Assessing the robustness of the U.S. power grid under extreme wind events

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September 17, 2025

CCS Italy 2025

Motivation

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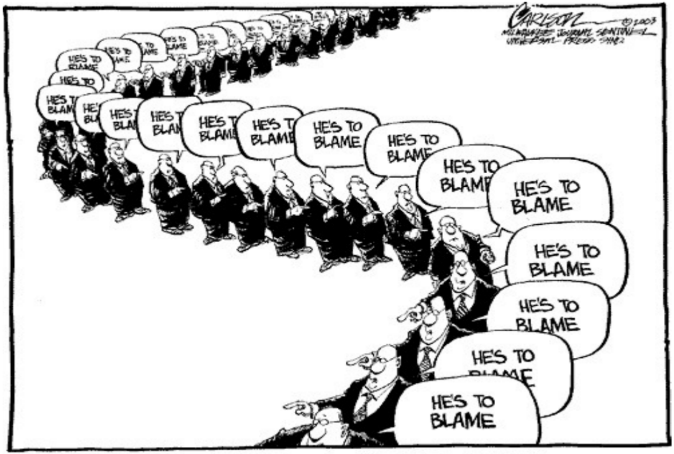
Iberian Peninsula blackout (2025)

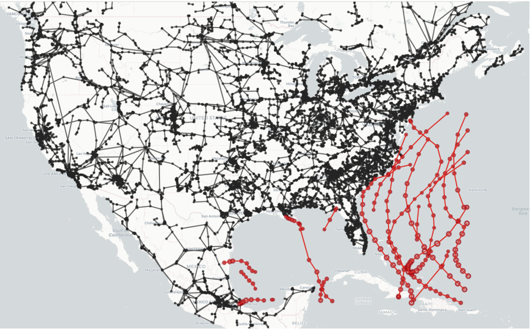
Italy blackout (2003)

What happened?

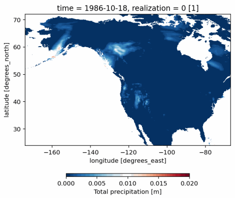


BLACKOUT OF '03 —The "CASCADE EFFECT"

Weather is a primary cause of disruptions

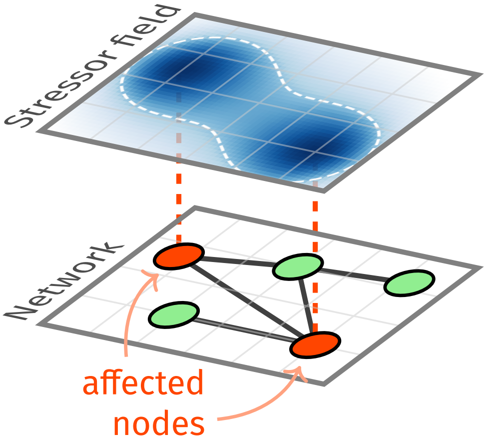


Hurricane paths and US grid



Modelling

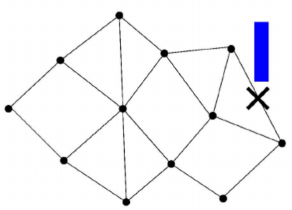
- Can we build a dynamical model of cascade spreading?
- How to model the impact of exogenous events (e.g. strong winds)?
- Can we validate using real weather data and historical blackouts?



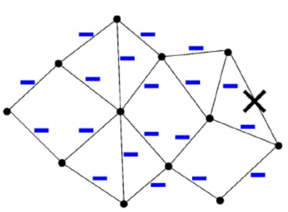
The basic framework

Flow redistibution in a power grid

Initial failure

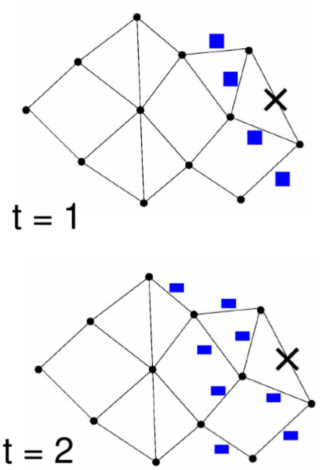


Stationary model



e.g. Motter model

Dynamic model



Flow conserving model

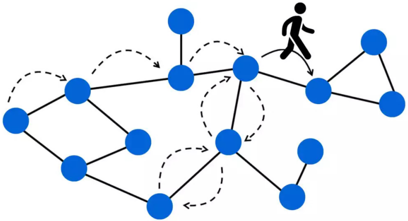
We can imagine the current flow with a random-walk like model.

$$n_j(t+1) - n_j(t) = \underbrace{\sum_i \frac{W_{ij}}{k_i} n_i(t)}_{\text{inflow}} - \underbrace{\sum_i \frac{W_{ji}}{k_j} n_j(t)}_{\text{outflow}} + n_j^{\pm}(t)$$

where $k_i = \sum_j W_{ij}$ is the degree and $T_{ij} = \frac{W_{ij}}{k_i}$ the transfer matrix from i to j.

Basic ingredients:

- ✔ Flow must be conserved!
- ✔ Flow redistribution
- ✔ Initial failures triggered by weather



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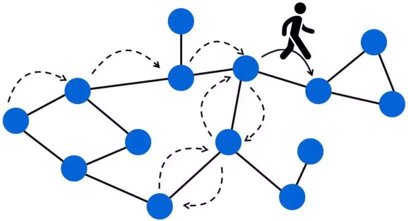


De Groot model

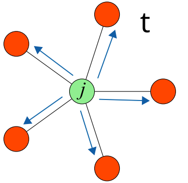
By introducing the density of walkers $\rho_j(t) \equiv \frac{n_j(t)}{M}$

$$\rho_j(t+1) = \sum_i \frac{W_{ij}}{k_i}\rho_i(t) + \rho_j^{\pm}(t)$$

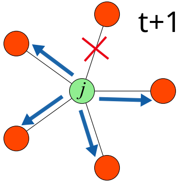
We introduce $c_j(t) \equiv \frac{\rho_j(t)}{k_j}$ the outgoing current per unit weigth

$$c_j(t+1) = \sum_{i=1}^{N} \frac{W_{ij}}{k_j} c_i(t) = \sum_i^{N} Q_{ji} c_i(t)$$

Note that the transfer matrix $Q_{ji} = \frac{W_{ij}}{k_j} = (T_{ij})^{\intercal}$ is the transpose of a random walk.



$c_j(t)$



$c_j(t+1) > c_j(t)$

Stationary solution

This model was introduced to describe opinion dynamics (De Groot model, 1974)
In vector form, and inserting source/sink terms $\vec{j}^{\pm}$

$$\vec{c}(t+1) = \vec{c}(t)\hat{Q} + \vec{j}^{\pm}$$

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In vector form, and inserting source/sink terms $\vec{j}^{\pm}$

$$\vec{c}(t+1) = \vec{c}(t)\hat{Q} + \vec{j}^{\pm}$$

If $\vec{j}^{\pm} = 0$ then the stationary solution is a constant vector $c_i^{(0)}(\infty) \sim \frac{1}{\sqrt{N}}$

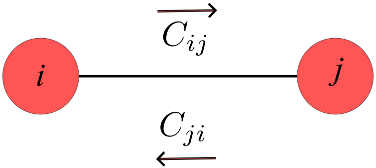
If $\vec{j}^{\pm} \neq 0$, it can be expressed as

$$\vec{c}(\infty) = \vec{c}^{(0)}(\infty) + (\vec{1} - \vec{Q})^{+}\vec{j}^{\pm}$$

When does a link fail?

Total directed current on link $i \to j$ becomes

$$C_{ij}(t) = W_{ij} c_j(t)$$



from which we can compute the total current on link $j \leftrightarrow i$

$$L_{ij}(t) = C_{ij}(t) + C_{ji}(t)$$

When does a link fail?

Maximum capacity $\mathcal{M}$ is related to the initial load (L^0_{ij}) via a tolerance parameter $\alpha > 0$

$$\mathcal{M}_{ij} = (1 + \alpha) L^0_{ij}$$

A link fails whenever its current load L_{ij} exceed the capacity of that link

Link $i - j$ fails if

$$L_{ij}(t) > \mathcal{M}_{ij}$$

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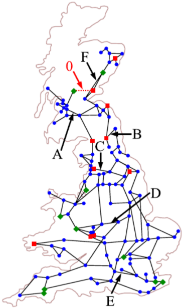
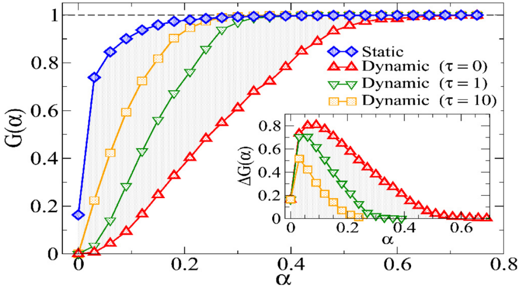
A second discrete parameter is the overload exposure time τ
$\tau > 0$: the system will have to be overloaded for a certain time before causing a failure.

Simulation on the UK power grid





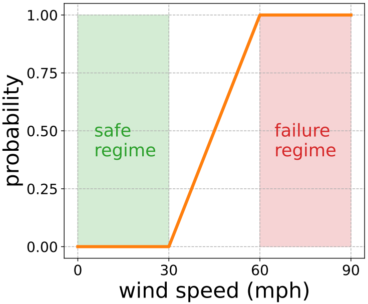
$$G(\alpha) = \frac{\mathcal{N}(\text{Survived links})}{\mathcal{N}(\text{Links})}$$

(Simonsen, et al. Physical review letters 100.21 (2008): 218701.)

Fragility model: initial failures

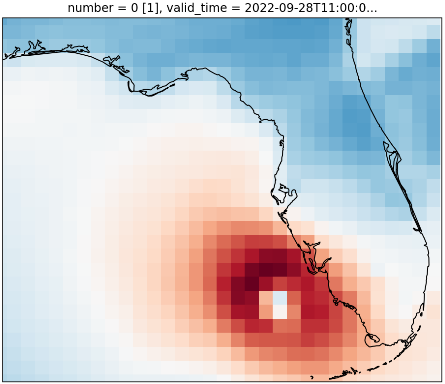
Link failure with probability p
and wind speed w (mph)

$$p(w) = \begin{cases} 0, & w < 30 \\ (w-30)/30 & 30 \leq w < 60 \\ 1 & w \geq 60 \end{cases}$$

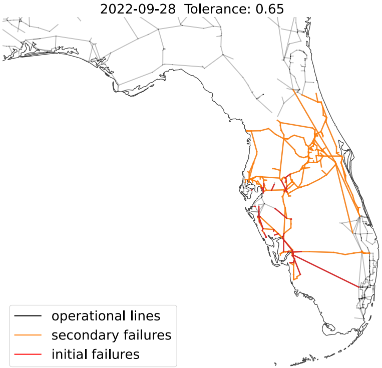


(Mathaios et al. 2017. "Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures." IEEE Transactions on Power Systems 32 (5): 3747–57.)

Hurricane hits Florida (2022)

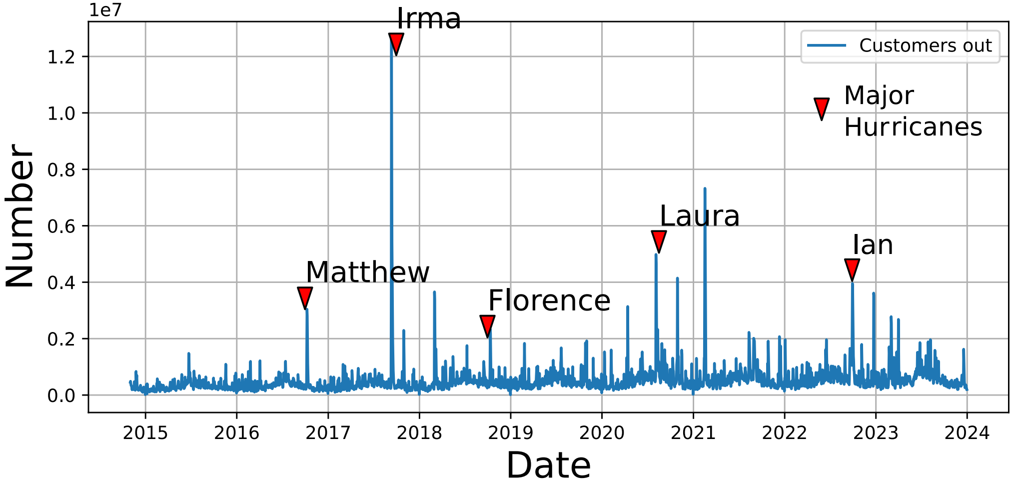


Wind strength

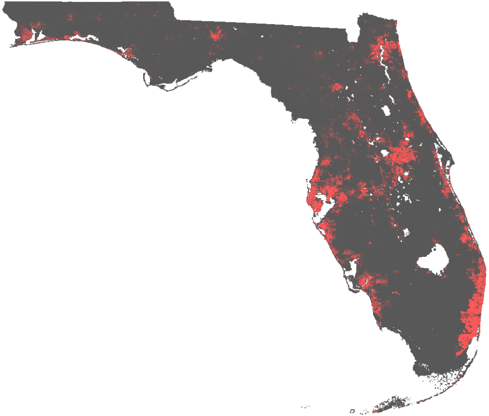


Simulated cascade

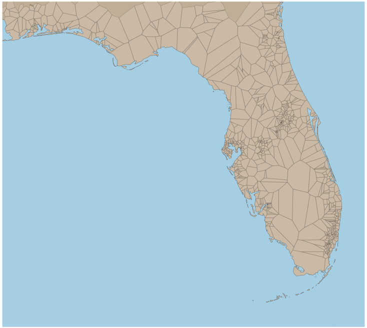
Blackout time series



Estimation of customers out

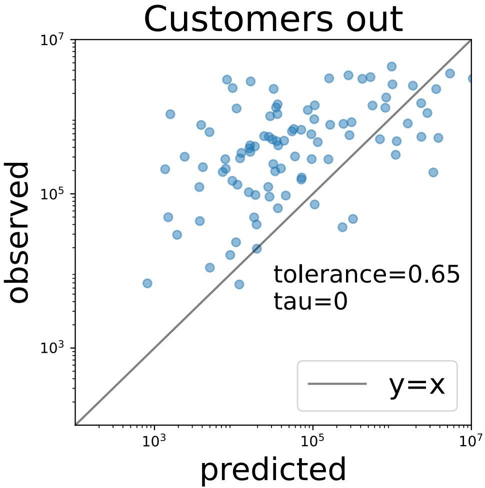


Population density



Voronoi tesselation of Florida grid

Best fit



- Each dot represents an extreme event in our dataset
- We find significant ($p << 0.01$) Spearman correlation between predictions and observations
- Best fitted parameter are $\alpha = 0.65$ and $\tau = 0$

Questions?

Joint work with:

Manlio De Domenico

Mauro Faccin

- Model of flow propagation in power grids
- Use of weather data to fit the model
- Use of historical data for validation

CoMuNe lab
COMPLEX MULTILAYER NETWORKS

UNIVERSITÀ DEGLI STUDI DI PADOVA

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Thanks for your attention!