RESILIENT POWER

A project of Clean Energy Group

Severe Weather and the Reliability of the US Electric Power Grid

October 14, 2015

Seth Mullendore
Project Manager
Clean Energy Group

Clean Energy Group
Innovation in Finance, Technology & Policy

Housekeeping

All participants are in “Listen-Only” mode. Select “Use Mic & Speakers” to avoid toll charges and use your computer’s VOIP capabilities. Or select “Use Telephone” and enter your PIN onto your phone key pad.

Submit your questions at any time by typing in the Question Box and hitting Send.

This webinar is being recorded.

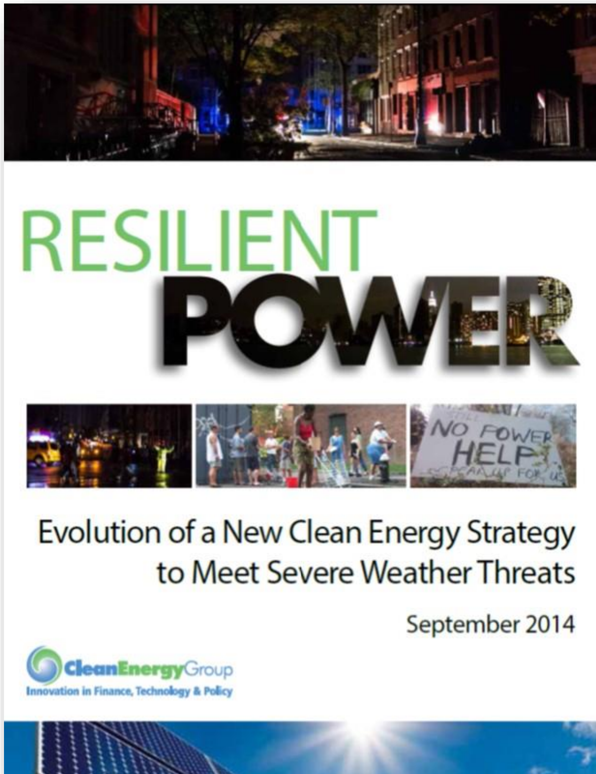
You will find a recording of this webinar, as well as previous Resilient Power Project webinars, online at:

www.cleanegroup.org/ceg-projects/resilient-power-project/webinars/

and at

vimeo.com/channels/resilientpower

Who We Are



www.cleanegroup.org

www.resilient-power.org

CleanEnergyGroup
Innovation in Finance, Technology & Policy

Meridian Institute
Connecting People to Solve Problems

CleanEnergy States Alliance

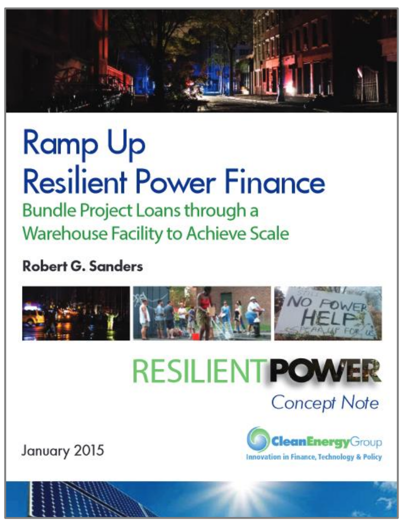
THE JPB FOUNDATION

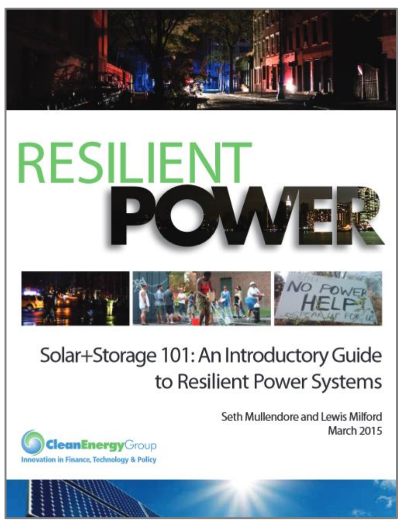
THE KRESGE FOUNDATION

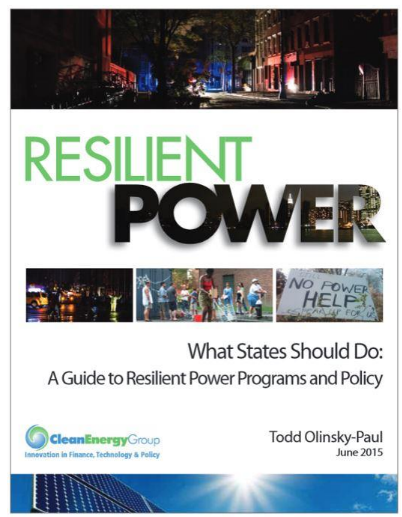
SURDNA FOUNDATION
Fostering sustainable communities in the United States

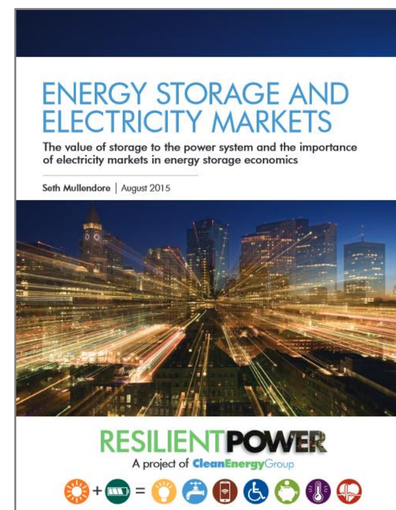
Resilient Power Project

- Increase public/private investment in clean, resilient power systems
- Engage city officials to develop resilient power policies/programs
- Protect low-income and vulnerable communities
- Focus on affordable housing and critical public facilities
- Advocate for state and federal supportive policies and programs
- Technical assistance for pre-development costs to help agencies/project developers get deals done
- See www.resilient-power.org for reports, newsletters, webinar recordings





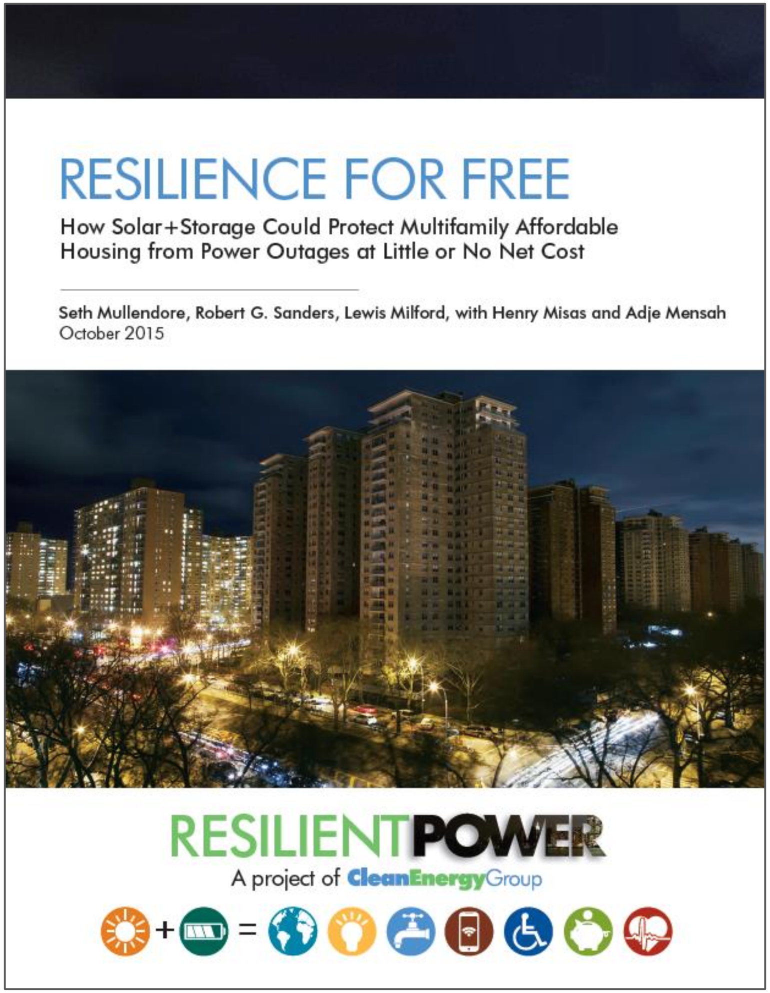




New Report & Webinar: Resilience for Free

Read the full report at http://bit.ly/Resilience-For-Free

Upcoming webinar 10/29/15, details at http://bit.ly/Resilience-For-Free-Webinar



Today's Guest Speaker

- **Pete Larsen,** Research Scientist and Assistant Group Leader in the Electricity Markets and Policy Group, Lawrence Berkeley National Laboratory

BERKELEY LAB
Lawrence Berkeley National Laboratory

Severe Weather and the Reliability of the U.S. Electric Power Grid

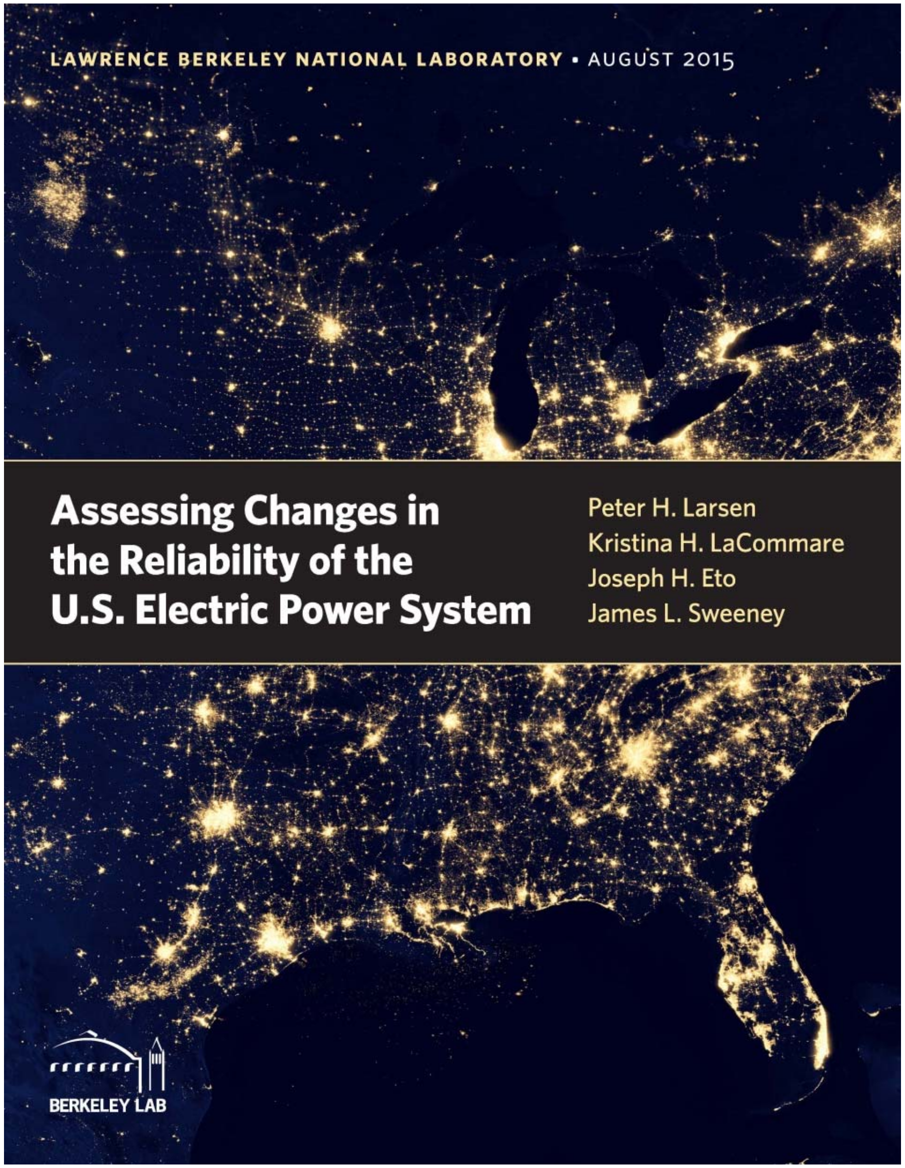
Helena Independent Record (10/12/15)

Peter Larsen

Lawrence Berkeley National Laboratory/Stanford University

October 14, 2015

Co-investigators and funding source



The work described in this presentation was funded by the Office of Electricity Delivery and Energy Reliability (OE) of the U.S. Department of Energy (DOE) under Contract No. DE-AC02-05CH11231.

Agenda

- Background and study questions
- Reported causes and reliability metrics
- Data collection and review
- Analysis method and base model
- Principal findings
- Discussion and caveats
- Summary and next steps

Background

- Eto et al. (2012) analyzed reliability information from 155 U.S. electric utilities over a 10-year span.

- Study accounted for ~50% of total U.S. electricity sales and 58% of total U.S electricity customers.

- Found that duration and frequency of power interruptions had been increasing ~2% per year from 2000 to 2009.

- Future research should investigate:
  - more disaggregated measures of weather variability (e.g., lightning strikes and severe storms);
  - other utility characteristics (e.g., the number of rural versus urban customers, the extent to which transmission and distribution (T&D) lines are overhead versus underground); and
  - utility spending on transmission and distribution maintenance and upgrades.

Study questions

- Are warmer/cooler/wetter/drier/windier/stormier than average years correlated with measurable changes in the duration and/or frequency of power interruptions?

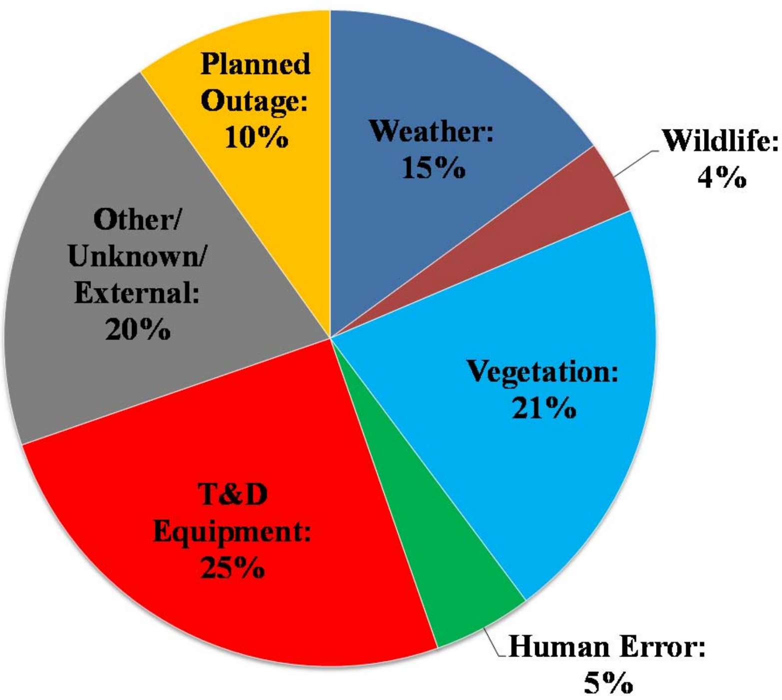
- Are the number of customers, annual sales, share of underground lines, and presence of outage management systems (OMS) correlated with changes in reliability?

Study questions (cont.)

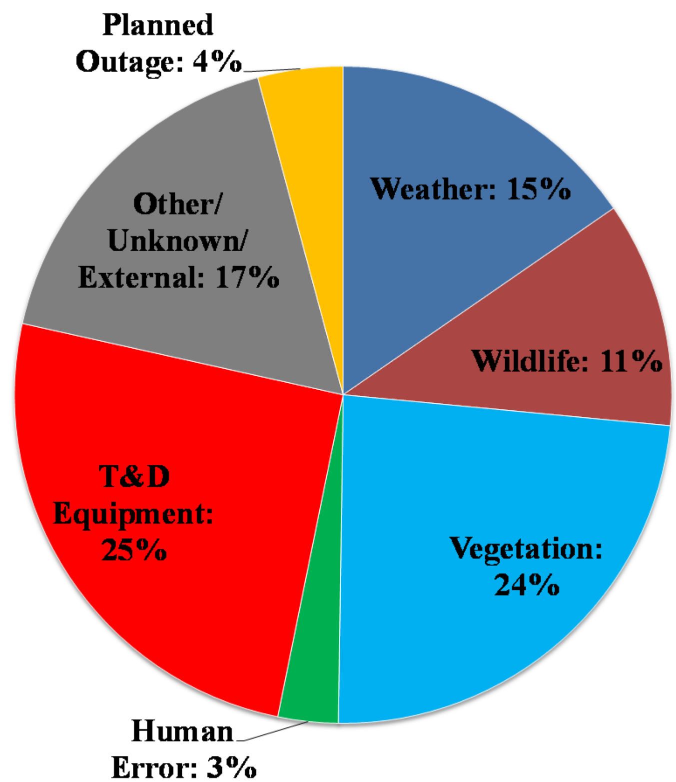
- Is there a non-linear relationship between weather, including temperature, precipitation, and wind—and any corresponding changes in system reliability?
- Are previous year T&D expenditures correlated with subsequent year reliability?
- Are power interruptions occurring more frequently and/or lasting longer?

Reported causes from selected utilities

What causes increase the *duration* of reliability events?



What causes increase the *frequency* of reliability events?



Common reliability metrics

System Average Interruption Duration Index (SAIDI)

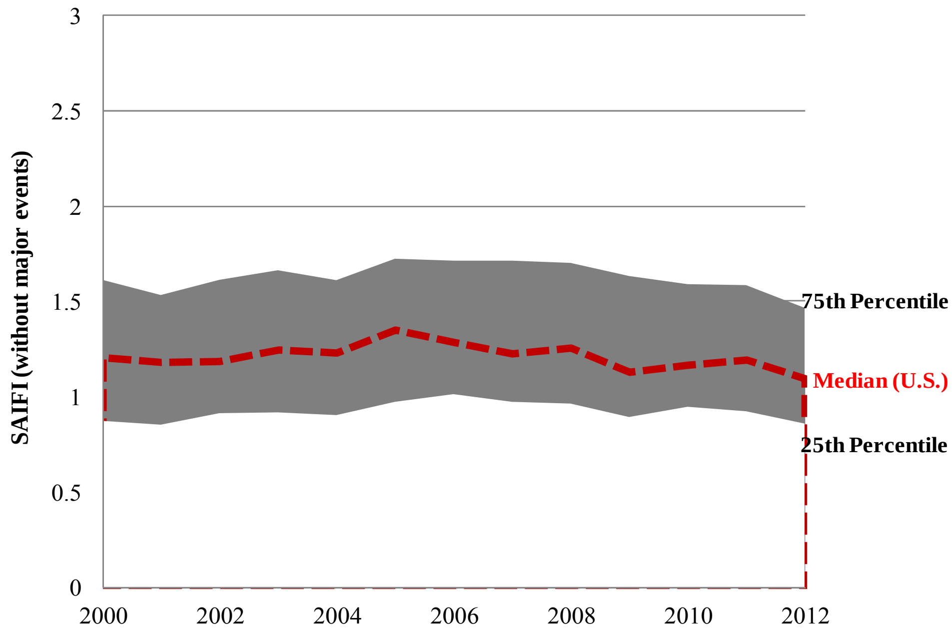
$$\text{SAIDI}_t = \frac{\sum \text{Time}_t \times \text{Affected}_t}{\text{Customers}_t}$$

System Average Interruption Frequency Index (SAIFI)

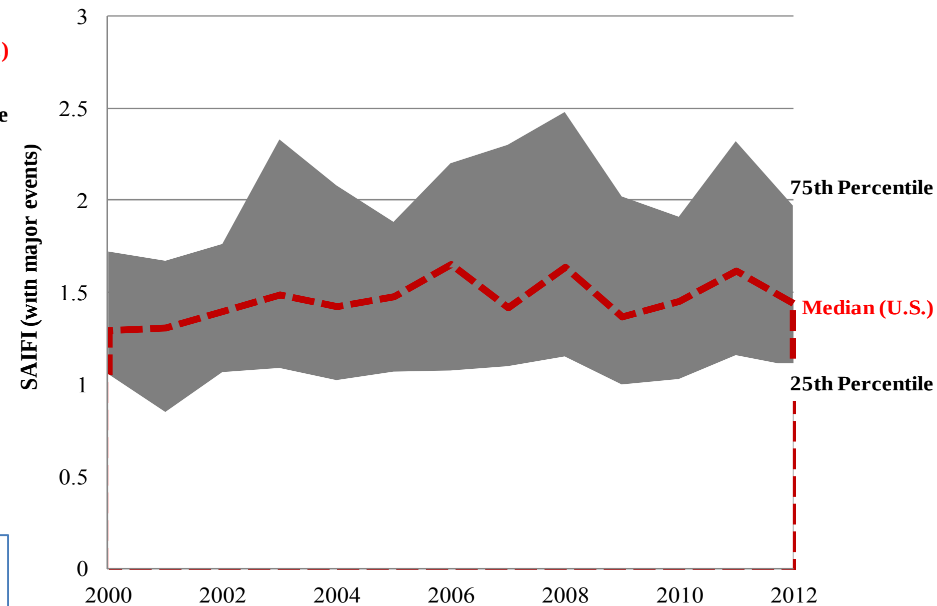
$$\text{SAIFI}_t = \frac{\sum \text{Affected}_t}{\text{Customers}_t}$$

Interruptions more frequent?

(without "major events")



SAIFI: Average # of interruptions per customer



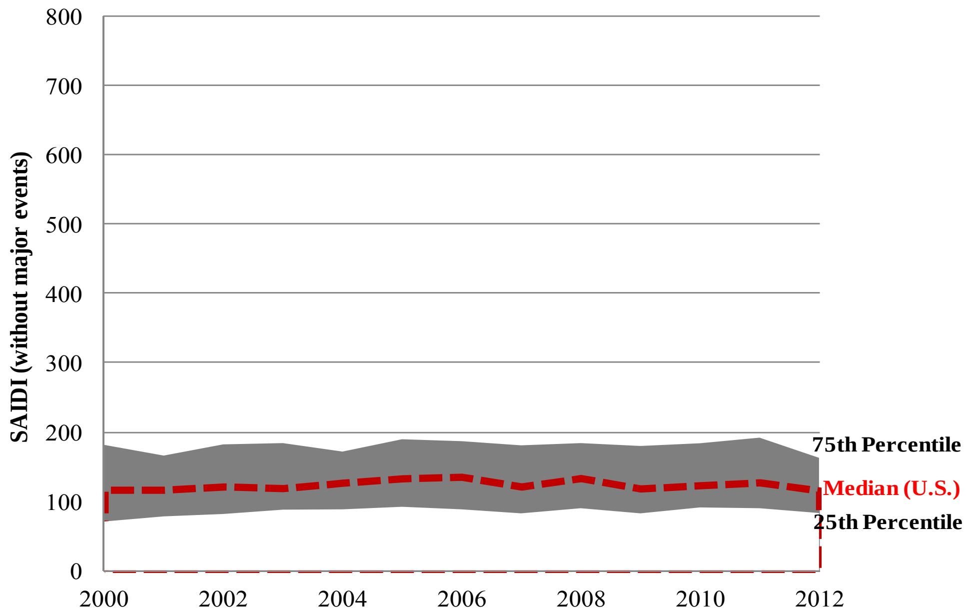
Typically abnormally severe weather (e.g., hurricanes, tornadoes, blizzards, and other catastrophic events)

(with "major events")

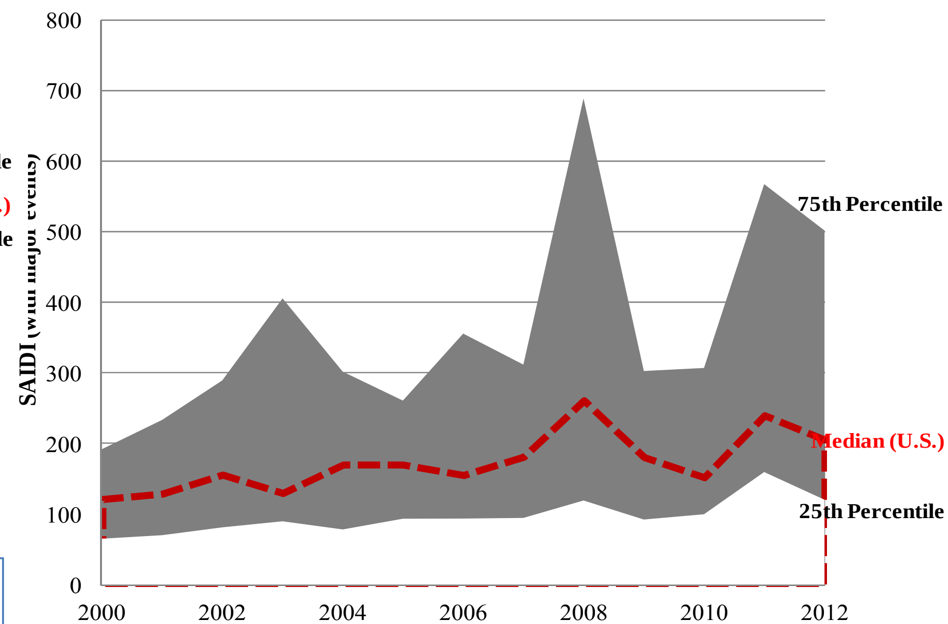
Interruptions lasting longer?

BERKELEY LAB

(without “major events”)



SAIDI: Average # of minutes customer without power



The criterion used to classify major events varies from utility to utility (and regulatory jurisdiction) (Eto and LaCommare 2008; Eto et al. 2012).

(with “major events”)

Data collection and review

Data	Eto et al. (2012)	Larsen et al. (2015)	Source
Reliability metrics (SAIDI/SAIFI)	155 utilities spanning years 2000-2009 (50% of U.S. sales)	195 utilities spanning years 2000-2012 (70% of U.S. sales)	PUCs, utilities, etc.
Presence of outage management system (OMS)	Information as of 2009	Information as of 2012	PUCs, utilities, etc.
Adoption of IEEE Std 1366	Information as of 2009	Information as of 2012, but not evaluated	PUCs, utilities, etc.
Retail electricity sales	Information as of 2009	Information as of 2012	EIA Form 861
Heating/Cooling degree-days	State-level	Utility-level	Ventyx
T&D line miles	N/A	Total for each utility by year	FERC Form 1
T&D expenditure data	N/A	Total for each utility by year	FERC Form 1
Lightning data	N/A	Strike count summed to each utility by year	NLDN
Wind speed	N/A	Average for each utility by year	Ventyx
Precipitation	N/A	Average for each utility by year	Ventyx

Data collection and review (cont.)

(without "major events")

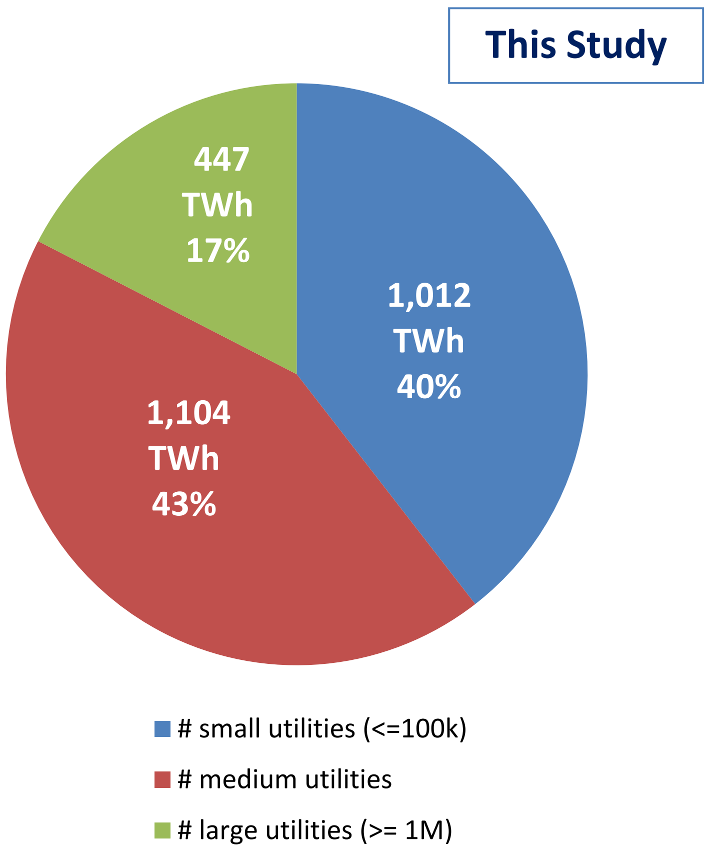
Variable (units)	Number of observations	Min	Mean	Median	Max	Standard Deviation
SAIDI (minutes)	2,062	0	143.1	125.6	1,015.1	86.9
SAIFI (# of events)	2,026	0	1.4	1.2	20.9	0.9
HDD (# of degree days)	2,210	198	4,807.1	5,020.7	9,697.0	2,023.7
CDD (# of degree days)	2,210	0	1,319.6	1,026.0	4,313.0	894.9
Lightning strikes (strikes per customer)	2,181	0	0.5	0.1	189.9	5.2
Precipitation (inches)	2,210	1.8	35.9	37.9	79.3	14.9
Wind speed (mph)	2,210	3.4	7.3	7.0	12.7	1.5
T&D lines (customers per line mile)	2,024	0	172.2	23.3	8,942.6	672.8
Share of underground (%)	840	0.1%	22.2%	20.4%	89.8%	15.3%
Delivered electricity (MWh per customer)	2,288	1.1	26.7	25.0	181.7	14.4
T&D expenditures ($2012 per customer)	2,084	$4.4	$883.0	$239.8	$52,261.0	$2,328.4

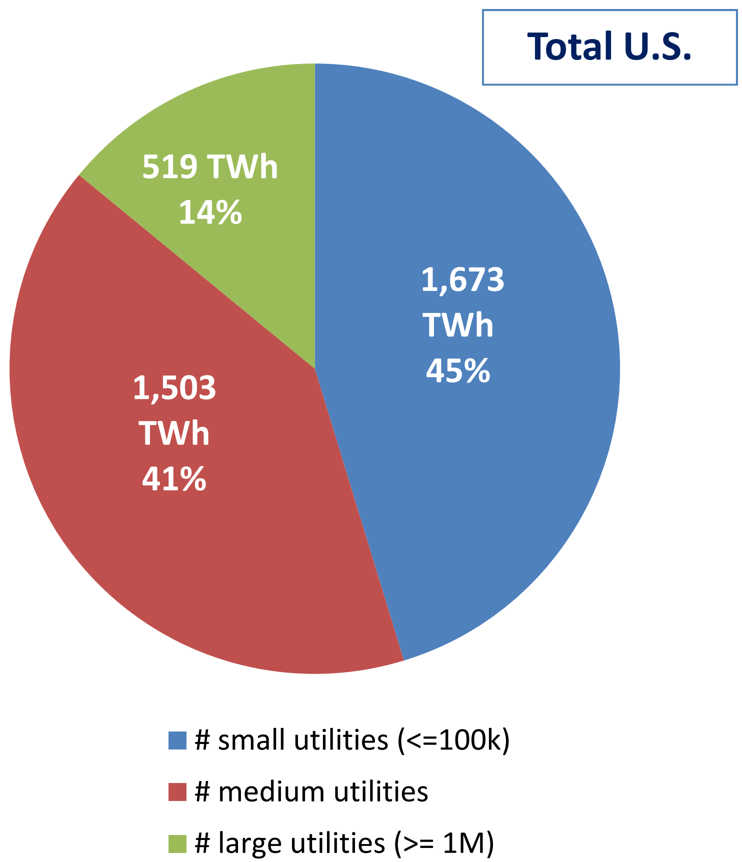
(with "major events")

Variable (units)	Number of observations	Min	Mean	Median	Max	Standard Deviation
SAIDI (minutes)	1,438	1.2	372.2	173.0	14,437.6	825.8
SAIFI (# of events)	1,440	0	1.8	1.5	37.3	2.0
HDD (# of degree-days)	1,794	198	5,160.8	5,329.0	9,136.0	2,000.6
CDD (# of degree-days)	1,794	0	1,168.1	897.0	4,921.0	874.6
Lightning strikes (strikes per customer)	1,748	0	0.5	0.1	189.9	5.8
Precipitation (inches)	1,794	1.8	34.9	37.1	73.2	13.6
Wind speed (mph)	1,794	3.2	7.0	6.9	12.1	1.6
T&D lines (customers per line mile)	1,471	0.0	148.2	27.9	3,832.1	409.9
Share of underground (%)	648	0.6%	24.6%	23.4%	89.8%	16.1%
Delivered electricity (MWh per customer)	1,856	1.1	27.3	24.2	257.3	22.8
T&D expenditures ($2012 per customer)	1,499	$4.4	$734.6	$235.1	$11,076.0	$1,659.2

Representative sample of utilities?

*Number and proportion of utilities by **size**…*



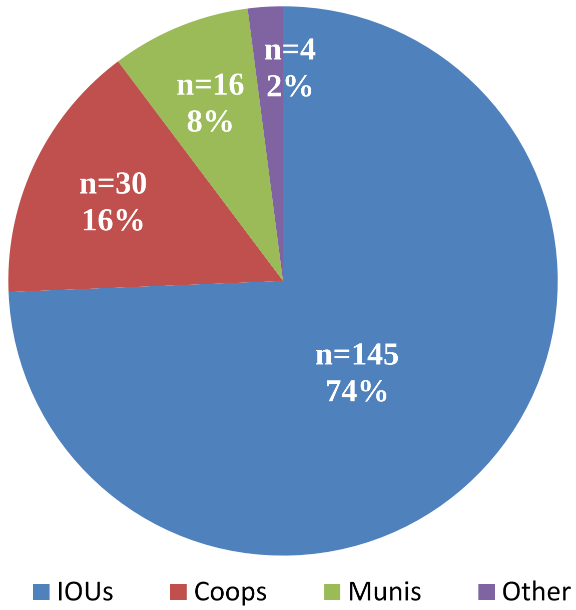


Represented sales (TWh) and proportion of utilities, by size, included in this study and for total U.S.

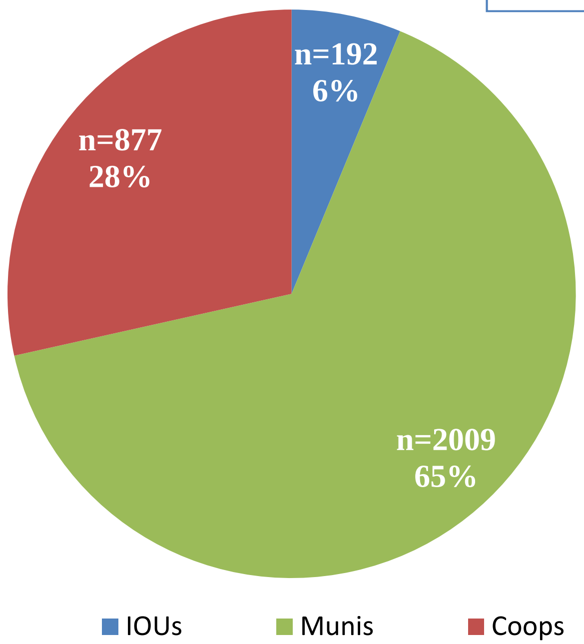
Representative sample of utilities? (cont.)

*Number and proportion of utilities by **ownership**…*

This Study

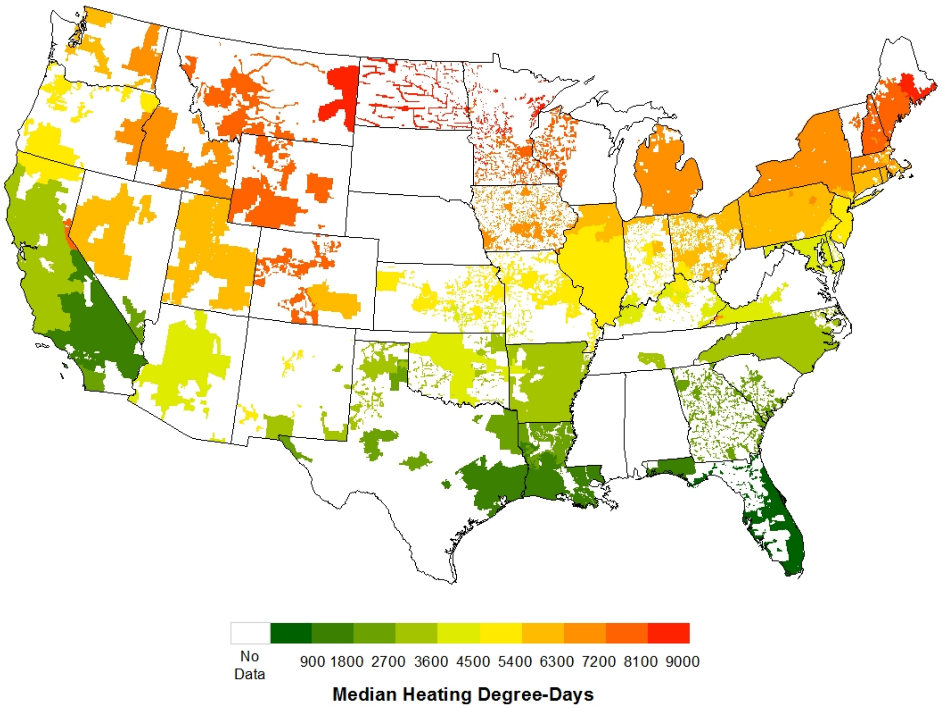


Total U.S.

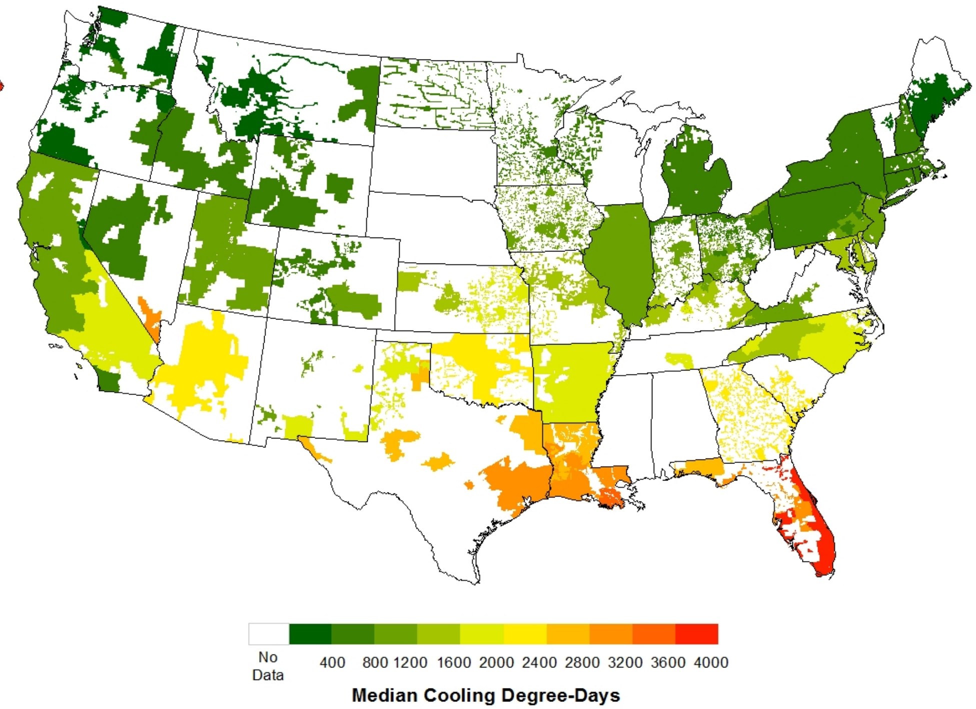


IMPORTANT: This study under-represents the number of cooperatives and municipally-owned utilities operating in the U.S.

Factors: heating & cooling degree days

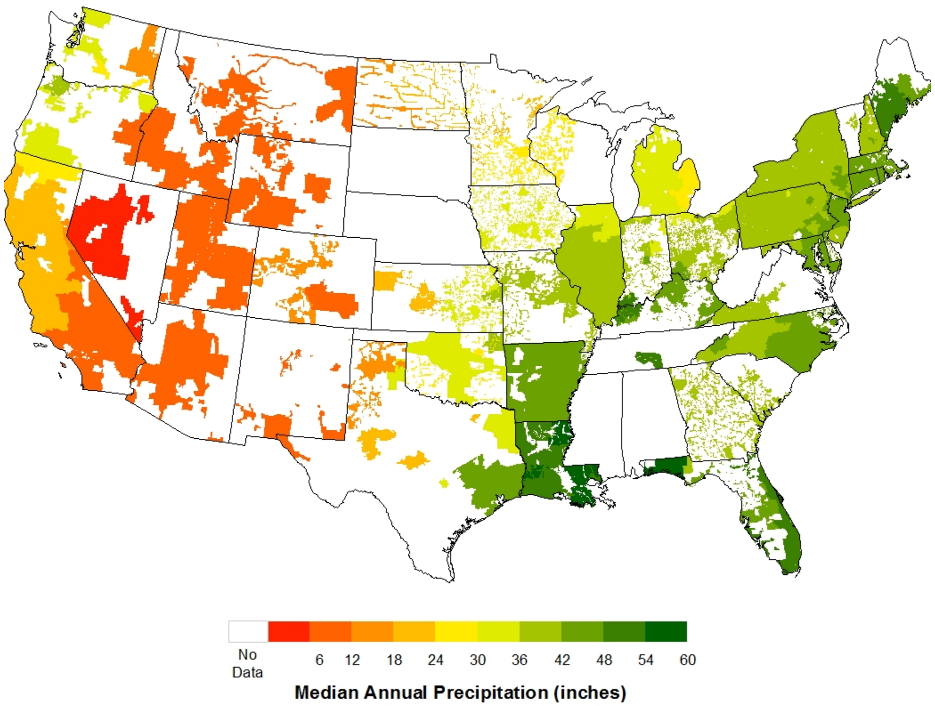


Heating Degree-Days

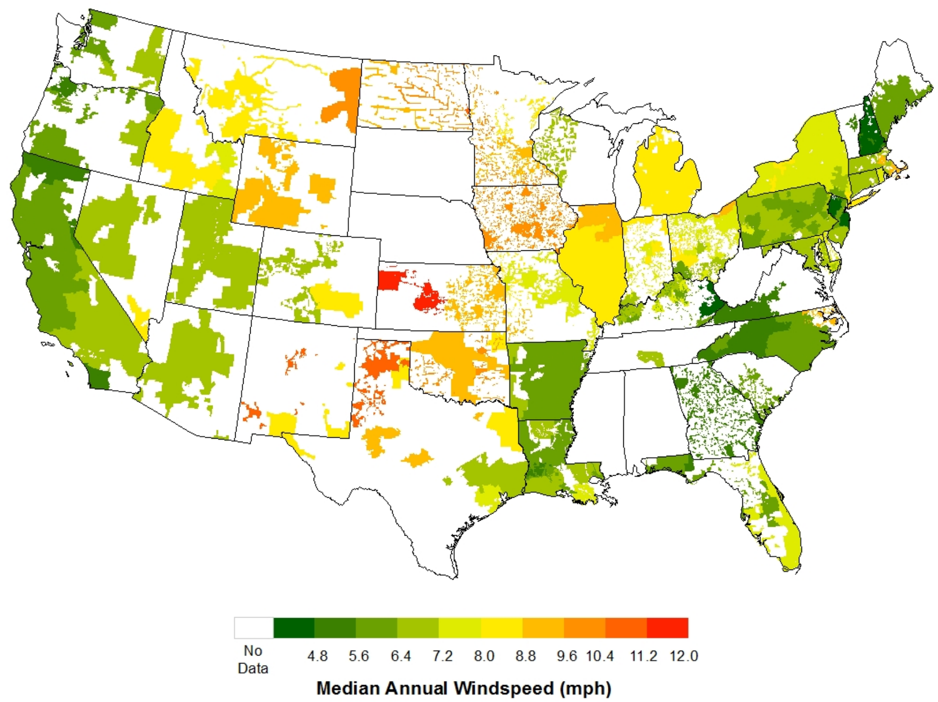


Cooling Degree-Days

Factors: precipitation & wind speed

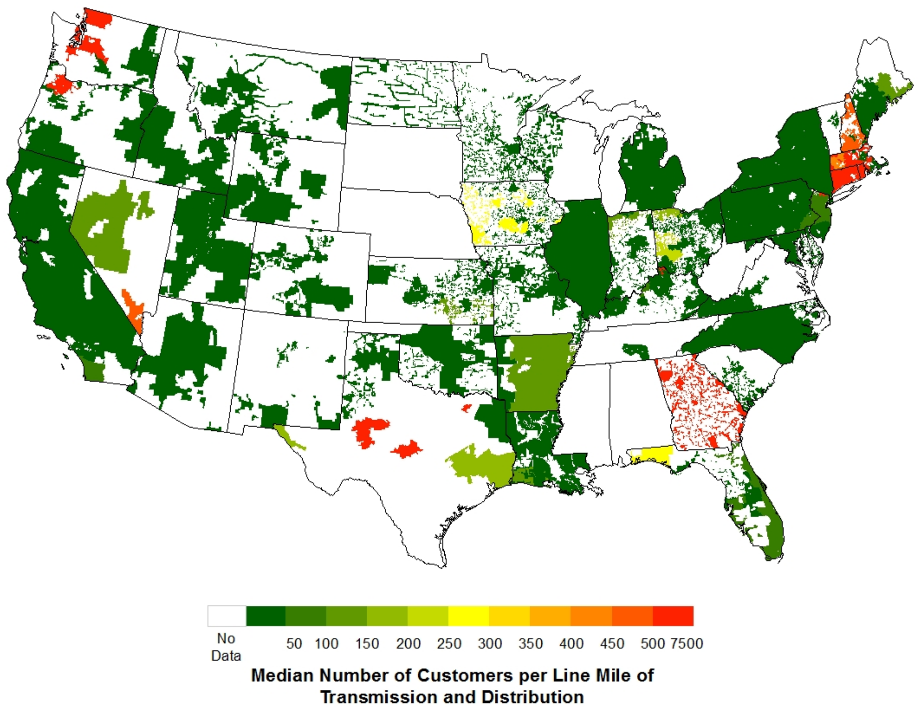


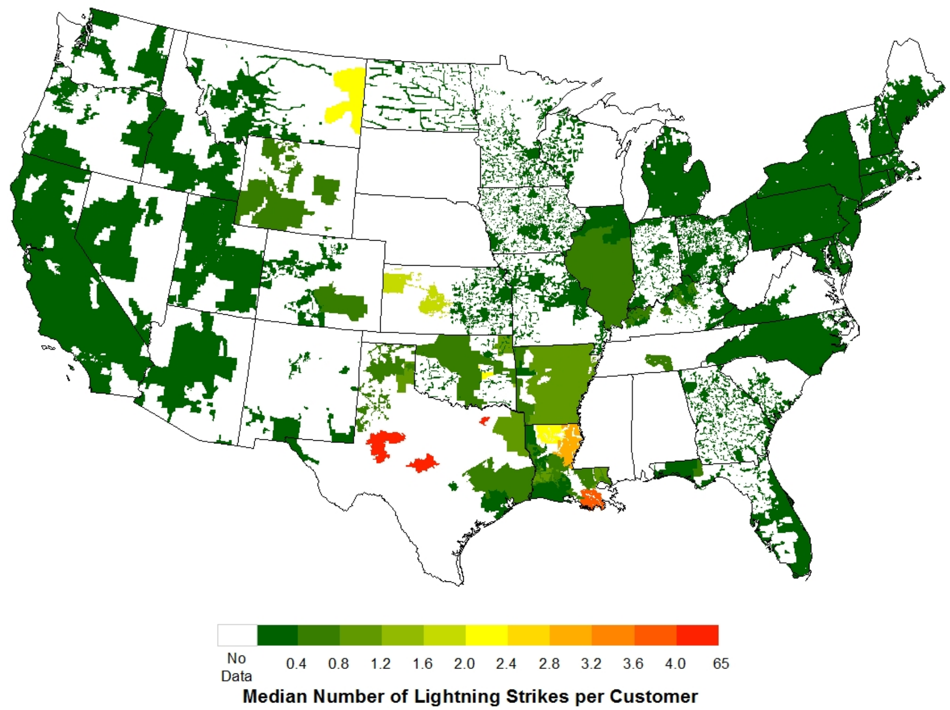
Annual Precipitation



Annual Windspeed

Factors: customers & lightning strikes

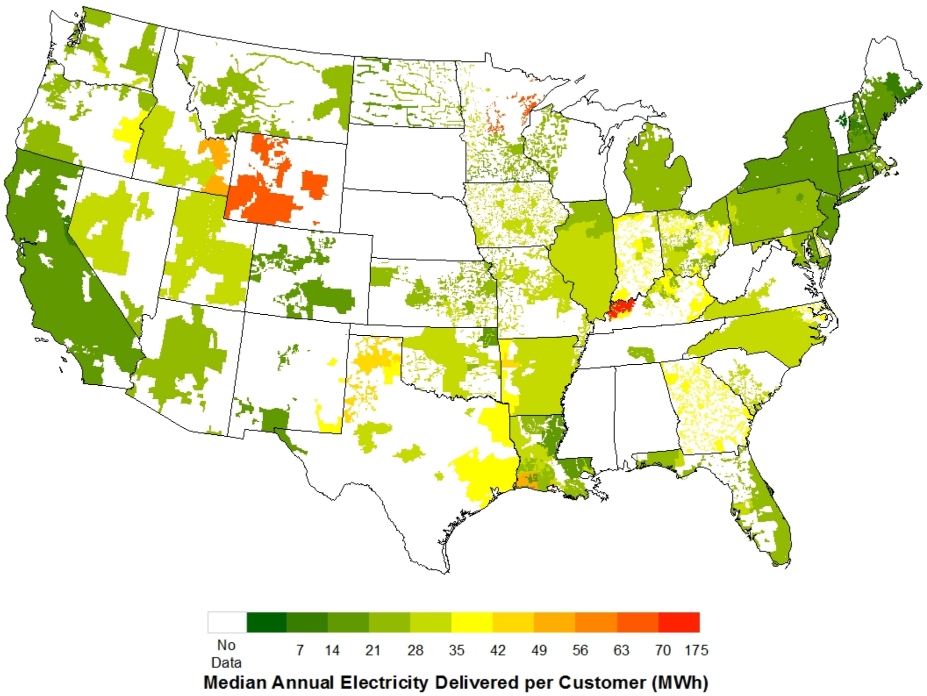


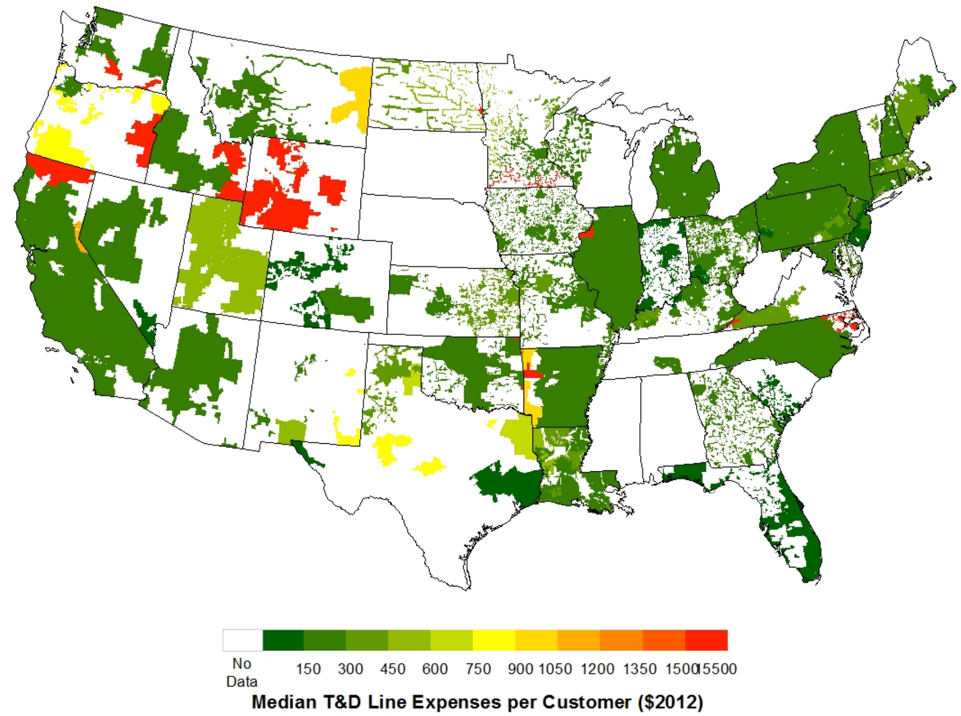


Customer/Line Mile

Lightning Strikes

Factors: electricity sales & T&D spending





Electricity Sales/Customer

T&D Spending/Customer

Analysis method

- Generalized analysis method

- Key data transformations
  - Incorporation of metrics to capture "abnormal" annual weather
  - Addition of non-linear weather metrics
  - Previous year expenditures affecting subsequent year reliability metrics

- Sequential modeling approach following the lead of Hoen et al. (2009)

Method: generalized model

Four types of annual utility reliability metrics are represented by the dependent variable: Y_{it}. Electric utility and reporting year are represented by subscript $_i$ and $_t$, respectively. Subscript $_d$ and $_f$ are used to differentiate between observed and unobservable variables, respectively—and X_{di} and Z_{fi} represent observed and unobservable variables. Finally, ε_{it} represents the model error term and *T* is a variable to capture a time trend.

$$\ln(Y_{it}) = \beta_1 + \sum_{d=2}^{e} \beta_d X_{dit} + \sum_{f=1}^{g} \gamma_f Z_{fi} + \delta T + \varepsilon_{it}$$

As indicated above, the array of Z_{fi} variables are unobservable. Accordingly, we define a new term, α_i, which represents the combined effect of the unobservable variables on the dependent variable, Y_{it}.

$$\ln(Y_{it}) = \beta_1 + \sum_{d=2}^{e} \beta_d X_{dit} + \alpha_i + \delta T + \varepsilon_{it}$$

Method: data transformation

Positive deviation:

$$\overset{+}{\Delta}\vec{W}_{it}\begin{cases}\dfrac{\left(W_{it}-\overline{W}_i\right)}{\overline{W}_i}\times 100: & \dfrac{\left(W_{it}-\overline{W}_i\right)}{\overline{W}_i}\times 100>0\\ 0: & \dfrac{\left(W_{it}-\overline{W}_i\right)}{\overline{W}_i}\times 100\leq 0\end{cases}$$

Negative deviation:

$$\overset{-}{\Delta}\vec{W}_{it}\begin{cases}0: & \dfrac{\left(W_{it}-\overline{W}_i\right)}{\overline{W}_i}\times 100\geq 0\\ \dfrac{\left(W_{it}-\overline{W}_i\right)}{\overline{W}_i}\times 100: & \dfrac{\left(W_{it}-\overline{W}_i\right)}{\overline{W}_i}\times 100<0\end{cases}$$

TOM:	Transmission-related O&M costs
DOM:	Distribution-related O&M costs
HW:	Handy-Whitman utility cost index
W:	Annual weather observation (e.g., wind speed)
$\overline{W}$:	13-year weather average

Prev. year utility T&D O&M expenditures:

$$\text{Expenditures}_{it\text{-}1}=\left(\frac{\text{TOM}_{it\text{-}1}+\text{DOM}_{it\text{-}1}}{\text{Customers}_{it}}\right)\times\left(\frac{\text{HW}_{2012}}{\text{HW}_{t\text{-}1}}\right)$$

Method: sequential modeling

Step (1): Test for presence of no utility-specific effects (null)

- F-test

Step (2): Random effects model is consistent (null)

- Hausman (1978) test

Step (3): Evaluate alternative model specifications

- Start with Eto et al. (2012) specification
- Add groupings of like regressors and evaluate model: performance (RMSE, R^2); parsimony (BIC); and coefficient stability (sign reversal)

Step (4): Select “base model” and interpret results

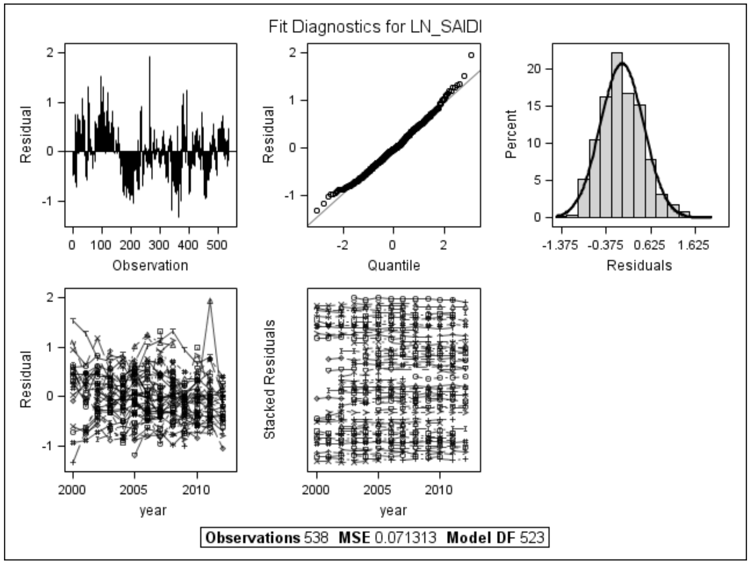
Method: sequential modeling (cont.)

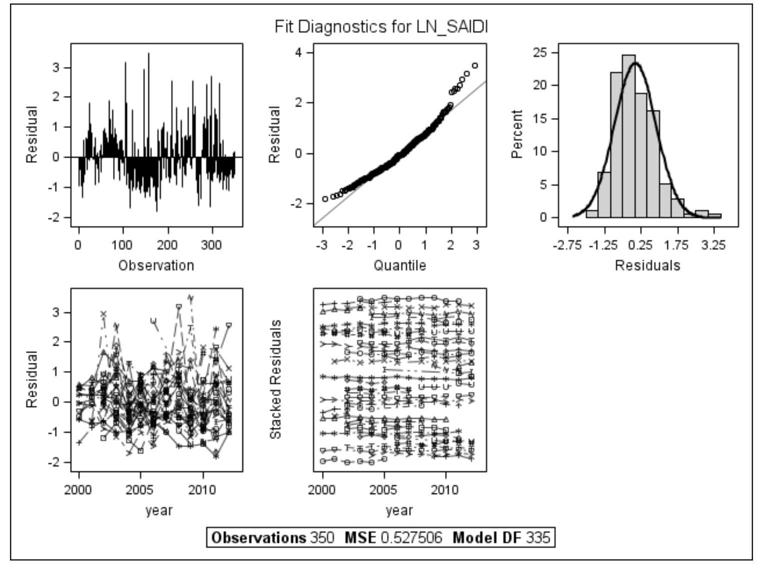
Model	Eto et al. (2012)	B	C	D	E	F	G
Intercept	●	●	●	●	●	●	●
Electricity delivered (MWh per customer)	●	●	●	●	●	●	●
Heating degree-days (#)	●						
Cooling degree-days (#)	●						
Outage management system?	●	●	●	●	●	●	●
Years since outage management system installation	●	●	●	●	●	●	●
Year	●	●	●	●	●	●	●
Abnormally cold weather (% above average HDDs)		●	●	●	●	●	●
Abnormally warm weather (% above average CDDs)		●	●	●	●	●	●
Abnormally high # of lightning strikes (% above average strikes)		●	●	●	●	●	●
Abnormally windy (% above average wind speed)		●	●	●	●	●	●
Abnormally wet (% above average total precipitation)		●	●	●	●	●	●
Abnormally dry (% below average total precipitation)		●	●	●	●	●	●
Abnormally cold weather squared			●	●			●
Abnormally warm weather squared			●	●			●
Abnormally windy squared			●	●	●	●	●
Abnormally wet squared			●	●			●
Abnormally dry squared			●	●			●
Lagged T&D expenditures ($2012 per customer)				●	●	●	●
Number of customers per line mile					●	●	●
Share of underground T&D miles to total T&D miles						●	●

Base model diagnostics: fit

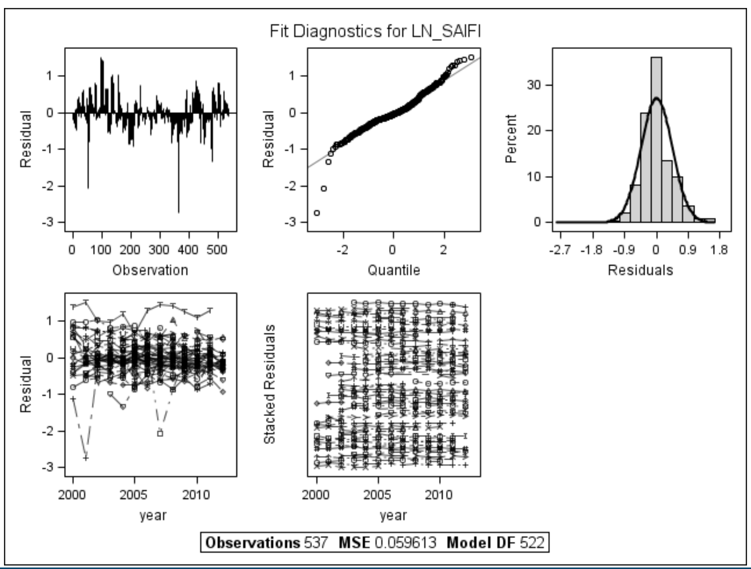
(without "major events") (with "major events")

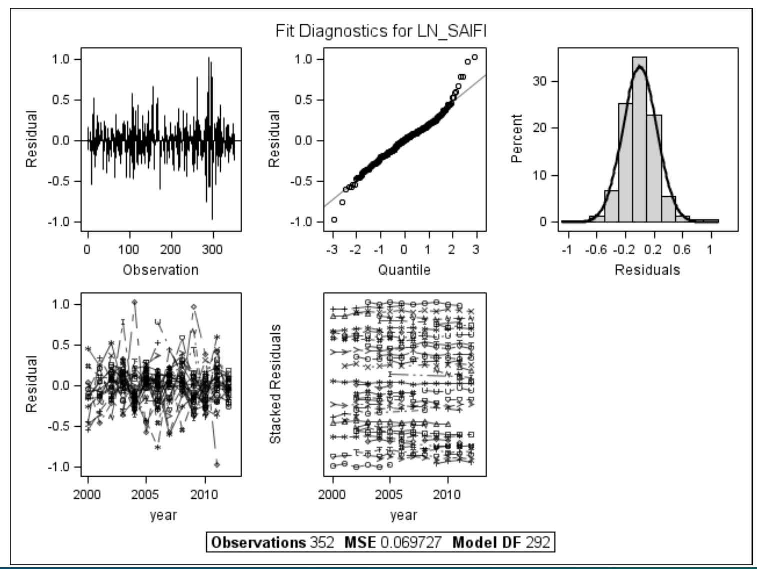
SAIDI:





SAIFI:





Findings: trends in SAIDI and SAIFI

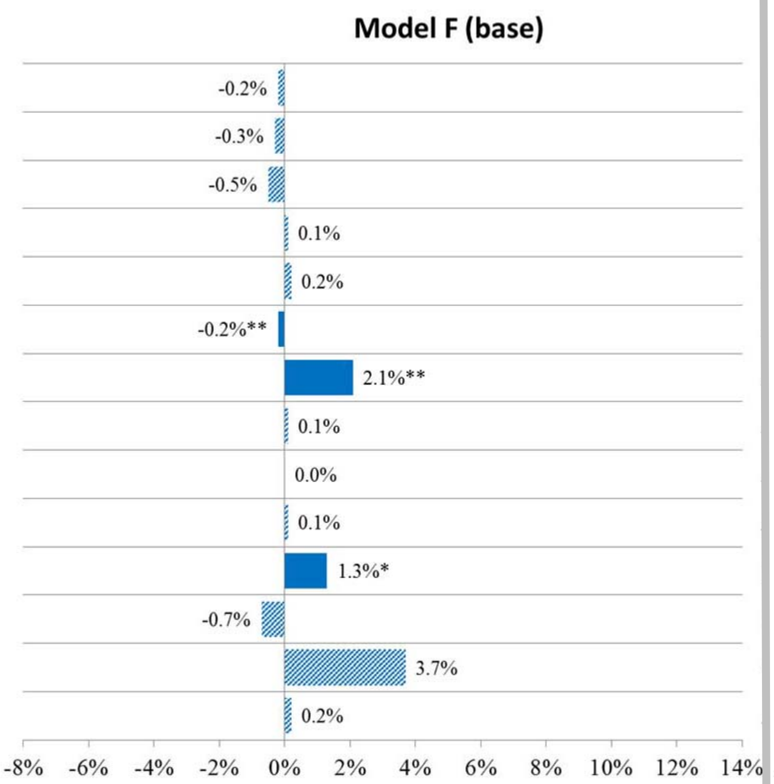
Are power interruptions becoming more frequent and lasting longer?

- *If major events are included in SAIDI and SAIFI,* **total interruption minutes and number of events are increasing**.
  - 9.5% increase in duration per year is statistically significant at 1% level

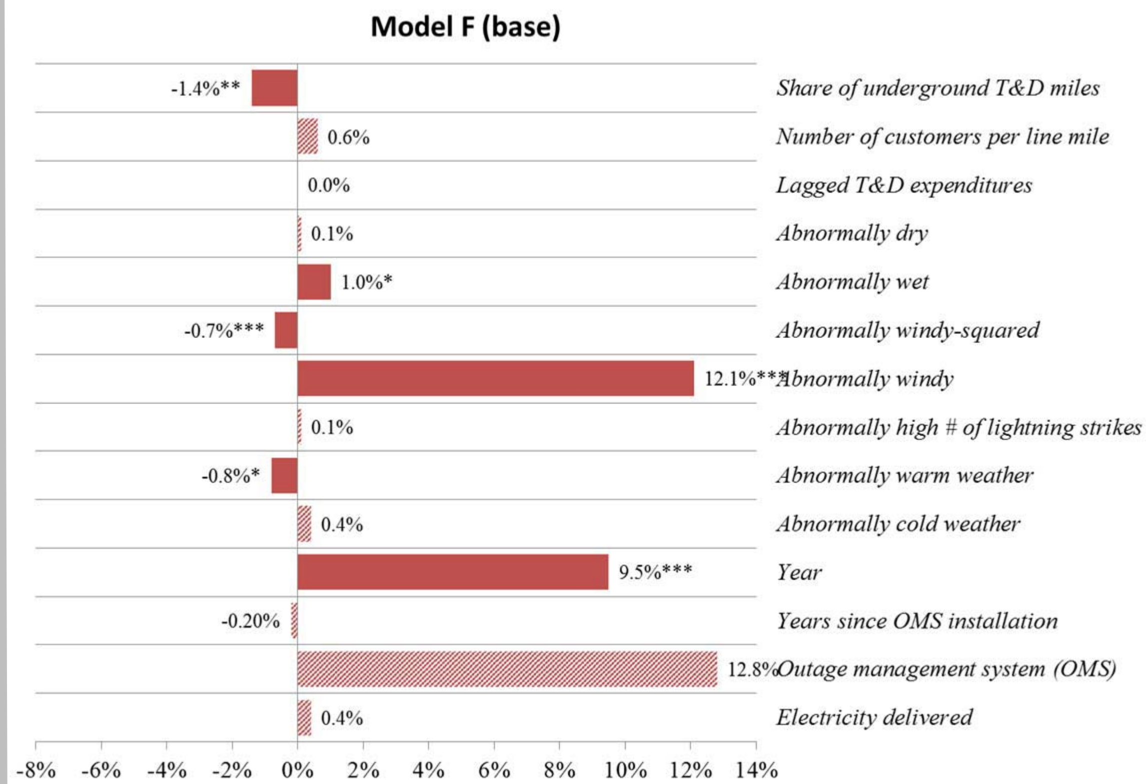
- *If major events are not included,* **total interruption minutes and number of events are slightly increasing**.
  - Trend for total interruption minutes (+1.3%/year) is statistically significant at 10% level; the trend for number of events is not statistically significant

Findings: factors correlated with duration

SAIDI (without major events)

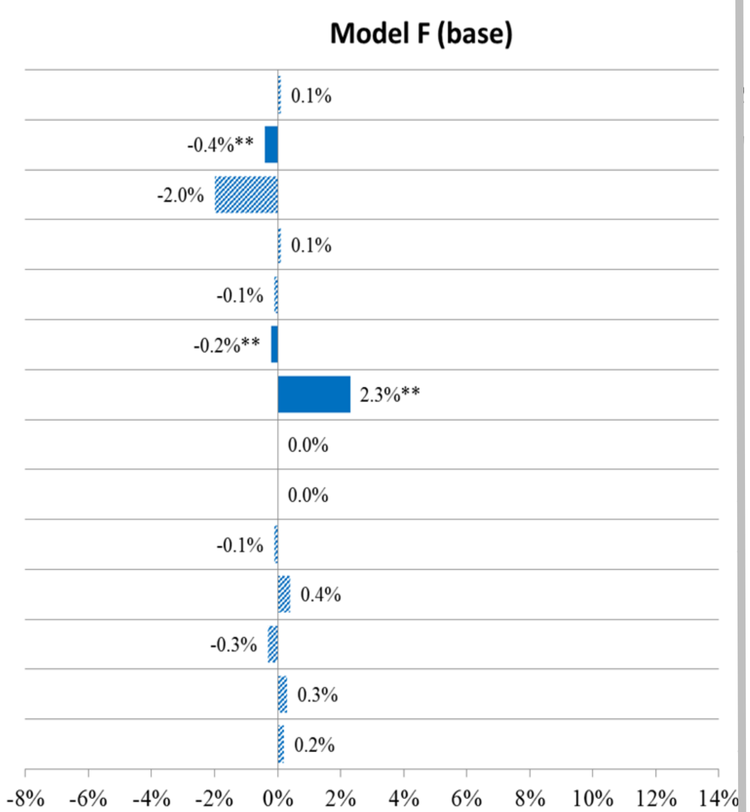


SAIDI (with major events)

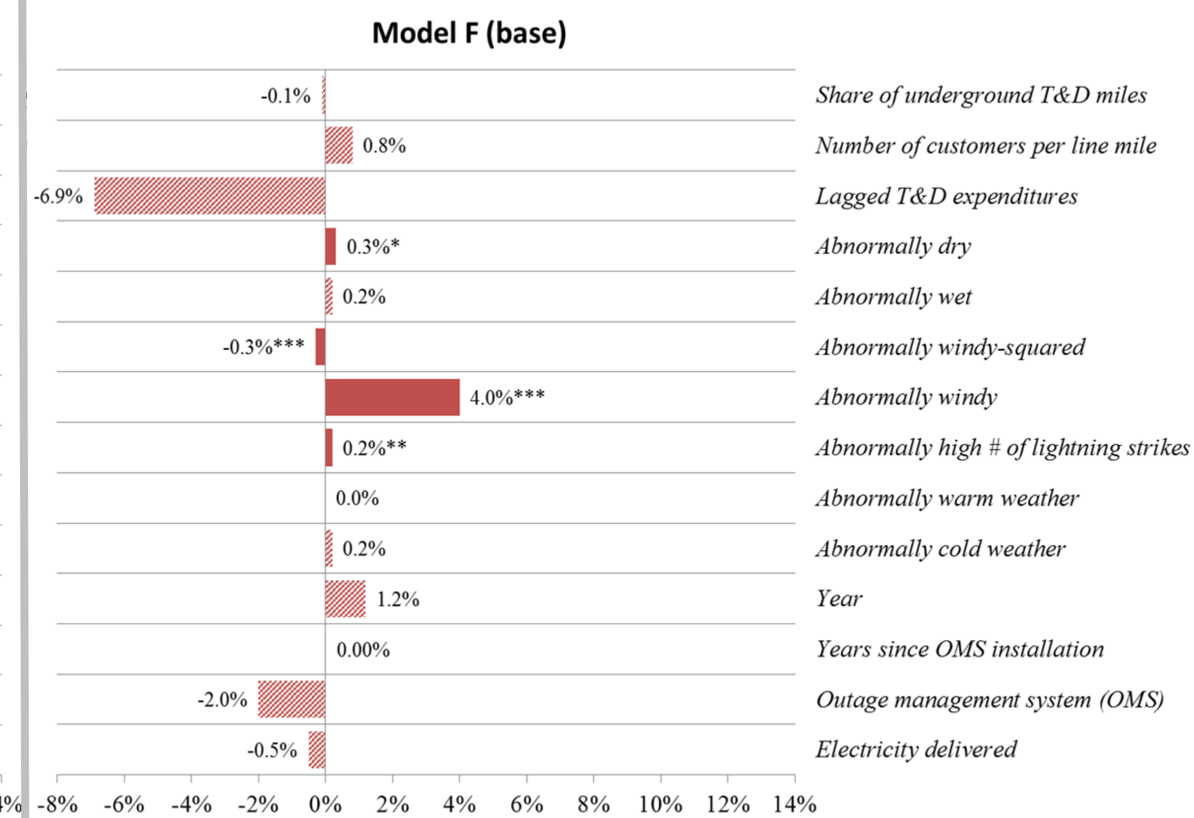


Findings: factors correlated with frequency

SAIFI (without major events)



SAIFI (with major events)



Caveat emptor

- Inconsistent definitions of major events
- Reactive vs. proactive spending “wash out effect”
- Capital investments not considered
- Multi-collinearity across weather regressors
- Regressors as simple proxies for inconsistently reported causes (e.g., lightning strikes as proxy for severe storms)
- Other unobservable and/or intangible factors (e.g., penetration of smart grid technologies)

Summary

- **Overall reliability appears to be getting worse over time** due to an increase in the number and severity of major events during which the energy delivery system experiences stresses beyond those that are normally expected.

- Average total minutes of interruptions is increasing, with strong statistical significance, by ~**9% per year**, and the frequency of interruptions is increasing, with marginal statistical significance, by ~**1% per year**.

- Some measures of abnormal weather (e.g., above average wind speed) are consistently and significantly correlated with changes in reliability; previous-year utility expenditures are not.

Next steps

- Explore the relationship between reactive and proactive capital/O&M expenditures and utility reliability.
- Investigate whether investor-owned utilities (IOUs) and non-IOUs have statistically significant differences in reliability
- Explore relationship between reliability and the long-run deployment of other "smart" technologies
- There may be more appropriate annual weather parameters available to better capture the impact of major events (e.g., number of days per year with wind speeds greater than 30 mph).

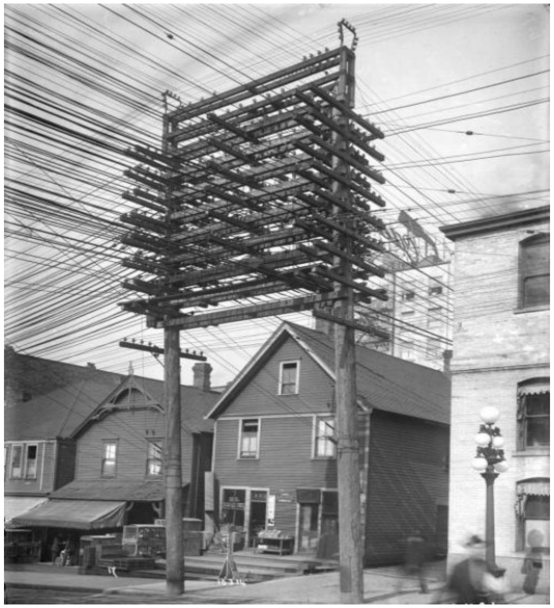
Thank you

Peter Larsen

Email: PHLarsen@lbl.gov *or* PHLarsen@stanford.edu

Phone: (510) 486-5015 *or* (510) 326-0394

Report: https://emp.lbl.gov/publications/assessing-changes-reliabi



Sign up for the RPP e-Distribution List to get notices of future webinars and the monthly *Resilient Power Project Newsletter*: http://bit.ly/RPPNews-Sign-UP

More information about the Resilient Power Project, its reports, webinar recordings, and other resources can be found at www.resilient-power.org.

Thank you for attending our webinar

Seth Mullendore
Project Manager
Clean Energy Group
seth@cleanegroup.org

Find us online:
www.resilient-power.org
www.cleanegroup.org
www.facebook.com/clean.energy.group
@cleanenergygrp on Twitter
@Resilient_Power on Twitter

CleanEnergyGroup
Innovation in Finance, Technology & Policy

RESILIENT POWER
A Project of Clean Energy Group