



engineering and public policy

Preparing Technical Leaders to Address Policy Issues
that Involve Science and Technology.



Uncertainty in the integration of renewable energy sources:

Part 1: Insights from the RenewElec Project

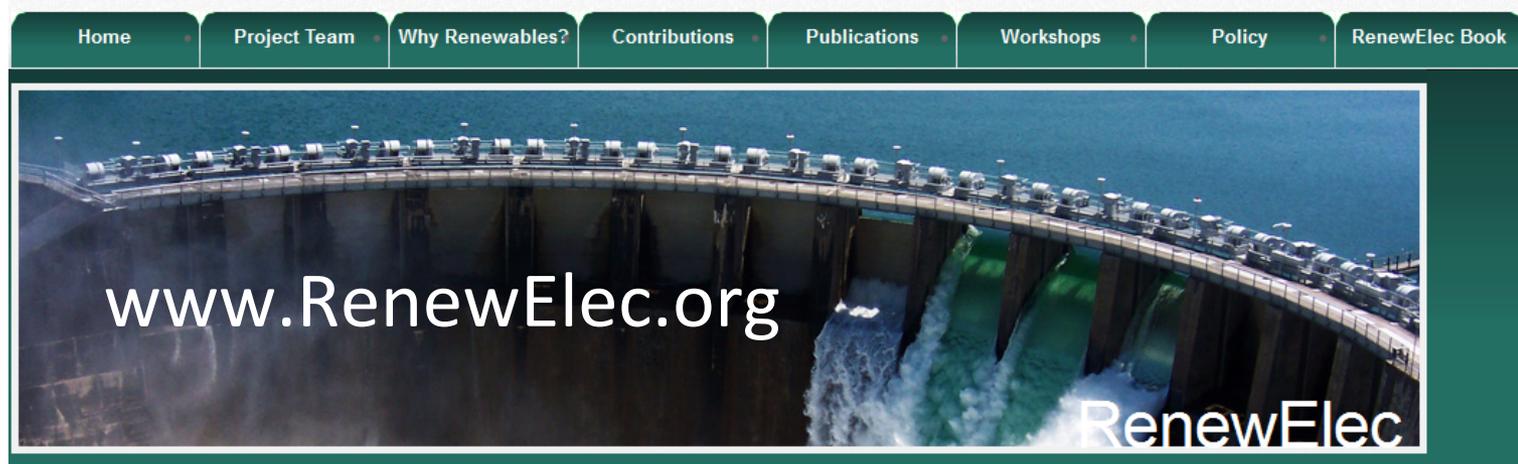
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Thanks to Jay Apt

Who provided most of the slides on which this talk is based, but who could not join us today because of conflicts.

CMU's long-standing research in renewables laid the foundation for the RenewElec project that began in 2009

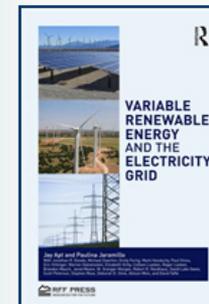


Peer-reviewed publications on which this talk is based can be found on the web site.

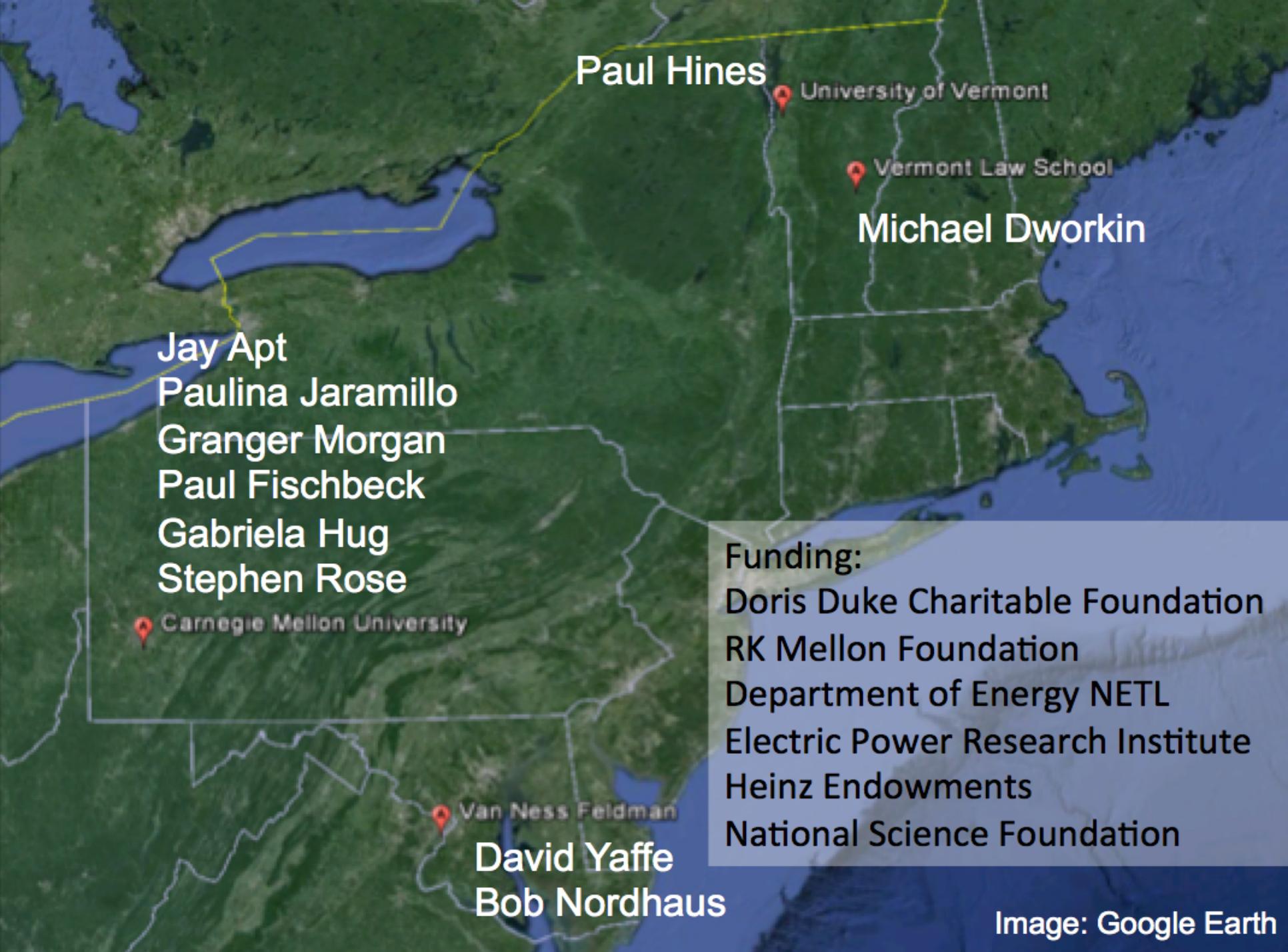
RenewElec Project Home

A majority of U.S. states have enacted legislation requiring that renewable electricity make up as much as 25% of electric generation. In contrast to most conventional sources of power, electricity produced from wind and solar, the two most abundant sources of renewable power, are both variable and intermittent: variable because the wind does not blow all the time and clouds sometimes cover the sun, and intermittent, because there is no sun at all during the night. Today wind contributes roughly one percent and solar about one one-hundredth of a percent of all U.S. electricity generated. Biomass availability is also intermittent.

Proponents of renewables argue that large amounts of variable and intermittent power can be easily accommodated in the present power system. Opponents argue that even levels as low as 10% of generation by variable and intermittent power can cause serious disruptions to power system operation.



The RenewElec book is now available. To get more information and to purchase your copy, visit the publisher's [website](#) or Amazon. You can also see Jay Apt discuss the results of the RenewElec project in this video.



Paul Hines

University of Vermont

Vermont Law School

Michael Dworkin

Jay Apt

Paulina Jaramillo

Granger Morgan

Paul Fischbeck

Gabriela Hug

Stephen Rose

Carnegie Mellon University

Van Ness Feldman

David Yaffe

Bob Nordhaus

Funding:

Doris Duke Charitable Foundation

RK Mellon Foundation

Department of Energy NETL

Electric Power Research Institute

Heinz Endowments

National Science Foundation

Image: Google Earth

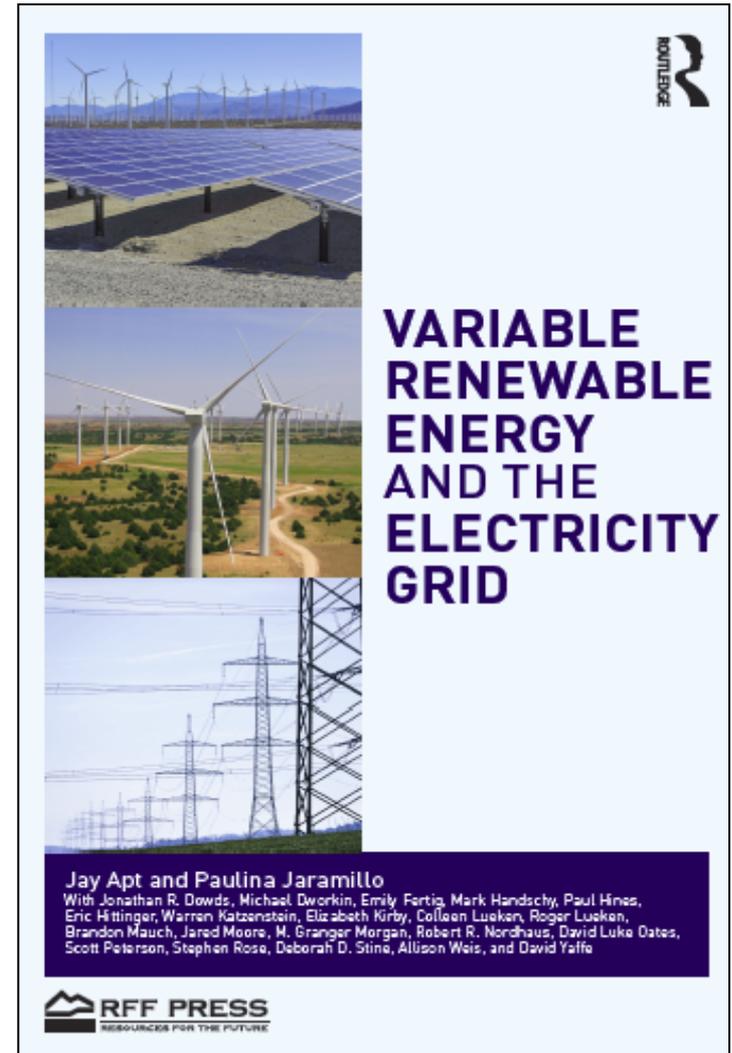
Project insights have been summarized in an RFF Press Book

Format:

A 16-page Executive Summary

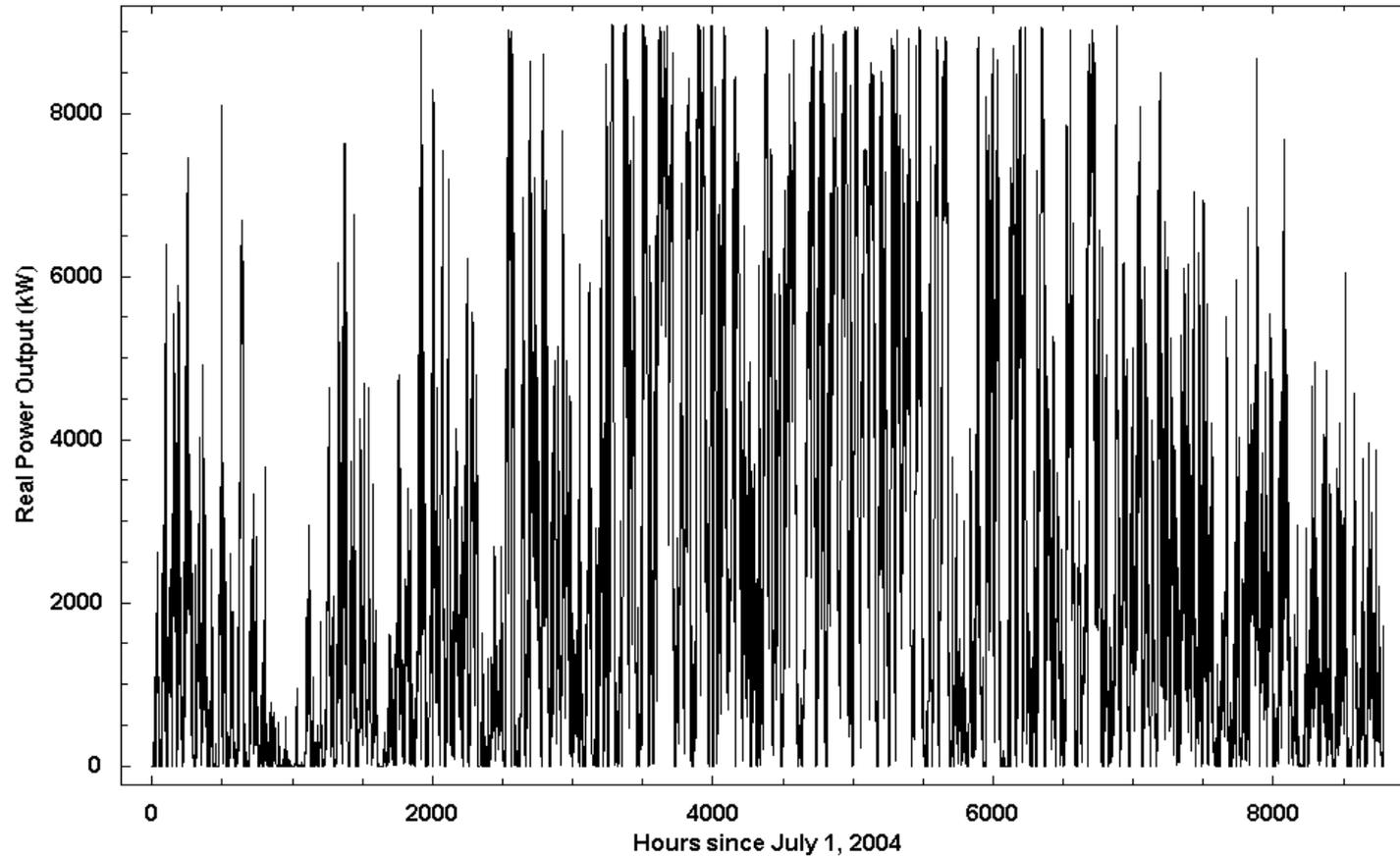
Chapters 1-6 are readable by a non-technical audience

Chapters 7-17 have enough technical information to allow implementation of the results by practitioners

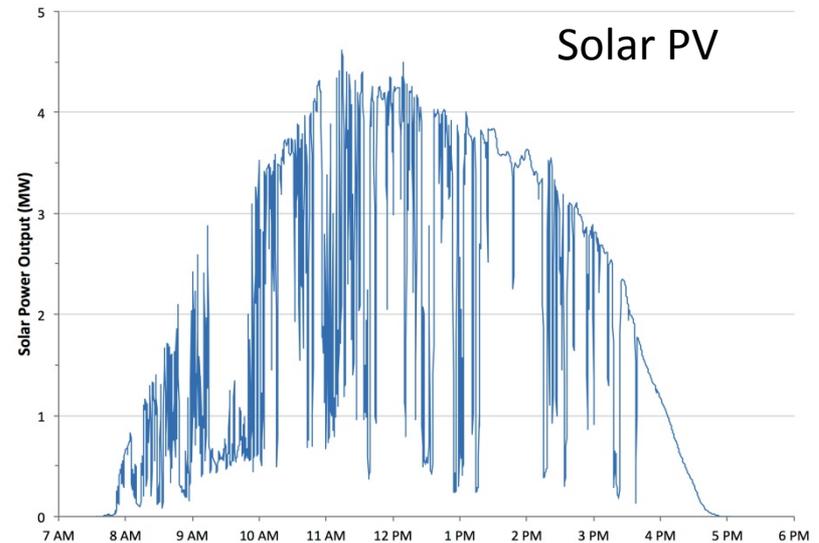
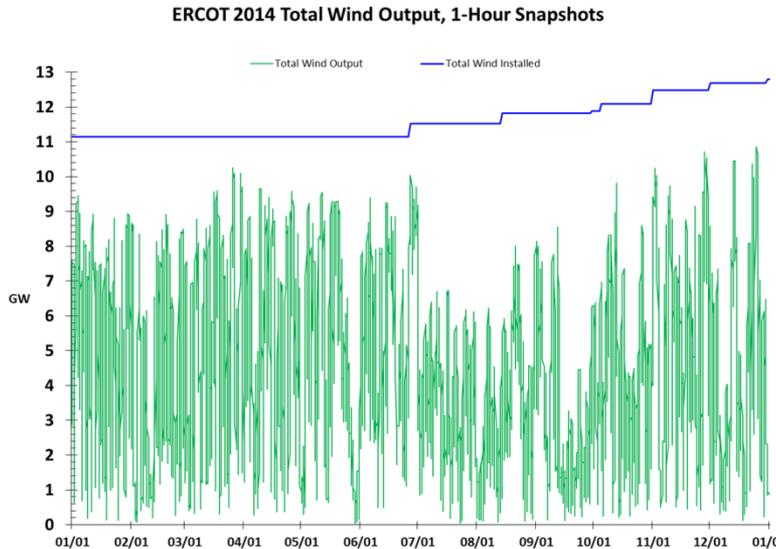


Wind and solar power is highly variable.

Here, for example, is a year's worth of output from an entire wind farm.



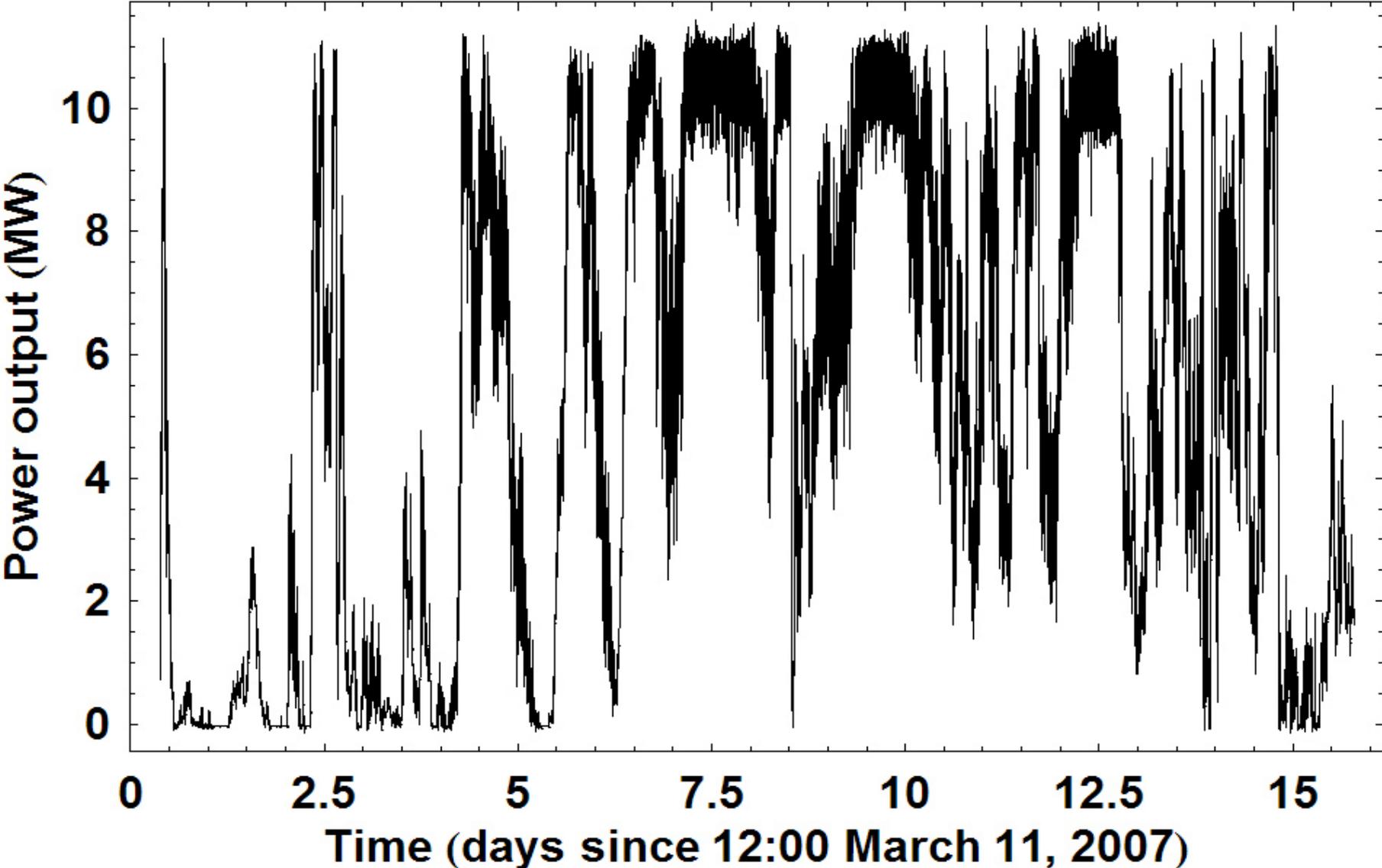
The variability from wind and solar is *not* white noise.



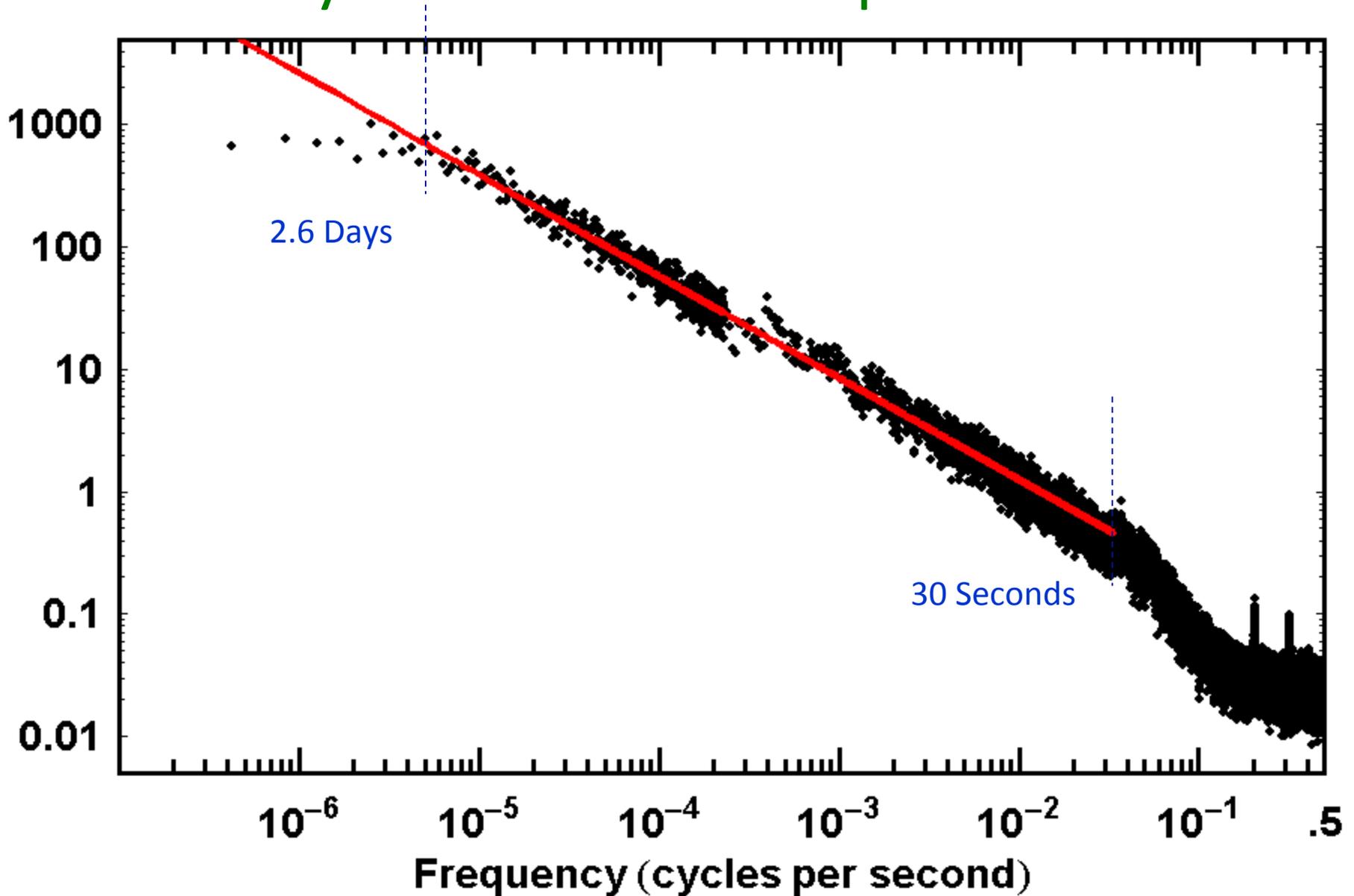
If it were, the grid would need a lot of very fast-adjusting power to compensate.

But, the fluctuations are 30 times larger at long periods than at short, so slow fossil fuel plants can compensate, and relatively few batteries or other storage is needed.

15 Days of 10-Second Time Resolution Wind Data

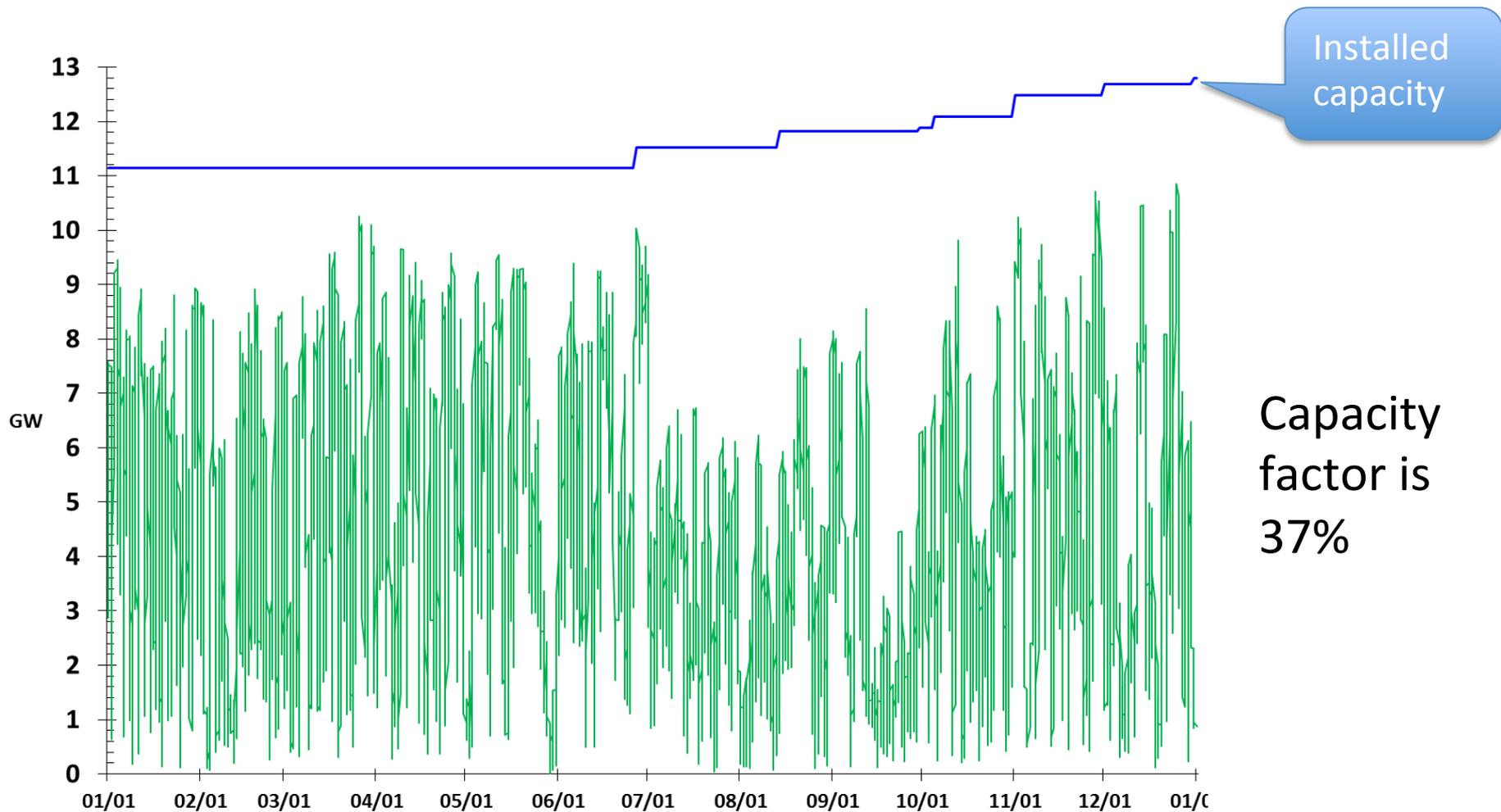


Performing a Fourier Transform yields this Power Spectrum



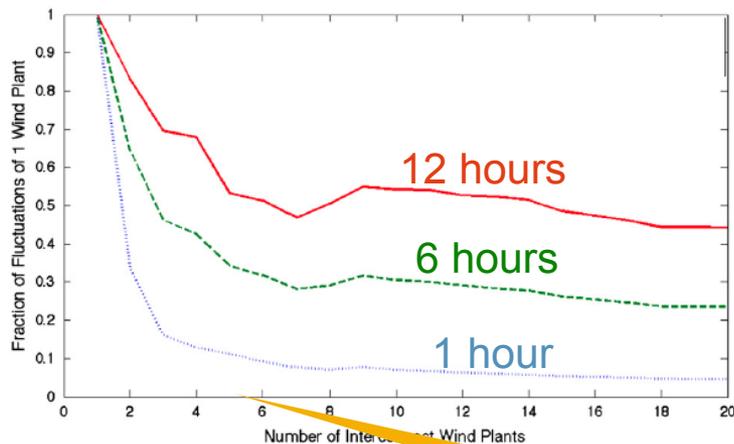
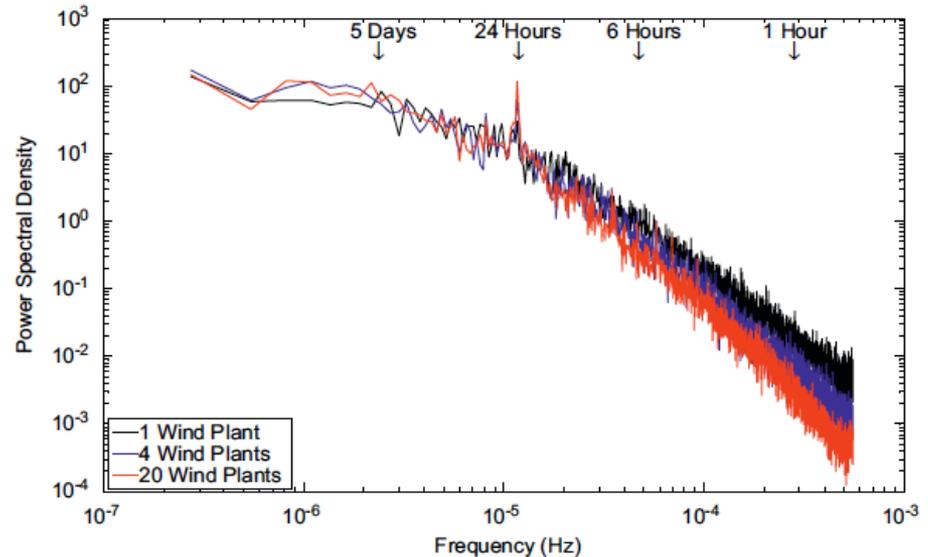
If we interconnect multiple
plants how much
smoothing can be gotten?

Hourly wind output for *all* of Texas in 2014



Texas results

The maximum reductions in variability occur at the higher frequencies and diminish as the frequencies decrease until at 24 hours there is no reduction in variability.

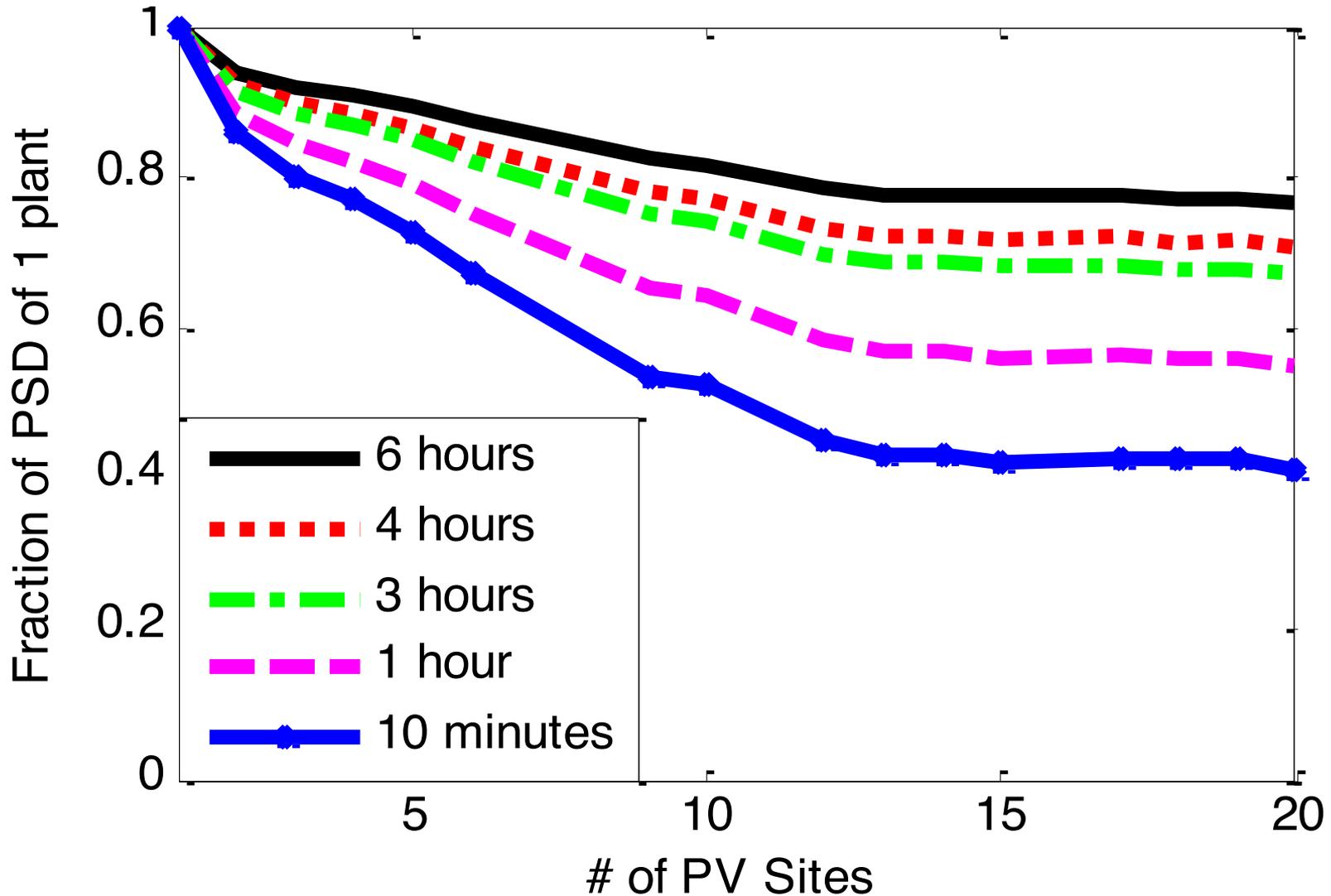


This figure shows the amount of reduction in variability achieved as a function of the number of interconnected wind farms for frequencies corresponding to 1, 6 and 12 hours.

Katzenstein, W., E. Fertig, and J. Apt,
The Variability of Interconnected Wind Plants.
Energy Policy, 2010. **38(8)**: 4400-4410.

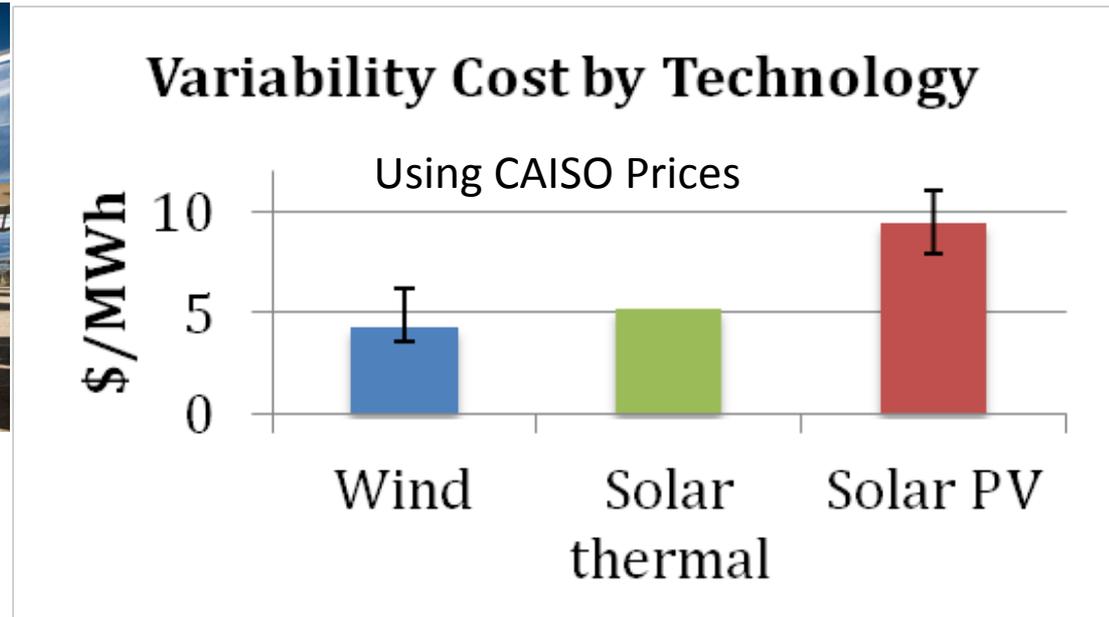
Note that after the first few wind farms are interconnected there is little additional reduction in the fluctuations.

MUCH less smoothing than for wind

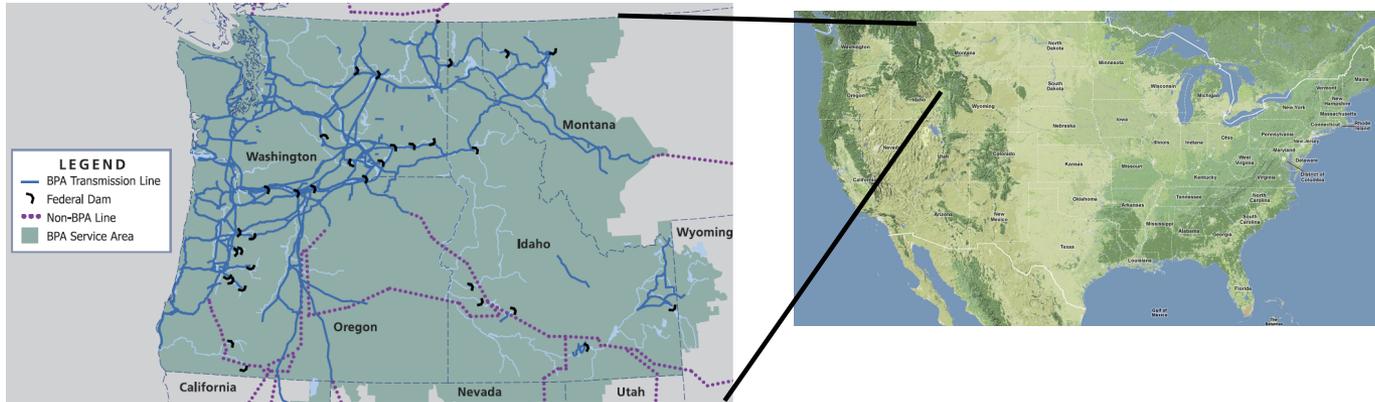


Wind and solar thermal are less expensive to integrate than PV

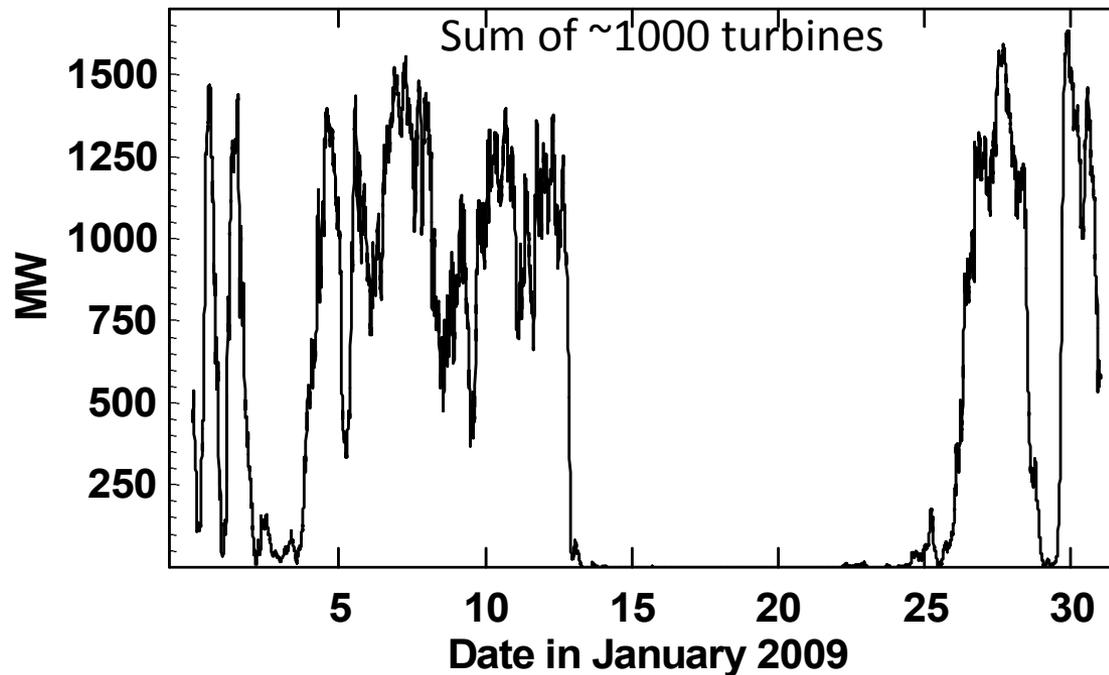
Concentrating solar thermal systems have much lower variability than do solar PV systems, and so compensating for their fluctuations is less expensive.



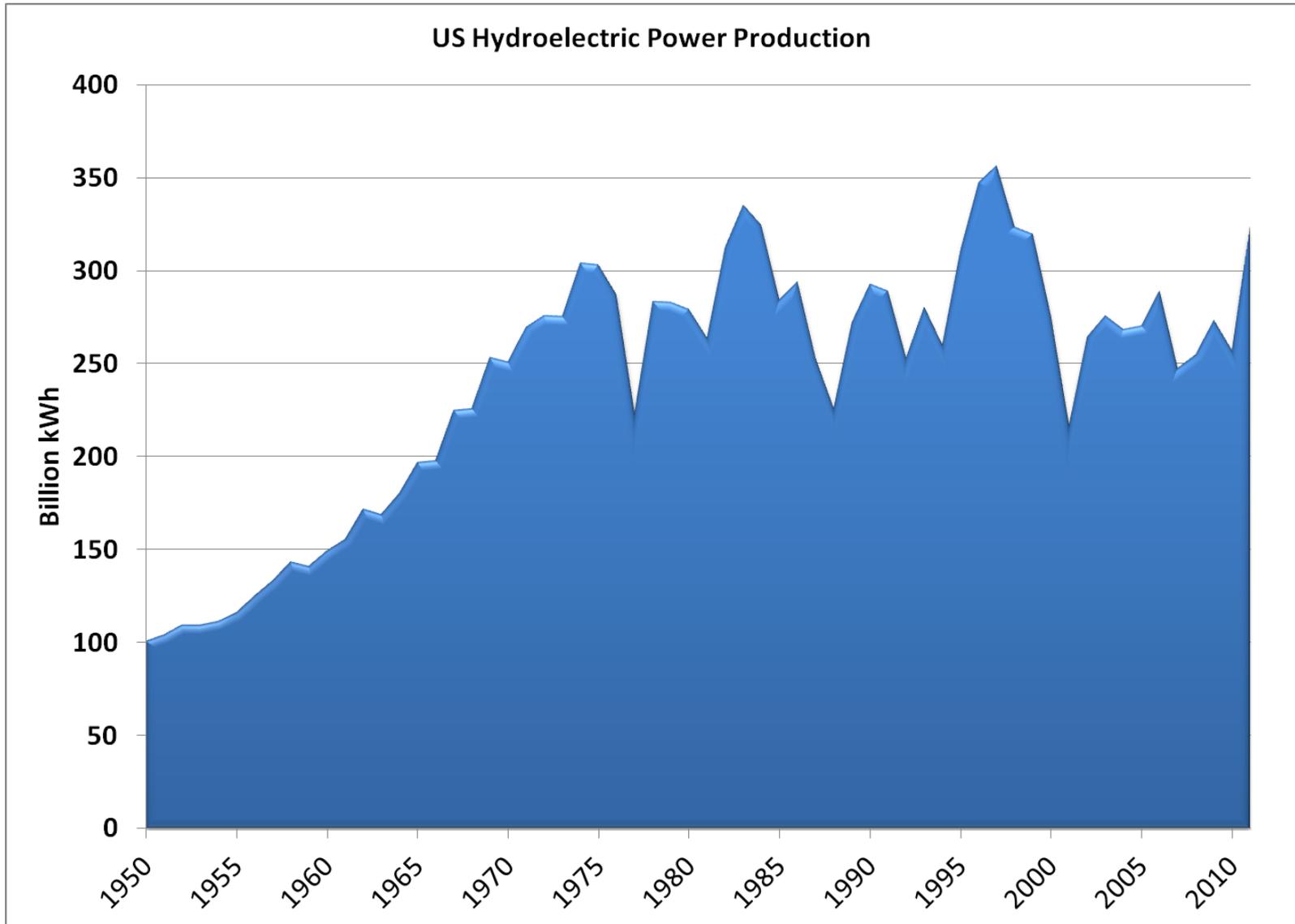
Wind occasionally fails for many days



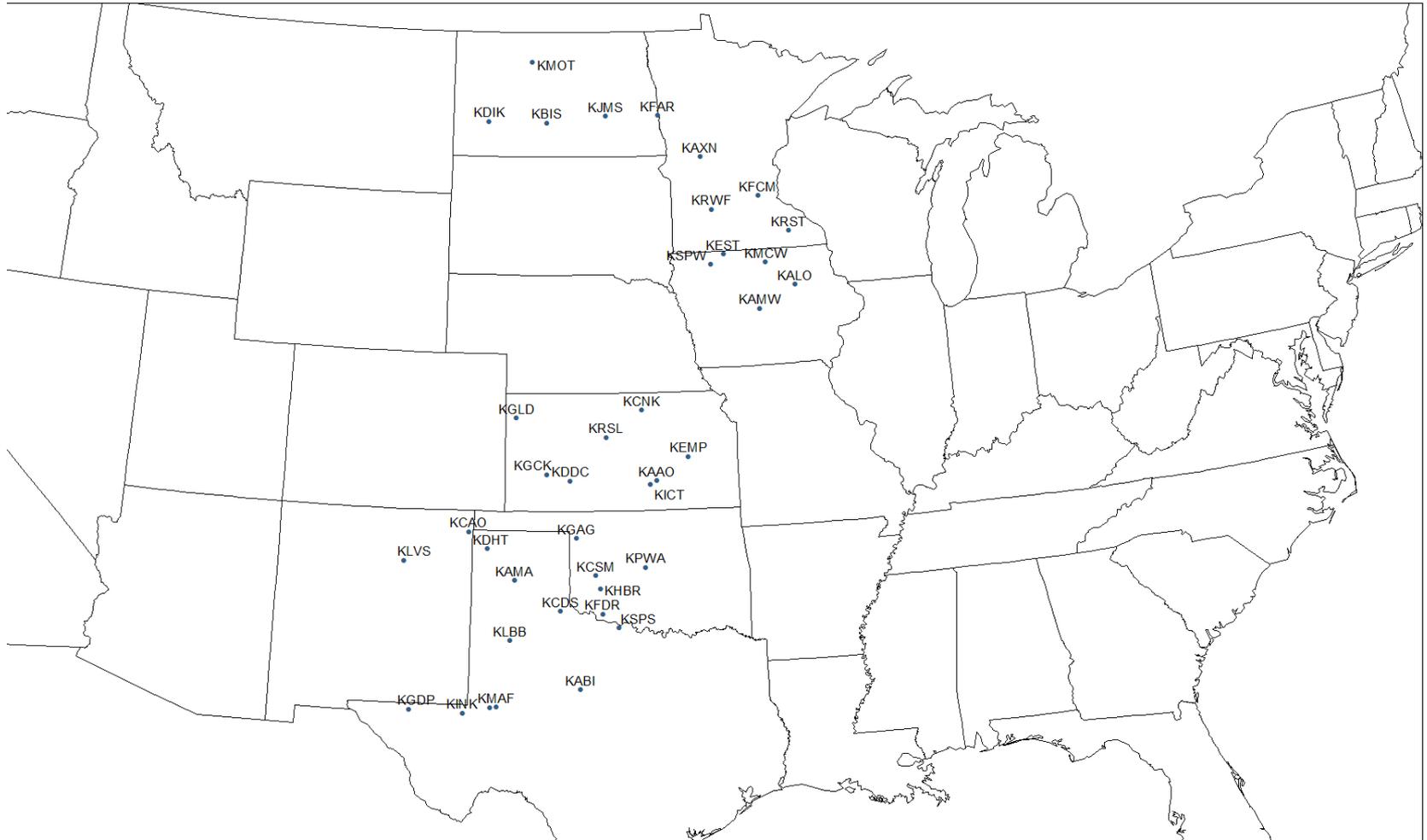
BPA Balancing Authority Total Wind Generation



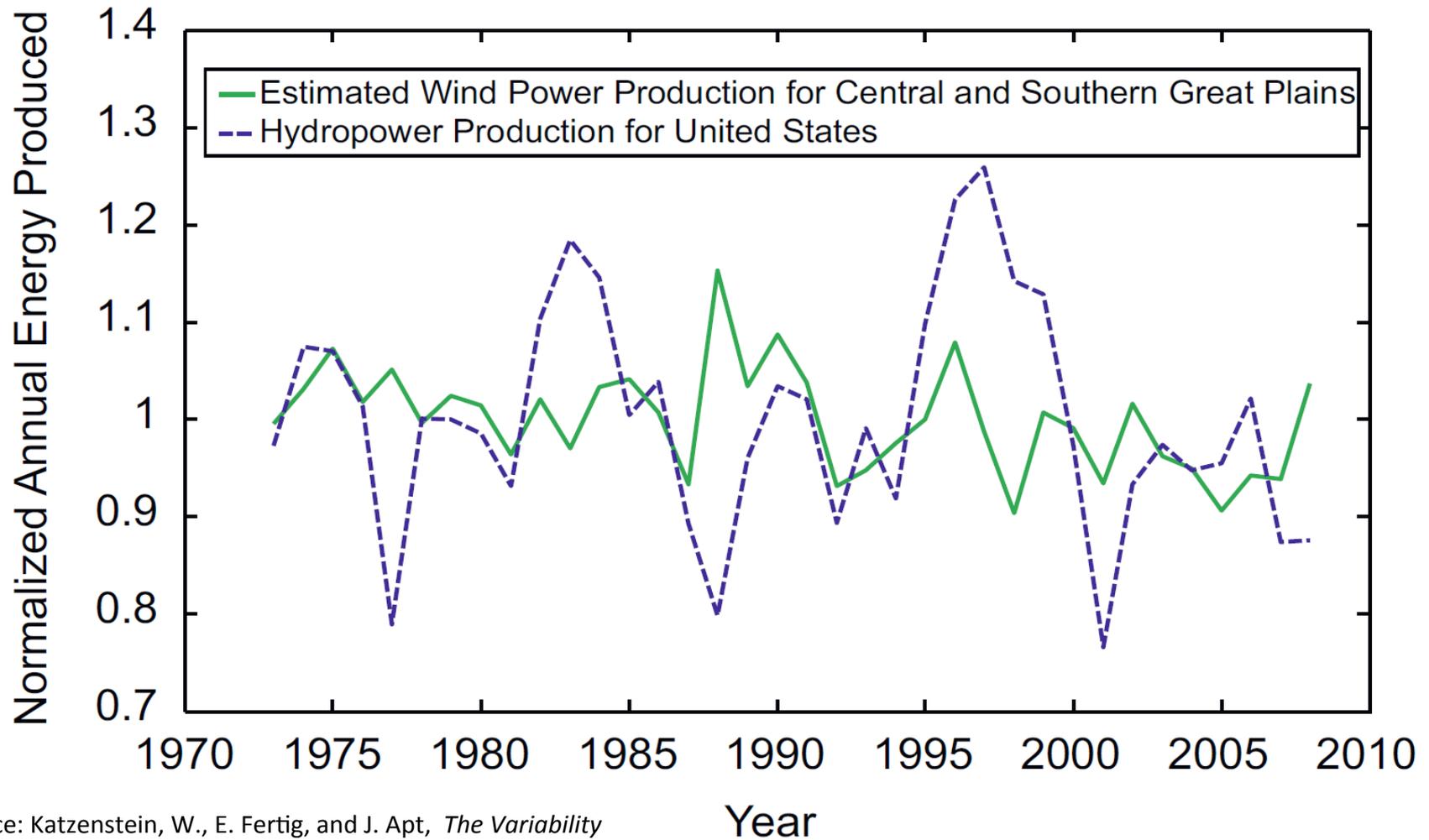
Hydroelectric Power has Droughts



Does wind power have droughts?



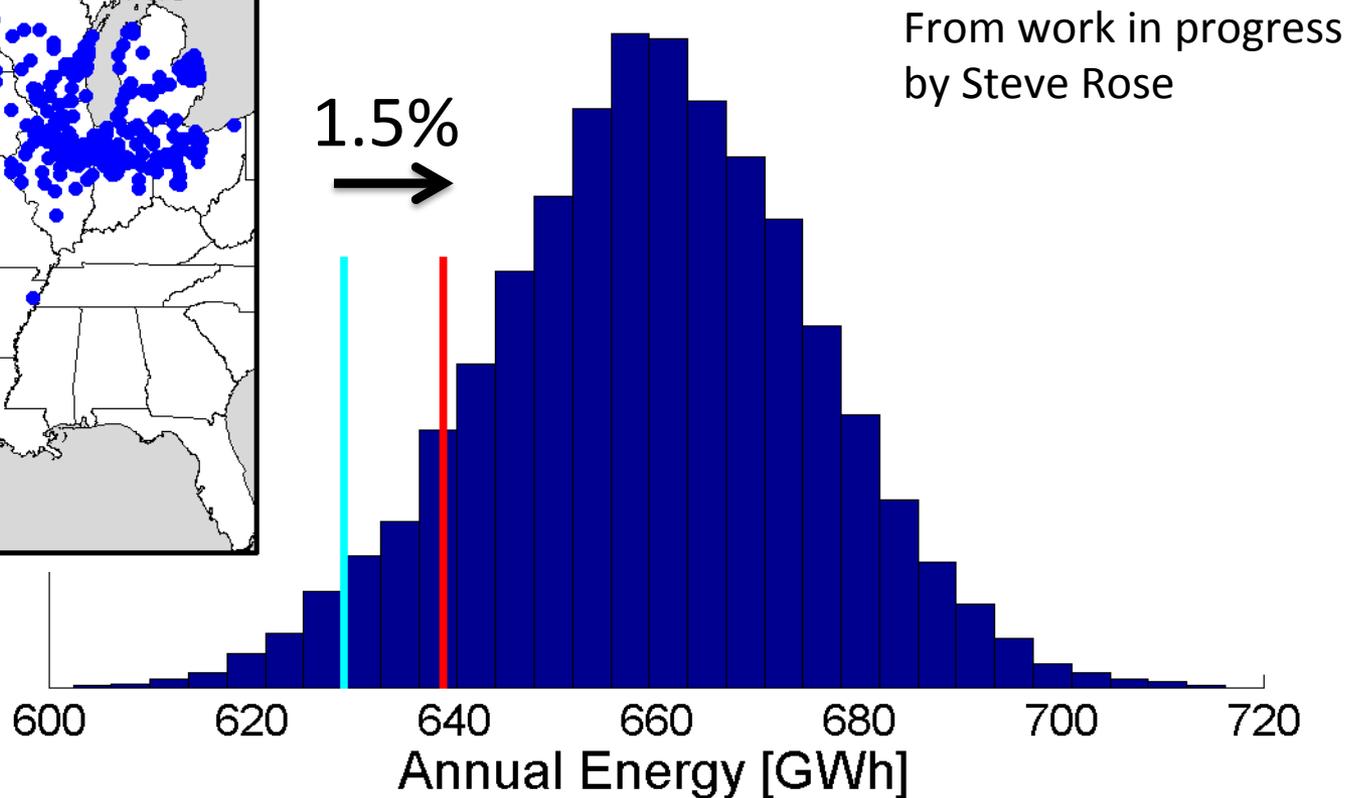
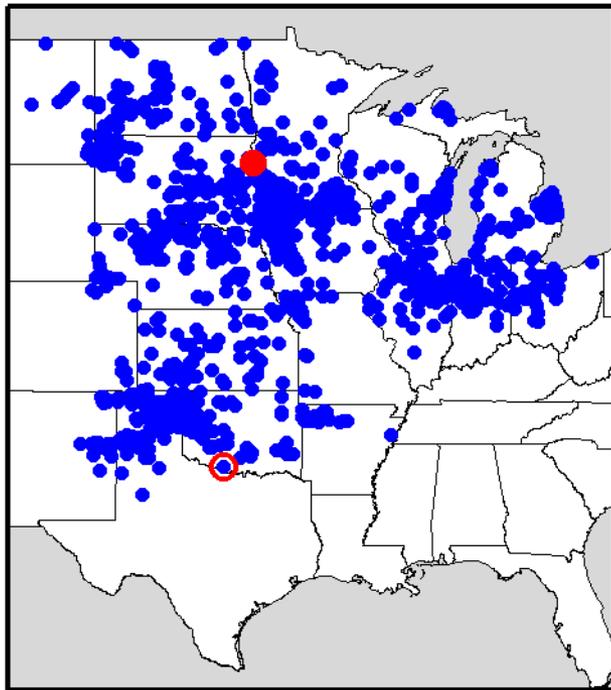
Answer looks to be yes... but probably more modest



Source: Katzenstein, W., E. Fertig, and J. Apt, *The Variability of Interconnected Wind Plants*. *Energy Policy*, 2010.

38(8)4400-4410

Diversify Portfolio By Finding Least-Correlated Site

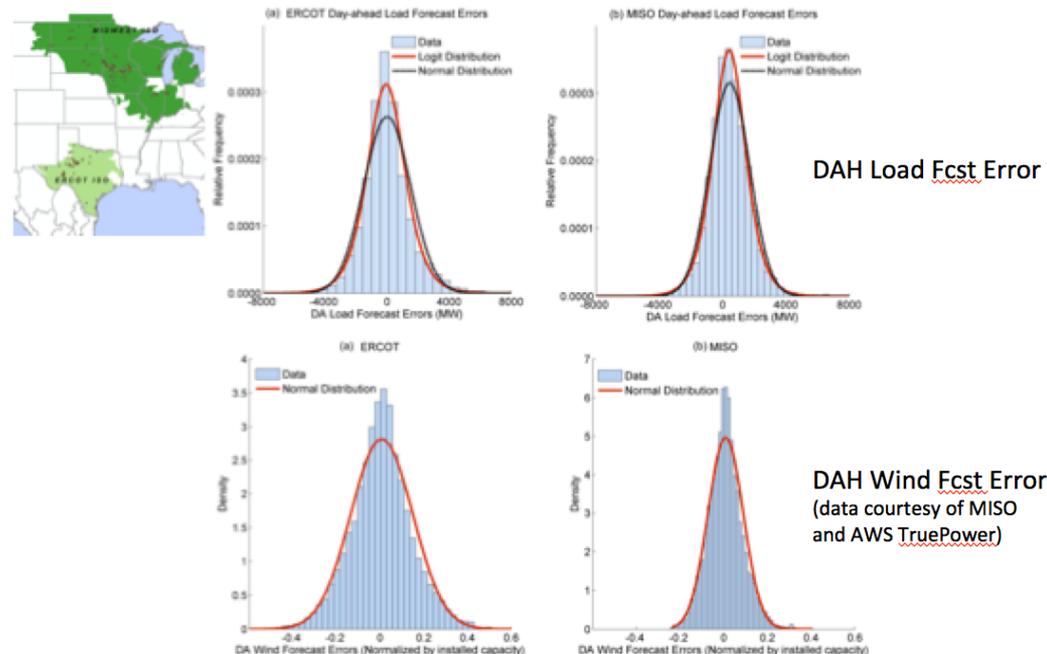
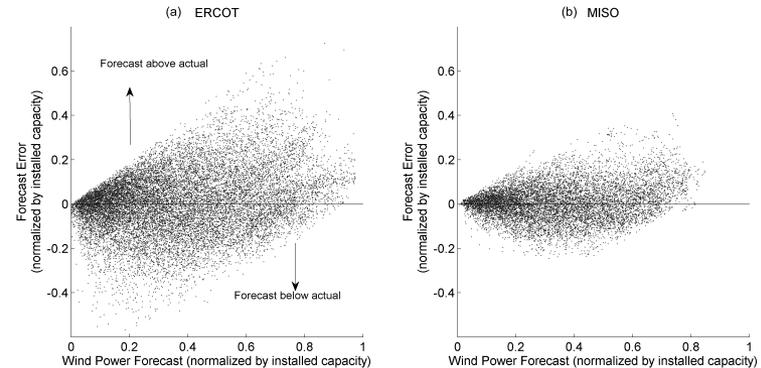


Other topics Jay and his students are studying now include

Errors in wind forecasts

Size of needed reserves

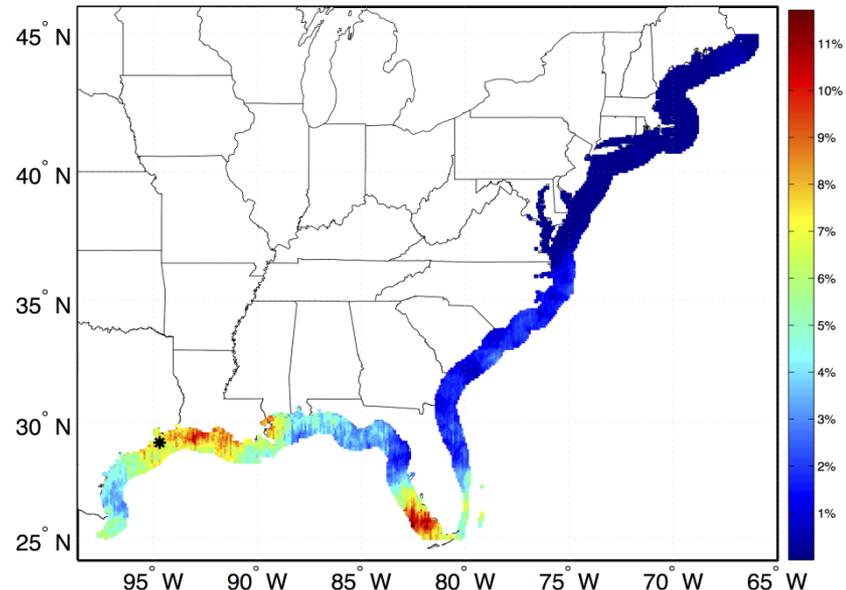
Requiring dynamic limiting of wind turbine output



Hurricane Risk to Offshore Wind

Hurricanes pose surmountable risks to offshore wind turbines.

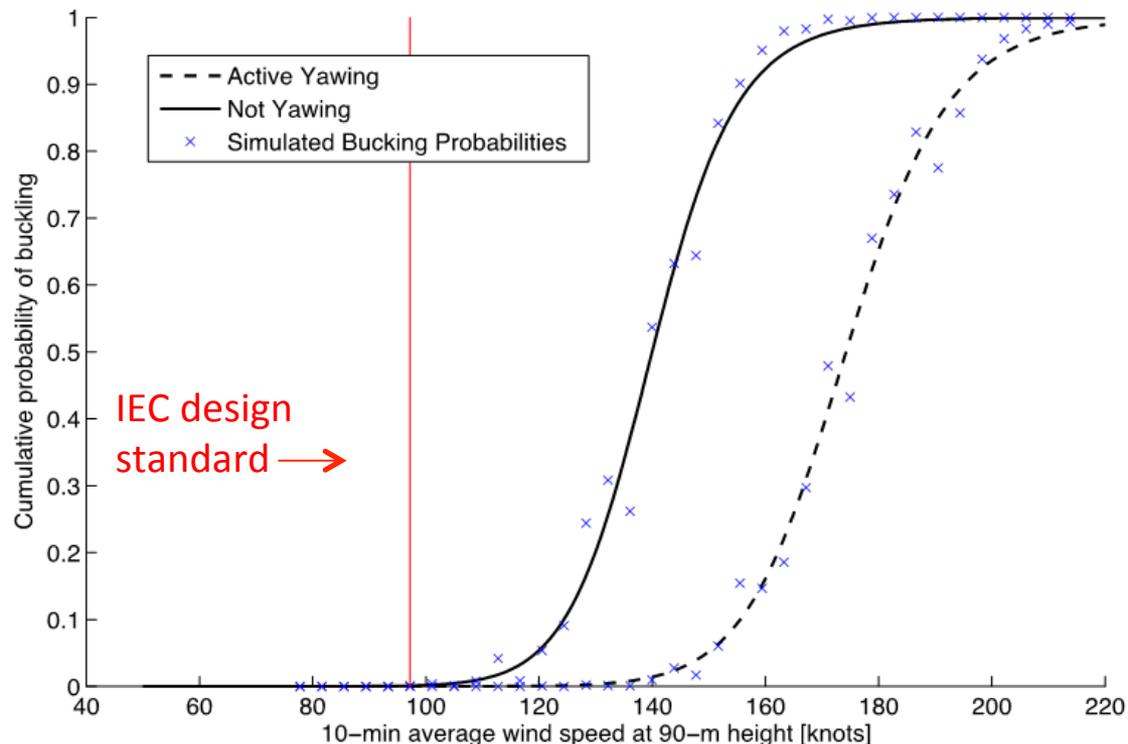
- Small changes, such as having emergency power to turn the nacelle into the wind, can dramatically improve the survivability.
- We quantified the riskier and safer areas to build.



Hurricane Risk to Offshore Wind

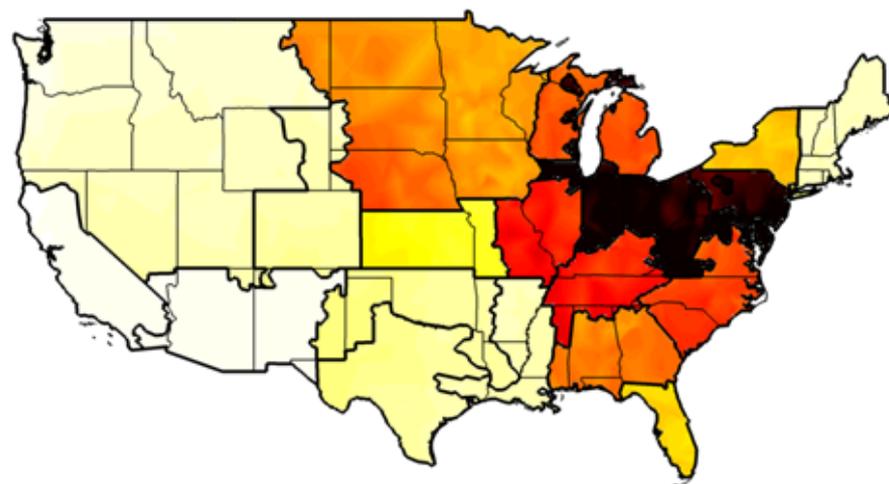
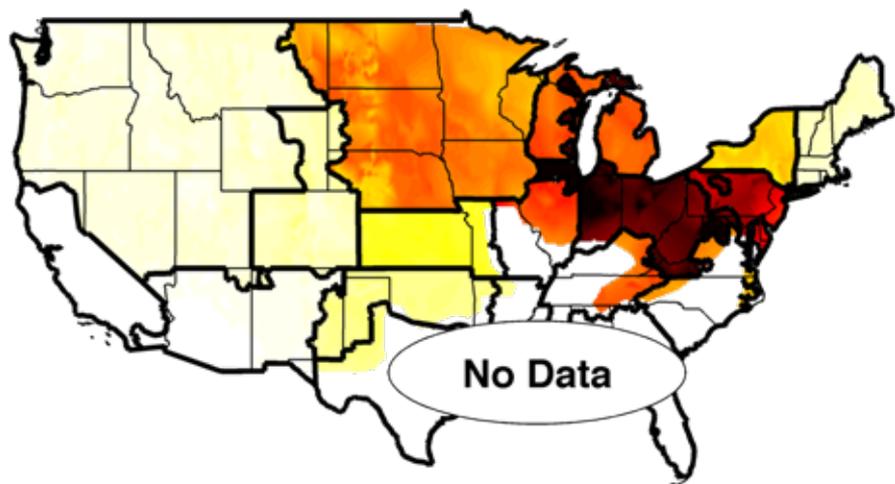
Small changes, such as having emergency power to turn the nacelle into the wind, can dramatically improve the survivability.

Rose, S., P. Jaramillo, M. Small, and J. Apt, *Quantifying the Hurricane Catastrophic Risk to Offshore Wind Power*. Risk Analysis, 2013. **33**(12): 2126-2141.



Where should wind & solar be sited?

If the goal is reducing pollution, it is MUCH better to locate wind and solar in the mid-Atlantic states than in the southwest.



Wind: Annual Health & Environmental Benefits
From Displaced SO_2 , NO_x , and $\text{PM}_{2.5}$
(\$ per kW installed)

Solar: Annual Health & Environmental Benefits
From Displaced SO_2 , NO_x , and $\text{PM}_{2.5}$
(\$ per kW installed)

Siler-Evans, K., I.L. Azevedo, M.G. Morgan, and J. Apt, *Regional Variations in the Health, Environmental, and Climate Benefits of Wind and Solar Generation*. PNAS, 2013. **110**(29): 11768-11773.

Plan for the day

- 08:30 – 09:15 Overview of >25 years of HDGC, CDMC and CEDM – Granger Morgan
- 09:15 – 10:00 Uncertainty in energy efficiency, Part 1: technologies, strategies, behavior and policy – Inês Azevedo
- 10:00 – 10:30 Uncertainty in energy efficiency, Part 2: technologies, strategies, behavior and policy – Alex Davis
- 10:45 – 11:15 **Coffee break**
- 11:15 – 11:45 Decision support for implementing the EPA Clean Power Plan Proposed Rule – Jeff Anderson
- 11:45 – 12:30 Marginal emissions factors, health and climate change co-benefits and trade-offs - Inês Azevedo
- 12:30 – 13:30 **Lunch break**
- 13:30 – 13:55 Insights from twenty years of work on expert elicitation and projections – Granger Morgan
- 13:55 – 14:05 Transitioning to a low carbon economy, Part 1: Insights from the RenewElec Project – Granger Morgan
- 14:05 – 14:30 Transitioning to a low carbon economy, Part 2: Insights from ITC and BC's Climate Policy – Hadi Dowlatabadi
- 14:30 – 15:10 Strategies for supporting investment decisions about large energy infrastructure in the face of regulatory and other uncertainty – Dalia Patiño
- 15:10 – 15:40 **Coffee break**
- 15:40 – 16:00 Reflections on Research and Governance wrt Albedo Modification – Granger Morgan
- 16:00 – 16:45 Insights From Our Experience in Building and Using ICAMs – Hadi Dowlatabadi
- 17:45 – 17:00 Muddling through on climate policy: good, but not good enough to avoid the risk of dead ends – Granger Morgan
- 17:00 – 17:30 Discussion and round table on what investigators in CEDM might best work on in the next several years to be most useful to the IA and energy modeling communities.