Wind variability and impact on markets

March 2021

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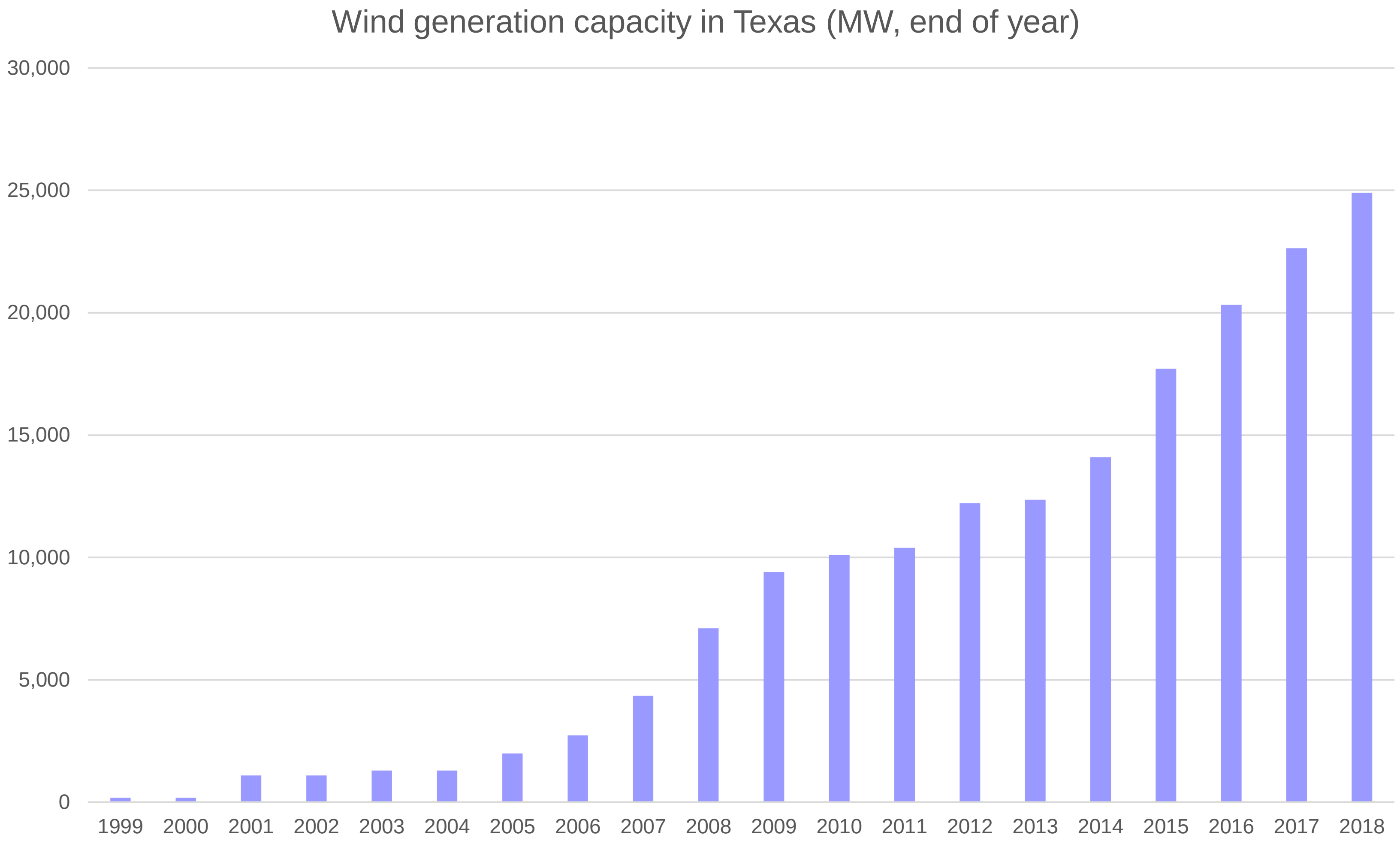
Outline

- 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.

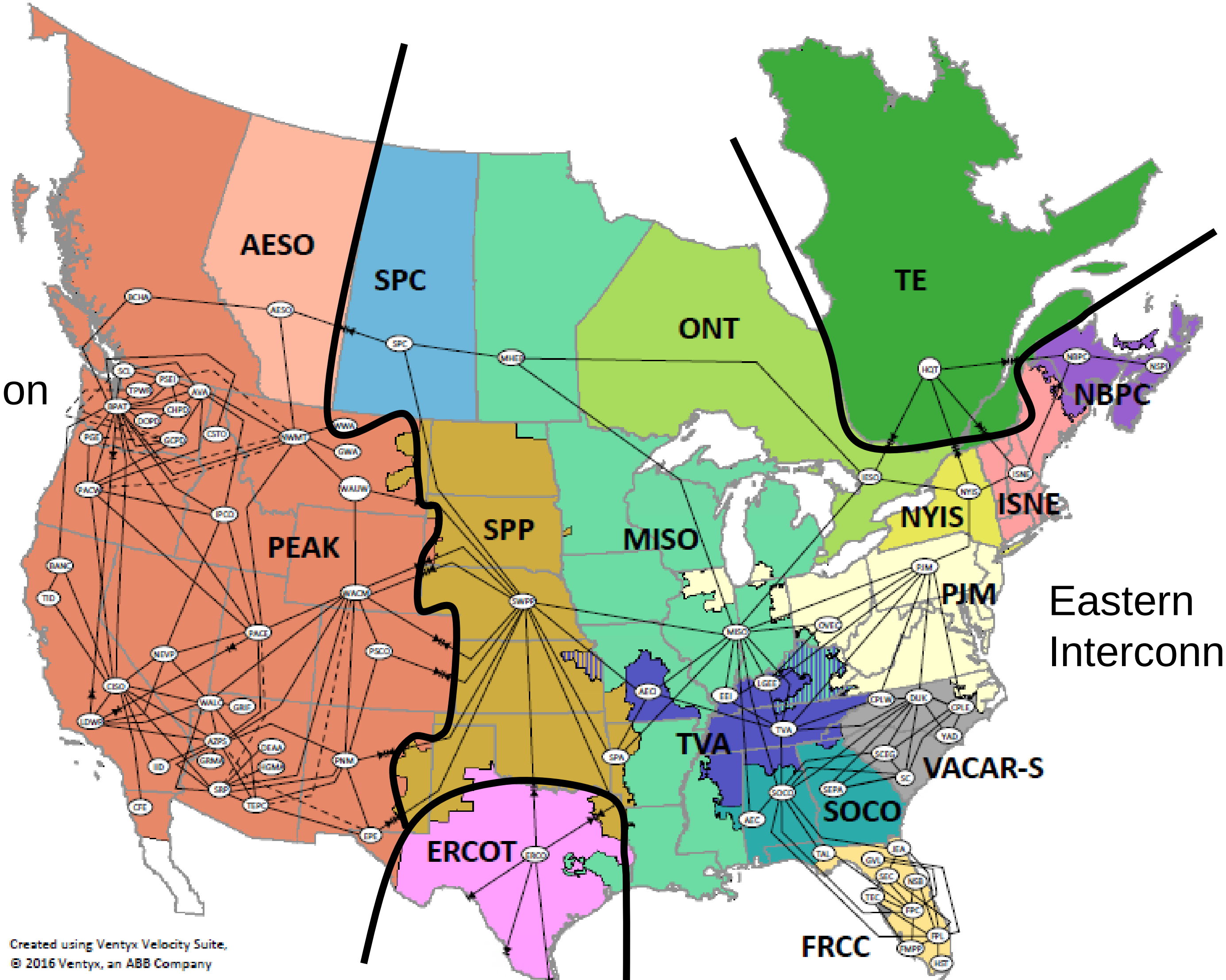
- Typical time of daily peak of US *inland* wind production coincides with daily minimum of electrical load and *vice versa*:
  - Difference between load and wind (“net load”) must be supplied by other resources.
- Variability of wind production:
  - Changes in supply-demand balance must be compensated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

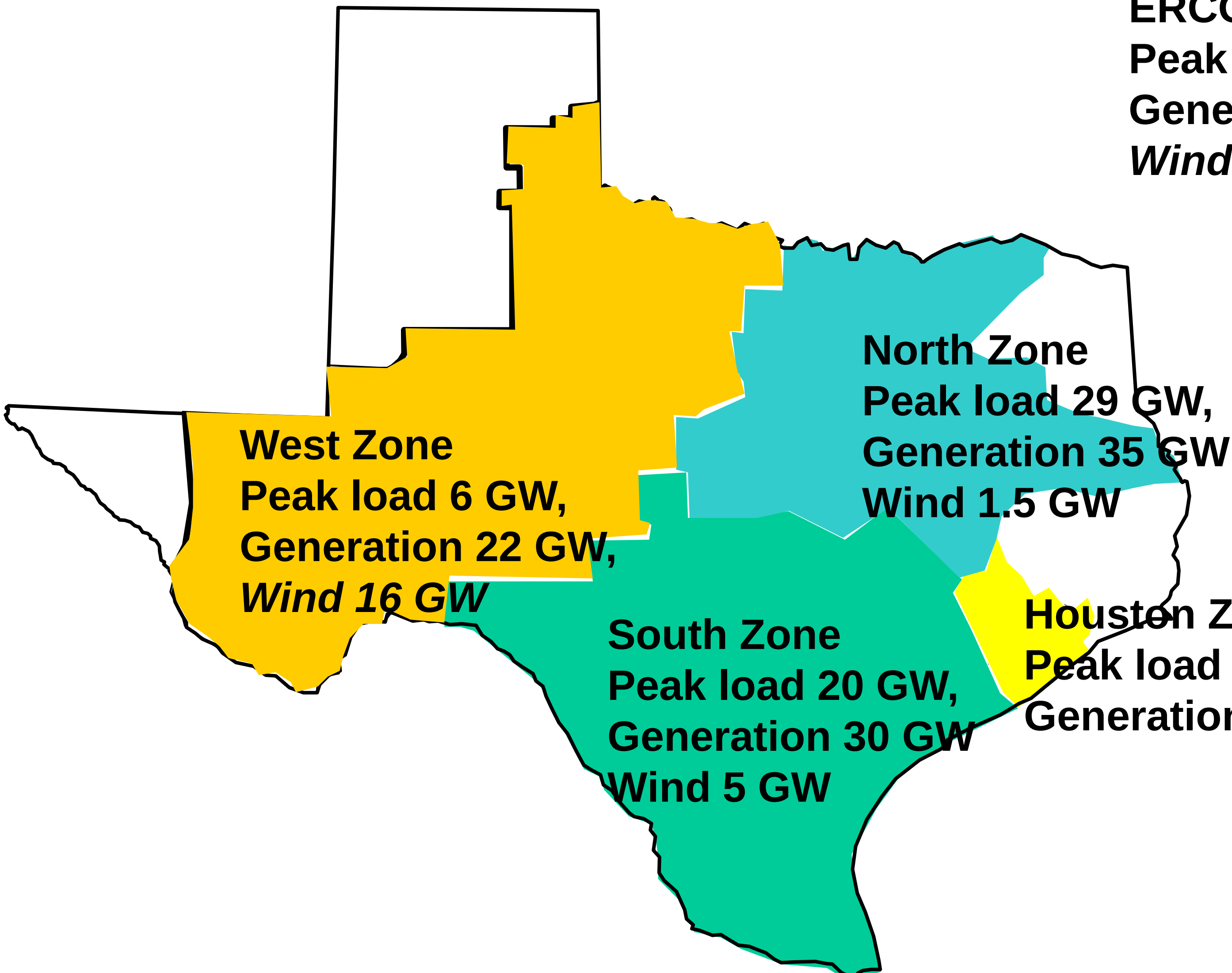
Source: NERC 2015

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 one of the largest penetrations 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

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 are thermal contingency, but some related to voltage or steady-state or transient stability,
  - Western Interconnection and 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.

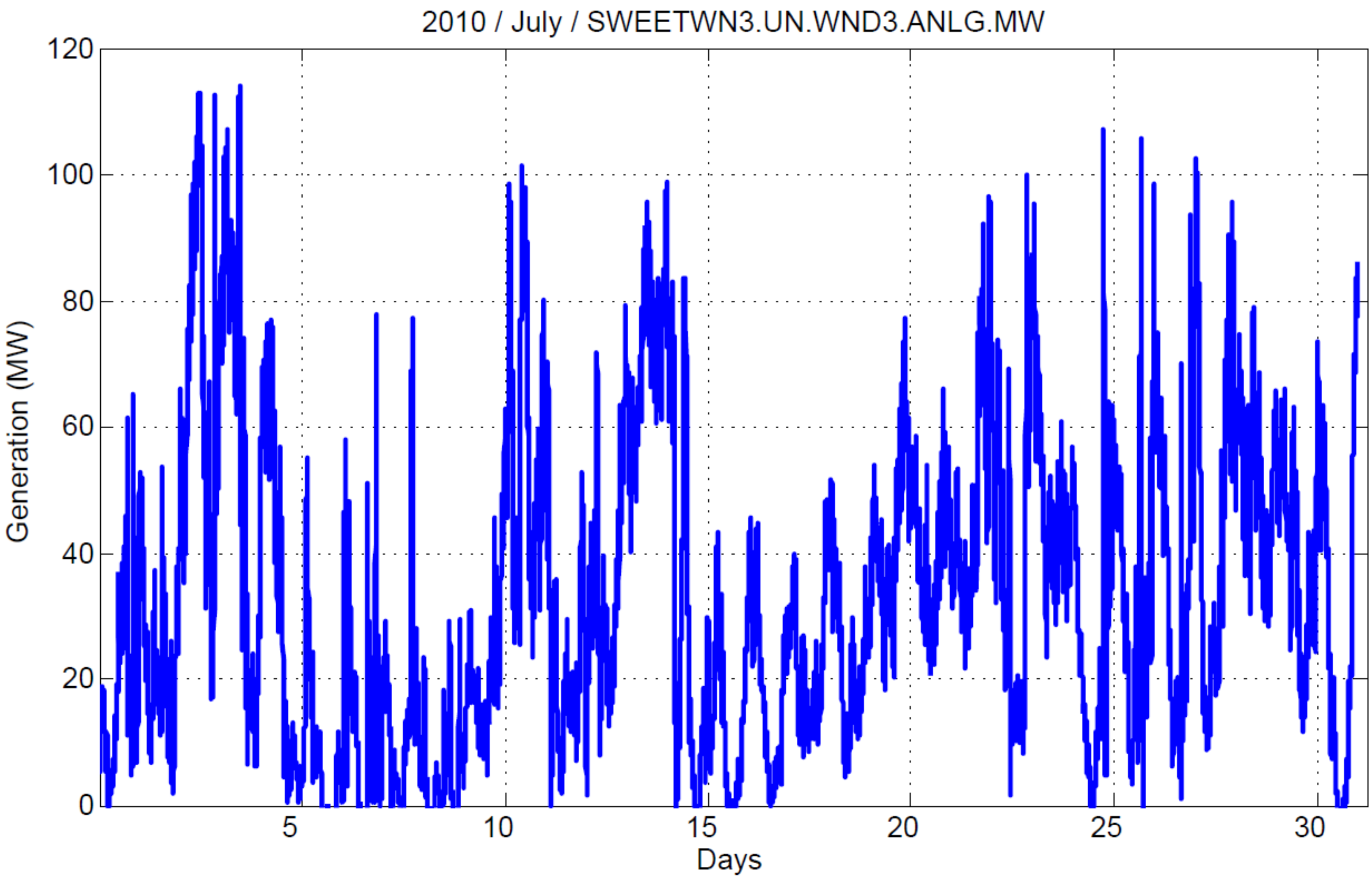
Wind production modeling to better understand challenges.

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

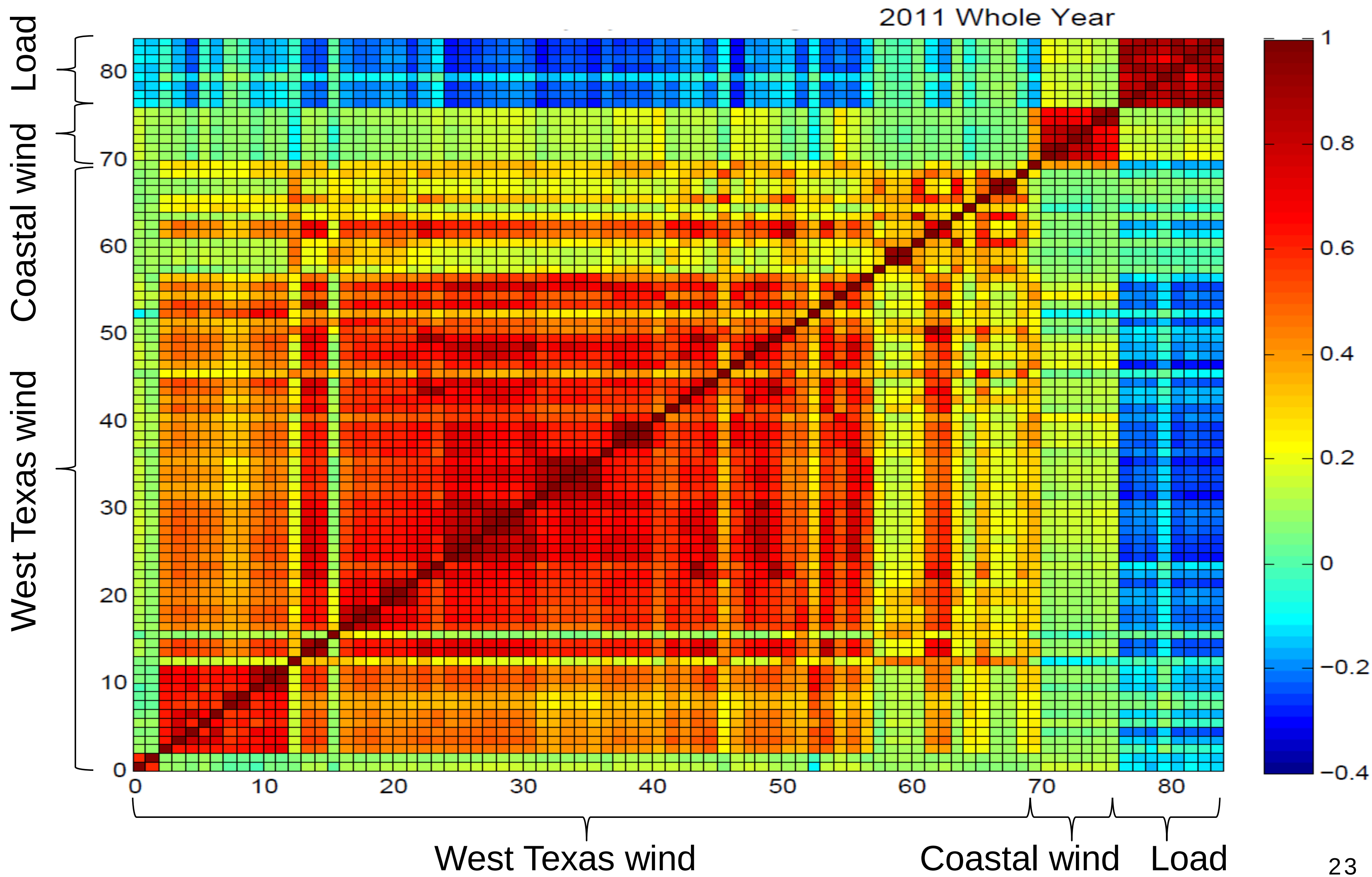
Wind production modeling to better understand challenges.

- 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.

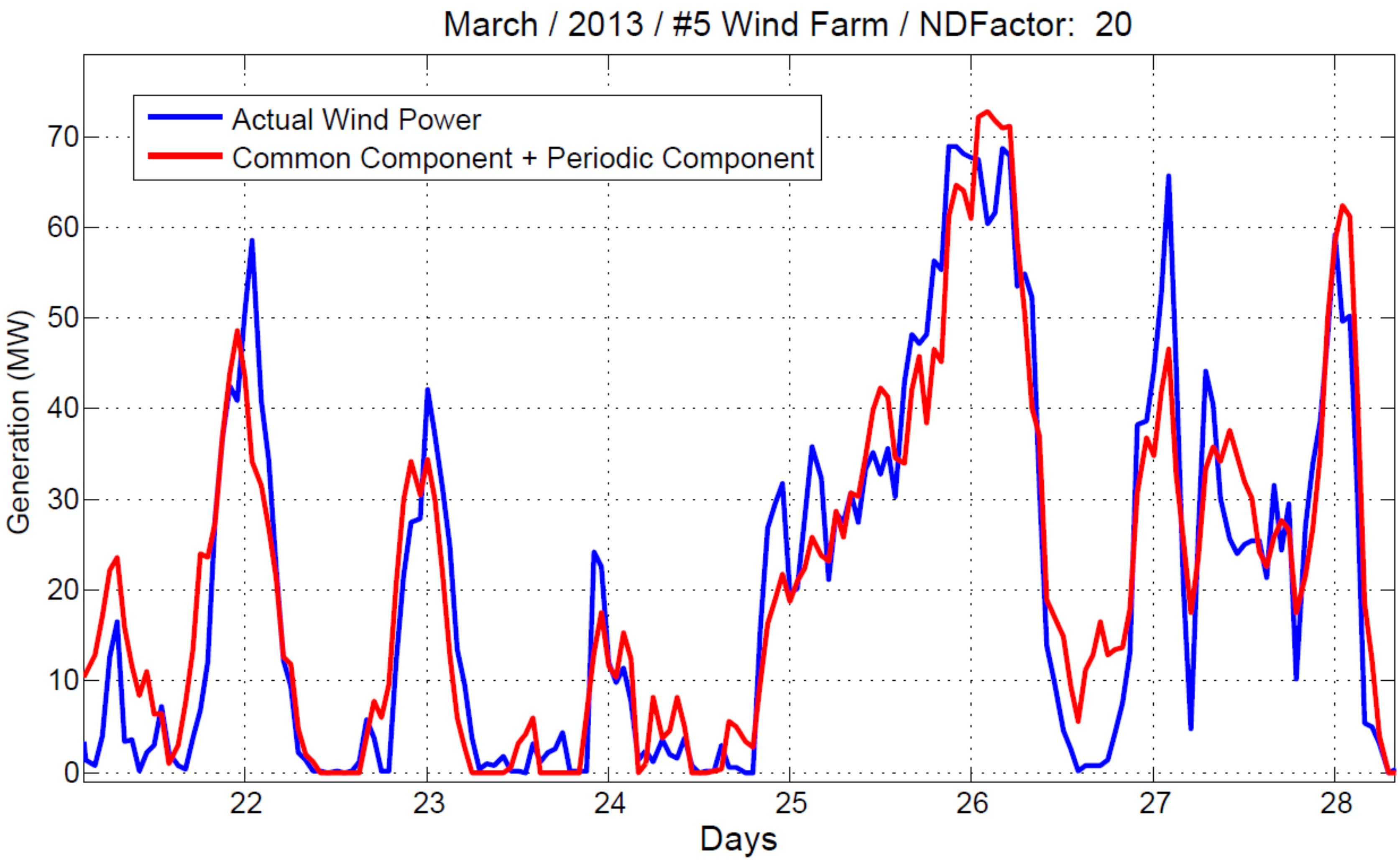


Statistical wind power model.

- 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.

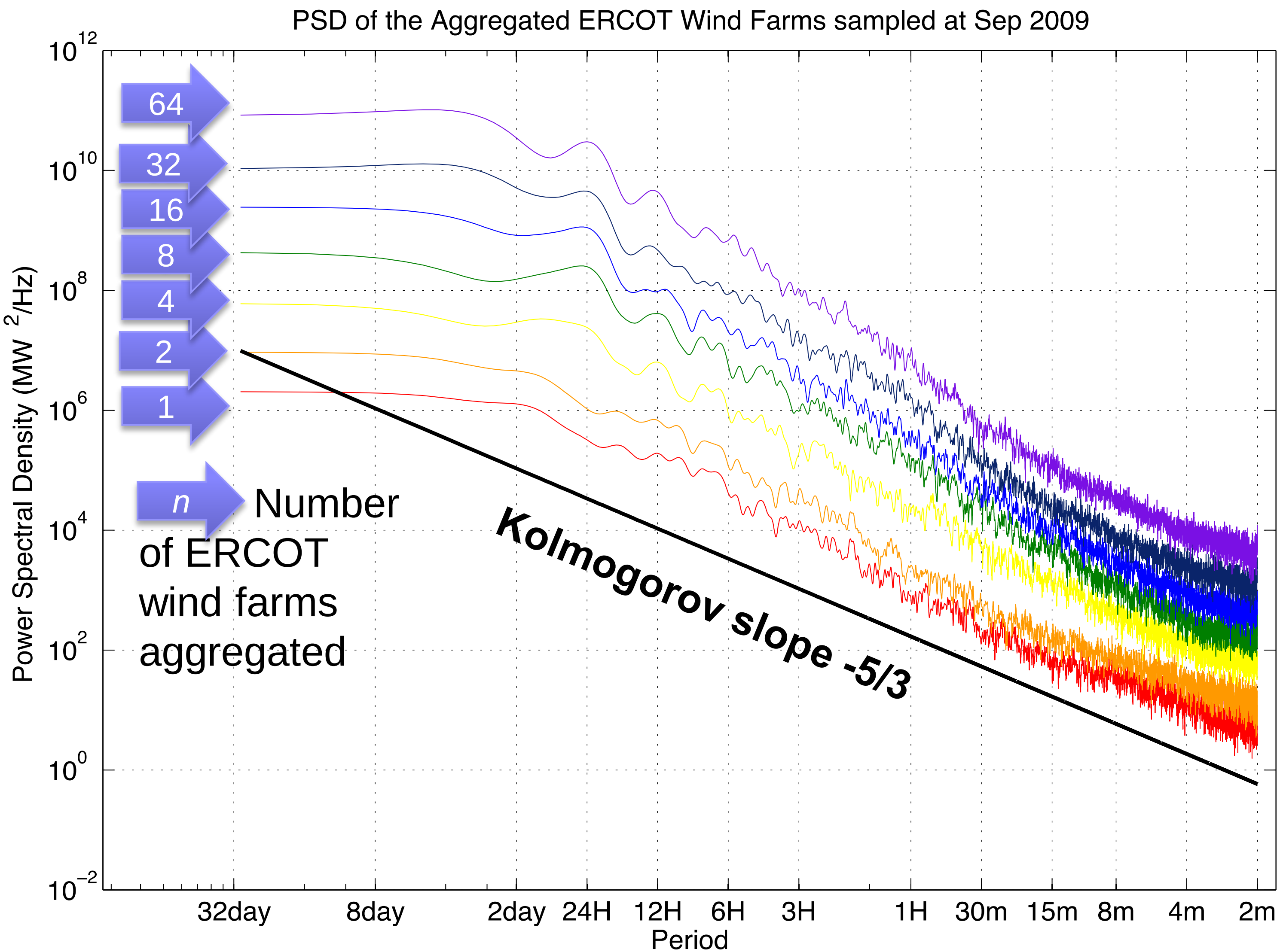
Periodic plus common accounts for most variation.



Kolmogorov slope of wind power spectrum

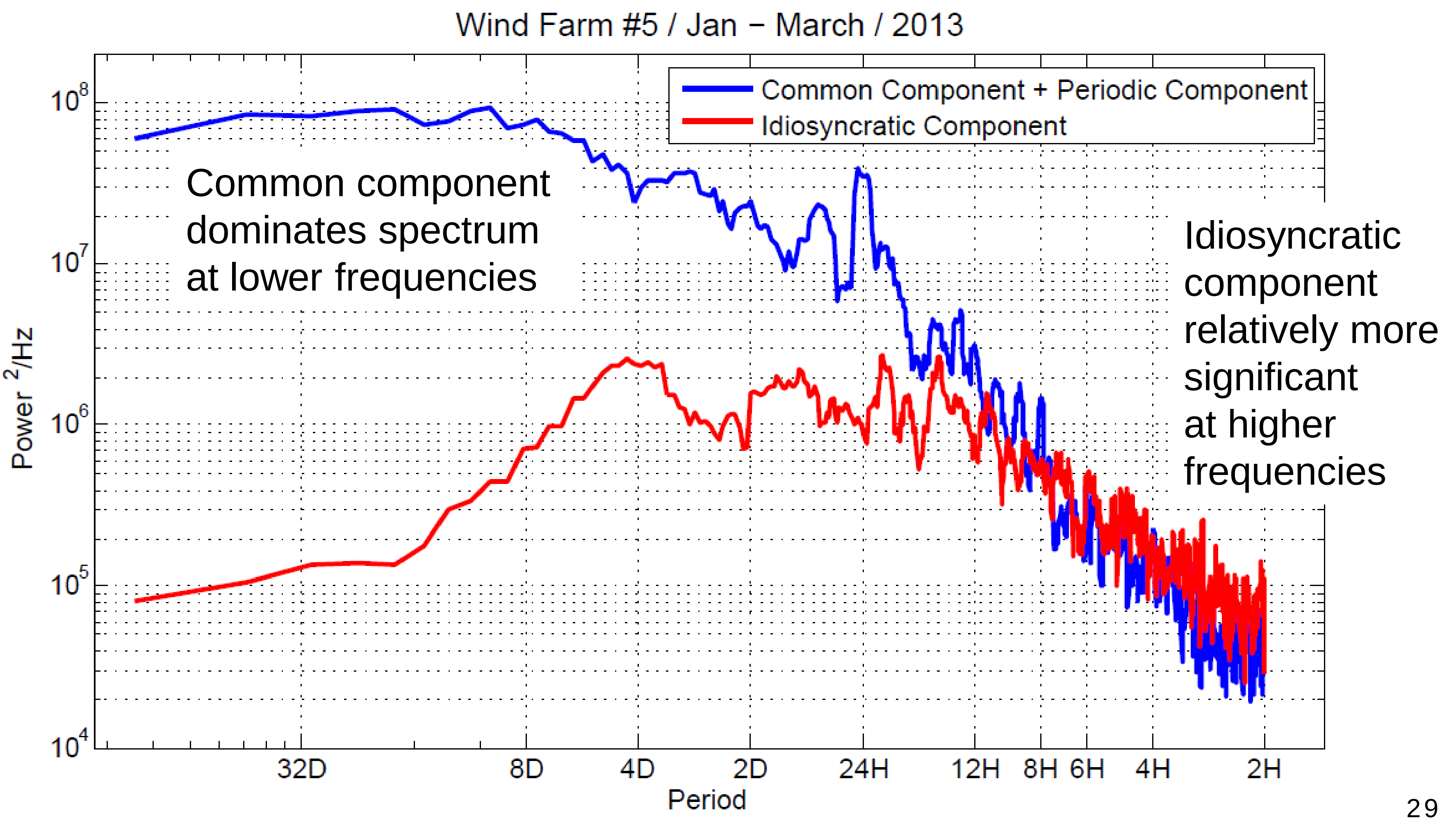
- A. N. Kolmogorov mainly known to electrical engineers through contributions to understanding of stochastic processes.
- Related contributions in turbulent flow crossed over to electrical engineering community through Apt (2007).
- Kolmogorov used dimension analysis to predict that power spectral density 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).

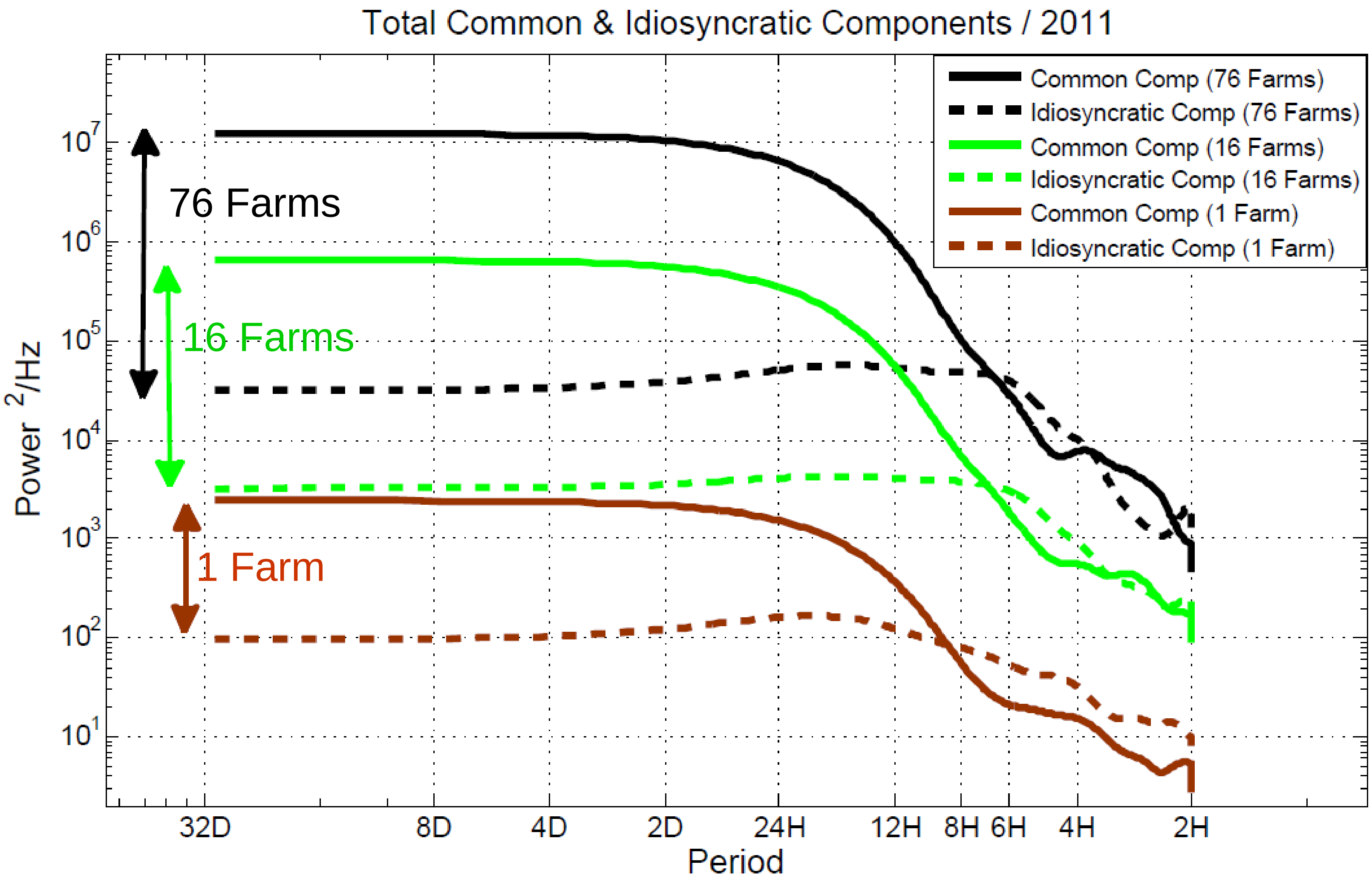
Spectrum of common and idiosyncratic components.



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.

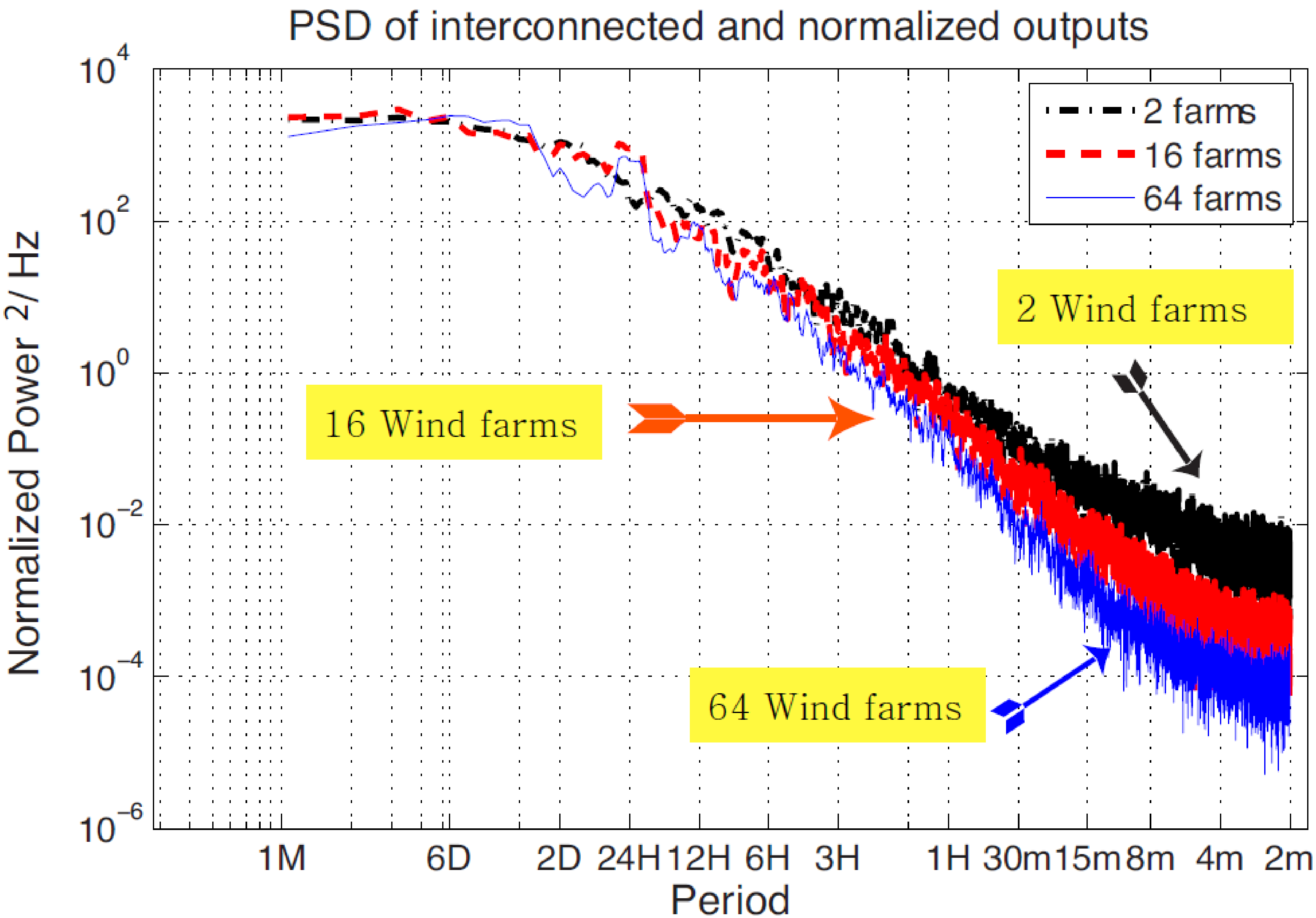
Scaling of wind power and wind variability.



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.

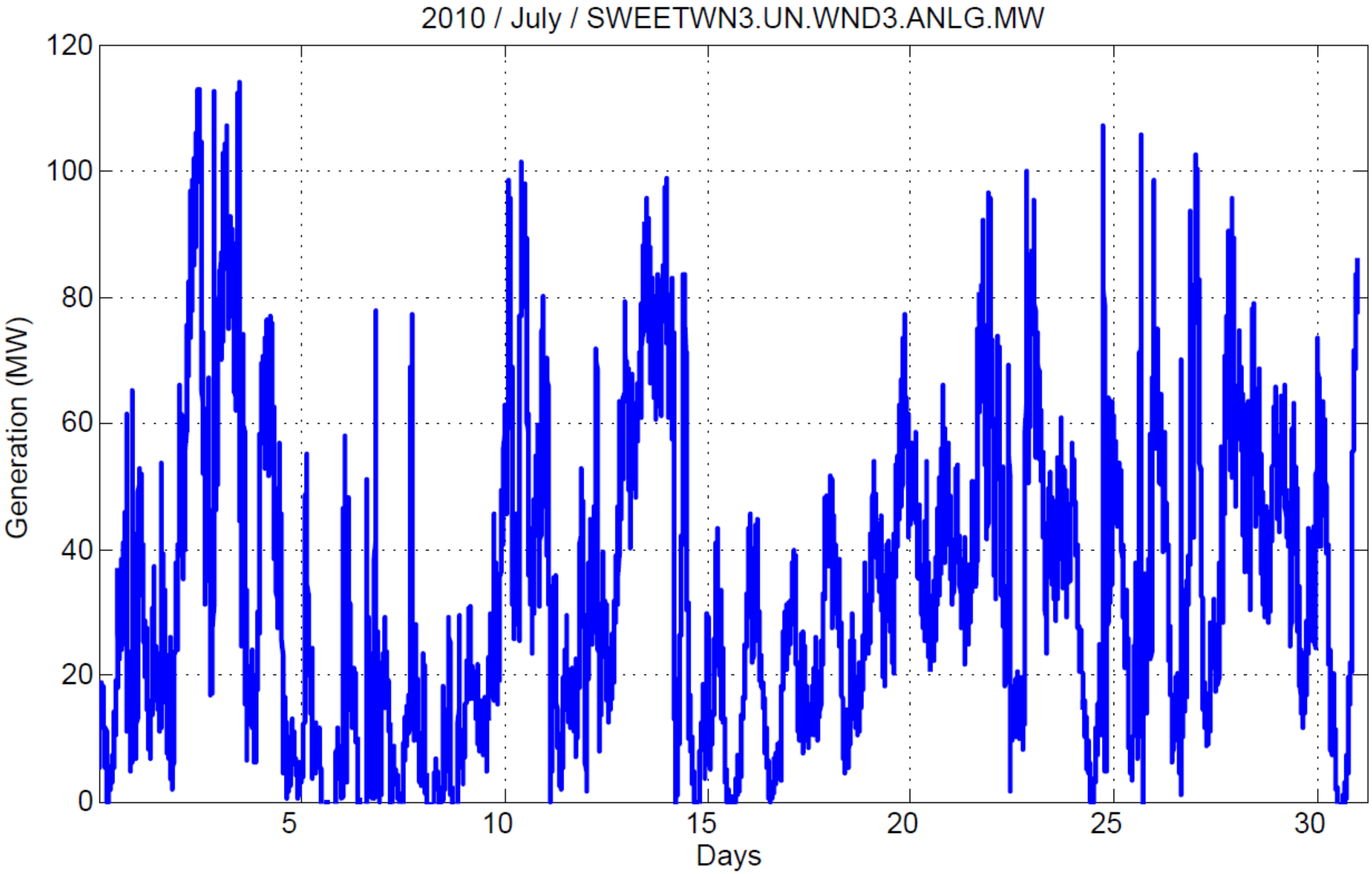


Source: based on Apt (2007), and Lee and Baldick (2014).

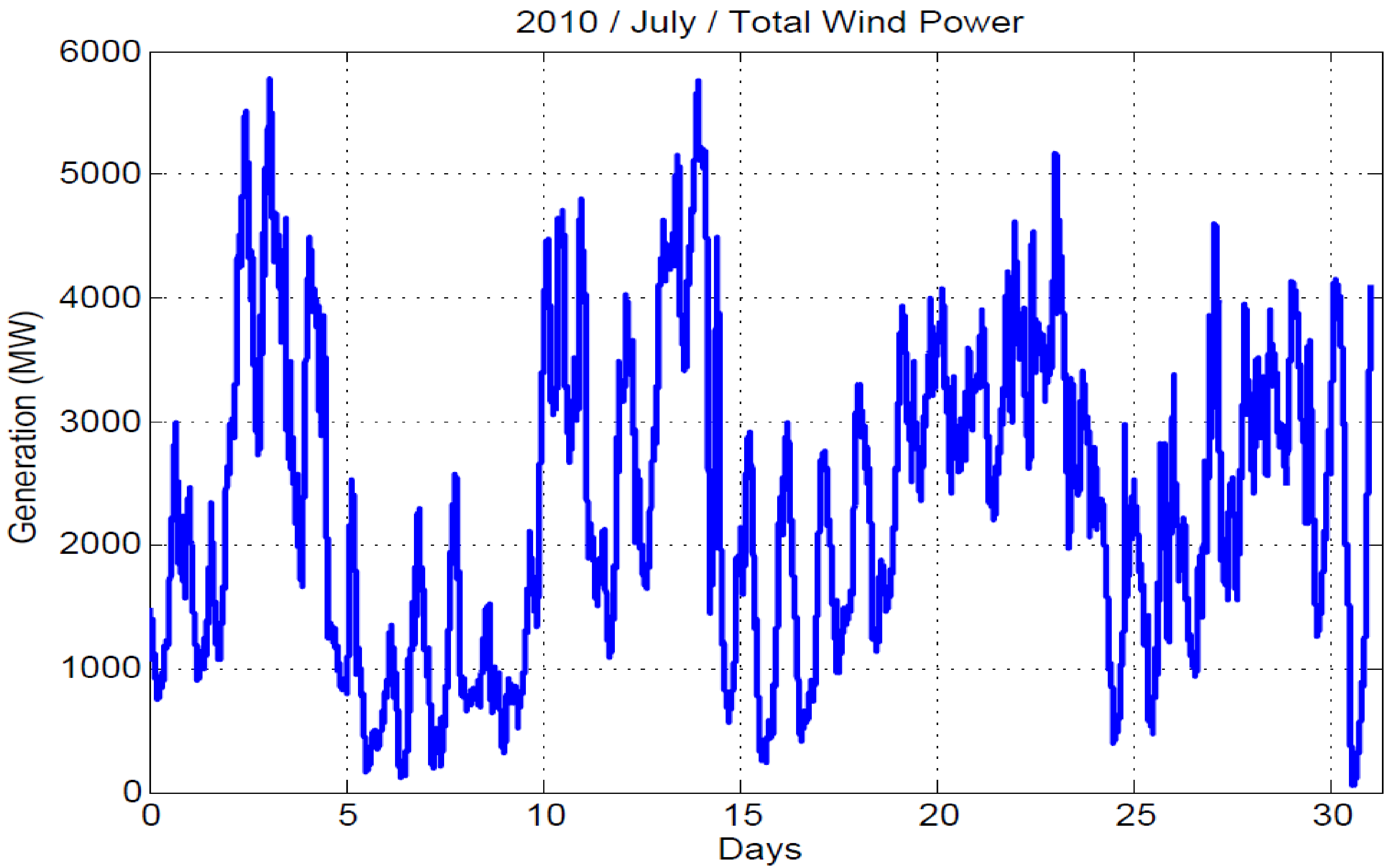
Scaling of wind power and wind variability

- 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.



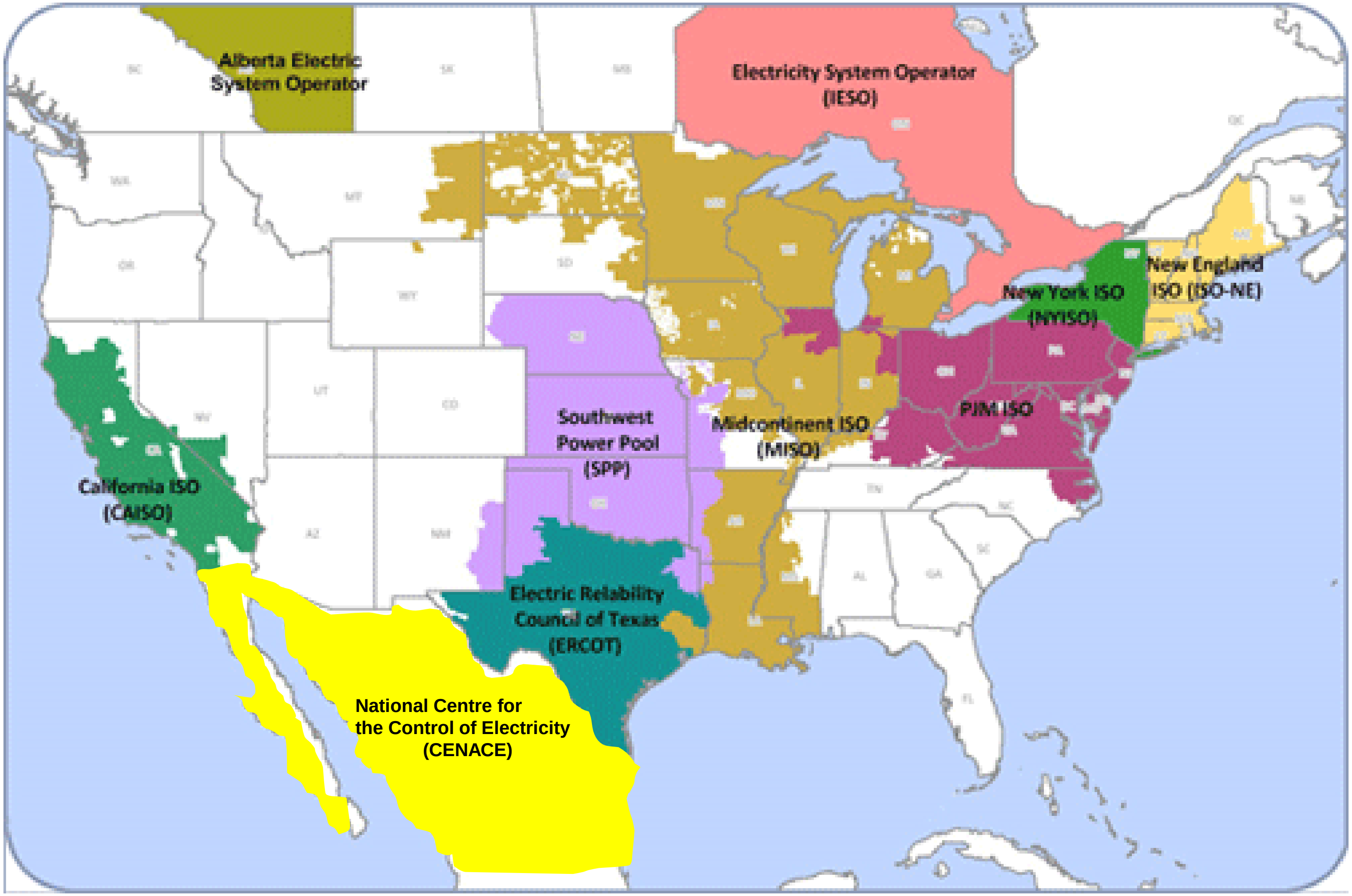
Implications for electricity systems.

- Electricity supply must match load continuously (first law of thermodynamics),
- In short-term, variation between mechanical power and net 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.

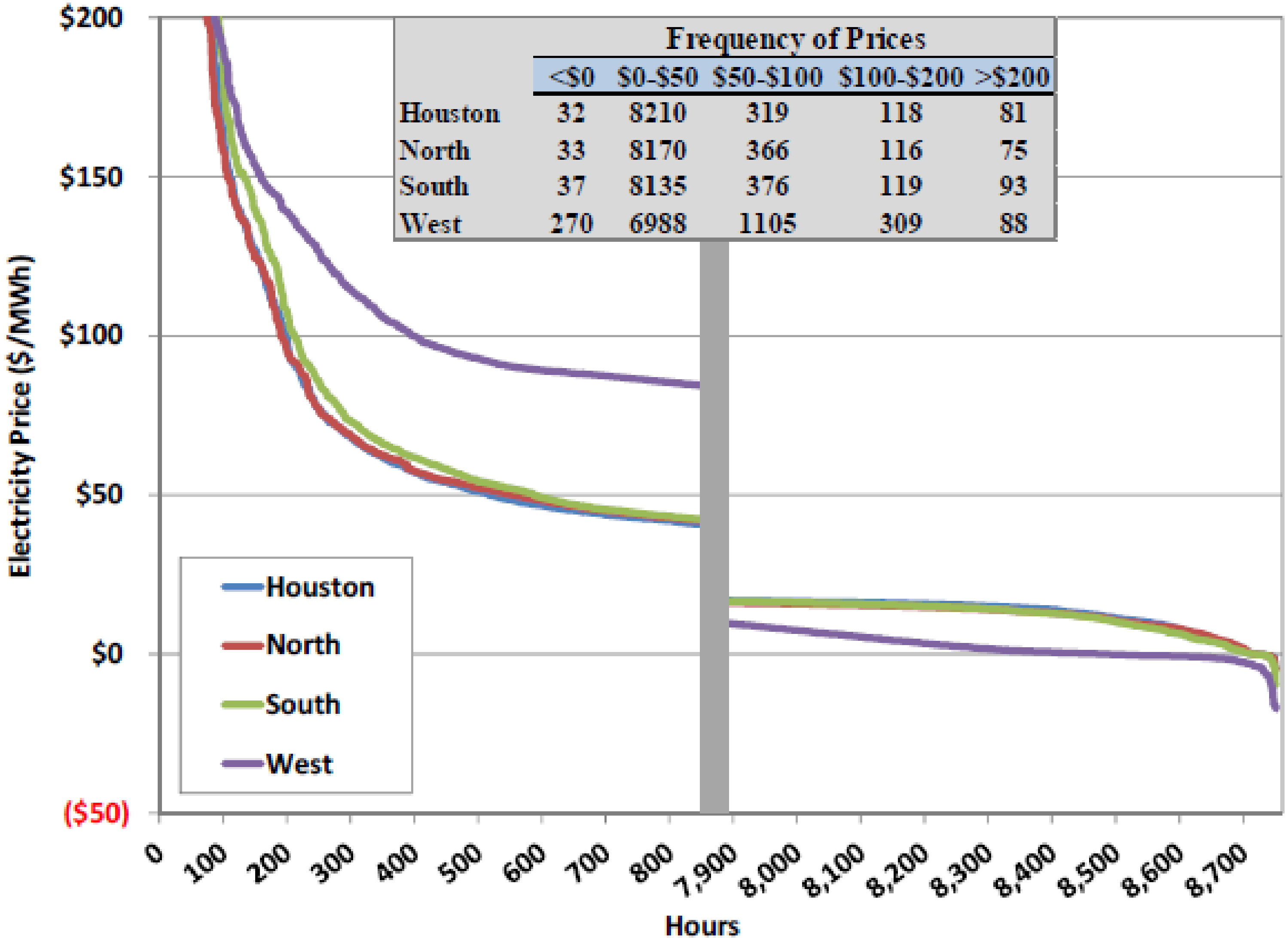
Must-take resources.

- 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 typically 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:
  - "Merit order effect."

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.

Diurnal periodic variation, intermittency, and markets.

- Conversely, West Texas wind typically has minimum production when load is high.
- In February 2021 extreme cold event in Texas, wind had somewhat lower than expected output, and load was especially high.

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.

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