Wind variability and impact on markets

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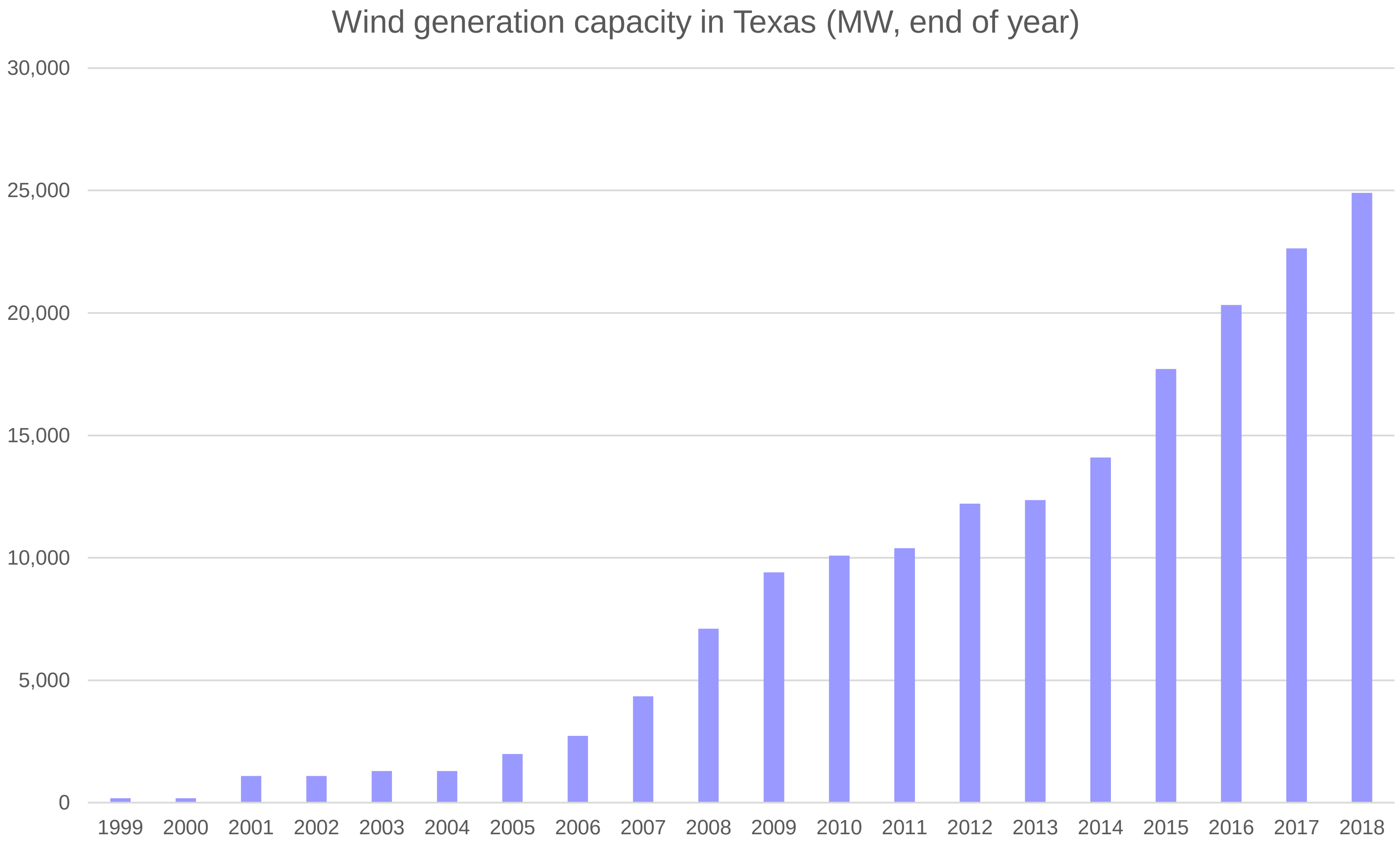
Outline

- Growth of wind in Texas,
- Challenges under high levels of wind,
- Comparison of Texas wind penetration to rest of US,
- Comparison of: West Texas/ERCOT; Denmark/EU; and, South Australia/Australia,
- Texas as microcosm of high wind challenges,
- Statistical modeling to understand challenges under high penetration,
- Generalized dynamic factor model and Kolmogorov spectrum,
- Scaling of wind power and wind power variability,
- Implications for electricity systems and organized wholesale markets,
- Conclusion.

Texas has experienced remarkable wind growth.



Source: USDOE 2019.

Challenges under high levels of wind integration.

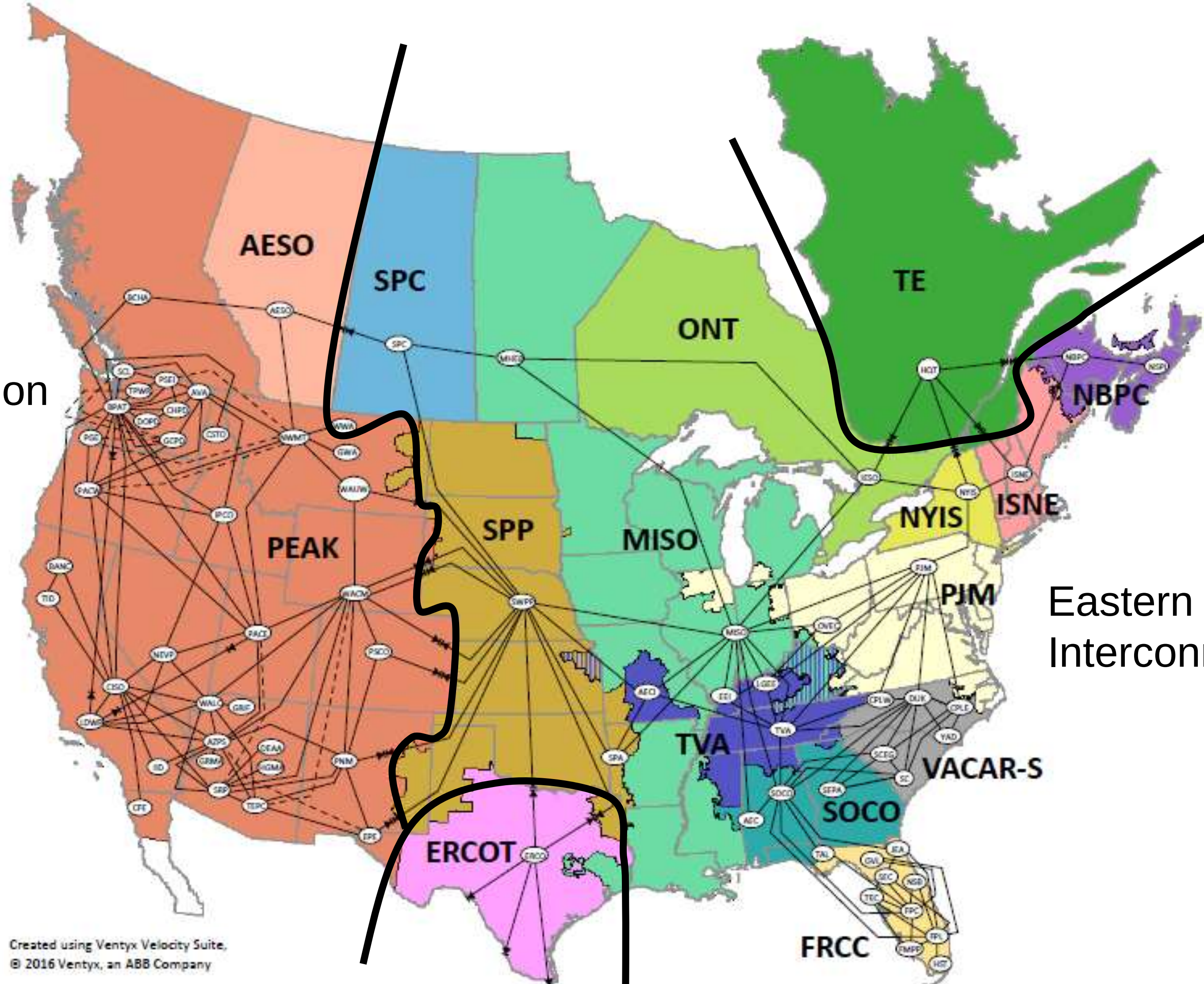
- Typical time of daily peak of US *inland* wind production coincides with daily minimum of electrical load and *vice versa*:
  - Difference between load and wind (“net load”) must be supplied by other resources.
- Variability of wind production:
  - Changes in supply-demand balance must be compensated by other resources.
- With higher wind penetrations, timing and variability become more critical.

Measurement of wind penetration.

- Important metrics of penetration are wind as a fraction of load energy or power in “balancing area” or in interconnection.
- Contiguous US has tens of balancing areas and three interconnections:
  - Western,
  - Eastern,
  - Electric Reliability Council of Texas (ERCOT), most of Texas, smallest of US interconnections, peak load around 75 GW.

Balancing Areas and Interconnections.

Western Interconnection



Eastern Interconnection

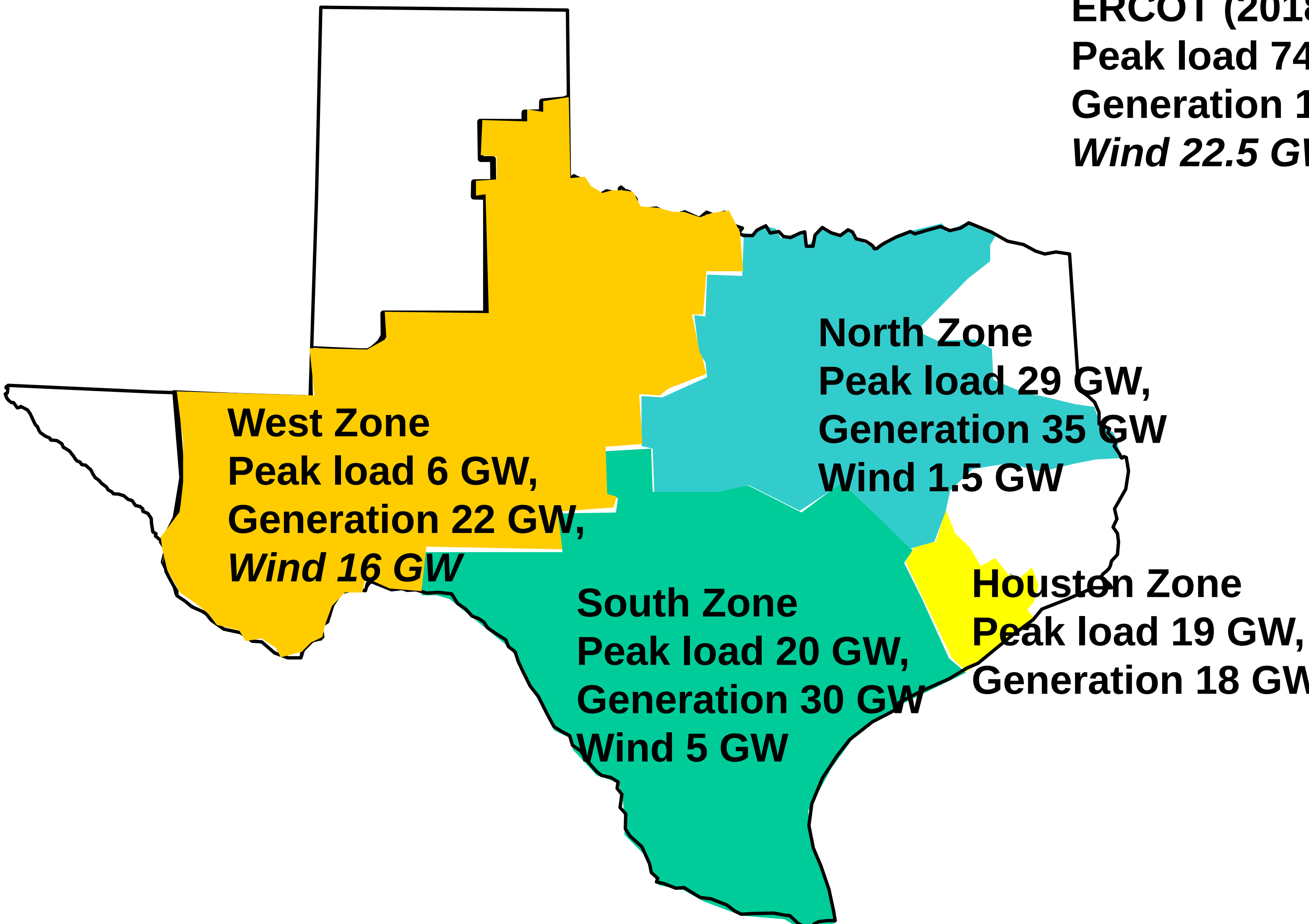
Source: NERC 2015

Comparison of Texas and ERCOT to rest of US.

- Wind provided **7.2%** of electricity by energy in 2019 in **US** (AWEA, 2020).
- Wind provided **17.5%** of electricity by energy in 2019 in **Texas** (AWEA, 2020).
- Wind provided **20%** of electricity by energy in 2019 in **ERCOT** (ERCOT, 2020).
- ERCOT has, *by far*, the greatest wind penetration of the three US interconnections, and largest of any *large* balancing area.

Most ERCOT wind is in West Texas zone.

ERCOT (2018)
Peak load 74.5 GW,
Generation 106 GW,
Wind 22.5 GW



Source: Potomac 2019

Comparison of West Texas/ERCOT to Denmark/EU to South Australia/Australia

- The International Energy Agency highlights that Denmark and South Australia are in “Phase 4” of renewable integration, or even more advanced, (IEA, 2018), requiring “advanced technologies to ensure reliability.”
- Australia and US are in “Phase 2,”
- European Union is in “Phase 3.”

Comparison to Denmark.

- Denmark noted for high wind penetration.
- Denmark has two AC electrical networks:
  - Eastern Danish power system is part of the Nordic interconnection (peak load around 63 GW in 2015, NordREG, 2016),
  - Western Danish power system is part of the Continental Western European system (peak load around 530 GW, ENTSO-E, 2016).
  - 600 MW HVDC link between them.
- Even the Eastern Danish system *alone* is integrated into a system with peak load nearly as high as ERCOT.

West Texas zone vs Denmark: Area and generation capacity.

- West Texas zone area about 2.5 times Denmark area.
- Total installed power generation capacity in **West Texas** zone around **22 GW**, (compares to around **16 GW** in **Denmark**, (ENTSO-E, 2019)),
- So *total* Danish generation capacity is somewhat *smaller* than the total West Texas zone generation capacity.

West Texas vs South Australia: Area and generation capacity.

- West Texas zone area about one tenth of South Australia area:
  - Stability issues more pressing in SA,
- Total installed power generation capacity in **West Texas** zone around **22 GW**, (compares to around **6 GW** in **South Australia**, (AEMO, 2018)),
- So South Australia generation capacity is significantly *smaller* than the total West Texas zone generation capacity.

West Texas vs Denmark vs South Australia: Wind capacity.

- Wind power generation capacity in **West Texas** zone around 16 GW, **72%** of total installed generation capacity, compares to:
  - 9.5 GW of wind, **60%** of installed generation capacity, in **Denmark** (ENTSO-E, 2019), and
  - 1.8 GW of wind, 1 GW of solar, under **50%** of installed generation capacity in **South Australia** (AEMO, 2018),
- Total wind capacity higher in West Texas than Denmark or South Australia, and higher as %.

West Texas vs Denmark vs South Australia: Wind energy.

- Annual wind energy production in West Texas zone as a fraction of electric energy consumption in **West Texas** around **100%**, compares to:
  - under **60%** in **Denmark**, (ENTSO-E, 2019), and
  - under **40%** in **South Australia**, (AEMO, 2018).

West Texas vs Denmark vs South Australia.

- But these are all misleading statistics, since West Texas, Denmark, and South Australia are each embedded in much larger interconnections!
- Relevant comparison statistics require comparison to total capacity in interconnection or total energy throughout year.

ERCOT vs EU vs Australia.

- Annual wind energy production in ERCOT as a fraction of electric energy consumption in **ERCOT** around **20%** (ERCOT, 2020), compares to:
  - around **11%** in **EU**, (ENTSO-E, 2019), and
  - around **7%** in **Australia**, (CEC, 2019).
- Overall renewable penetration in EU (32%, (ENTSO-E, 2019)) and Australia (21%, (CEC, 2019)) higher than ERCOT:
  - Due to hydro and solar.

ERCOT is microcosm of high wind challenges.

- Large amount of wind capacity:
  - Largest capacity of any US state,
- Small interconnection:
  - Smallest of three US interconnections,
- Significant wind production off-peak:
  - Due to West Texas wind,
  - Coastal wind better correlated with demand.

ERCOT is microcosm of high wind challenges.

- West Texas wind resources far from load centers:
  - Most transmission constraints thermal contingency, but some related to voltage or steady-state or transient stability,
  - Australian system may have more significant stability constraints.
- Little flexible hydroelectric generation:
  - Unlike Eastern and Western US, Europe, and Australia.

Wind production modeling to better understand challenges.

- Big data flavor:
  - Roughly 100 wind farms in ERCOT,
  - Relevant issues at timescales from sub-minute to multi-year,
  - One year of 1-minute data from 100 farms is around 50 million measurements,
  - Understanding inter-year variability requires multi-year data sets.

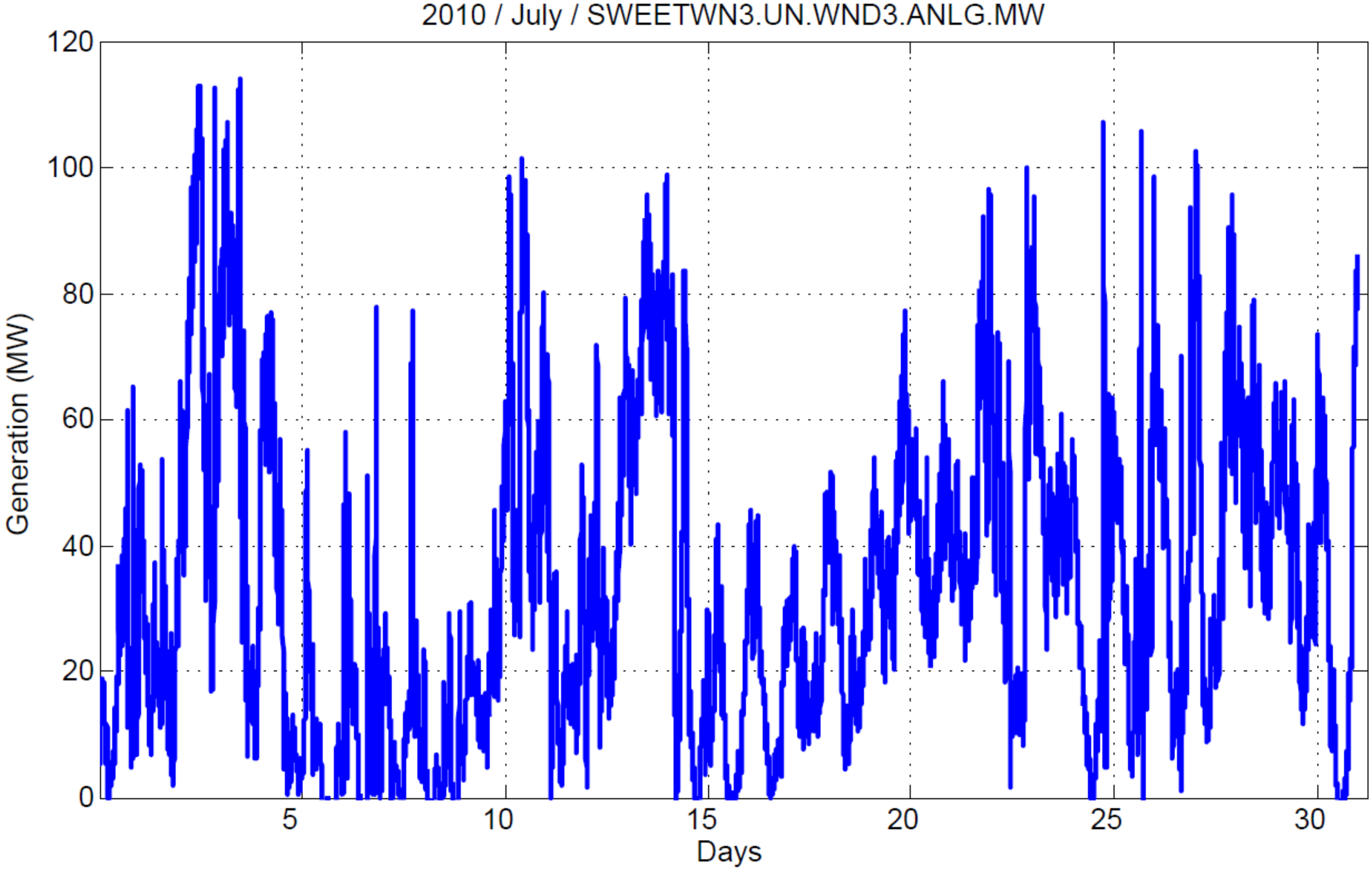
Wind production modeling to better understand challenges.

- Use statistical techniques:
  - relationship between **time/season** of **maximum** wind production and time of maximum load,
  - **variability** of wind and **scaling** of variability,
  - implications for needed **flexibility** in “residual” thermal system that provides for net load.

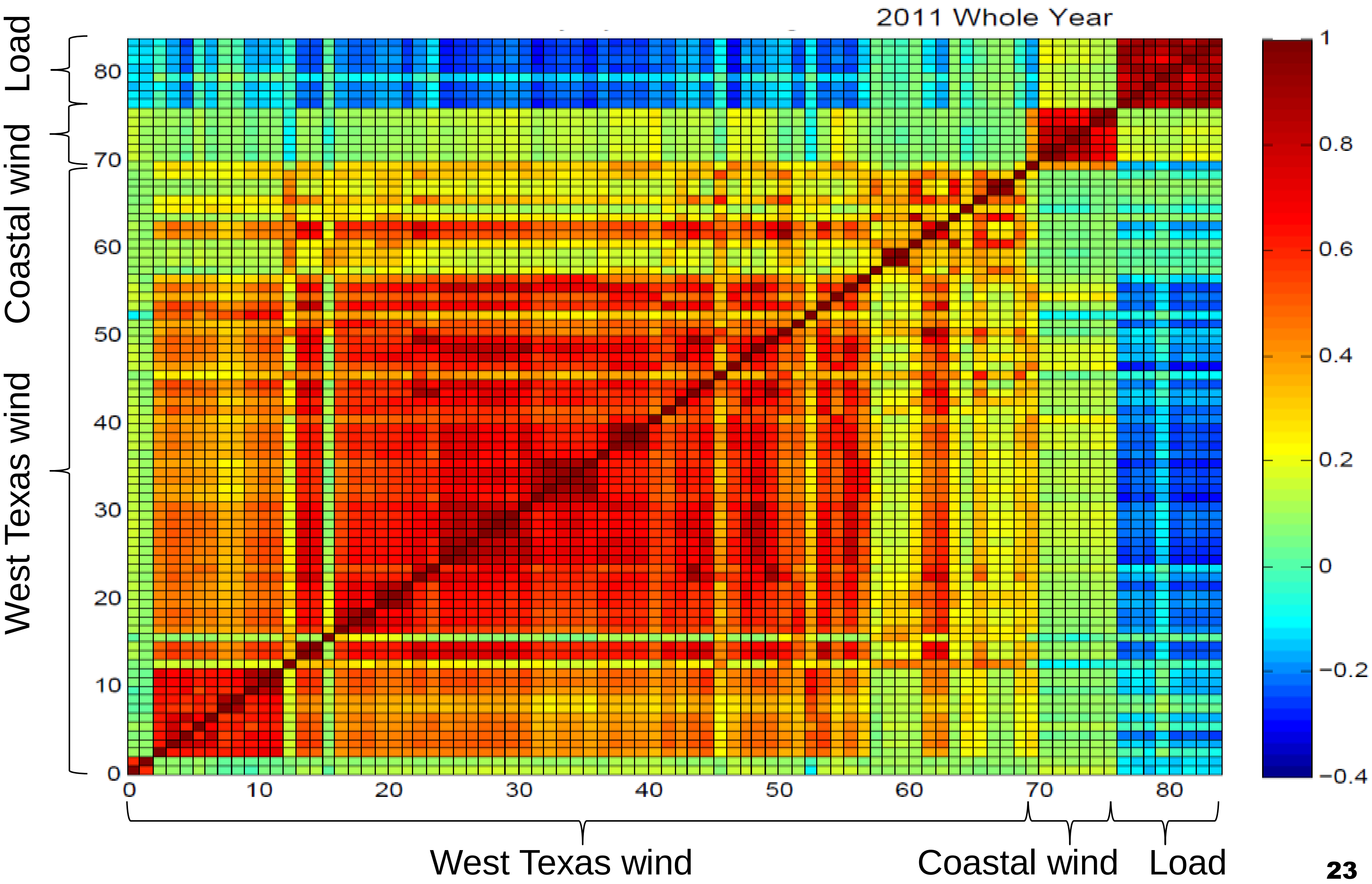
Wind production modeling to better understand challenges.

- Modeling issues:
  - Intermittency of wind resource,
  - Correlation between wind and load,
  - Power production from wind is affected by multiple issues, including:
    - Curtailment,
    - Cut-in and cut-out speeds,
    - Turbine size compared to rated capacity,
    - Turbine transfer function characteristics (Tobin et al., 2015).

Intermittent wind power production.



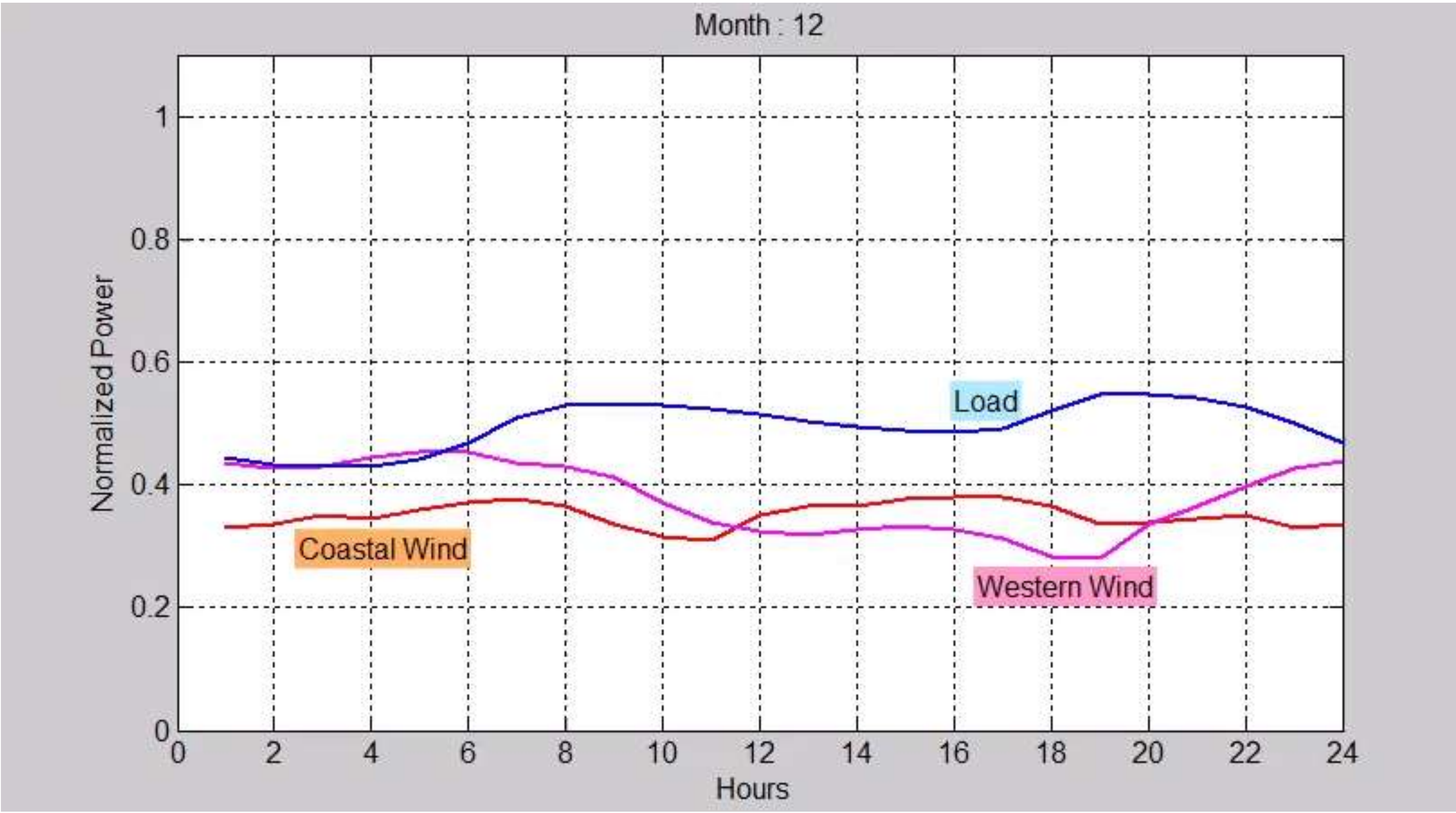
Correlation of ERCOT wind and load.



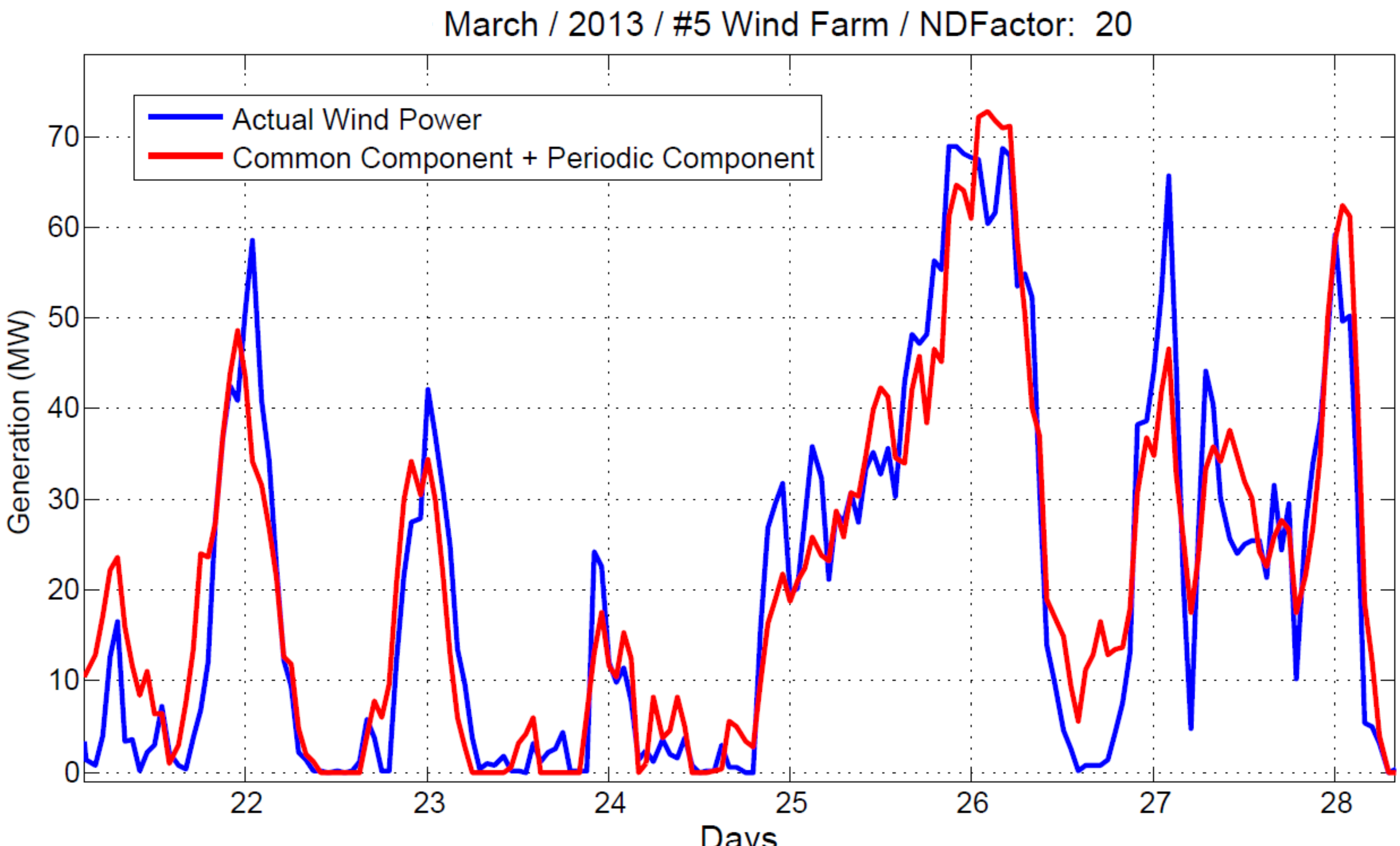
Statistical wind power model.

- Model wind power production and load as sum of (slowly varying) diurnal **periodic** component plus **stochastic** component.
- Use “generalized dynamic factor model” (GDFM, Forni et al., 2005) for stochastic:
  - Decompose stochastic into sum of “**common**” component and “**idiosyncratic**” component.
  - Common component for wind and load powers expressed in terms of fewer underlying independent stochastic processes, the “factors,”
  - Idiosyncratic component different for each farm.

Diurnal periodic component slowly varies over year.



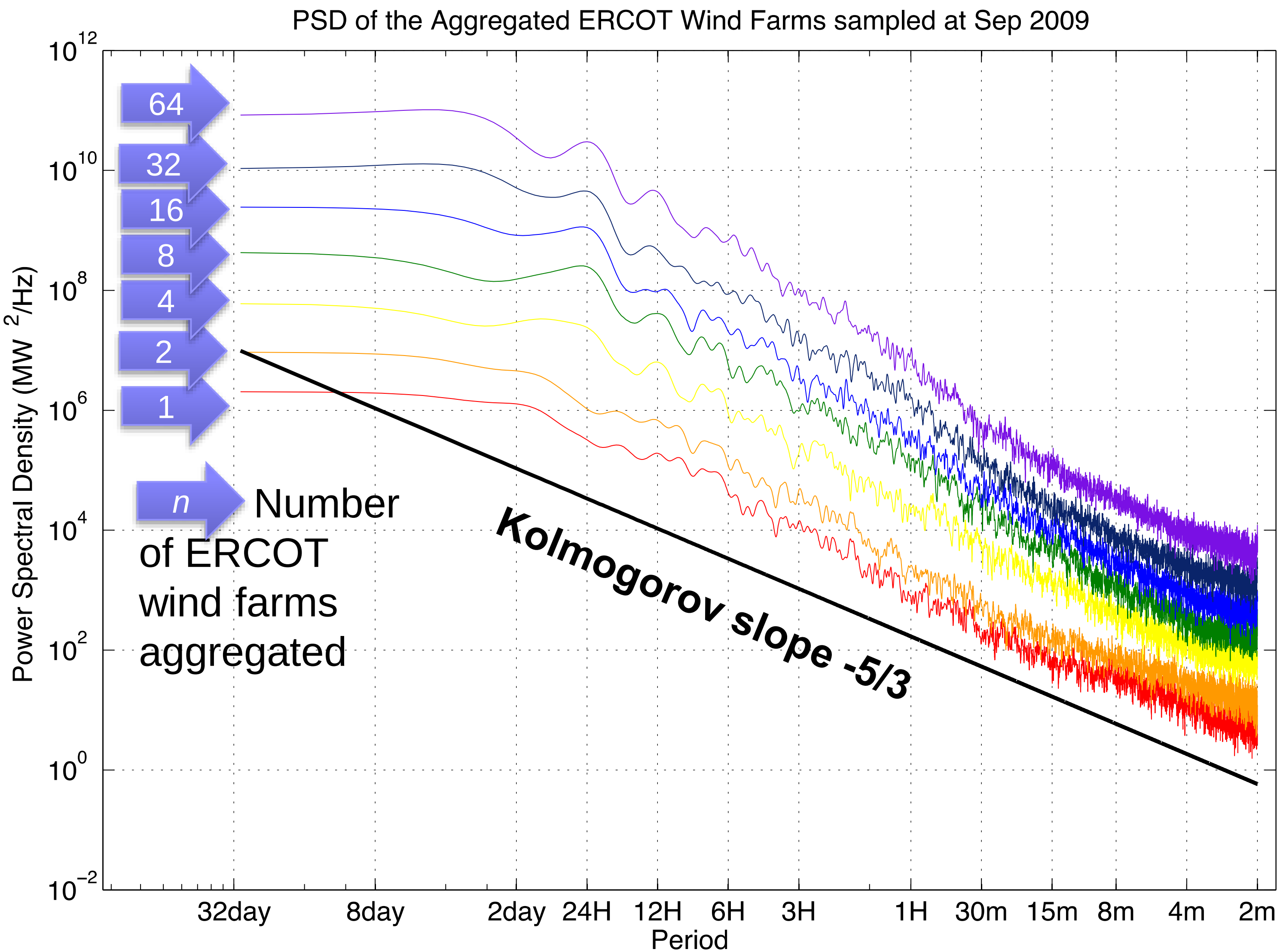
Periodic plus common accounts for most variation.



Kolmogorov slope of wind power spectrum

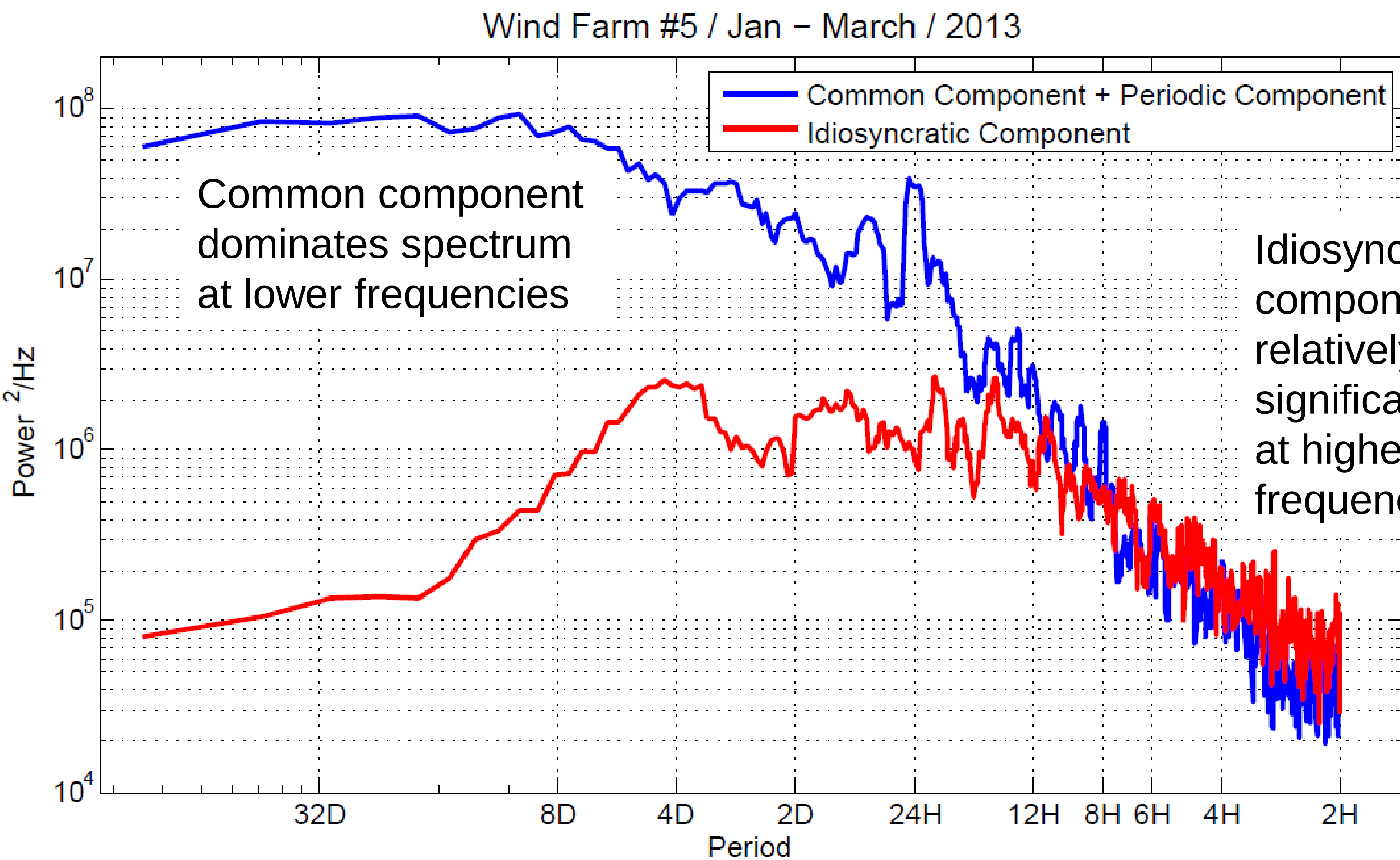
- A. N. Kolmogorov mainly known to electrical engineers through contributions to understanding of stochastic processes.
- Related contributions in turbulent flow crossed over to electrical engineering community through Apt (2007).
- Kolmogorov used dimension analysis to predict that power spectral density of wind power would have characteristic roll-off of slope -5/3.
- Verified in Apt (2007).

Wind power spectrum.



Source: ERCOT data, Analysis based on Apt (2007).

Spectrum of common and idiosyncratic components.



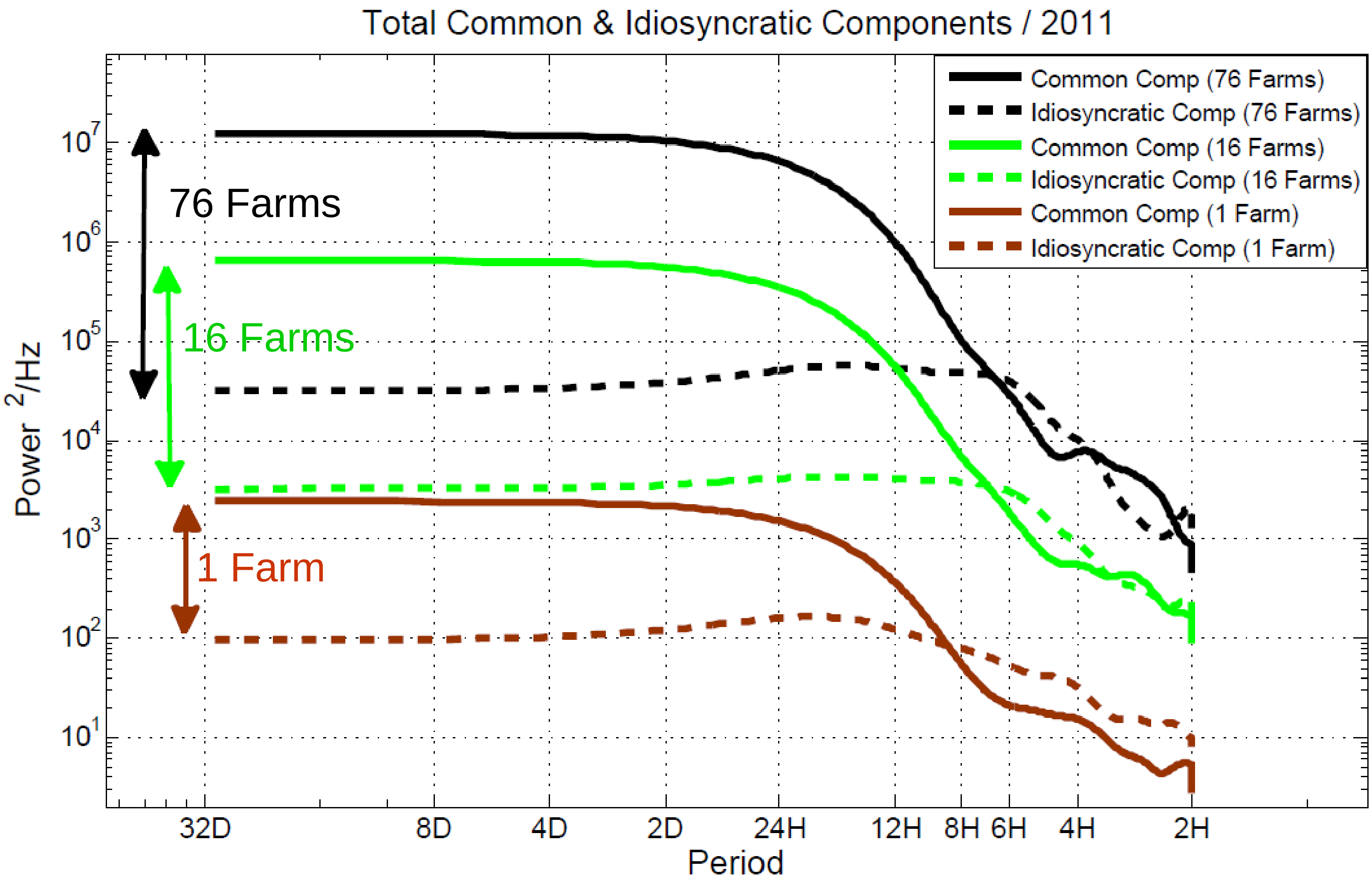
Common component dominates spectrum at lower frequencies

Idiosyncratic component relatively more significant at higher frequencies

Scaling of wind power and wind variability.

- Intuitive that aggregating of wind over large areas should reduce relative variability.
- However, variability of each component scales differently with aggregation:
  - Periodic:
    - Scales approximately linearly with capacity,
  - Common stochastic:
    - Effects of underlying (weather) factors tend to add,
  - Idiosyncratic stochastic:
    - Weakly correlated between farms, so grows slowly.

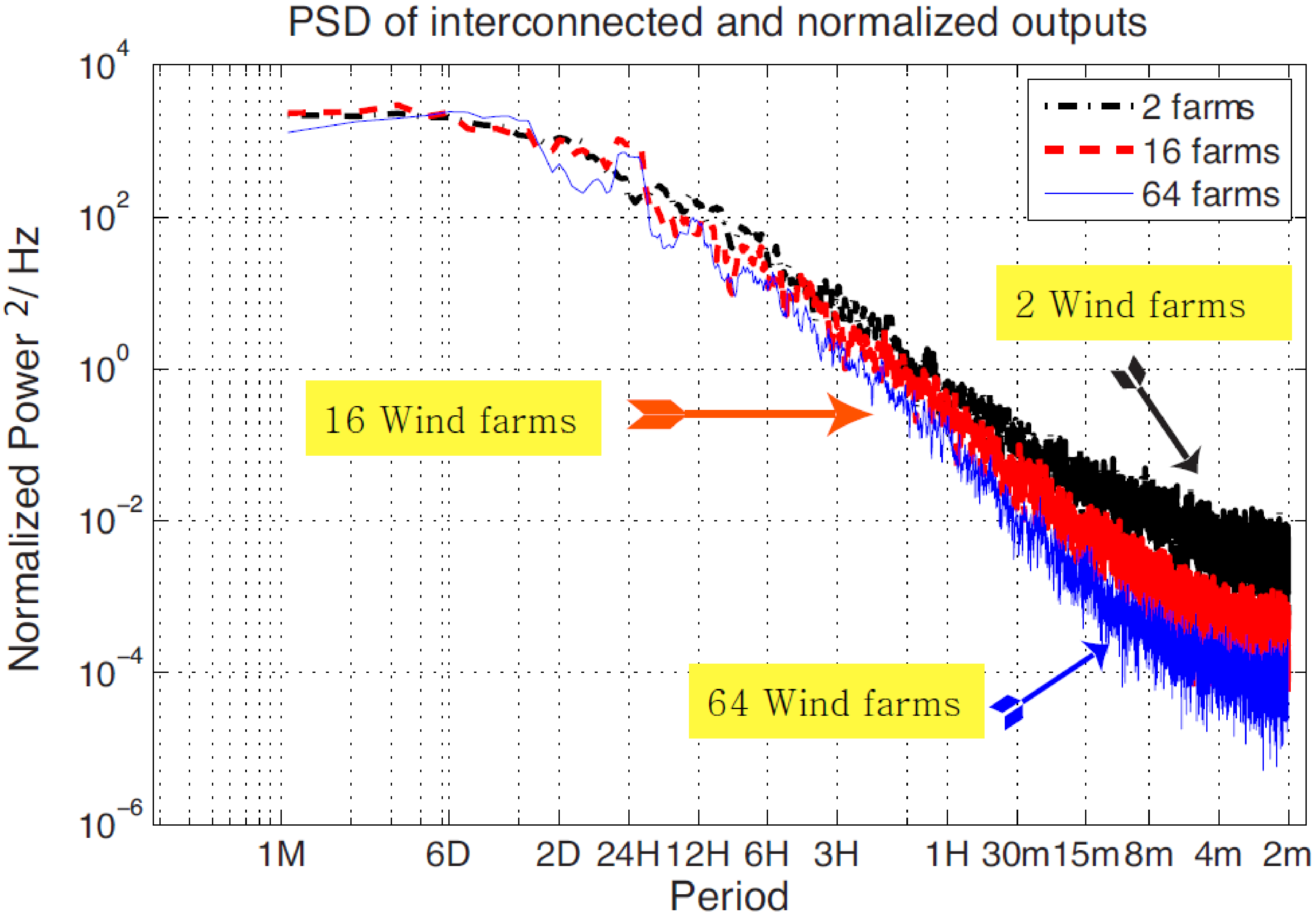
Scaling of wind power and wind variability.



Scaling of wind power and wind variability.

- Higher frequency components of stochastic components grow more slowly with aggregation than lower frequency components:
  - Because idiosyncratic component grows slowly,
  - Aggregation reduces high frequency components relative to low frequency.
- Aggregation does not solve variability:
  - Diurnal periodic component,
  - Common stochastic component.

Scaling of wind power and wind variability.

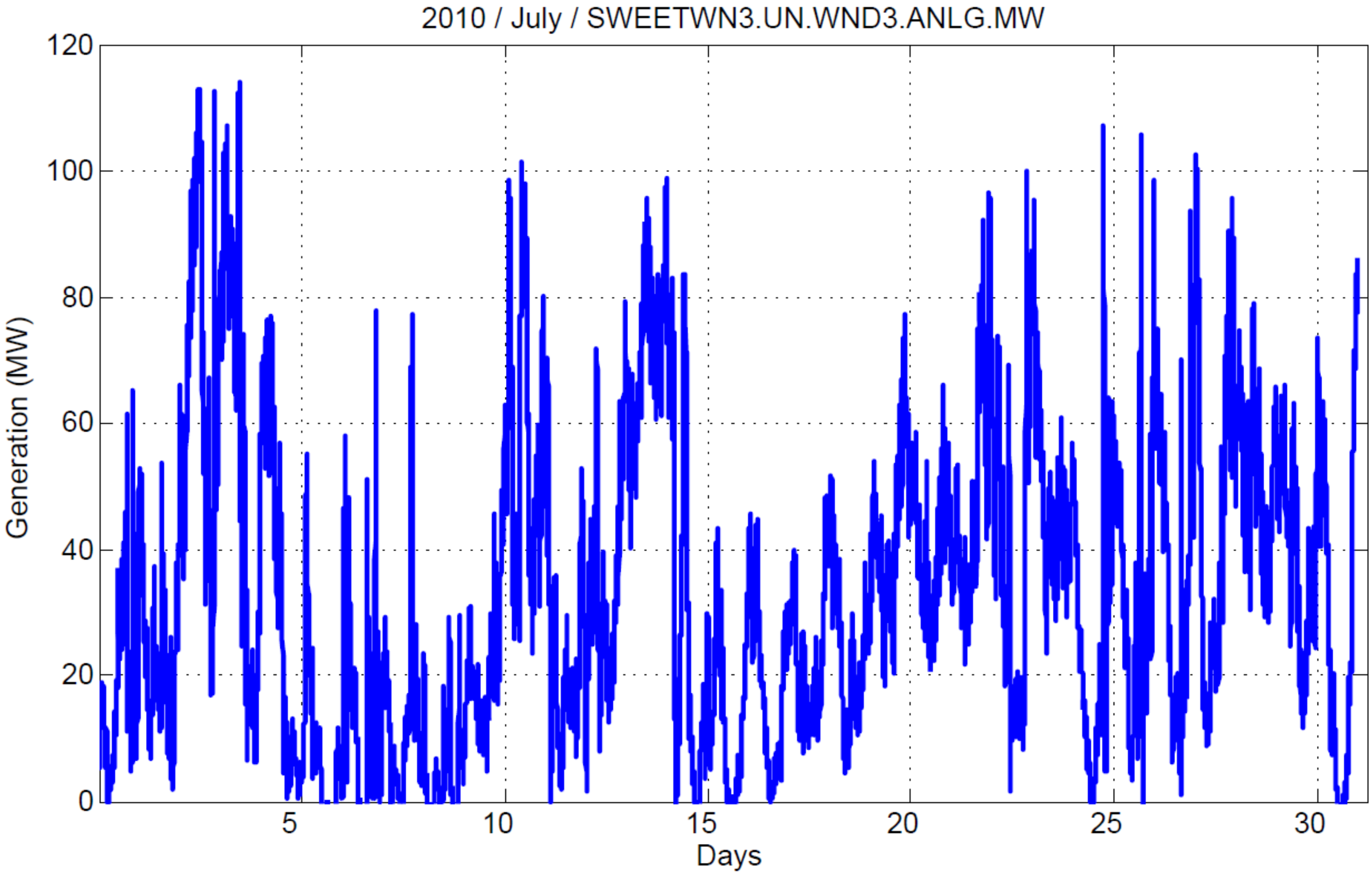


Source: based on Apt (2007), and Lee and Baldick (2014).

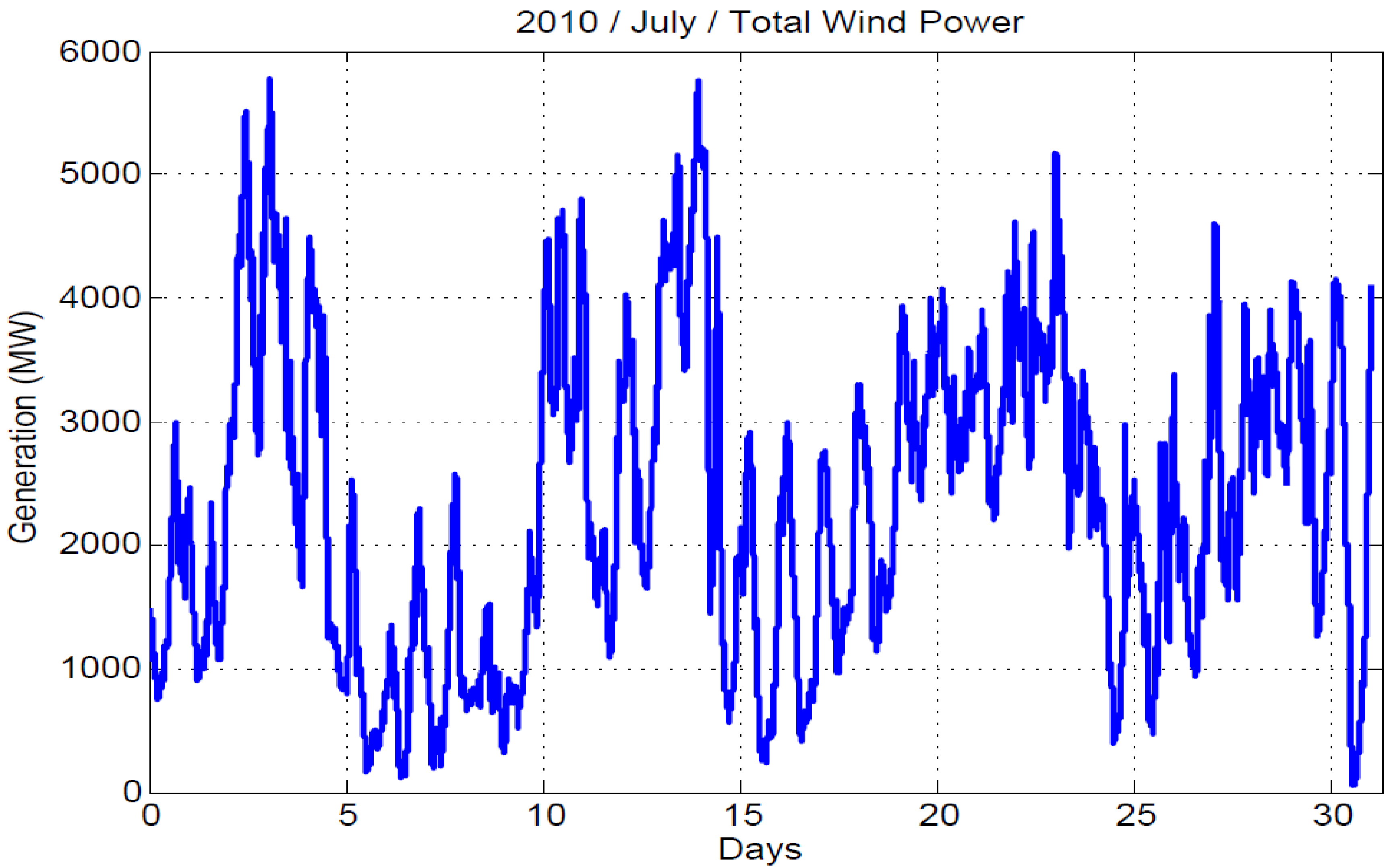
Scaling of wind power and wind variability

- Echoes observations in Katzenstein, Fertig, and Apt (2010):
  - Most reduction of variability is obtained by aggregating relatively few farms,
  - Still expect significant intermittency in total wind, even aggregating many farms in a region,
  - Intermittency only reduced further by aggregating over geographical scales that span different wind regimes:
    - Inland and coastal Texas wind.

Intermittent wind power production.



Intermittent wind power production.



Implications for electricity systems.

- Electricity supply must match load continuously (first law of thermodynamics),
- In short-term, variation between mechanical power and electrical load is compensated by inertia of electrical machines:
  - About 8 seconds of supply in inertia.
- Over longer time-frames, generators are instructed ("dispatched") to adjust mechanical power to balance generation and load.
- Wind variability complicates balancing.

“Organized” wholesale markets.

- About 60% of US electric power supply is sold through “organized” markets administered by Regional Transmission Organizations (RTOs) (USEIA, 2016).
- RTOs include Midcontinent, California, New England, New York, PJM, Southwest Power Pool, Electrical Reliability Council of Texas (ERCOT).
- Will focus on organized markets.

Organized wholesale markets in North America.

Source: www.ferc.gov

Organized wholesale markets.

- Dispatchable generation typically receives a target generation level every 5 minutes:
  - Ramp to this level over next 5 minute interval,
- Target generation level based on forecast of the load minus renewable production for the end of the 5 minute interval.
- Fluctuations from linear ramps within 5 minute intervals and error in forecast:
  - compensated by generation that responds to faster signals, “regulation ancillary service,”
  - more variability requires more regulation.

Organized wholesale markets.

- Scaling analysis implies that wind variability in 5 minute interval grows slowly with total wind:
  - Required amount of regulation ancillary service grows slowly with total wind capacity,
  - Needed regulation capacity in ERCOT still mostly driven by load variability,
  - Various changes to market design have enabled better utilization of regulation capacity.
- Variability over tens of minutes to hours to days:
  - Growing with wind.

Day-ahead market.

- Short-term forward market based on anticipation of tomorrow's conditions,
- Provides advance warning for "slow start" generators that require hours to become operational, "committed,"
- Wind forecasts can be poor day-ahead:
  - Implications if generator fleet is mostly slow start,
  - Necessitates commitment of significant capacity "just in case," with implications for lower efficiency, increased emissions.

Real-time market.

- Arranges for 5 minute dispatch signals,
- Increasingly also represents commitment of “fast-start” generators through “lookahead dispatch” (not, yet, in ERCOT).
- Increasing availability of fast-start generators avoids commitment except when they are very likely to be needed.
- Large wind ramps and high off-peak wind can still be problematic if not enough installed and available flexible capacity to compensate for wind variability.

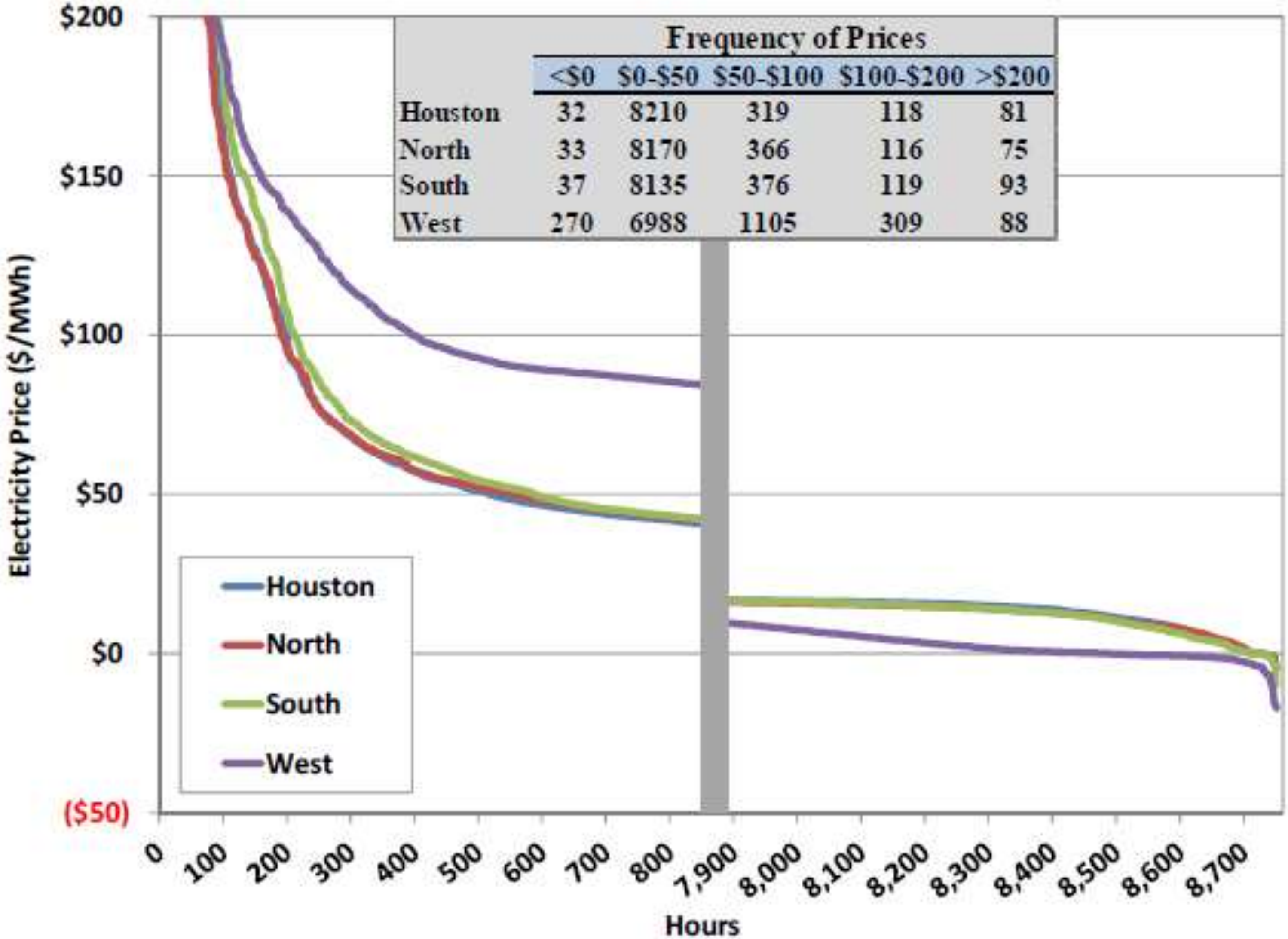
Must-take resources.

- In some markets, wind is “must take,” necessitating that other resources compensate for almost all wind variability.
- In ERCOT, Midcontinent, and some other areas, wind farms participate by offering into market and being dispatched within limits:
  - Just like all other generators,
  - Provides flexibility to RTO to curtail “economically,” with prices falling low, to zero, or even negative,
  - Arguably facilitated high level of wind in ERCOT.

Diurnal periodic variation, intermittency, and markets.

- West Texas wind has peak production when load is low.
- When stochastic wind component adds to periodic peak but load is low, total wind production requires thermal generation to dispatch down or switch off.
- In market-based approach to integrating wind, this results in low, zero, or even negative prices.

ERCOT price-duration curve in 2018.



Frequency of Prices	<$0	$0-$50	$50-$100	$100-$200	>$200
Houston	32	8210	319	118	81
North	33	8170	366	116	75
South	37	8135	376	119	93
West	270	6988	1105	309	88

Source: Potomac (2019), Figure 9.

Conclusion.

- Periodic component plus GDFM for stochastic component provides good match to statistics of empirical wind power production data:
  - Periodic, common stochastic, and idiosyncratic stochastic components.
- Explains characteristics of aggregated wind production and scope for reduction of variability by aggregation.
- Markets with wind will experience times of low, zero, or negative prices.

Ongoing and future work.

- Development of Matlab GDFM toolbox.
- Analyze multi-year data sets:
  - Year-on-year changes in diurnal periodic and stochastic components,
  - Assess year-on-year variability in resource, changes in wind turbine fleet characteristics, and changes in levels of curtailment,
- Analyze solar production data:
  - Effect of intermittent cloud cover.

References

- N. Tobin, H. Zhu, and L. P. Chamorro, 2015, “Spectral behaviour of the turbulence-driven power fluctuations of wind turbines,” *Journal of Turbulence*, 16(9):832—846.
- USDOE, 2019, “U.S. Installed and Potential Wind Power Capacity and Generation,” Available from: https://windexchange.energy.gov/maps-data/321, Accessed April 2, 2019.

References

- North-American Electric Reliability Corporation, 2015, “NERC Balancing Authorities as of October 1, 2015,” Available from: http://www.nerc.com/comm/OC/RS%20Landing%20Page%20DL/Related%20Files/BA_Bubble_Map_20160427.pdf, Accessed April 30, 2016.
- American Wind Energy Association, (AWEA), 2020, “Wind Energy in the United States,” Available from: https://www.awea.org/wind-101/basics-of-wind-energy/wind-facts-at-a-glance, Accessed May 23, 2020.

References

- ERCOT, 2020, "Fact Sheet," available at http://www.ercot.com/content/wcm/lists/197391/ERCOT_Fact_Sheet_5.11.20.pdf, accessed May 22, 2020.
- Potomac Economics, 2019, "2018 State of the Market Report for the ERCOT Wholesale Electricity Markets," Available from www.potomaceconomics.com, Accessed September 18, 2019.
- International Energy Agency (IEA), 2018, "World Energy Outlook."

References

- NordREG, 2016, “Statistical Summary of the Nordic Energy Market 2015, Available from: http://www.nordicenergyregulators.org/wp-content/uploads/2017/01/highlights.pdf, Accessed November 8, 2017.
- ENTSO-E, 2016, “Yearly Statistics & Adequacy Retrospect 2015,” Available from: https://www.entsoe.eu/Documents/Publications/Statistics/YSAR/entso-e_YS_AR2015_1701_web.pdf, Accessed November 8, 2017.

References

- ENTSO-E, 2019, "Statistical Factsheet 2018," Available from: https://www.entsoe.eu/Documents/Publications/Statistics/Factsheet/entsoe_sfs2018_web.pdf, Accessed September 24, 2019.
- Australian Energy Market Operator (AEMO), 2018, "South Australian Electricity Report," November, Available from: www.aemo.com.au, Accessed September 29, 2018.

References

- Clean Energy Council (CEC), 2019, “Clean Energy Australia, Report 2019,” https://www.cleanenergycouncil.org.au/resources/resources-hub/clean-energy-australia-report, Accessed September 24, 2019.

References.

- M. Forni, M. Hallin, M Lippi, and L. Reichlin, 2005, “The generalized dynamic factor model: One sided estimation and forecasting,” *Journal of the American Statistical Association*, 100(471):830-840.
- J. Apt, 2007, “The spectrum of power from wind turbines,” *Journal of Power Sources*,169:369–374.

References.

- D. Lee and R. Baldick, 2014, “Future wind power sample path synthesis through power spectral density analysis,” *IEEE Transactions on Smart Grid*, 5(1):490-500, January.
- W. Katzenstein, E. Fertig, and J. Apt, 2010, “The variability of interconnected wind plants,” *Energy Policy*, 38:4400–4410.

References

- USEIA, 2016, “Today in energy,” Available from: https://www.eia.gov/todayinenergy/detail.cfm?id=790, Accessed April 27, 2016.
- Federal Energy Regulatory Commission, 2015, “Regional Transmission Organizations,” Available from: http://www.ferc.gov/industries/electric/indus-act/rto/elec-ovr-rto-map.pdf, Accessed April 30, 2016.