RUTGERS

Edward J. Bloustein School of Planning and Public Policy

Center for Energy, Economic and Environmental Policy (CEEEP) http://ceeep.rutgers.edu/

One-Day Workshop

Analyzing the Costs and Benefits of Electric Utility Hardening Efforts in Response to Severe Weather

Oct 21, 2014

Draft v.1

RUTGERS

AGENDA & LEARNING OBJECTIVES

Period	Session	Coordinator
9:00 – 9:15	Welcome and Introduction	F. Felder
9:15 – 10:30	Fundamentals of Reliability and Resiliency	D. Coit
10:30 – 10:45	BREAK	
10:45 – 12:15	Strategies for Improving Reliability and Resiliency	D. Coit
12:00 – 13:00	BREAK	
13:00 – 15:00	Integration of CBA with Reliability and Resiliency Analysis	F. Felder
15:00 – 15:45	Comments and Discussion	All

Learning Objectives

- Understand the key terms, assumptions and outcomes of cost-benefit analysis as applied to utility hardening in response to severe weather
- Appreciate how the electric industry defines, measures and evaluates reliability and resiliency
- Learn about various option to harden the electric power grid in response to sever weather, their implications, and costs and benefits
- Enable the NJ BPU to raise and discuss issues related to utility hardening in response to severe weather

Fundamentals of Reliability and Resiliency

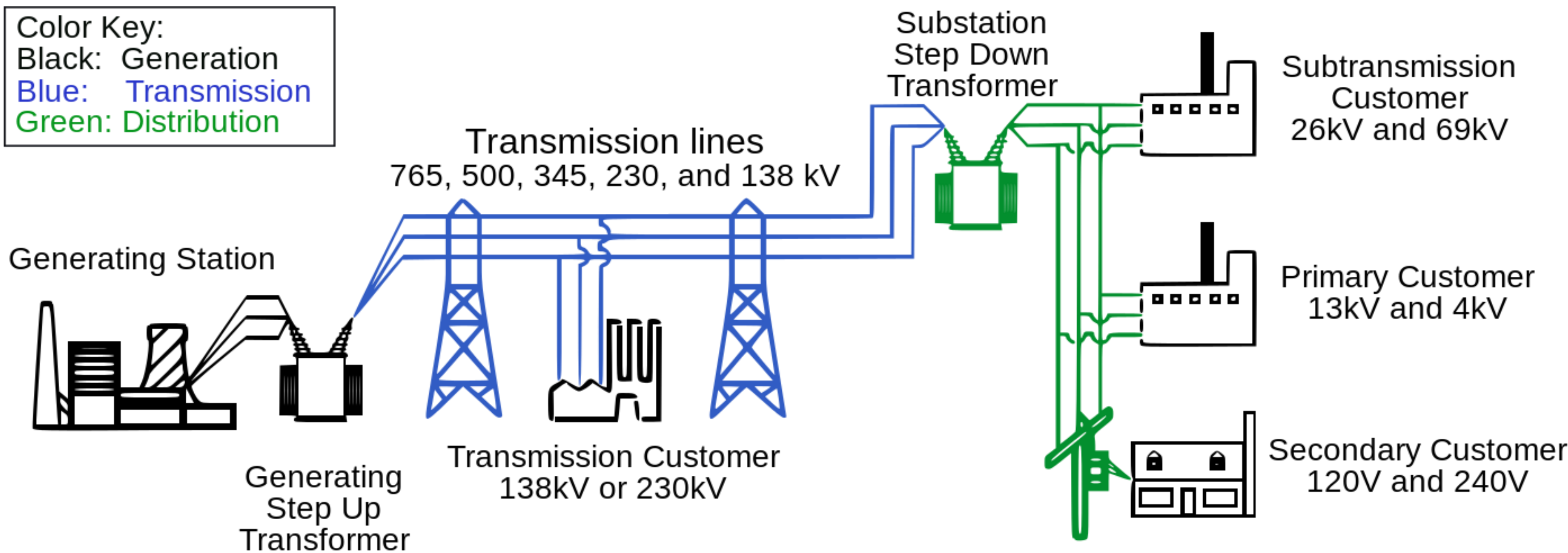
- Definitions of reliability and resiliency
- Failure modes
- Reliability modeling

Electric power grid reliability

- **In USA, many electric utilities are old and getting older**
  - use old and aging equipment
- **As equipment ages, the component failure rates increase**
  - impacts the total system downtime
  - leads to an increased cost of unmet demand

- **There is a need to develop cost-effective strategies to improve reliability to respond to extreme and catastrophic events**

Electric power grid



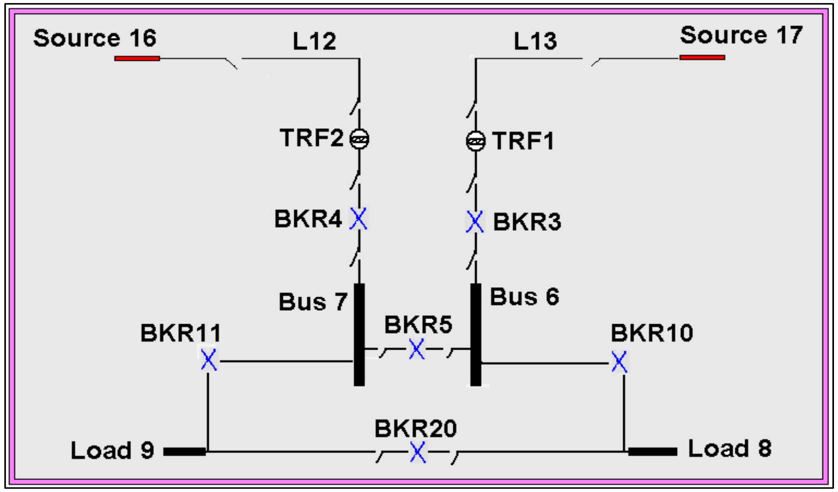
Source: https://www.e-education.psu.edu/eme810/node/592

Power transmission

- Process in the delivery of electricity to consumers
- It refers to the 'bulk' transfer of electrical power from place to place
- Transmission normally takes place at high voltage
- Redundant paths and lines are used to improve reliability

Power distribution

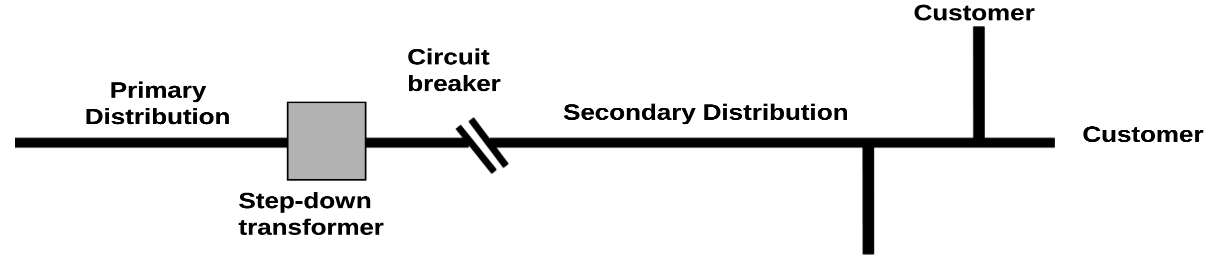
- Concerned with the delivery from the substation to final customers
- Provides the final link between a utility's bulk transmission system and its customers
- 80% of all customer interruptions occur due to failures in the distribution systems



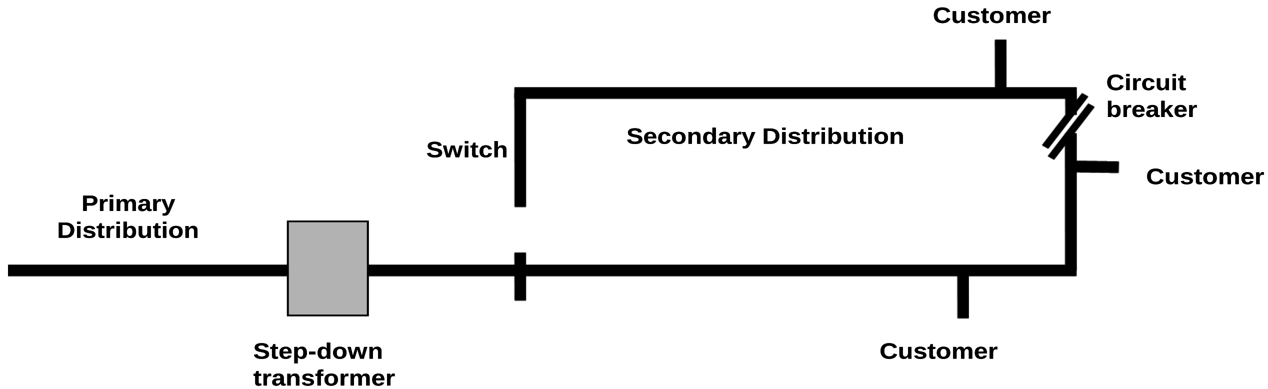
DESN Configuration

Types of distribution systems

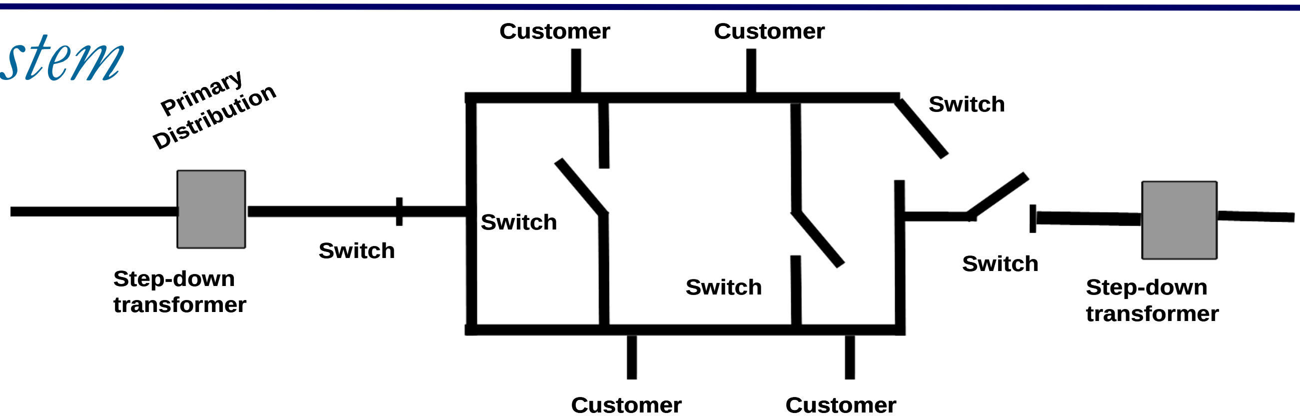
Radial Feed



Loop Feed

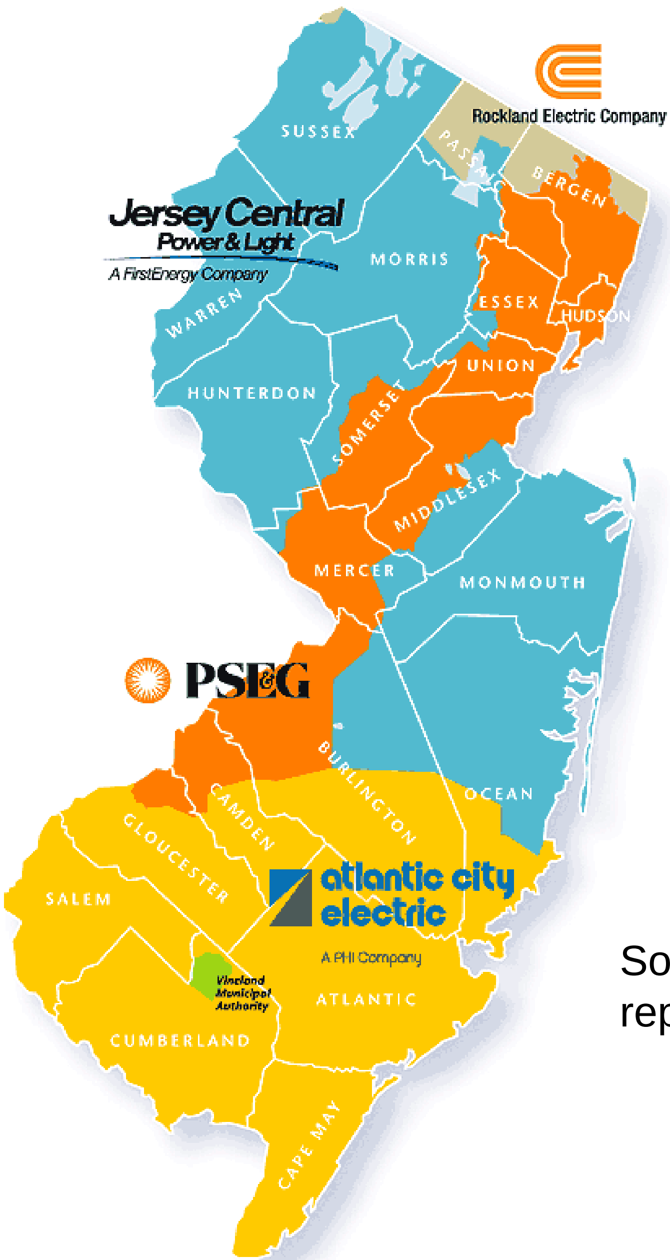


Network System



Source: Hanser PQ. 2013. Climate change impacts on the utility industry, Executive forum on business and climate

Electric Distribution Companies in NJ



Source: http://www.njcleanenergy.com/main/public-reports-and-library/links/electric-utilities-territory-map

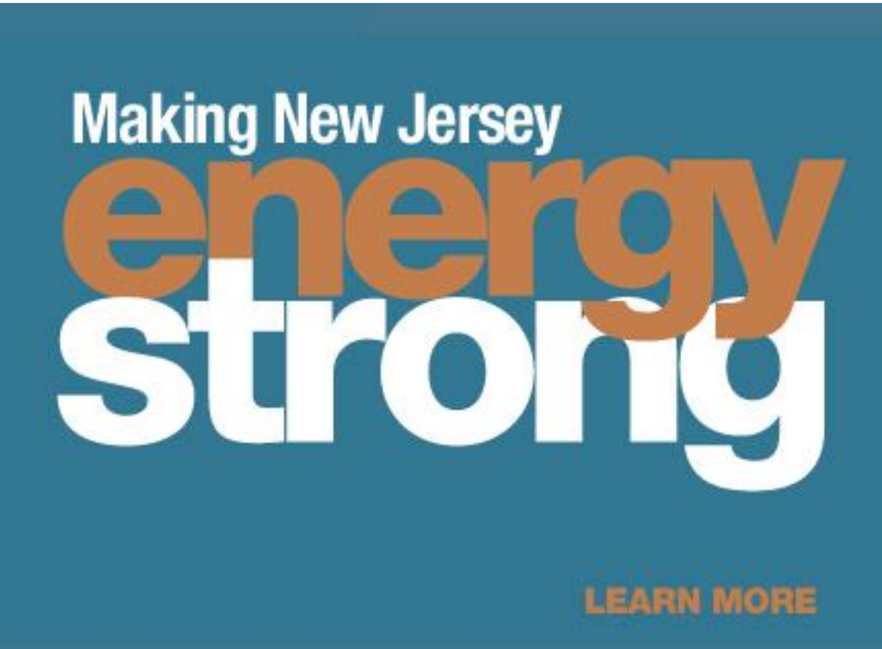
Electric power grid reliability


The Star-Ledger
GO TO NJ.COM FOR UP-TO-THE-MINUTE COVERAGE
PURE HELL
Sandy leaves state with neighborhoods underwater, at least 12 dead, massive power outages, fears of gas shortages

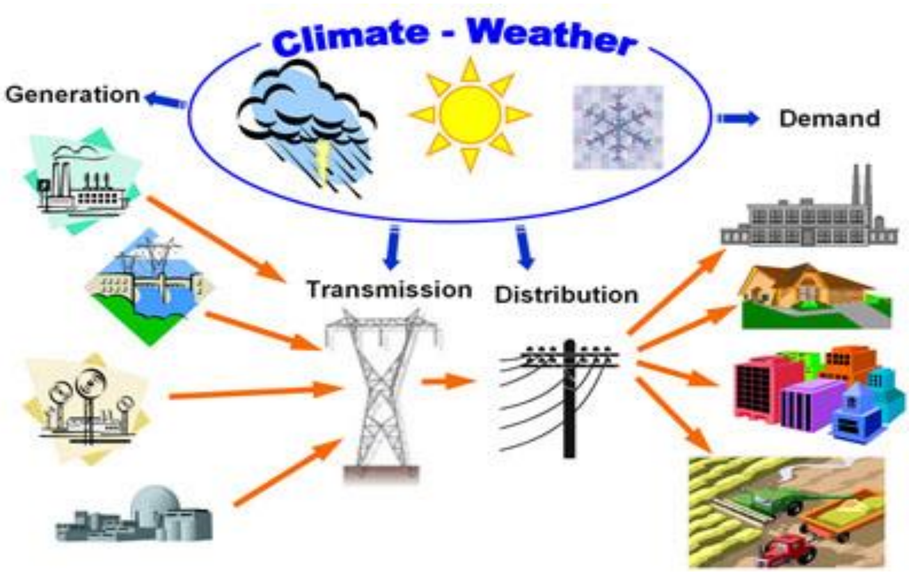

The New York Times
AFTER THE DEVASTATION, A DAUNTING RECOVERY
Subway Flooded — Millions in the Dark
Ohio Working Class May Offer Key to Second Term for Obama
In Storm Deaths, Mystery, Fate and Bad Timing

Source: Star Ledger (2012), The New York Times (10/31/2012)

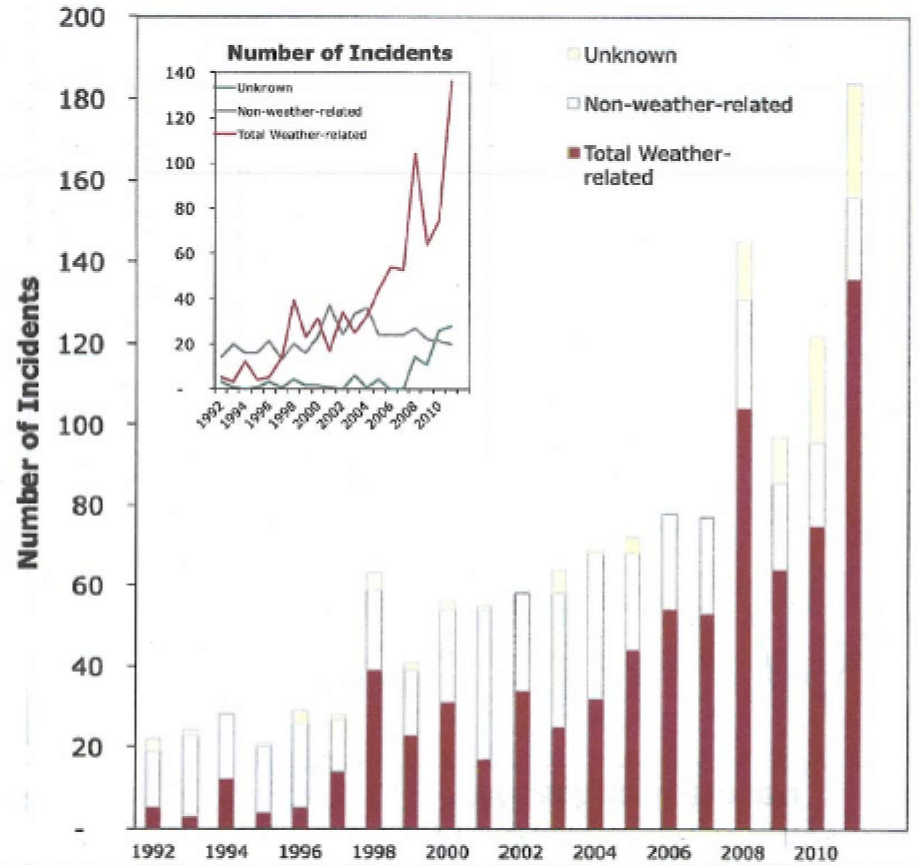
Electric power grid reliability



Weather influence on power systems



The Decision and Information Sciences Division,
http://www.dis.anl.gov/news/WECC_ClimateChange.html

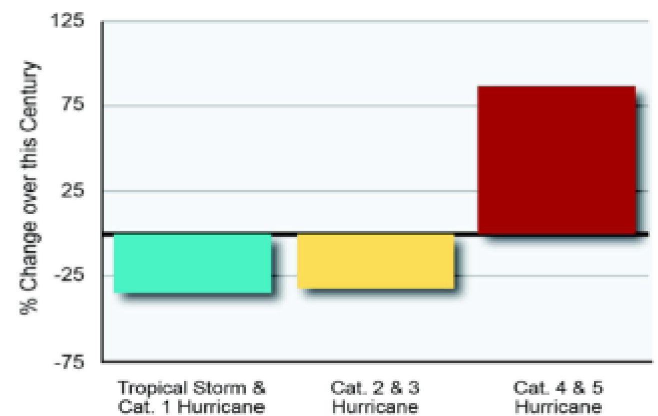


Source: *Electric Grid Disruptions and Extreme Weather*. See http://evanmills.lbl.gov/presentations/Mills-Grid-Disruptions-NCDC-3May2012.pdf

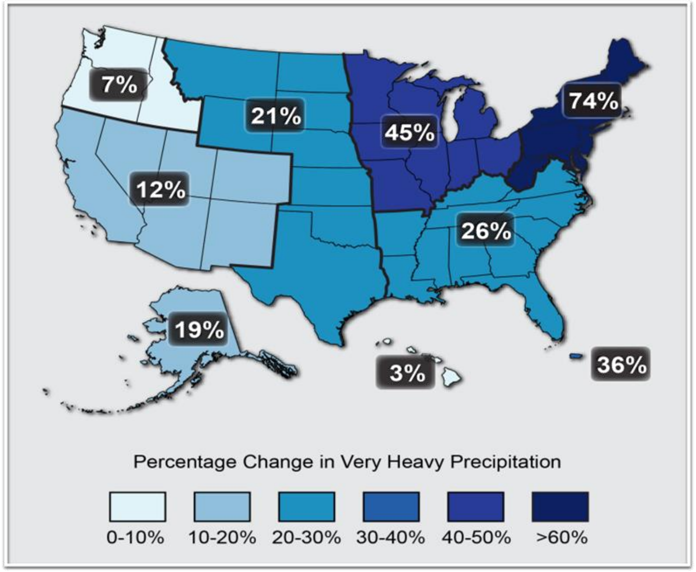
Notes: Historical "Grid Disturbance" data from the U.S. Department of Energy, Energy Information Administration. Form OE-417, "Electric Emergency Incident and Disturbance Report" (and before 1978 fro National Electric Reliability Council, Disturbance Analysis Working Group).

Extreme Events

Northeast trend: increasing frequency and intensity (Storm, flooding, heat wave, wildfire)



- Increase maintenance time
- Lead to potential shutdown
- Damage transmission line
- Increase the peak demand
- Require higher reliability



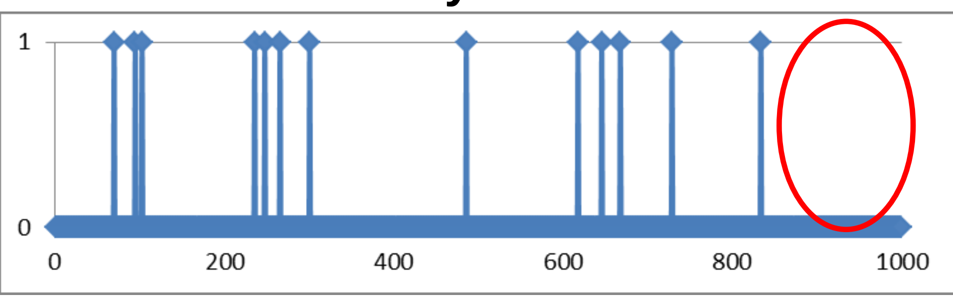
Department of Energy (DOE), 2013, *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather*
NCADAC, 2013, *Federal advisory committee draft climate assessment*

Frequency of severe weather events

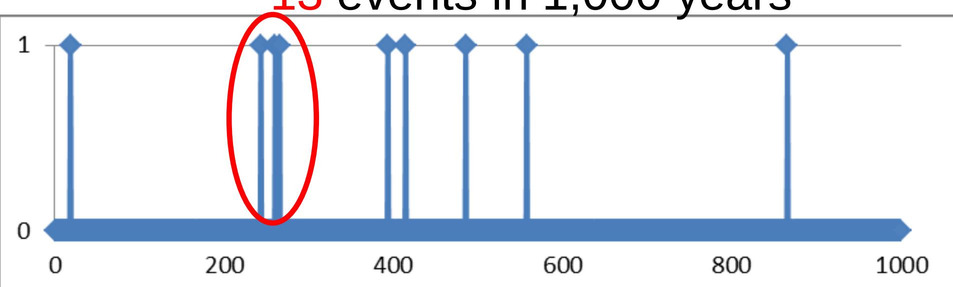
100-year storm vs. 50-year storm

- Return period: 100 year vs. 50 year
- Annual probability: $\frac{1}{100}$ vs. $\frac{1}{50}$
- Two types of storms could have similar occurrence frequency

100-year storm

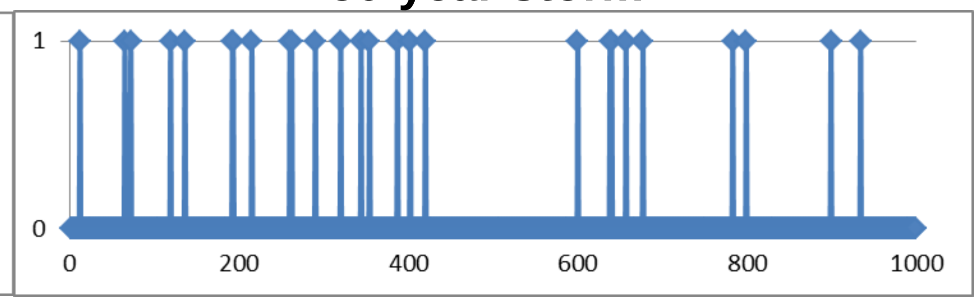


13 events in 1,000 years

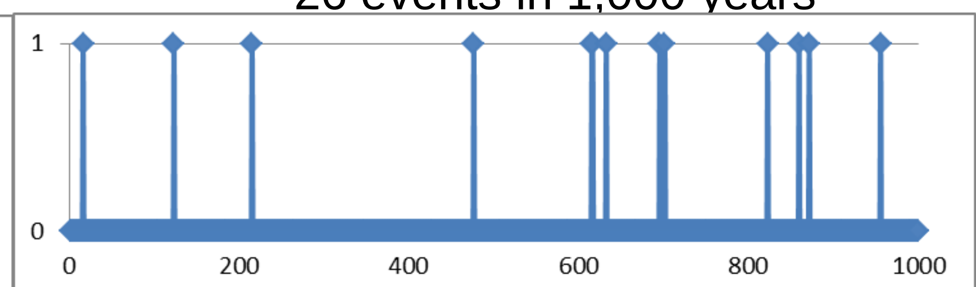


9 events in 1,000 years

50-year storm

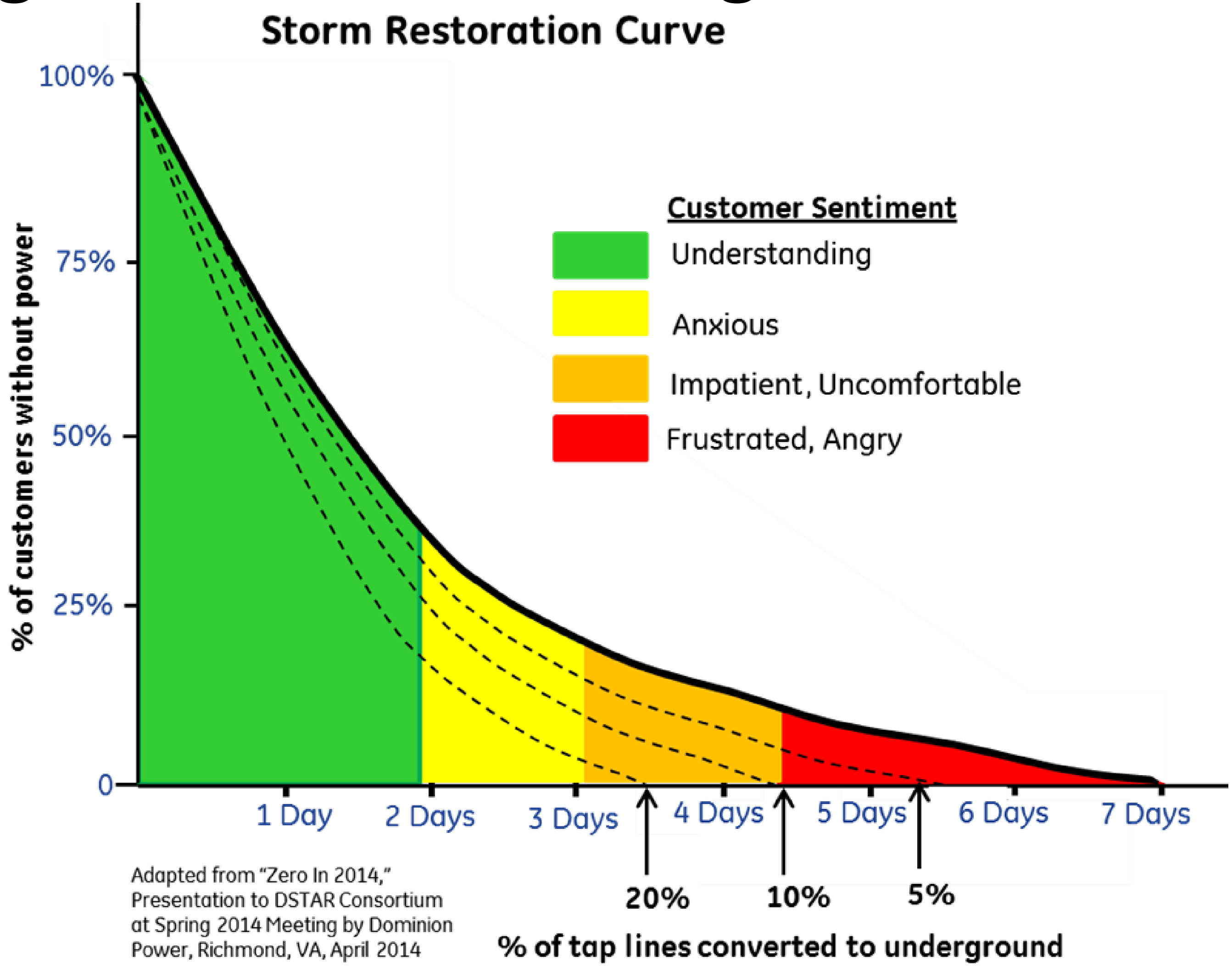


26 events in 1,000 years



13 events in 1,000 years

Outage: duration and magnitude



Source: General Electric (GE). 2014. NJ storm hardening recommendations and review/comment on EDC major storm response filings, referencing "Zero in 2014," presentation to DSTAR consortium at spring 2014 meeting by Dominion Power, Richmond, VA, April 2014.

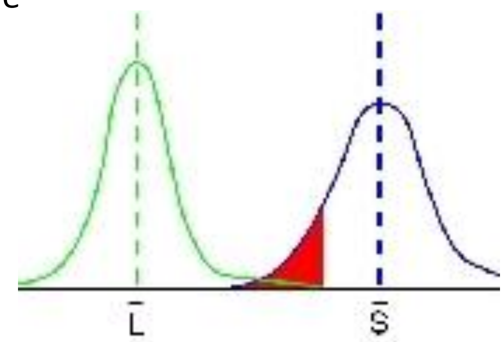
Agenda

A. Definitions of reliability and resiliency
B. Failure modes
C. Reliability modeling

Fundamentals of Reliability, Resiliency and Risk

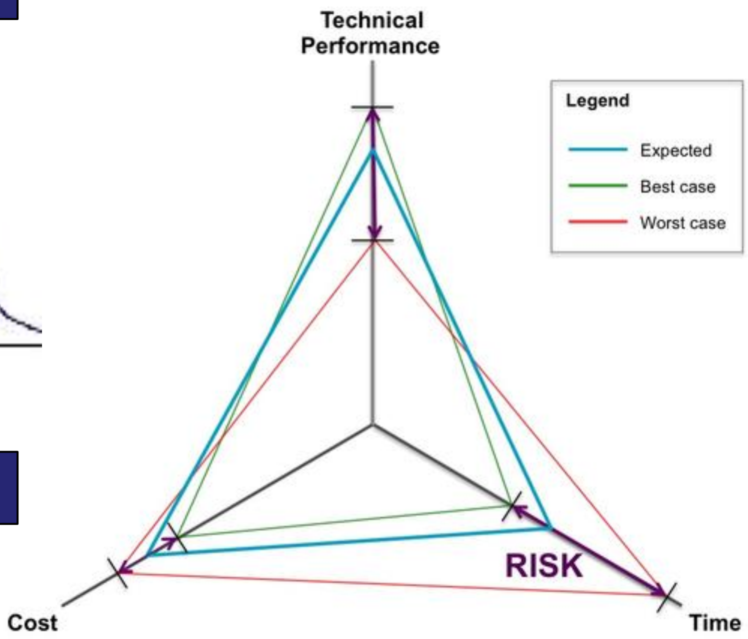
Fundamentals of Reliability

- "Reliability" dependability in the lifecycle management of a product
- A product fails if its stress exceed its tolerance
- Reliability can be perceived as the probability that a product does not fail under certain condition for a specified
- period of time



Fundamentals of Resiliency

- "Resilience" the ability to become strong, healthy, or successful again after something bad happens –from Merriam-Webster
- In English, when fails, bounce back

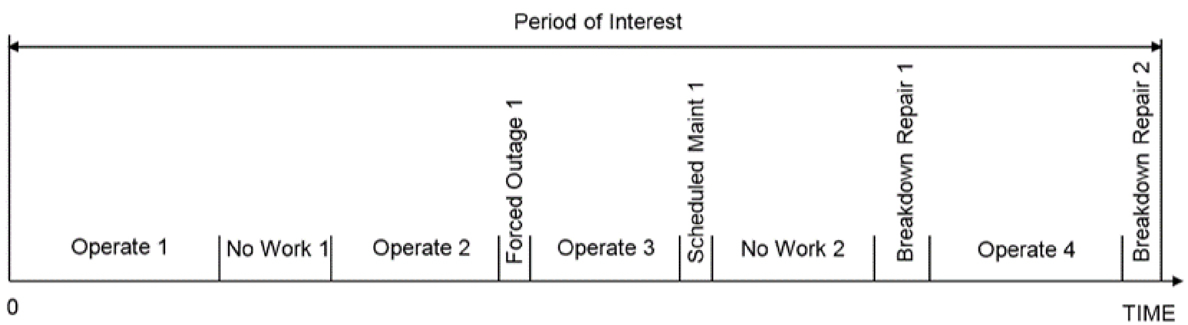


Source, UCLA Department of Space & Climate Physics, Mullard Space Science Laboratory

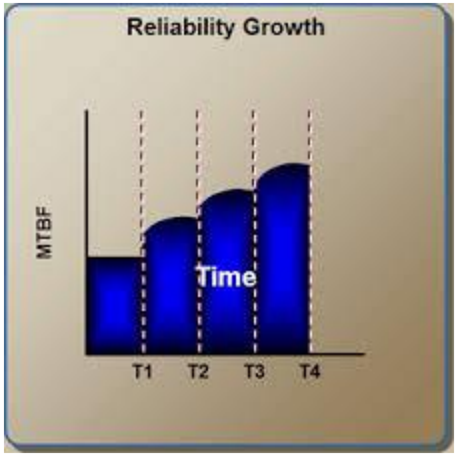
Reliability of power systems

	Traditional Reliability	Electricity Transmission & Distribution Systems
Metrics	***R*(*t*)** **Mean Time Between Failures (MTBF)** **Mean Time To Failure**	**Outage rate: System Average Interruption Frequency Index (SAIFI)** **Repair rate : Customer Average Interruption Duration Index (CAIDI)** **System downtime**
System Configuration	**Series** **Parallel** **Complex**	**Breaker-and-a-half** **Breaker-and-a-third** **DESN**

Reliability could mean different things in various contexts



Mean Time Between Failures



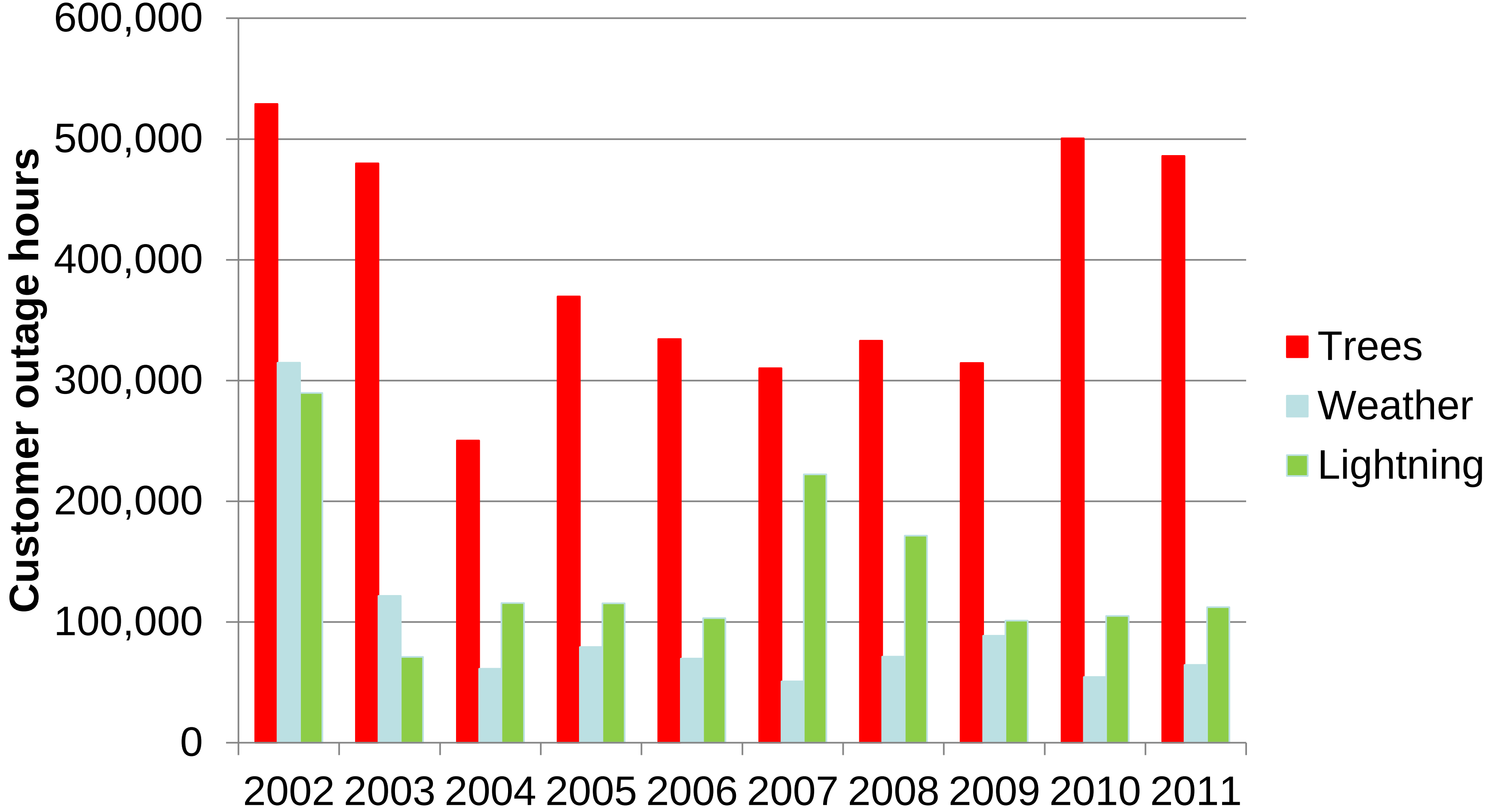
Reliability Analysis

- To make improvements to reliability, it is necessary to measure or quantify reliability
- Application of statistical theory
  - Estimate reliability and distribution parameters
  - Test whether reliability is significantly changing
- Application of probability theory
  - Predict the probability of failure over some mission time, t
  - Determine system-level failure probabilities based on component-level failure probabilities

Role of Probability and Statistics

- *Statistics*
  - Used for monitoring reliability performance or for reporting
  - System Average Interruption Duration Index (SAIDI), etc.
  - Time series of above metrics
  - Allow optimization
- *Probability*
  - Used for predictions of performance
  - Used for planning and expansion decisions
  - Loss of Load Probability (LOLP)

Public Service Electric & Gas (PSE&G): customer hours by outage cause 2002-2011



Source: Public Service Electric & Gas (PSE&G) Annual System Performance Report 2011.

IEEE-1366: key metrics/statistics

- **System** Average Interruption **Frequency** Index (SAIFI): indicates how often the average customer experiences a sustained interruption
- **Customer** Average Interruption ***Duration*** Index (CAIDI): represents the average time required to restore service
- **System** Average Interruption ***Duration*** Index (SAIDI): interruption duration for the average customer
- **Momentary** Average Interruption **Frequency** Index (MAIFI): the average frequency of momentary interruptions
- IEEE-1366 contains other less commonly used metrics as well

Reliability metrics

Statistic metrics for monitoring and reporting reliability performance

- **System** Average Interruption **Frequency** Index (SAIFI) =
$$\frac{\text{TOTAL NUMBER OF CUSTOMER INTERRUPTIONS}}{\text{TOTAL NUMBER OF CUSTOMERS SERVED}}$$

- **Customer** Average Interruption ***Duration*** Index (CAIDI) =
$$\frac{\sum \text{CUSTOMER}-\text{HOURS OF INTERRUPTIONS}}{\text{TOTAL CUSTOMER INTERRUPTIONS}}$$

- **System** Average Interruption ***Duration*** Index (SAIDI) =
$$\frac{\sum \text{CUSTOMER}-\text{HOURS OF INTERRUPTIONS}}{\text{TOTAL NUMBER OF CUSTOMERS SERVED}}$$

Source: Brown R. (2009) Electric power distribution reliability, p52.

Example of SAIFI, SAIDI & CAIDI: Atlantic City Electric (ACE)

	TOTAL NUMBER OF CUSTOMER INTERRUP-TIONS	CUSTOMER-HOURS OF INTERRUP-TIONS	TOTAL NUMBER OF CUSTOMERS SERVED	System Average Interruption Frequency Index (SAIFI)	Customer Average Interruption Duration Index (CAIDI)	System Average Interruption Duration Index (SAIDI)
Major event excluded	867,570	1,893,902	530,599	$\frac{867,570}{530,599}=1.64$	$\frac{1,893,902}{867,570}=2.18$	$\frac{1,893,902}{530,599}=3.57$
Major event only	175,345	1,166,706	530,599	$\frac{175,345}{530,599}=0.33$	$\frac{1,166,706}{175,345}=6.65$	$\frac{1,166,706}{175,345}=2.20$
Major event included	867,570 +175,345 =1,042,915	3,060,609	530,599	$\frac{1,042,915}{530,599}=1.97$	$\frac{3,060,608}{1,042,915}=2.93$	$\frac{3,060,608}{530,599}=5.77$

Note: only one major event – Hurricane Irene

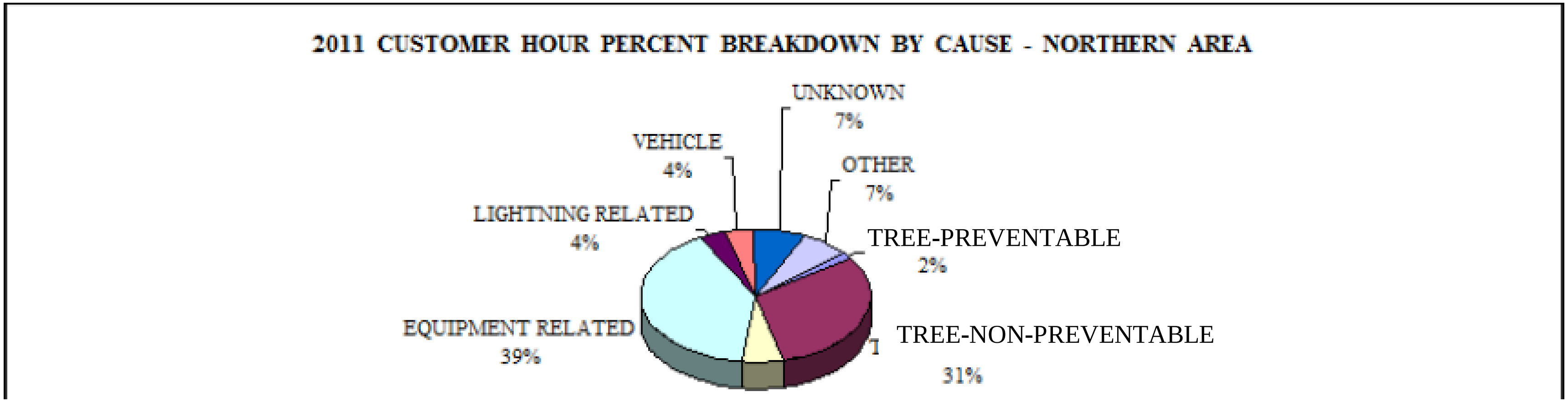
Source: Atlantic City Electric (ACE) Company's Annual System Performance Report for 2011.

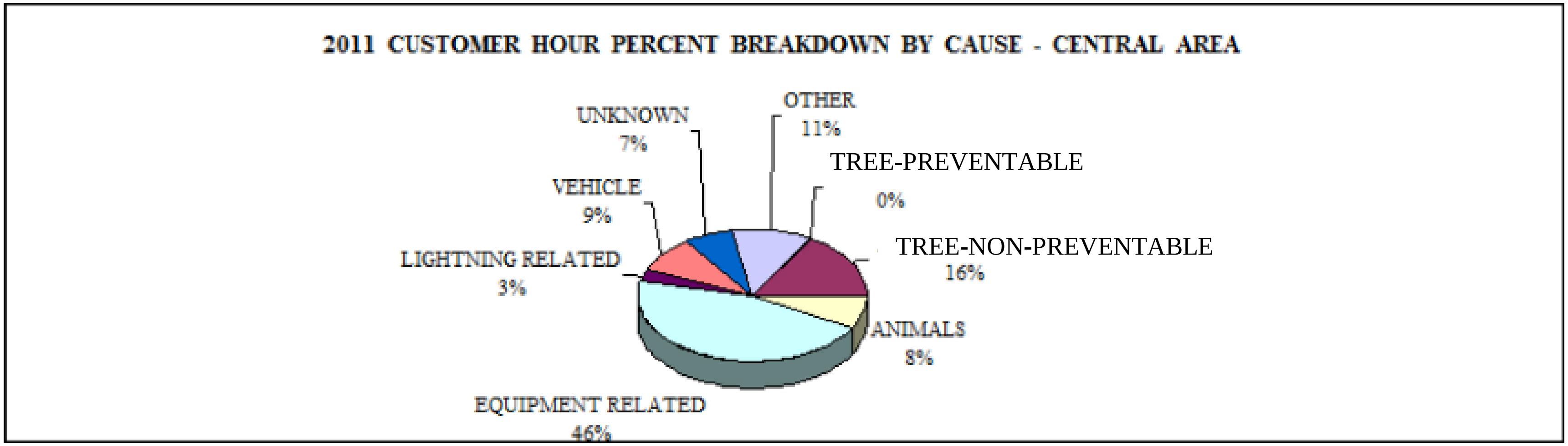
Atlantic City Electric (ACE): System Average Interruption Frequency Index (SAIFI) & Customer Average Interruption Duration Index (CAIDI) by outage causes

Cause	Events	Pct	Rank	Cust Out	Pct	Rank	Hours	Pct	Rank	SAIFI	CAIDI
Animal	1,800	13%	4	66,897	5%	7	259,729	5%	5	0.13	3.9
Dig In	100	1%	9	2,352	0%	9	5,421	0%	9	0.00	2.3
Equipment Failure	2,865	20%	3	241,030	20%	3	427,869	8%	3	0.45	1.8
Equipment Hit	391	3%	6	98,622	8%	5	132,298	2%	6	0.18	1.3
Other	370	3%	7	100,360	8%	4	123,538	2%	7	0.19	1.2
Overload	330	2%	8	29,017	2%	8	58,488	1%	8	0.05	2.0
Tree	**3,895**	**27%**	**1**	**316,032**	**26%**	**1**	**1,966,249**	**35%**	**2**	**0.59**	**6.2**
Unknown	1,203	8%	5	71,964	6%	6	384,438	7%	4	0.13	5.4
Weather	3,346	23%	2	290,880	24%	2	2,245,488	40%	1	0.54	7.7

Source: Atlantic City Electric (ACE) Company's Annual System Performance Report for 2011.

Jersey Central Power & Light (JCPL): customer hours percent by cause and district in 2011





Source: Jersey Central Power & Light (JCPL) Annual System Performance Report 2011, p.16-17.

Example of SAIFI & CAIDI by outage causes per circuit with data from Atlantic City Electric (ACE) (1/2)

Circuit NJ0383: customers served are 2,749

Cause	Outage Events	Customers Affected	Customer-Hours	System Average Interruption Frequency Index (SAIFI)	Customer Average Interruption Duration Index (CAIDI)
Animal	11	107	81	$\frac{107}{2,749} = 0.04$	$\frac{81}{107} = 0.8$
Circuit Overload	0	-	-	-	-
Equipment Failure	11	36	231	$\frac{36}{2,749} = 0.01$	$\frac{231}{36} = 6$
Lightning Contact	4	136	402	$\frac{136}{2,749} = 0.05$	$\frac{402}{136} = 3$
Other	11	950	2,332	$\frac{950}{2,749} = 0.3$	$\frac{2,332}{950} = 2$
Transformer Overload	0	-	-	-	-
Tree	8	17	65	$\frac{17}{2,749} = 0.006$	$\frac{65}{17} = 4$
Work Error	0	-	-	-	-

Source: Atlantic City Electric (ACE) Company's Annual System Performance Report for 2011.

Example of SAIFI & CAIDI by outage causes per circuit with data from Atlantic City Electric (ACE) (2/2)

Circuit NJ0374: customers served are 1,668

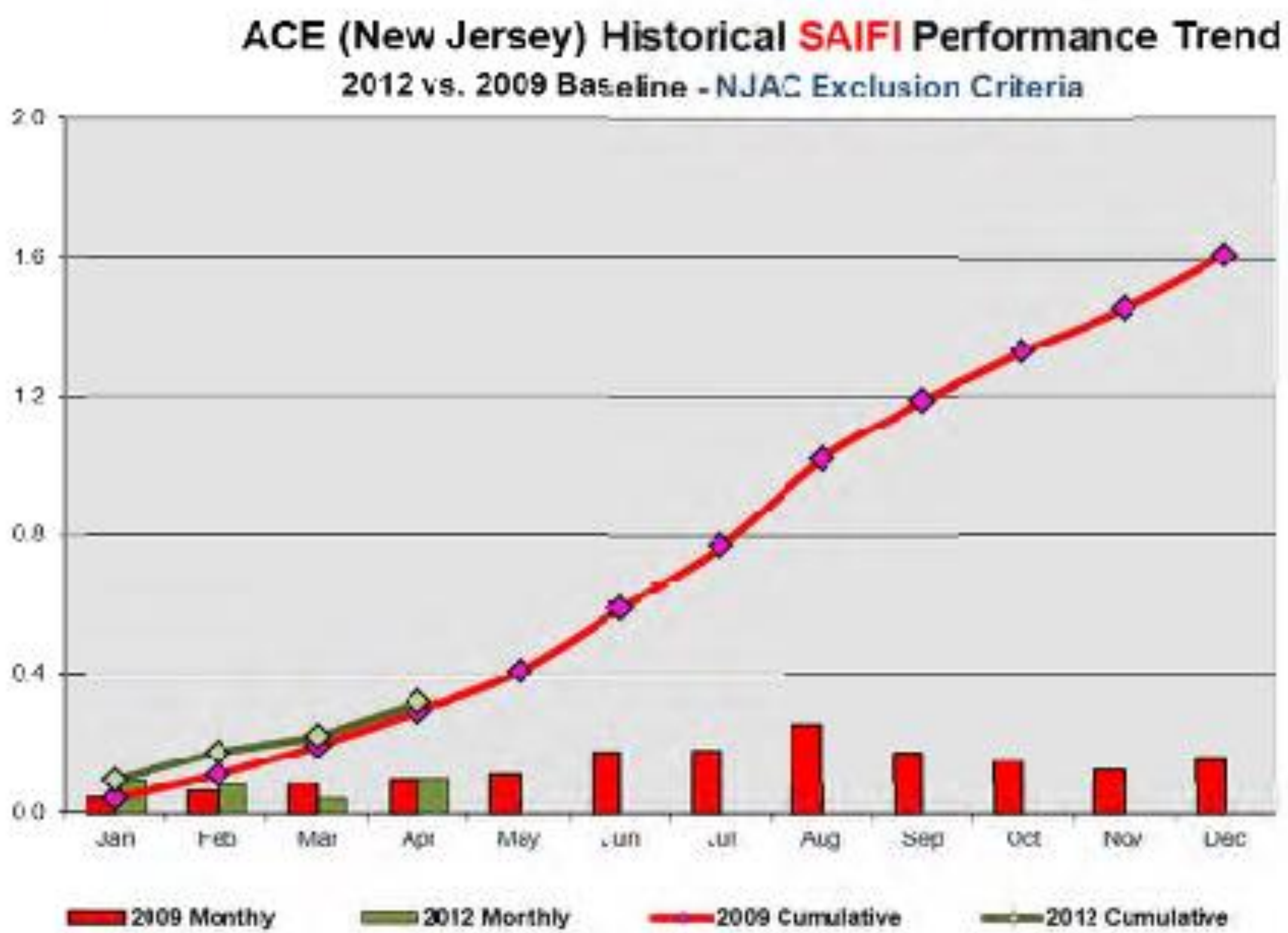
Cause	Outage Events	Customers Affected	Customer-Hours	System Average Interruption Frequency Index (SAIFI)	Customer Average Interruption Duration Index (CAIDI)
Animal	0	-	-	-	-
Circuit Overload	0	-	-	-	-
Equipment Failure	10	1,685	1,813	$\frac{1{,}685}{1{,}668} = 1$	$\frac{1{,}813}{1{,}668} = 1$
Lightning Contact	2	1,677	3,548	$\frac{1{,}677}{1{,}668} = 1$	$\frac{3{,}548}{1{,}677} = 2$
Other	11	1,702	1,531	$\frac{1{,}702}{1{,}668} = 1$	$\frac{1{,}531}{1{,}702} = 1$
Transformer Overload	0	-	-	-	-
Tree	0	-	-	-	-
Work Error	0	-	-	-	-

Source: Atlantic City Electric (ACE) Company's Annual System Performance Report for 2011.

Monthly System Average Interruption Frequency Index (SAIFI) & Customer Average Interruption Duration Index (CAIDI) with data from Atlantic City Electric (ACE)

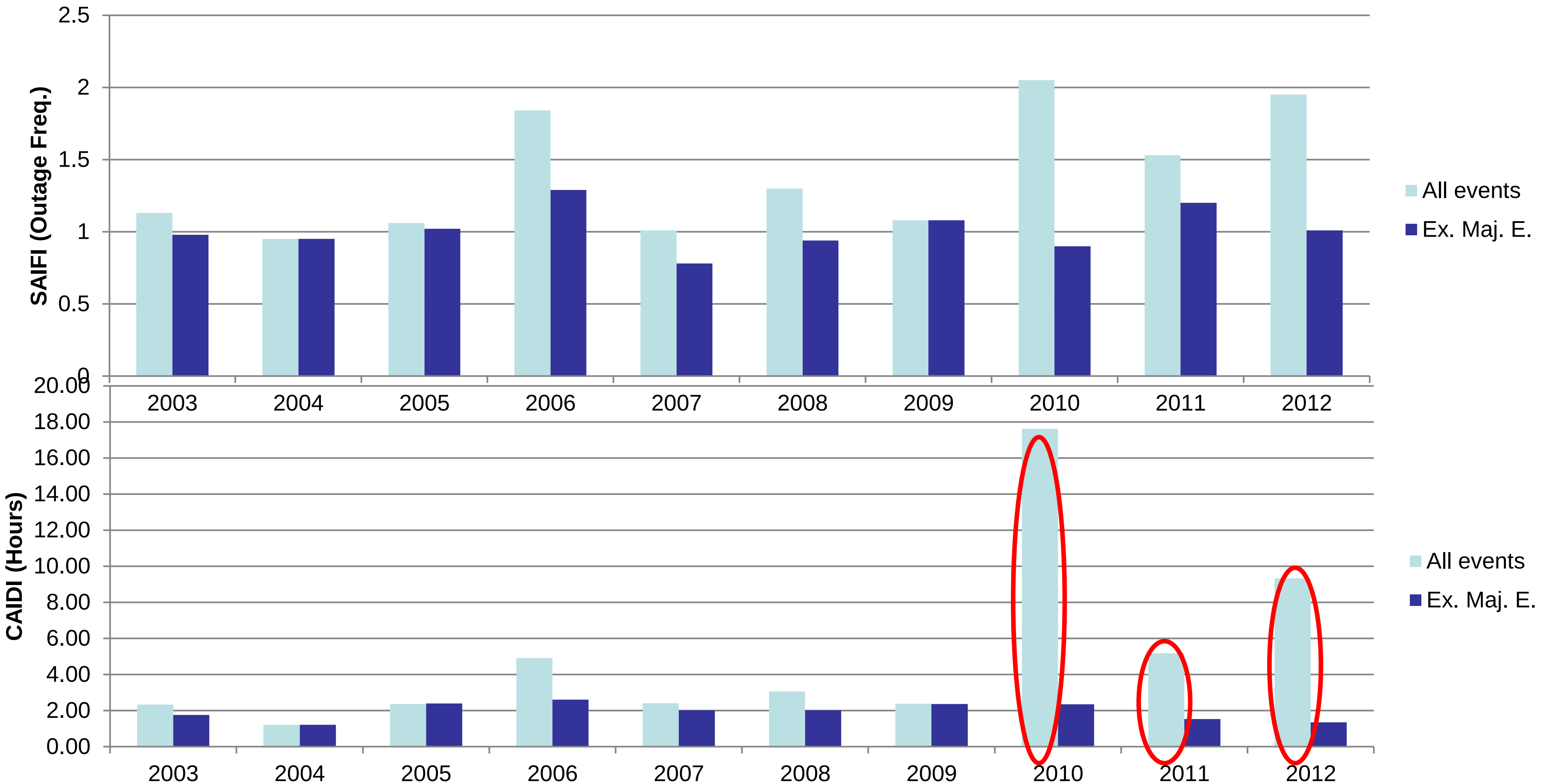
Source: Atlantic City Electric (ACE) Company's Annual System Performance Report for 2011, p. 140.

Monthly System Average Interruption Frequency Index (SAIFI) & Customer Average Interruption Duration Index (CAIDI) with data from Atlantic City Electric (ACE)



Source: Atlantic City Electric (ACE) Company's Annual System Performance Report for 2011.

Time series of System Average Interruption Frequency Index (SAIFI) & Customer Average Interruption Duration Index (CAIDI) with data from Atlantic City Electric (ACE)



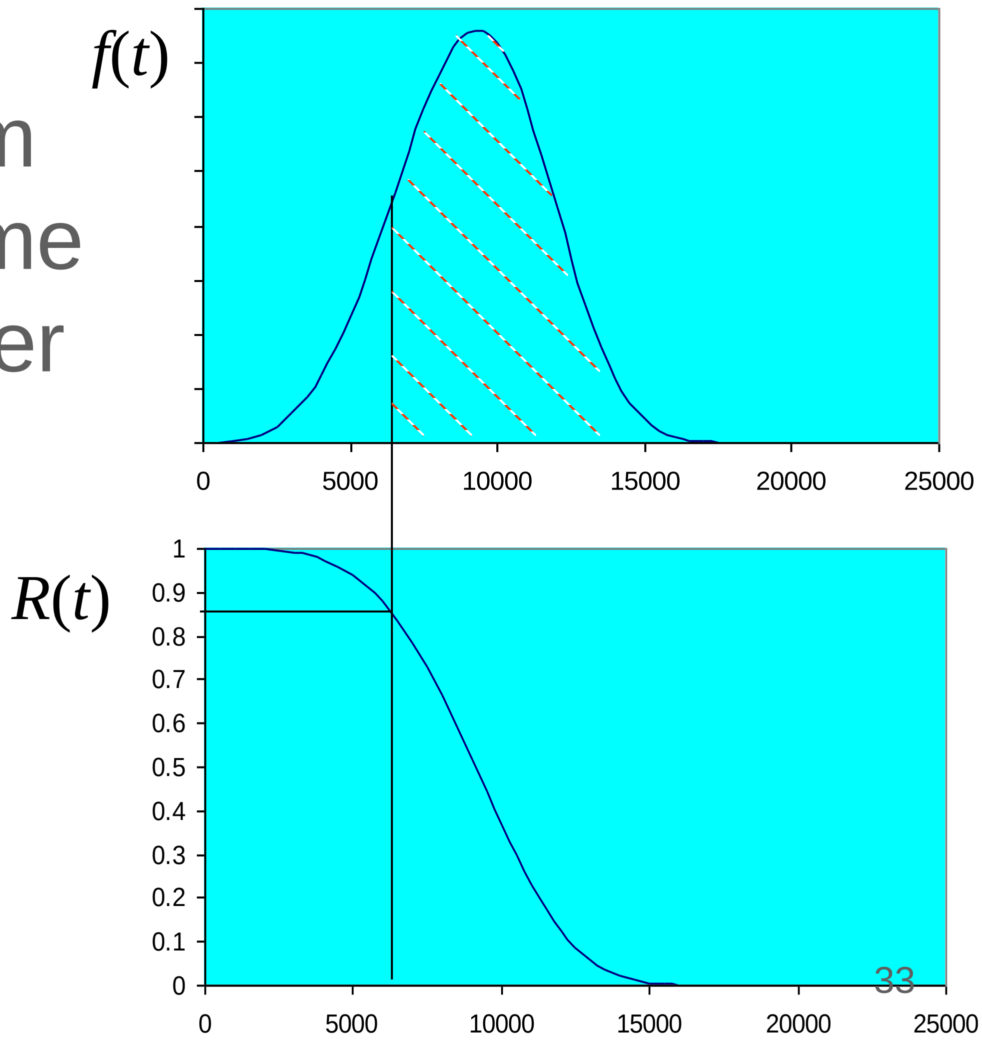
Major events: 2010 – 7 events (pg. 40 of part d), 2011 – Hurricane Irene, 2012 – 3 events
Source: Atlantic City Electric (ACE) Company's Annual System Performance Report for 2011.

Reliability vs. Maintainability vs. Resiliency

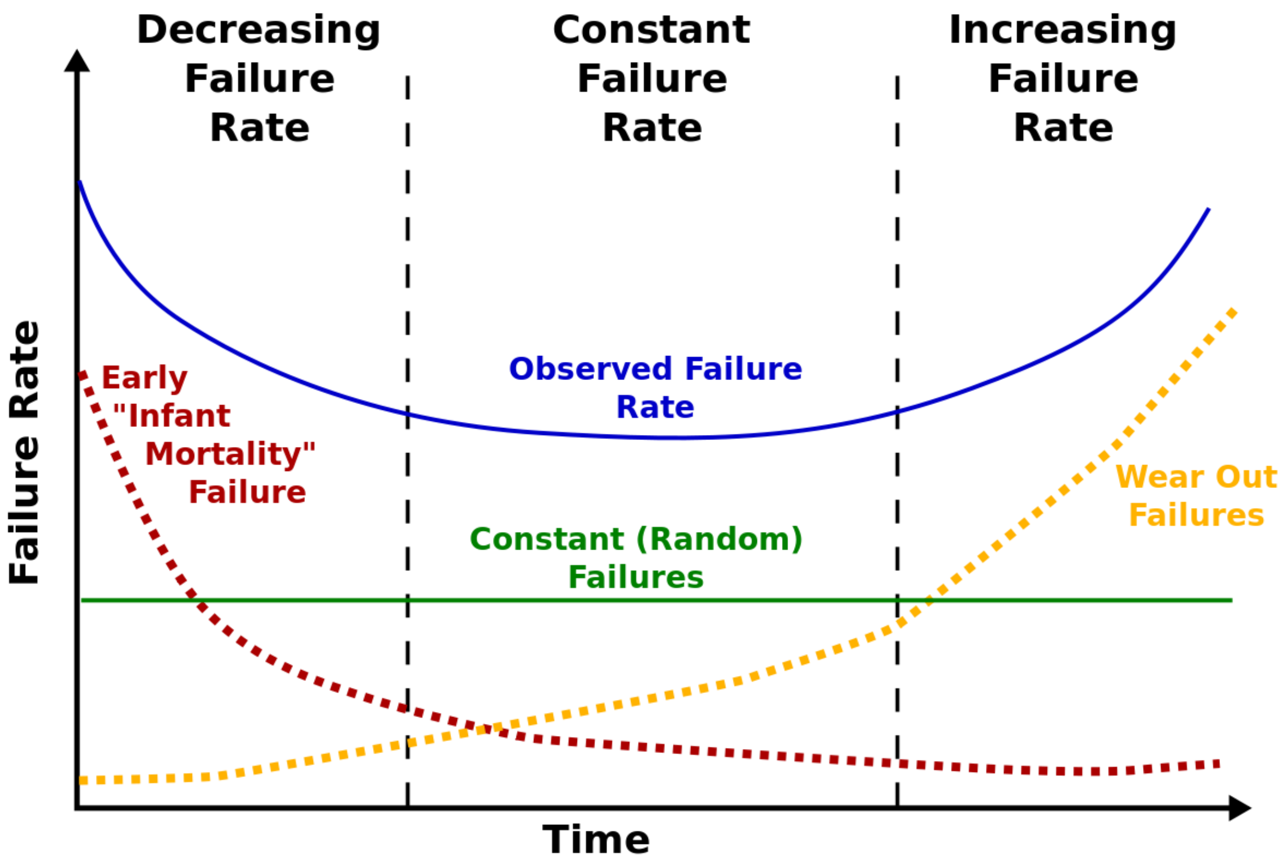
- *Reliability*
  - relates to the frequency of failure or the probability of failures
- *Maintainability*
  - relates to the ability to restore systems to a working state
- *Resiliency*
  - relates to the ability of the system to respond to extreme or catastrophic events
  - established metrics do not yet exist

Reliability Function, R(t)

- *Reliability* is the probability of an item surviving mission time *t* without failure under stated conditions



Failure rate changes with age



Agenda

A. Definitions of reliability and resiliency
B. Failure modes
C. Reliability modeling

Component Outages

- **Permanent/sustained**: associated with damaged faults requiring the component to be repaired or replaced

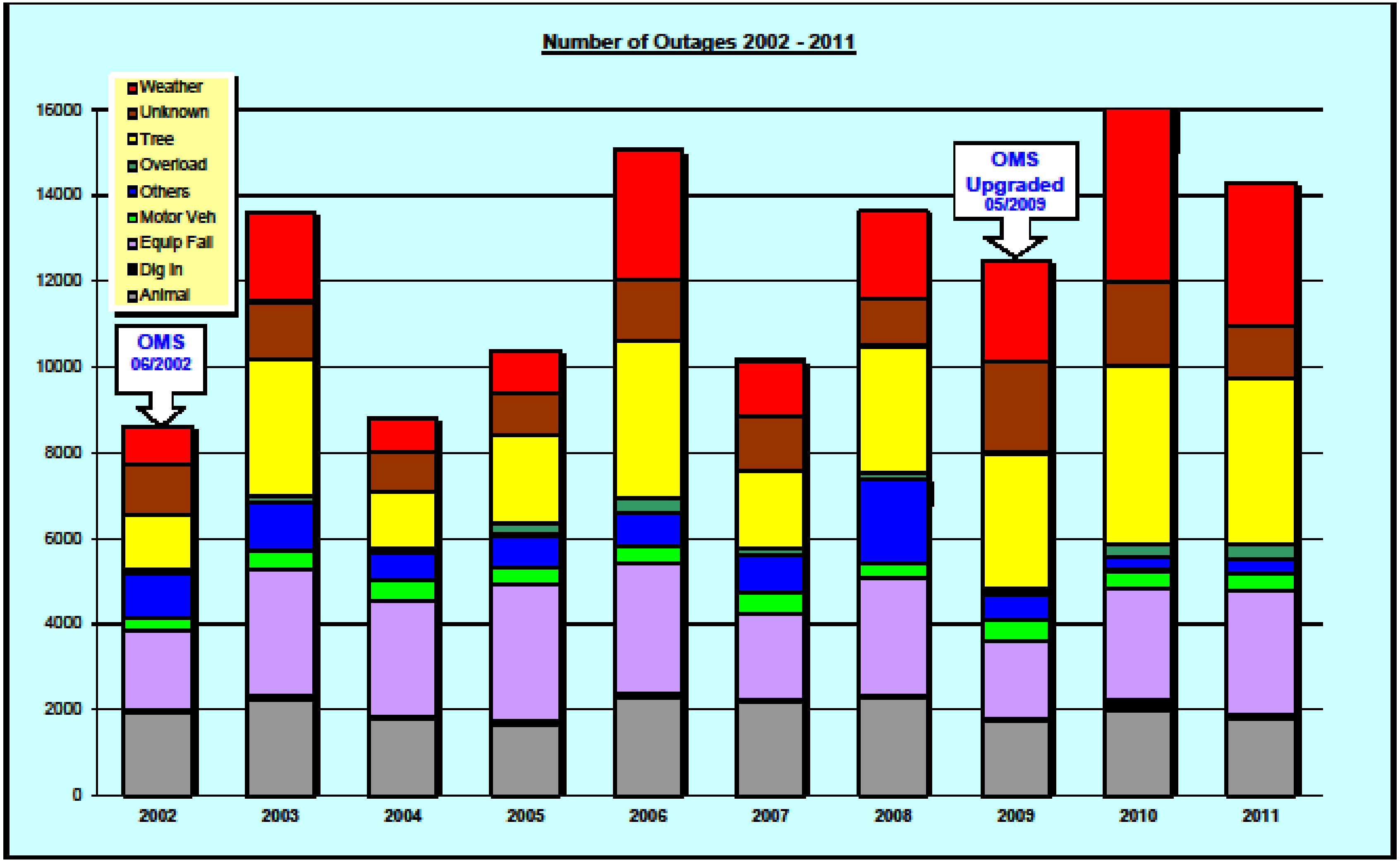
- **Temporary**: are associated with undamaged faults that are restored by manual/automatic switching

- **Maintenance**: outages planned in advance in order to perform preventive maintenance

Classification of interruption causes - do not consider dependent failures

- Weather
- Unknown
- Tree
- Overload
- Other
- Motor Vehicles
- Equipment failure
- Dig in
- Animals

Power outage by causes and years
OMS=Outage Management System

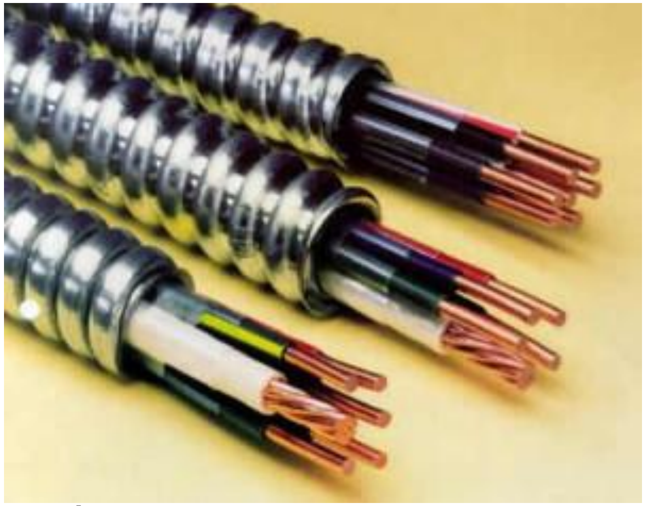


Source: Atlantic City Electric Company's Annual System Performance Report for 2011.

Failure modes

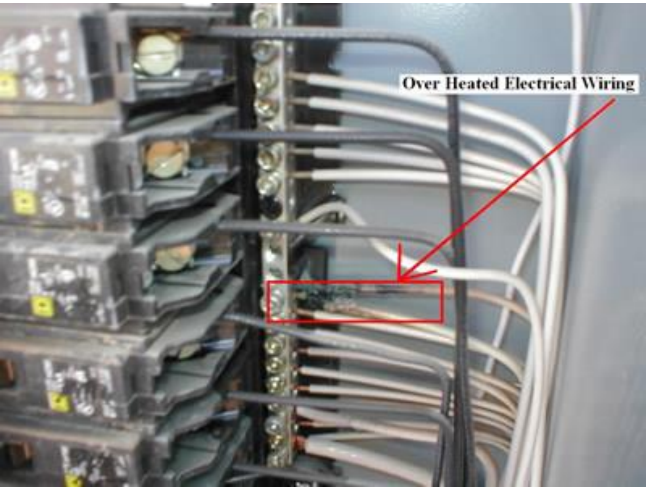
Sub-Component Failure (1/2)

Substation breakers
Source: http://smartgridcenter.tamu.edu/ratc/index.php/circuit-breaker-operation-evaluation/



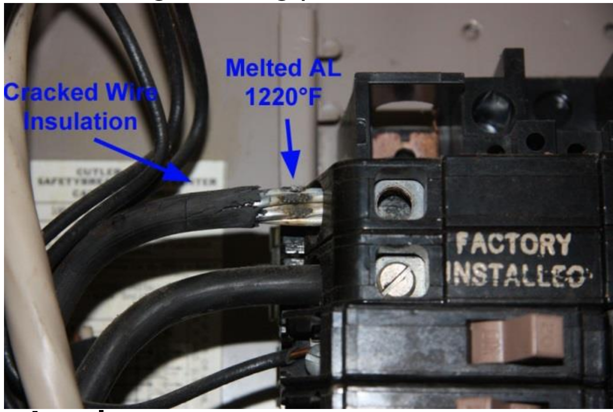
Conductors
Image courtesy of SNSU-Physics.org
Source: http://www.upsbatterycenter.com/blog/different-types-conductors/

Transformers
Source: http://www.powertransformersblog.com/tag/power-transformer/



Wires
Source: http://roncoelectricnj.com/electrical-inspections/

Arrester
Source: http://www.inmr.com/2014/07/principal-failure-modes-surge-arresters/



Insulators
Source: http://www.electrical-forensics.com/CircuitBreakers/CircuitBreakers.html

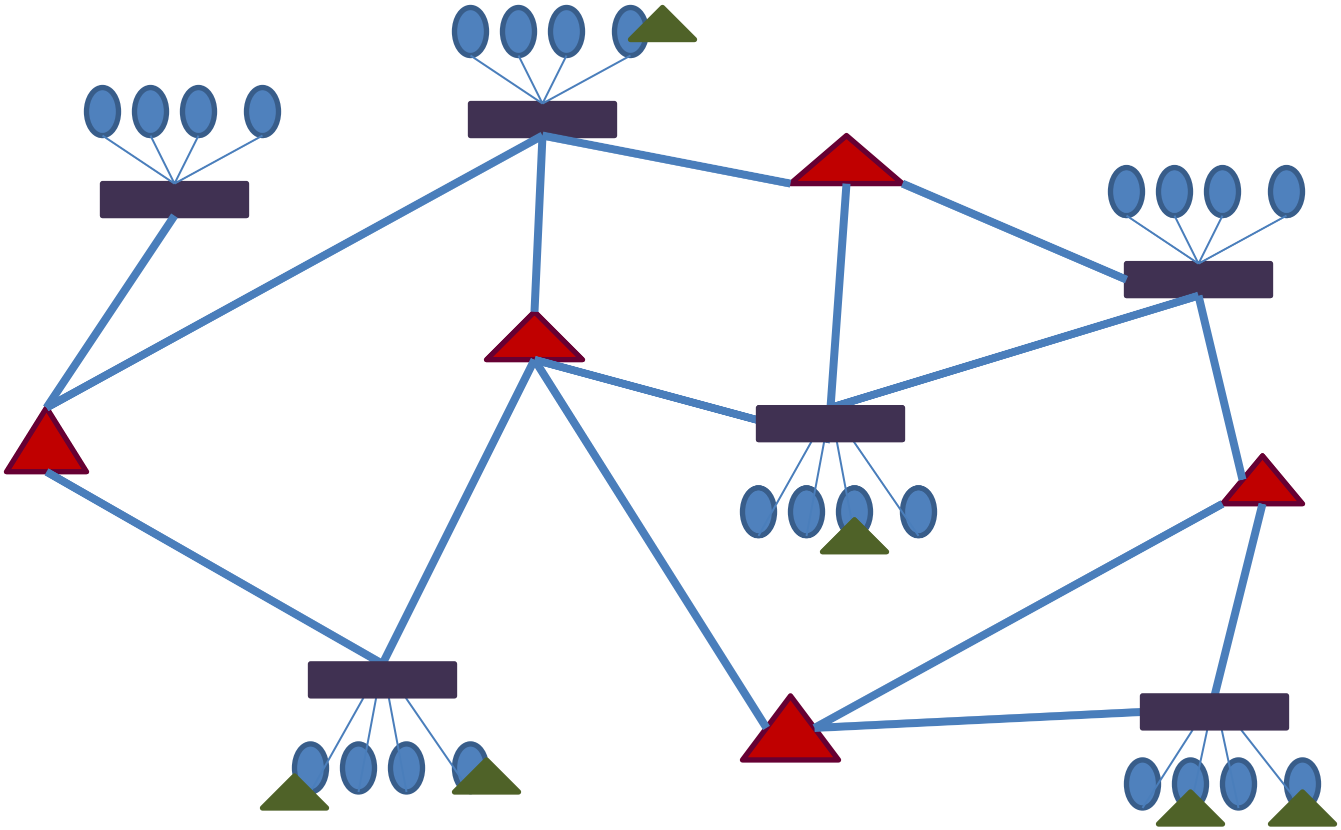
Sub-Component Failure (2/2) Maryland data

Percent of Customer Interruptions Associated With System Components

System Components	Snowmageddon 2/2/2010 – 2/12/2010			Hurricane Irene 8/27/2011 – 9/6/2011			Derecho 6/29/2012 – 7/8/2012		
	BGE	Pepco	Potomac Edison	BGE	Pepco	Potomac Edison	BGE	Pepco	Potomac Edison
Transmission Lines	0%	0%	0%	0%	0%	0%	0%	0%	0%
Transmission Substations	0%	0%	0%	0%	0%	0%	0%	0%	0%
Substation Supply Lines	3%	11%	21%	9%	22%	22%	15%	28%	19%
Distribution Substations	0%	0%	0%	0%	0%	0%	0%	0%	1%
Fuses	34%	7%	16%	34%	7%	20%	33%	5%	4%
Distribution Lines	27%	79%	40%	24%	67%	39%	21%	62%	57%
Reclosers	34%	2%	19%	32%	3%	18%	28%	2%	19%
Transformers	1%	1%	3%	1%	1%	1%	2%	2%	0%
Service Lines	1%	0%	unknown	1%	0%	unknown	1%	1%	unknown

Source: Weathering the Storm, Office of Governor, Maryland, 2012

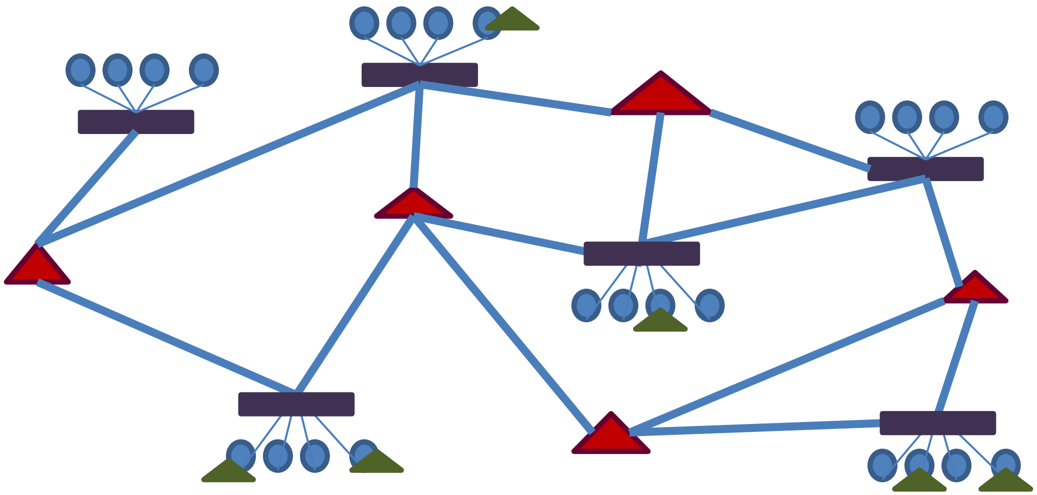
Electricity network components



Distributed Generation Units

Transmission Lines

Possible states for network components



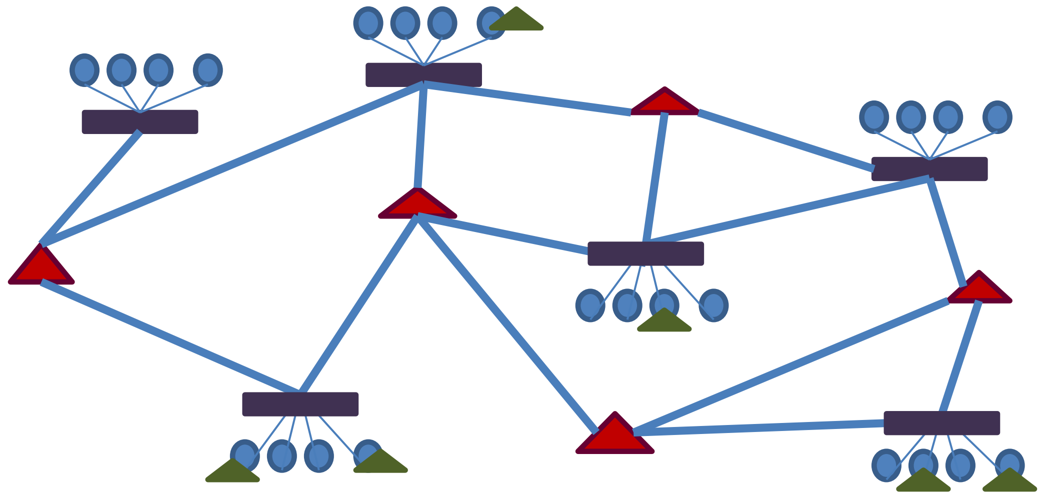
Centralized generator(s) might be unavailable

Available Capacity of Centralized Units

Failure of centralized generators

Source: http://mikesmithspoliticalcommentary.blogspot.com/2011/03/result-of-affirmative-action-at-south.html

Possible states for network components



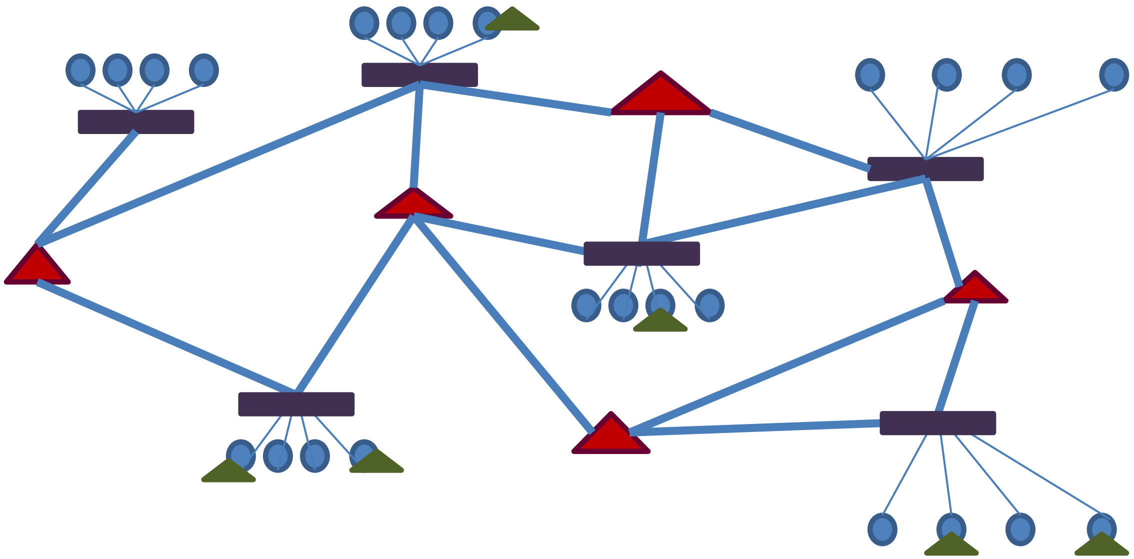
Transmission line(s) might be unavailable

Available Capacity of Transmission Lines

Failure of transmission line(s)

Source: http://basinelectric.wordpress.com/2010/01/25/ice-and-wind-take-a-toll-on-basin-electric-transmission-lines/

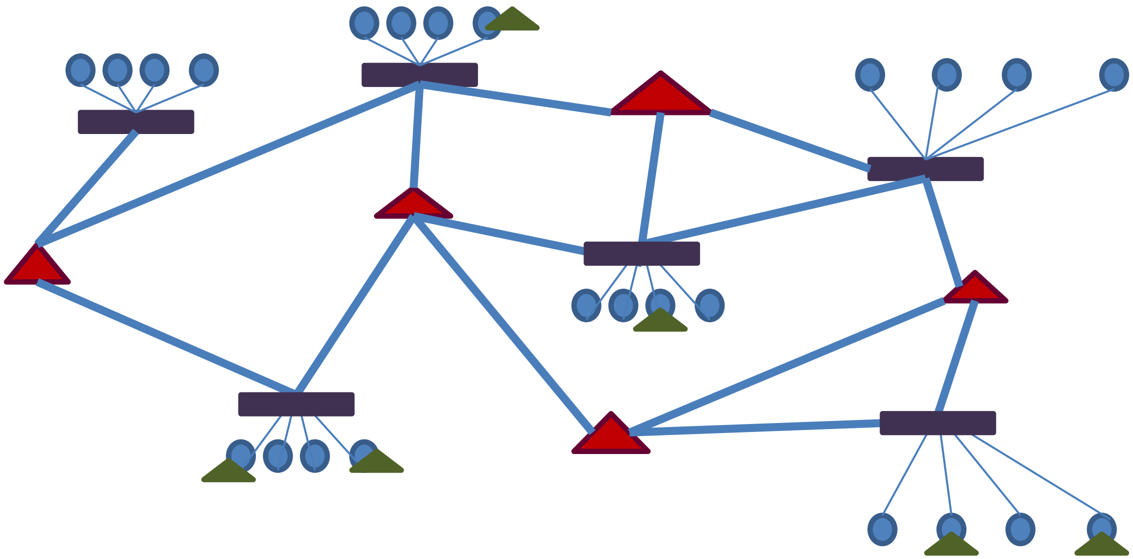
states for network components



Distribution line(s) might be unavailable

Satisfiable Demand or Locally Satisfiable Demand

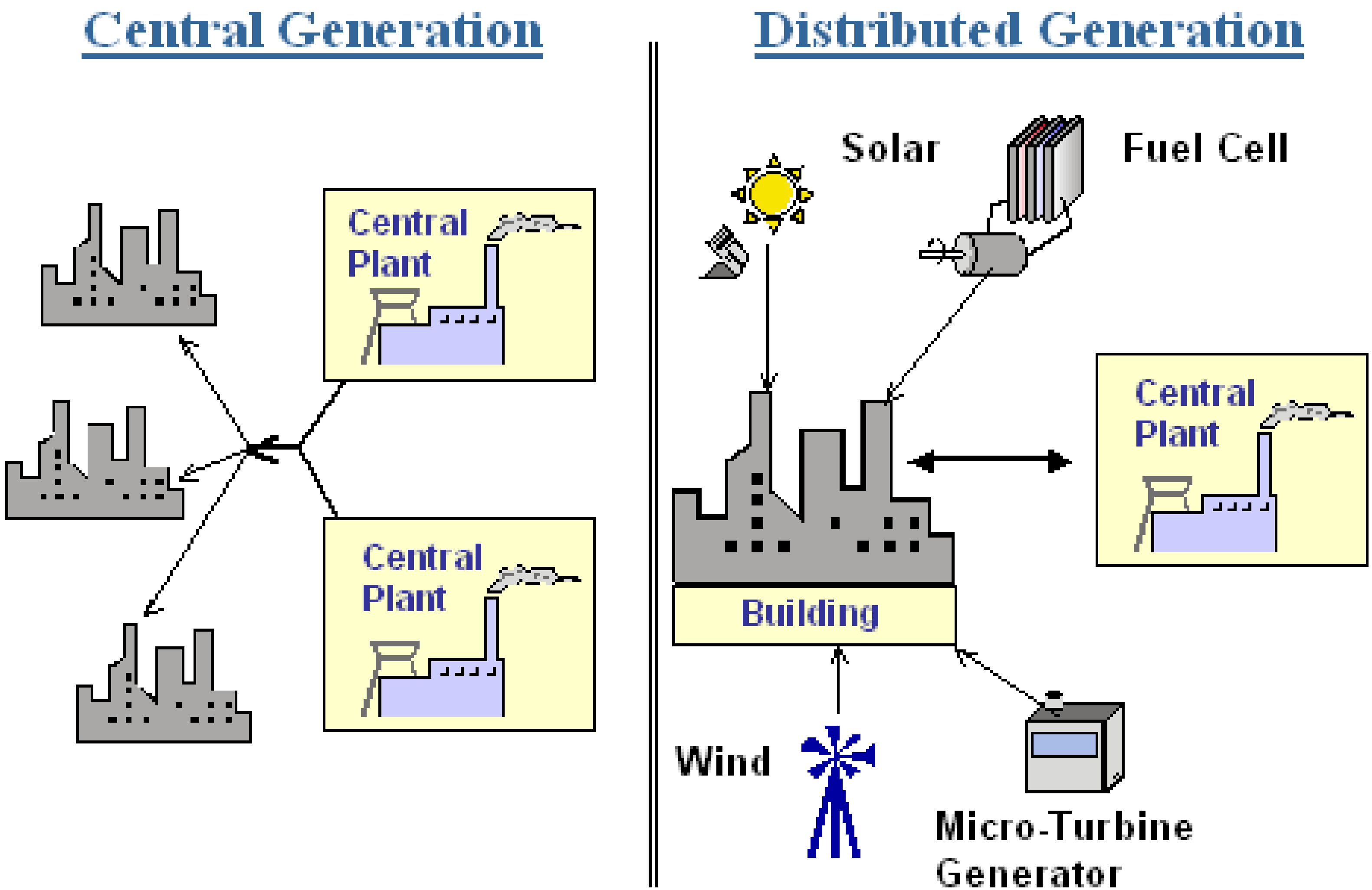
states for network components



Distributed generation unit(s) might be unavailable

Available Capacity of Distributed Generation Units

CENTRAL vs. DISTRIBUTED GENERATION



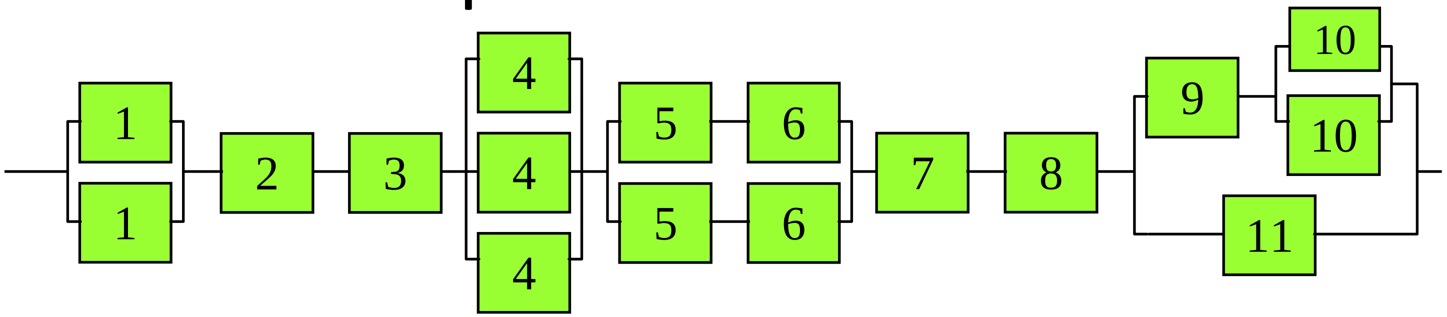
Source: www.nga.org

Agenda

A. Definitions of reliability and resiliency
B. Failure modes
C. Reliability modeling

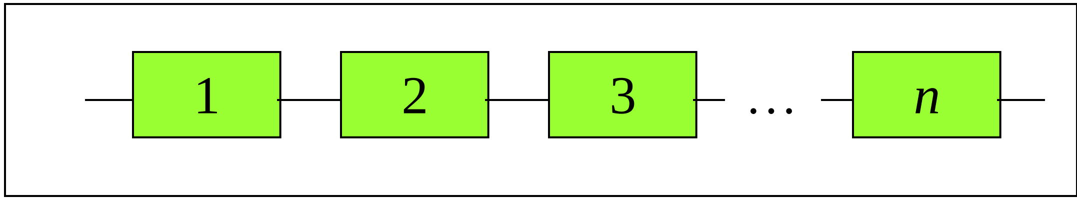
System Reliability

- Predict reliability of components, $r_i(t)$, based on statistical analysis or an assumed distribution, e.g., Weibull, exponential
- Determine system reliability based on a reliability block-diagram
- Assume independent failures

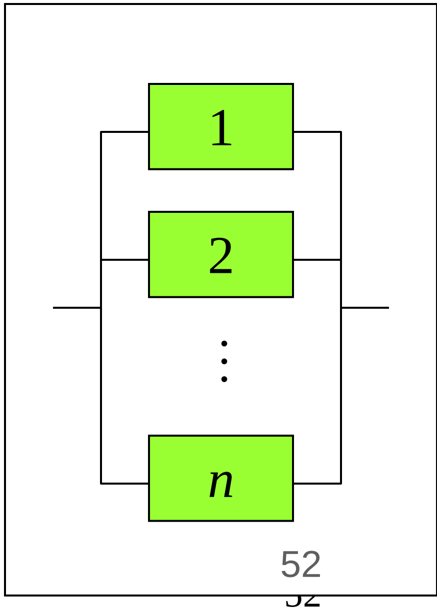


System Reliability

- <u>series system</u>
  Increase reliability of individual components

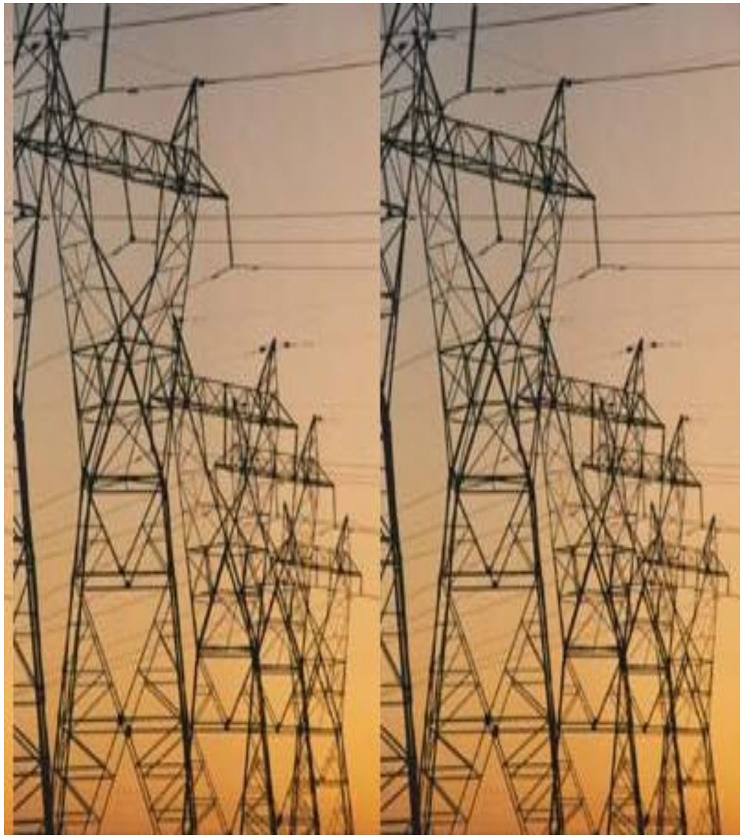


- <u>parallel system</u>
  Increase redundancy of components

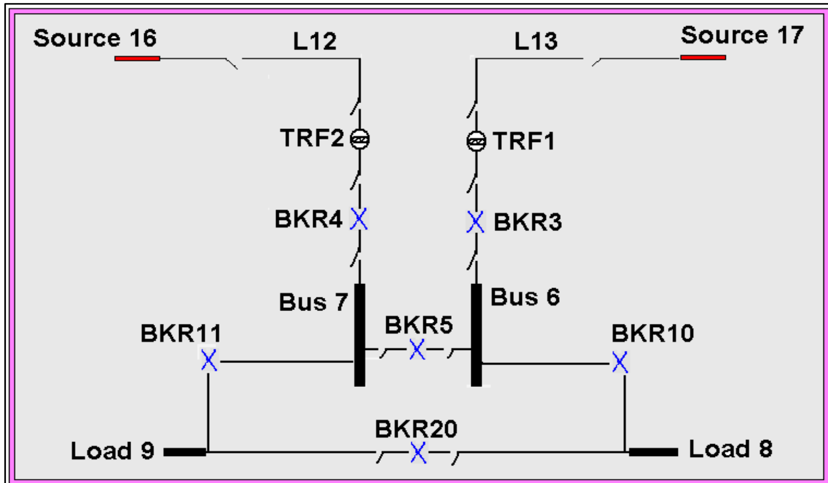


Reliability modeling

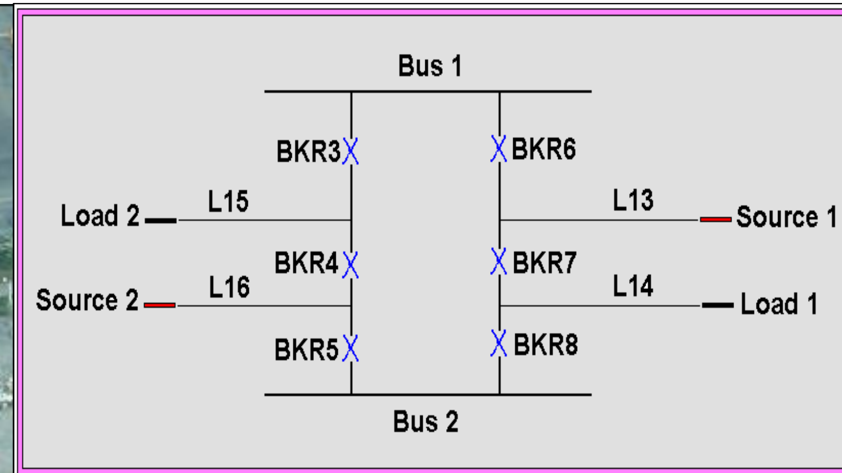
- Develop convenient approximate models for bigger systems
- General equations for series systems have been developed in the past
- Equations for components arranged in parallel to obtain failure rate, average repair time
- Markov Chains provide exact solutions, but complexity grows with actual systems



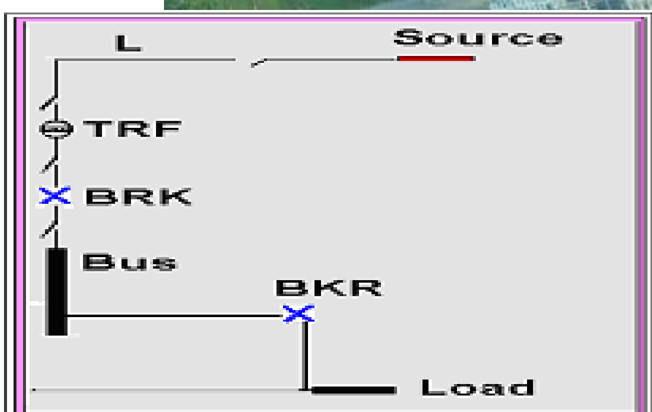
Common configurations

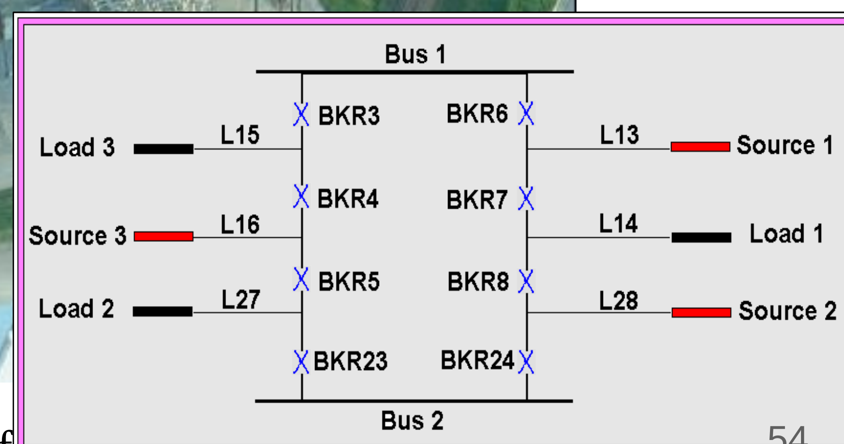


DESN Configuration



Breaker-and-a-Half Configuration



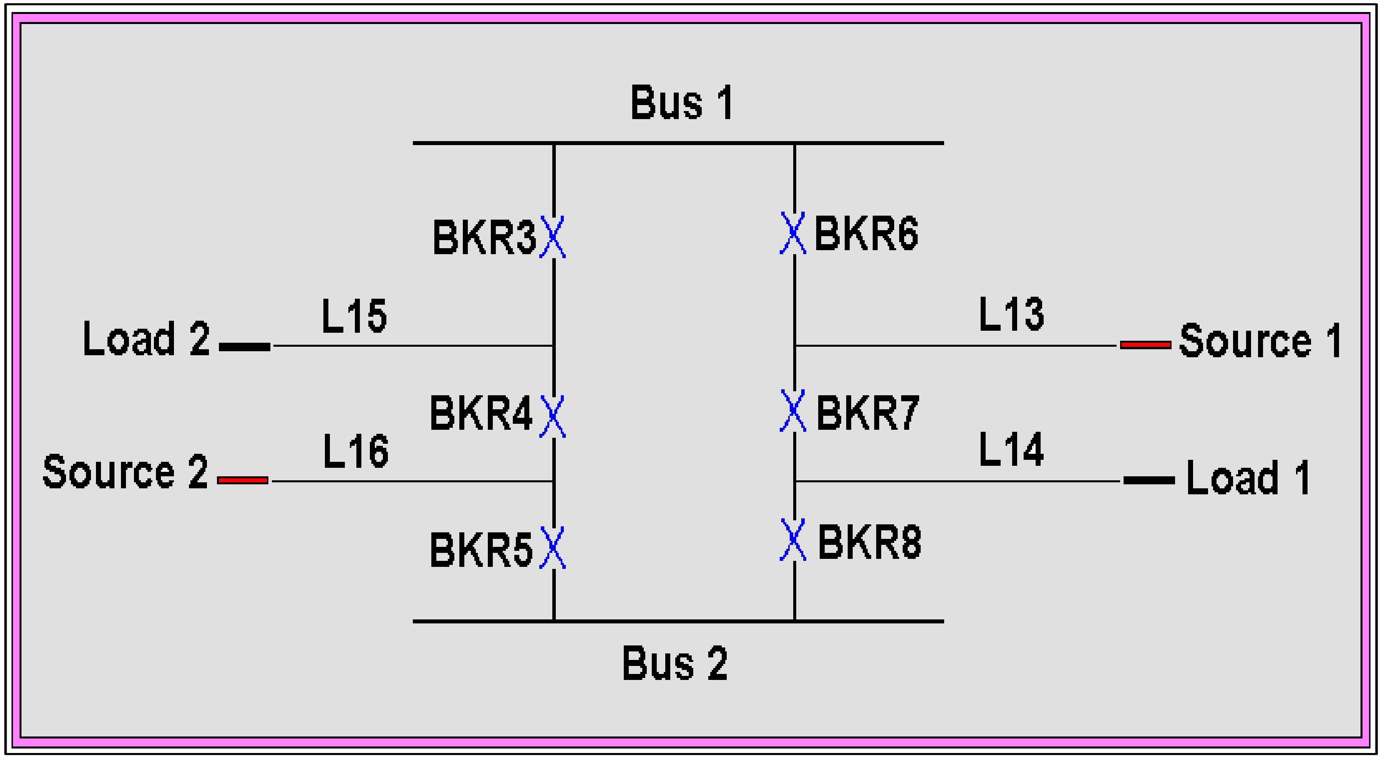


DESN Configuration

Radial Configuration

Breaker-and-a-Third Configuration

Reliability modeling with cut sets



Breaker-and-a-Half Configuration

Series-Parallel transformation

Cut-Sets & Path-Sets

- *Cut Sets* – set of components whose failure will result in a system failure
- *Path Sets* – set of components whose functioning ensures the system will function

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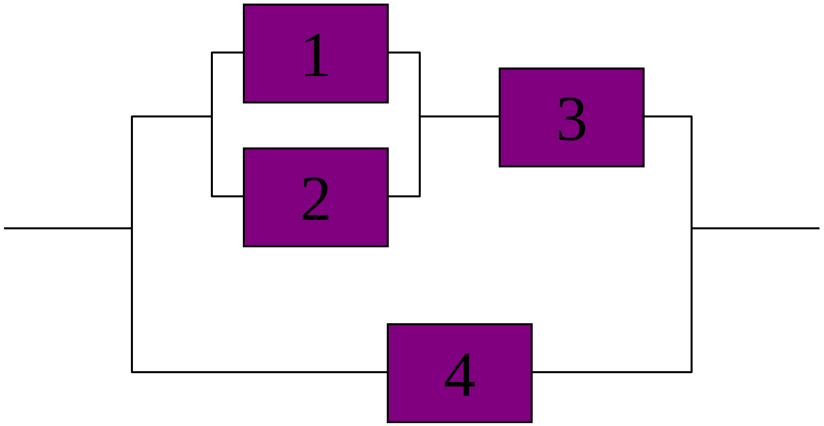
- *Minimal Cut Sets* – set of components who all must failure to result in a system failure
- *Minimal Path Sets* – set of components who all must function for the system to function

Cut Set/Path Set Example



<u>Minimal cut sets</u>

{3,4}

{1,2,4}

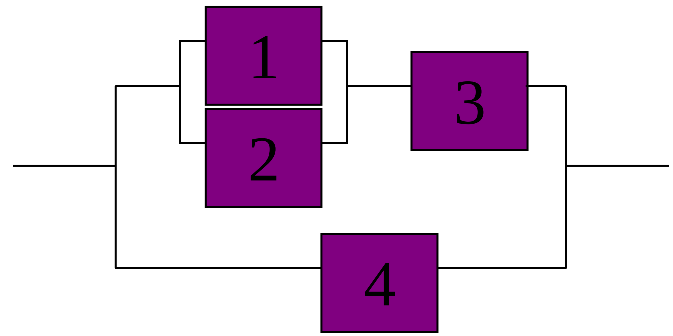
<u>Minimal path sets</u>

{4}

{1,3}

{2,3}

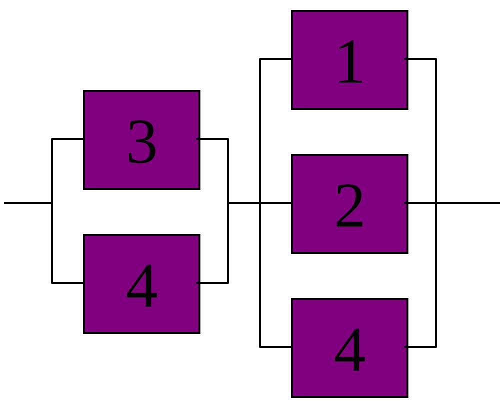
Cut sets & path sets can be used to approximate system reliability



<u>Minimal cut sets</u>

{3,4}

{1,2,4}



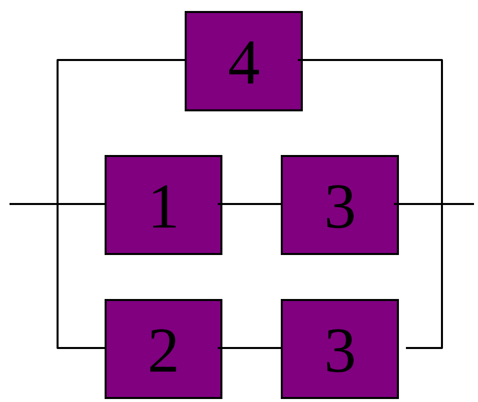
Lower-bound approximation

<u>Minimal path sets</u>

{4}

{1,3}

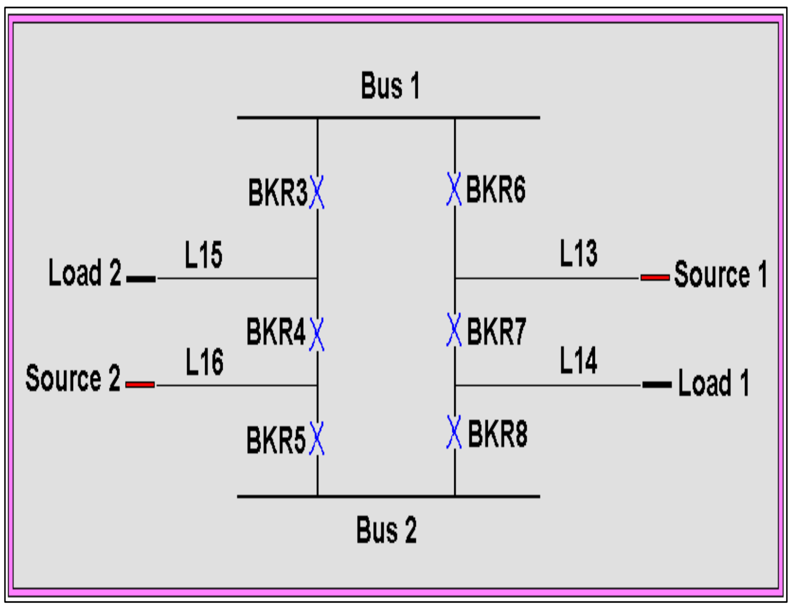
{2,3}



Upper-bound approximation

Cut sets of Electric Distribution Systems

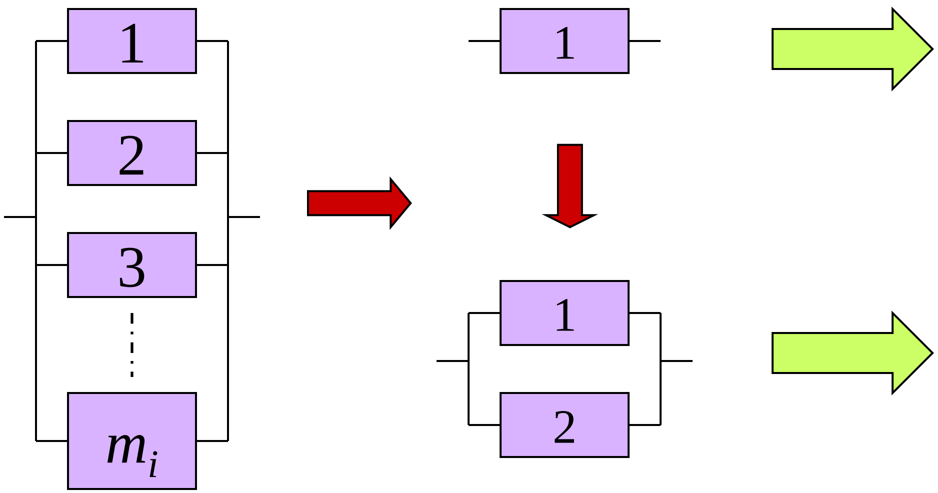
- Electric distribution systems are highly reliable
- Combination of failure from different components in order to have an outage at a specific load point
  - Component **sustained** failure **overlapping** component **sustained** failure



Breaker-and-a-Half Configuration

{LINE 14}	{LINE 13,BKR 4,BKR 5}	{LINE 13,BKR 3,BUS 8}
{BKR 7,BKR 8}	{LINE 13,BKR 4,BUS 2}	{LINE 13,BUS 1,BKR 5
{BKR 7,BKR 5}	{LINE 13,BKR 4,BKR 8}	{LINE 13,BUS 1,BUS 2}
{BKR 7,BUS 2}	{LINE 13,BKR 3,BKR 5}	{LINE 13,BUS 1,BKR 8}
{LINE 13,LINE 16}	{LINE 13,BKR 3,BUS 2}	{LINE 13,BKR 5,BKR 6}
{LINE 16,BKR 6,BKR 7}	{LINE 16,BKR 3,BKR 7}	{LINE 13,BUS 2,BKR 6}
{LINE 16,BUS 1,BKR 7}	{LINE 16,BKR 4,BKR 7}	{LINE 13,BKR 8,BKR 6}

Failure rate for 2-component redundant system



λ = component failure rate

r = component repair time

λ_1 = component 1 failure rate

λ_2 = component 2 failure rate

r_1 = component 1 repair time

r_2 = component 2 repair time

<u>component 1 fails first</u>:

system failure rate = $\lambda_1 (\lambda_2 \, r_1)$

<u>component 2 fails first</u>:

system failure rate = $\lambda_2 (\lambda_1 \, r_2)$

<u>either component fails first</u>:

system failure rate = $\lambda_1 \, \lambda_2 (r_1 + r_2)$

Summary

- Severe weather events post a challenge to the aging electric power systems
- Power outages can be characterized by frequency, magnitude and duration
- Geographic locations and circuit configuration determines its outage characteristics (cause, magnitude)
- Assessment of various failure modes and detailed data collection are critical to analysis

RUTGERS

Strategies for Improving Reliability and Resiliency

- Utility hardening measures
- Time value of money
- Net present value
- Considerations of uncertainty

Agenda

A. Utility hardening measures
B. Time value of money
C. Net present value
D. Consideration of uncertainty

Strategies to improve reliability

Rockland Electric Company (RECO) outage causes during Sandy

customers =71,182

	# interruptions	# affected customers
Tree contact	739	62,727
Equipment failure	26	597
No cause found	2	93
Total	767	63,417

Source: Rockland Electric Company (RECO) Revised Major Events Report – October 28-November 10, 2012.

Component failures in Switching station/Substation failure of Public Service Electric & Gas (PSEG) in Sandy

- breaker (compartments)
- control cabinets
- voltage regulator controls
- AC and DC control systems
- auxiliary power system
- battery chargers
- auxiliary switches
- relay equipment
- Transformer
- Transformers' auxiliary equipment
- reactor
- disconnect motor operators

Source: Public Service Electric & Gas (PSE&G)'s final report to the BPU Major Event Superstorm Sandy/Nor'easter October 27 – November 15, 2012

Strategies to improve reliability of Switching station/Substation (1/2)

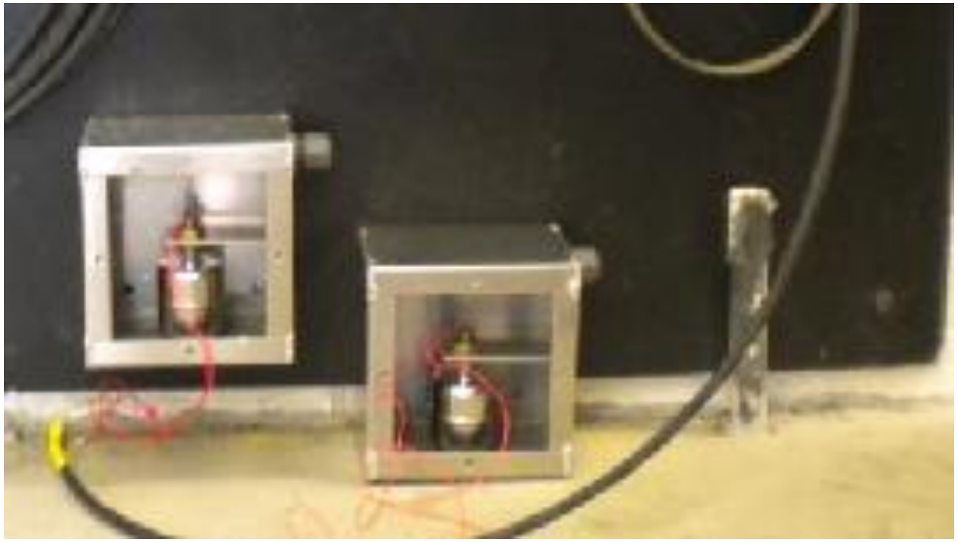
Flood control strategies

- Install *float switches*
- Install *flood walls*
- Install or replace with *high-capacity pumps*
- Build *drainage* pathways for water to reach *sumps*
- Use *submergible equipment* in floor-prone areas
- Install *watertight doors*
- *Seal building penetrations*

Source: General Electric (GE). 2014. NJ storm hardening recommendations and review/comment on EDC major storm response filings.

Float switches monitor flood status

Selected placement and integrated into control system improve flood monitoring



Source: Boggess, Becker, and Mitchell. 2014. IEEE 2014 T&D conference paper 14TD0564 storm flood hardening of Electrical Substations.

Flood walls

Photo: Brian A. Pounds
Source: http://www.ctpost.com/local/article/UI-hardens-substations-against-high-water-4682439.php

High capacity pumps

Source: http://www.bbc.com/news/uk-england-somerset-26512330

Conduits and pump drainage

Photo: Brian A. Pounds
Source: http://www.ctpost.com/local/article/UI-hardens-substations-against-high-water-4682439.php

Water-tight doors

Source: http://www.westernpower.co.uk/About-us/News/WPD-makes-watertight-investment.aspx

Photo: Brian A. Pounds
Source: http://www.ctpost.com/local/article/UI-hardens-substations-against-high-water-4682439.php#photo-4950557

Seal penetrations to buildings

Source: http://www.cablejoints.co.uk/sub-product-details/duct-seals-duct-sealing-csd-rise-duct-seal/duct-seals-denso-mastic-16a#sthash.CpGwtksN.dpuf

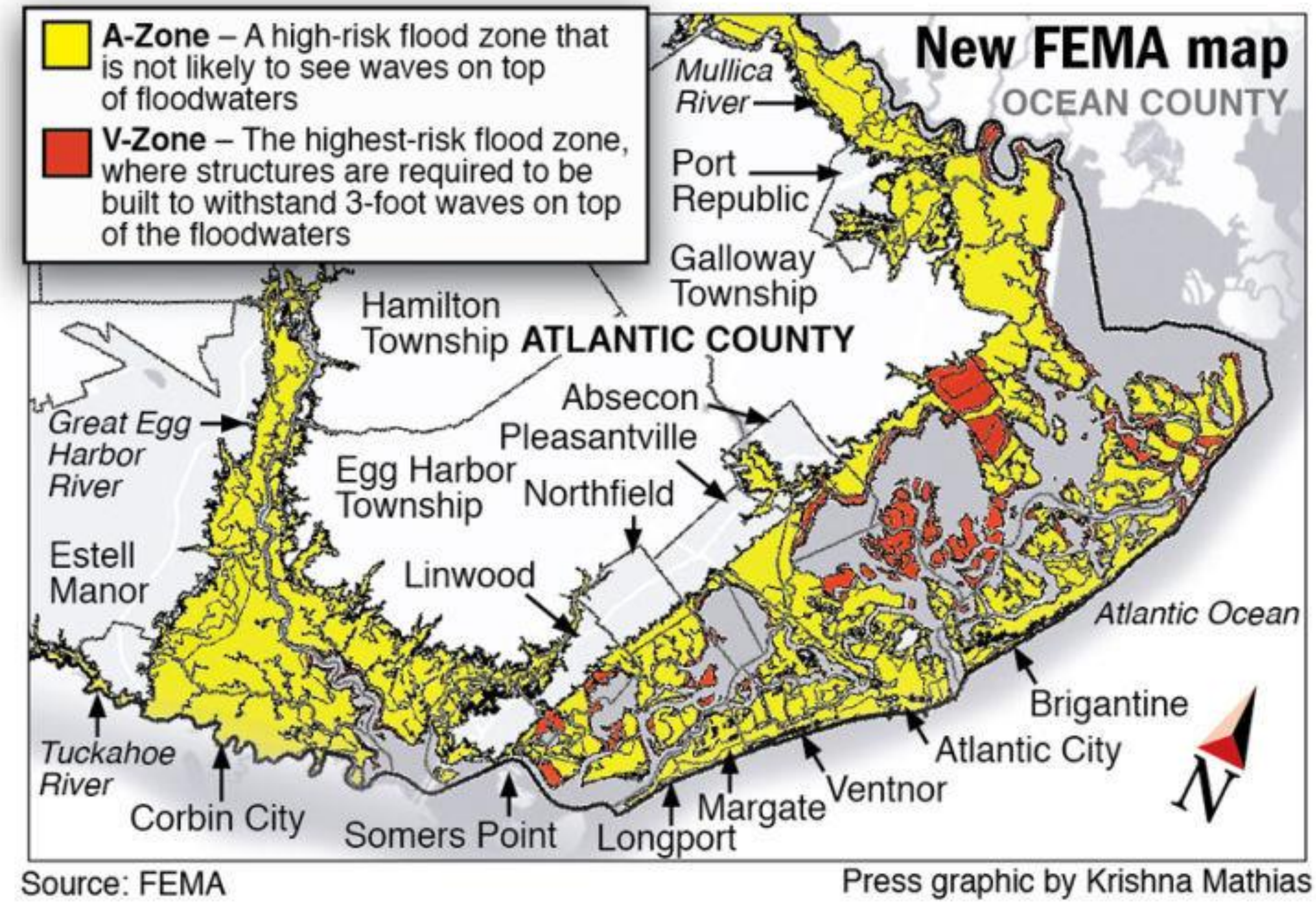
Strategies to improve reliability of Switching station/Substation (2/2)

Flood avoidance strategies

- Build new substations outside flood zones
- Raise substation grade
- Install sheet pile walls around the substation
- Install critical equipment in elevated positions
- Install enclosures or raise equipment
- Locate equipment above ground if multistory station
- Install moveable racks for interior panels

Source: General Electric (GE). 2014. NJ storm hardening recommendations and review/comment on EDC major storm response filings.

Build new substations outside flood zones



Source: McKelvey W. FEMA shrinks flood zones on new maps, a relief to homeowners. PressofAtlanticCity. June 14, 2013.
http://www.pressofatlanticcity.com/news/press/atlantic/fema-shrinks-flood-zones-on-new-maps-a-relief-to/article_eb3a276a-d570-11e2-98af-0019bb2963f4.html

Processes to improve reliability

Identify flood vulnerability to a Texas utility

	Within 50 miles of coast line	Vulnerable to storm surge
Overhead Distribution (%)	34%	17%
Underground Distribution (%)	66%	33%
Overhead Transmission (%)	22%	11%
Underground Transmission* (%)	0%	0%
Substations in 100-yr flood plain	14	

* No underground transmission
Source: Quanta. 2009. Cost-benefit analysis of deployment utility infrastructure upgrades and storm hardening programs.

Elevate Switching station/Substation

Source: Boggess, Becker, and Mitchell. 2014. IEEE 2014 T&D conference paper 14TD0564 storm flood hardening of Electrical Substations.

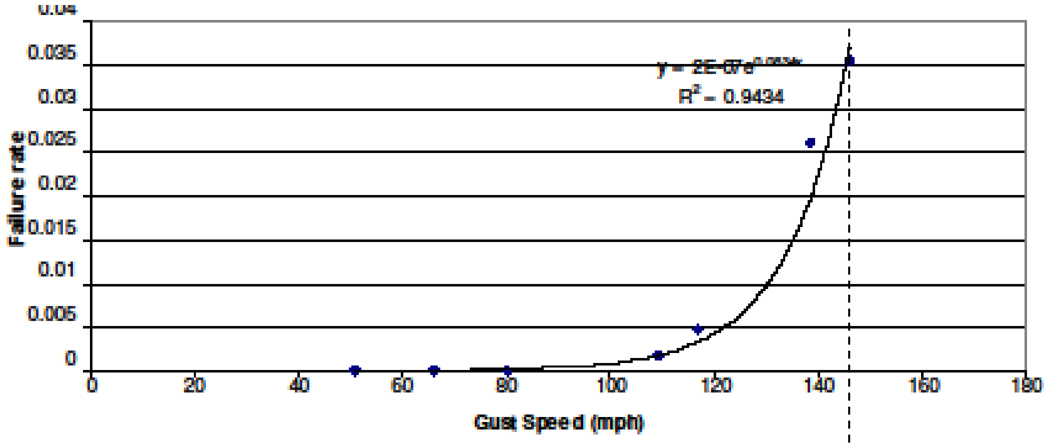
Hardening measures could be complementary or substitute

Hardening Measures	Float Switches	Metal Clad MV Vacuum Switchgear	Duplex Pumps	Automatic Transfer Switch	Flood Walls	Raise Racks	Raise Equipment	Grade Site
Float Switches		●	●	●	●	○	○	○
Metal Clad MV Vacuum Switchgear	●		●	●	●	●	●	●
Duplex Pumps	●	●		●	●			
Automatic Transfer Switch	●	●	●		●	●	●	●
Flood Walls	●	●	●	●		-	-	-
Raise Racks	○	●	-	●	-		●	-
Raise Equipment	○	●	-	●	-	●		-
Grade Site	○	●	-	●	-	-	-	

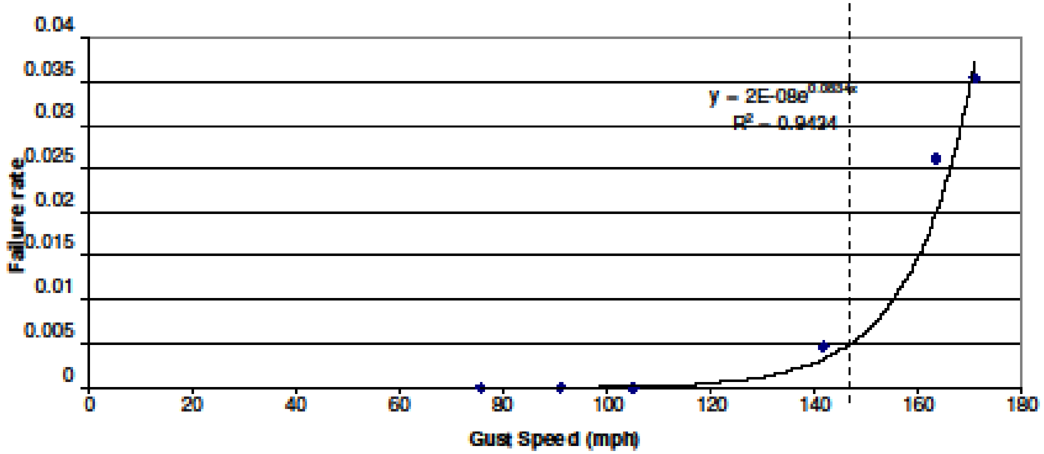
● Indicates strategies are fully compatible
○ Indicates strategies may be compatible on a case-by-case basis
Indicates strategies are redundant

Source: General Electric (GE). 2014. NJ storm hardening recommendations and review/comment on EDC major storm response filings.

Hardening effects on transmission structures



Existing transmission structure failure rate



Hardened transmission structure failure rate

Source: Quanta. 2009. Cost-benefit analysis of deployment utility infrastructure upgrades and storm hardening programs.

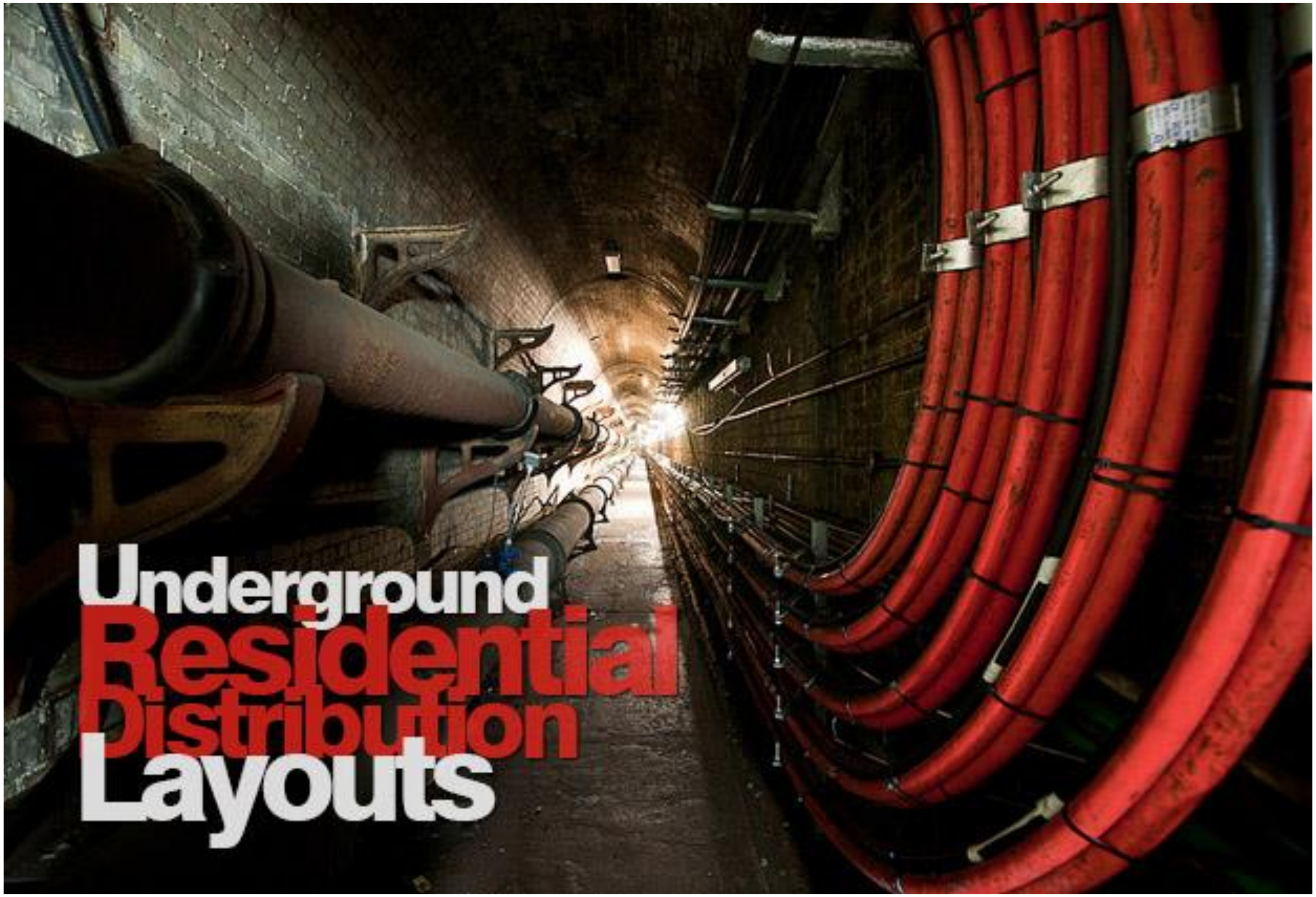
Vegetation management and inspection of substations, transmission/distribution poles & wires

Source: http://articles.mcall.com/2014-03-04/business/mc-ppl-electricity-reliabilty-20140304_1_outages-reliability-dudkin

Source: http://www.utilityproducts.com/articles/print/volume-7/issue-6/product-focus/tools-__supplies/pole-inspections_go.html

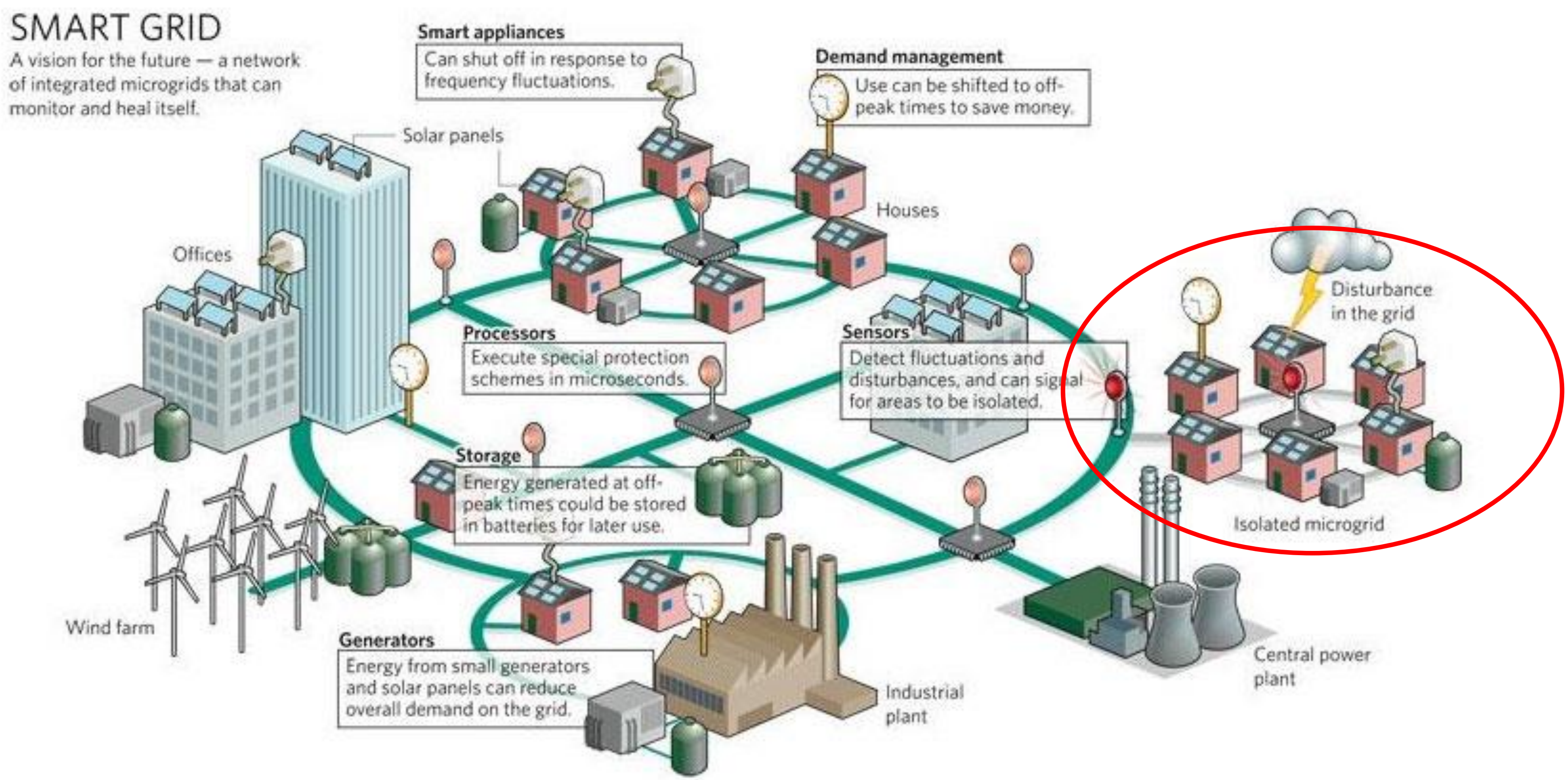
Source: http://reliabilityweb.com/index.php/articles/ultrasonic_electrical_inspection_corona_are_you_listening_or_pretendin/

Targeted undergrounding



Source: http://electrical-engineering-portal.com/underground-residential-distribution-layouts

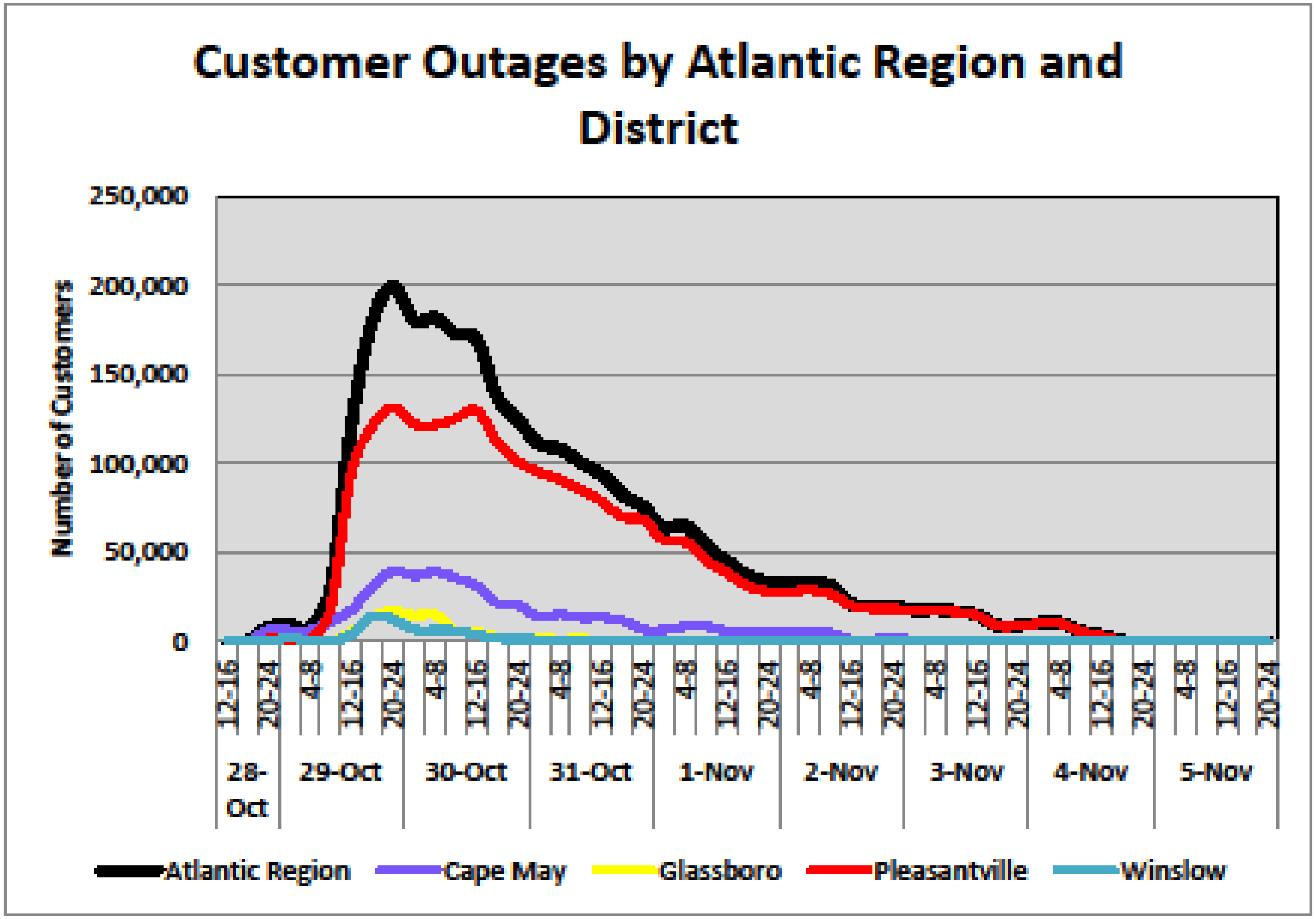
Microgrid



Source: http://file.scirp.org/Html/2-6201335_37364.htm

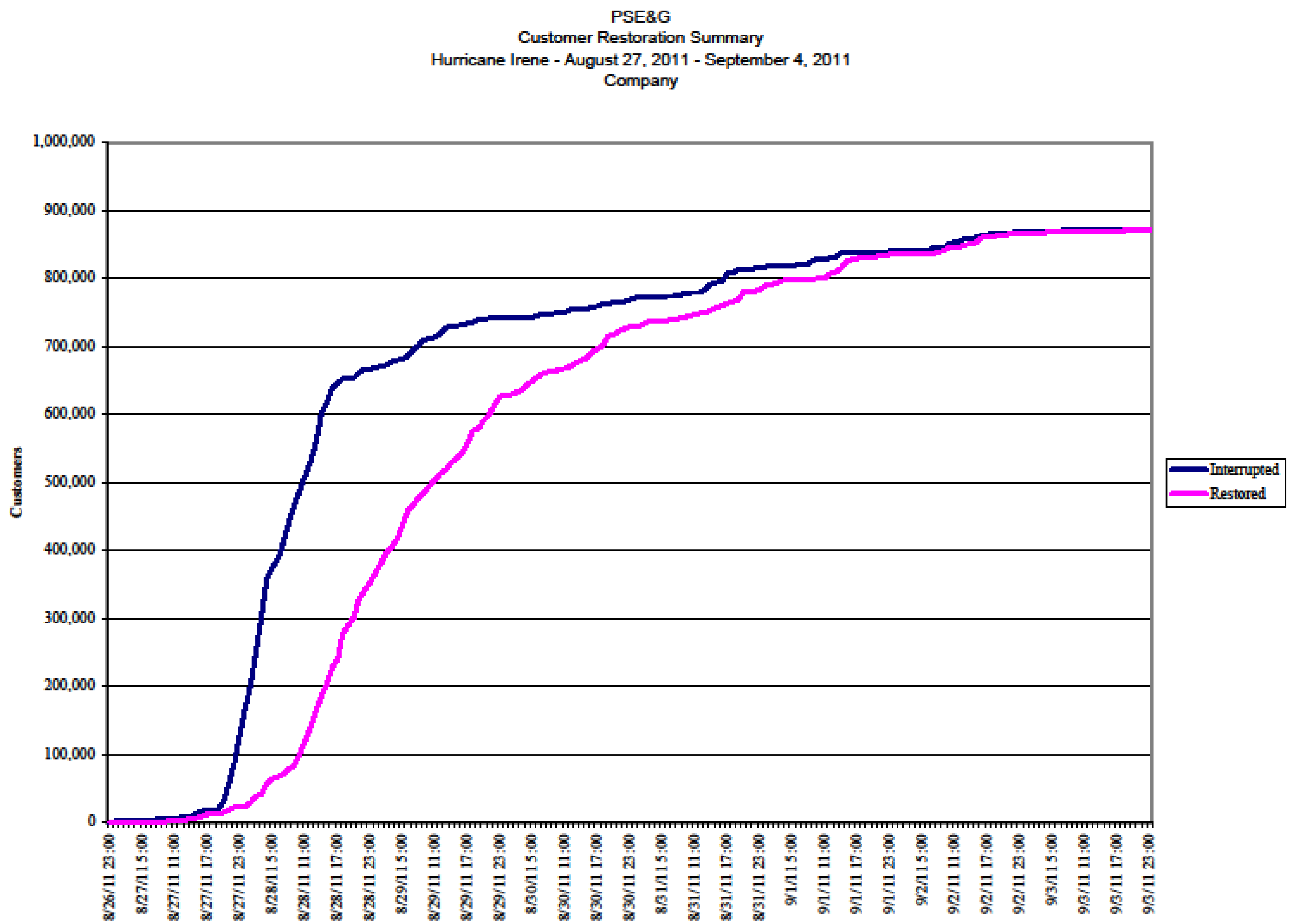
Strategies to improve resiliency

Restoration time could vary – Sandy data from Atlantic City Electric (ACE)



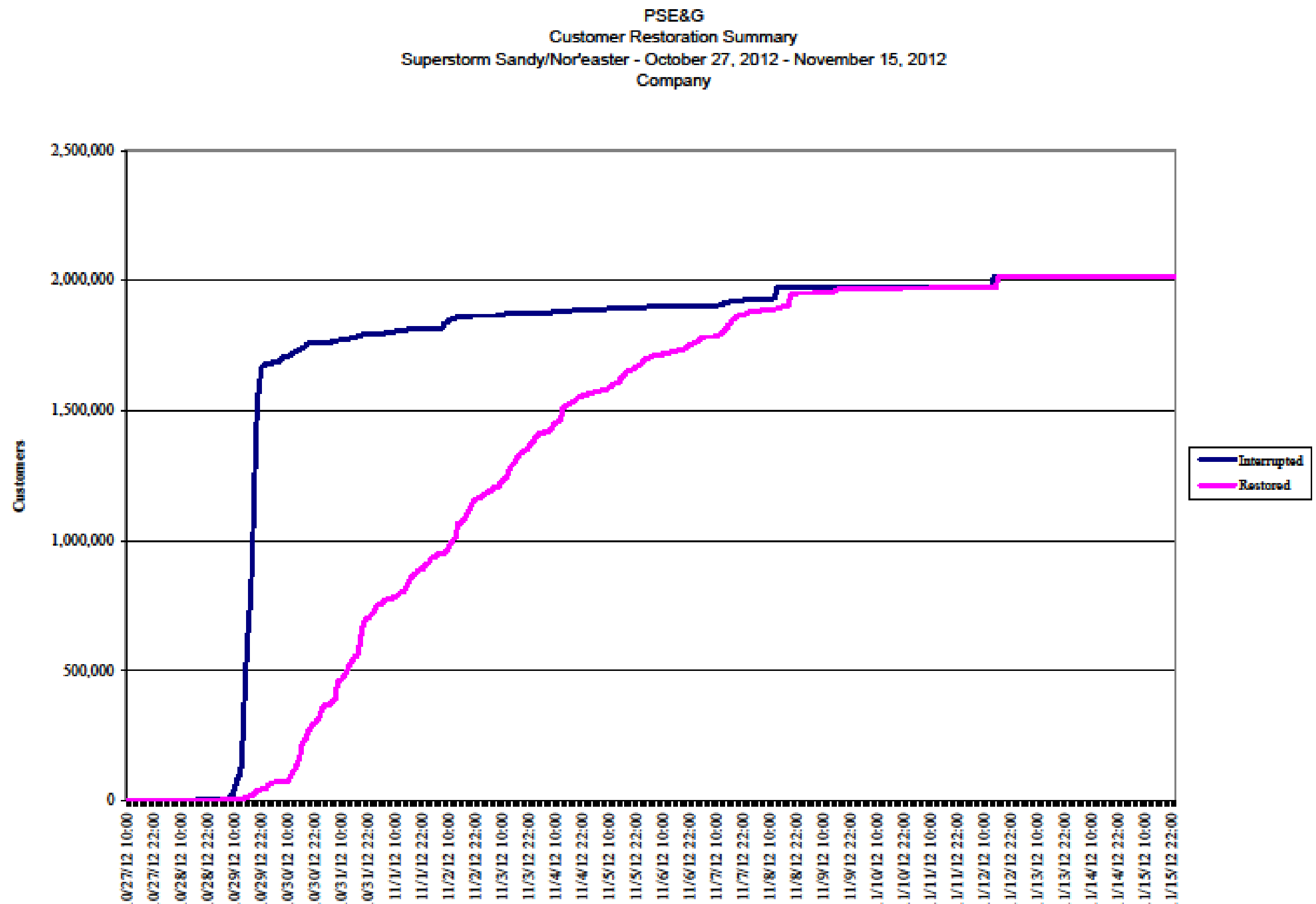
Source: Atlantic City Electric (ACE) Company – Major event report pursuant to N.J.A.C. 14:5-8.8 for the Major Event of October 28 to November 5, 2012- Hurricane/Superstorm Sandy

Public Service Electric & Gas (PSE&G) restoration time for Irene



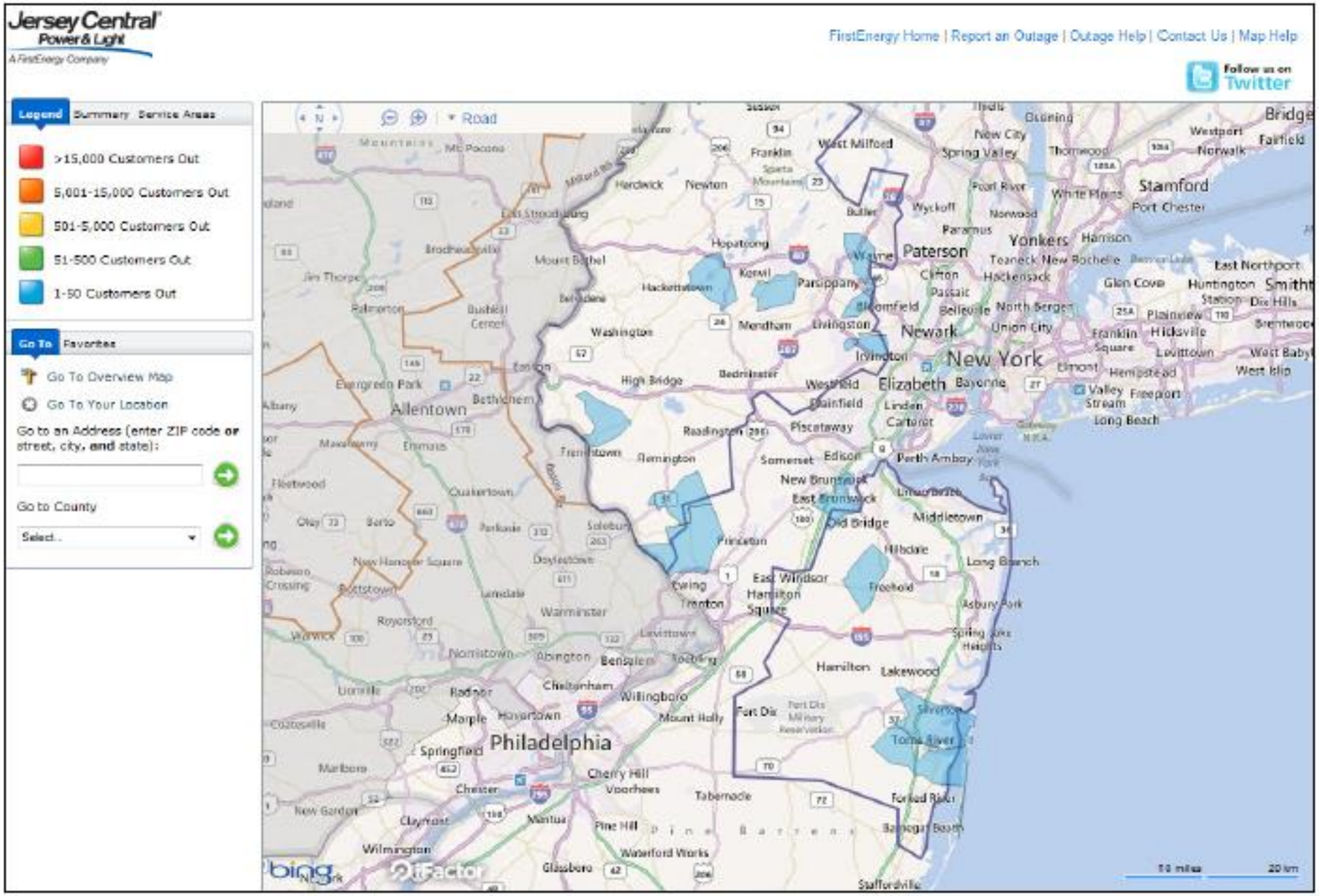
Source: Public Service Electric & Gas (PSE&G)'s final report to the BPU Major Event Hurricane Irene August 27 – September 4, 2011, p17.

Public Service Electric & Gas (PSE&G) restoration time for Sandy



Source: Public Service Electric & Gas (PSE&G)'s final report to the BPU Major Event Superstorm Sandy/Nor'easter October 27 – November 15, 2012, p. 18.

Soft measures such as communication to customers



Source: Jersey Central Power & Light (JCPL) Annual System Performance Report 2011, p.62.

Vegetation management and outage prediction tools

- Remove danger/hazard trees so that during storms less fallen trees block road

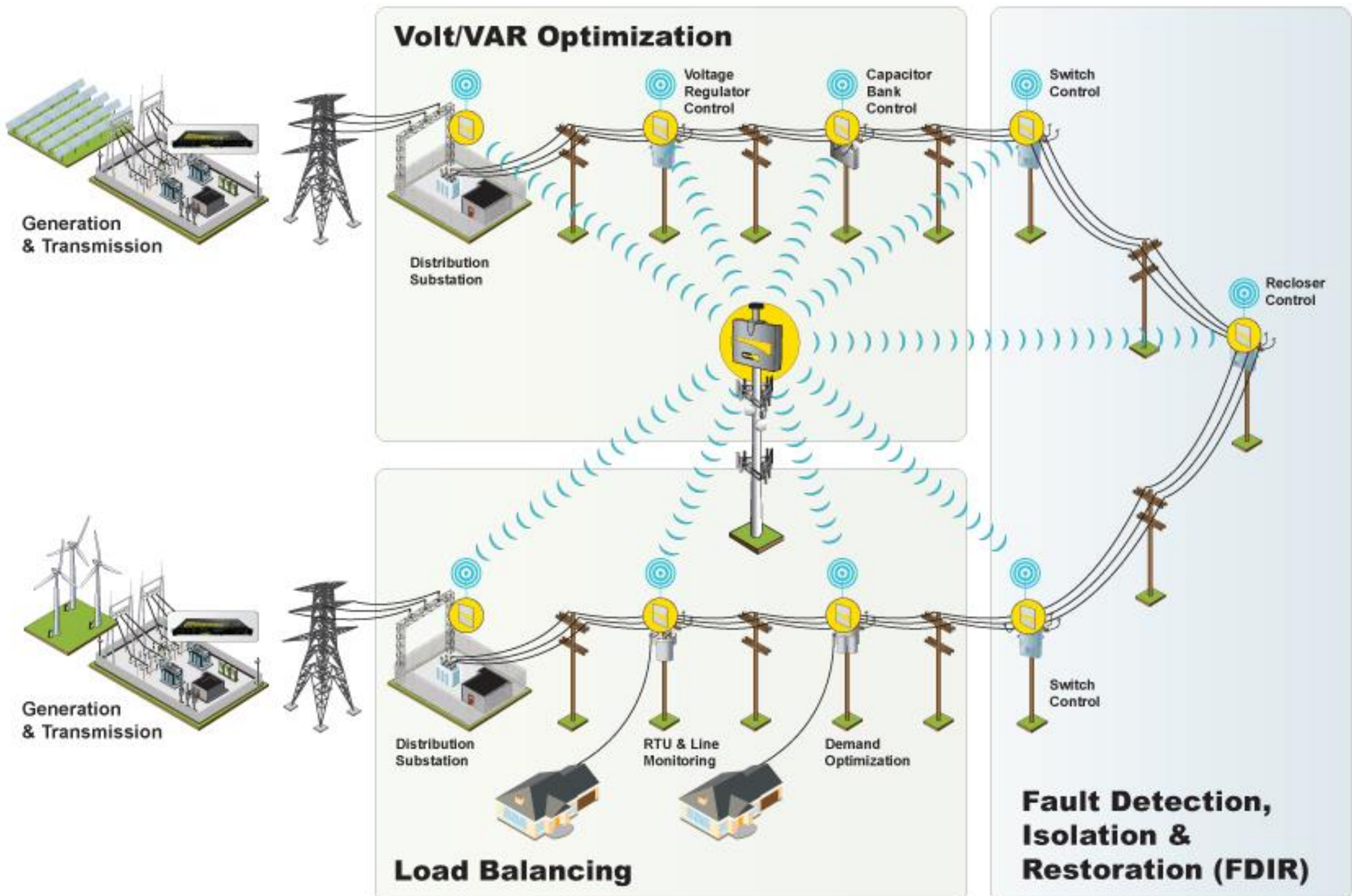
  -> Quick access to outage sites for repairs

- Outage prediction tools help utilities to efficiently deploy limited resources (mobilizing crews and resources) for quick restorations

Source: http://www.montserratreporter.org/news0798-1.htm

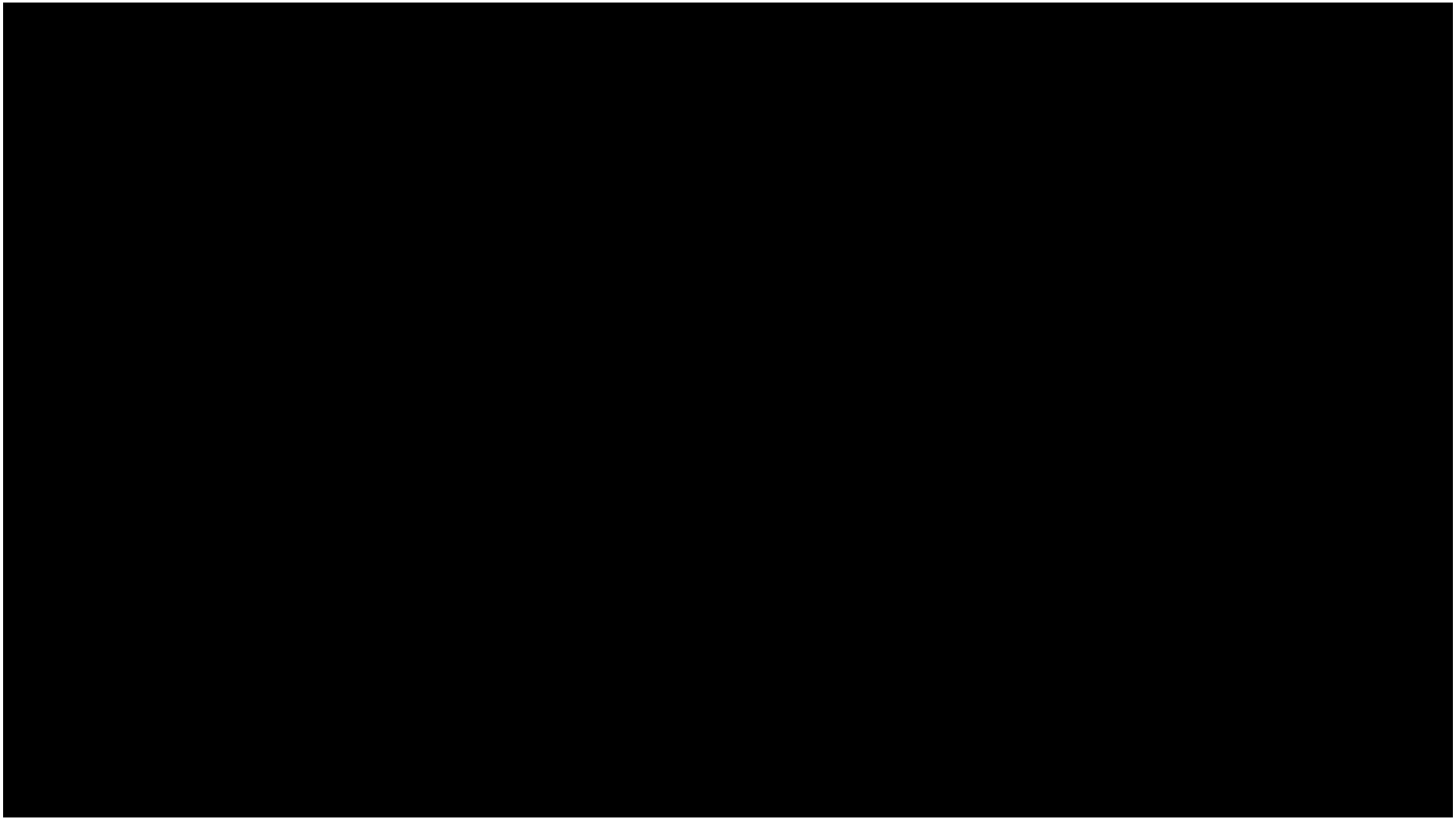
Source: http://www.salon.com/2012/11/01/power_loss_threatens_vote_in_6_plus_states/

Distribution automation



Source: http://www.ruggedcom.com/pac/

Short video on distribution automation



Actions to Improve SAIFI/CAIDI

Actions to Improve SAIFI	Actions to Improve CAIDI
Identify flood vulnerability	Communication
Substation hardening • Flood control strategies • Flood avoidance strategies	Vegetation management
Vegetation management	Outage prediction tools
Selected transmission and distribution structure hardening	Distribution automation
Microgrid	

Agenda

A. Utility hardening measures
B. Time value of money
C. Net present value
D. Consideration of uncertainty

Time value of money

- Engineering economics applies the concept of the time value to the evaluation of design and engineering projects

- Value of money depends on when it is received or paid – time value of money

- A dollar today is worth more than a dollar tomorrow due to the opportunity cost (cost of money) and inflation

- The cost of money depends on investment risk (uncertainty)

Cost of money

Debt and equity (along with many variations) are typically used in combination to fund large-scale capital investments

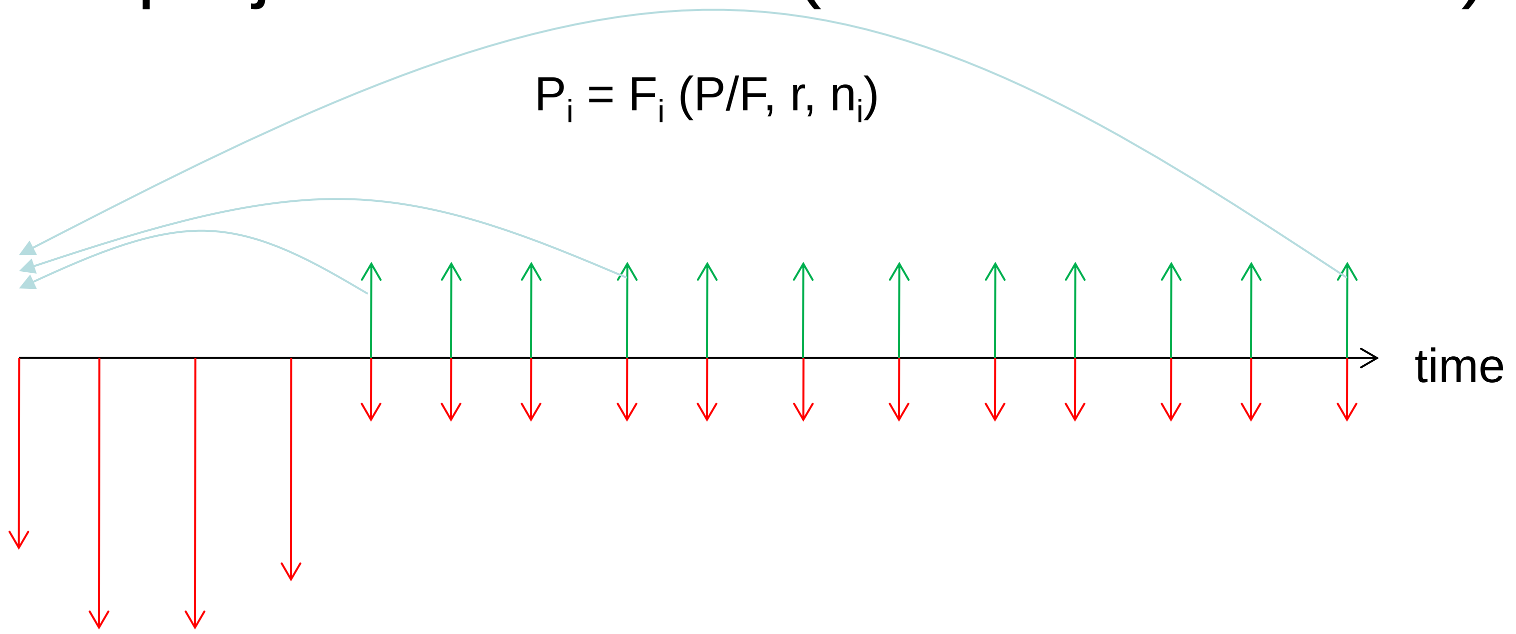
- Governments use only debt

Cost of capital depends on investment risk, reflected in capital structure and cost of various debt and equity components (Weighted Average Cost of Capital (WACC))

- Debt is paid interest, although term "interest" is commonly used
- Discount rate: numerical value used in time value of money formulas to account for cost of capital

WACC = % Debt × Cost of Debt× (1−marginal corporate income tax rate) + % Equity × Cost of Equity

Typical project cash flows (certain & constant)



Each future revenue or expenditure can be moved forward or backward in time to the same base year, usually the first year of the project

These calculations are independent of one another

Net Present Value (NPV) = $\sum (P_i)$ summed over all costs and revenues

Future and present value

Example: What is the future value (F) of a $1,000 loan at 5% interest rate per year compounded annually in five years?

$F = \$1{,}000 \times (1 + 0.05)^5 = \$1{,}276.28$

Compound Amount Factor = (F/P, i, n)

$\Rightarrow$ F = P(F/P, i, n) (e.g., mortgage)

Present worth is value of discounted future cash flows to present time:

$P = F\,(1 + i)^{-n}$

What is present value (or present worth) of a future payment in five years of $1,276,28?

=> These formulas allow moving money across time so that all expenditures and revenues can be evaluated at same base year

Discount rate and interest rate

Simple "interest" or no compounding (only pay the cost of capital on the principle not on the cost of capital itself)

$F(n) = P + P \times n \times i$

$F(n)$ = future sum of money at period n

P = present sum of money

n = number of periods

i = discount rate per period

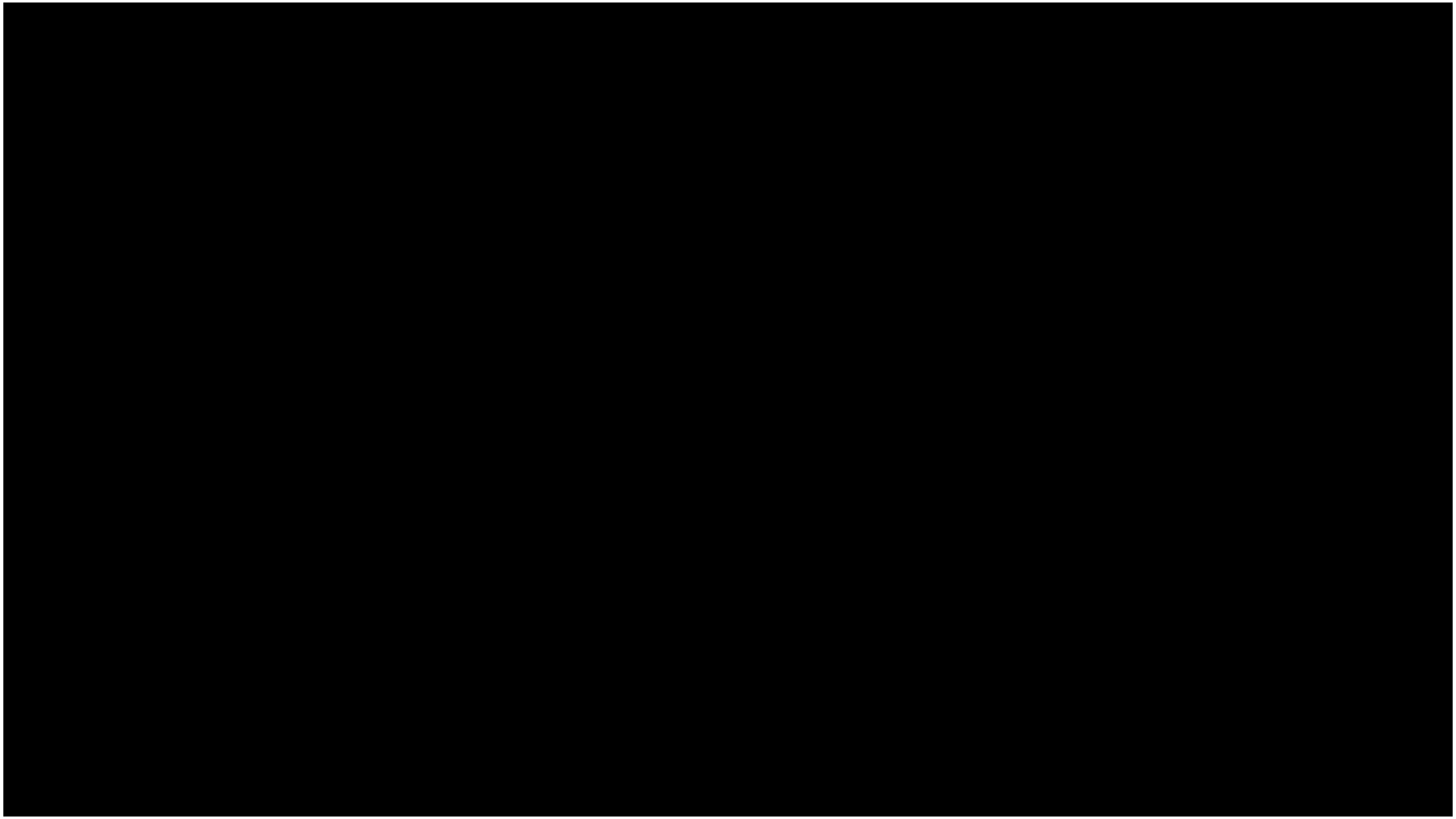
Compounding per period:

$F(n) = P(1 + i)^n$

Payments and receipts occur at beginning or end of the period differ

Assume discount rate is annual with annual compounding

Short video on time value of money



Discount factors table

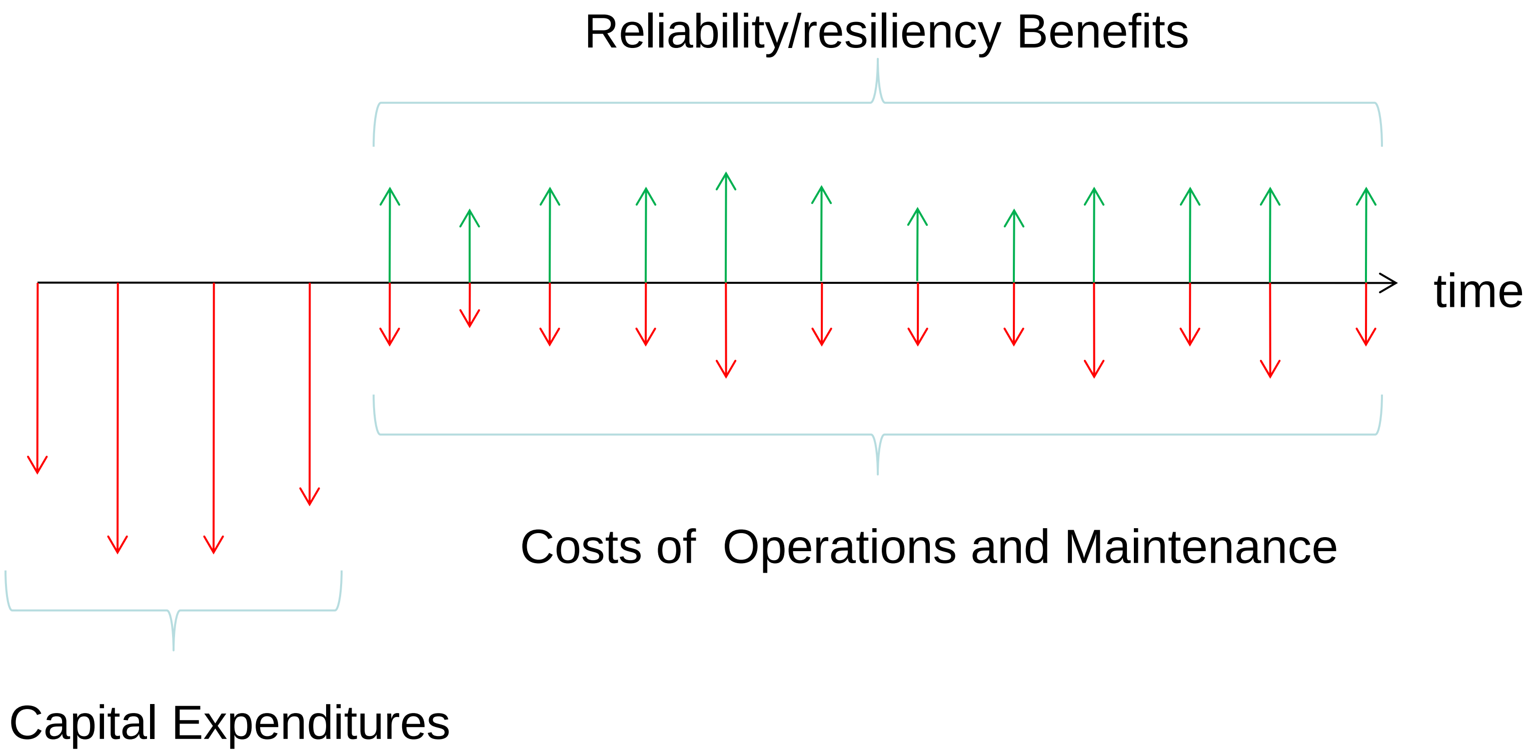
factor name	converts	symbol	formula
single payment compound amount	P to F	$(F/P, i\%, n)$	$(1+i)^n$
single payment present worth	F to P	$(P/F, i\%, n)$	$(1+i)^{-n}$
uniform series sinking fund	F to A	$(A/F, i\%, n)$	$\frac{i}{(1+i)^n - 1}$
capital recovery	P to A	$(A/P, i\%, n)$	$\frac{i(1+i)^n}{(1+i)^n - 1}$
uniform series compound amount	A to F	$(F/A, i\%, n)$	$\frac{(1+i)^n - 1}{i}$
uniform series present worth	A to P	$(P/A, i\%, n)$	$\frac{(1+i)^n - 1}{i(1+i)^n}$
uniform gradient present worth	G to P	$(P/G, i\%, n)$	$\frac{(1+i)^n - 1}{i^2(1+i)^n} - \frac{n}{i(1+i)^n}$
uniform gradient future worth	G to F	$(F/G, i\%, n)$	$\frac{(1+i)^n - 1}{i^2} - \frac{n}{i}$
uniform gradient uniform series	G to A	$(A/G, i\%, n)$	$\frac{1}{i} - \frac{n}{(1+i)^n - 1}$

to answer previous question

4 types of cash flows

	Certain	**Uncertain**
Constant	Put money in saving or money market account with constant return	Normal utility operation in a constant climate
Changing	Invest in government-backed bonds in a changing environment	Utility hardening against weather events in a changing climate

Electric distribution: Normal operation cash flows (uncertain & constant)

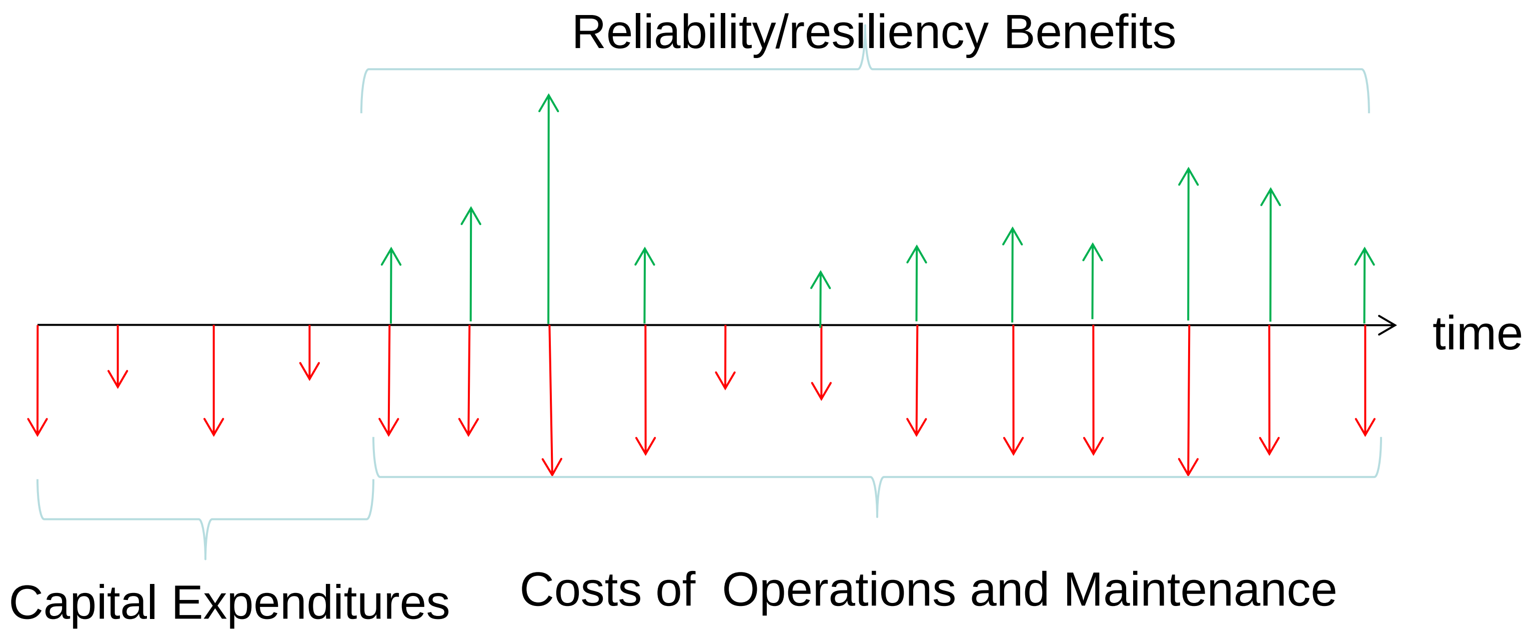


Given the time value of money, do the future revenues exceed the immediate capital expenditures and on-going costs?

What does this diagram imply that is not likely the case regarding reliability/resiliency benefits?

Cash flows with major events (uncertain & changing)

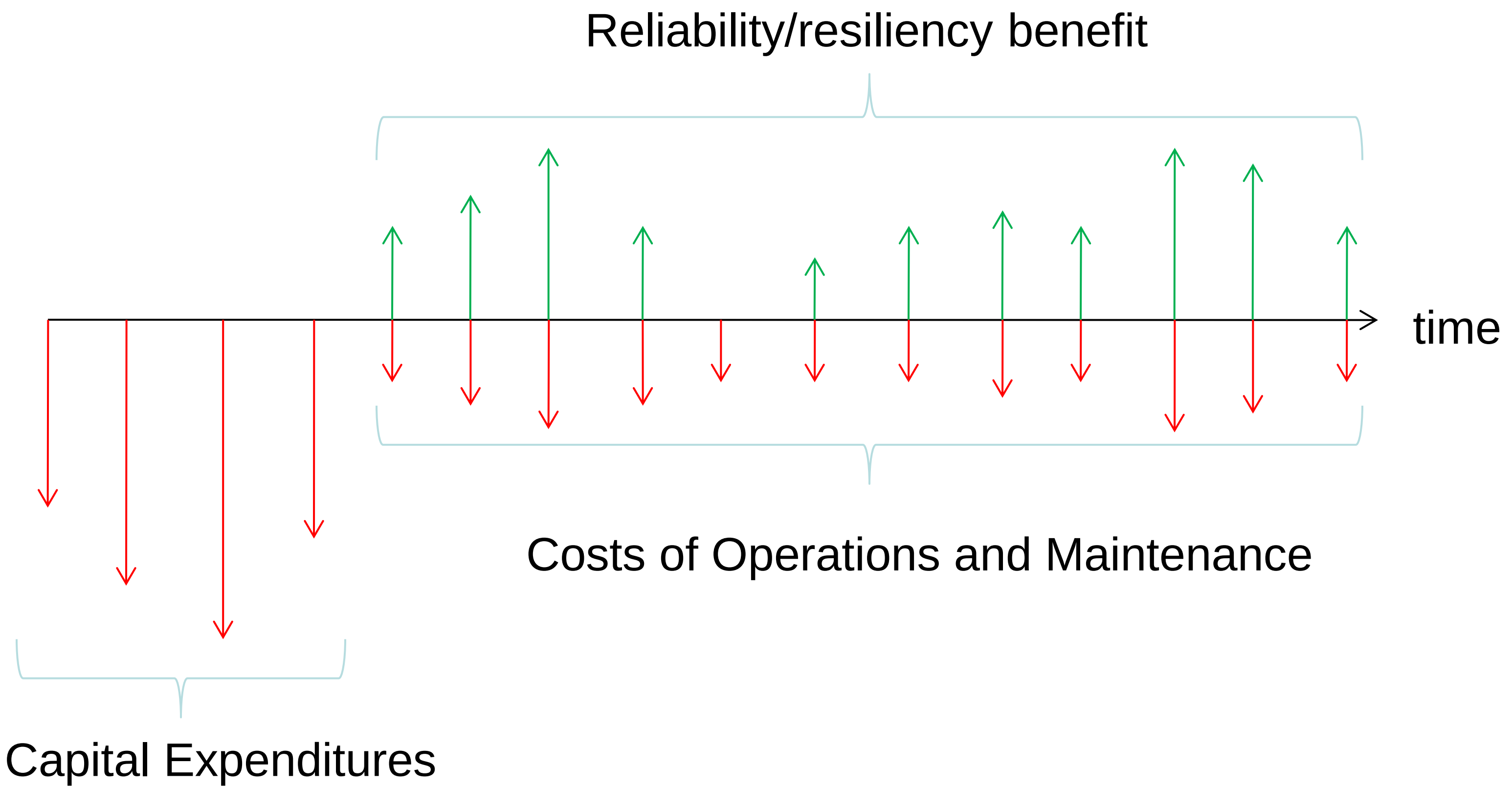
Low capital cost but high Operations and Maintenance costs



Flexibility is achieved with low initial capital expenditures but justified?

Cash flows with major weather events (uncertain & changing)

High capital cost but low Operations and Maintenance costs

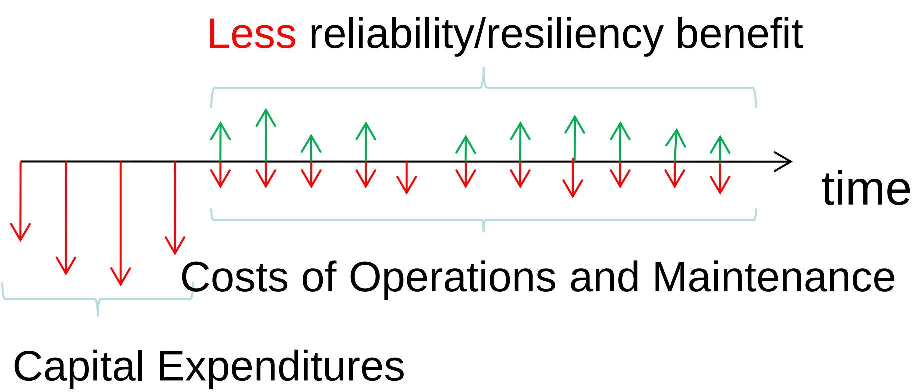


If more certain about the increase in intensity and frequency of major weather events, high initial capital expenditures justified.

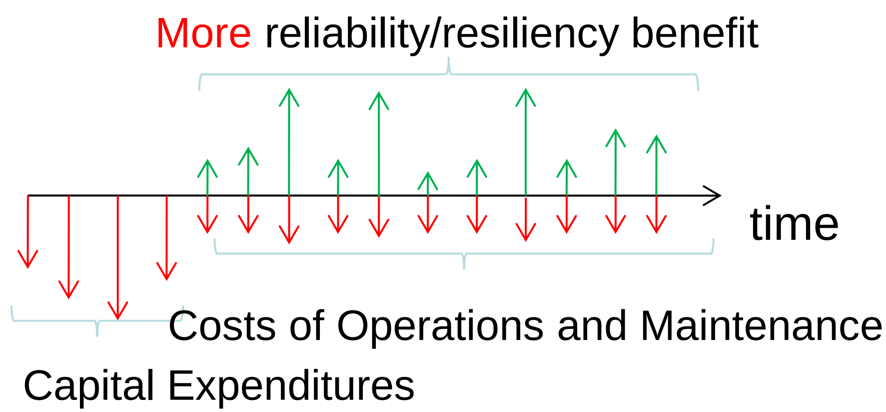
Cash flows with major events (uncertain &changing)

High capital cost but low Operations and Maintenance costs

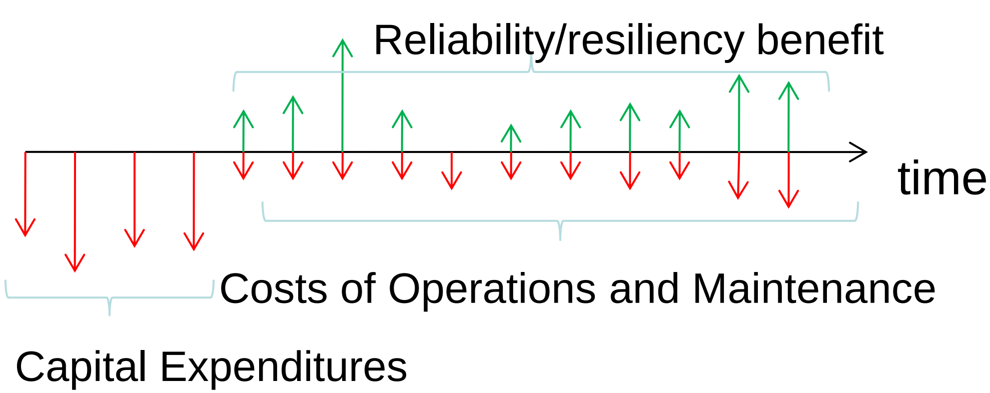
Scenario 1: weather events less



Scenario 2: weather events more



Scenario 3: weather events stay the same



Agenda

A. Strategies for improving reliability and resiliency
B. Time value of money
C. Net present value
D. Consideration of uncertainty

Project investment rules

- **Simple payback** is number of years it takes to payoff initial investment, assuming no discounting
- **Net Present Value (NPV)** Rule: If NPV is $\geq$ 0, invest, otherwise do not
- **Cost-benefit Analysis (CBA)**: If ratio of discounted benefits exceeds discounted costs (i.e., $\geq$ 1), invest
- **Internal Rate of Return (IRR)**: If IRR $\geq$ r, then invest
  - ✓ Internal Rate of Return is discount rate such that present value of expenditures and revenues equal zero

Example – evaluate a single project

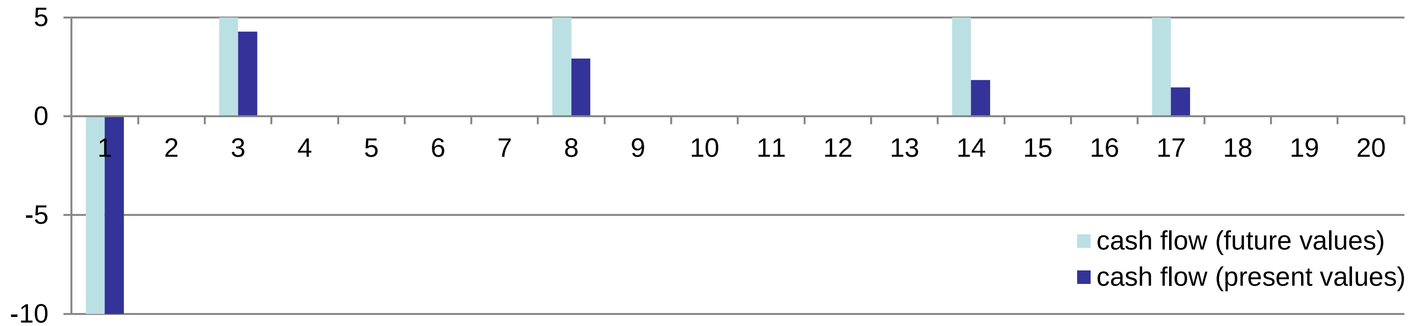
Net Present Value (NPV) Rule: If NPV is ≥ 0, invest, otherwise do not

The lifespan of hardening project is 20 years and discount rate is 8%.

Utility hardening cost $10 million

Outage reduction benefit in storms $ 5 million

Storms happen in years 3, 8, 14, 17 (once every five years)

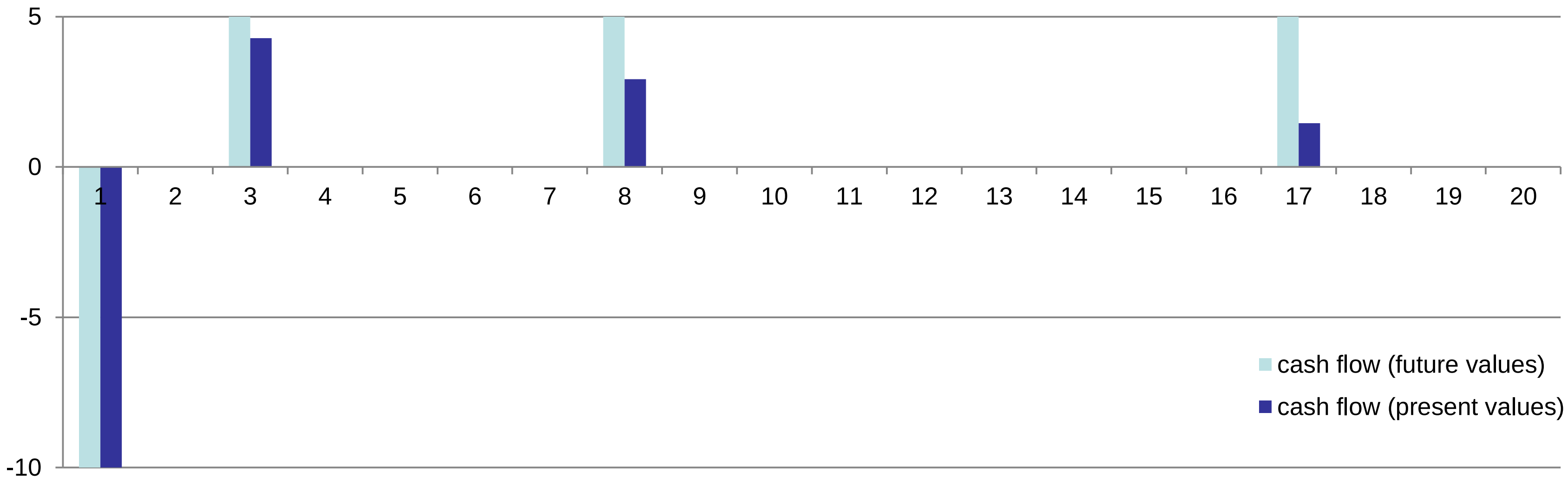


NPV = $0.5 million, invest

What if storms happen less often?

Say, in year 14, there is no storm.

There are 3 storms in 20 years instead of 4.

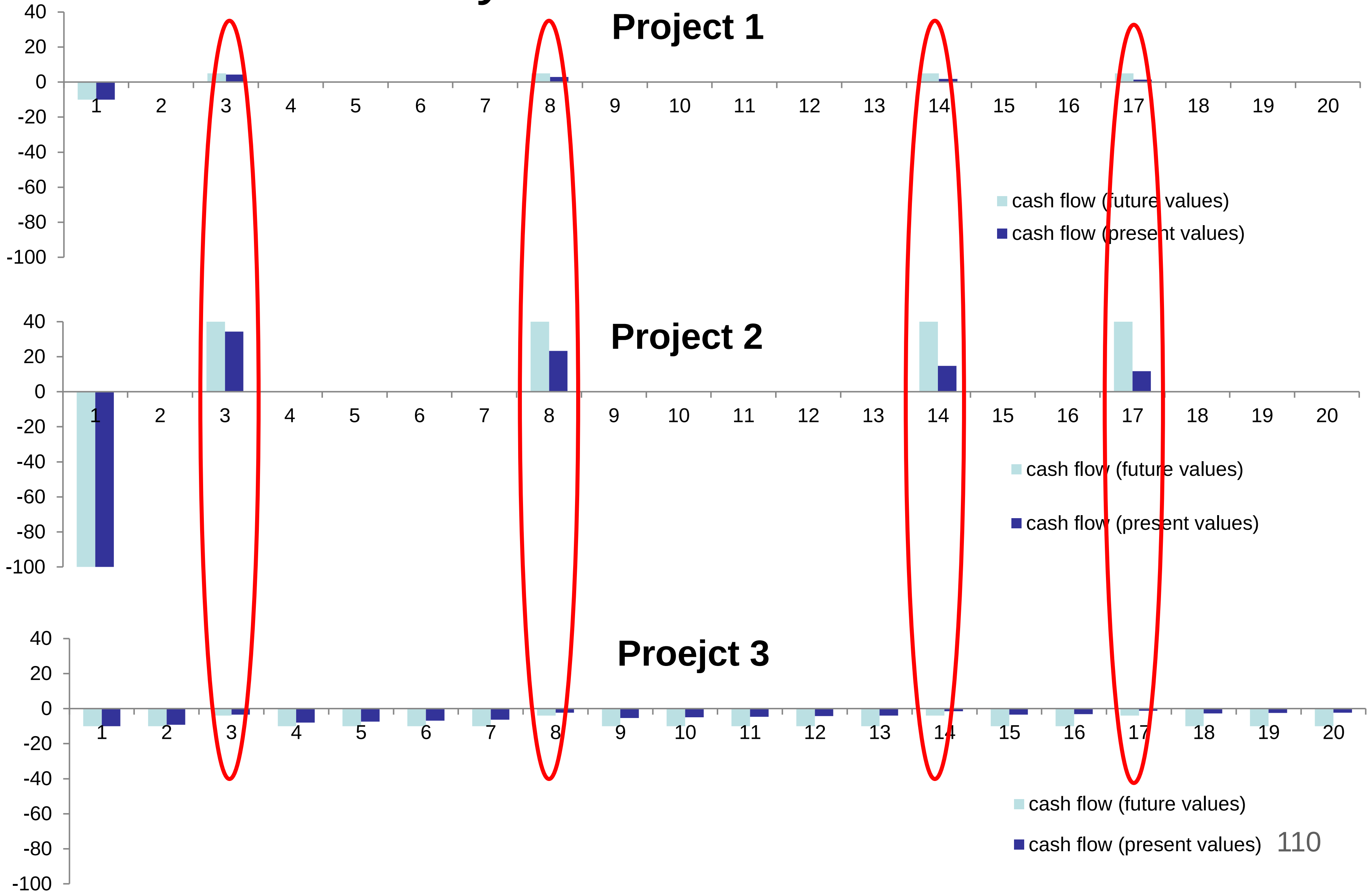


Net Present Value (NPV) = -$1.34 million, DO NOT invest

Compare alternative projects

Project	Timeline of investment	Costs ($,000)	Yearly operations and maintenance costs ($,000)	Benefits ($,000)
Project 1	1st year	10	0	5 per storm
Project 2	1st year	100	0	40 per storm
Project 3	Every year	10	10	6 per storm

Cash flow in 20 years



Project 1 has the highest NPV, invest

- Net Present Value (NPV) comparison of 3 projects

Project 1's NPV= $0.50 million

Project 2's NPV= – $15.98 million

Project 3's NPV= – $22.29 million

Agenda

A. Utility hardening measures
B. Time value of money
C. Net present value
D. Consideration of uncertainty

Consideration of uncertainty

- Benefits and costs are treated as certain in the above example

- In reality, there are uncertainty, much more for benefits

- Treat as random variable described by probability distribution

Estimation of benefit under uncertainty

- In previous example, assumption about 4 storms in 20 years is based on probability of a major storm happening in NJ once every 5 years

- A small change in probability estimation could affect investment decision

- Develop scenarios and assign corresponding probabilities to deal with uncertainty

Summary

- Net Present Value (NPV) rule is key to investment decisions
- Uncertainty in future returns of reliability/resiliency investments make them much more challenging than normal operations
- Uncertainty in probability of severe weather affect investment decision
- Detailed and systematic data collection could reduce uncertainty

Questions?

- Backup slides

Causes	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Trees	529,041	479,930	250,302	369,631	334,297	310,150	333,015	314,466	500,485	485,897
Construction OH	401,557	250,464	267,260	271,172	238,865	266,403	312,779	314,948	505,578	413,838
Construction UG	298,404	228,883	258,447	279,941	241,808	266,229	245,267	233,274	294,022	232,197
Supply & Station Equipment	356,298	184,214	201,891	169,823	195,899	336,857	172,690	123,954	144,035	300,714
Lightning	289,613	71,108	115,654	115,402	103,084	222,209	171,423	101,191	105,007	112,317
Other	227,958	147,256	173,019	132,205	151,716	132,735	99,902	96,153	116,972	92,302
Weather	314,631	121,490	61,333	79,214	69,725	50,855	71,263	88,634	54,384	64,523
Outside Plant Equipment	78,850	80,598	63,866	84,445	84,633	80,398	100,668	126,620	124,166	151,559
External	54,934	65,618	80,276	69,700	103,374	98,765	100,123	112,093	103,084	117,632
Animals	134,972	85,694	64,098	54,527	124,716	82,081	77,695	67,372	124,036	75,603

Policy considerations

- Applications of engineering economics typically do not capture the key insight of economics, which is that incentives matter

- An important example of the importance of incentives, although not the only one, is given the large amounts of uncertainty over the life of investments, flexibility has value that needs to be incorporated into the analysis

- Another is that government financing typically involves the transfer of risk to residents of that jurisdiction