Probabilistic analysis of power grids: how do large blackouts occur?

Bert Zwart

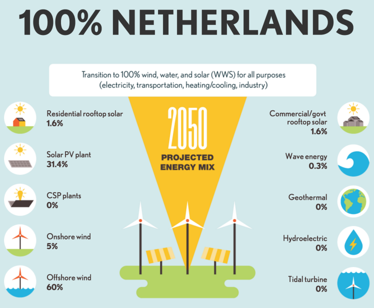
CWI and TU/e

December 16, 2022

based on
T. Nesti, F. Sloothaak, B. Zwart.
Emergence of scale-free blackout sizes in power grids.
Physical Review Letters **125**, 058301, 2020.

Centrum Wiskunde & Informatica

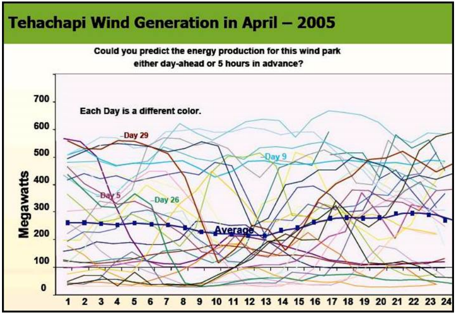
The energy transition

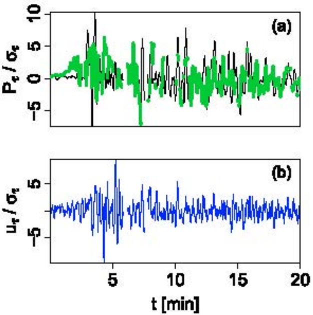


Suggested solutions (renewables, demand response, ...) lead to

- Increased decentralization (e.g. rooftop solar panels)
- Increased complexity [e.g. between physical network and communication network]
- More uncertainty

More variability in supply

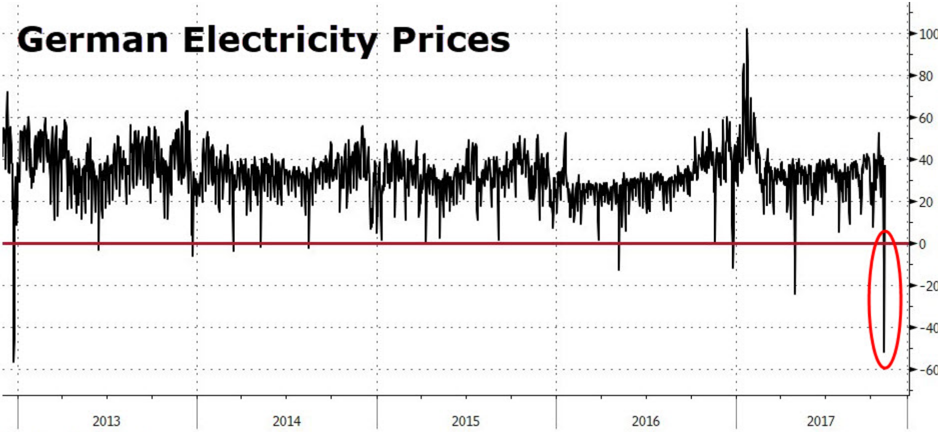




Wind, and also solar, are variable over many time-scales.

More variability in demand

More variability in prices



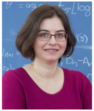
Source: Epex Spot

Applied probability and energy

EURANDOM

Stella Kapodistria

Fiona Sloothaak



Maria Vlasiou

NETWORKS
THENETWORKCENTER.NL

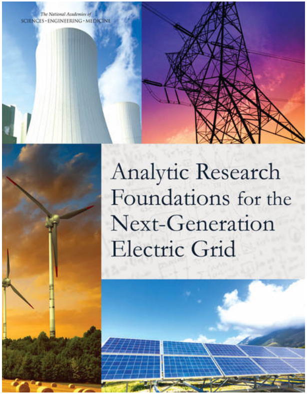
Vision: mathematics can help to transform the power grid into a smart grid, like it helped to transform phone networks into the Internet.

Specific topics:

- Distribution grids with EV charging
- RL, preventive maintenance (e.g. for wind turbines)
- Reliability, rare events, rare-event simulation

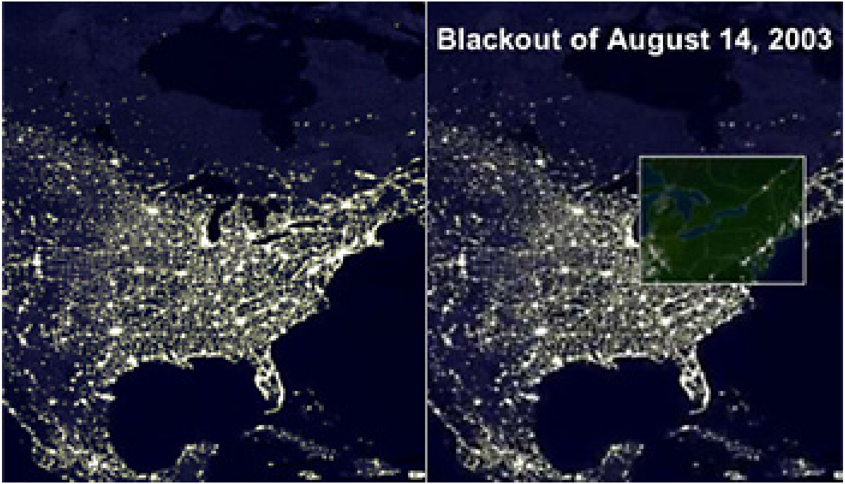
Mathematical challenges

- Optimization
- Dynamics/control
- Complex systems
- Probability/Statistics
- AI
- Market design (traditional, P2P,...)



Community building: co-organized semester on mathematics for energy networks at the Isaac Newton Institute, Cambridge UK, spring 2019.

Todays focus: understanding large blackouts



$80B$ of annual economic damage to US economy from blackouts

Unrest in South Australia (2016 - 2017)

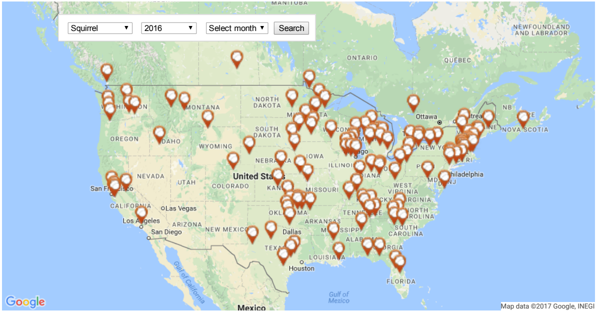
- Rolling blackouts during heat wave. Renewable energy (wrongfully) blamed. Problems mitigated by 100 MW Tesla battery
- Other controversial disruptions: Los Angeles (2018), Texas (2021), UK (2019, concurrent disruptions at wind park + classical generator)

Successful squirrel attacks

1/23/2017 CyberSquirrel1.com

Cyber Squirrel 1

Disrupting at the highest levels, its #CyberWar4Ever!



TOTAL SUCCESSFUL CYBER WAR OPS AS OF 2017.01.08 - 1748

Agent	Success
Squirrel	879
Bird	434
Snake	83
Raccoon	72
Rat	36
Marten	22

ABOUT THIS MAP

This map lists all unclassified Cyber Squirrel Operations that have been released to the public that we have been able to confirm. There are many more executed ops than displayed on this map however, those ops remain classified.

Confirmation for all ops has been preserved by the Internet Archive's WayBack Machine whenever possible.

"I don't think paralysis [of the electrical grid] is more likely by cyberattack than by natural disaster.

MOST RECENT UNCLASSIFIED OPS

Tweets by @CyberSquirrel1

CyberSquirrel
@CyberSquirrel1

We can neither confirm nor deny our involvement at this time.

3h

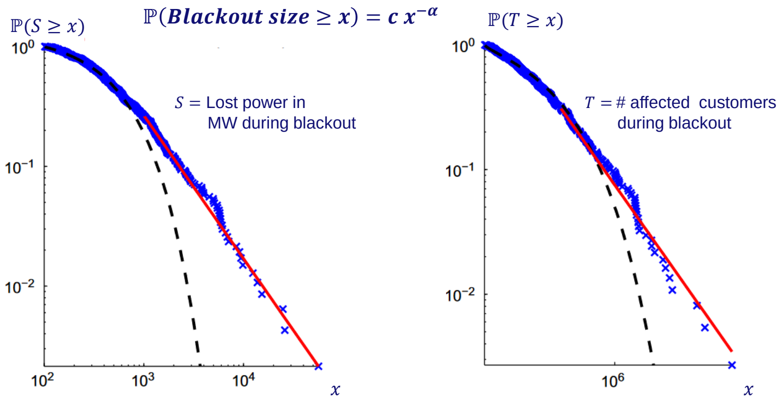
CyberSquirrel
@CyberSquirrel1

Linemen are not our enemies, much respect.

Can we mathematically understand blackouts?

- We cannot model everything
- Statistical physics of complex networks: aim to understand how macroscopic phenomena evolve out of microscopic interactions.
- Some quote made by some of my colleagues:
  - "It is not complex, but complicated"
  - "It is not possible to come up with a both interesting and useful result"
- It can take a long time to determine the cause of a blackout - even after it occurred.
- To understand, predict and/or detect anomalies, should we use simple black box methods from machine learning or sophisticated mathematical models?
- At least one feature of blackouts is not complicated

Pareto laws in power grids (Hines 09)



WHY?

Goal: provide explanation using rare event analysis.

Probabilistic analysis of rare events

1. Large deviations theory:
   - compute (analytically) the probability that a rare event occurs
   - determine the most likely way a rare event occurs, if it occurs
2. Extreme value theory:
   - growth rate of maxima
   - how to extrapolate from data
3. 'Dutch' application: determining dike heights as part of Deltawerken
4. Other Applications
   - dimensioning safety/buffer/storage levels in finance, insurance, computer, communication networks, ...
   - vulnerability assessment: finding weakest links in complex systems

Rare Events depend on “Tail Behaviors”

Light-Tailed Distributions

- Extreme Values are Very Rare
- Normal, Exponential, etc

Heavy-Tailed Distributions

- Extreme Values are Frequent
- **Pareto Law**, **Weibull**, etc

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Heavy tails are not as well understood as light tails.

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Systemwide rare events

arise because

EVERYTHING goes wrong.

(Conspiracy Principle)

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Systemwide rare events

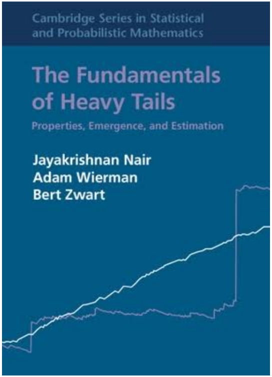
arise because of

A FEW Catastrophes.

(Catastrophe Principle)

Heavy tails are not as well understood as light tails.

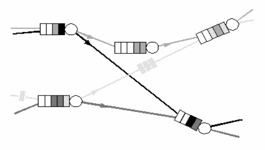
New book



Free pdf at https://adamwierman.com/book/

Heavy Tails are Everywhere:

Computer systems

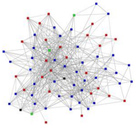


delays, files, ...

Finance

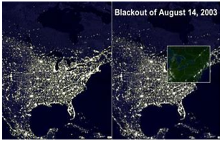
losses

Social networks



popularity, contagion

Energy Systems



blackouts

How do heavy tails occur?

Heavy tails can occur in many ways

- Queues: exogenous factors (e.g. job sizes)
- Finance: nonlinear internal dynamics (e.g. compounding losses)
- Growing social networks: preferential attachment
- Power systems: not well understood.
  Most popular narrative to date: self-organized criticality

Heavy tails and critical phenomena

Consider a Branching Process with $Z_0 = 1$ and

$$Z_{n+1} = \sum_{i=1}^{Z_n} C_{ni}.$$

If $\mathbf{E}[C_{ni}] = 1$ the branching process is said to be critical. The total size and depth of the tree are heavy-tailed.

Self-organized criticality: many natural and man-made systems appear to be self-organizing and also behave like critical systems

Attempts have been made to model cascading failures as branching processes.

A better explanation

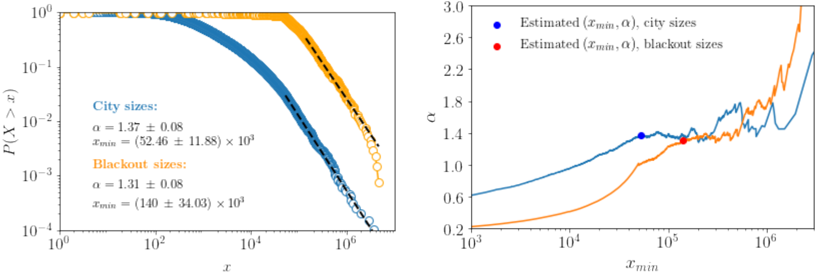
Let C be the size of a city, in terms of number of people, and let T be the size of a blackout, in terms of number of customers affected
Both have statistically significant, almost identical power law for US:

$$P(C > x) \approx x^{-1.37} \qquad\qquad P(T > x) \approx x^{-1.31}.$$

German city sizes: power law with index 1.28

2015 rank	City	State	2015 Estimate	2011 Census	Change	2015 land area	2015 po
1	**Berlin**	Berlin	3,520,031	3,292,365	+6.91%	891.68 km² 344.28 sq mi	
2	**Hamburg**	Hamburg	1,787,408	1,706,696	+4.73%	755.3 km² 291.6 sq mi	
3	**Munich** (München)	Bavaria	1,450,381	1,348,335	+7.57%	310.7 km² 120.0 sq mi	
4	*Cologne* (Köln)	North Rhine-Westphalia	1,060,582	1,005,775	+5.45%	405.02 km² 156.38 sq mi	
5	*Frankfurt am Main*	Hesse	732,688	667,925	+9.70%	248.31 km² 95.87 sq mi	

log-log plots and Hill plots



US city size data (2000 census) and US outage data (NERC, 2002-2018). Cutoff chosen according to the PLFIT method of Clauset et. al (2009).

Mathematical model - main features

- Graph with n nodes, fixed topology.
  Demand at node i: X_i, with $P(X_i > x) \sim cx^{-\alpha}$.
  $\mathbf{X} = (X_1, \ldots, X_n)$.

- To model electricity, we use the DC load flow model.

- We consider three stages in our model:
  - Planning: determine line capacities/limits
  - Operation: determine network flows, keeping some slack, quantified by a parameter λ.
  - Emergency: failure propagation, starting from a random line failure

Main result

Let X be a generic city size, with $P(X > x) \sim C_X x^{-\alpha}$.
Note that T is the blackout size [in terms of number of customers affected]

$$P(T > x) \sim C_T x^{-\alpha}, \qquad x \to \infty, \tag{1}$$

$$C_T = C_X n \sum_{j=1}^{n} P(|A_1| = j)(1 - j\lambda/n)^{\alpha}. \tag{2}$$

A_1 denotes the (random) set of nodes making up the island with the largest city in the network once the cascade is over.

Proof challenge: reduce network to the case of a single big city, and many small cities, reducing the problem to the analysis of a cascade to a single-sink network.

Numerical studies

Our result holds up against several simulation studies

- Generation constraints
- Extending DC to AC
- No heavy tailed blackout size if city sizes are uniformly distributed
- IEEE test networks
- Synthetic scalable networks, tailored to power grids [Wang, Scaglione, and co-authors]

Critical assumption: frozen vs random city sizes [quenched vs annealed] becomes irrelevant if network is sufficiently large

SciGRID case study - Impact of λ

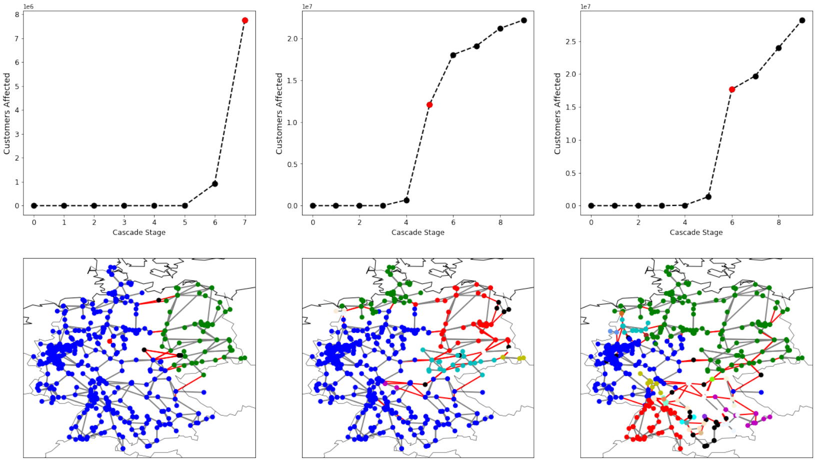


Figure: Dissection of biggest blackout for loading factors $\lambda = 0.7$ (left panels), $\lambda = 0.8$ (middle) and $\lambda = 0.9$ (right) in terms of the cumulative number of affected customers at each consecutive stage as displayed in the top charts with the biggest jump colored red.

Number of load shedding events during cascade

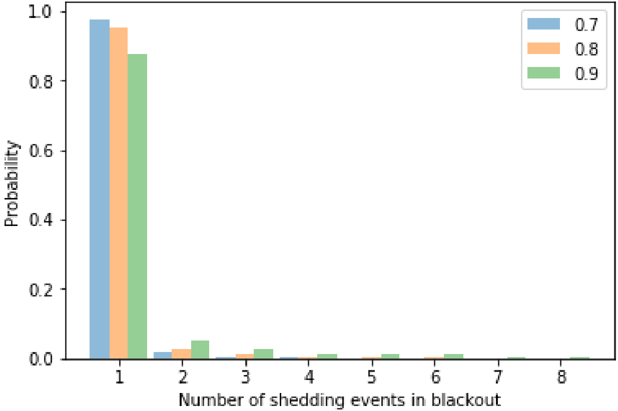


Figure: Histogram of the total number of load shedding events in the SciGRID network. For a moderate loading factor $\lambda = 0.7$, nearly 99% of the blackouts only involved a single jump. Even for a high loading factor $\lambda = 0.9$, 87% of the blackouts involve just a single jump. The fraction of blackouts with four or more jumps remains below 5%

Insights

$$P(T > x) \sim C_T x^{-\alpha}, \qquad x \to \infty,$$

- Using our methods, we can compute

  $$P(\text{ blackout starts with failure at line } i \mid \text{ large blackout occurs})$$

  This helps to determine the most vulnerable lines.

- However, line upgrades only make C_T smaller. α will not chance. Thus: upgrades provide limited effect in preventing large blackouts.

- Duration of blackout is light-tailed, and seems independent of size.

- It makes more sense to invest in making cities more resilient (e.g. be capable to operate in islanded mode for several hours in case of need).

Possible next questions

- What would be a fair price for an insurance against blackouts?
- How much storage do we need if we are (close to) 100 percent renewables, and want to limit shortages to, say, 30 minutes per year?
- What is the value of storage as mitigation against future rare events?
- Can we design congestion management schemes with probabilistic reliability guarantees?