What May Emerge as Renewables Become Large Scale?

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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. This gap has not been bridged, in part because the level of advocacy required to enact renewables requirements has not been compatible with rigorous systems analysis.

A *much-expanded* role for variable and intermittent renewables is possible. But it will only happen if we adopt a systems approach that considers and anticipates the many changes in power system design and operation, while doing so at an affordable price, and with acceptable levels of security and reliability. There is a considerable risk that if we do not do the necessary planning, and develop the necessary new policy

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Updates

[5/7] RenewElec launches public website.

News Headlines

GOP fights funding for vital Nevada renewable projects - Las Vegas Sun
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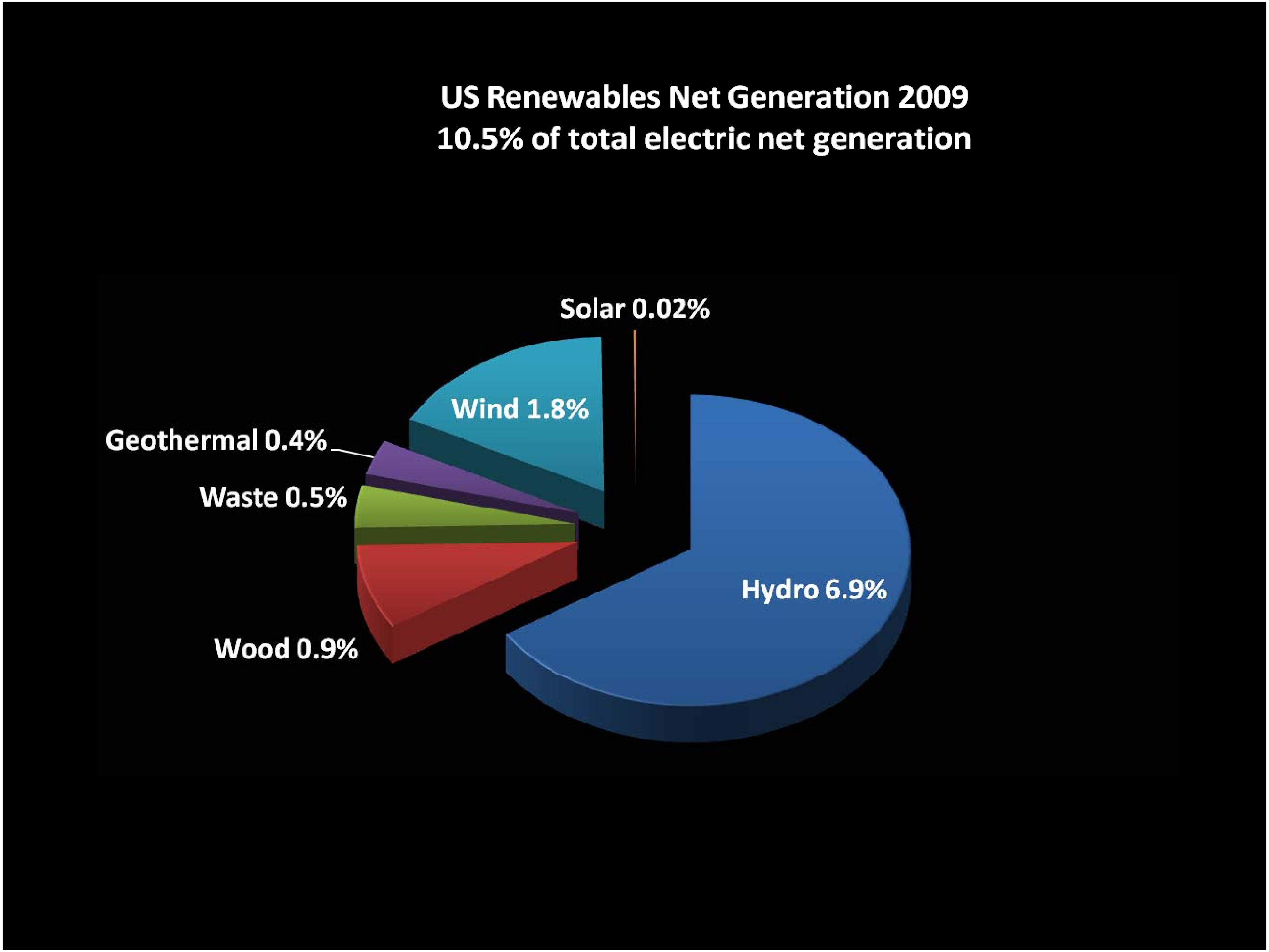
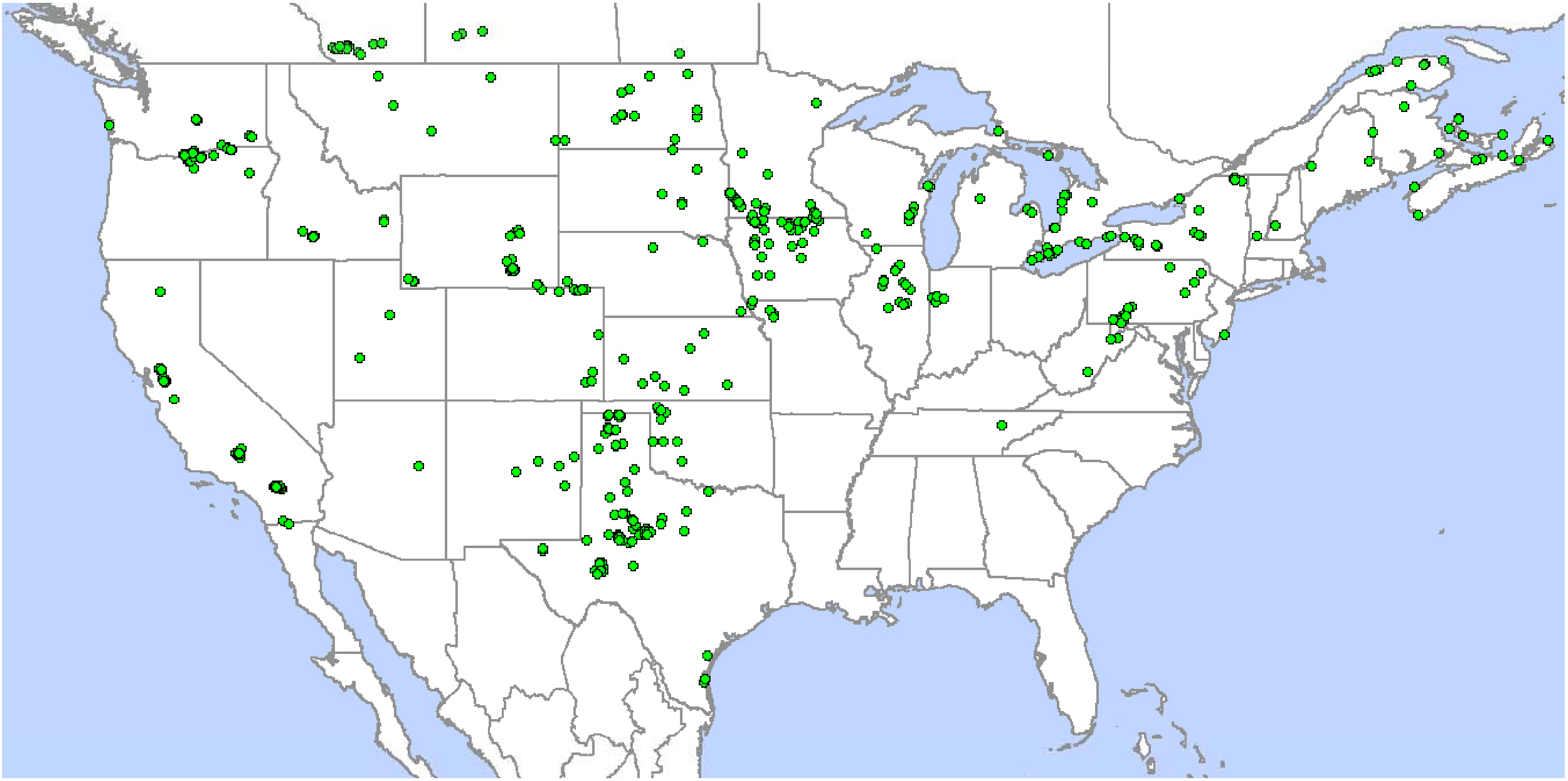
www.RenewElec.org


US Renewables Net Generation 2009
10.5% of total electric net generation
Solar 0.02%
Wind 1.8%
Geothermal 0.4%
Waste 0.5%
Wood 0.9%
Hydro 6.9%

Operating Wind Farms February 21, 2011

Wind farms > 5 MW



Does wind power have atmospheric risks?

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, D19101

Can large wind farms affect local meteorology?

S. Baidya Roy and S. W. Pacala
Department of Ecology and Evolutionary Biology, Princeton University, Princeton, New Jersey, USA

R. L. Walko
Department of Civil Engineering, Duke University, Durham, North Carolina, USA

Received 11 March 2004; revised 9 July 2004; accepted 20 July 2004; published 1 October 2004.

"…the wind farm significantly slows down the wind… usually leading to a warming and drying of the surface air…"

The influence of large-scale wind power on global climate

David W. Keith*†, Joseph F. DeCarolis‡, David C. Denkenberger§, Donald H. Lenschow¶, Sergey L. Malyshev‖, Stephen Pacala‖, and Philip J. Rasch¶

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Communicated by Stephen H. Schneider, Stanford University, Stanford, CA, September 19, 2004 (received for review April 16, 2004)

Large-scale use of wind power can alter local and global climate by extracting kinetic energy and altering turbulent transport in the atmospheric boundary layer. We report climate-model simulations that address the possible climatic impacts of wind power at regional to global scales by using two general circulation models and several parameterizations of the interaction of wind turbines with the boundary layer. We find that very large amounts of wind power can produce nonnegligible climatic change at continental scales. Although large-scale effects are observed, wind power has a negligible effect on global-mean surface temperature, and it would deliver enormous global benefits by reducing emissions of CO_2 and air pollutants. Our results may enable a comparison between the climate impacts due to wind power and the reduction in climatic impacts achieved by the substitution of wind for fossil fuels.

Global wind-power capacity is growing by ≈8 GW·yr^{-1}, making wind the fastest growing nonfossil source of primary energy (1). The cost of electricity from wind power is now ≈40 dollars per

experiment, the drag coefficients were perturbed uniformly over an area defined by one of three wind-farm arrays, denoted A, B, and C (outlined in black in Figs. 1, 5*A*, and 5*B*, respectively). The reason for choosing these arrays is discussed below.

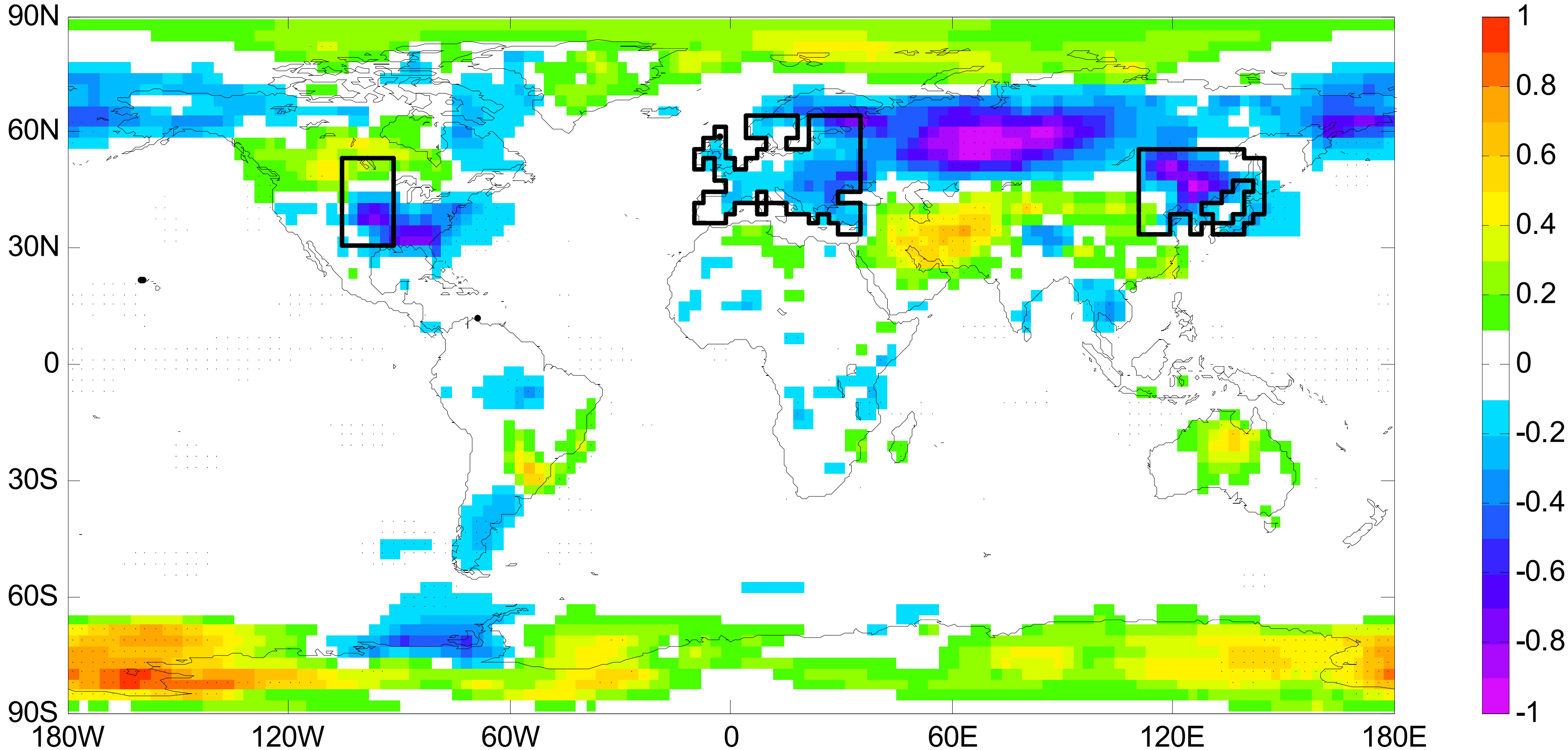
We used two methods to parameterize the additional drag due to the turbines. The first method was a modification of the roughness length, z_0. In the boundary-layer parameterizations of the models (6, 7), z_0 determines the drag coefficient C_D, and ultimately, the surface fluxes through the following:

$$C_D = f(Ri)\frac{k^2}{\ln(z_1/z_0)^2}, \qquad [1]$$

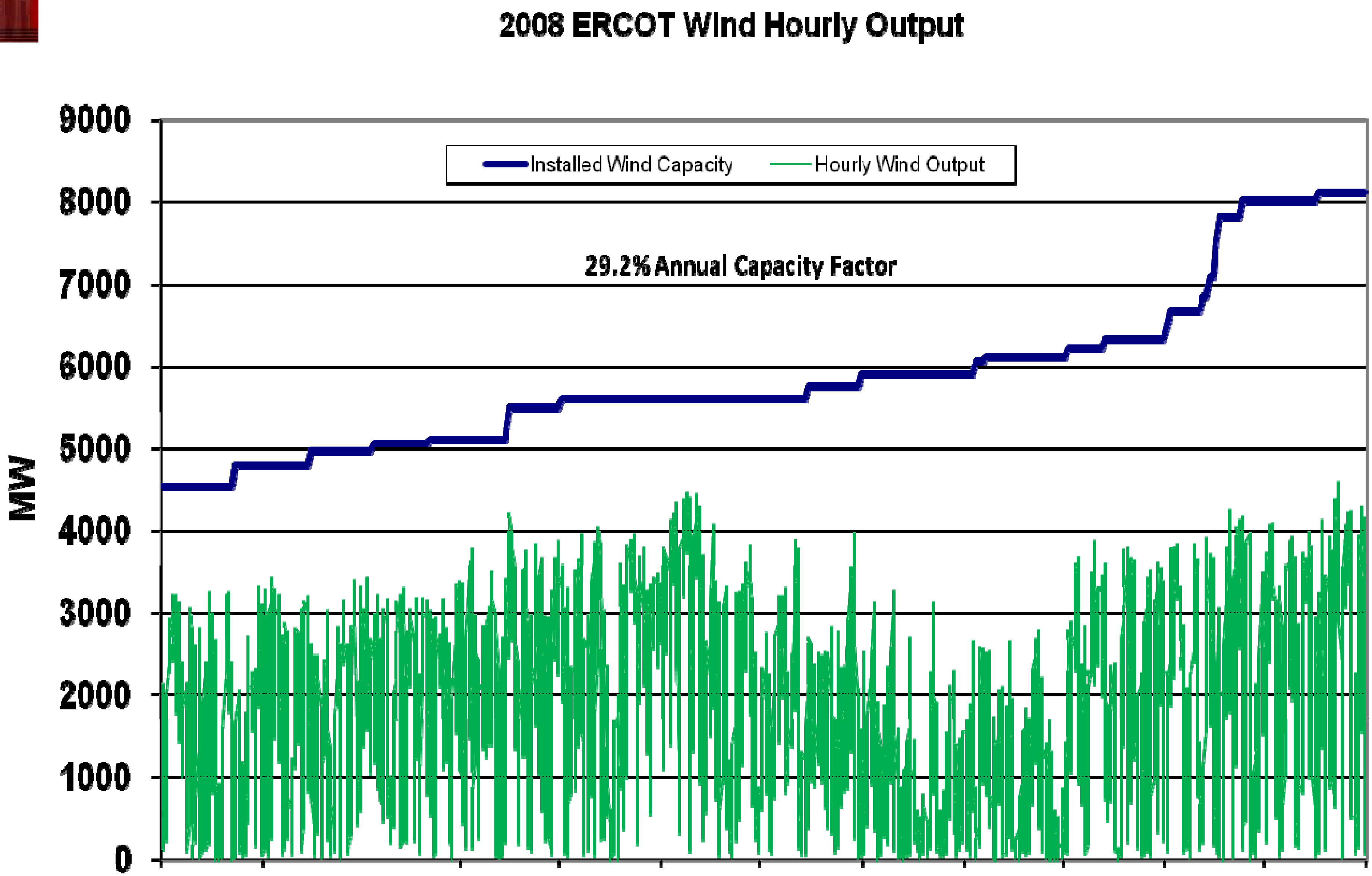
where z_1 is the height of the first-layer midpoint, $k = 0.4$ is the von Karman constant, and f is function that modifies C_D because of the influence of buoyancy on shear-driven turbulent mixing, which is parameterized by the Richardson number Ri. To simulate the effect of a uniform increase in drag, δC_D, we

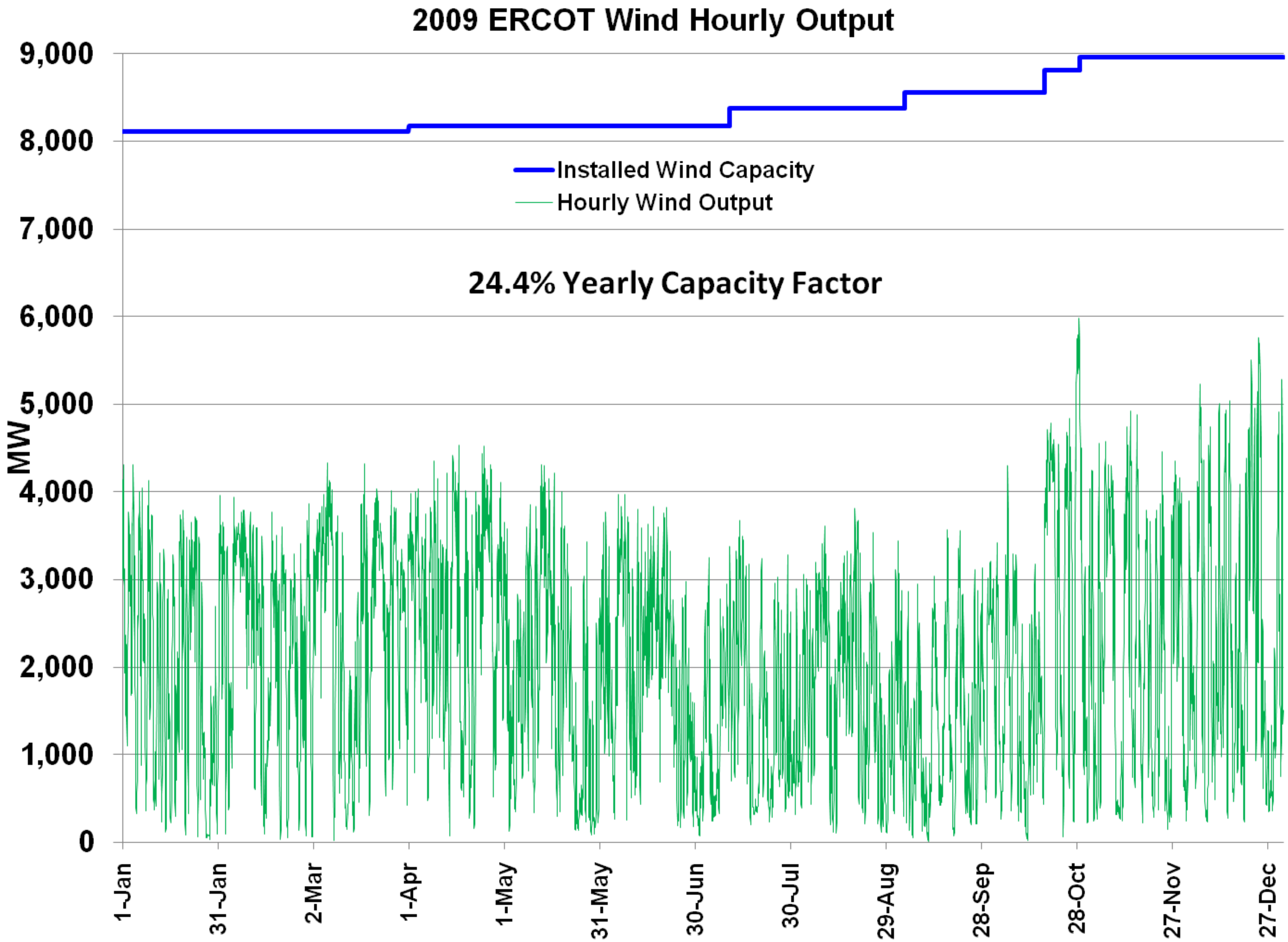
Models show wind causes temperature changes ~ 1°C

Annual surface temperature response (GFDL model)

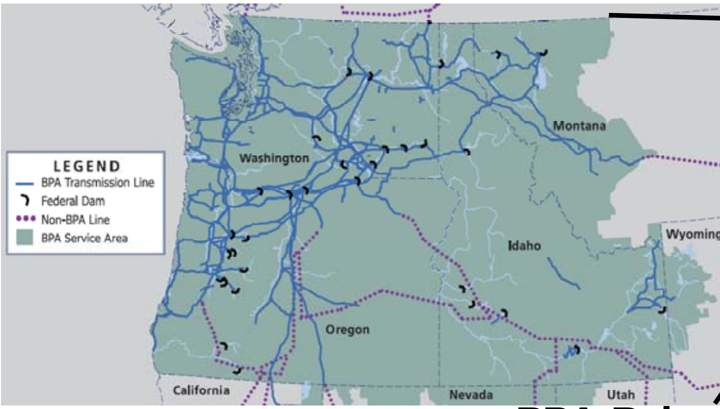


Surface (2 m) air temperature response. Drag perturbation of 0.005. Showing 20 yr of perturbed run versus 20 years of control.

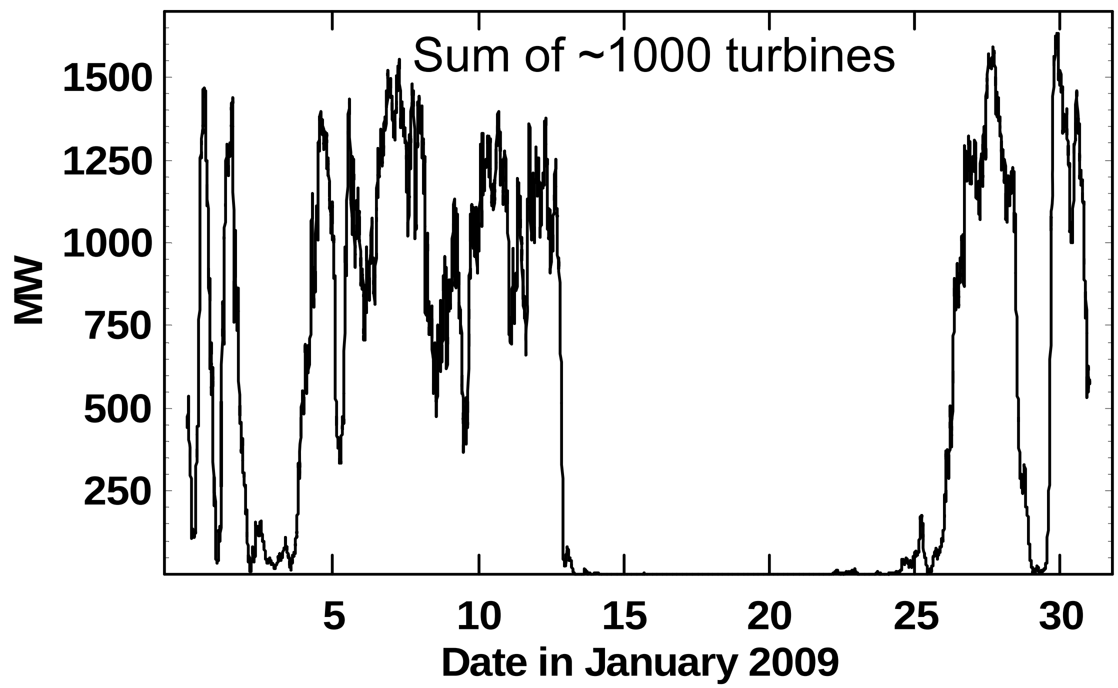

2008 ERCOT Wind Hourly Output
Installed Wind Capacity
Hourly Wind Output
29.2% Annual Capacity Factor
MW
9000
8000
7000
6000
5000
4000
3000
2000
1000
0


2009 ERCOT Wind Hourly Output
MW
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Installed Wind Capacity
Hourly Wind Output
24.4% Yearly Capacity Factor
1-Jan
31-Jan
2-Mar
1-Apr
1-May
31-May
30-Jun
30-Jul
29-Aug
28-Sep
28-Oct
27-Nov
27-Dec

Wind sometimes fails for many days



BPA Balancing Authority Total Wind Generation



[CEC:2010] R. Masiello, K. Vu, L. Deng, A. Abrams, K. Corfee, J. Harrison, D. Hawkins, and K. Yagnik, "Research evaluation of wind generation, solar generation, and storage impact on the California grid," tech. rep., Public Interest Energy Research (PIER), California Energy Commission, 2010.

[CEER:2009] Council of European Energy Regulators (CEER), "Regulatory aspects of the integration of wind generation in European electricity markets." 2009.

[DOE:2008] "20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply," tech. rep., US Dept. of Energy, 2008.

[Doherty:2005] R. Doherty and M. O'Malley, "A new approach to quantify reserve demand in systems with significant installed wind capacity," IEEE Transactions on Power Systems, vol. 20, no. 2, pp. 587–595, 2005.

[ERCOT:2008] "ERCOT Wind Impact / Integration Analysis," tech. rep., GE Energy Consulting, 2008.

[EWIS:2010] EWIS, "European wind integration study (EWIS): Towards a successful integration of large scale wind power into European electricity grids," tech. rep., European Wind Integration Study, 2010.

[EWIS:2010] Wilhelm Winter, ed., "Towards A Successful Integration of Large Scale Wind Power into European Electricity Grids," tech. rep., European Wind Integration Study, 2010.

[MacCormack:2010] J. MacCormack, A. Hollis, H. Zareipour, and W. Rosehart, "The large-scale integration of wind generation: Impacts on price, reliability and dispatchable conventional suppliers," Energy Policy, vol. 38, pp. 3837–3846, 2010.

[MN:2006] R. Zavadil, "Final Report - 2006 Minnesota Wind Integration Study: Volume I," tech. rep., EnerNex Corporation, 2006.

[NREL:2010] D. Corbus, "Eastern wind integration and transmission study," tech. rep., National Renewable Energy Laboratory/EnerNex, 2010.

[NYSERDA:2005] John Saintcross, ed. "The Effects of Integrating Wind Power on Transmission System Planning, Reliability, and Operations, Report on Phase 2: System Performance Evaluation." New York State Energy Research and Development Authority.

[SPP:2010] T. B. Tsuchida, P. A. Ruiz, A. Rudkevich, P. W. Sauer, G. G. Lorenzón, R. Yeu, R. Baxter, J. Cooper, D. Cross-Call, S. L. Englander, and J. Goldis, "SPP WITF Wind Integration Study," tech. rep., Charles River Associates, 2010.

[Strbac:2007] G. Strbac, A. Shakoor, M. Black, D. Pudjianto, and T. Bopp, "Impact of wind generation on the operation and development of the UK electricity systems," Electric Power Systems Research, pp. 1214–1227, 2007.

[CEC:2010] R. Masiello, K. Vu, L. Deng, A. Abrams, K. Corfee, J. Harrison, D. Hawkins, and K. Yagnik, "Research evaluation of wind generation, solar generation, and storage impact on the California grid," tech. rep., Public Interest Energy Research (PIER), California Energy Commission, 2010.

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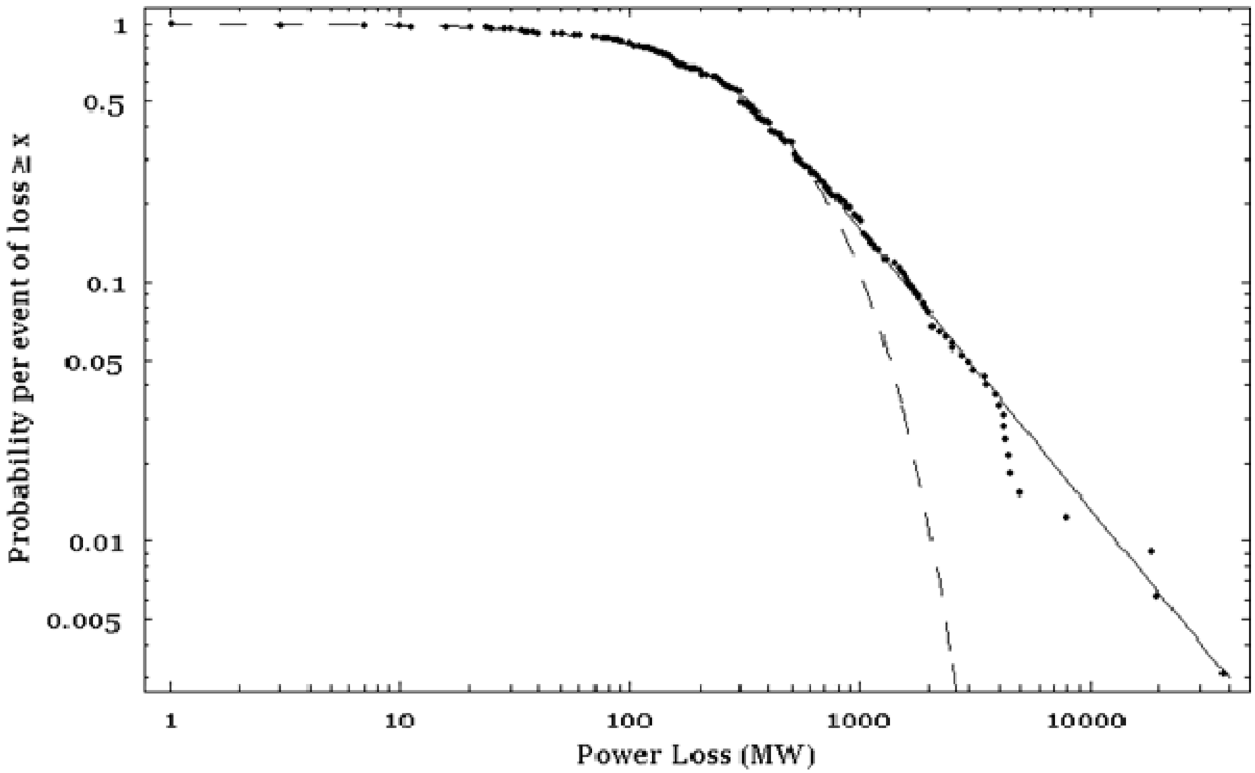
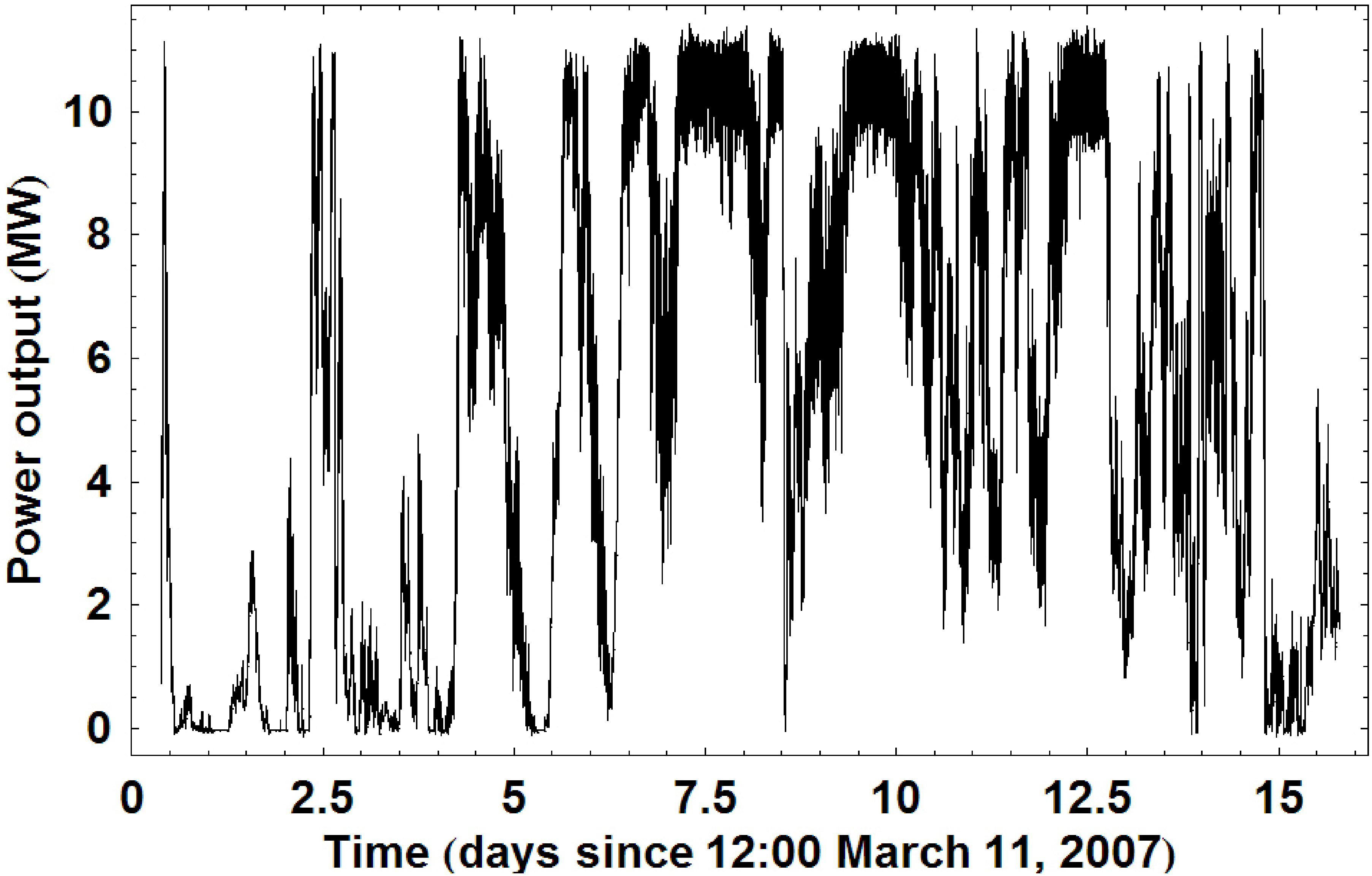
[Doherty:2005] R. Doherty and M. O'Malley, "A new approach to quantify reserve demand in systems with significant installed wind capacity," IEEE Transactions on Power Systems, vol. 20, no. 2, pp. 587–595, 2005.

[ERCOT:2008] "ERCOT Wind Impact / Integration Analysis," tech. rep., GE Energy Consulting, 2008.

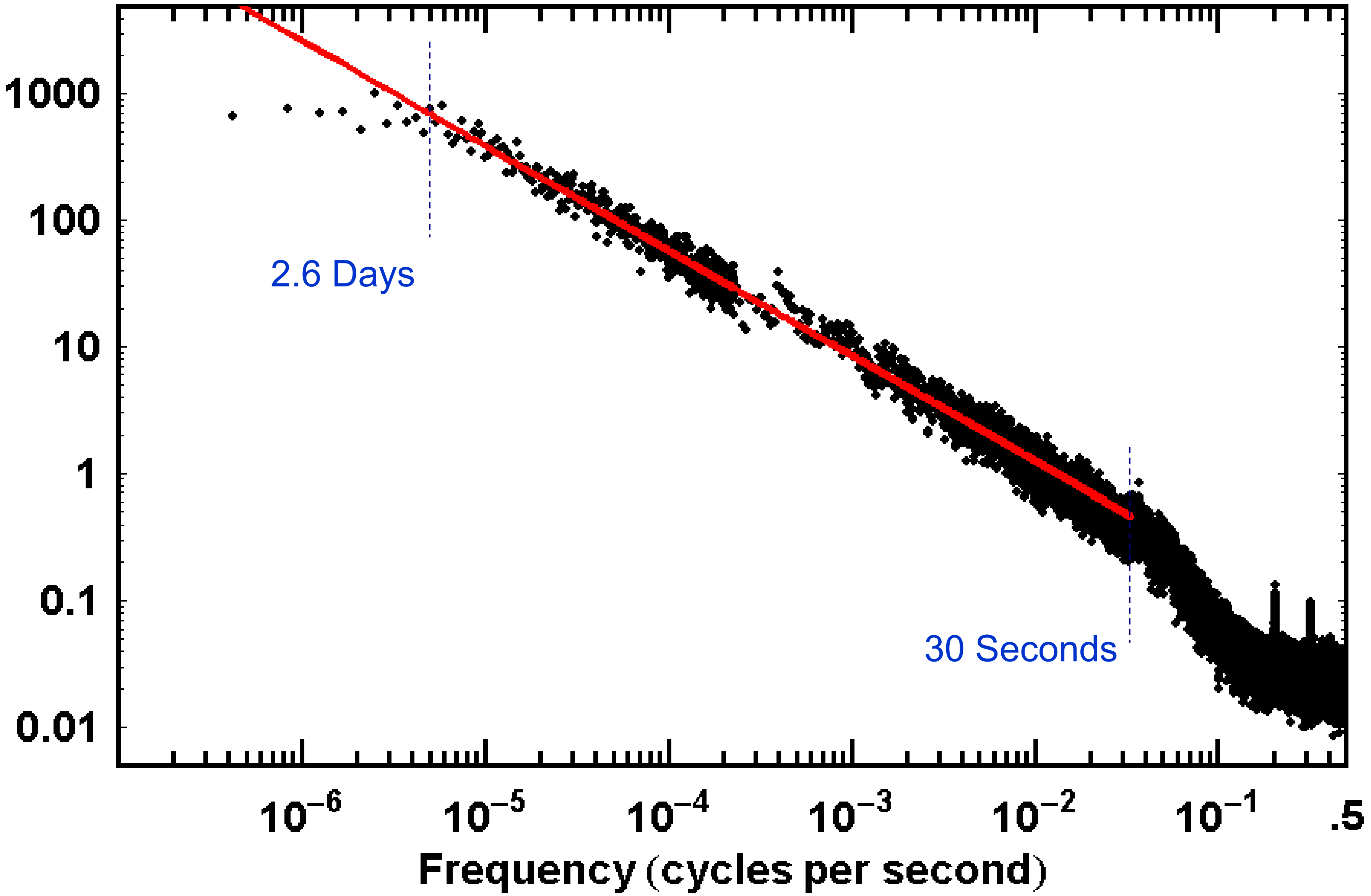
All of these assume Gaussian (normal) statistical distributions for wind



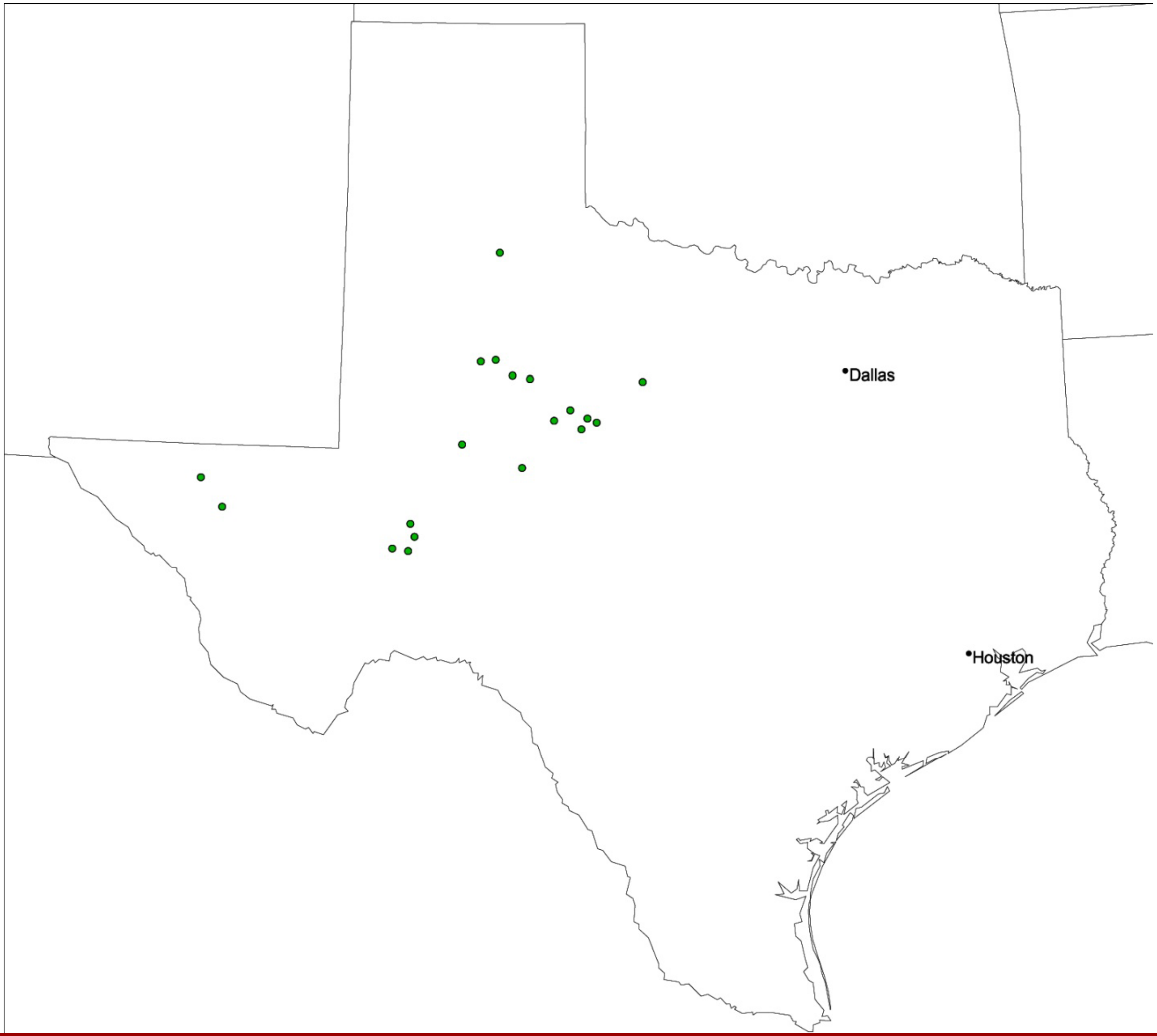
15 Days of 10-Second Time Resolution Data



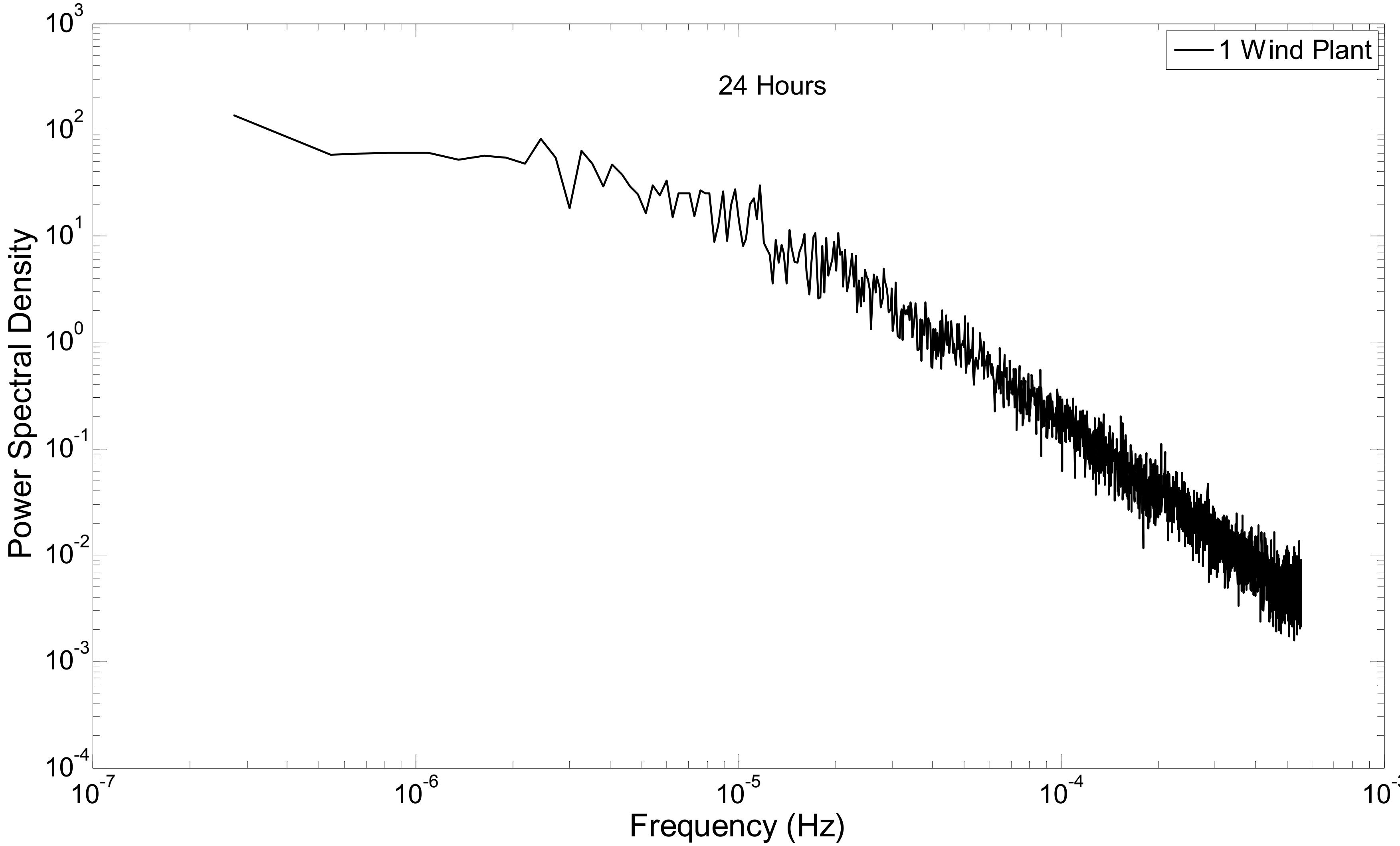
Fourier Transform to get the Power Spectrum



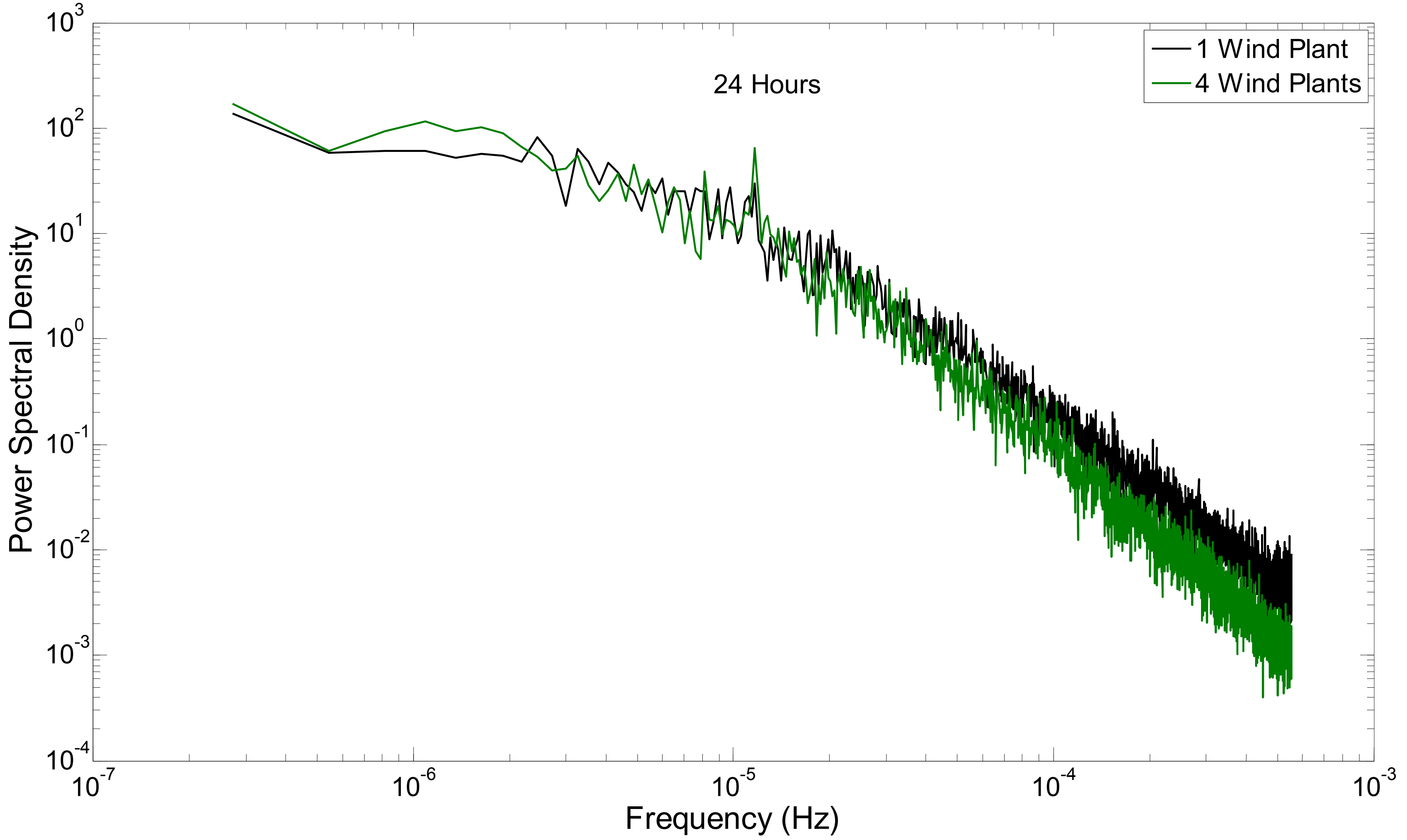
We can learn some important things from the power spectrum



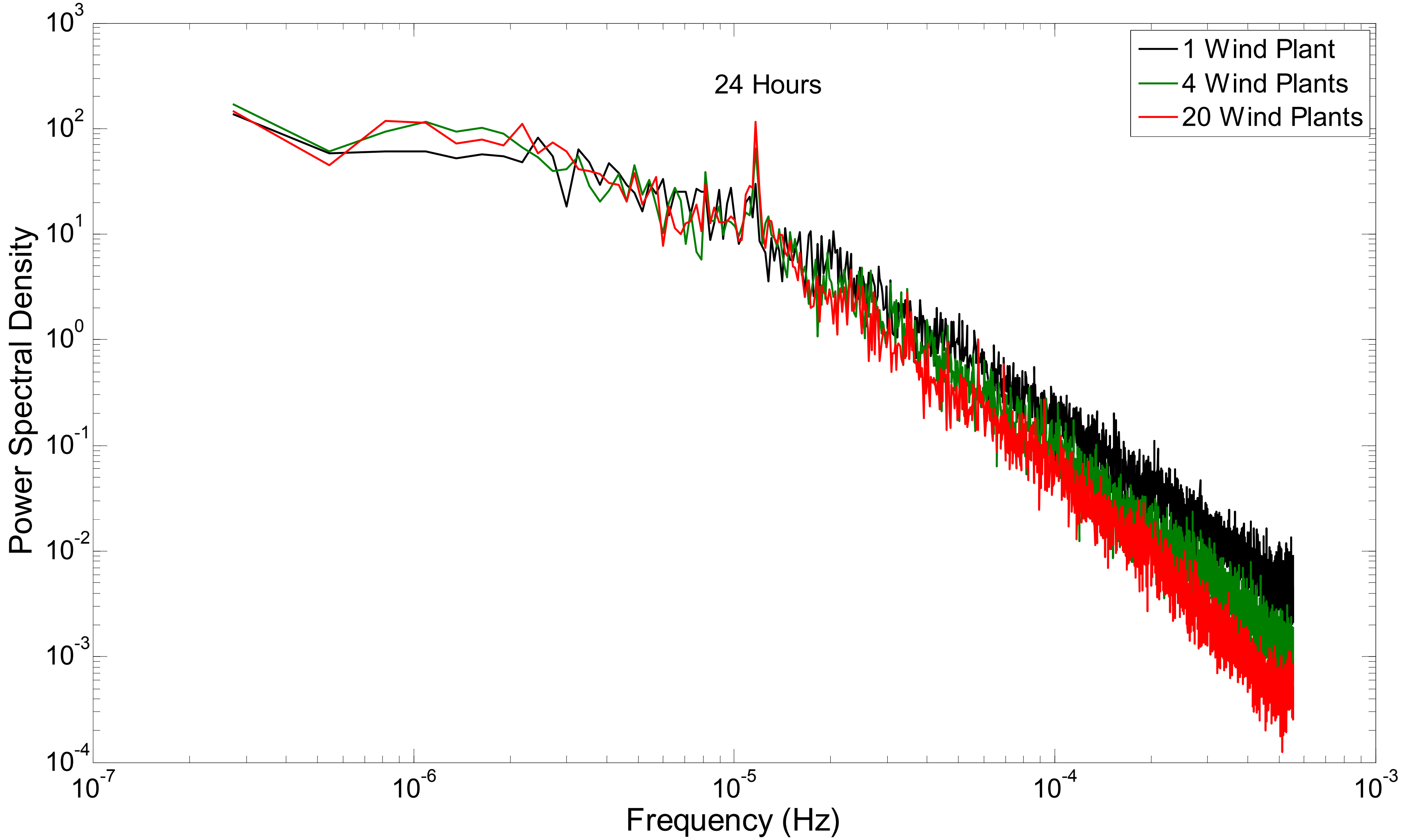
Smoothing by Adding Wind Farms



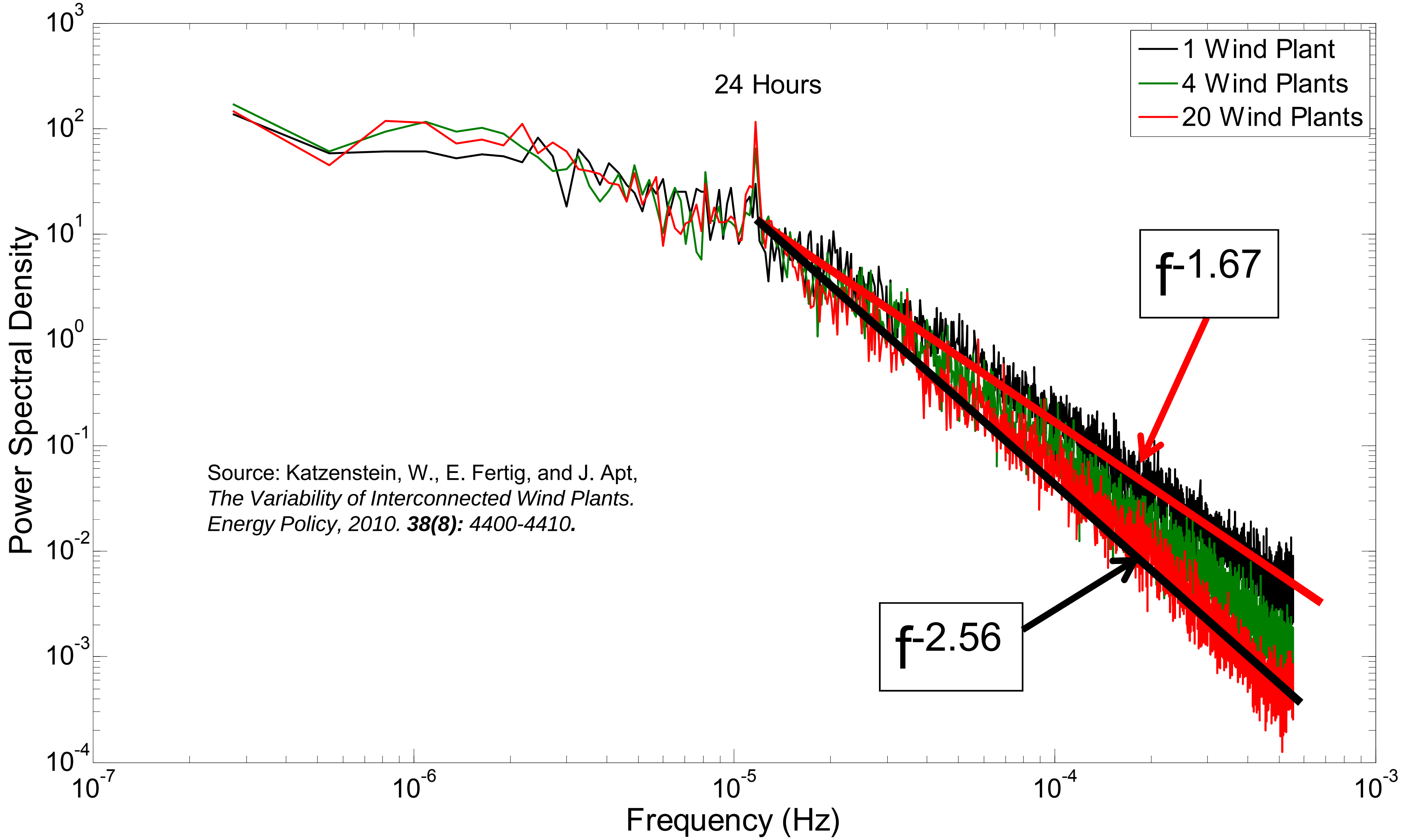
Smoothing by Adding Wind Farms



Smoothing by Adding Wind Farms

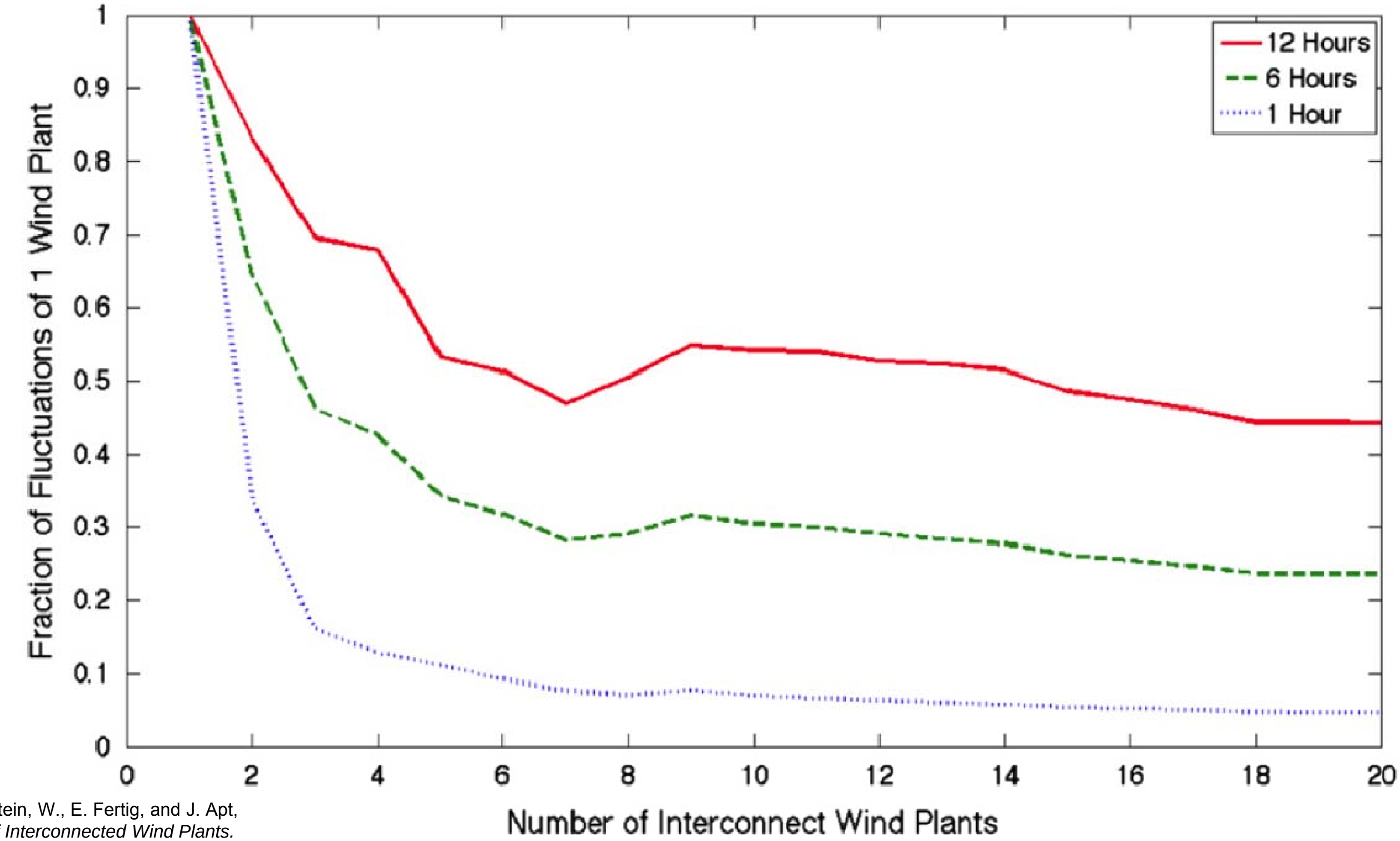


Smoothing by Adding Wind Farms



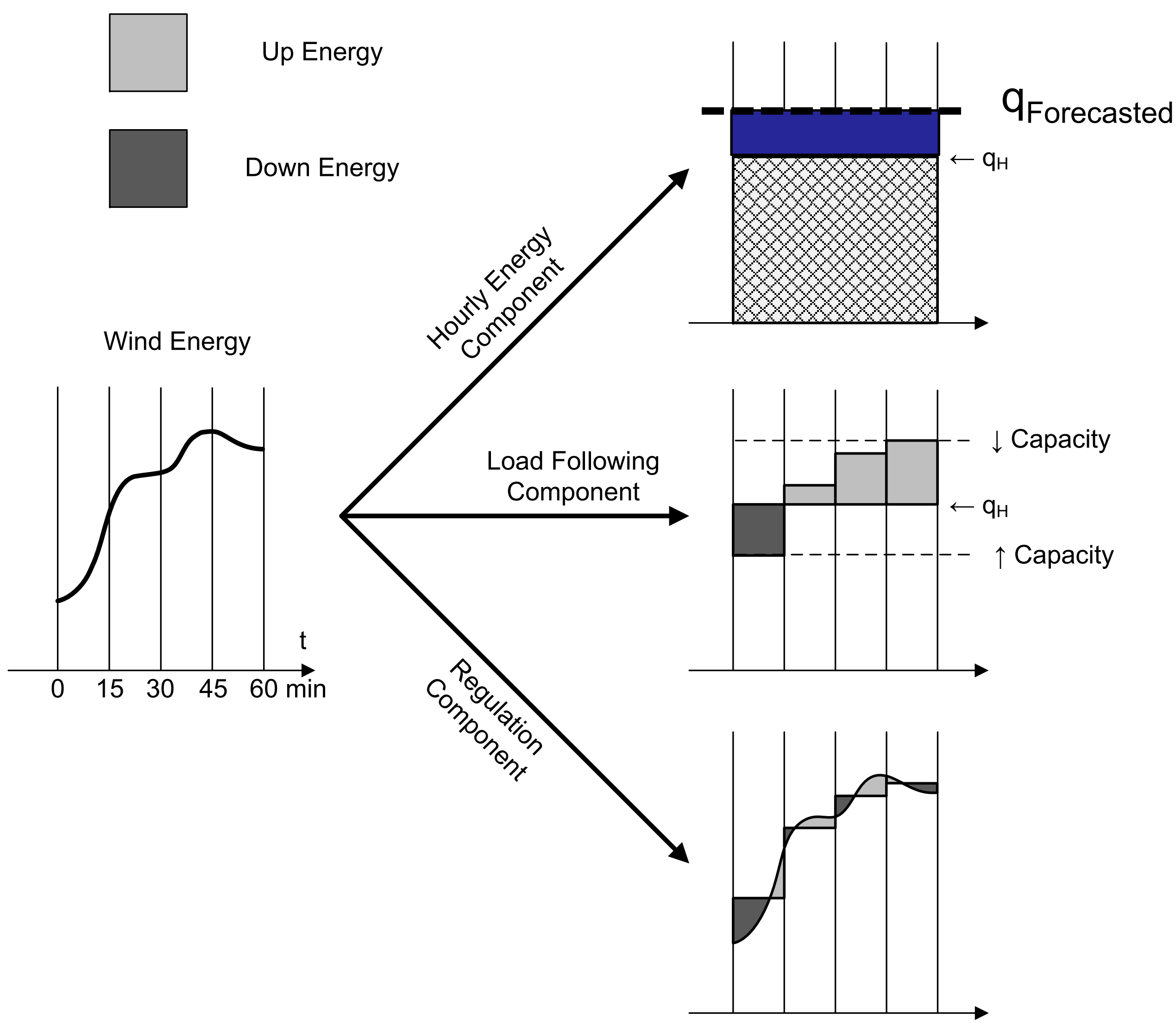
Source: Katzenstein, W., E. Fertig, and J. Apt, *The Variability of Interconnected Wind Plants. Energy Policy, 2010.* ***38(8):*** *4400-4410.*

Smoothing by Adding Wind Farms … has diminishing returns

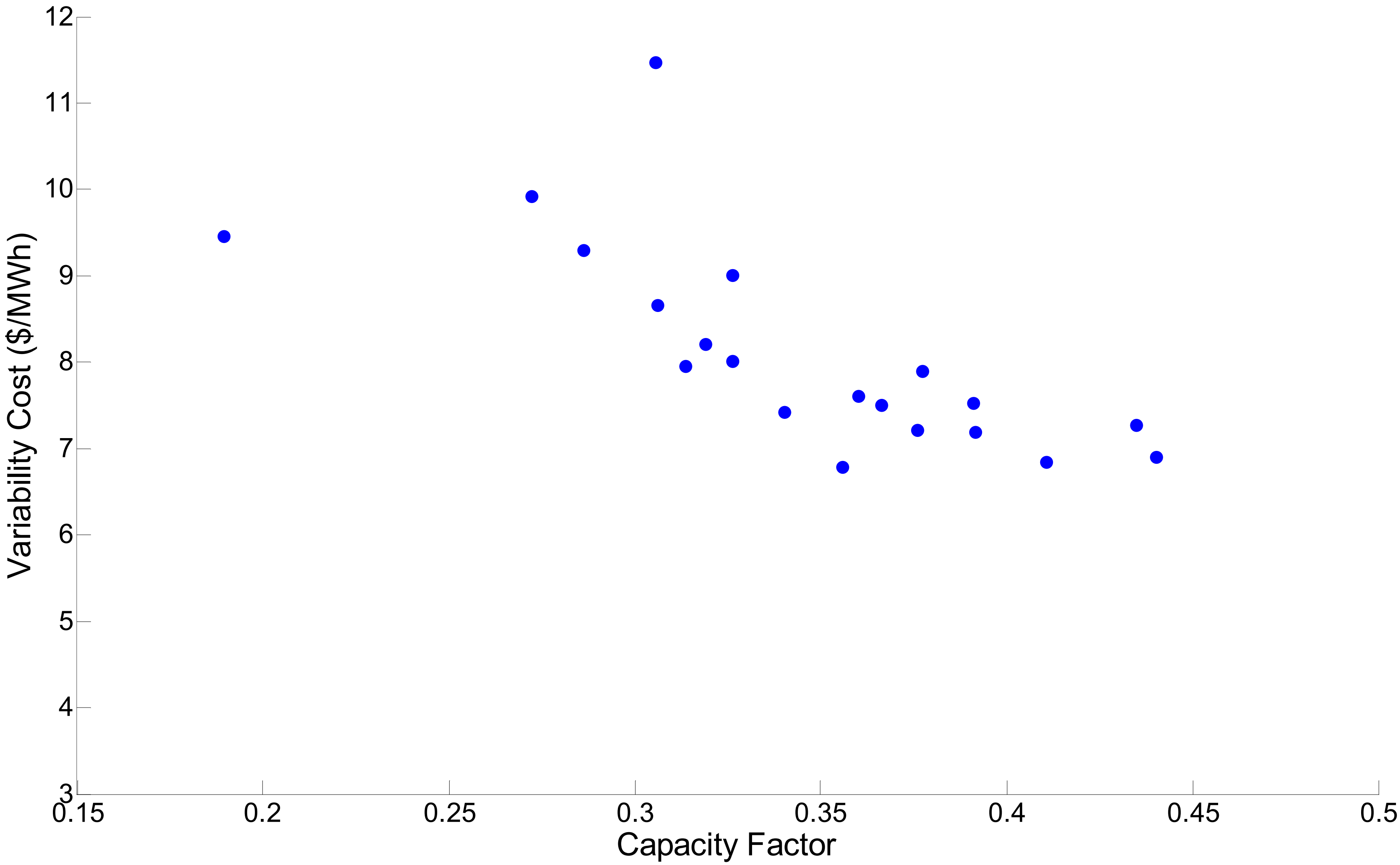


Source: Katzenstein, W., E. Fertig, and J. Apt, *The Variability of Interconnected Wind Plants. Energy Policy, 2010.* ***38(8):*** *4400-4410.*

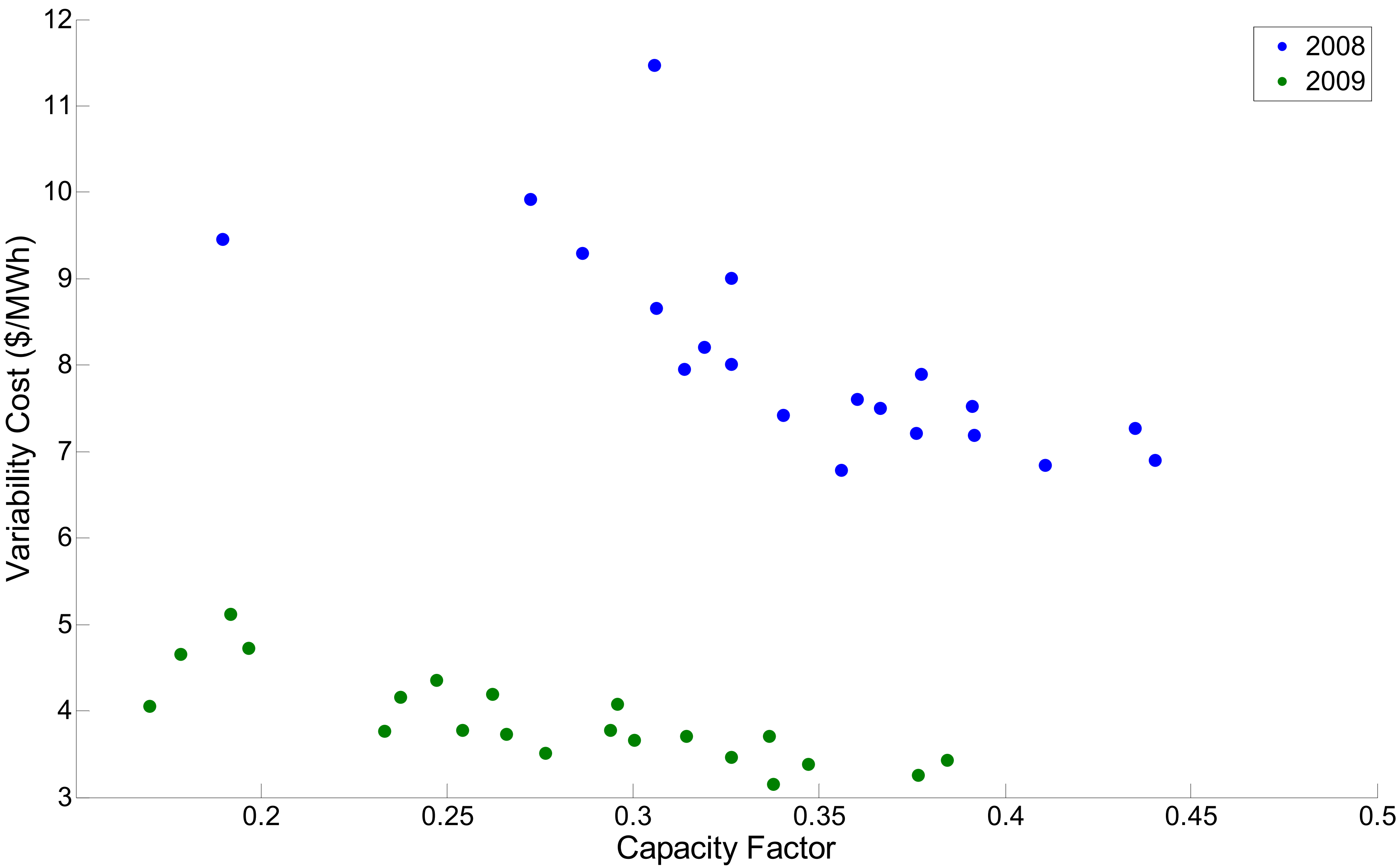
Each hour decompose wind energy
into the following components

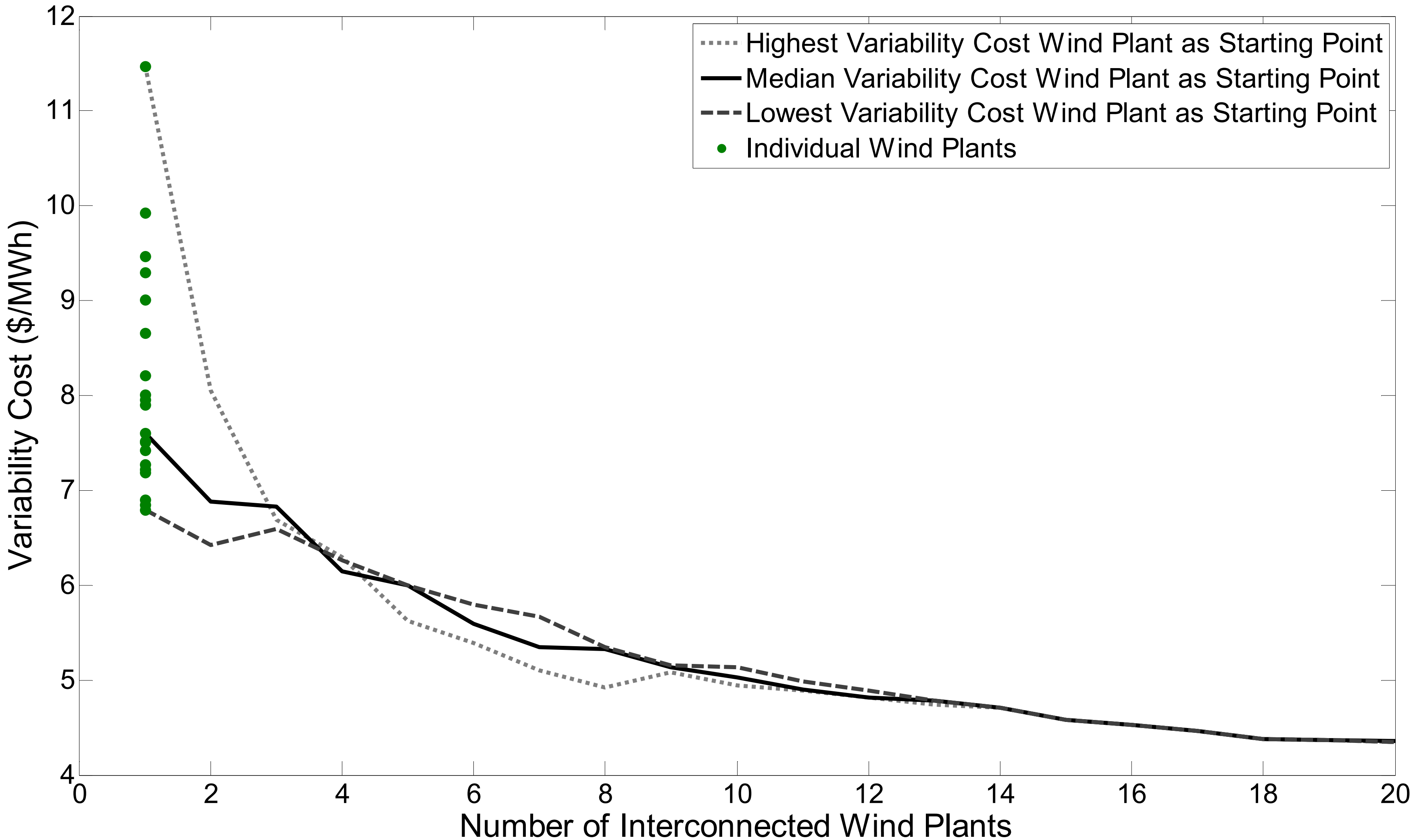


2008

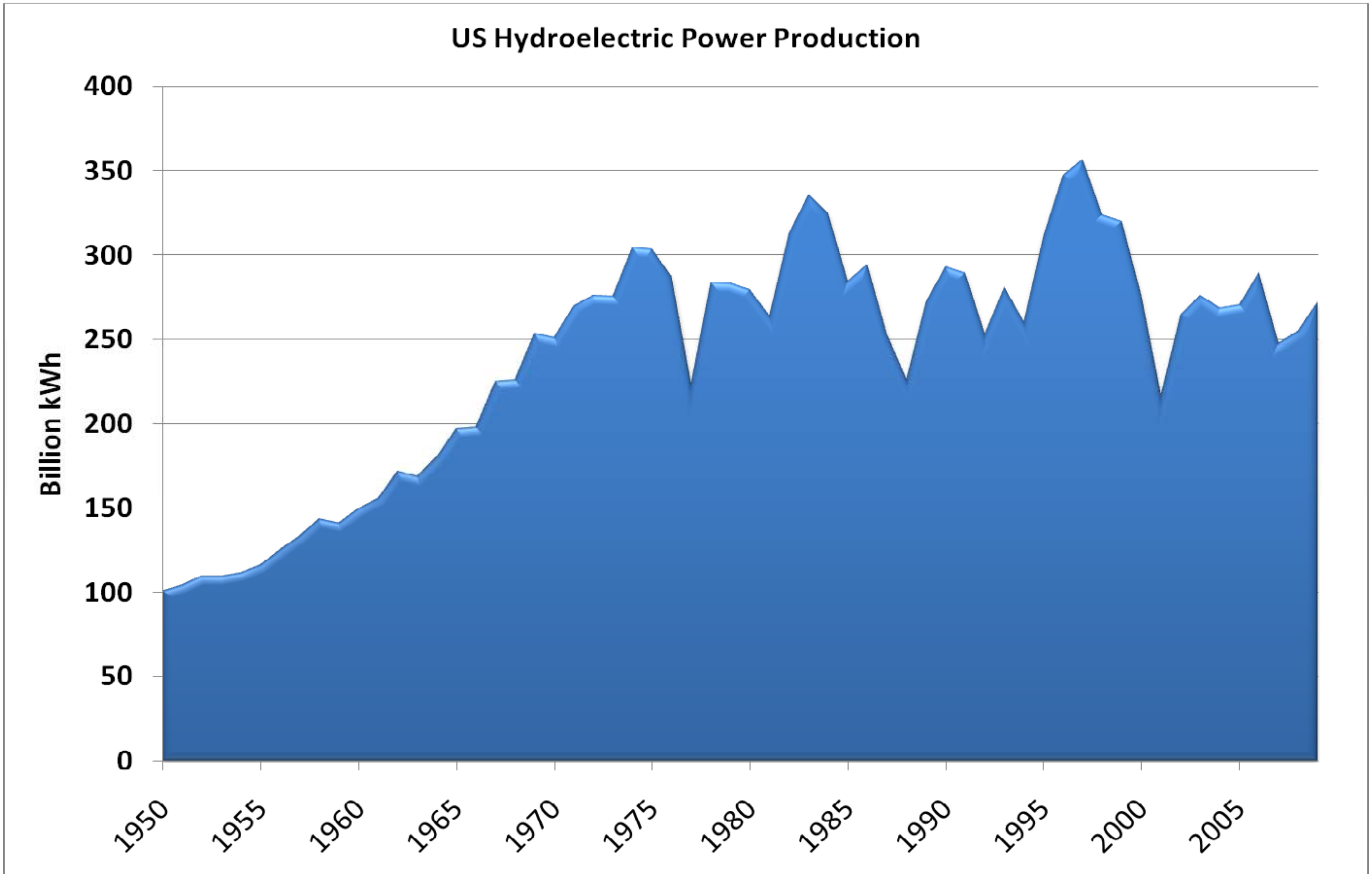

Variability Cost ($/MWh)
12
11
10
9
8
7
6
5
4
3
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Capacity Factor

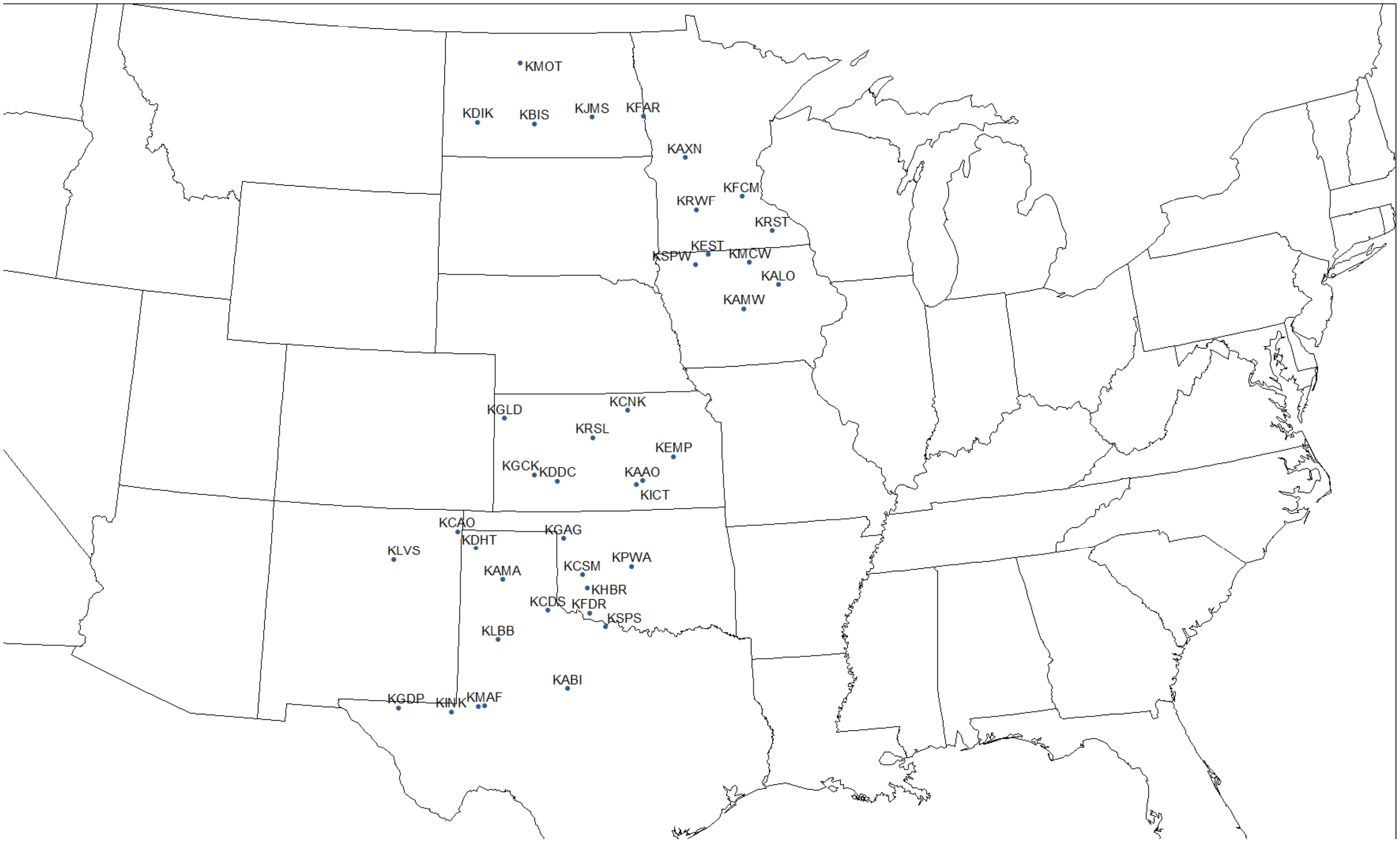
2008 and 2009




Highest Variability Cost Wind Plant as Starting Point
Median Variability Cost Wind Plant as Starting Point
Lowest Variability Cost Wind Plant as Starting Point
Individual Wind Plants
Variability Cost ($/MWh)
Number of Interconnected Wind Plants
12
11
10
9
8
7
6
5
4
0
2
4
6
8
10
12
14
16
18
20

Hydroelectric Power has Droughts





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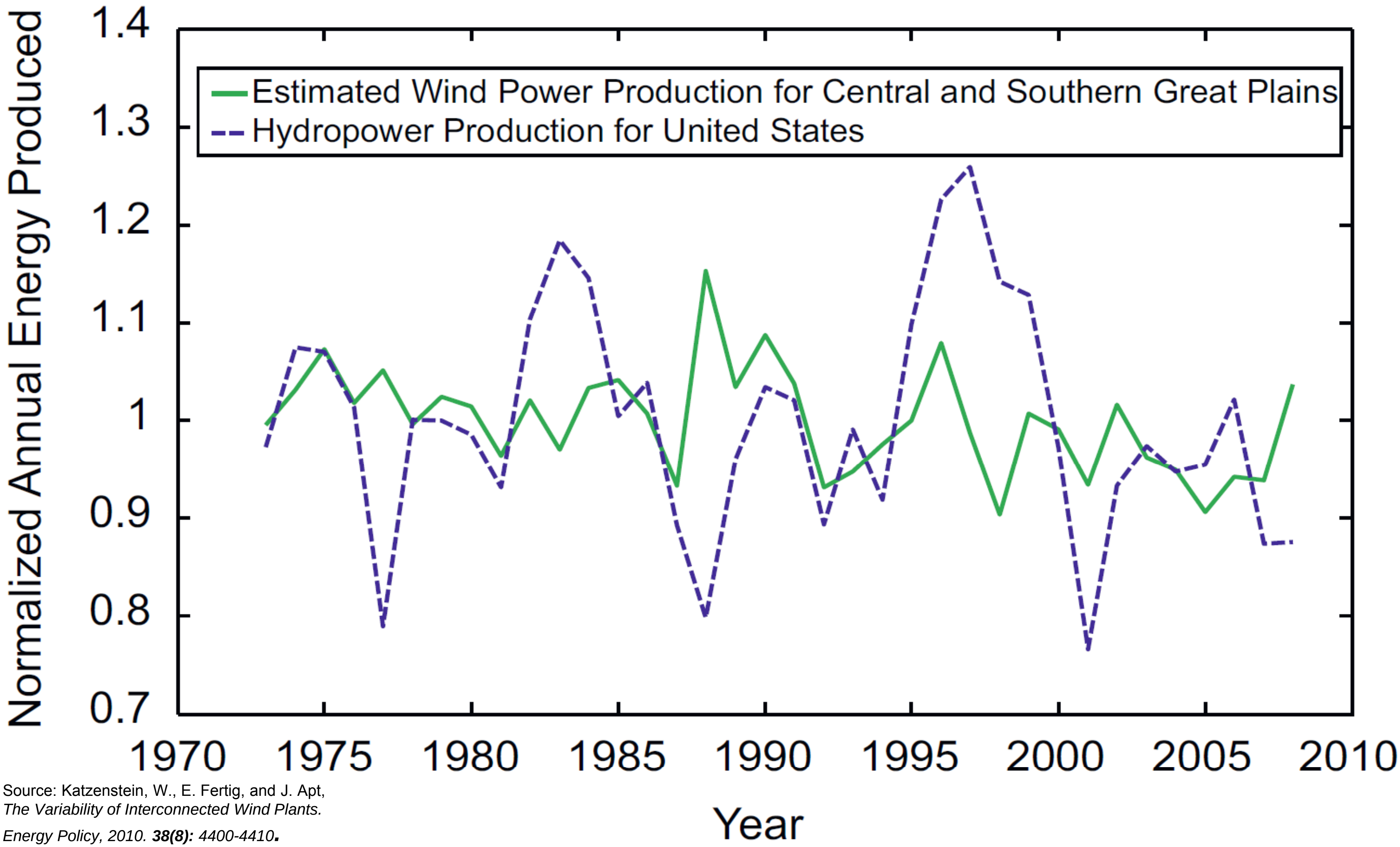
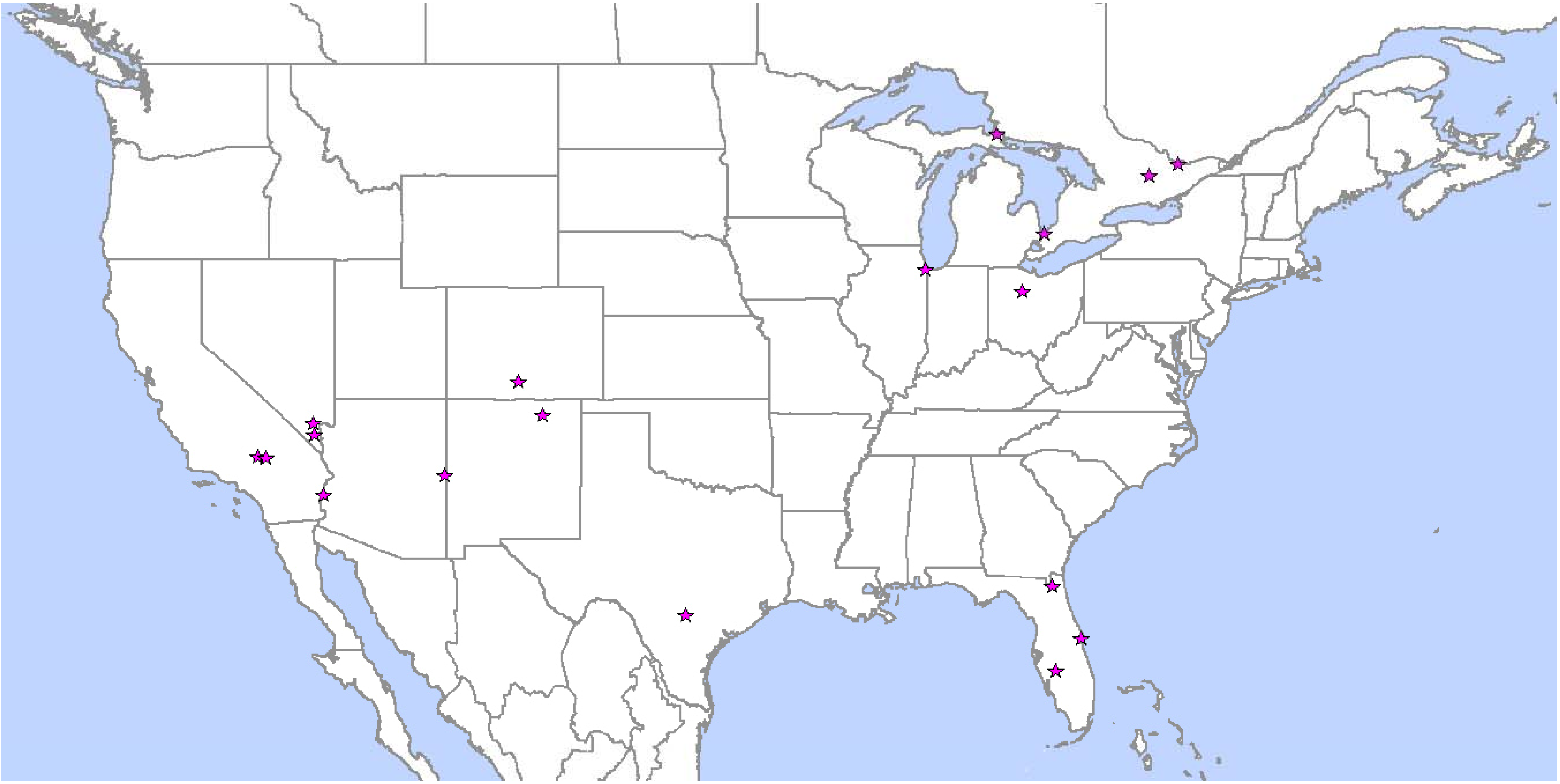
Wind Probably Does Too



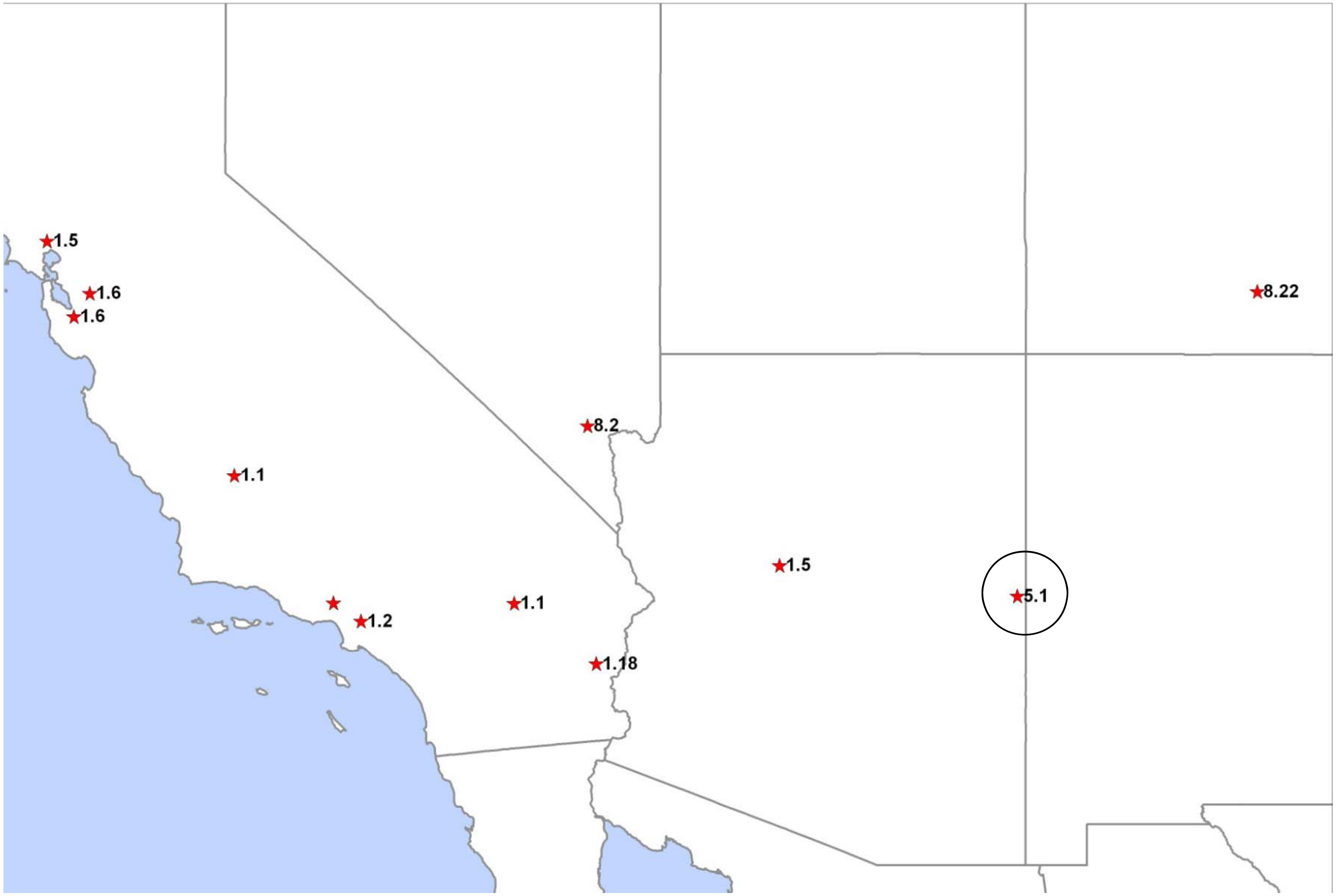
Source: Katzenstein, W., E. Fertig, and J. Apt, *The Variability of Interconnected Wind Plants. Energy Policy, 2010.* ***38(8):*** *4400-4410*.

Operating Solar PV February 21, 2011

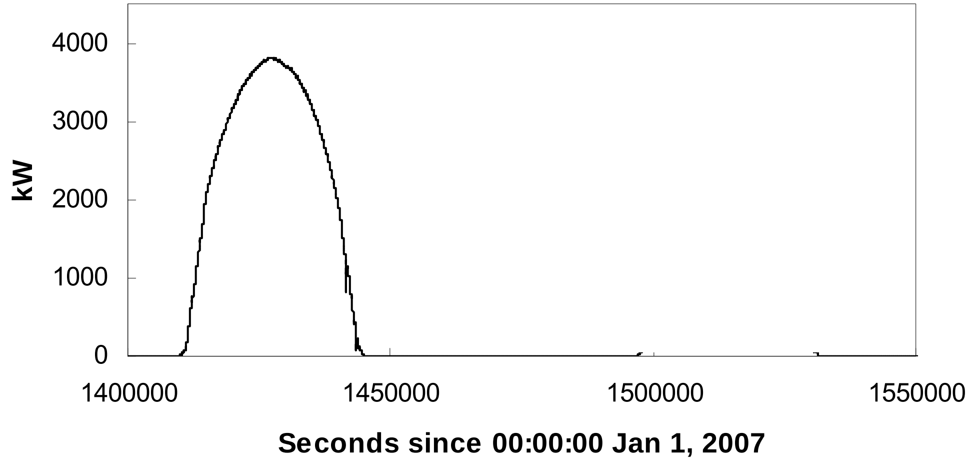
Units > 5 MW

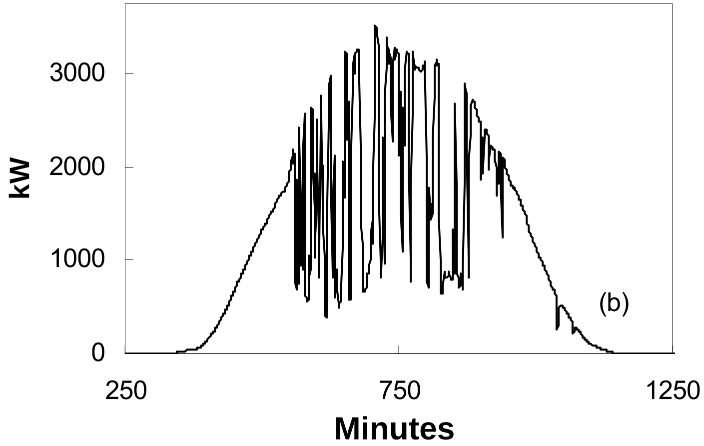


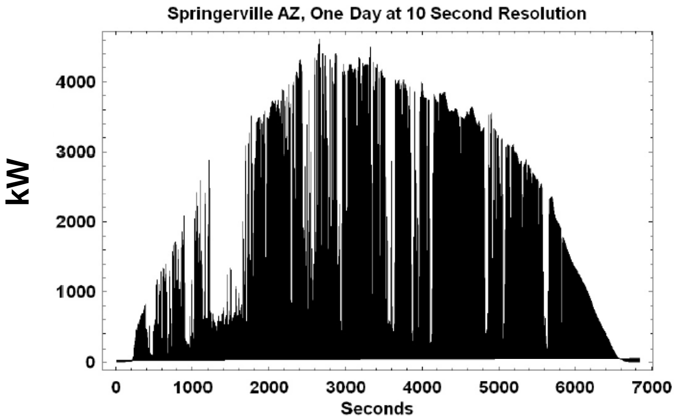
Solar



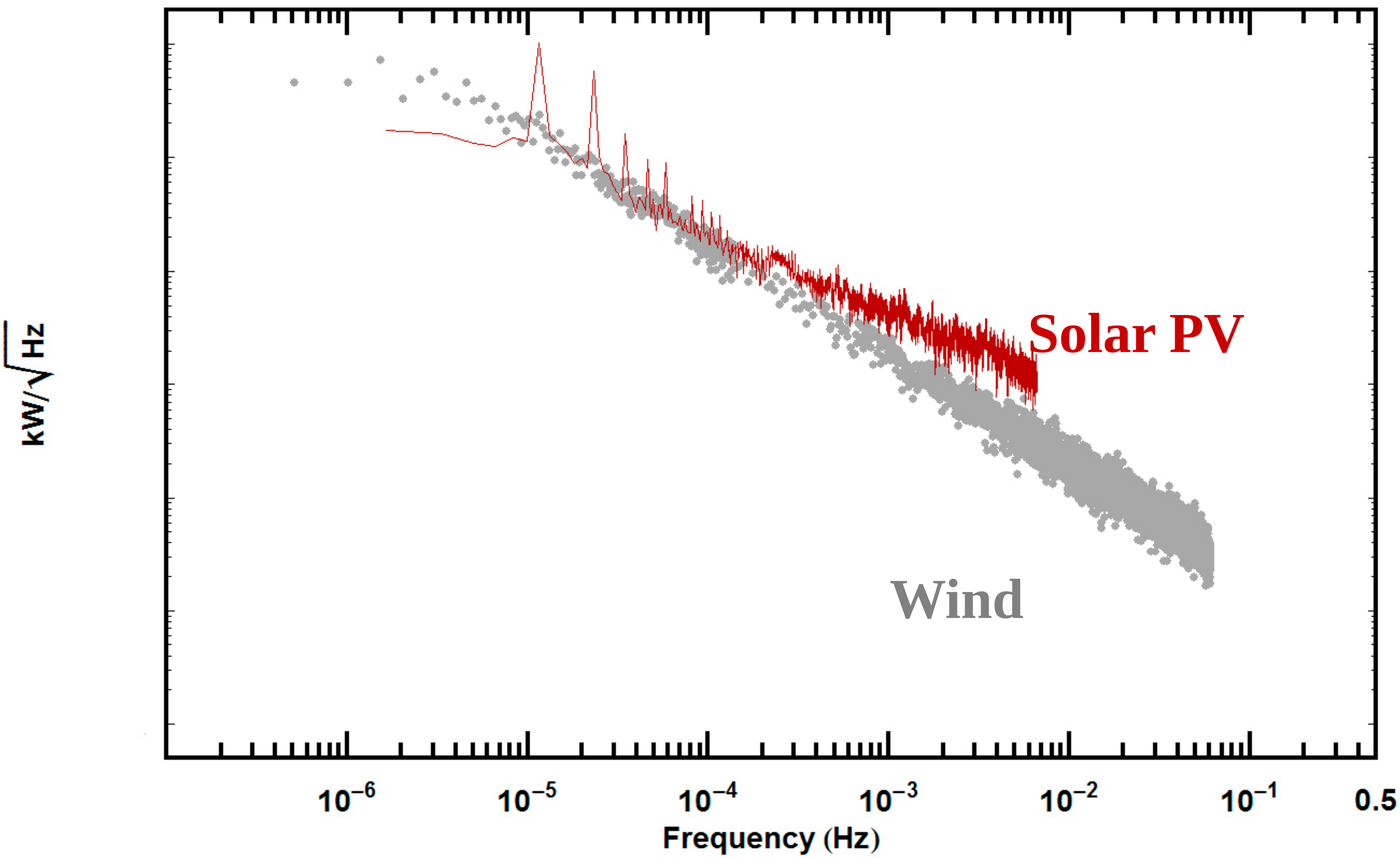
Comparison of Wind with Solar PV
4.6 MW TEP Solar Array (Arizona)







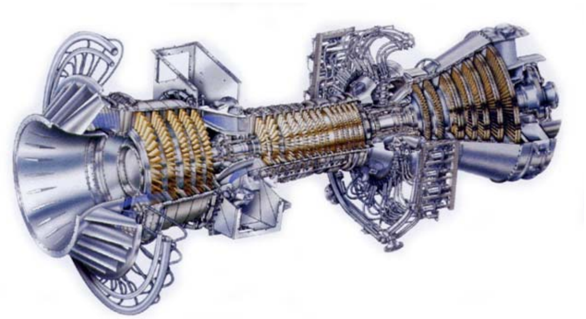
Comparison of wind and solar PV



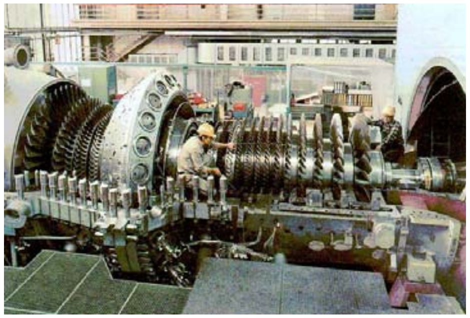
Source: CEIC Working Paper CEIC-07-12, available at www.cmu.edu/electricity

Work with Warren Katzenstein

NO_x and CO_2 Emissions from Gas Turbines Paired with Wind or Solar for Firm Power



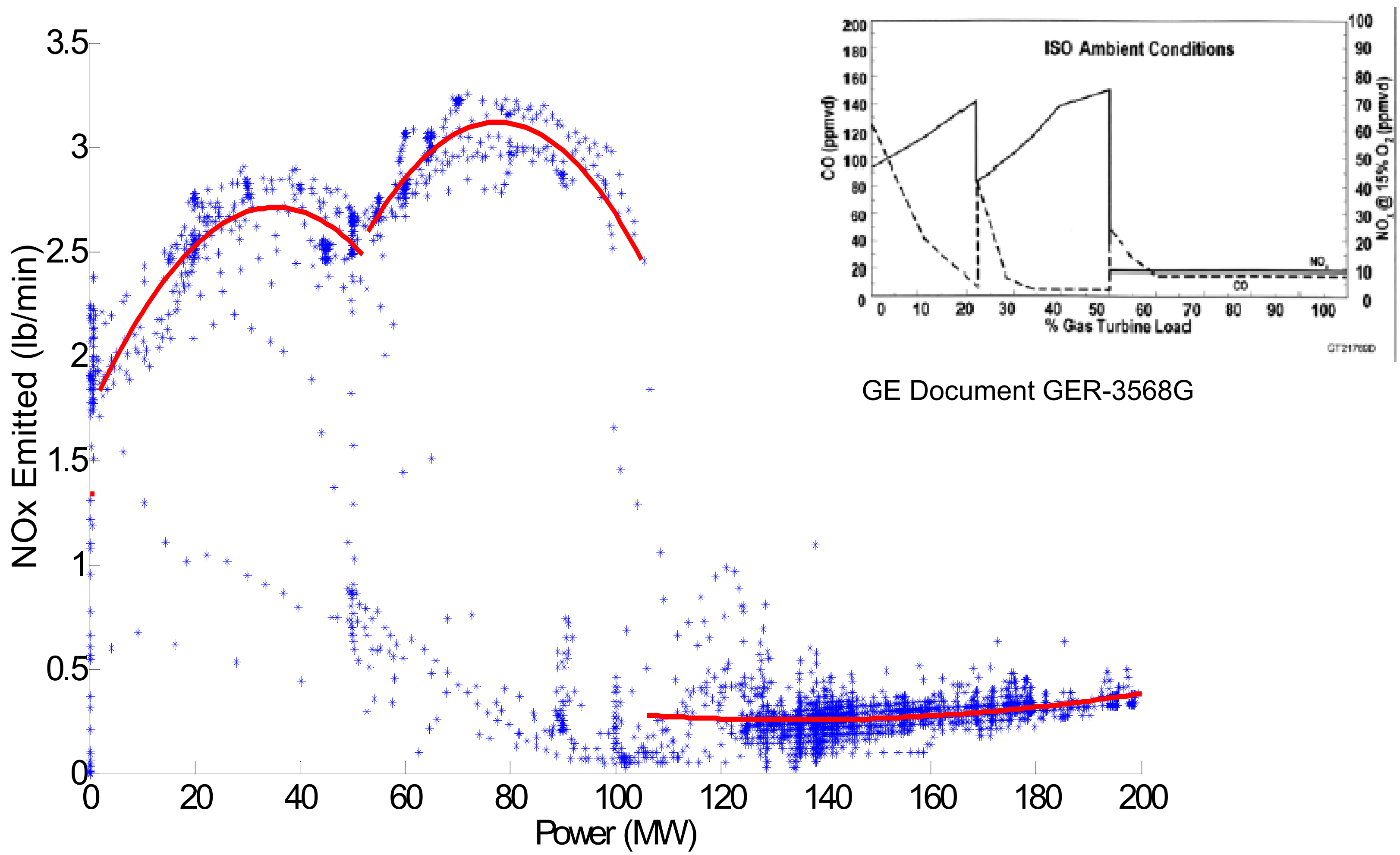
GE LM6000
sealegacy.com



Siemens-Westinghouse 501FD

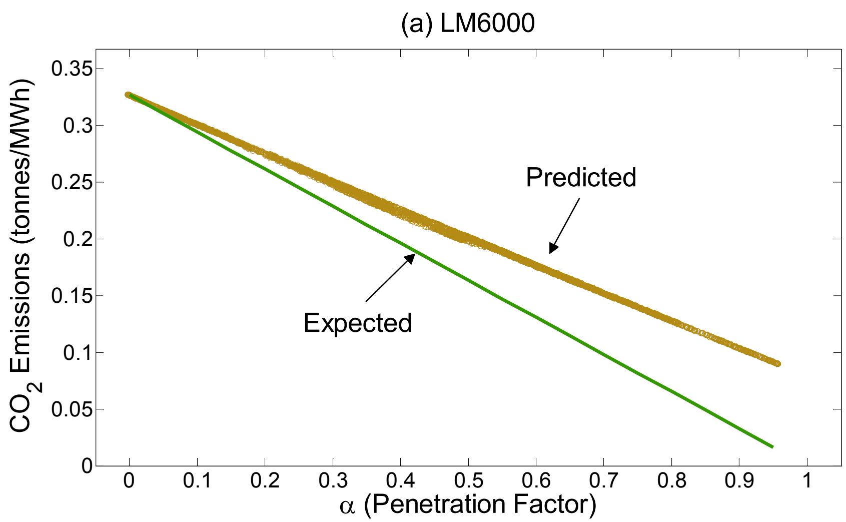
summitvineyardllc.com

Siemens-Westinghouse 501FD Regression Analysis

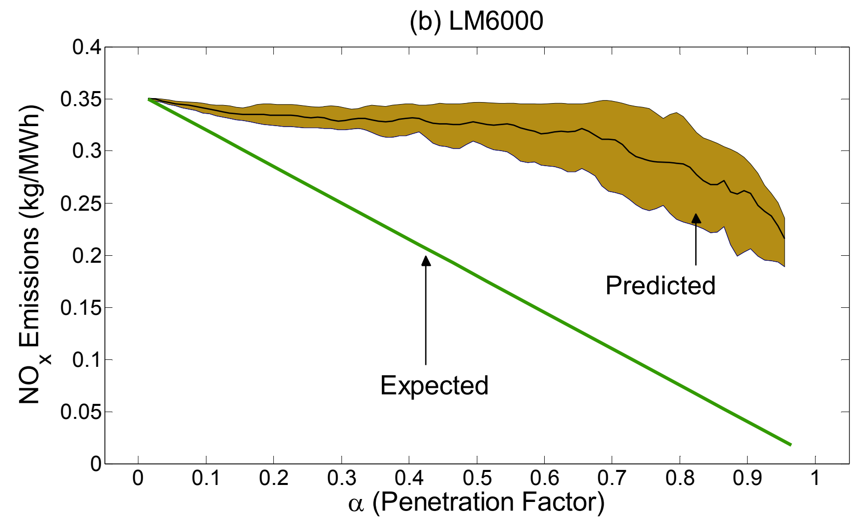


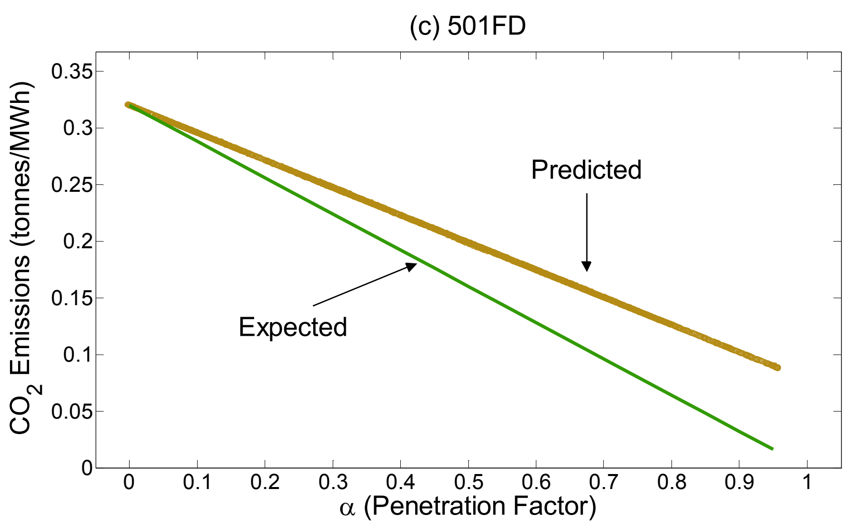
GE Document GER-3568G

Emissions Factors

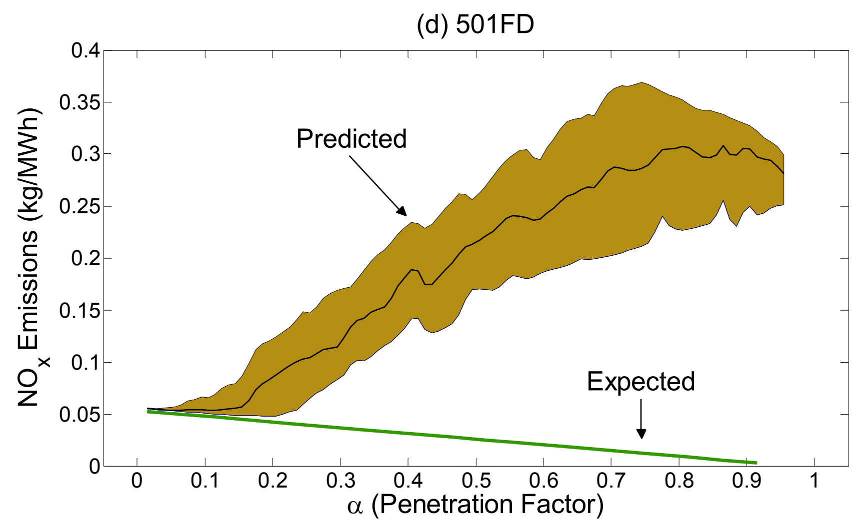


LM6000
Steam,
no SCR

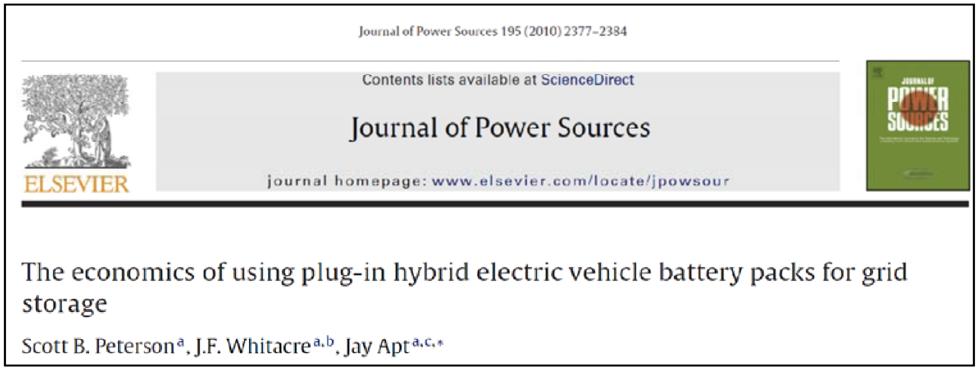




501FD
DLN,
SCR



Will Electric Vehicles Come to the Rescue?


Journal of Power Sources 195 (2010) 2377–2384

Contents lists available at ScienceDirect

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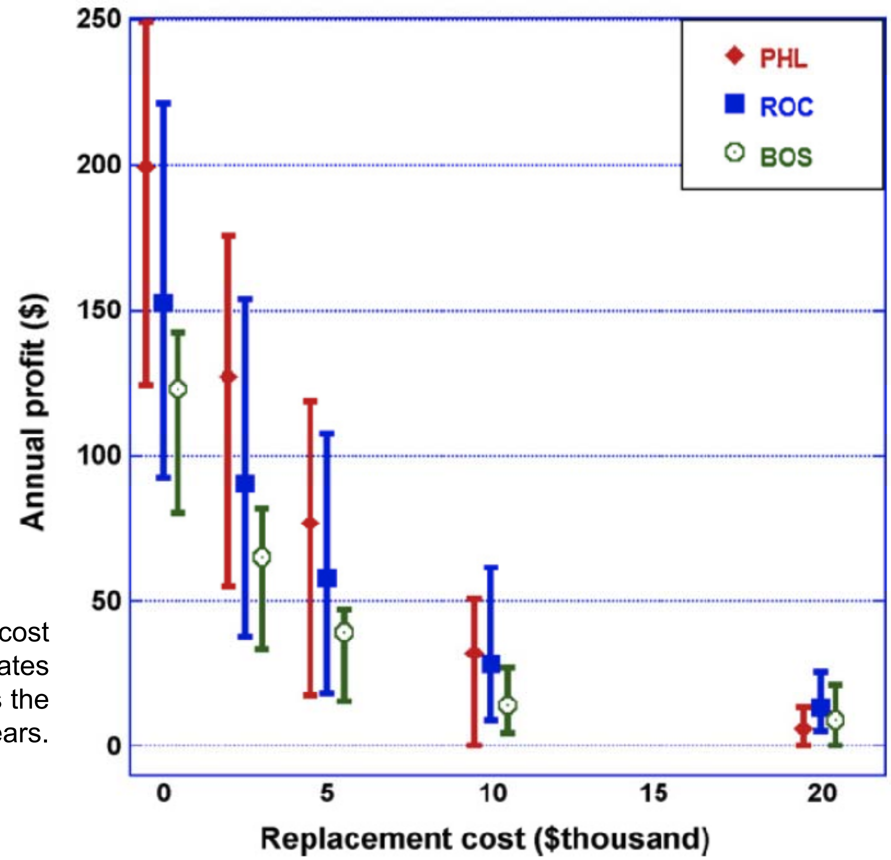
journal homepage: www.elsevier.com/locate/jpowsour

The economics of using plug-in hybrid electric vehicle battery packs for grid storage

Scott B. Peterson[a], J.F. Whitacre[a,b], Jay Apt[a,c,*]



V2G energy arbitrage profit sensitivity to battery pack replacement cost with perfect information in the three cities studied. The symbol indicates the median annual profit for the years studied and the range indicates the most and least profitable years.

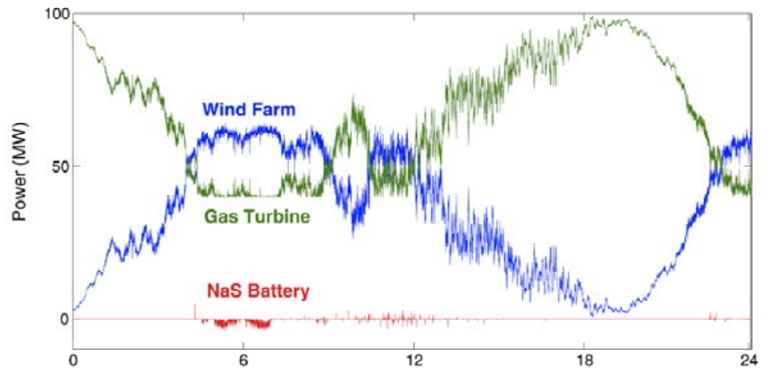
But, a very small battery installation can buffer a lot of wind variability

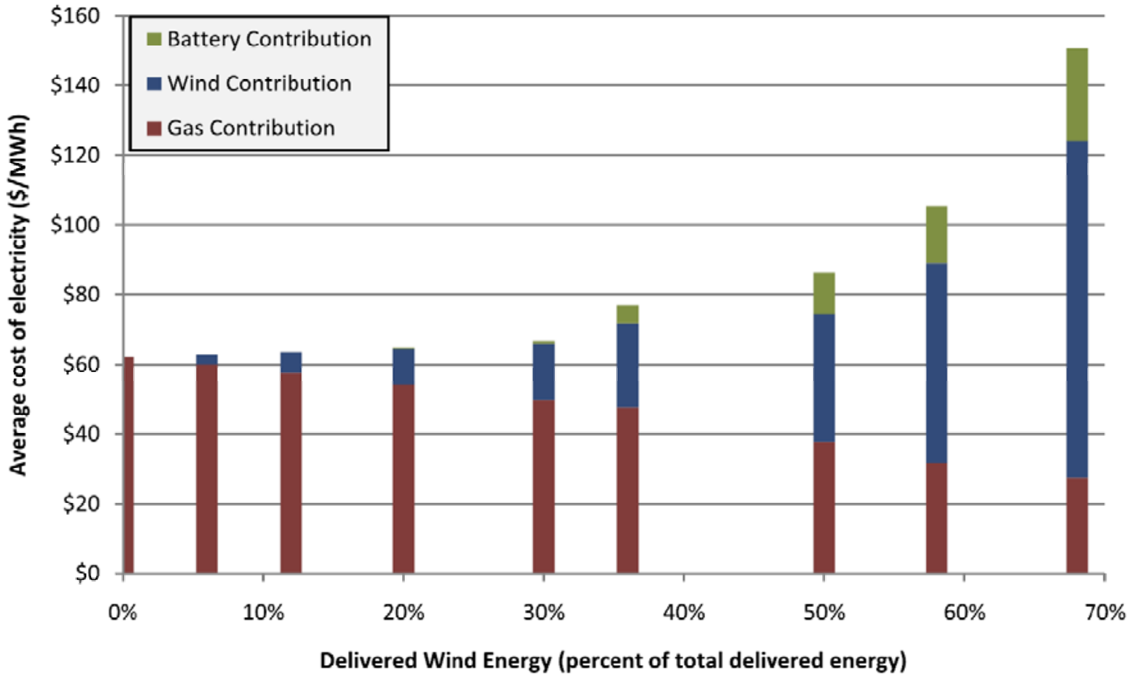
Energy Syst (2010) 1: 417–439
DOI 10.1007/s12667-010-0017-2

ORIGINAL PAPER

Compensating for wind variability using co-located natural gas generation and energy storage

Eric Hittinger · J.F. Whitacre · Jay Apt





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Final Comments

- None of this means that wind, geothermal, or solar (if costs ever come down) can't be used at large scale, but wind/solar will require a portfolio of fill-in power (some with very high ramp rates, some with slow) and R&D is required to optimize emissions control for fast and deep ramping.

Thank you.

Jay Apt

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