



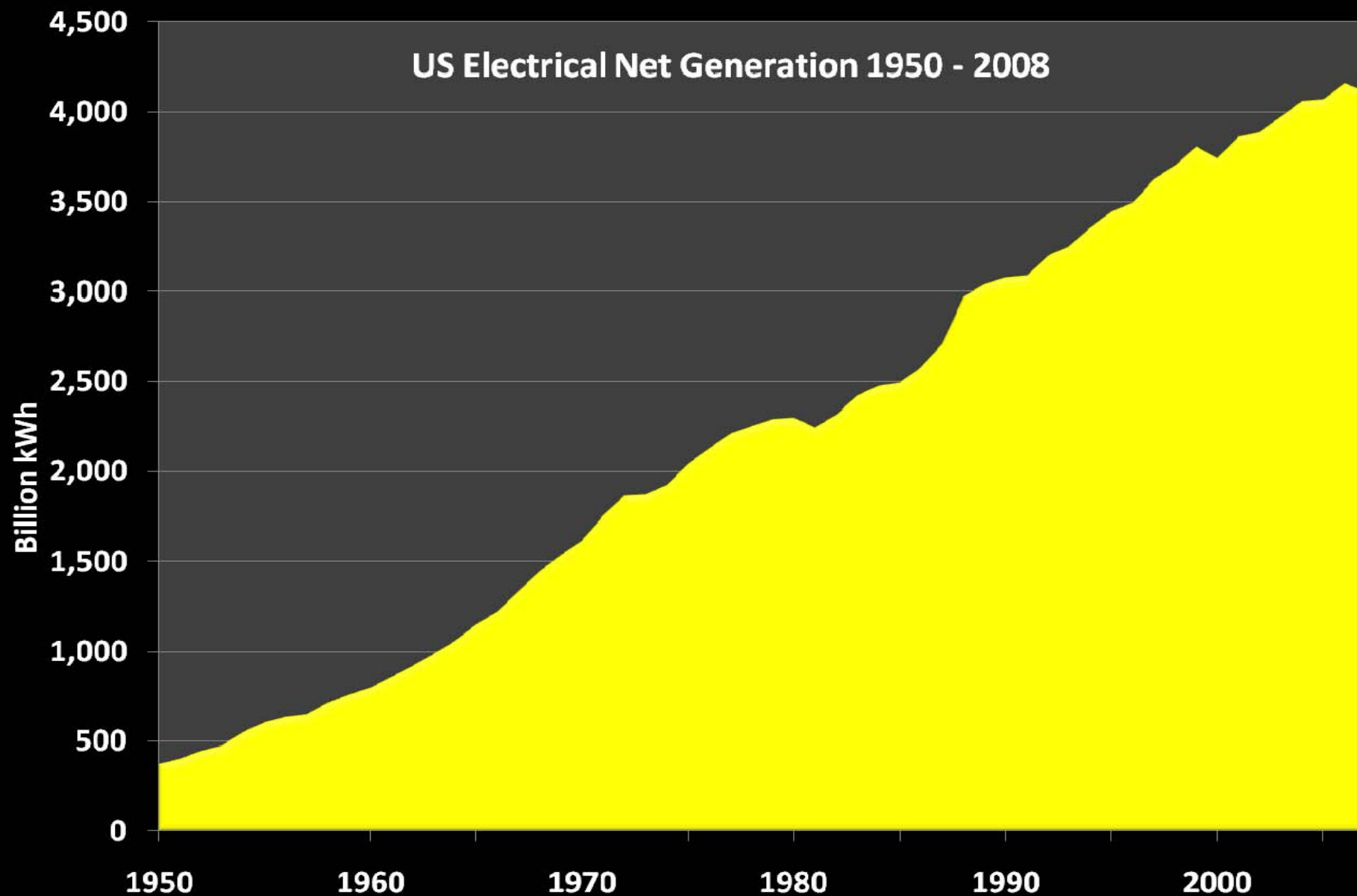
Integrating Renewables into the Electricity System - Overview

Jay Apt

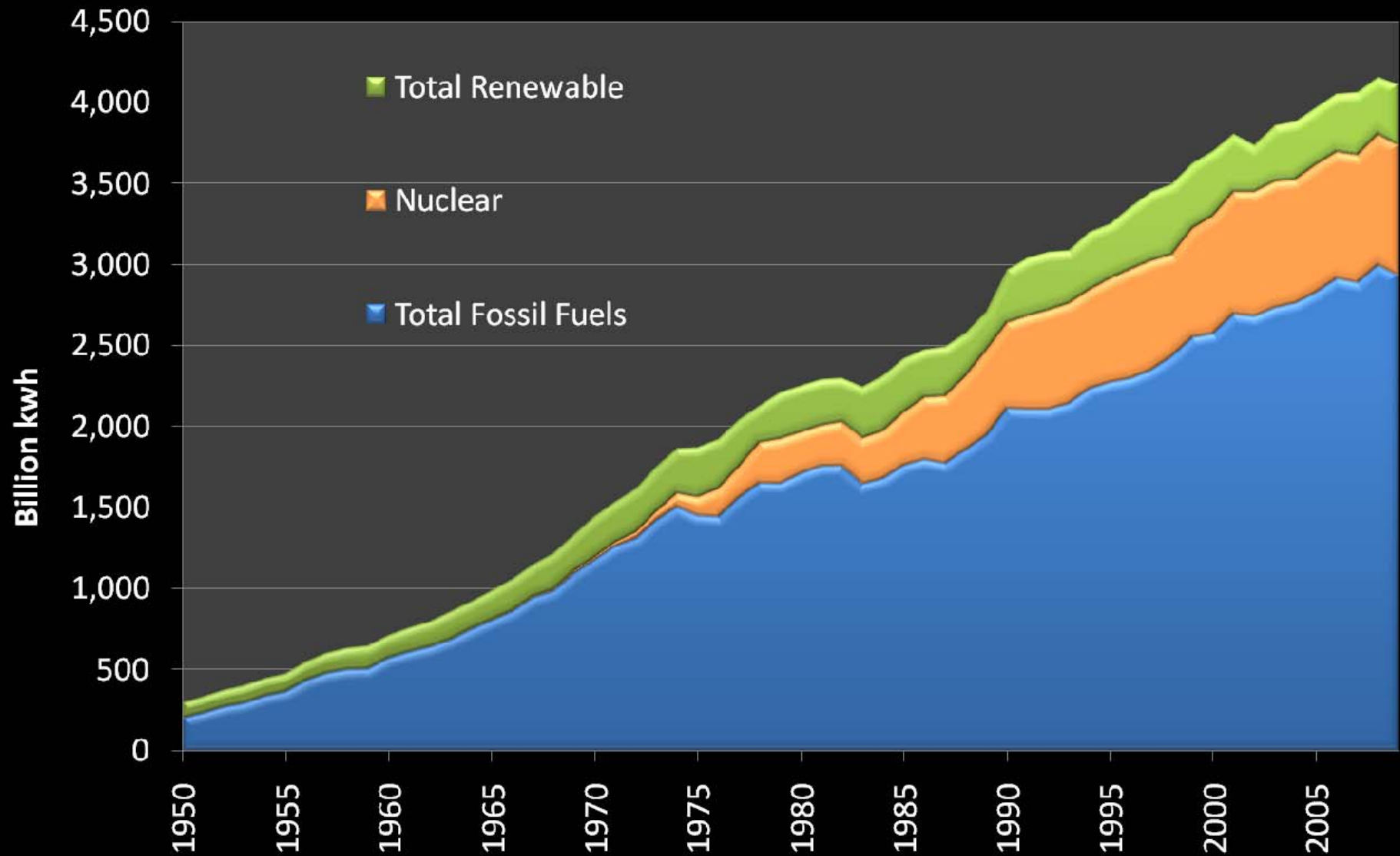
**Carnegie Mellon Electricity Industry Center (CEIC)
Carnegie Mellon University**

March 10, 2010



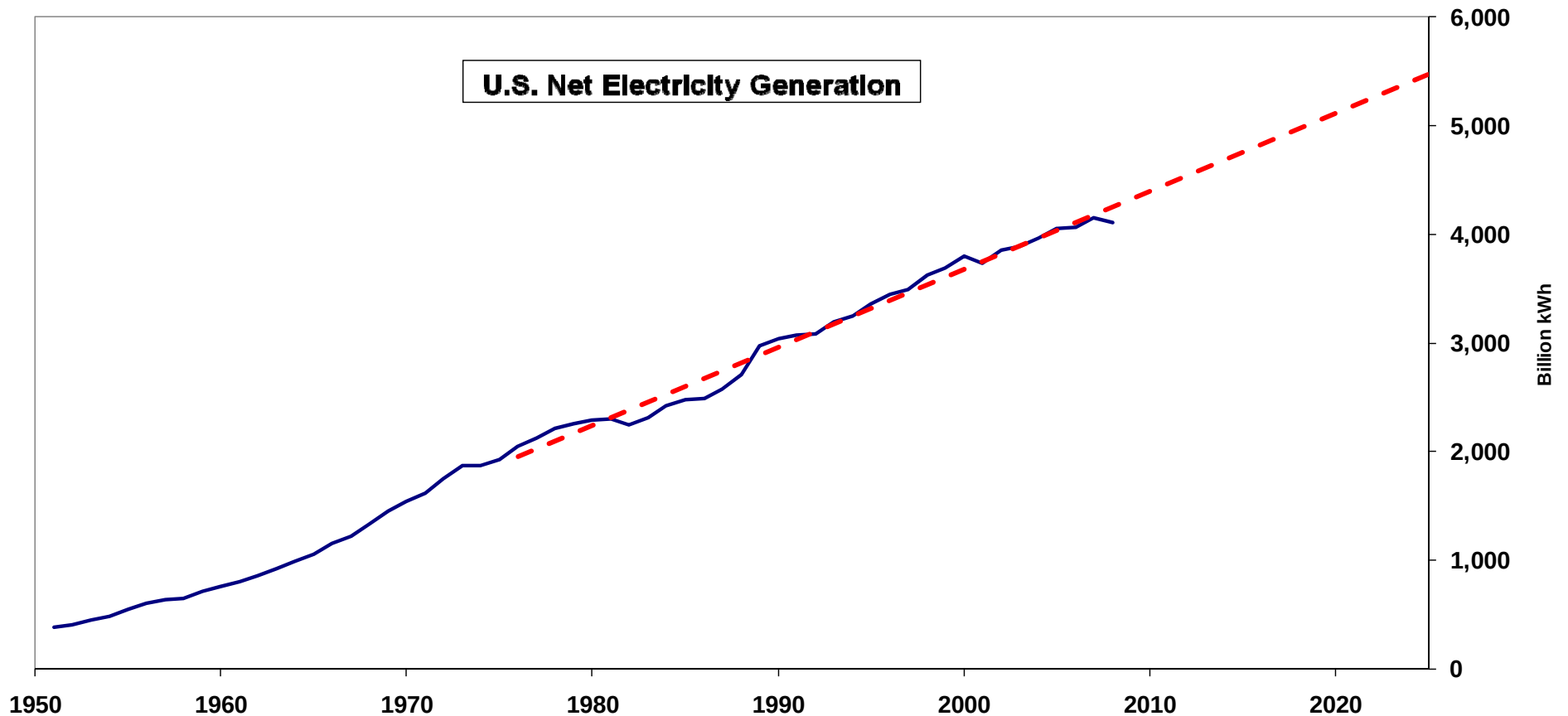


US Electrical Net Generation





35% Demand Growth by 2025?



(or more, with plug-in hybrid electric vehicles)





What percent of US electricity is now generated by renewables?

8.9 %

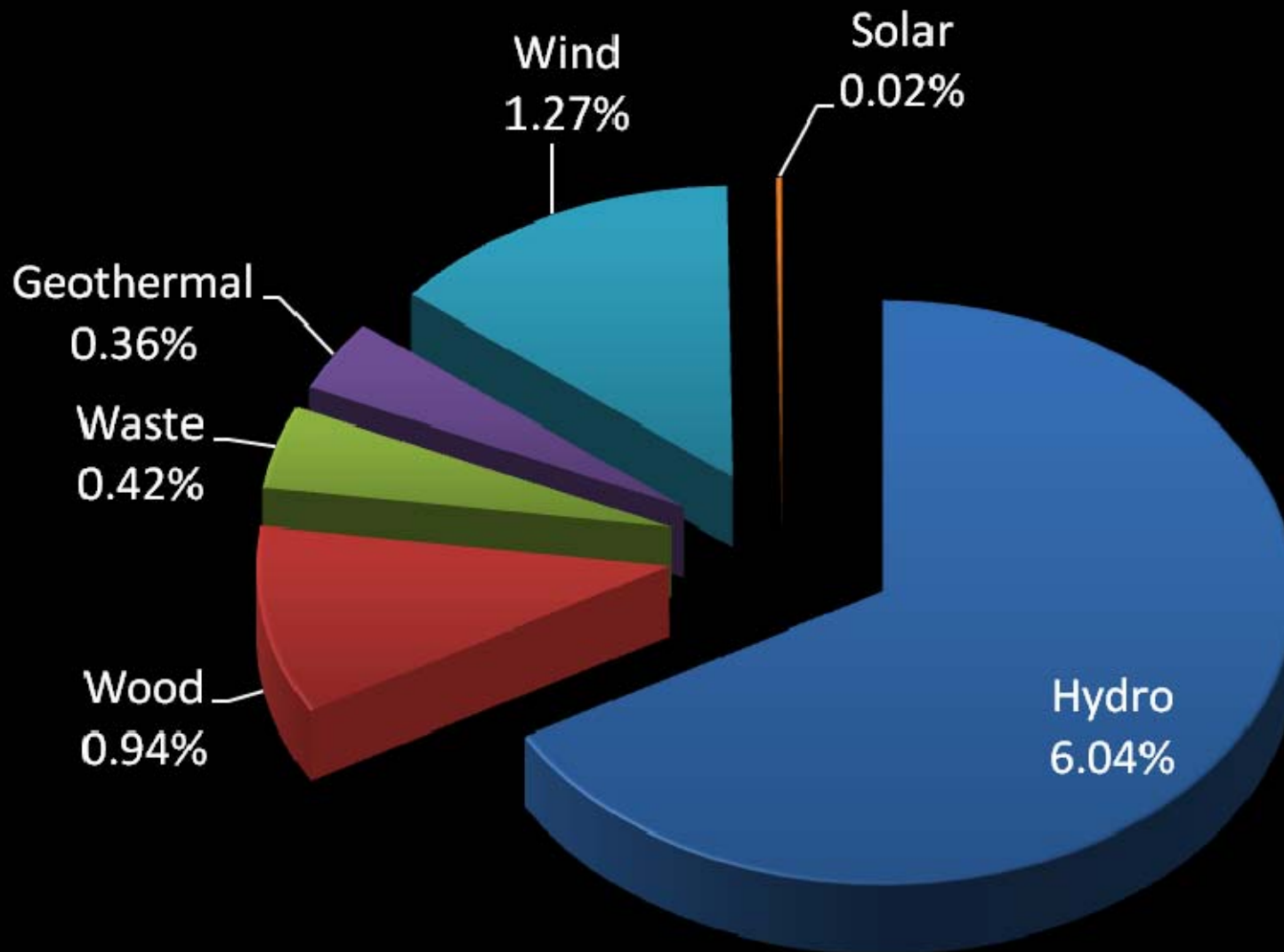


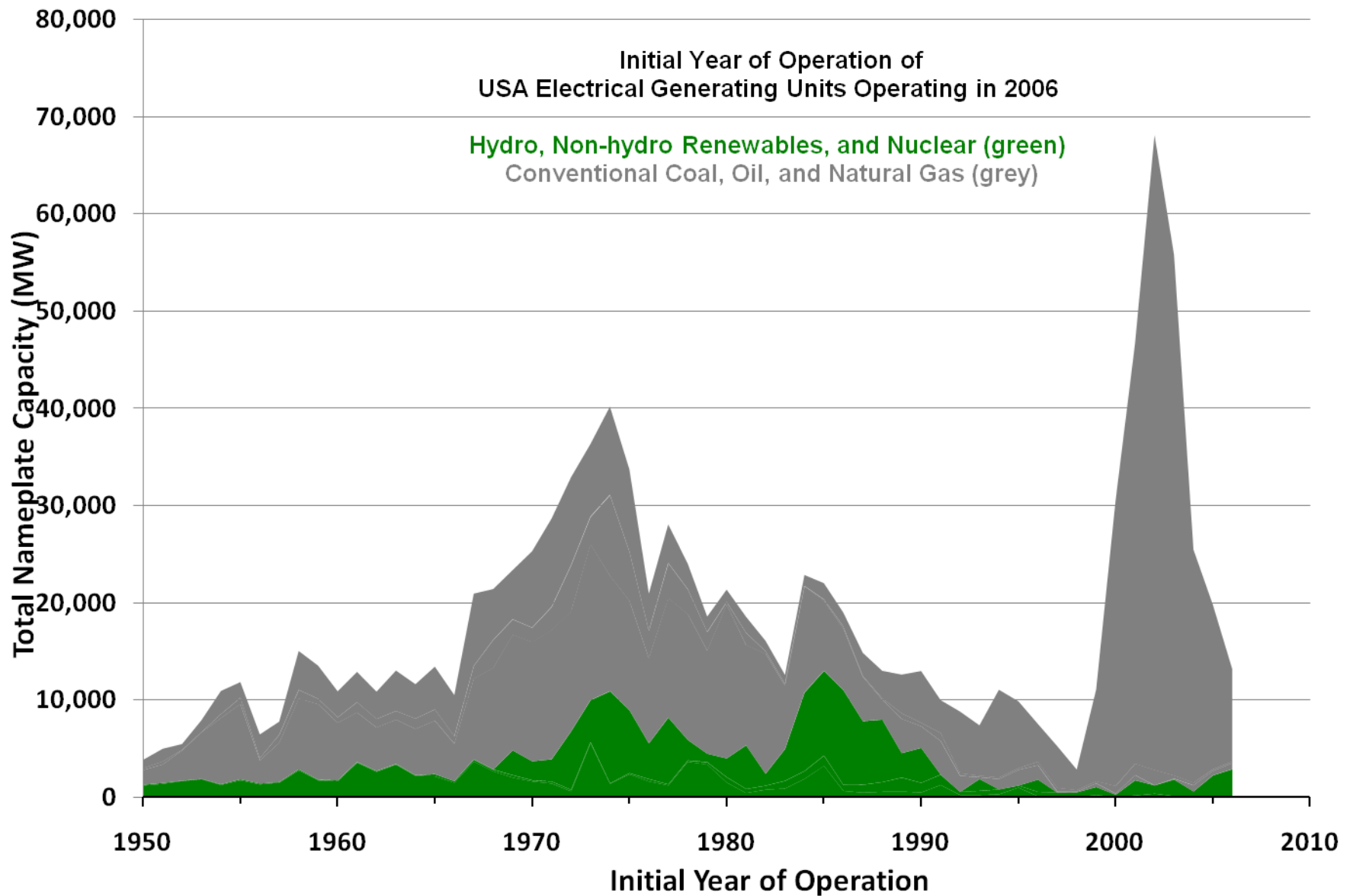
Percent of US Net Generation that is Renewable



US Renewables Net Generation 2008

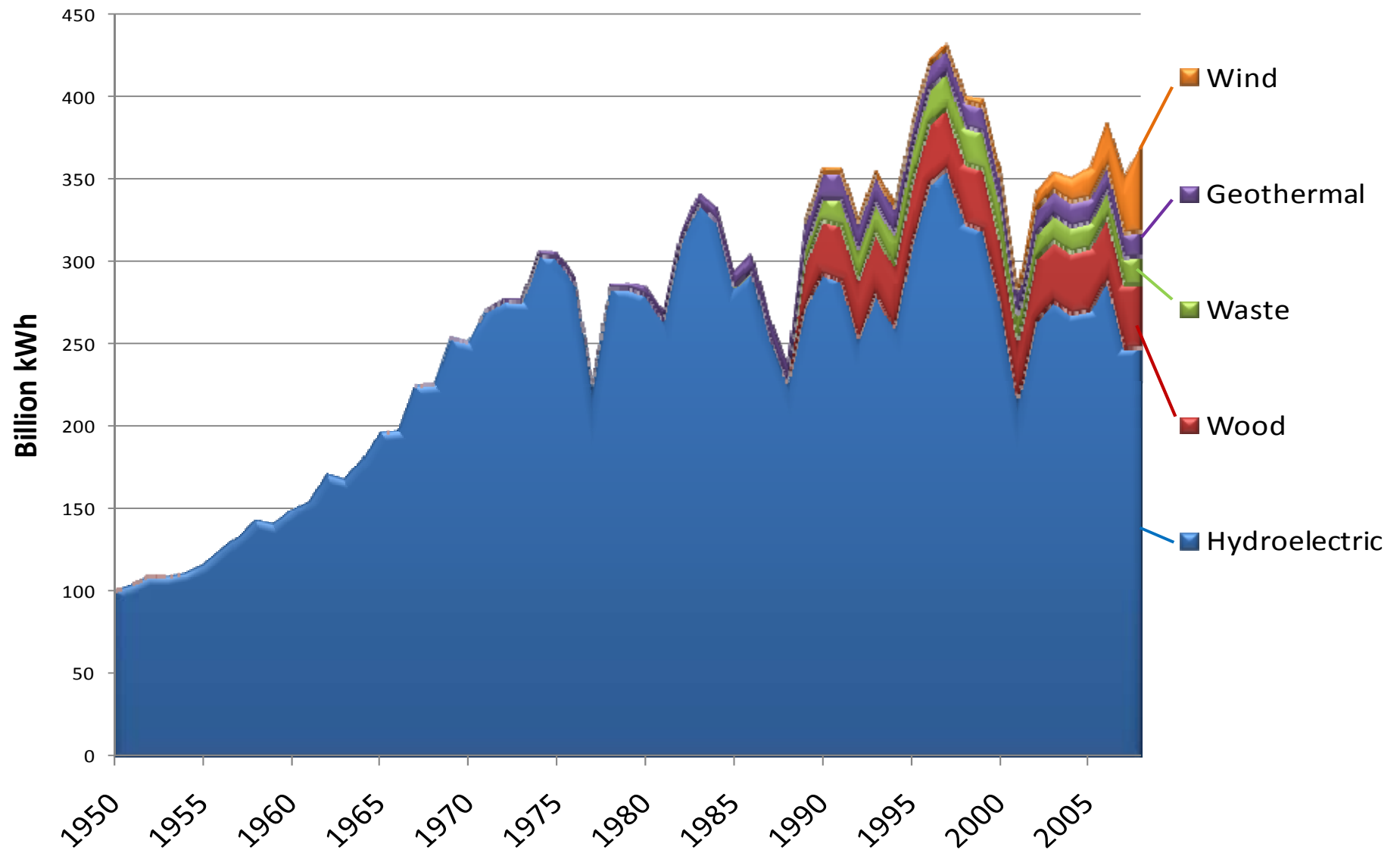
8.9% of total electric net generation



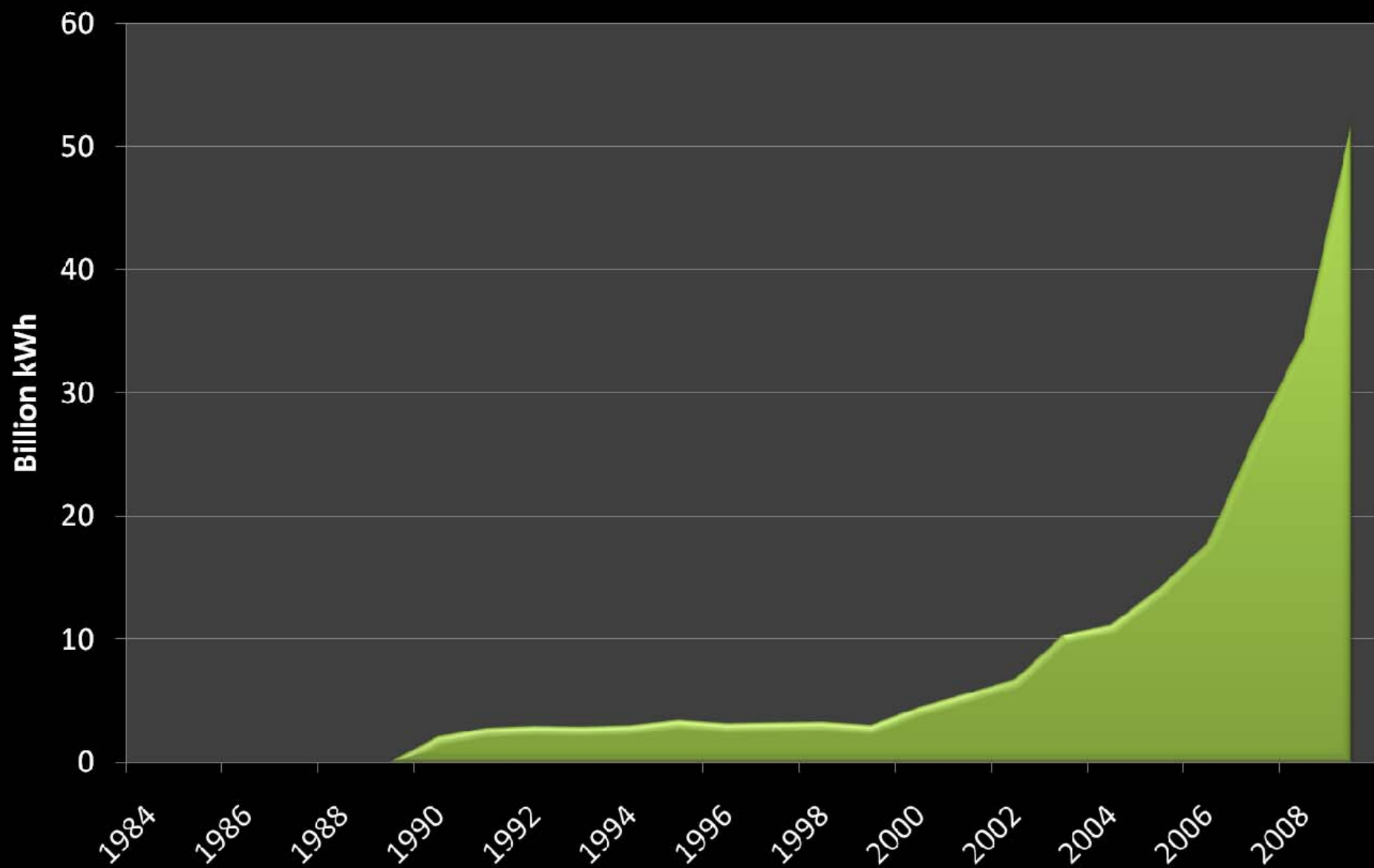




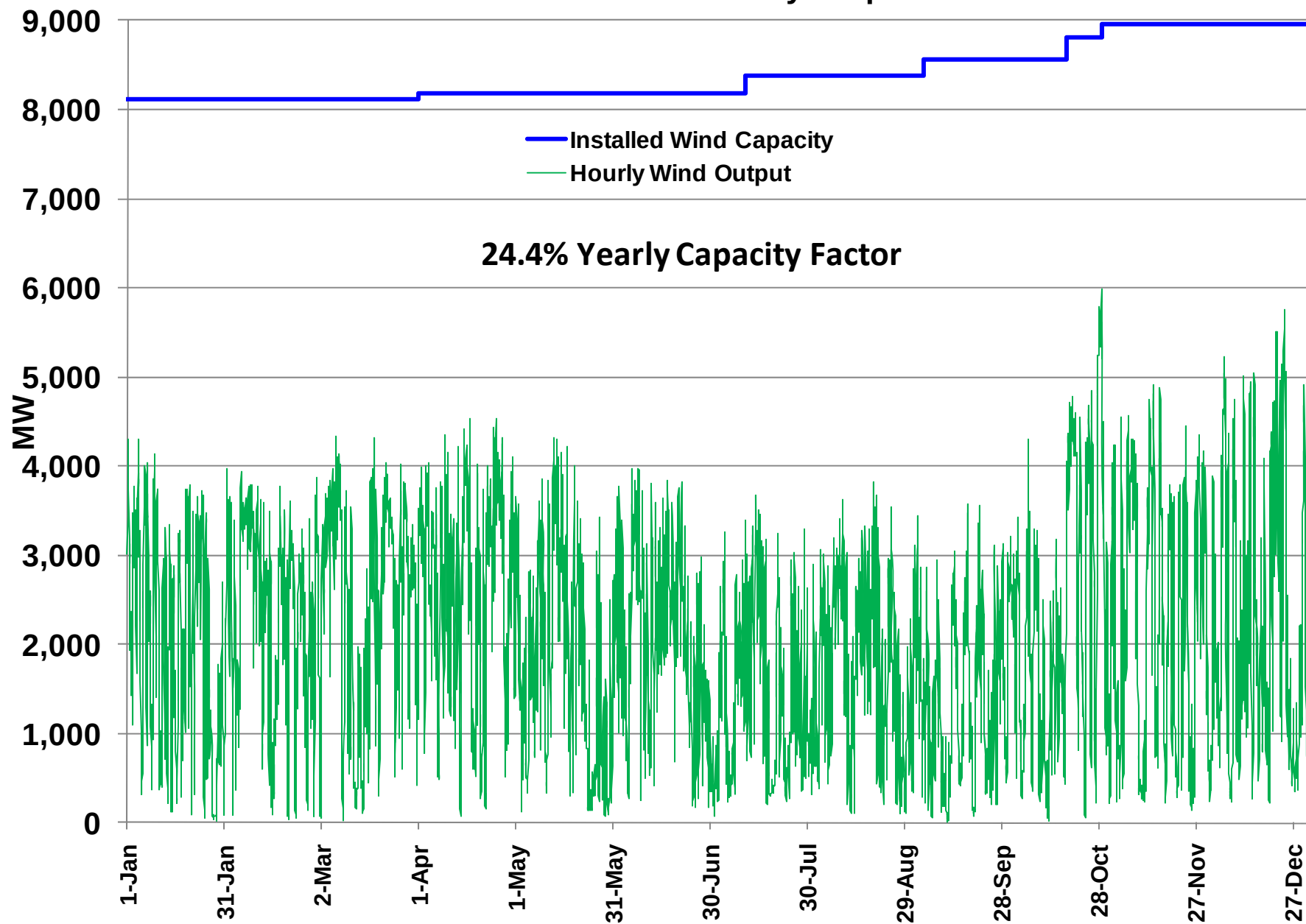
US Renewable Electricity Production



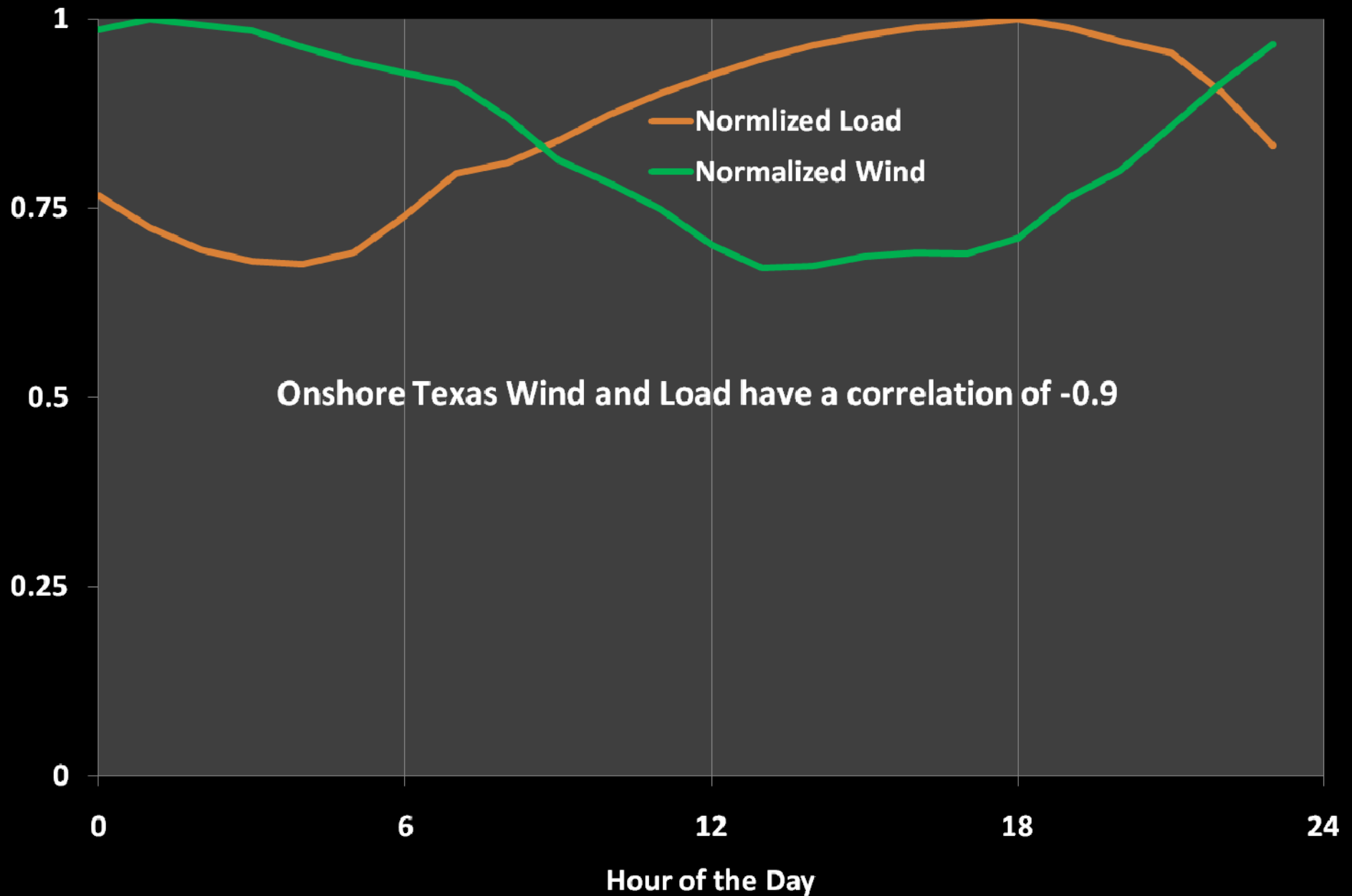
USA Wind Production



2009 ERCOT Wind Hourly Output

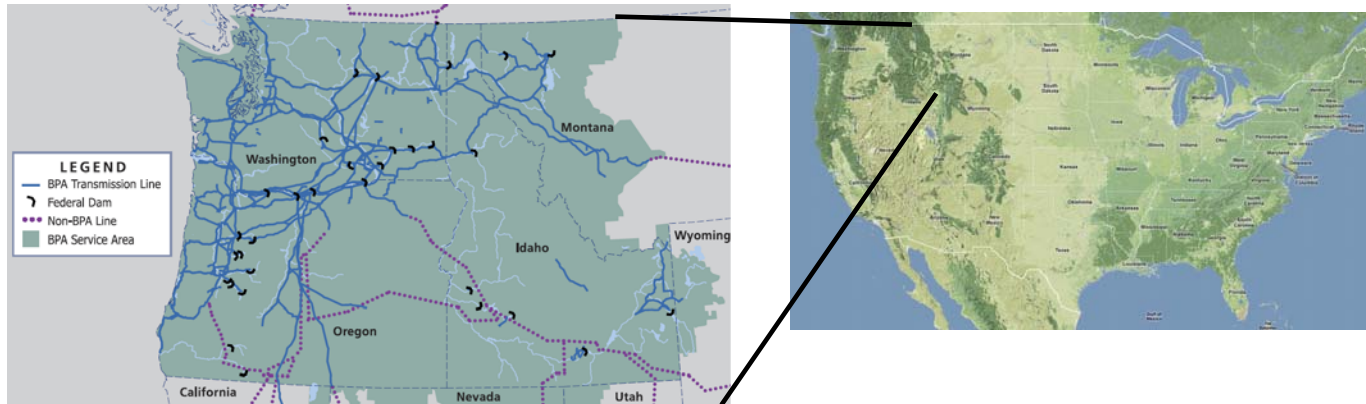


ERCOT Load and Wind in 2009 Averaged by Hour of the Day

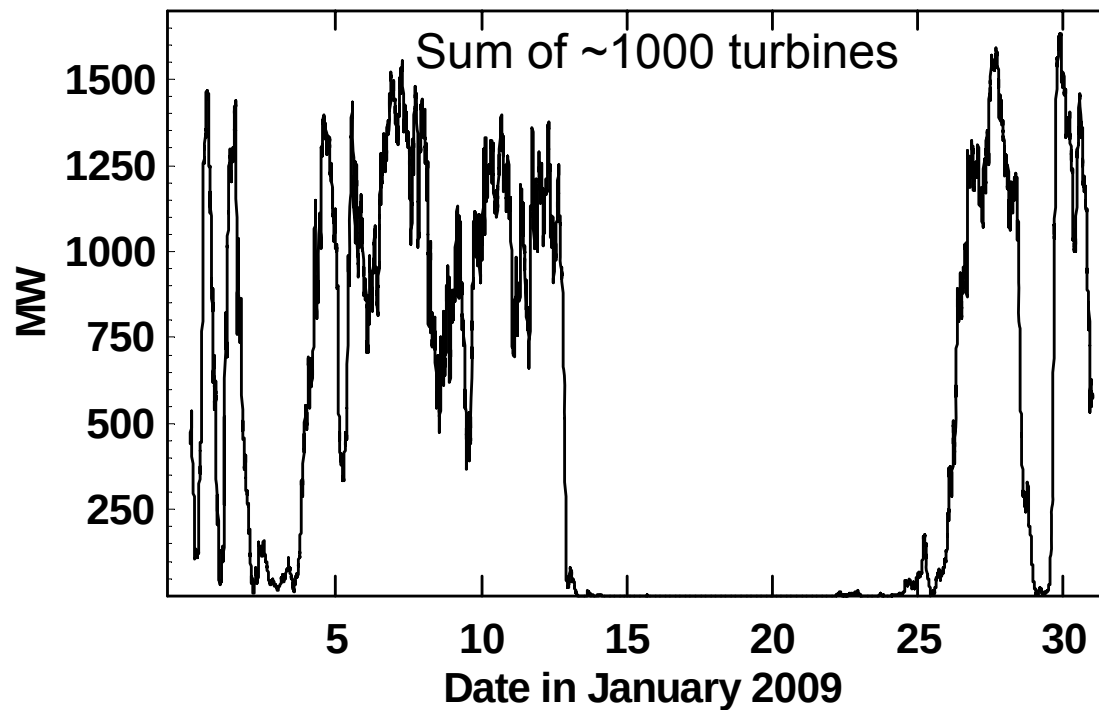




Wind sometimes fails for many days

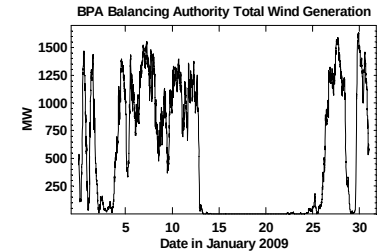


BPA Balancing Authority Total Wind Generation





Reserves: BPA January 2009

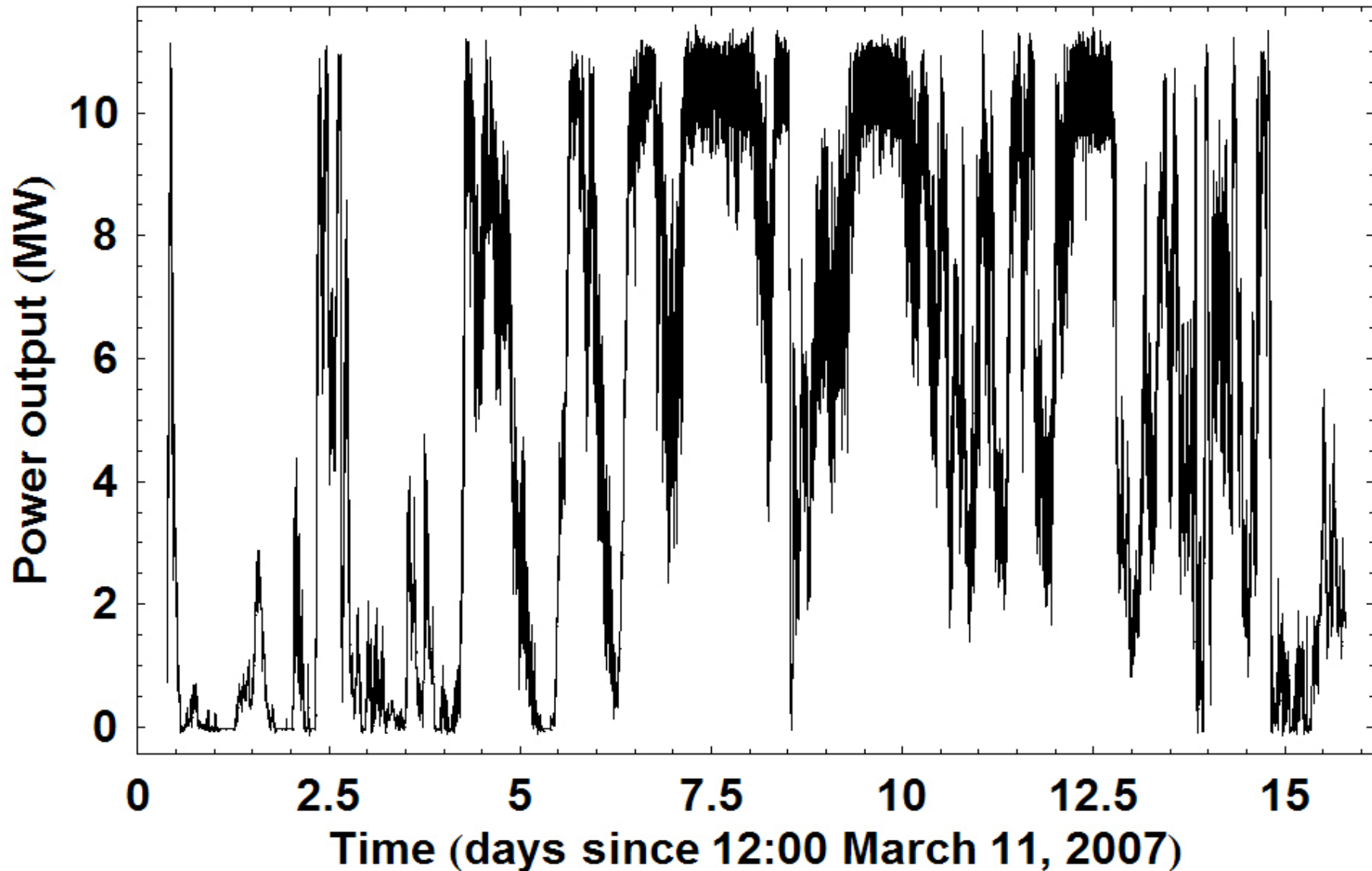


- In January 2009, 1600 MW capacity of wind supplied a maximum of 23.4% of the power required by Bonneville's load, and the output from the thousand wind turbines dropped to nearly zero for periods of 17 days that month.
- During this period, a maximum of 313 MW of spinning reserve was needed to counteract the fluctuations observed within 10 min (there were 73 occasions on which the 10 min fluctuations in wind were >100 MW).





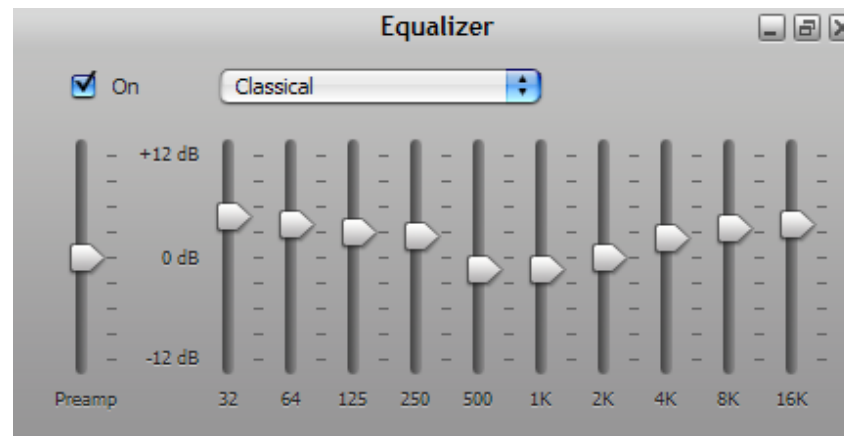
15 Days of 10-Second Time Resolution Data





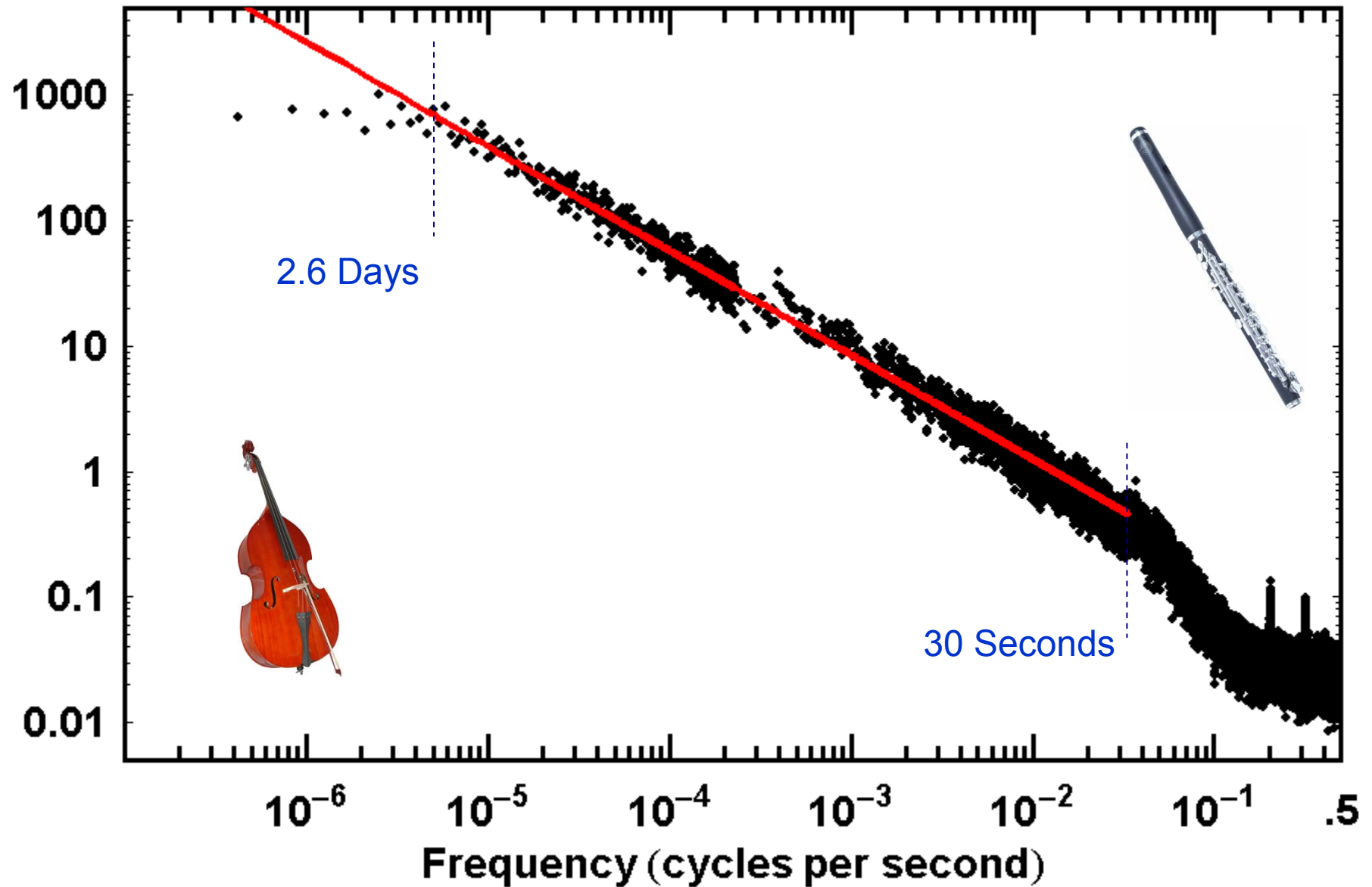
What is the character of the fluctuations?

What frequencies are present, and at what amplitudes?





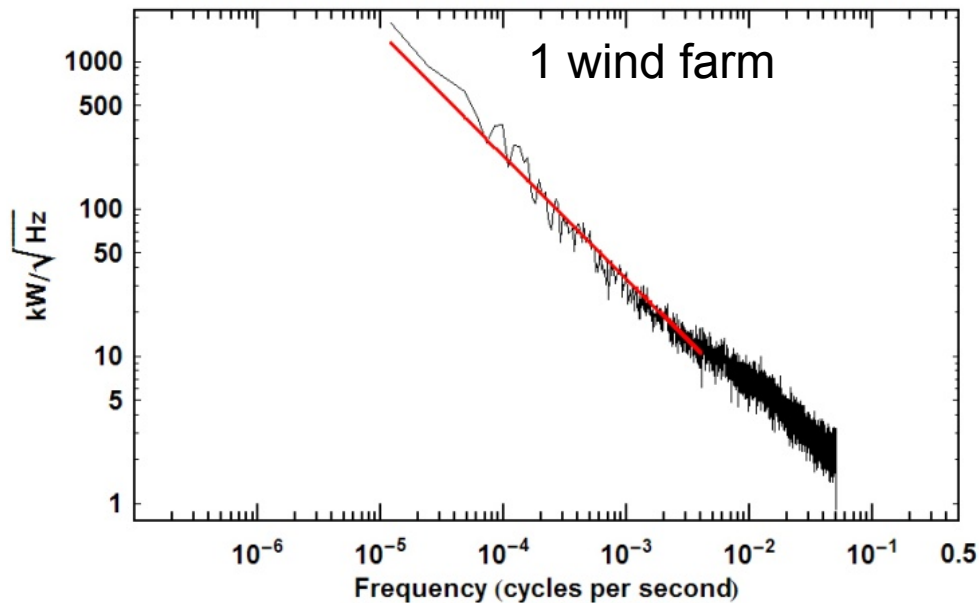
Fourier Transform to get the Power Spectrum



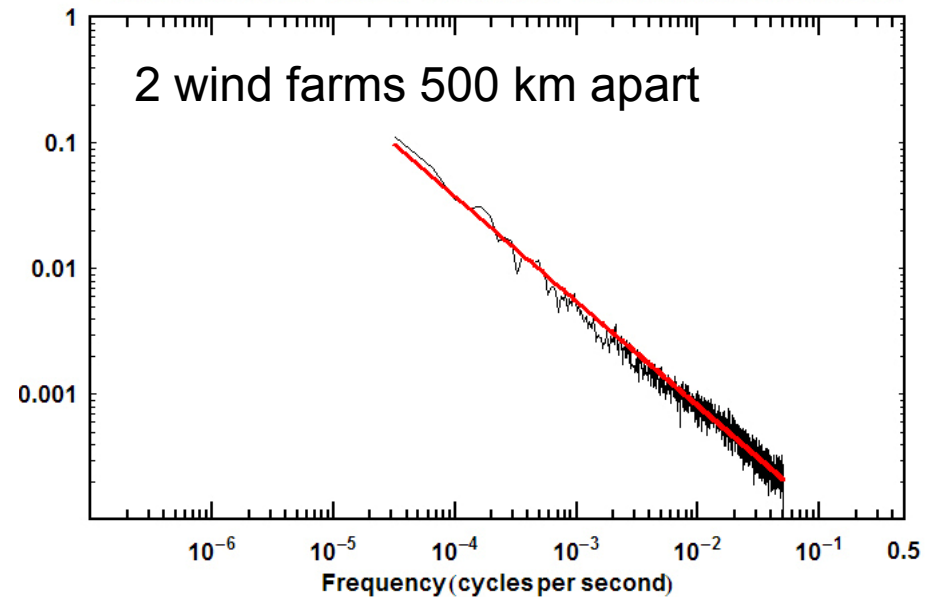


Texas, Oklahoma, North Dakota

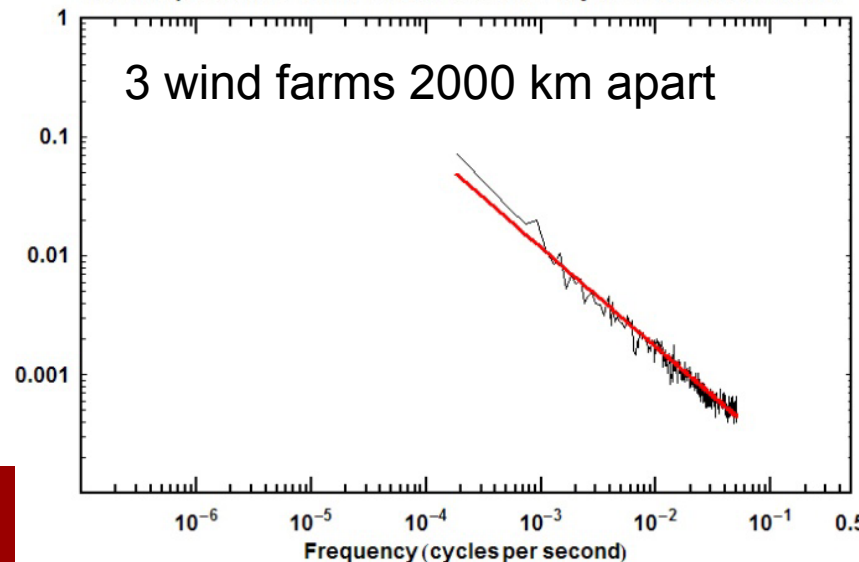
Power Spectrum of Texas for 15 days, 10 second resolution

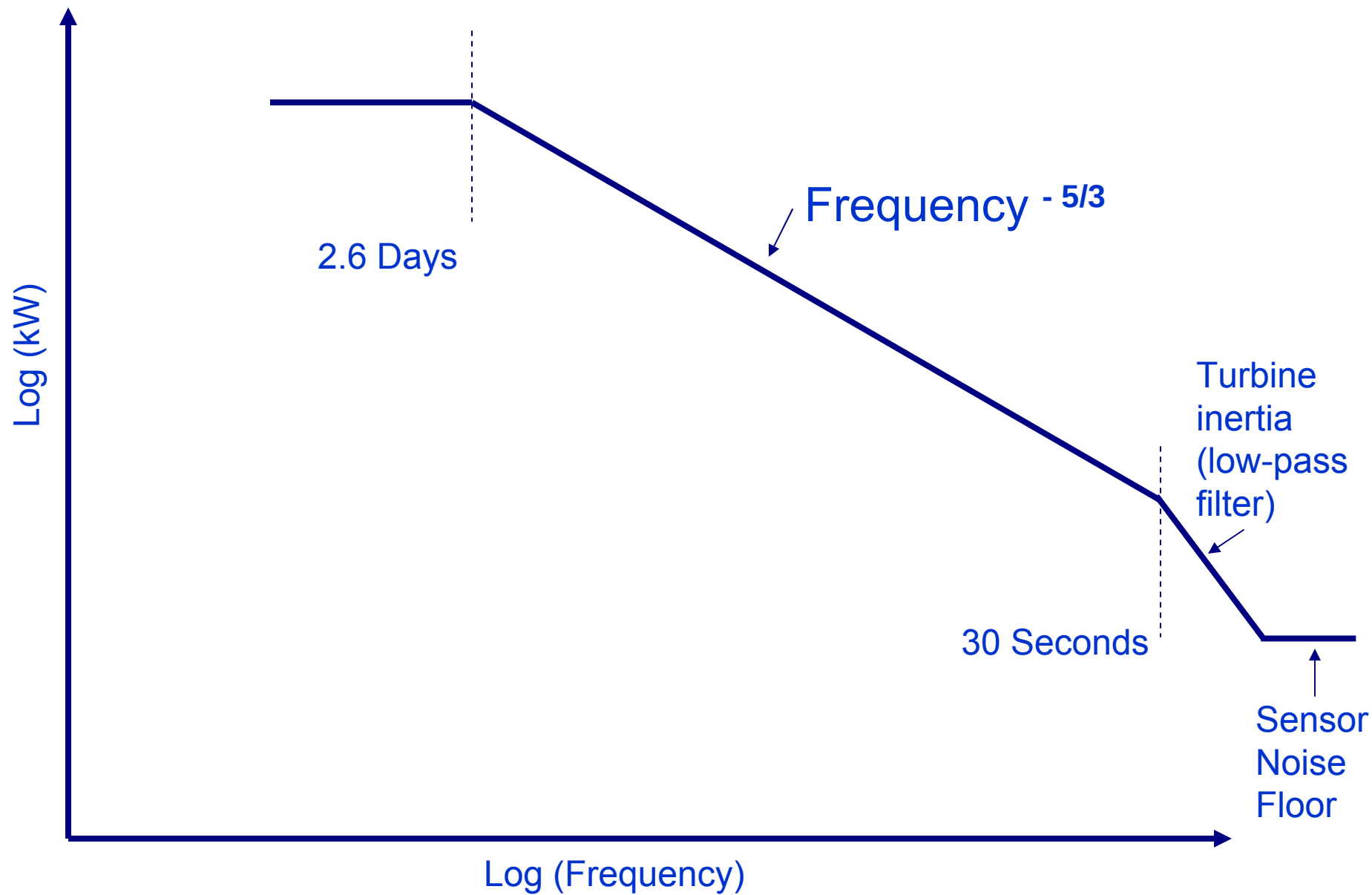


Power Spectrum of Texas + Oklahoma, 6 days at 10 second resolution



Power Spectrum of Texas + North Dakota, 1 day at 10 second resolution







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Journal of Power Sources 169 (2007) 369–374

JOURNAL OF
**POWER
SOURCES**

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Short communication

The spectrum of power from wind turbines

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Pittsburgh, PA 15213-3890, United States*

Received 6 February 2007; accepted 26 February 2007

Available online 12 March 2007

Abstract

The power spectral density of the output of wind turbines provides information on the character of fluctuations in turbine output. Here both 1-second and 1-hour samples are used to estimate the power spectrum of several wind farms. The measured output power is found to follow a Kolmogorov spectrum over more than four orders of magnitude, from 30 s to 2.6 days. This result is in sharp contrast to the only previous study covering long time periods, published 50 years ago. The spectrum defines the character of fill-in power that must be provided to compensate for wind's fluctuations when wind is deployed at large scale. Installing enough linear ramp rate generation (such as a gas generator) to fill in fast fluctuations with amplitudes of 1% of the maximum fluctuation would oversize the fill-in generation capacity by a factor of two for slower fluctuations, greatly increasing capital costs. A wind system that incorporates batteries, fuel cells, supercapacitors, or other fast-ramp-rate energy storage systems would match fluctuations much better, and can provide an economic route for deployment of energy storage systems when renewable portfolio standards require large amounts of intermittent renewable generating sources.

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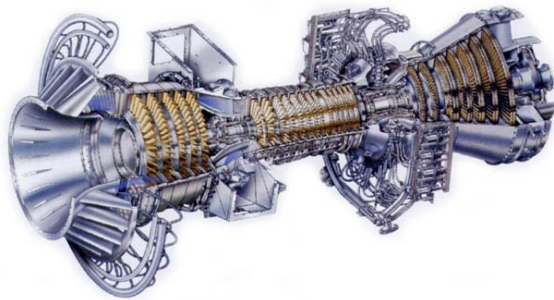
Keywords: Wind power generation; Spectral analysis; Energy storage; Intermittent; Renewable energy; Reliability



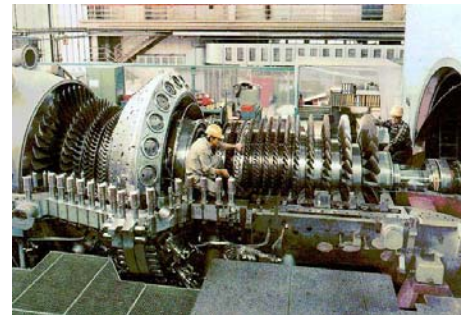


Work with PhD student Warren Katzenstein

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



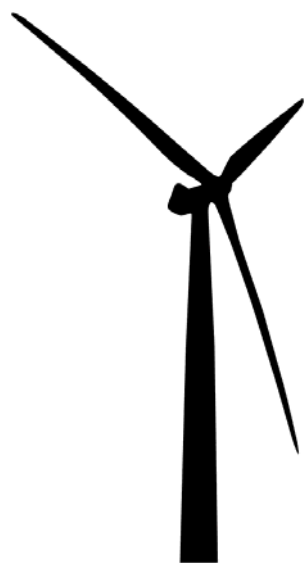


Approach

Compensating Power

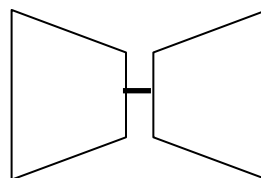
Variable Power

Firm Power



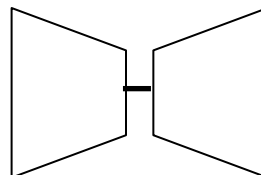
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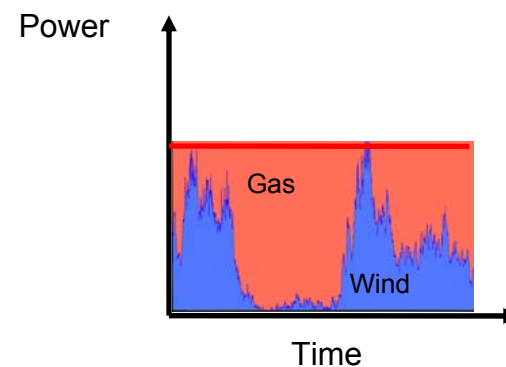
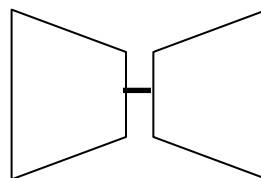
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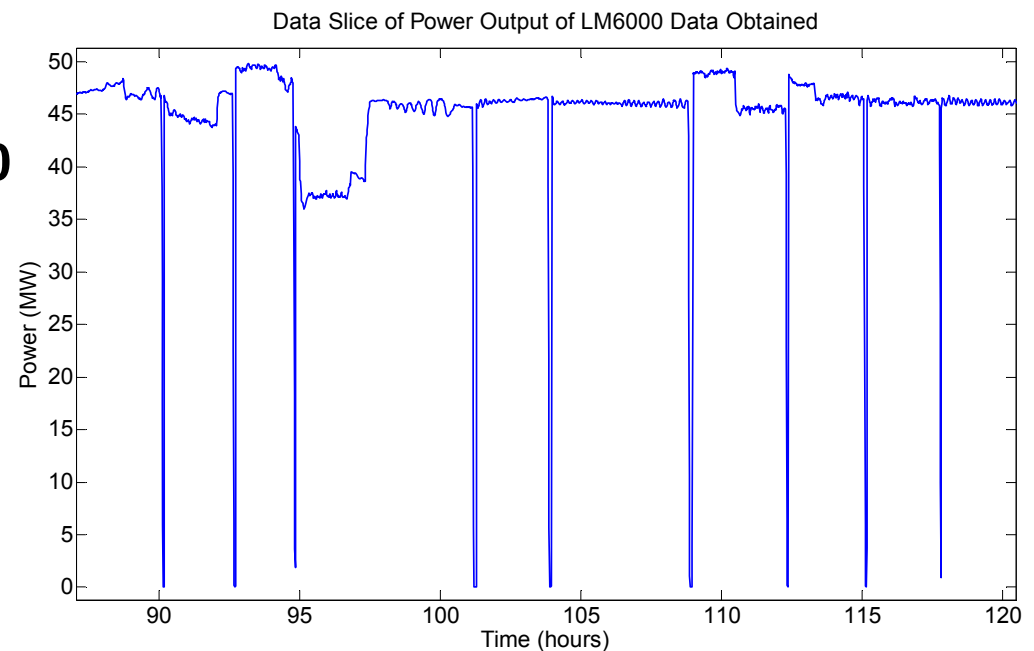
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Gas Turbine Data Obtained

- **NO_x emissions & heat rate**
 - 1 minute resolution
 - 11 days (from 2 501FDs: 200 MW, DLN, SCR)
 - 145 days (from 3 LM6000s: 50 MW, steam NO_x control)
 - Data:
 - Gas flow
 - Load (MW)
 - NO_x ppm and pounds
 - NO_x ppm corrected to 15% O₂
 - O₂ %
 - Heat rate (mBtu/hour)
 - From operating gas turbines in a US power company



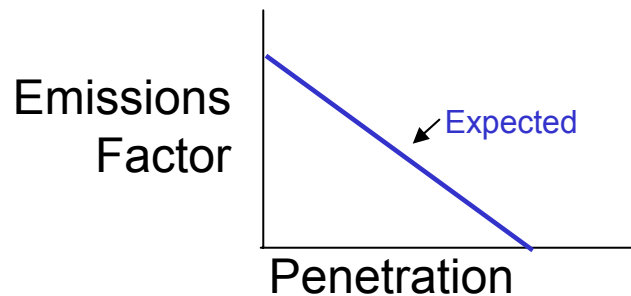


Results

- Penetration P of renewables from 0 to 100%
- Emissions factor (kg of CO₂ or NO_x per MWh)
- Expected reductions vs. our model's predictions:

If the actual system emissions are $M_{\text{gas+renewable}}$ then the fraction of expected emissions reductions that are achieved is

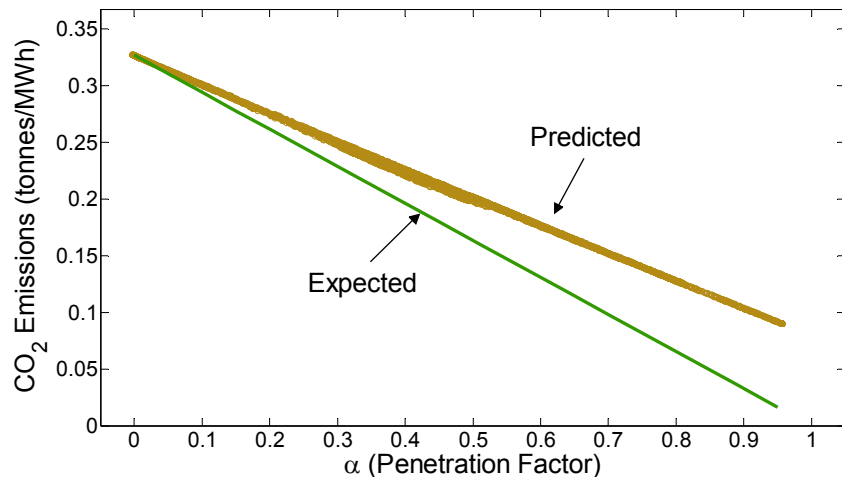
$$(M_{\text{gas}} - M_{\text{gas+renewable}}) / (M_{\text{gas}} * P)$$





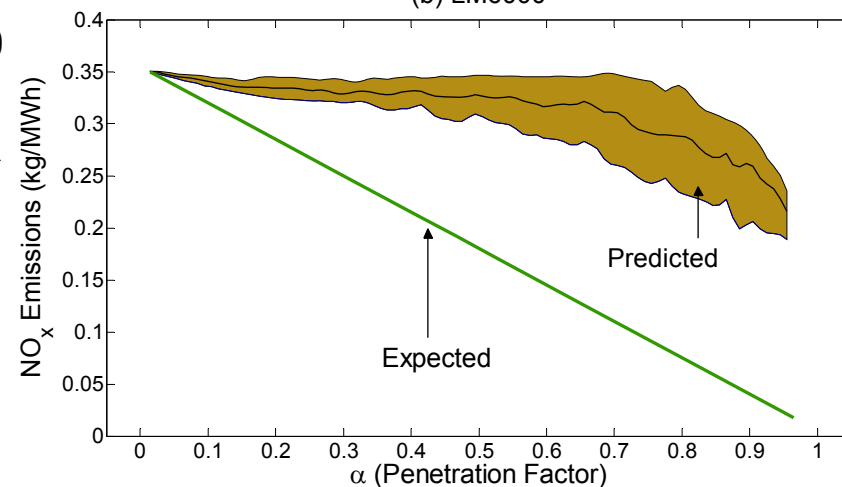
Emissions Factors

(a) LM6000

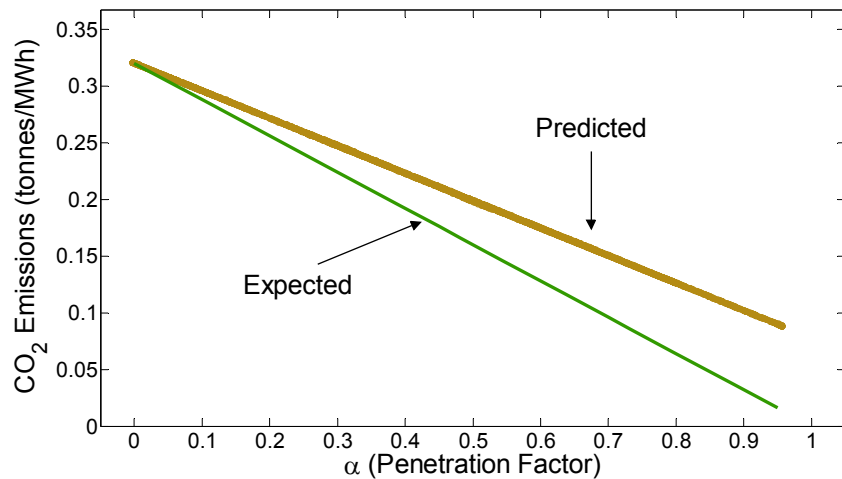


LM6000
Steam,
no SCR

(b) LM6000

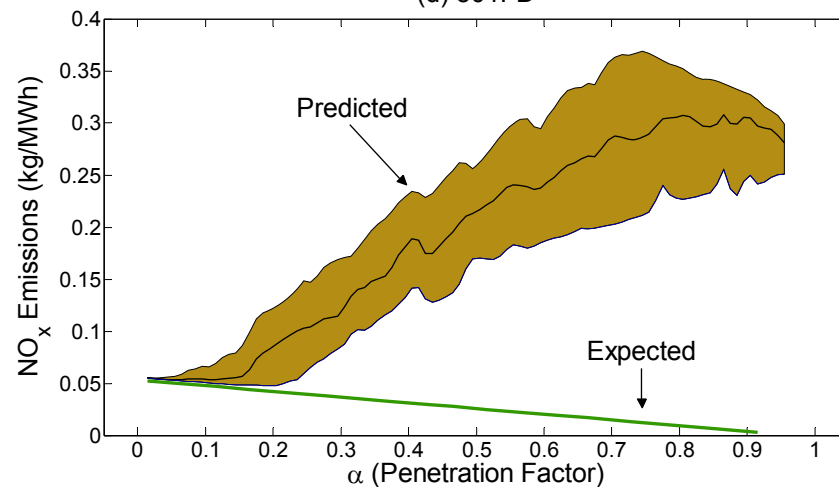


(c) 501FD



501FD
DLN,
SCR

(d) 501FD

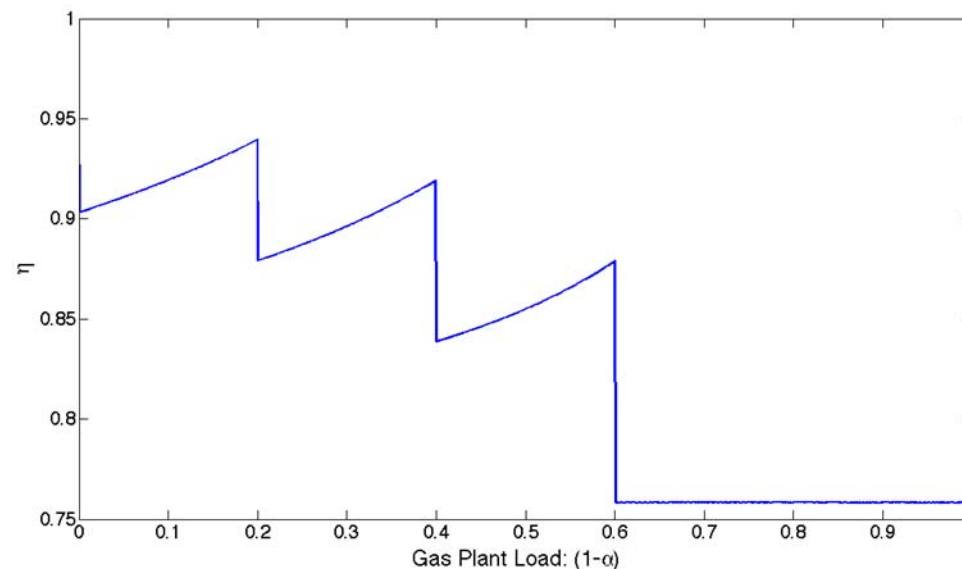




We analyzed up to 20 gas turbines smoothing wind and solar

η is the ratio of predicted to expected emissions
 α is the penetration of the wind or solar power

$$\eta = \frac{s\alpha + \frac{f_0}{P_{\max}} \left(1 - \frac{\sum_{i=1}^n u_i}{n}\right)}{\left(\frac{f_0}{P_{\max}} + s\right) \alpha}$$



Variation of η with α for 5 plants with one plant operating as spinning reserve





Environ. Sci. Technol. 2009, 43, 253–258

Air Emissions Due To Wind And Solar Power

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Carnegie Mellon Electricity Industry Center, Tepper School of Business, and Department of Engineering and Public Policy, 254 Posner Hall, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213

Received May 23, 2008. Revised manuscript received September 17, 2008. Accepted October 23, 2008.





Solar

- The Sun deposits on US land 3,900 times the US net electricity generation
- At 7% efficiency, solar cells to meet US electricity needs (not including packaging) would cover 0.5% of US land area, as compared to 27% cropland.
- Capacity factor: 19% in Arizona, 14% in New Jersey, 11% for the PV on the DOE HQ in DC, so significant storage would be required.

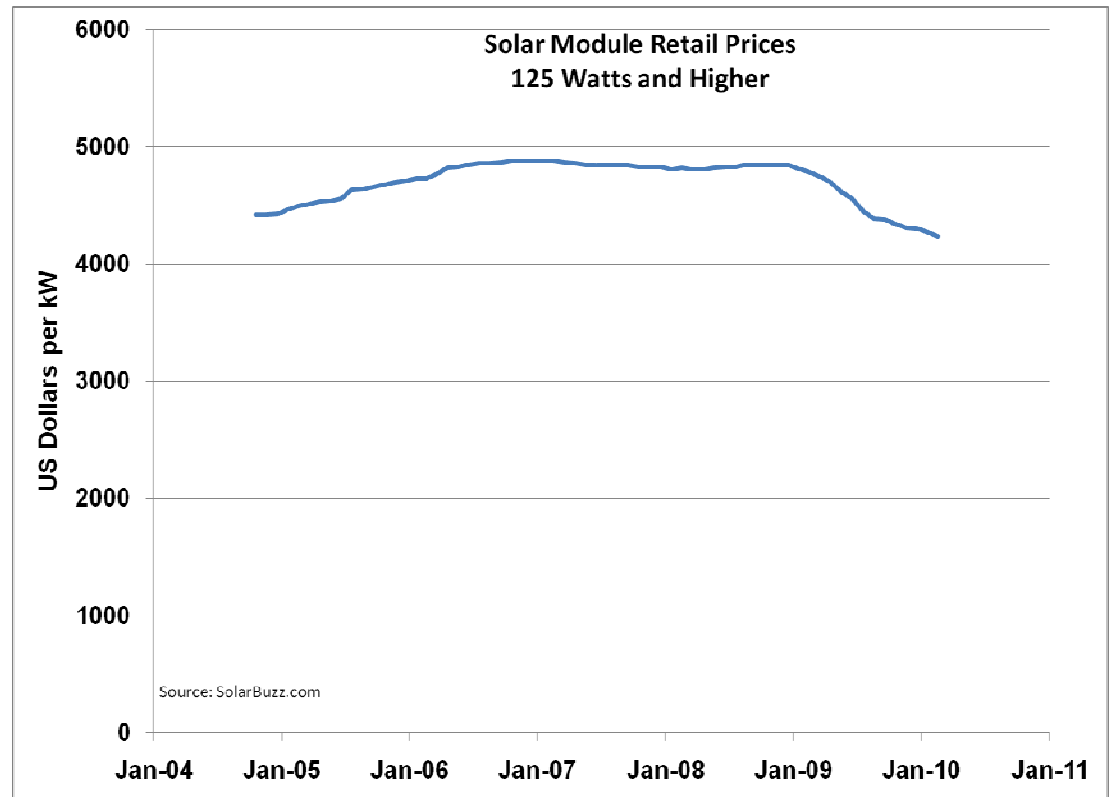




Solar Photovoltaic

Unsubsidized buss bar cost is ~ 23 cents per kWh. (Arizona; 8% blended cost of capital, \$3500/kW, 20 years, no storage).

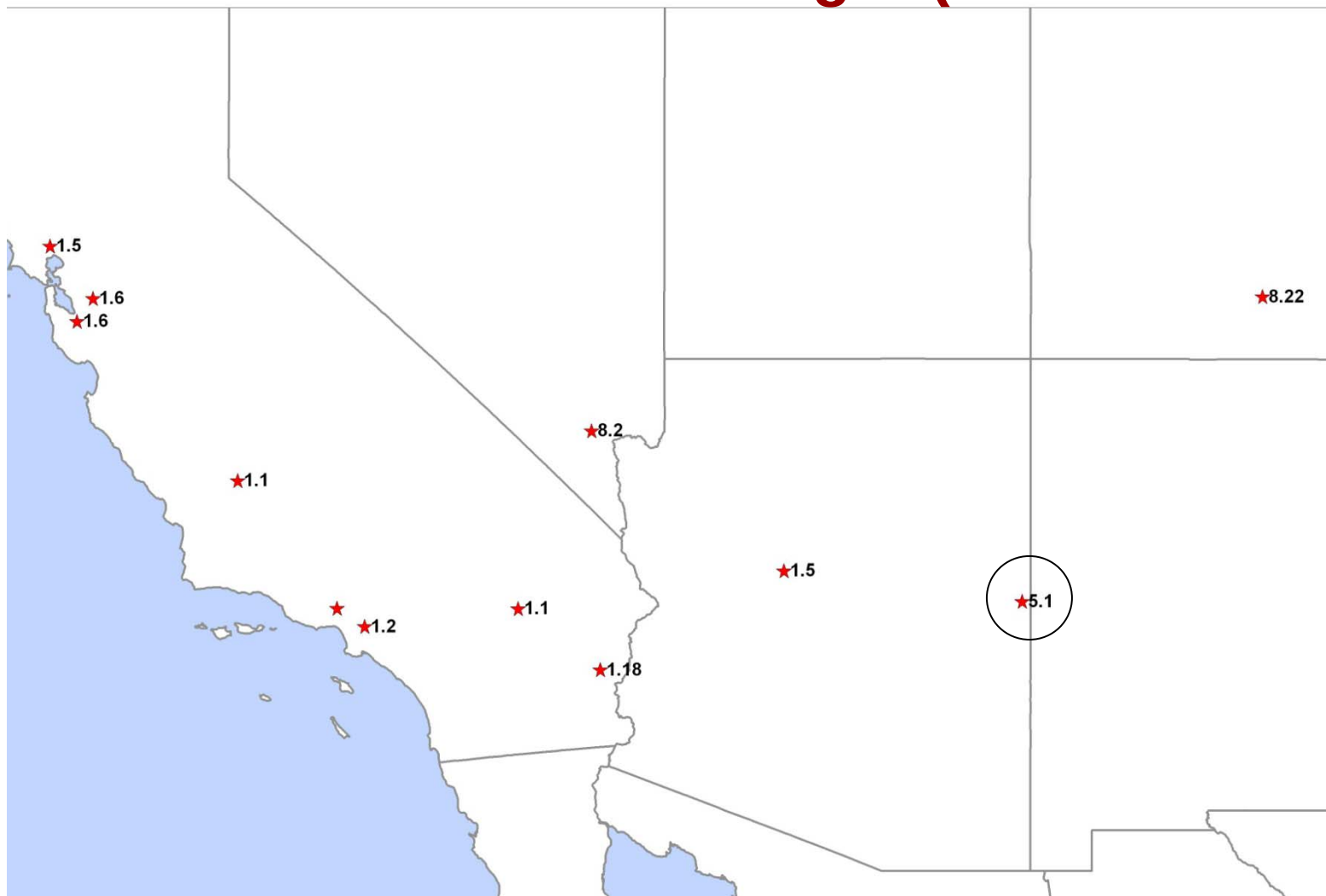
- Price of solar cells has not been decreasing much.
- Solar cells make up only 50-60% of the system price.





Solar

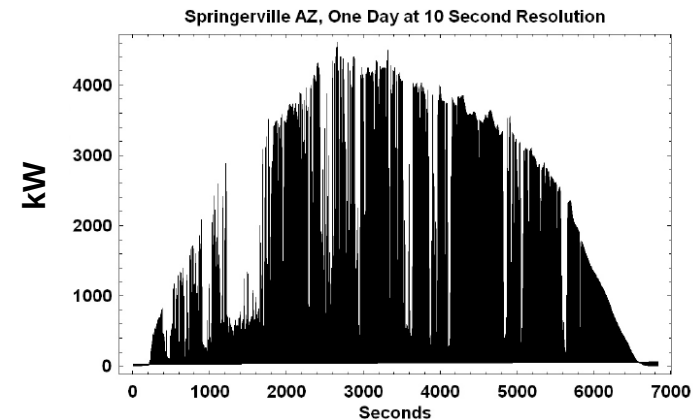
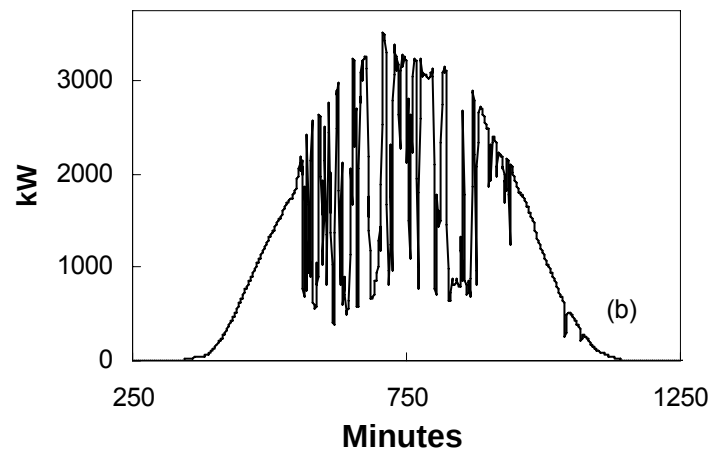
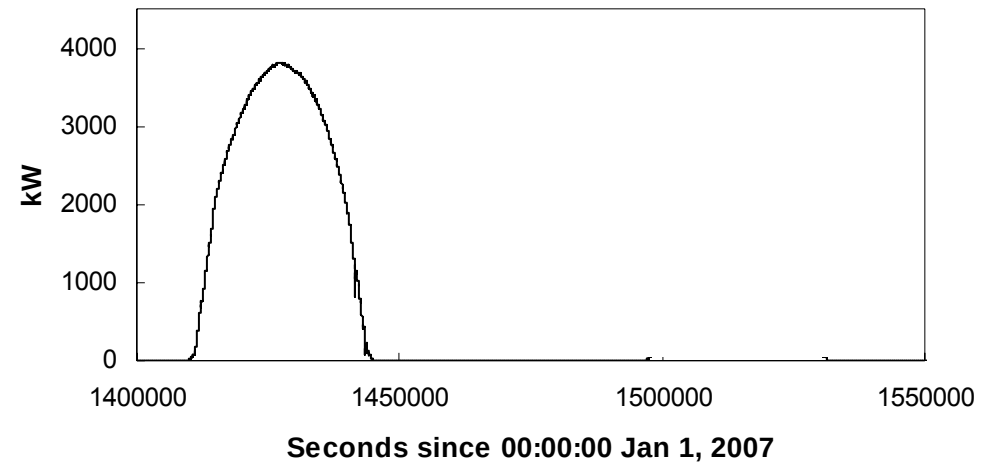
Work with Dr. Aimee Curtright (now at RAND)



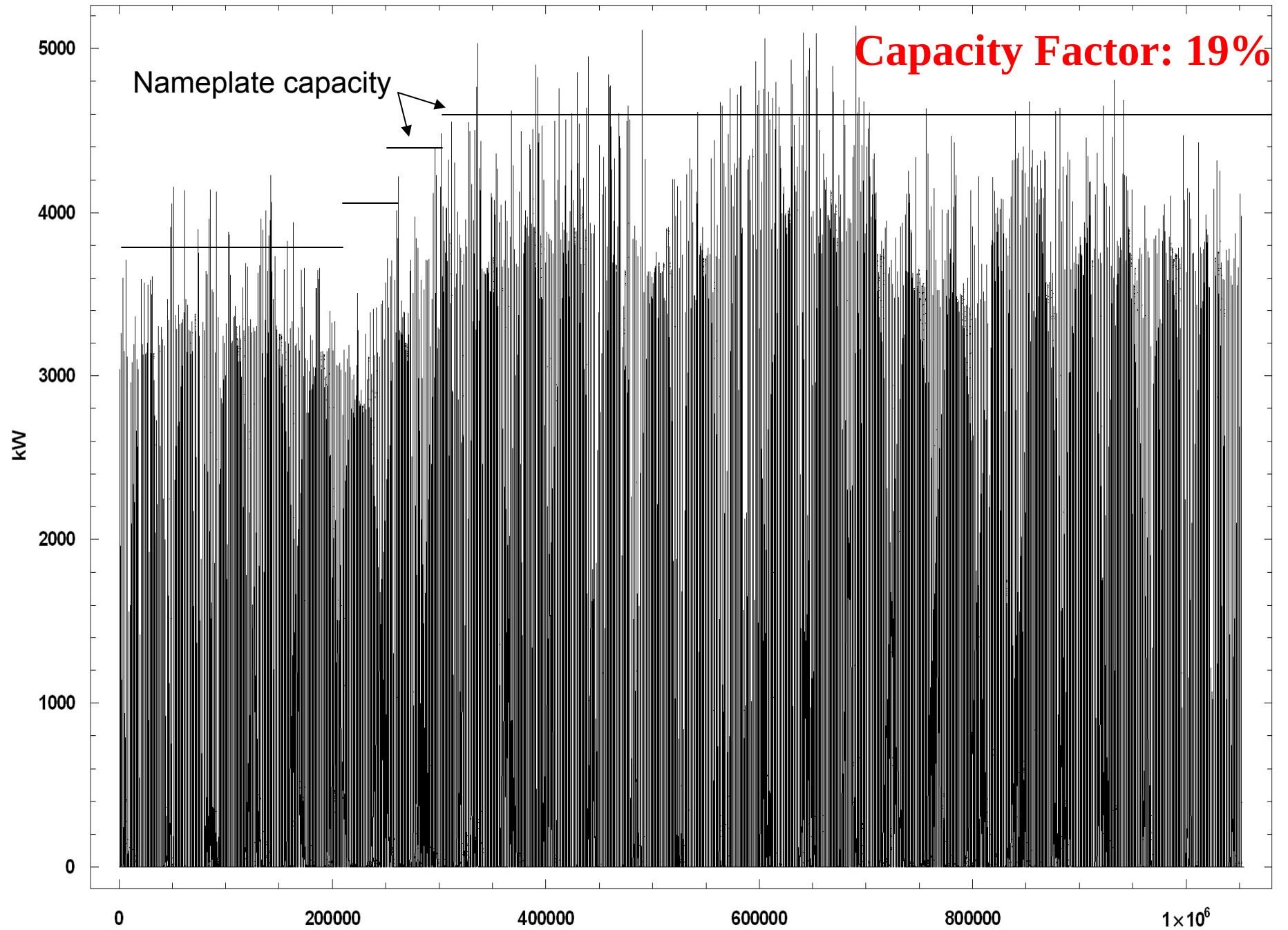


Comparison of Wind with Solar PV

4.6 MW TEP Solar Array (Arizona)

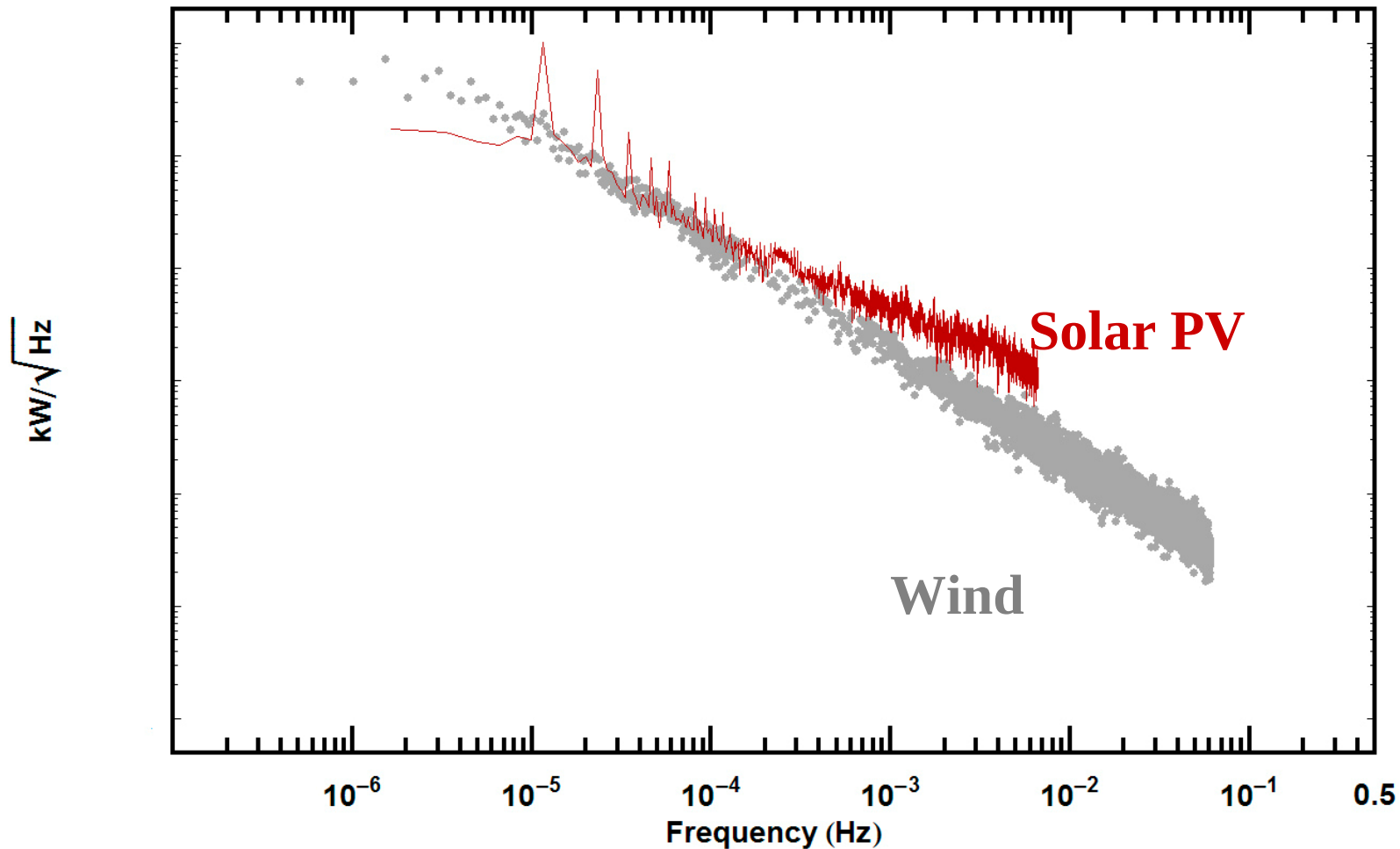


January 2004 – December 2005





Comparison of wind and solar PV



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





The solar PSD fit is $f^{-1.3}$

- Significantly flatter than that of wind ($f^{-1.7}$).
 - Fluctuations in the range of 10 minutes to several hours are relatively larger for PV than for wind.
 - Compensation for PV fluctuations is likely to be more expensive than for wind.





Application

The Character of Power Output from Utility-Scale Photovoltaic Systems

Aimee E. Curtright¹ and Jay Apt^{1,2*,†}

¹Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, USA

²Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213, USA

Power produced by utility-scale solar photovoltaic (PV) systems has fluctuations on both short and long time scales. Power spectral density (PSD) analysis provides information on the character of these power fluctuations. Examination of the correlation and step size of the power output between several PV sites within a multi-site system allows assessment of geographic diversification for addressing intermittency. Both techniques provide insight into the characteristics of required firm power and/or demand response required to accommodate large-scale PV deployment. Copyright © 2007 John Wiley & Sons, Ltd.

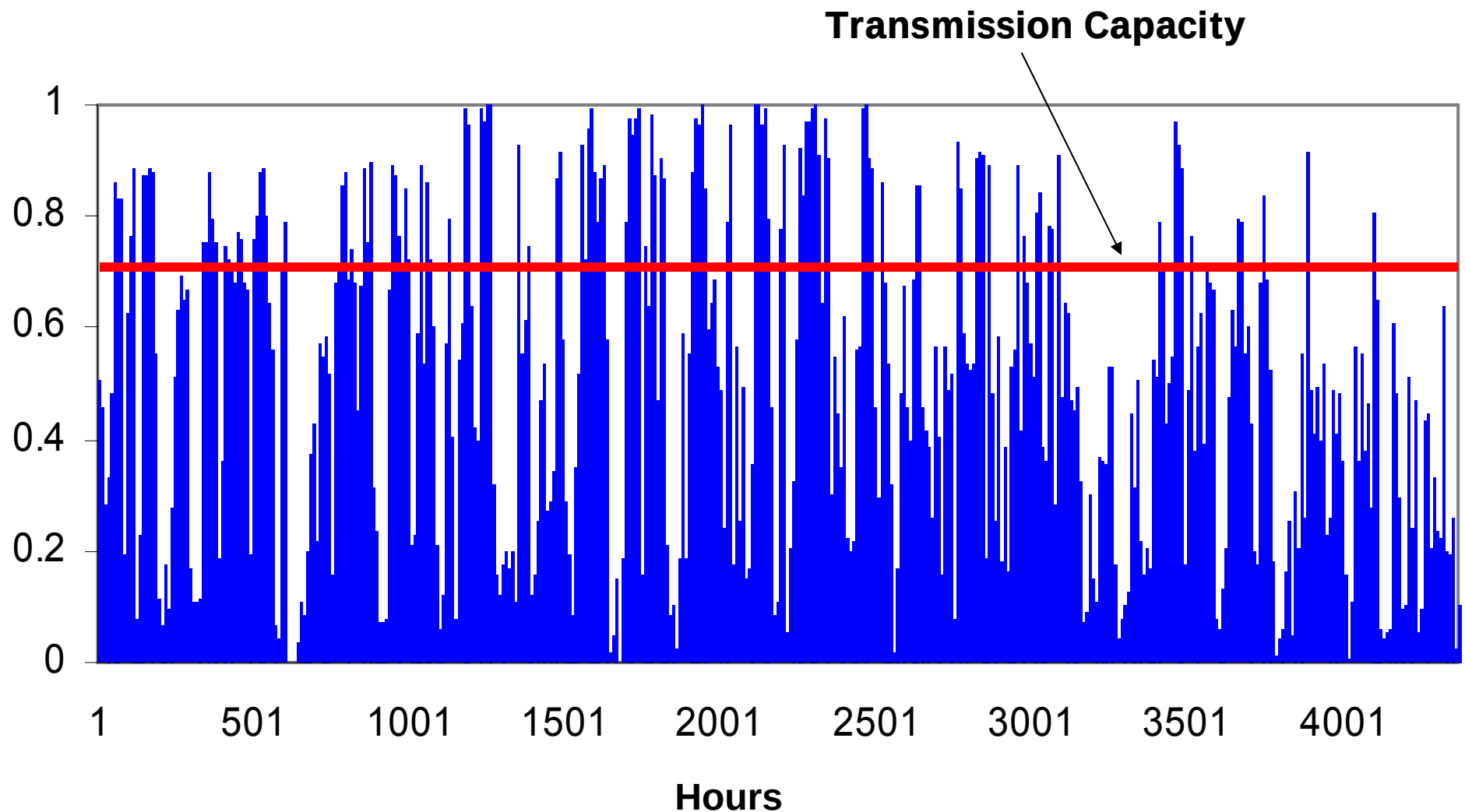
KEY WORDS: grid-connected PV systems; intermittency; spectral analysis

Received 14 June 2007



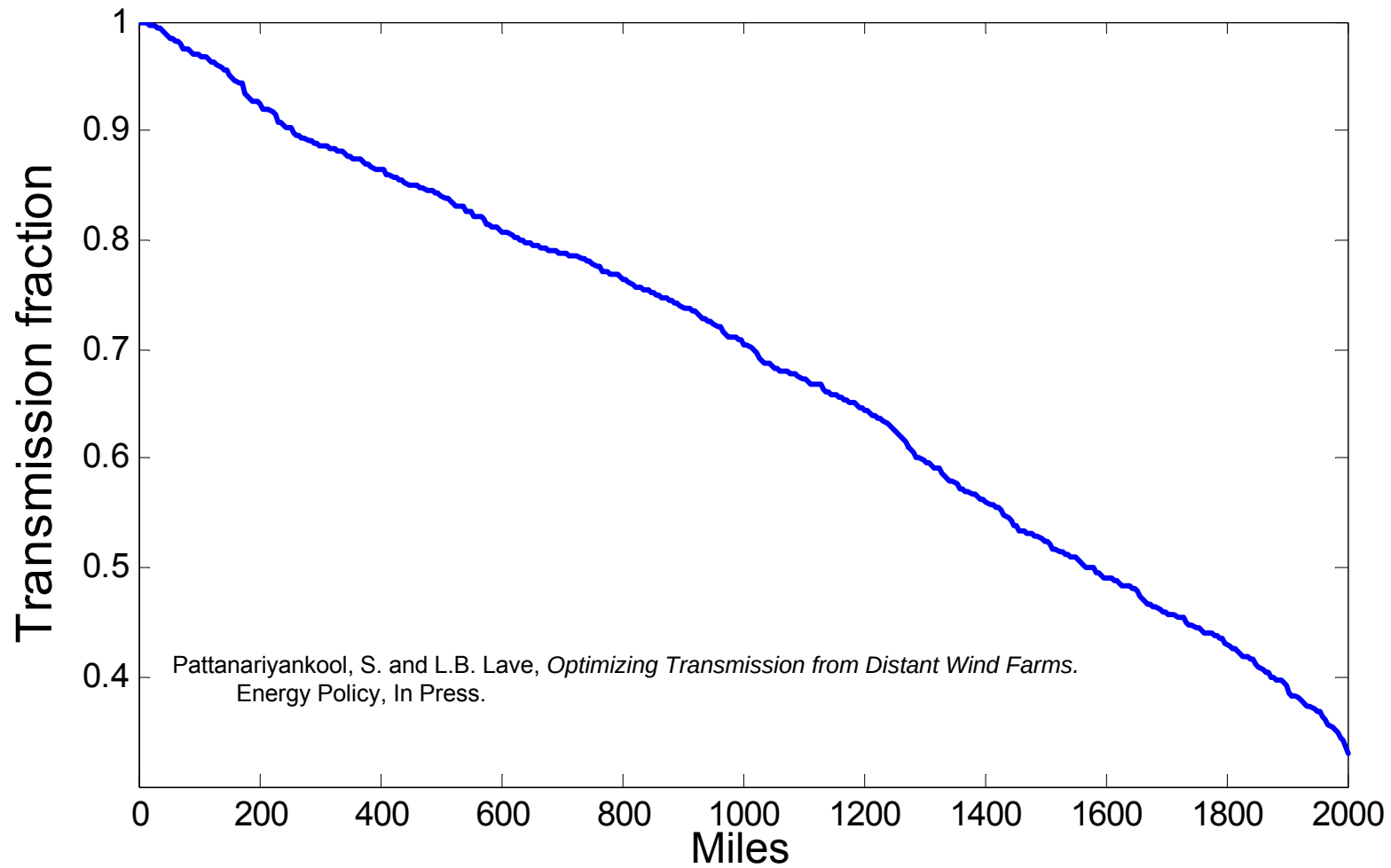


Do you build transmission for the nameplate wind capacity?





Transmission length vs. transmission capacity



Profit maximizing transmission capacity vs. length of the transmission line.





So, the least-cost solution may be a lower-class wind area close to load





Summary – wind

- Even 3000 summed wind turbines have fast and large power fluctuations.
- The PSD of wind follows a Kolmogorov spectrum over 4 orders of magnitude.
- Adding wind farms together smoothes the output, but the smoothing is a function of frequency, and has diminishing returns to scale.
- A portfolio of slow, fast, and very fast sources is the most economic way to match wind.





Summary – solar PV

- Solar PV in Arizona has fast and large power fluctuations.
- The capacity factor in NE Arizona over 2 years was 19%.
- The PSD of solar PV is significantly flatter than that of wind, implying more required firm power.





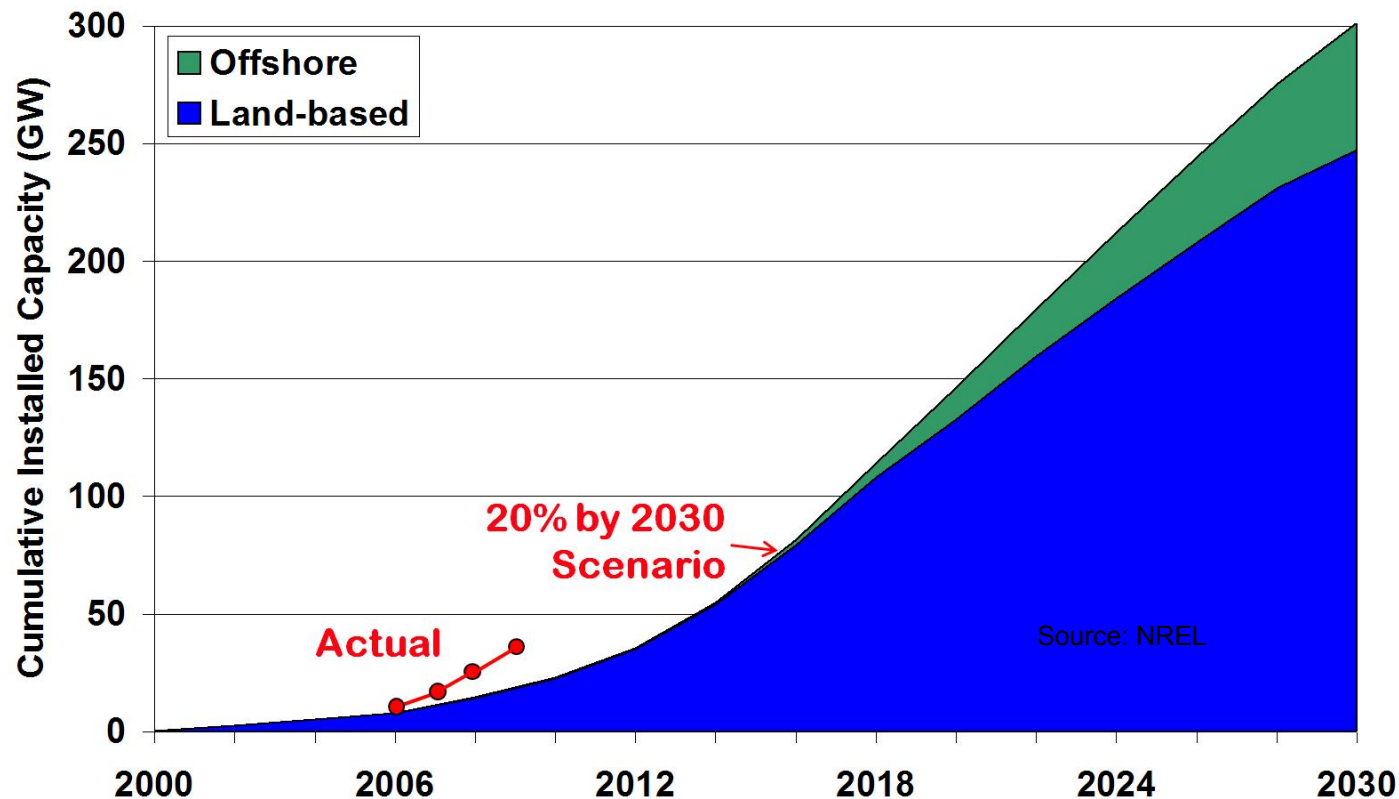
None of this means that wind (or solar if costs ever come down) can't be used at large scale, but it will require a portfolio of fill-in power (some with very high ramp rates, some with slow) and R&D is required to optimize the grid for fast and deep changes.





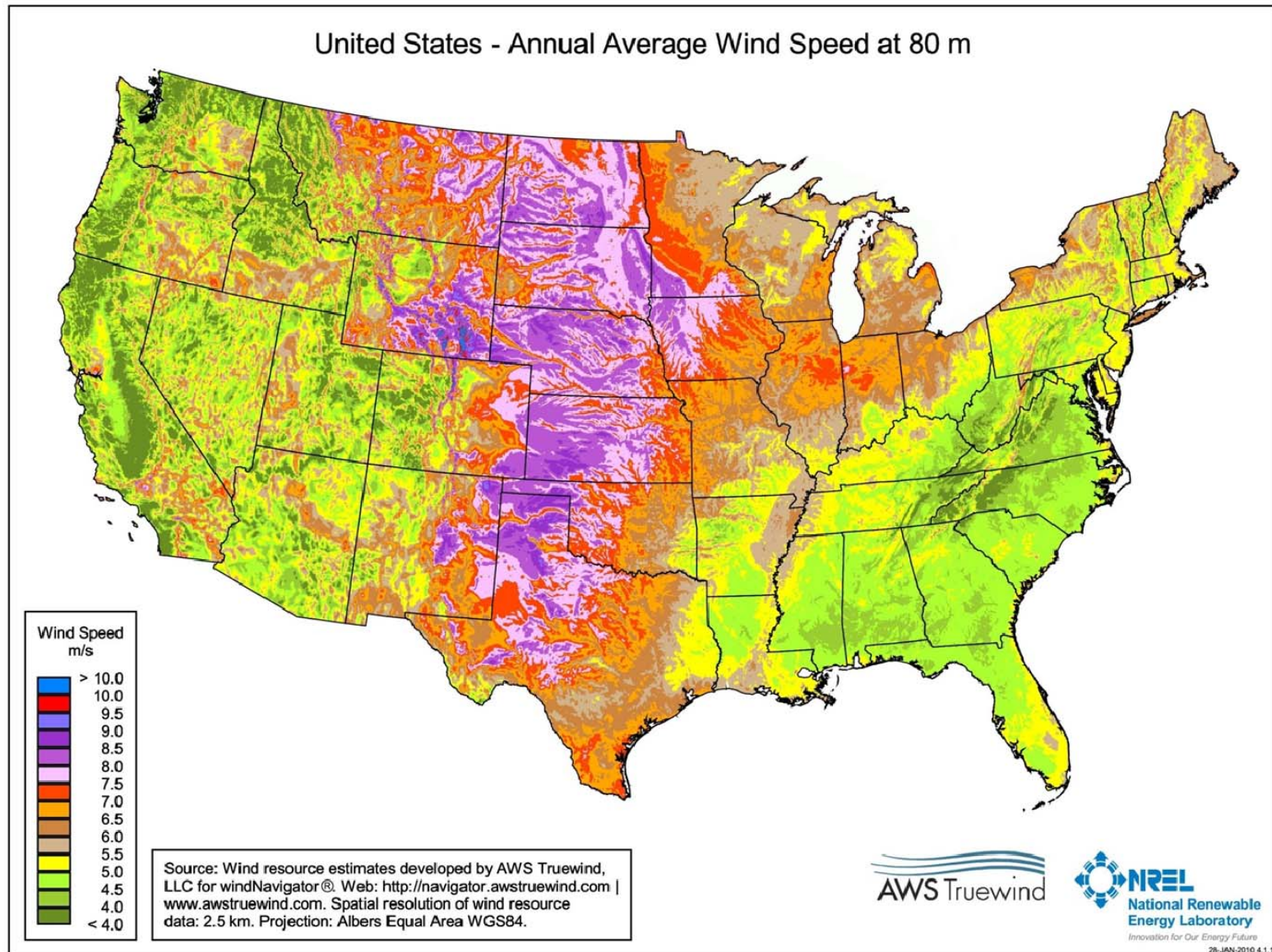
A Few of the Recent Studies

- July 2008 "20% Wind Energy by 2030"
 - Prepared by Energetics Inc. with NREL, AWEA, UWIG
 - Requires 300 GW installed capacity





Recent Studies





Recent Studies

- *Interstate Vision for wind Integration*, 2008. American Electric Power and the American Wind Energy Association.
 - Available at
<http://www.aep.com/about/i765project/docs/WindTransmissionVisionWhitePaper.pdf>.
- Recommends an investment of \$60 billion of transmission projects to support a 20% wind RPS.





Recent Studies

- FERC commissioned LBNL in mid-2009 to:
 - determine if frequency response is an appropriate metric to assess the reliability impacts of integrating renewables;
 - use the resulting metric to assess the reliability impact of various levels of renewables on the grid.
- NERC (April 2009), "Accommodating High Levels of Variable Generation"
 - Applicability of some recommendations in restructured states is problematic
 - Recommends large transmission investment
 - Demand response and storage treated in general terms





Recent Studies

- US National Academy of Sciences, June 2009
"Electricity from Renewable Resources"
 - "Some combination of intelligent, two-way electric grids, scalable and cost-effective methods for large-scale and distributed storage (either direct electricity storage or generation of chemical fuels); widespread implementation of rapidly dispatchable fossil-based electricity technologies; and greatly improved technologies for cost-effective long-distance electricity transmission will be required."
 - Did not quantify the engineering-economics





Recent Studies

- CAISO / Nexant 33% Renewables
 - Quantify sub-hourly ancillary service requirements
 - 4 scenarios (high wind, high solar, high imports, high DG)
 - Load, Wind, CSP, PV at hourly, 10, 5, and 1 minute resolution
 - Stochastic models, including generator forced outages and forecast errors
 - 33% RPS Operational Study phase 1 report "by Spring 2010"
 - <http://www.caiso.com/1c51/1c51c7946a480.html>
 - <http://www.caiso.com/242a/242abe1517440.html>

