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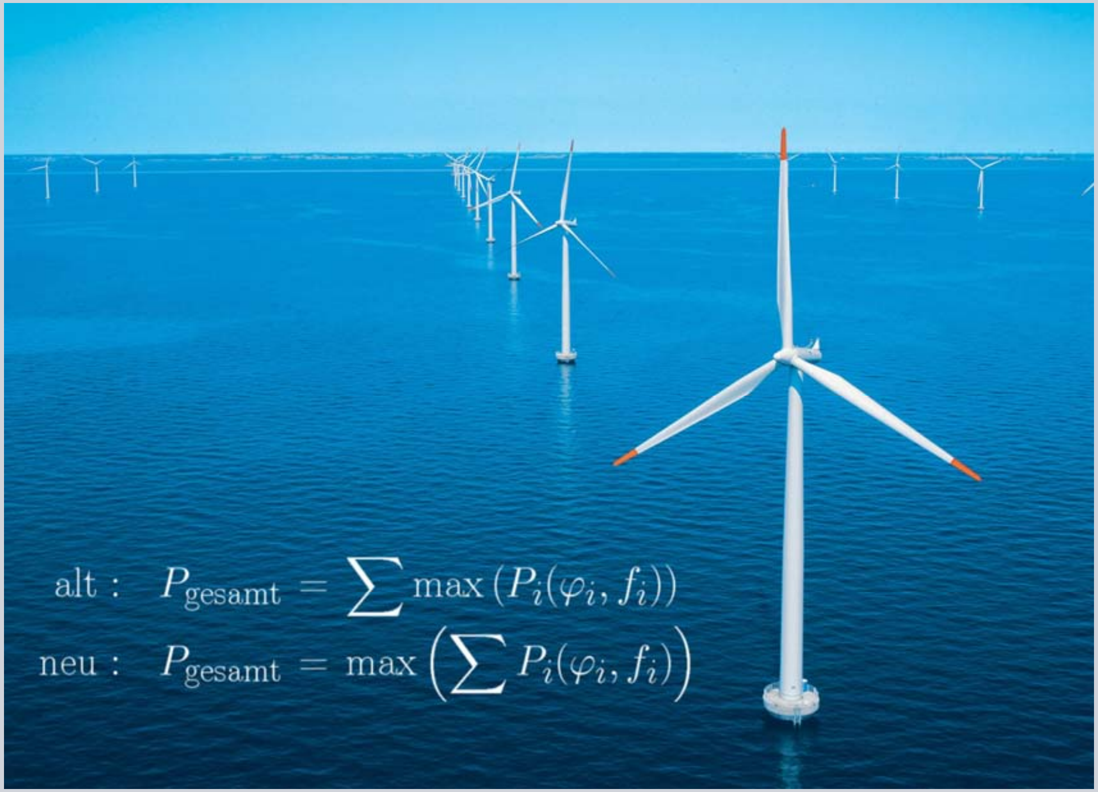
Corporate Technology

Optimization of Power Efficiency in Wind Farm Nysted



Overview

I. Modeling + optimization of wind farms
II. Turbulence ↔ energy cascade ↔ power grid
III. Complex networks: robustness against cascading failures
IV. Outlook

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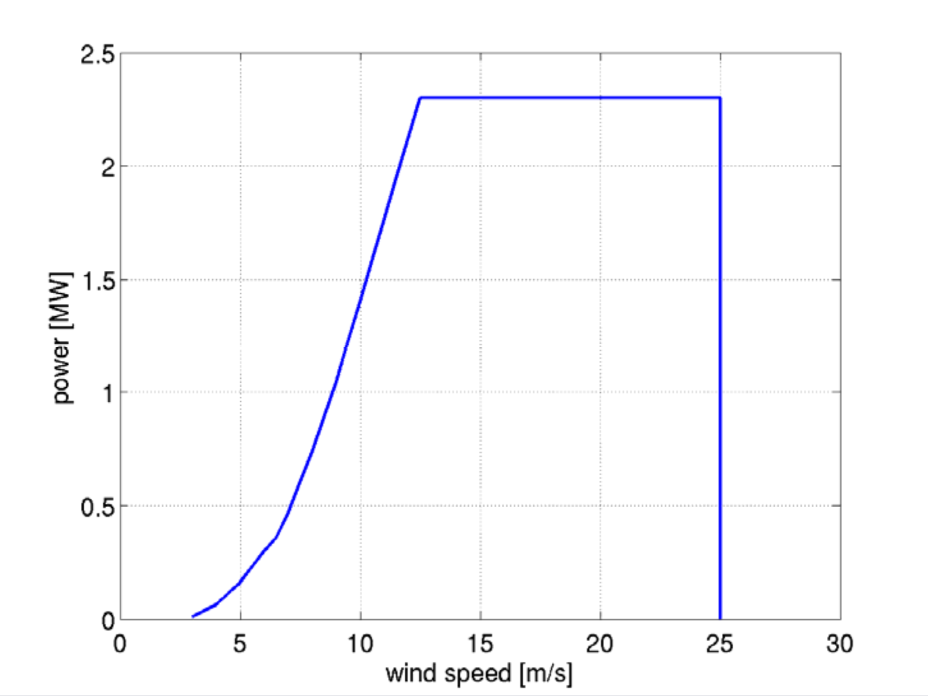
Wind-farm modeling I: power curve

$$P=\frac{1}{2}\frac{\Delta m}{\Delta t}\left(u_+^2-u_-^2\right)=\frac{1}{2}\rho A\frac{u_++u_-}{2}\left(u_+^2-u_-^2\right)=\frac{\rho A}{2}C_P u_+^3$$

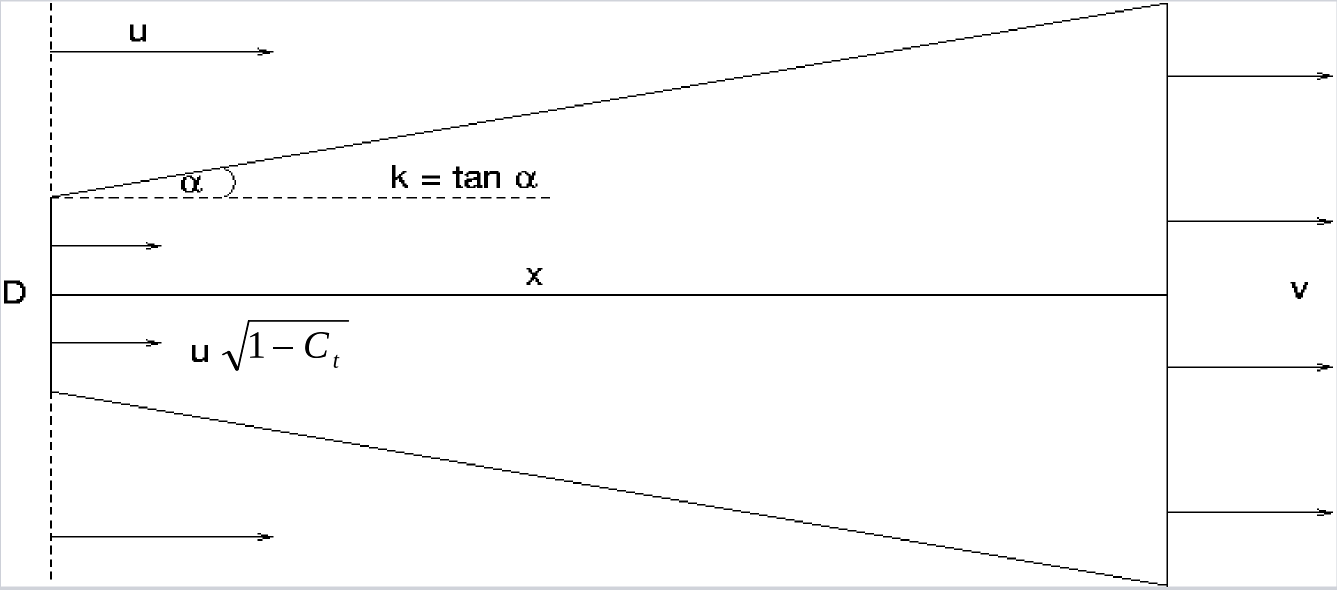


$$\max C_P(u_-/u_+)=0.59$$

$$\arg\max C_P(u_-/u_+)=0.33$$

$$C_T=\frac{u_+^2-u_-^2}{u_+^2}$$

Wind-farm modeling II: single wake

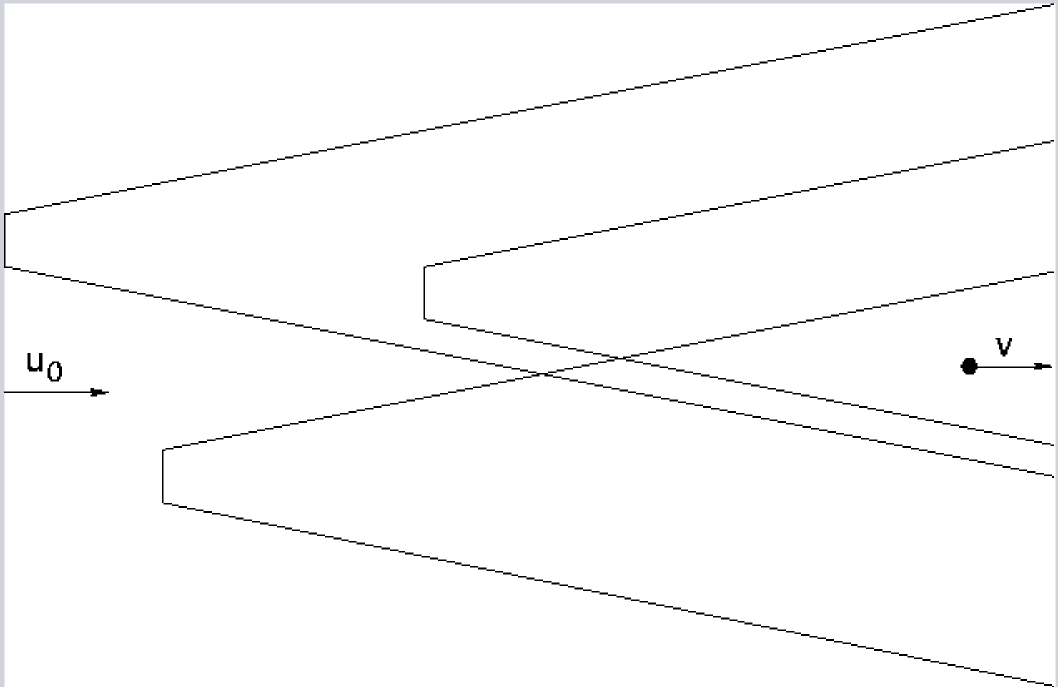


$$C_T = \frac{u^2 - v(0)^2}{u^2}$$

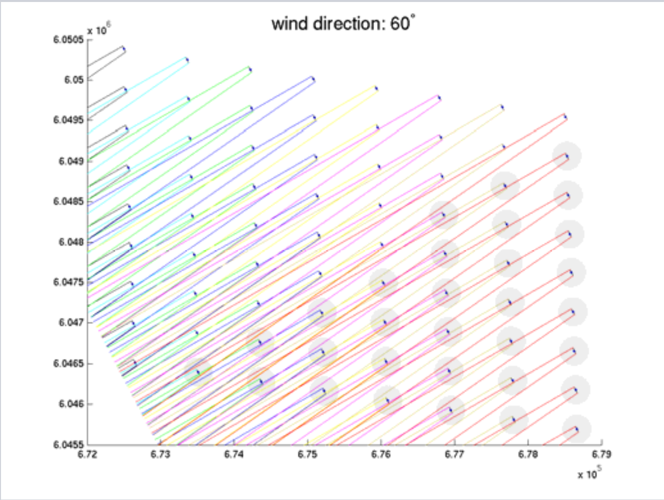
$$\pi\left(R + x\tan\alpha\right)^2 v(x) = \pi R^2 v(0_+) + \pi\left[(R + x\tan\alpha)^2 - R^2\right]u$$

$$v(x) = u\left[1 - \left(1 - \sqrt{1 - C_T}\right)\left(\frac{D}{D + 2kx}\right)^2\right]$$

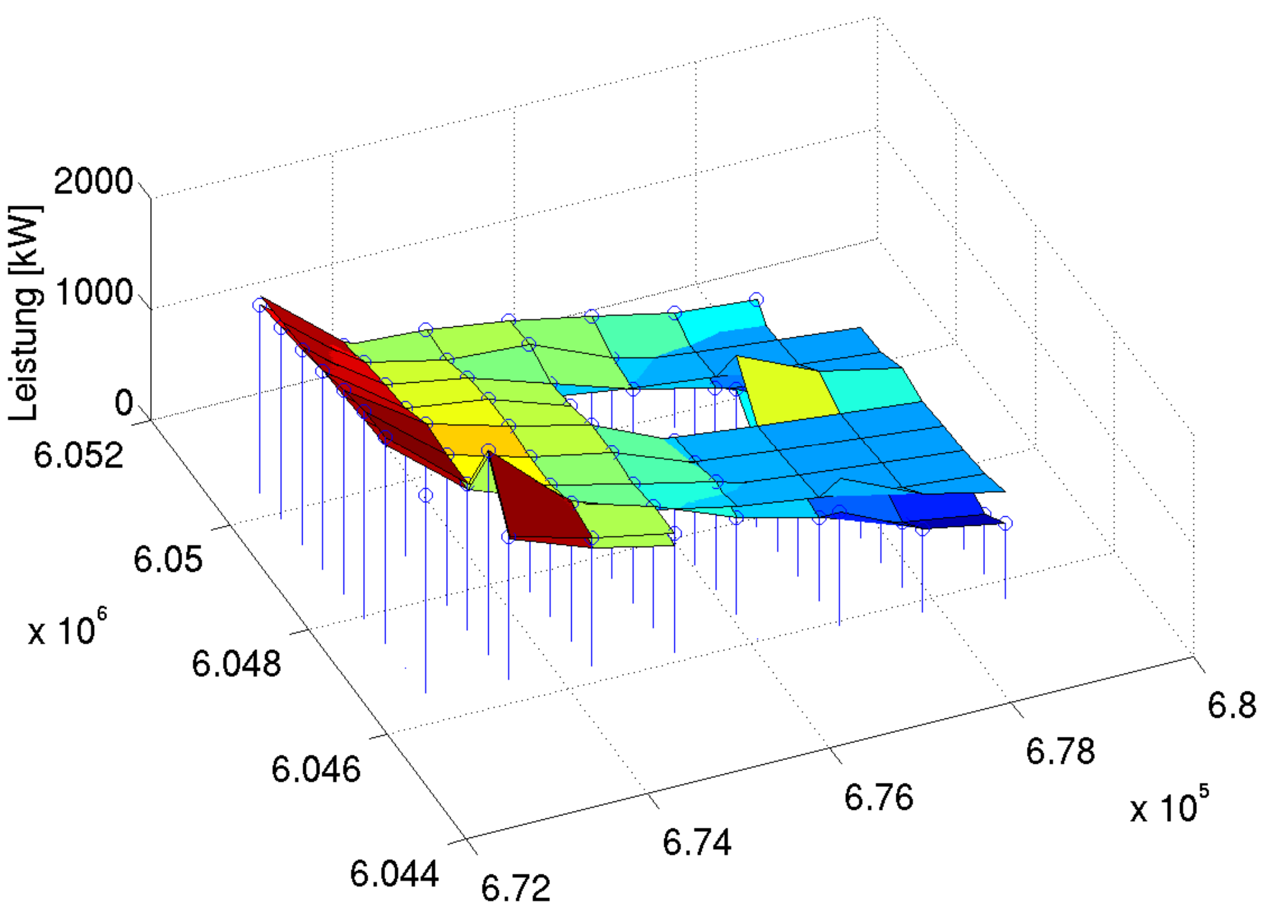
Wind-farm modeling III: multiple wakes



$$\left(1-\frac{v}{u_0}\right)^2 = \left[\left(1-\frac{v_1}{u_0}\right)\frac{A_1}{A_{disc}}\right]^2 + \left[\left(1-\frac{v_2}{u_0}\right)\frac{A_2}{A_{disc}}\right]^2 + \ldots$$



Wind-farm modeling IV: comparison with data



$k \approx 0.04$

Wind-farm optimization I

u, θ

wind-farm model →

+ turbine tables

$$C_P = C_P(\varphi, \mathrm{f} \mid \mathrm{v})$$
$$C_T = C_T(\varphi, \mathrm{f} \mid \mathrm{v})$$

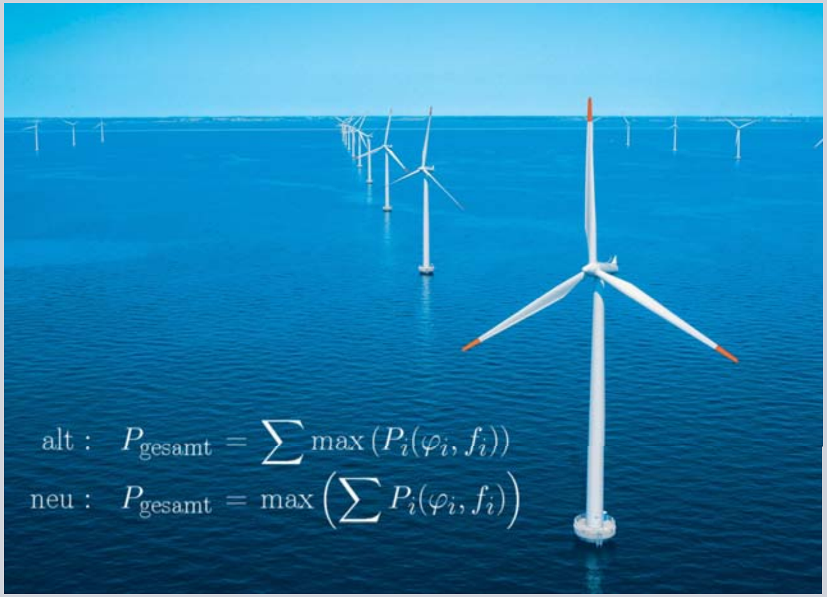
$$P_{\text{farm}} = \sum_{i=1}^{72} P_i$$

$$P_{\text{farm}}(\text{selfish}) = \sum_i \max(P_i(\varphi_i, f_i \mid v_i))$$
$$P_{\text{farm}}(\text{cooperative}) = \max\left(\sum_i P_i(\varphi_i, f_i \mid v_i, \theta)\right)$$

Wind farm optimization II: theoretical results

$$P_{\text{tot}} = \int p(u,\theta)\, P_{\text{farm}}(u,\theta)\, d\theta$$

$$\eta = \frac{P_{\text{tot}}(\text{cooperative}) - P_{\text{tot}}(\text{selfish})}{P_{\text{tot}}(\text{selfish})}$$



Nysted: 72 x 2.3MW (fixed speed) $\eta = 1.0\% \quad (1.2\%)$

Lillegrund: 48 x 2.3MW (variable speed) $\eta = 3.5\% \quad (4.3\%)$

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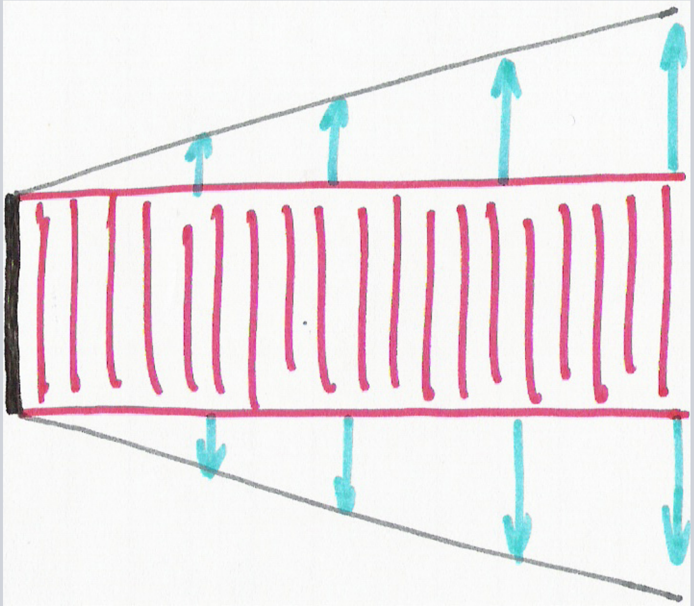
Turbulence in wind farms: dynamic wake flow

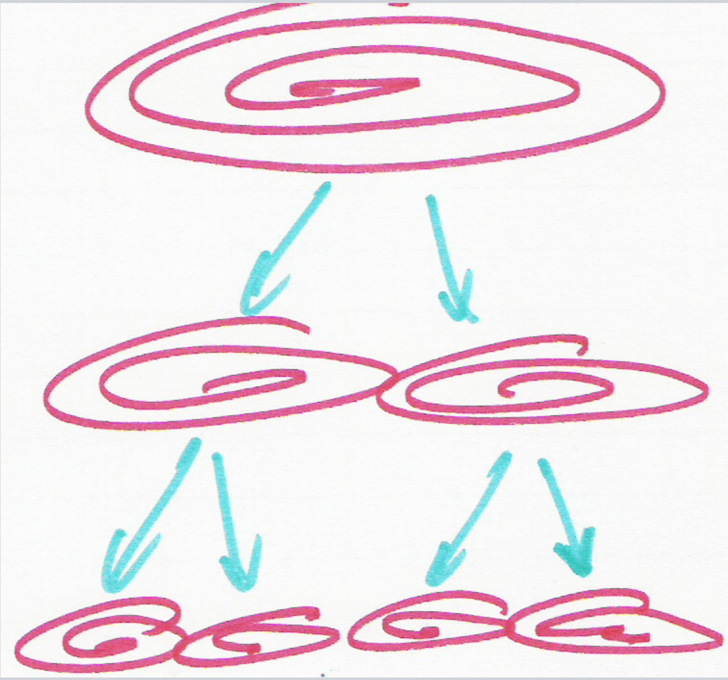


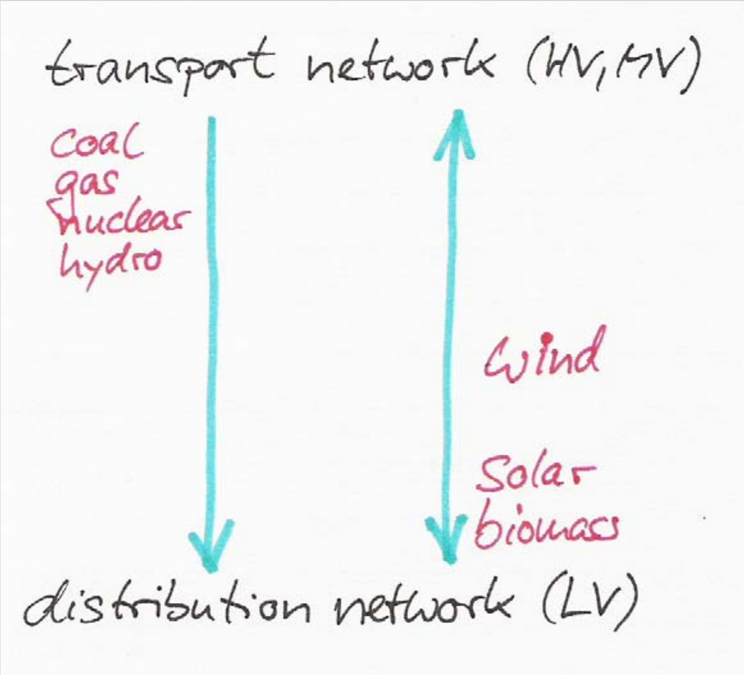
static wake = average of narrow meandering wake

lateral turbulence

k = 0.075 (onshore)
k = 0.04 (offshore)

Energy cascade: from turbulence to power grid





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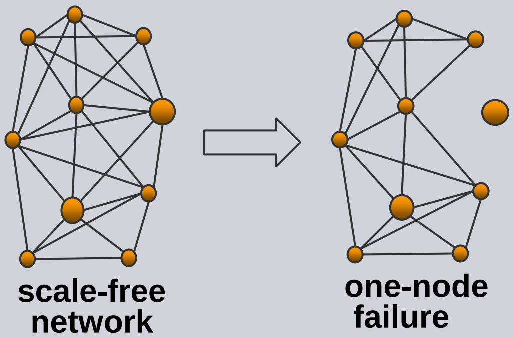
Network model I: cascading failure



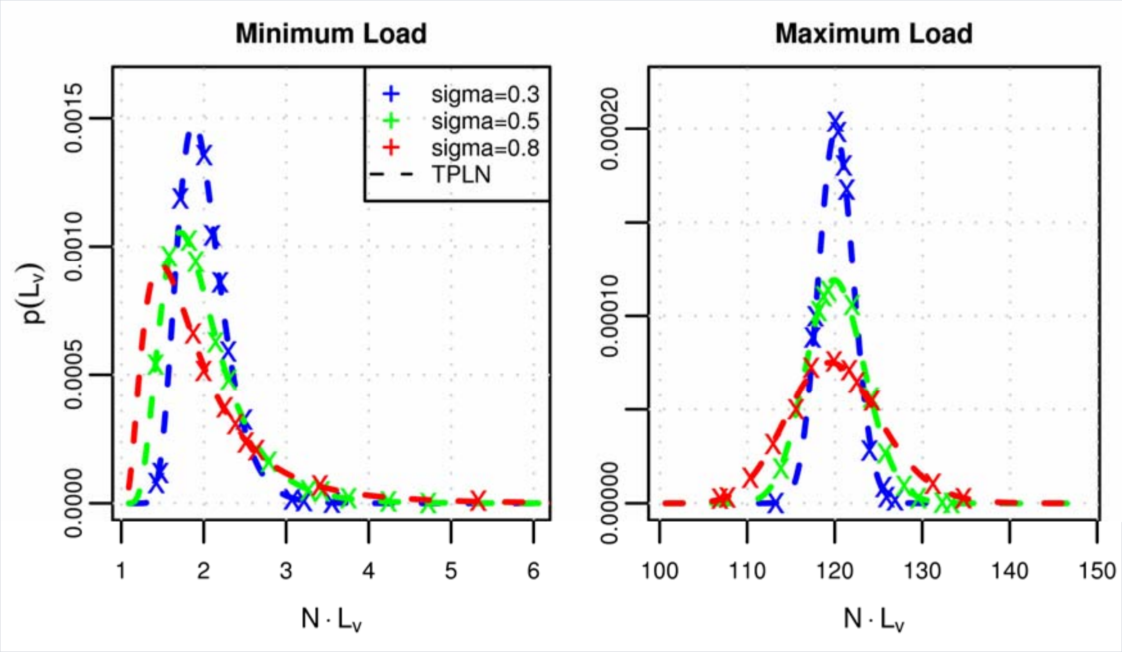
$$L_v = \sum_{i,f} \mathrm{path}\big([i \to f\,];v\big)\, s_{if}$$

$$C_v(\alpha) = (1+\alpha)\langle L_v \rangle$$

Network model II: fluctuations

$$L_v = \sum_{i,f} \text{path}([i \rightarrow f]; v) s_{if}$$

source / path fluctuations: $s = \text{iid lognormal}$



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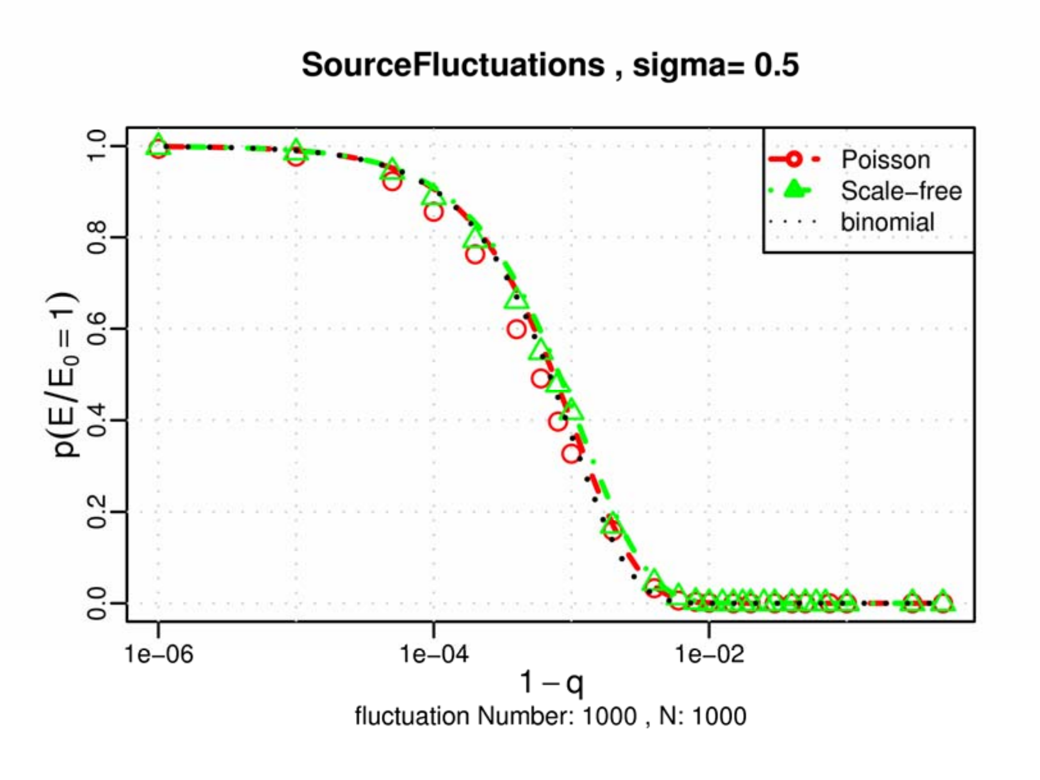
Network robustness I: efficiency

$$q = \int_0^{C_v} p_v(L_v)\, dL_v = F_v(C_v)$$

$$C_v(q) = F_v^{-1}(q)$$

$$E = \sum_{i \neq f} \frac{1}{d_{if}}$$



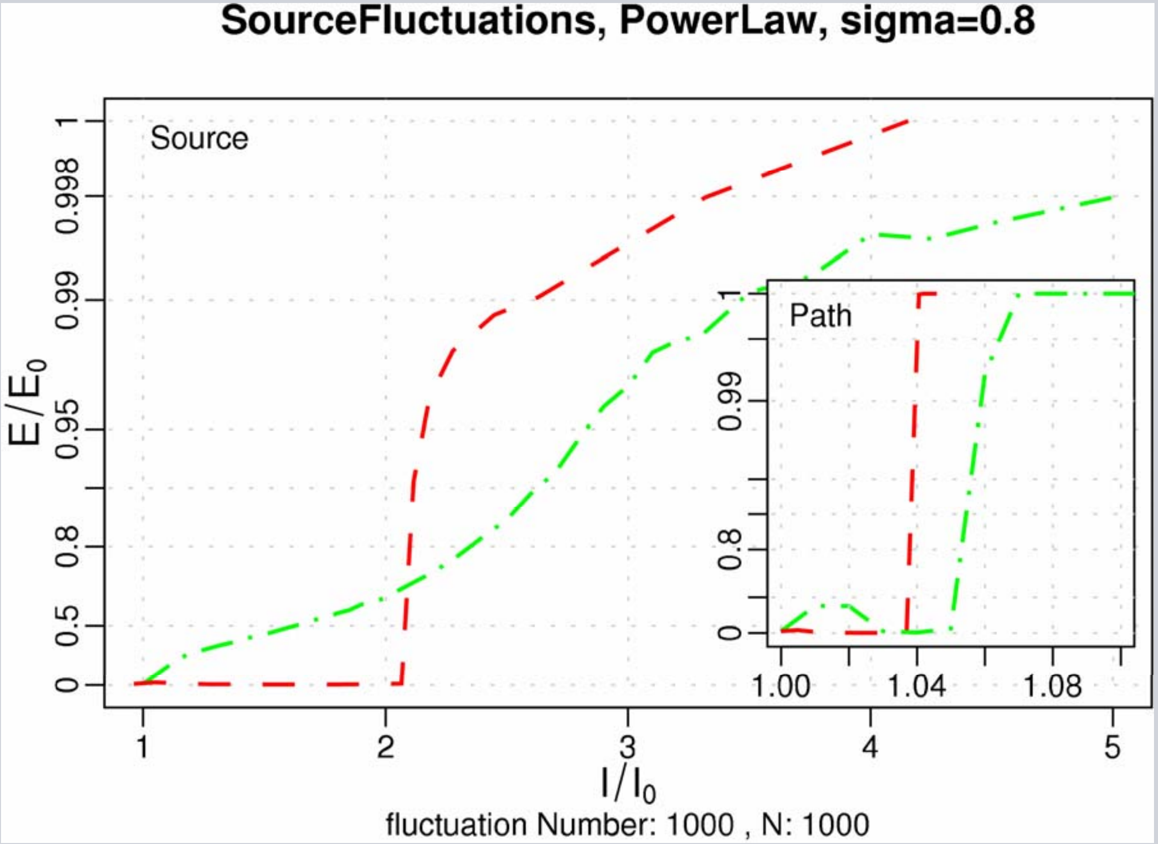
Network robustness II: investment costs

$$C_v(q) = F_v^{-1}(q)$$

$$C_v(\alpha) = (1+\alpha)\langle L_v \rangle$$

$$I = \sum_v C_v$$

$$E = \sum_{i \neq f} \frac{1}{d_{if}}$$



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Outlooks

- multifractal normal turbulence modeling of wind fields
  THURSDAY: JOCHEN CLEVE
- more wind-farm modeling + control
- self-organizing power grid

THANK YOU!

