florida, it will move along the straight-line trajectory determined by its landing position and approach angle, with a constant translation velocity. The wind speed decays after the hurricane lands, as the large land mass being the ultimate hindering factor for the hurricane intensity. It is assumed that the effect of a hurricane in Florida lasts until its wind speed reduces to less than 17.5m/s, which is the lower limit for tropical storm wind speed or the upper limit for wind speed in tropical depression, or the hurricane leaves Florida, whichever comes first.

- **Coverage**

It is usually of a utility's interest to estimate the percentage of its service territory affected by a hurricane and the average wind intensity across the affected areas. For any given simulated hurricane, its coverage at different utilities is projected based on the approximated service territories. The entire Florida territory is divided into small grids; each grid is 0.1° longitude wide and 0.1° latitude long (i.e., one grid is approximately 110 square kilometers³³). Each grid is presented as an Excel spreadsheet cell so that the utility service territories can be visually presented. Figure A9 and Figure A10 show this approximation for IOUs and Co-ops, respectively^{34,35}.

This grid division of course can be refined by using higher resolution. However, this tool does not involve the use of GIS database, the Florida coastline used for calculation in this tool is approximated as shown in Figure A2, and the available service territory information itself is also estimated; as a result, it is not necessary to pursue very high resolution for this territory approximation when it comes to system restoration and cost-benefit analysis, as most of variables are estimated.

³³ One degree of latitude corresponds to 111 kilometers, one degree of longitude is $111.3 \cdot \cos(\text{latitude})$ kilometers, approximately 98.3 kilometers within Florida area.

³⁴ Due to the limitation of available color scheme, the figures are shown only to demonstrate the approximation method; and the legends are omitted to prevent confusions caused by the repetition of the color scheme.

³⁵ The municipally owned utilities are considered as a point/specific location instead of an area in this study.

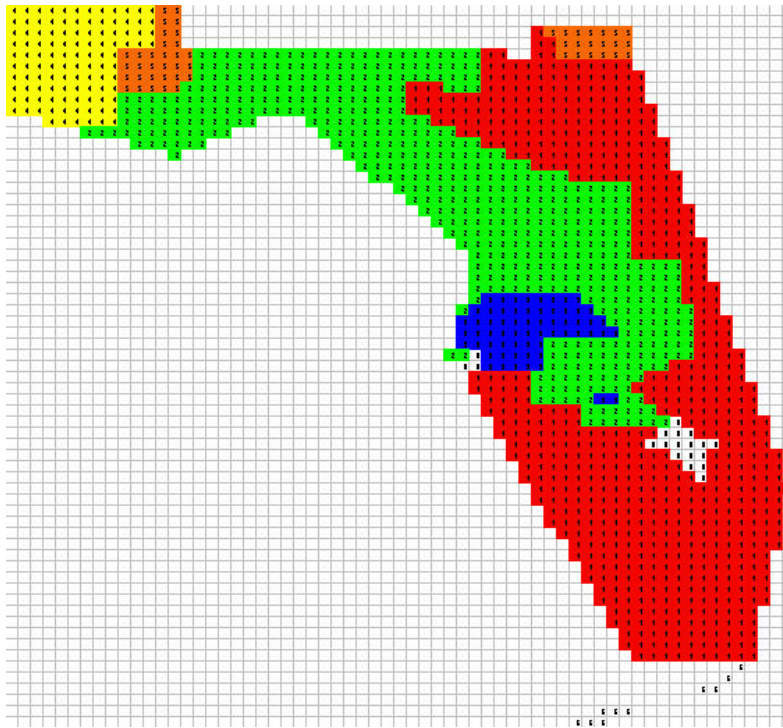


Figure A9. Approximated IOU Service Territories

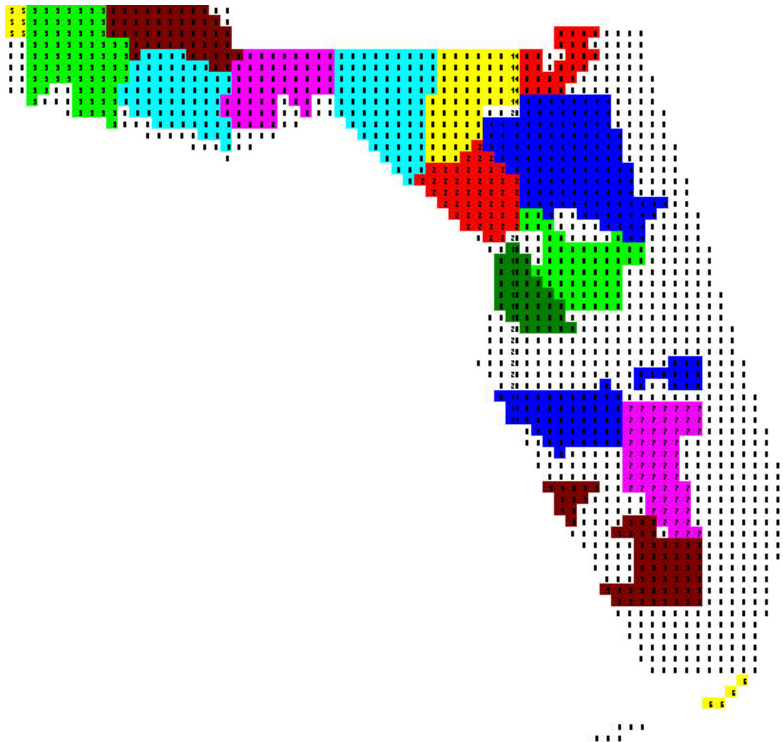


Figure A10. Approximated CO-OP Service Territories



For each simulated hurricane, the algorithm first calculates the wind speed experienced at a particular grid (the center location is used as the grid representation) at any time step. The maximum wind speed at a particular grid over the course of the hurricane activity is then recorded. The average wind speed across a utility's hurricane affected area is calculated as the root mean square value of the maximum wind speed at all hurricane affected areas within that utility's service territory. The calculation of root mean square of wind speed is shown as:

$$v_{rms} = \sqrt{\frac{1}{n} \sum_{i=1}^n v_i^2}$$

where v_{rms} is the root mean square value of wind speed experienced by a utility, v_i is the maximum wind speed experienced at the i^{th} grid, $i=1,2,\dots,n$, n is the total number of hurricane affected grids for a utility.

- **Local Wind Speed**

The hurricane coverage in the service territory of a particular utility provides the information to estimate the system-wide total restoration time needed; the wind speed at the project area determines the facility damage at the particular location, which further affects the local restoration duration. The hurricane induced strong wind experienced at different locations can be significantly different, depending on how far the location is from the hurricane center trajectory.

Given a complete hurricane simulation, it is straightforward to calculate the wind speed at specific local locations. After a hurricane makes landfall, the maximum wind speed at the hurricane "eye wall" (where the most severe weather of a cyclone occurs) at any given time is calculated using the wind speed decay rate model, the corresponding central pressure difference is calculated using pressure filling rate model, and then the corresponding radial wind field is updated such that the storm wind speed at any particular location is obtained.

The range of hurricane eye wall is approximated by the radius to maximum winds. If a location stays outside of the eye wall of a hurricane throughout its inland duration, then the locally experienced wind speed is caused by the outer cluster of the hurricane. Generally, the local wind speed first increases when the hurricane center approaches, and then decreases when the hurricane central moves away from the location, as shown in Figure A11.

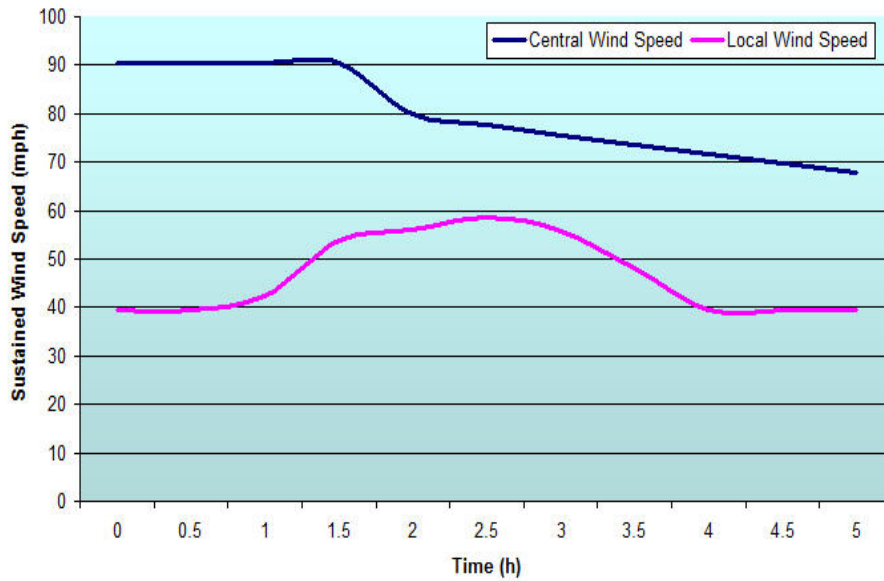


Figure A11. Local wind speed trend example

The center of a strong tropical cyclone is the region where calm weather is found; it is called the hurricane “eye” and it is surrounded by the eye wall. If the hurricane eye passes by a particular location at one point along the hurricane trajectory, then relatively slow wind speed is experienced during that period. The wind speed at the referenced location will first increase as the hurricane center approaches until the hurricane eye wall hits this area; then the wind speed will decrease when it gets into the hurricane eye, the wind speed increases once again as the opposite eye-wall gets closer then finally decreases again when the hurricane center moves away, as shown in Figure A12.

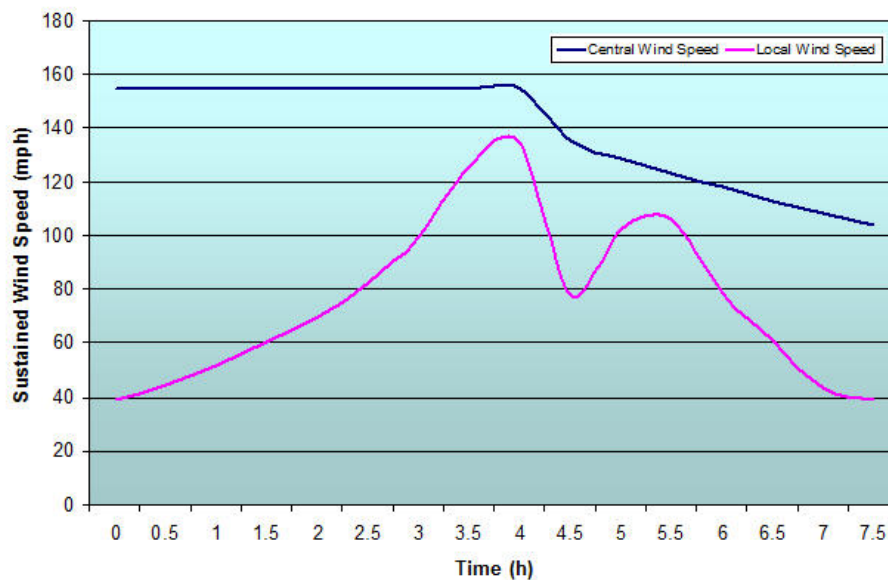


Figure A12. Local wind speed trend example



Appendix B: Hurricane Simulation Validation

The validation of hurricane simulation methodology consists of two steps to test the methodology against correctly reproducing the actual pattern of hurricane activity in Florida. Step 1 is the American Society of Civil Engineering (ASCE) 7 Wind Map simulation and Step 2 is the Hurricane Wilma simulation.

B.1 ASCE 7 Wind Map Validation

As previously discussed, uncertainties are involved in the hurricane simulation and hurricane restoration practices. Each individual case is unique and therefore exact replication cannot be obtained on a single run. The best approach to treat the situations with heavy uncertainty is probabilistic modeling through the use of a Monte Carlo simulation. This probabilistic approach accounts for variances in the data and via multiple iterations, this probabilistic approach can reproduce the scenarios close to the actual cases in the long run.

The ASCE 7 Wind Map represents the 3 second gust speed with a mean recurrence interval of 50 years. This map is derived from statistical analysis of peak gust data collected at weather stations and mathematically predictions of hurricane wind speeds in coastal areas. Through a Monte Carlo simulation, the worst 3 second peak gust of 50 years from the proposed hurricane simulation methodology can be compared against the ASCE 7 Wind Map to validate the algorithm.

The key step in accurately reproducing the ASCE 7 Wind Map is calibrating the hurricane simulation module parameters. Among the various models for adverse weather characteristics, some are empirical models with easily obtained parameters from public databases such as the model for the radius to maximum winds. Others are well-developed models with parameters easily determined from historical data such as the Poisson distribution for the hurricane frequency. Several models have parameters that are not easily obtained either because of the insufficient data or the lack of theoretical support.

The hurricane simulation module can best be calibrated by adjusting two parameters:

- HURDAT contains historical hurricane data (back to 1851). However, the central pressure has not been systematically recorded until recently (around 1960s). The parameters for the Weibull distribution that is used to model the central pressure difference at hurricane landfall extracted from the limited historical data may not be as accurate as the parameters for some other hurricane characteristics.
- In the proposed hurricane simulation methodology, the landing location sampling approach divides the Florida coastline into a number of segments (fifteen for each region in this case, i.e., sixty segments in total) and then calculates the number of historical hurricane landed in each segment, which forms the foundation for assigning simulated landfall position. The choice of the number of segments can affect the accuracy of simulation. If too few bins are assigned, it may be too coarse to include enough details, however, it may be too sensitive to data noise if too many bins are assigned, especially when the historical landing information is estimated from the six-hour interval records and the approximated Florida coastline.

By focusing on the calibration of these two parameters, a map presenting the worst 3-second peak gust in fifty years in Florida is generated; which is based on a 15,000-run Monte Carlo simulation of the proposed hurricane method. The simulated wind map is shown in Figure B1, comparing with the actual ASCE 7 Wind map using the same color scheme is shown in Figure B2.

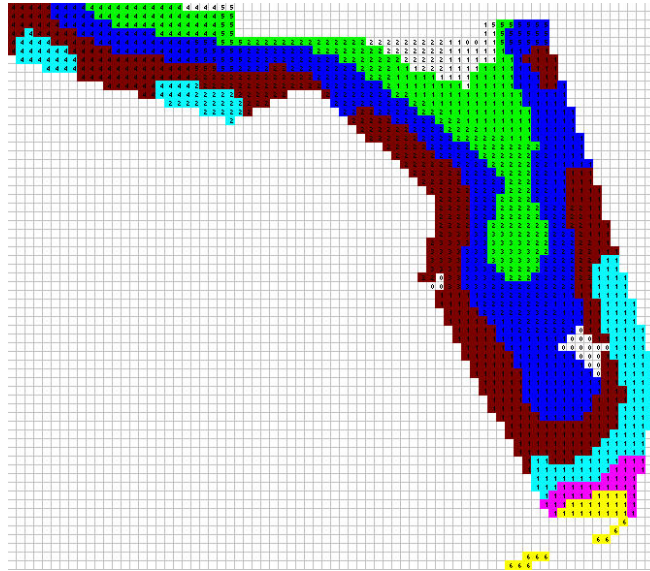


Figure B1. Simulated Wind Map for Florida

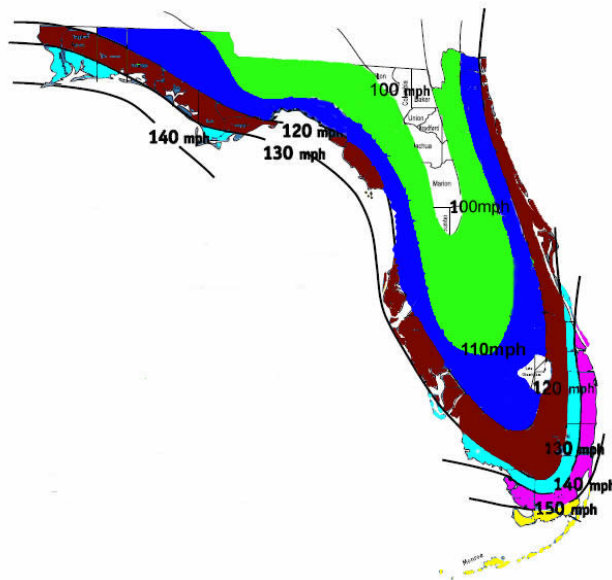


Figure B2. ASCE 7 Wind Map for Florida

It is shown from the comparison that the simulation generally reproduces the actual ASCE 7 Wind Map, with slightly higher simulated peak gusts inland than what the ASCE 7 Wind Map shows and little discontinuity along the northwest coast. This simulation achieves better approximation of the ASCE 7 Wind Map than what the HAZUS-MH hurricane model gets according to the results presented in its technical manual [18].



The slightly higher simulated peak gusts inland will lead the consequent damage assessment towards a conservative direction. The discontinuity in the northeast region is largely due to insufficient historical data since there are only 6 hurricanes recorded for the last 150 years. The discontinuity can be theoretically solved by significantly increasing the number of simulations, but it will exceed the capacity of Excel and cause memory overflow.

The ASCE 7 Wind Map presents the average effect of thousands of hurricane simulations; the good reproduction of the Florida portion of this map demonstrates that the proposed hurricane simulation approach is able to estimate Florida hurricane activities and hurricane induced distribution system damage once linked with damage module.

B.2 Hurricane Wilma validation

The intent of this hurricane simulation module is to track the statistically average hurricane effect as opposed to reproducing a specific hurricane that has occurred in the past. It is of small probability that the simulation algorithm generates a set of landing parameters exactly as those of an actual hurricane. It is still worthwhile however to compare past hurricanes against simulated scenarios by using the actual hurricane landing information as the simulated landfall parameters. In other words, this task focuses on validating the simulation of hurricane inland movement and wind field decay. Hurricane Wilma is used as an example for this validation. The actual landfall information of Wilma is inputted to the algorithm, and the following characteristics are examined:

- The decay rate of the maximum wind speed along the hurricane trajectory
- The filling rate of the central pressure difference along the hurricane trajectory

The ASCE 7 Wind Map validation puts an emphasis on landing characteristics parameter calibration, while the actual hurricane validation focuses on the storm inland movement and evolution. Many models in this group are empirical models, so there is limited space for parameter adjustment except in the boundary layer model. The boundary layer model adjusts the upper-level wind speed to surface level. It is known to overestimate the actual wind speed in many cases [29] therefore this boundary layer model becomes the main target for parameter adjustment in actual hurricane validation.

Table B1 shows a preliminary validation result, which compares the simulation with the hurricane data in Wilma's Tropical Cyclone Report released by National Oceanic and Atmospheric Administration (NOAA). Wilma's actual landfall information including the landing position (latitude and longitude), approach angle, central pressure, and translation velocity is used as inputs to the simulation module (shown in *italic* format). Given this information, the hurricane simulation module first calculates the maximum sustained wind speed upon landing, the corresponding 3 second peak gust speed, and the radius to maximum wind. The simulated wind speed at landfall is 55.8m/s, which is very close to the actual value of 54m/s. The actual Wilma data does not contain gust speed at landfall and corresponding radius to maximum wind recorded.



Table B1. Preliminary Validation for Hurricane Wilma (2005)

	Actual	Simulated
<i>Landing Position: Latitude</i>	25.9°N	25.9°N
<i>Landing Position: Longitude</i>	81.7°W	81.7°W
<i>Approach Angle</i>	50-60°	60°
<i>Central Pressure</i>	950mb	950mb
<i>Translation Velocity</i>	20-25kt/10.3-12.9mps	11.6mps
<i>Sustained Wind Speed at Landing</i>	105kt (cat3)/ 54mps	55.8mps
<i>Gust Speed</i>		70.7mps
<i>Radius to Maximum Wind</i>		31.52km
<i>Duration</i>	4.5hr	4.45hr
<i>Leaving Position: Latitude</i>	26.9°N	26.8°N
<i>Leaving Position: Longitude</i>	80.1°W	80.1°W
<i>Sustained Wind Speed at Leaving</i>	Near 95kt (cat2)/48.9mps	37.6mps

Hurricane simulation performance at particular locations and time stamps (i.e., the hurricane radial wind field) can be tracked using detailed Hurricane Wilma data collected at various weather stations. However, the information released from Tropical Cyclone Report is limited so comparisons can only be made to the hurricane status at the time it left Florida. The hurricane module simulates the hurricane inland movement based on the landing information to calculate the hurricane duration, leaving position, and the corresponding wind speed.

By examining the simulated leaving position, we can evaluate the straight line trajectory assumption. By examining the duration as well as the leaving position, we can evaluate the constant translation velocity assumption, and by examining the sustained wind speed when it left Florida, we can evaluate the maximum wind speed decay rate calculation.

It is seen from the table that the hurricane simulation reproduces the pattern quite well; both the leaving position and hurricane duration in Florida match closely to the historical actual data. The simulated wind speed upon exit is smaller than the actual. One possible explanation is that the hurricane picks up speed before it leaves land since it can accumulate moistures from the ocean. This characteristic is not accounted for in the module. However, since the focus is on the average effect of a large number of hurricane simulations, the lower wind speed upon exit is compensated by accurately simulating landing wind speed for those hurricanes which make landfall on the other side of Florida, as seen in the close reproduction of the ASCE 7 Wind Map.



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