PV Performance
Modeling Collaborative
2024 Modeling Workshop



May. 13th, 2025

[1]Clean Power Research, Napa, CA

Reevaluating PV and Wind Power Variability Across Temporal Domains:

Implications for Grid Integration

Marc Perez[1]

PVPMC[2025]

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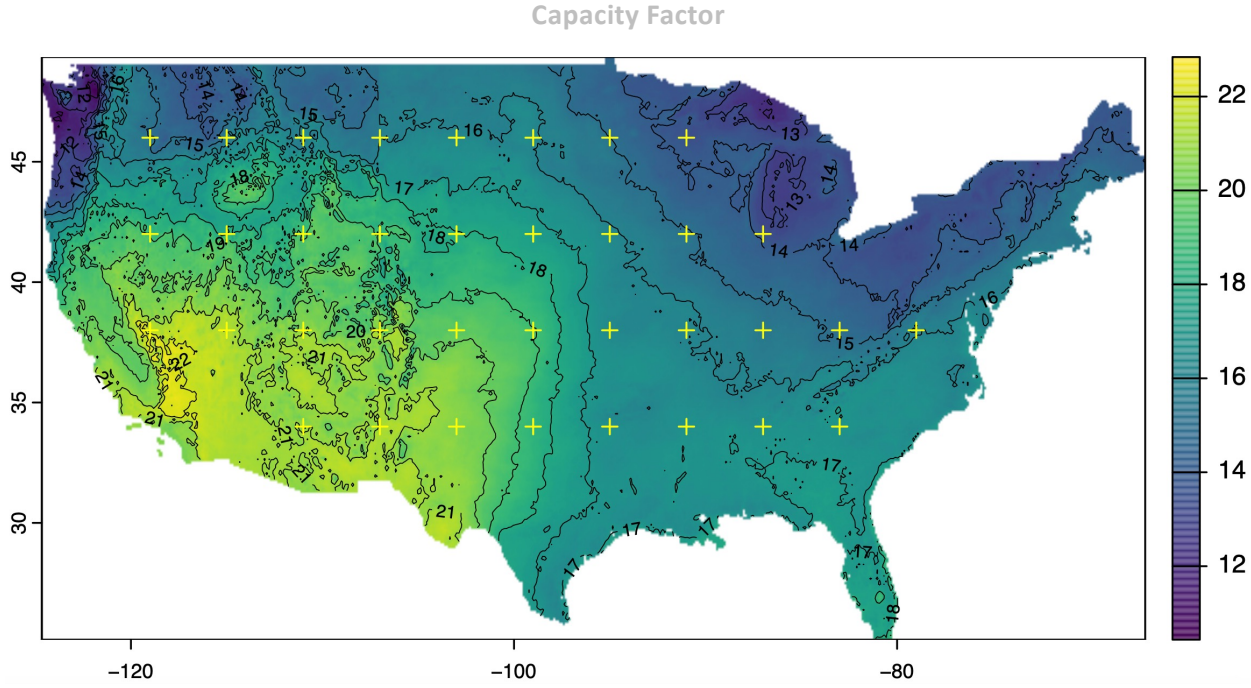
Why does Variability Matter?

Can hybrid PV systems reliably deliver the grid-support functions we model them for?

- Stochastic and deterministic variability influence the balancing resources required to mitigate it
  - Balancing resources cost money and add to the integration costs
  - Balancing resources like:



  - Understanding the characteristics of resource variability helps understand how much and which types of resources to integrate.
  - In fact, what truly matters is the relationship between the variations in the resource and the variations in the load.
  - Here, we investigate and characterize:
    - The variability of both the wind and solar resources
    - How this changes with temporal scale
    - How this changes with spatial extent
    - How this changes with location



Let's focus on the temporal characterization first

- 1 – hour time-averaging interval is of interest from a power capacity standpoint as fluctuations at this interval can induce large ramps that need quick-ramping capability to mitigate.
- We're going to look at the aggregate wind power production vs solar production @ fixed latitude tilt across the set of points indicated by crosses within the continental US

How do we characterize variability?

$X_{\Delta T=1}$ → **Hourly-Interval Timeseries**

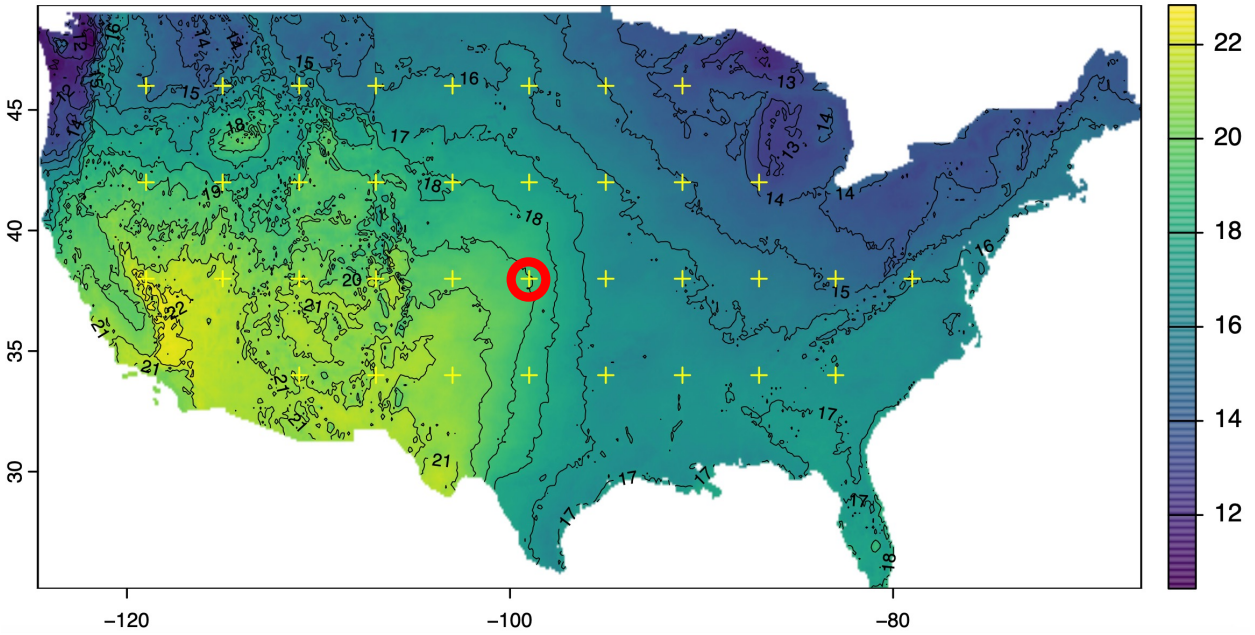
$X_{\Delta T=24}$ → **Daily-Interval Timeseries**

$X_{\Delta T=Y}$ → **Y-Interval Timeseries**

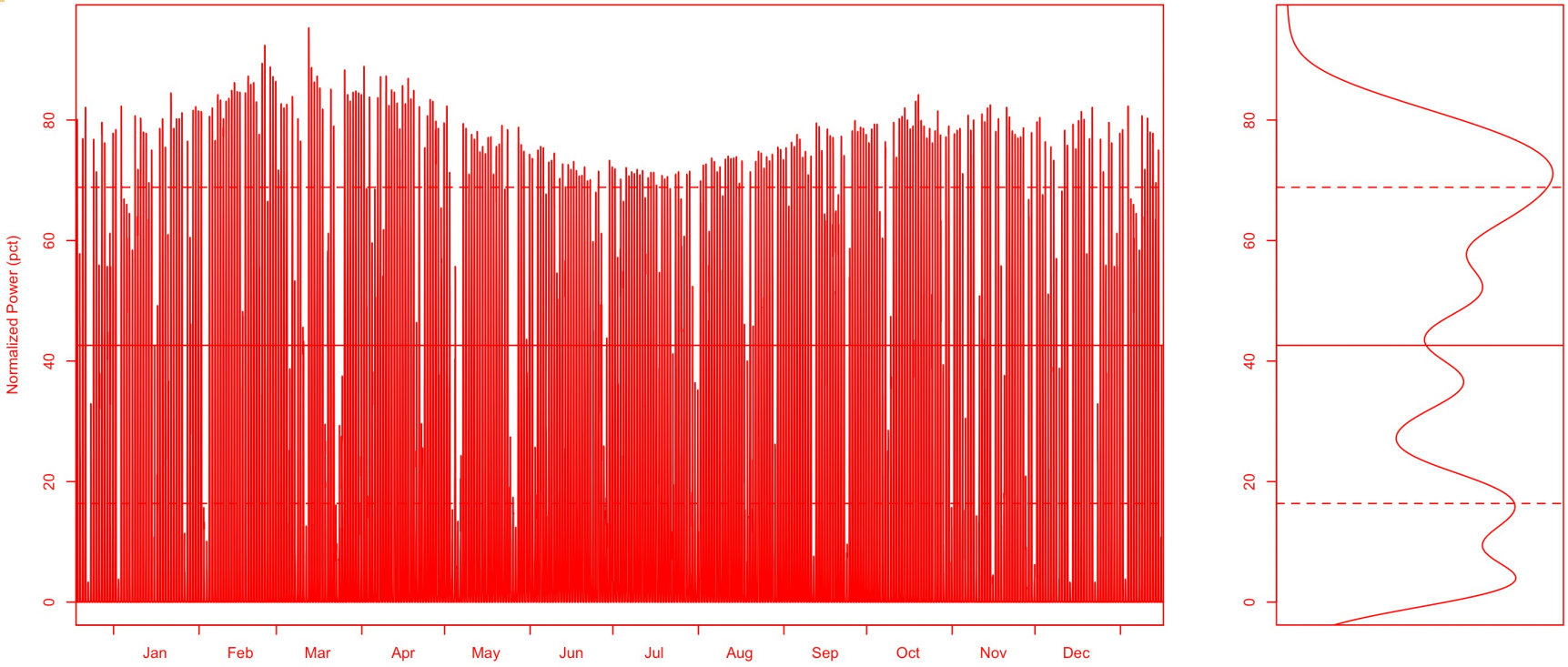
$\Delta X = X_i - X_{i-1}$ *for* $\forall_i$ → **Variability Timeseries**

$\sigma X_{\Delta T=Y}$ → **Variability of X at the Y time-averaging interval**

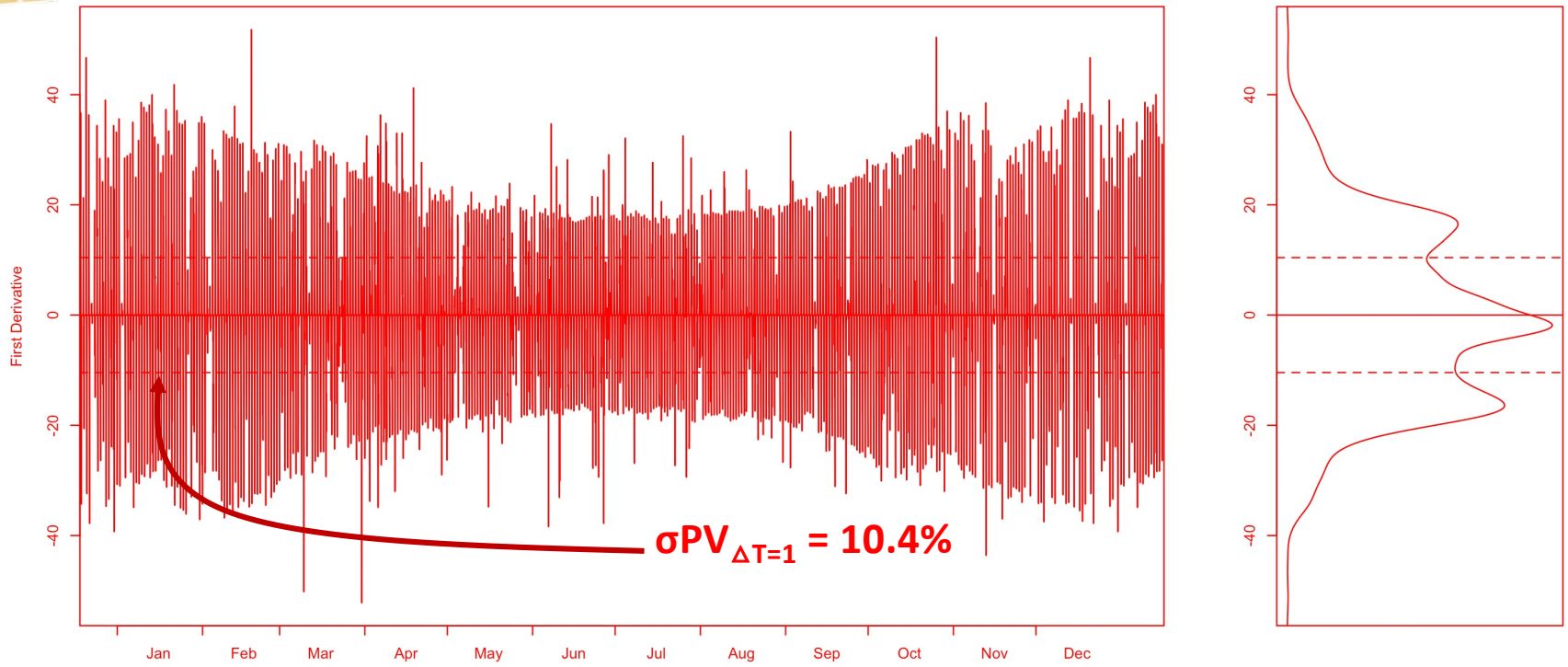
Let's look at hourly variability of PV & wind at this location



Normalized Hourly Power @ 38°N, 99°W

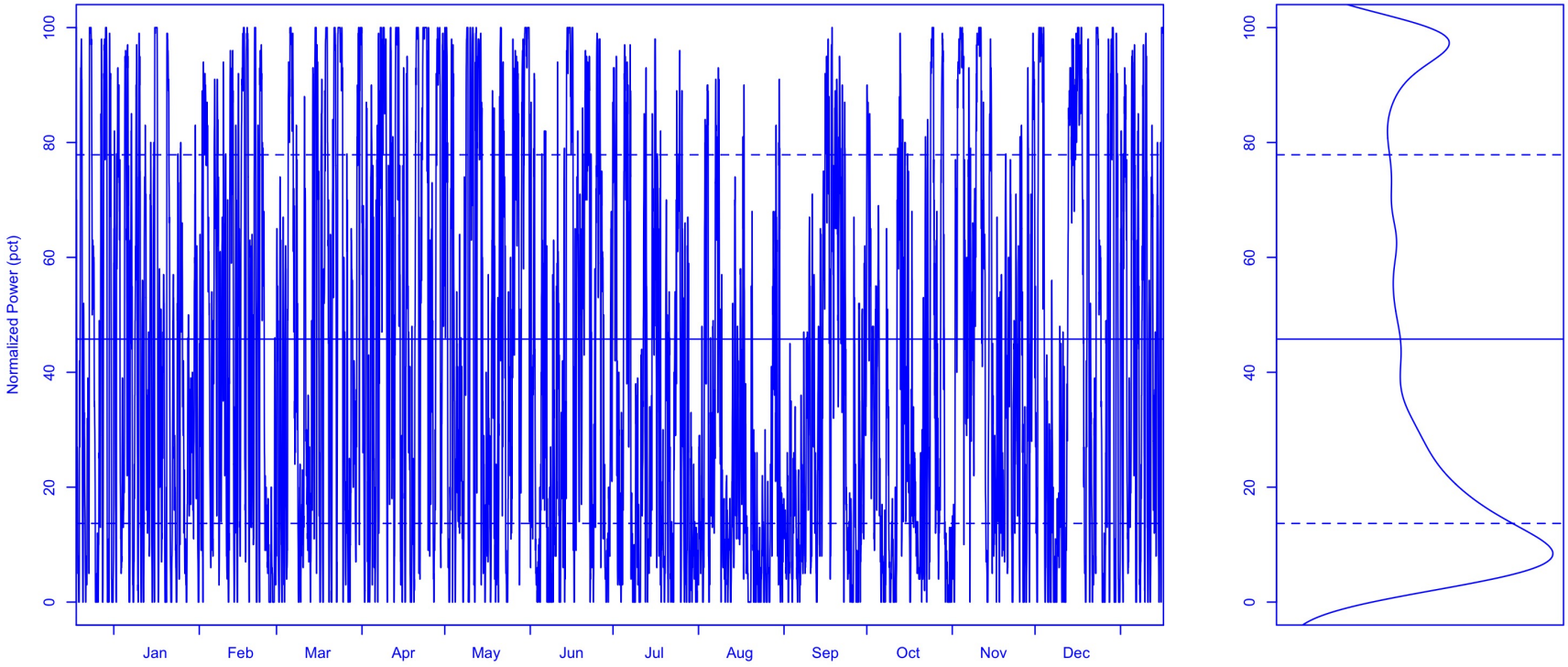


Hourly Fluctuations ($P_{\Delta T=1hr}$)

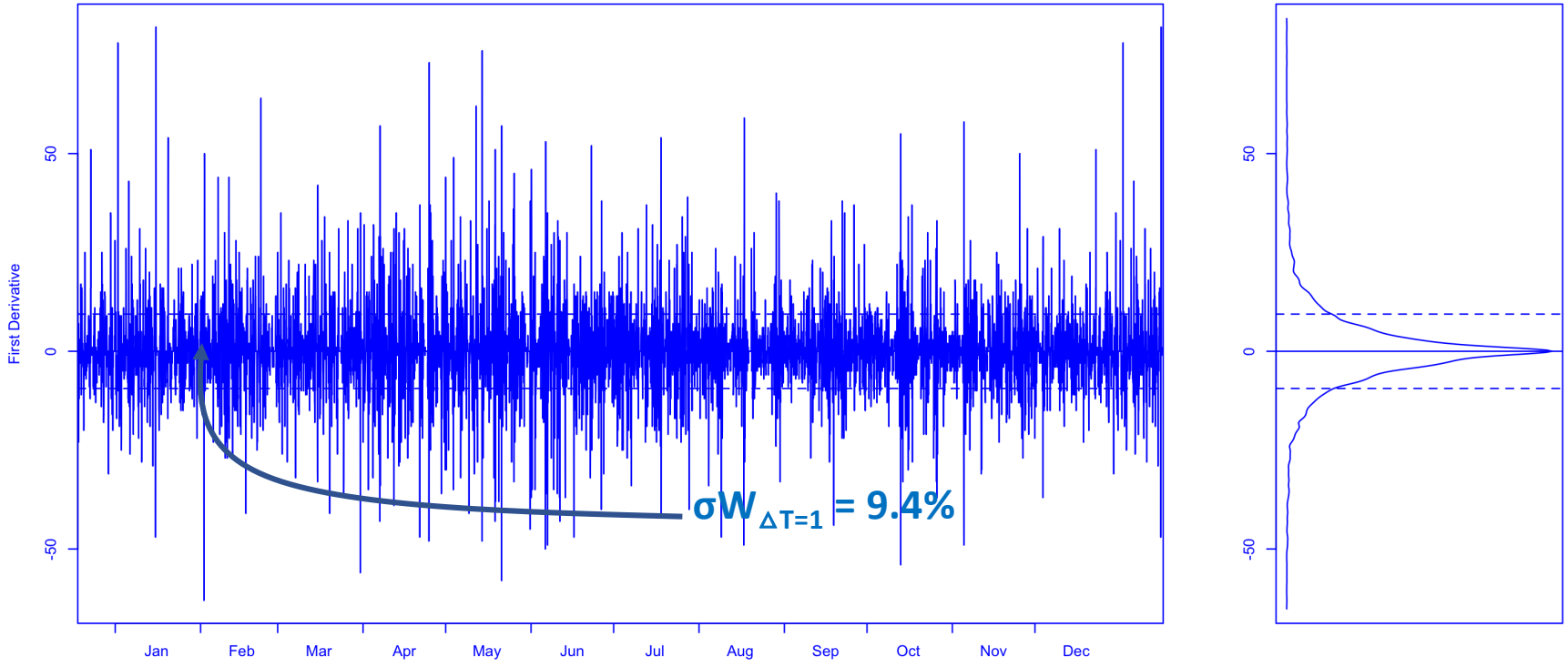


Hourly fluctuations range
between +/- 51% of rated capacity

Normalized Hourly Power @ 38°N, 99°W

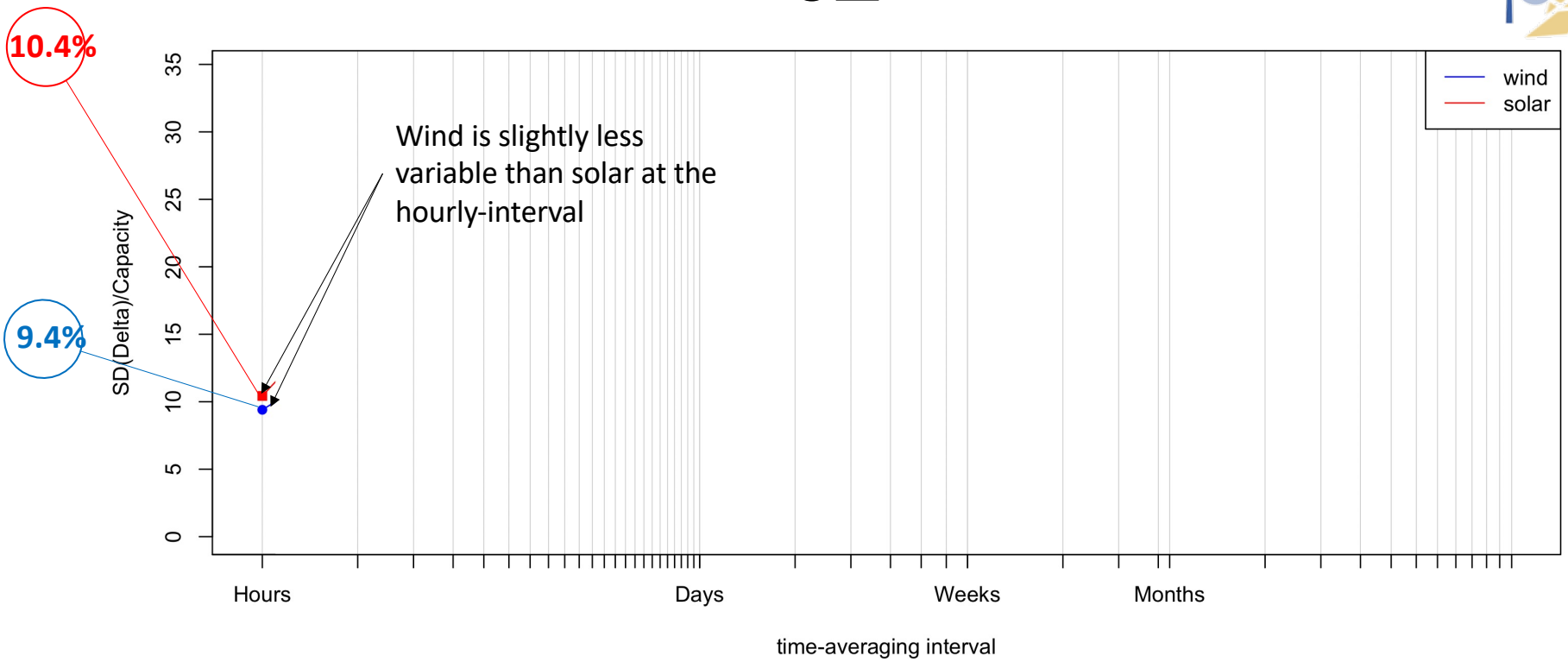


Hourly Fluctuations ($\Delta W_{t=1h}$)

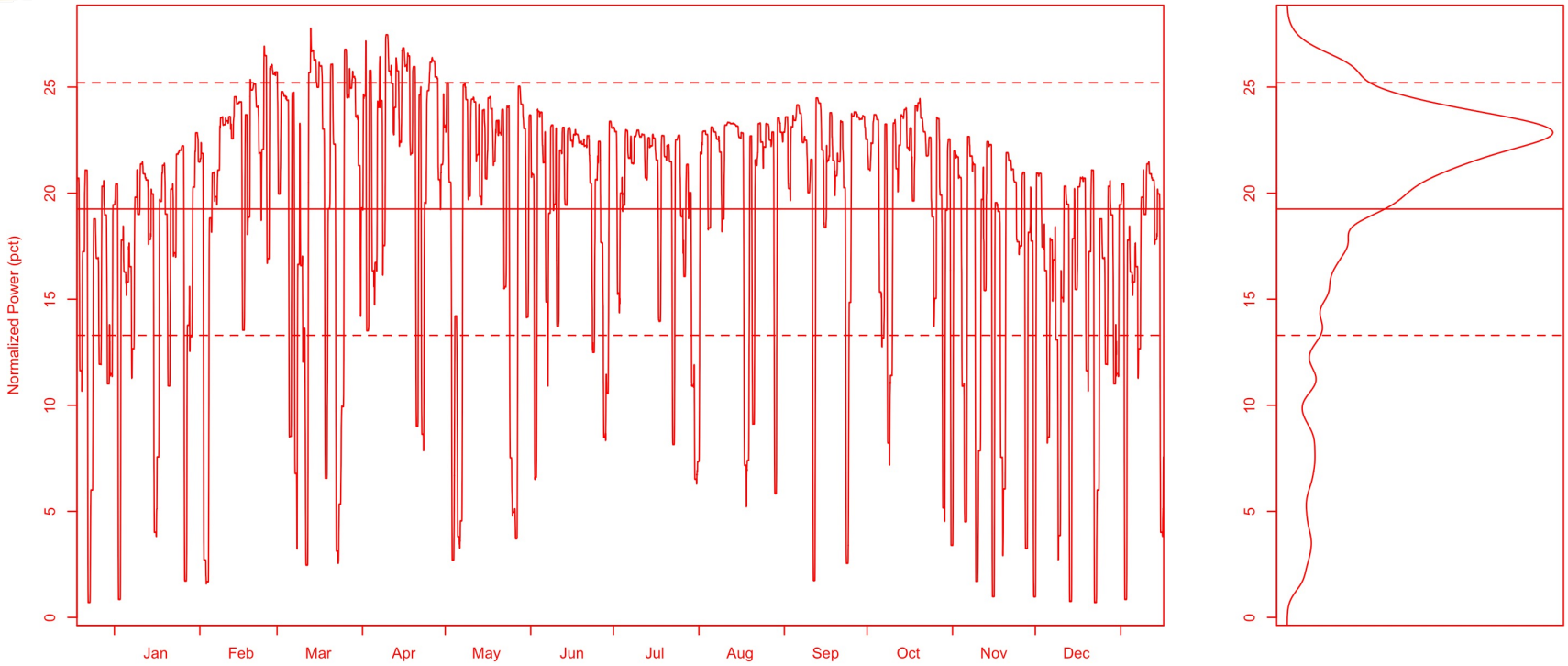


Hourly fluctuations range
between +/- 82% of rated capacity

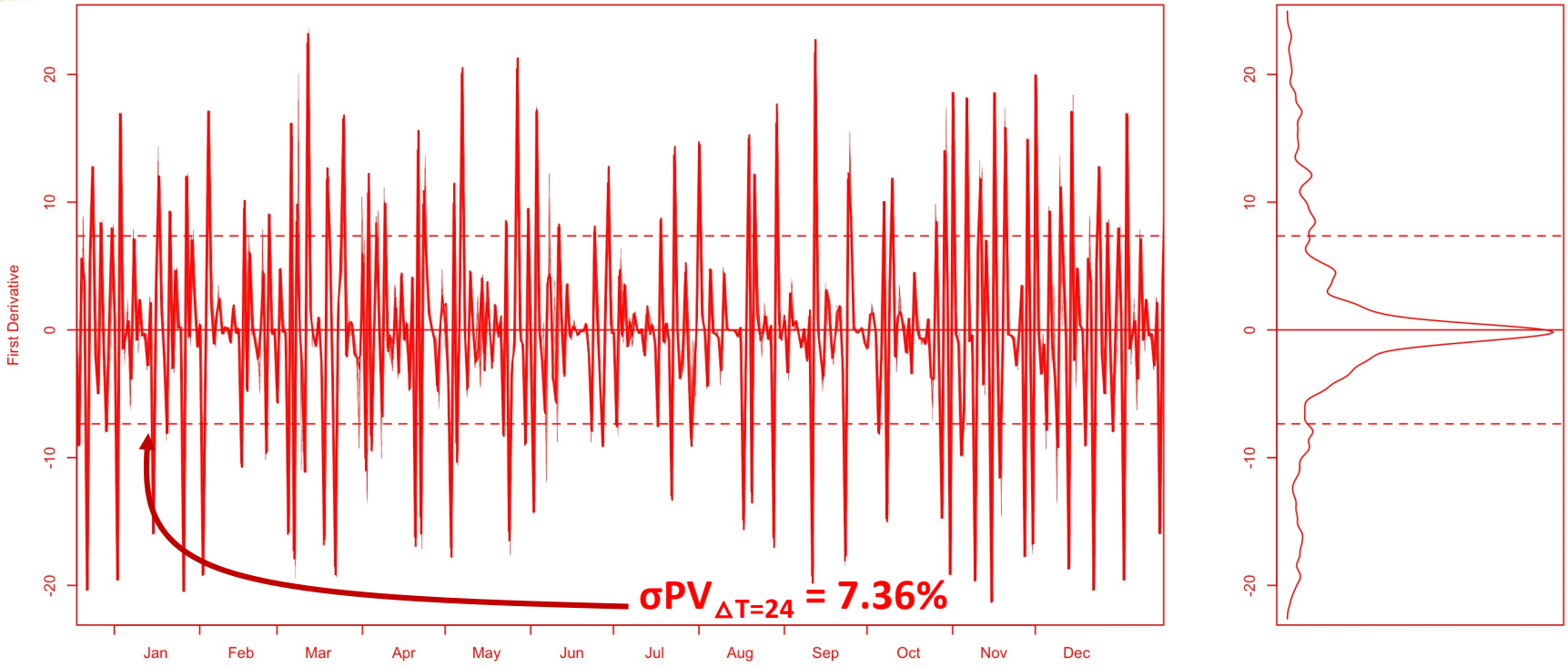
σΔ


10.4%
9.4%
SD(Delta)/Capacity
0
5
10
15
20
25
30
35
Wind is slightly less variable than solar at the hourly-interval
wind
solar
Hours
Days
Weeks
Months
time-averaging interval

Normalized Daily Power @ 38°N, 99°W

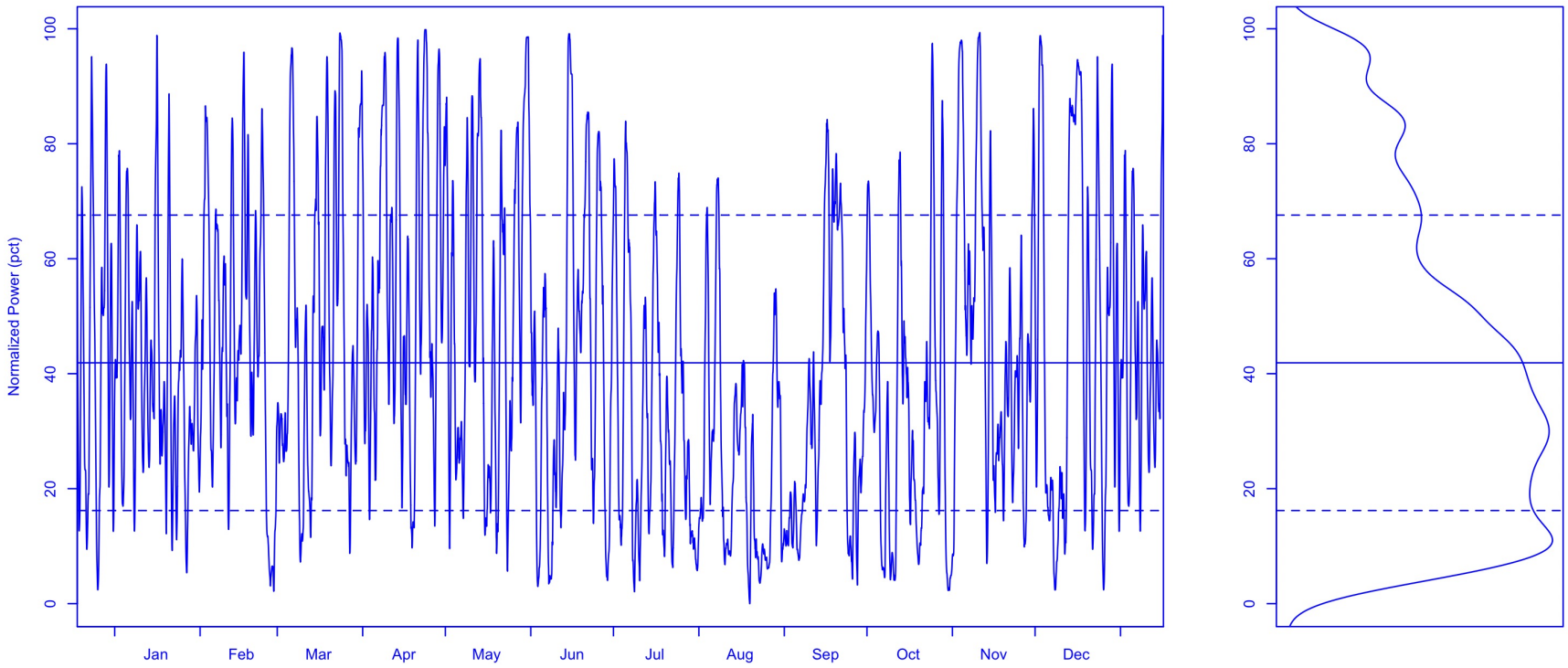


Daily Fluctuations ($P_{\Delta T=24hr}$)

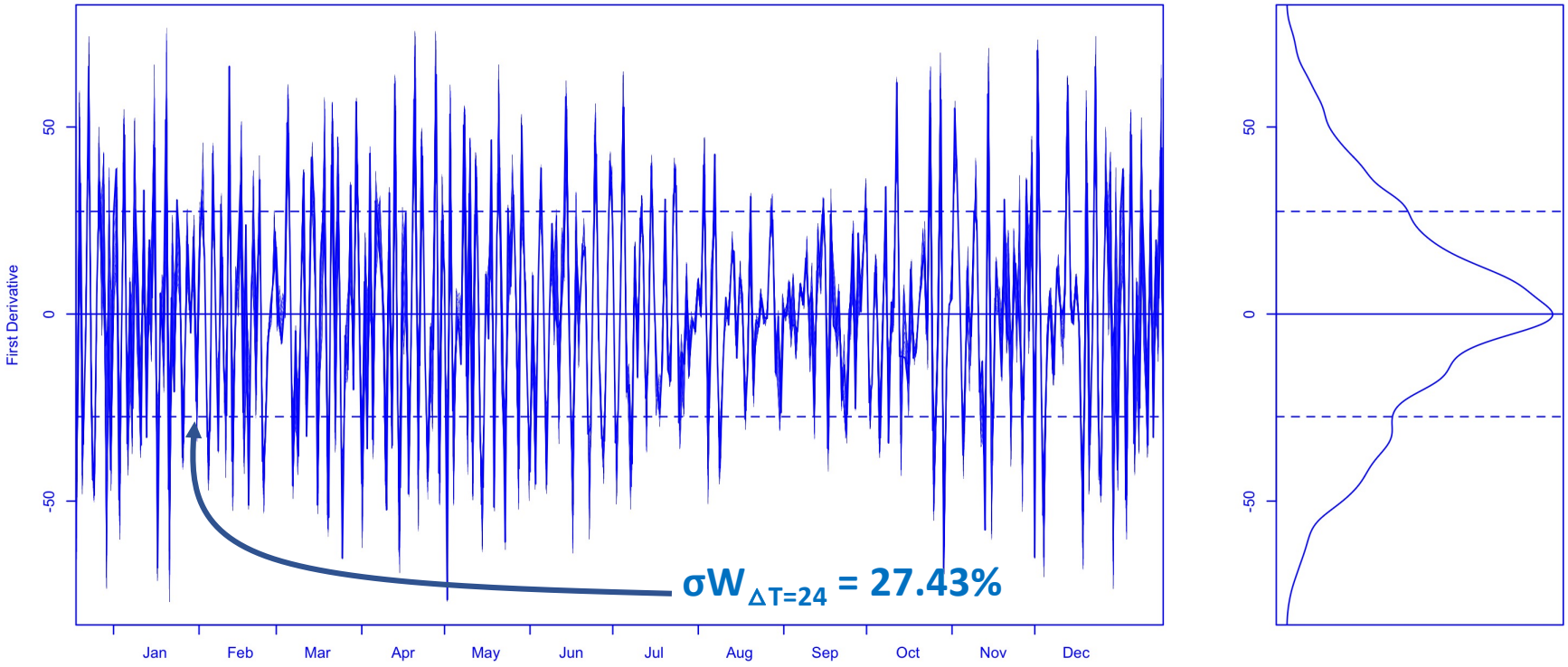


Daily fluctuations range between
+/- 23% of rated capacity

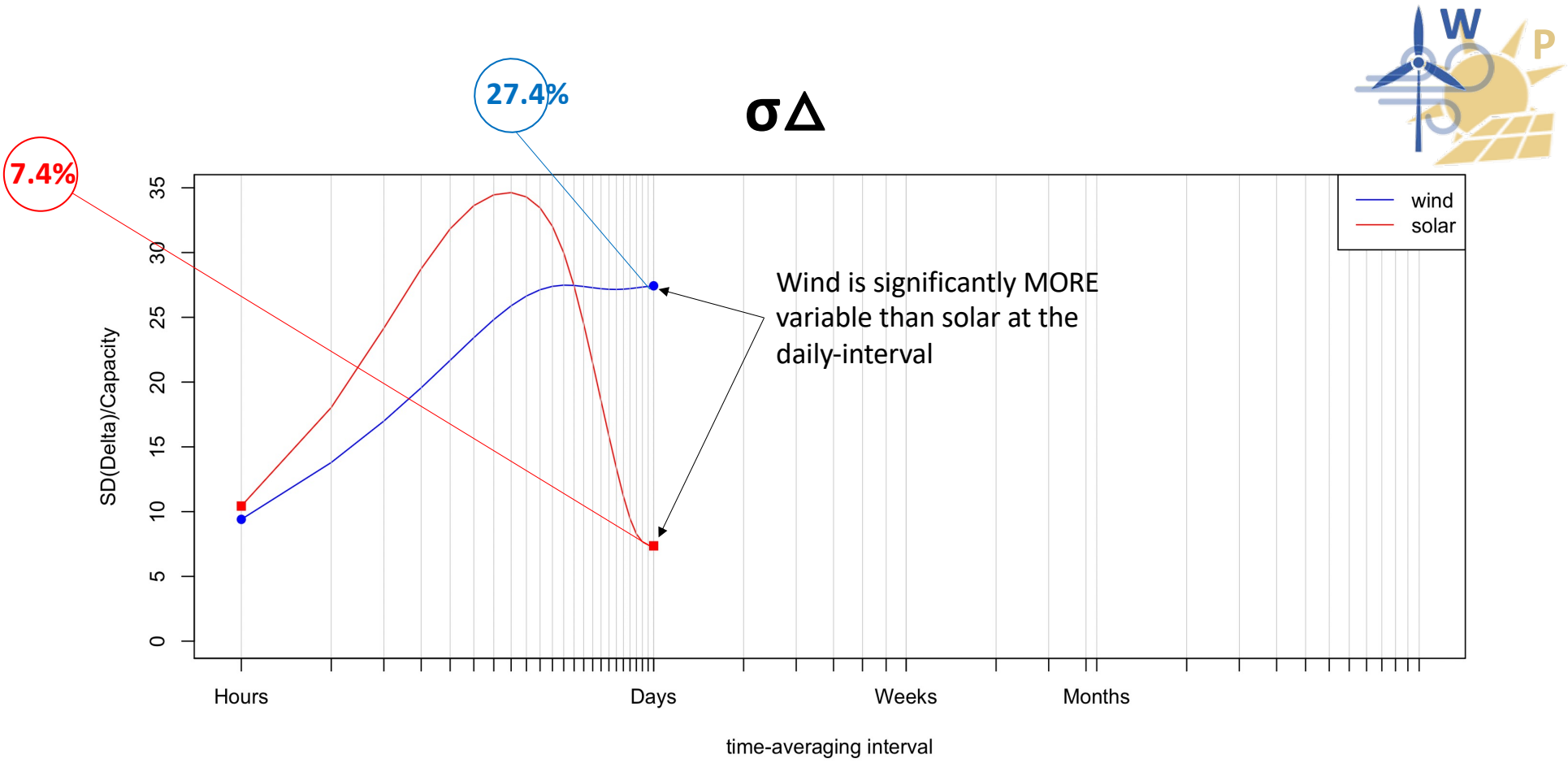
Normalized Daily Power @ 38°N, 99°W



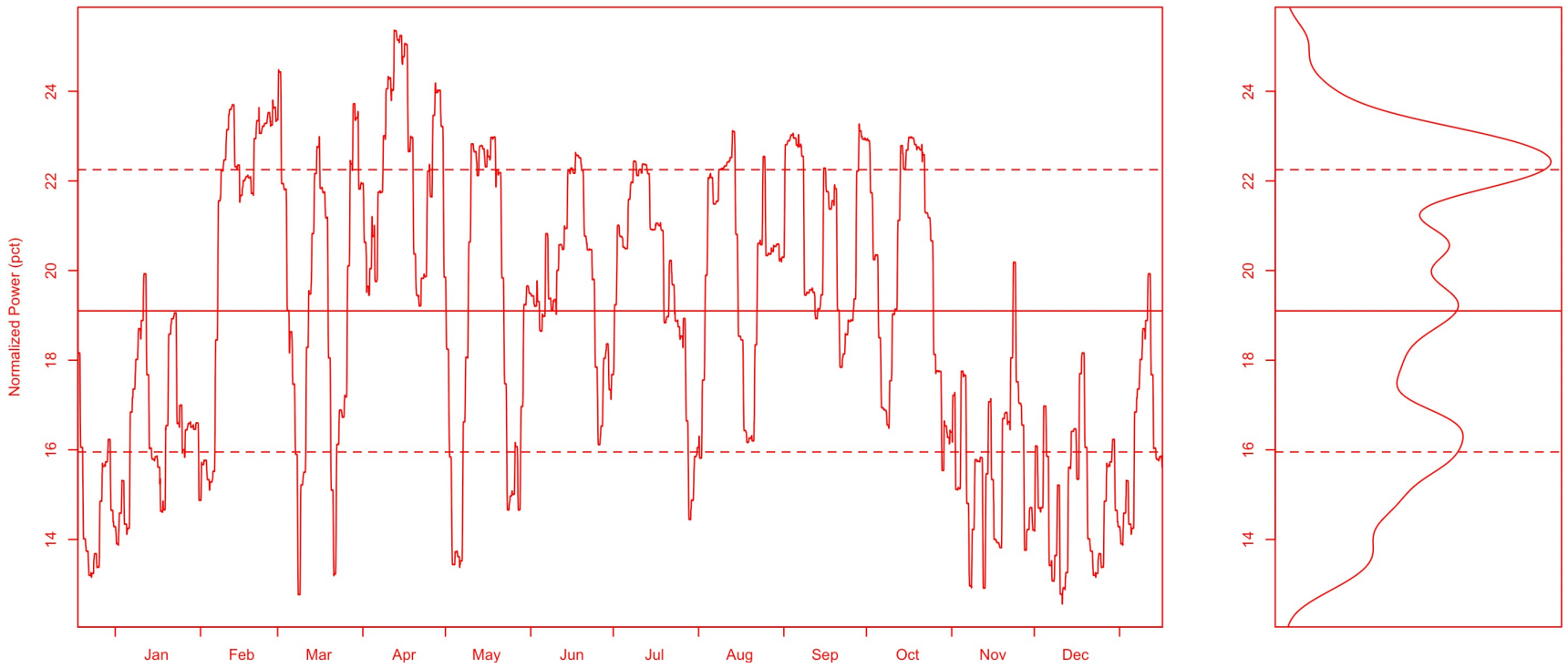
Daily Fluctuations ($\Delta W_{t=24h}$)



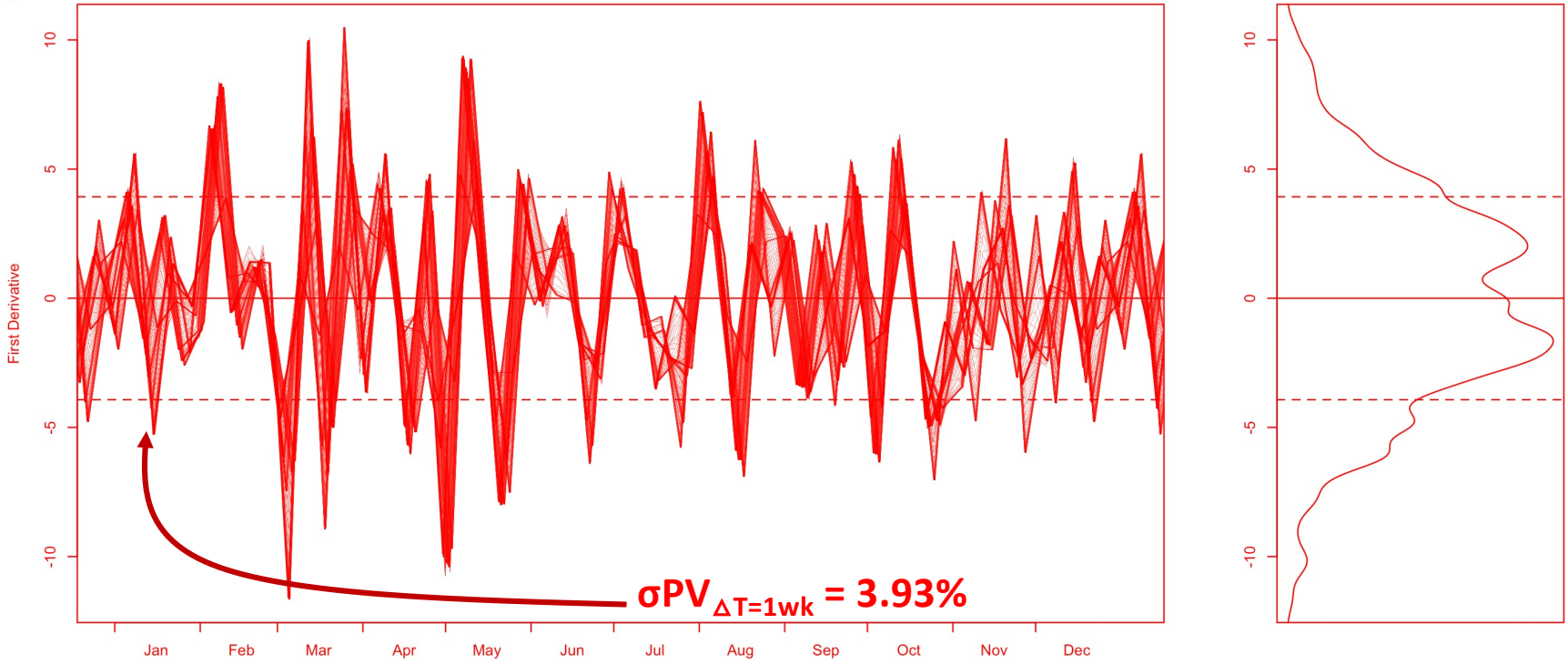
Daily fluctuations range between
+/- 76.96% of rated capacity


σΔ
27.4%
7.4%
wind
solar
Wind is significantly MORE variable than solar at the daily-interval
SD(Delta)/Capacity
0
5
10
15
20
25
30
35
Hours
Days
Weeks
Months
time-averaging interval

Normalized Weekly Power @ 38°N, 99°W

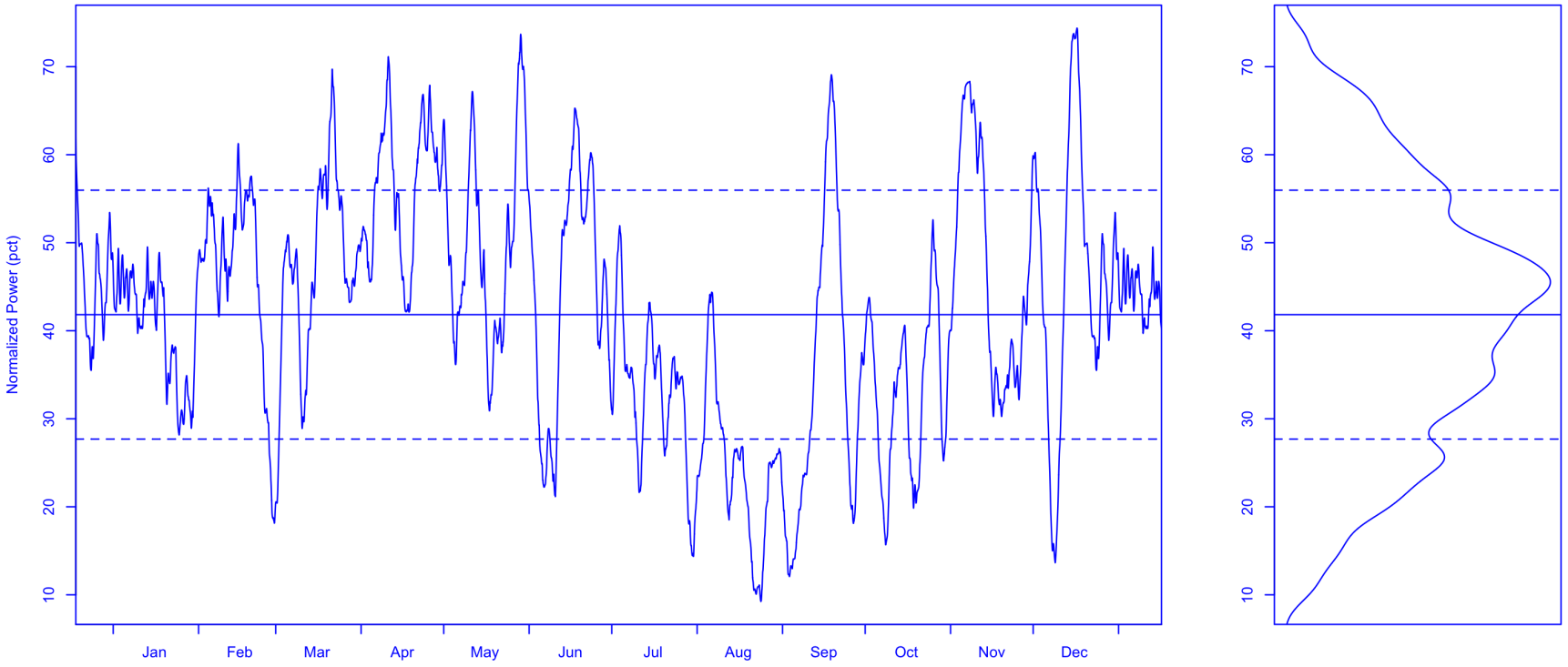


Weekly Fluctuations ($P_{\Delta T=1wk}$)

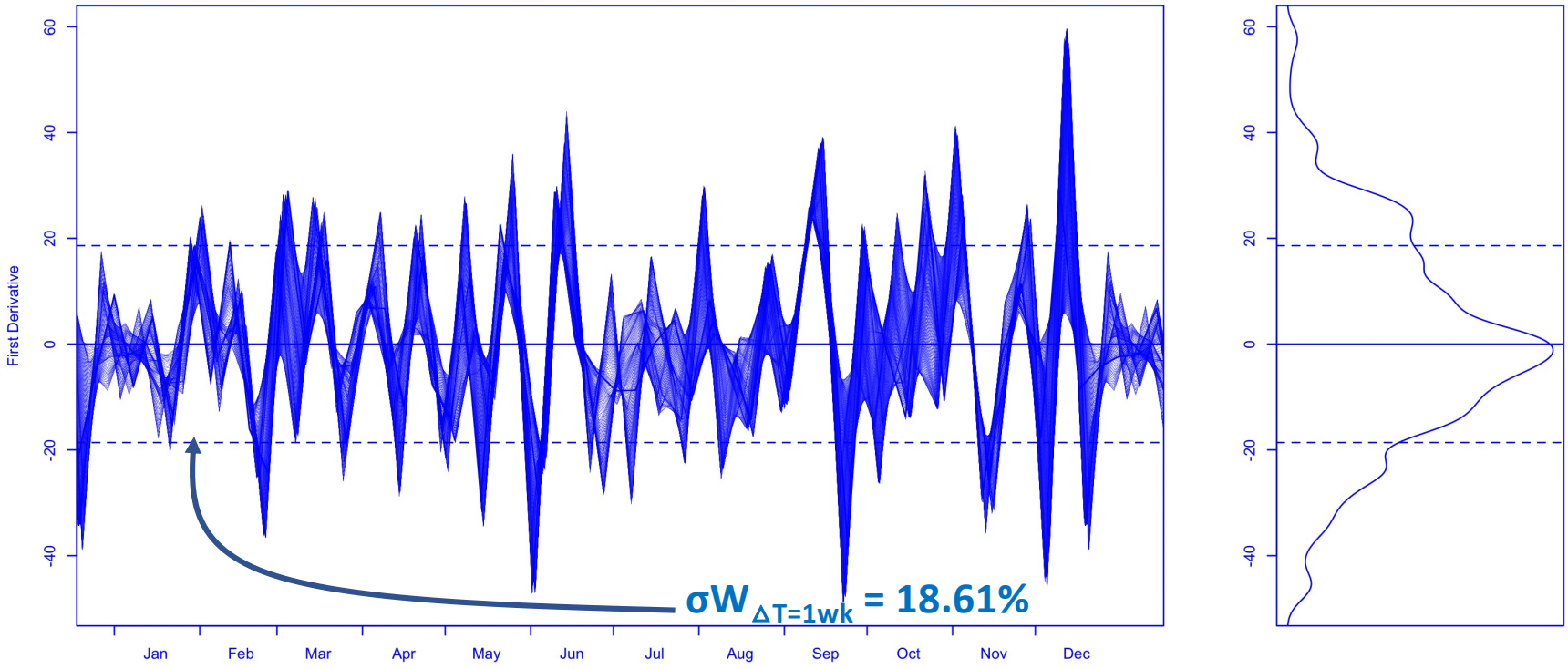


Weekly fluctuations range between
+/- 11.67% of rated capacity

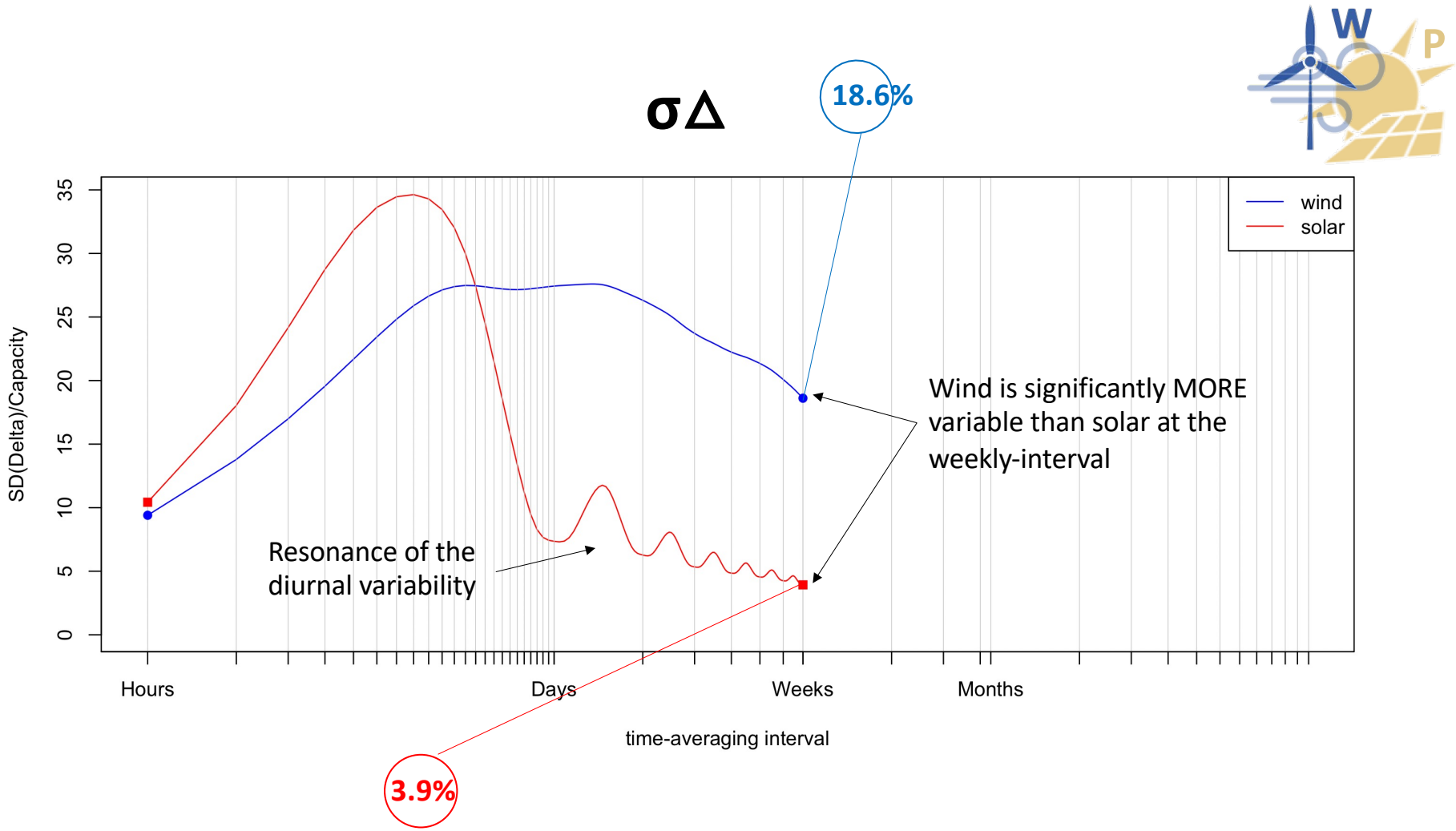
Normalized Weekly Power @ 38°N, 99°W



Weekly Fluctuations ($\Delta W_{t=1wk}$)



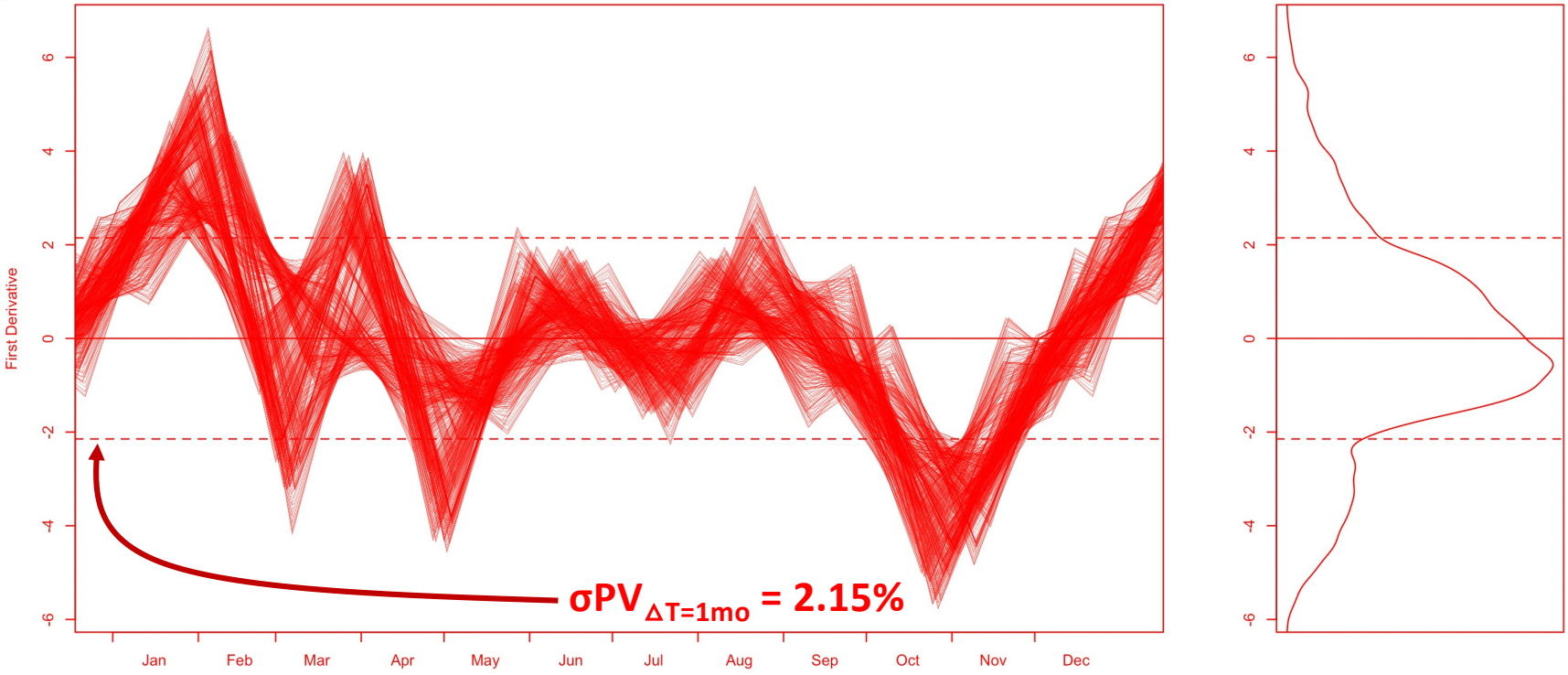
Weekly fluctuations range between
+/- 59.65% of rated capacity


σΔ
18.6%
3.9%
wind
solar
SD(Delta)/Capacity
0
5
10
15
20
25
30
35
Hours
Days
Weeks
Months
time-averaging interval
Resonance of the diurnal variability
Wind is significantly MORE variable than solar at the weekly-interval

Normalized Monthly Power @ 38°N, 99°W



Monthly Fluctuations ($P_{\Delta T=1mo}$)

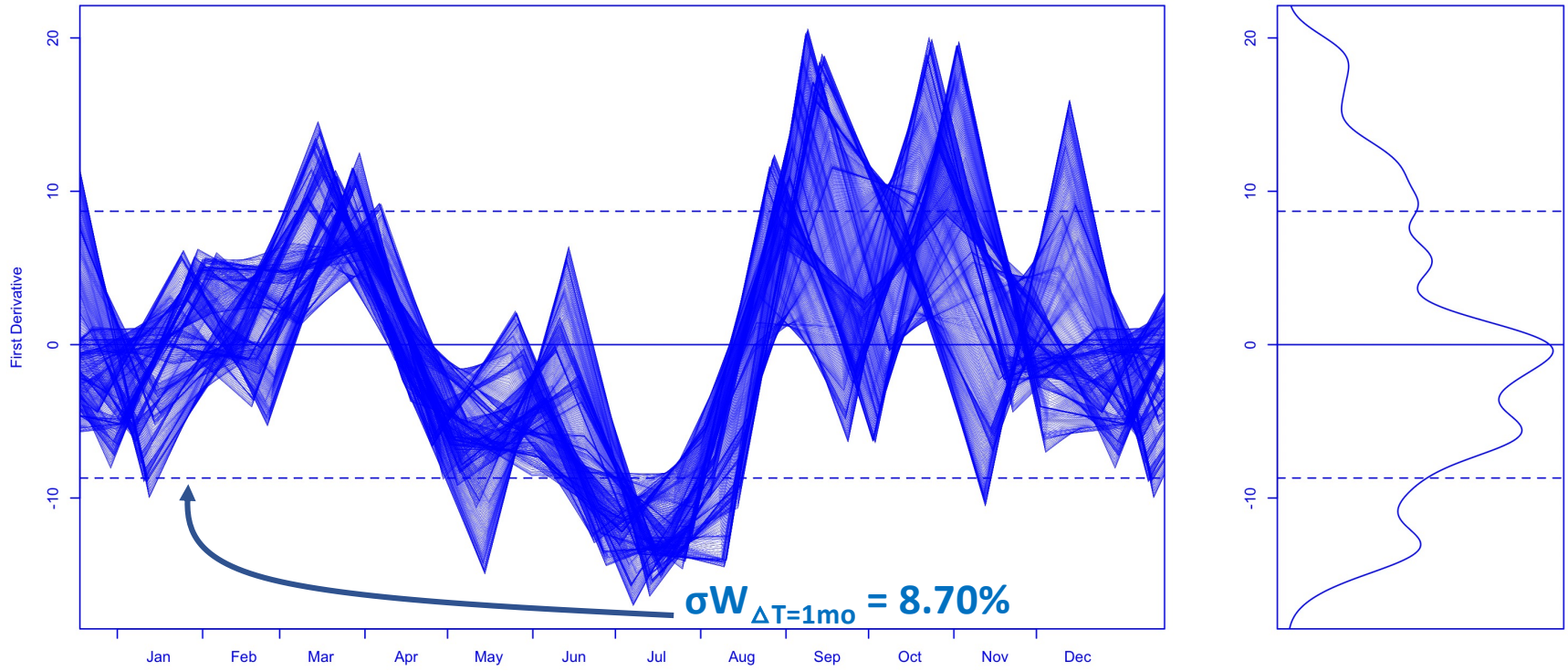


Monthly fluctuations range between +/- 6.63% of rated capacity

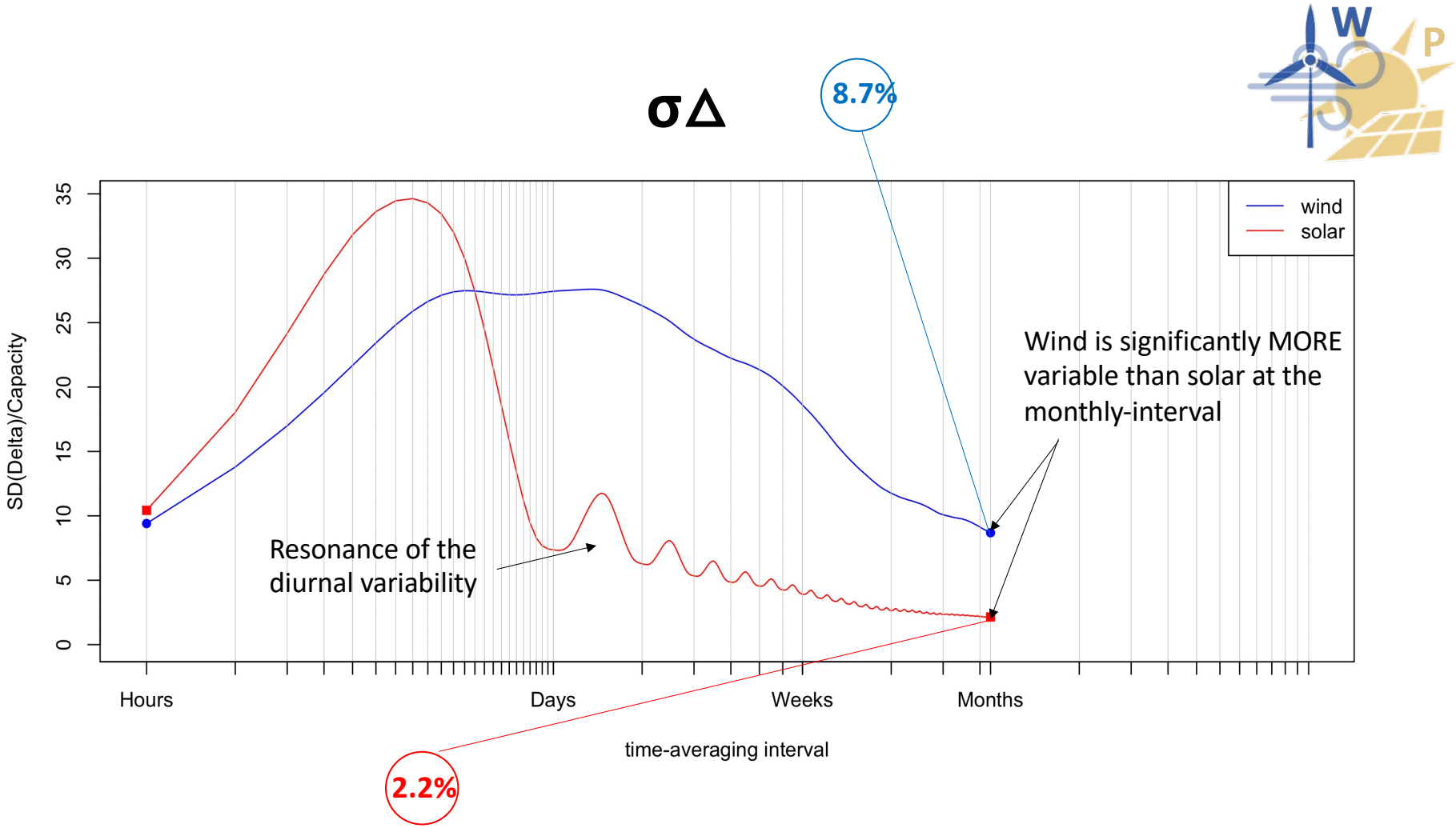
Normalized Monthly Power @ 38°N, 99°W



Monthly Fluctuations ($\Delta W_{t=1mo}$)



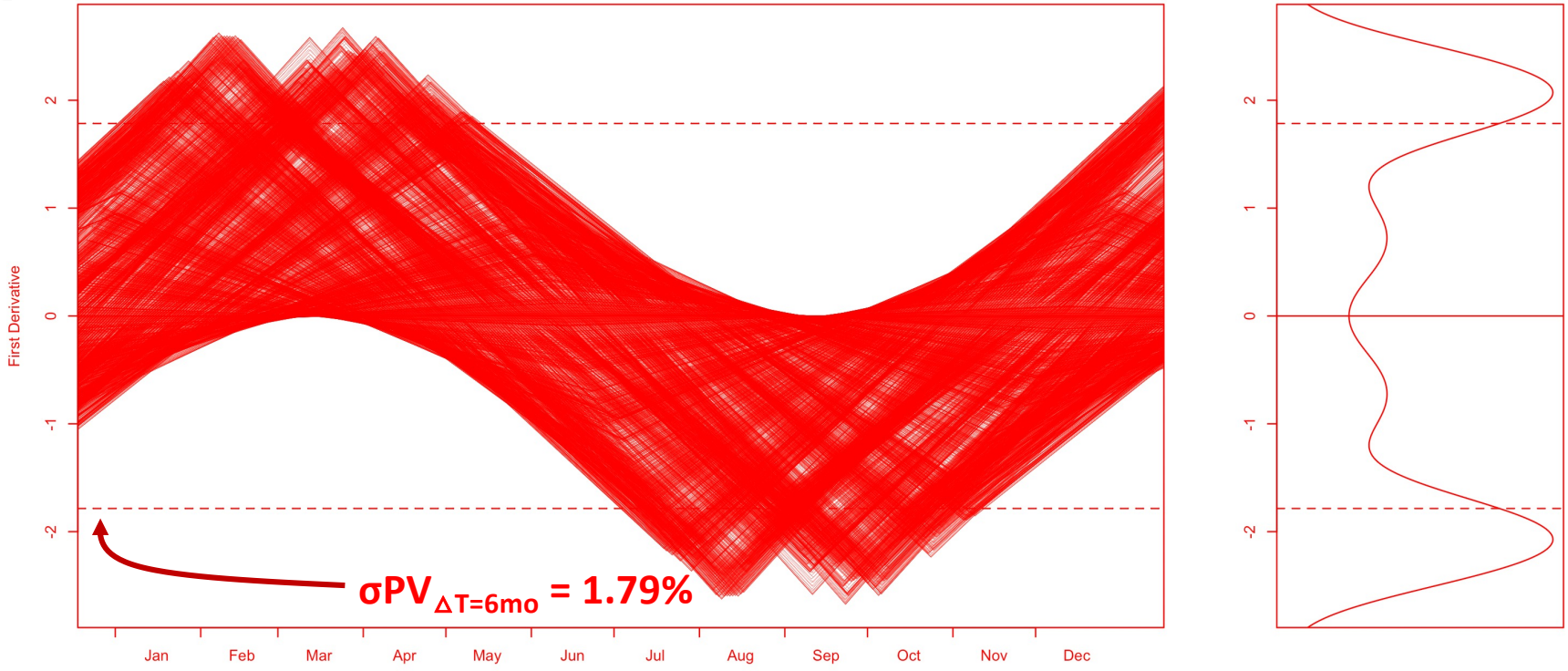
Monthly fluctuations range between
+/- 20.6% of rated capacity


σΔ
8.7%
wind
solar
SD(Delta)/Capacity
0
5
10
15
20
25
30
35
Hours
Days
Weeks
Months
time-averaging interval
Resonance of the diurnal variability
Wind is significantly MORE variable than solar at the monthly-interval
2.2%

Normalized 6-mo Power @ 38°N, 99°W

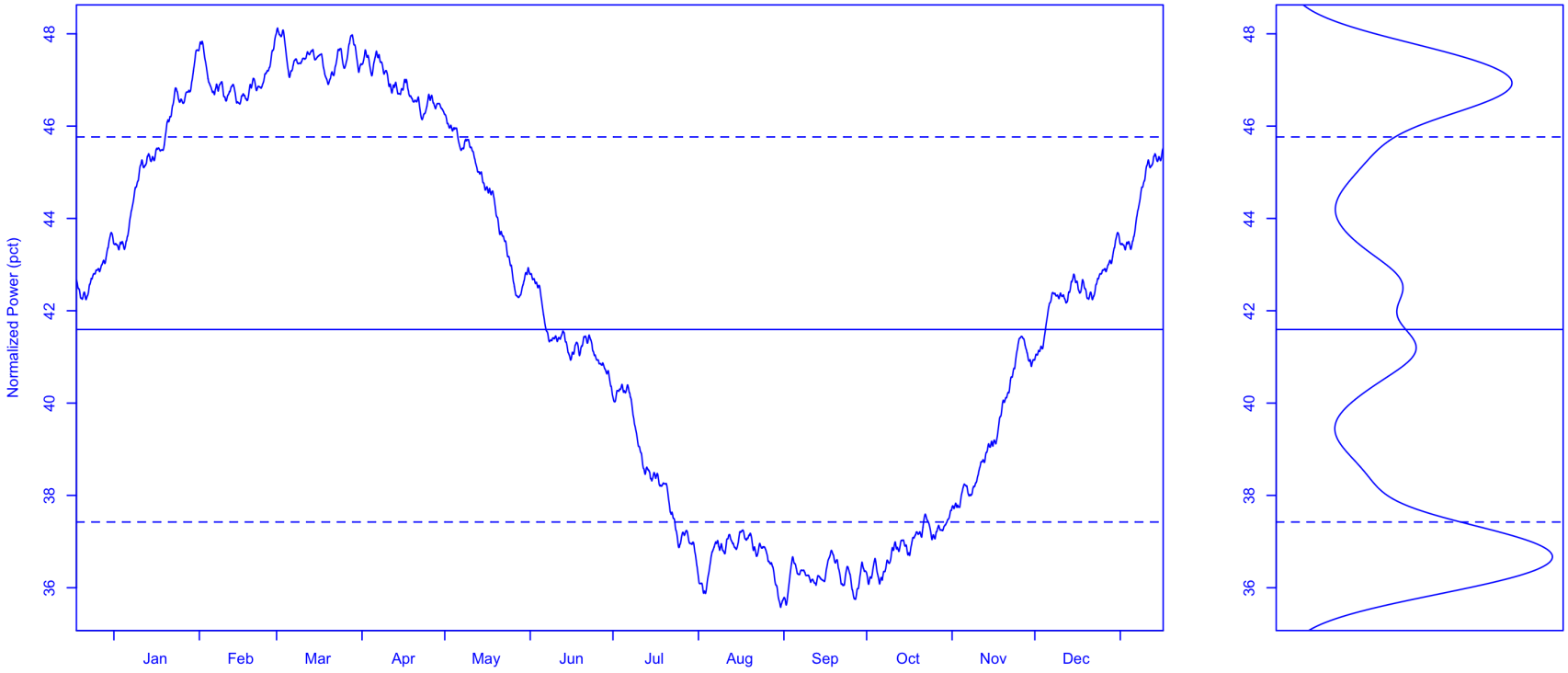


Seasonal Fluctuations ($P_{\Delta T=6mo}$)

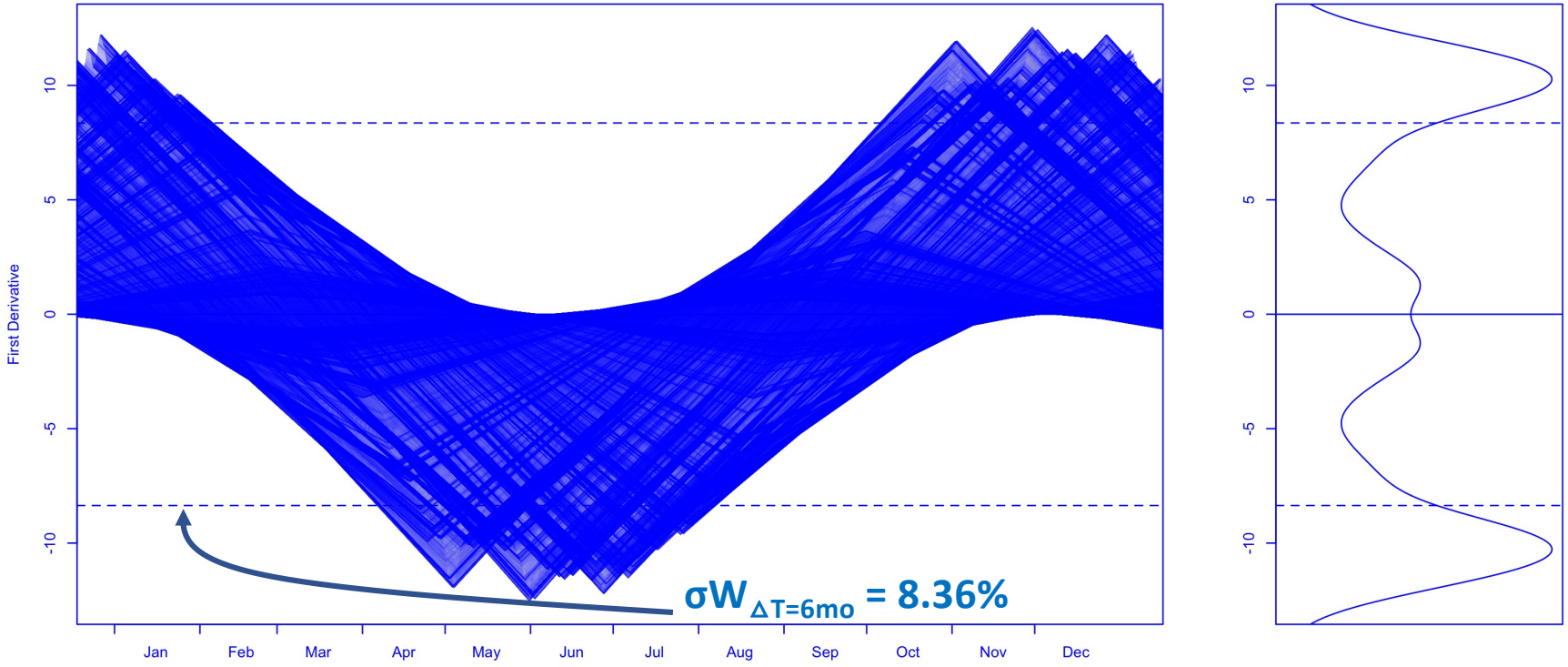


Seasonal fluctuations range
between +/- 2.68% of rated capacity

Normalized 6-mo Power @ 38°N, 99°W

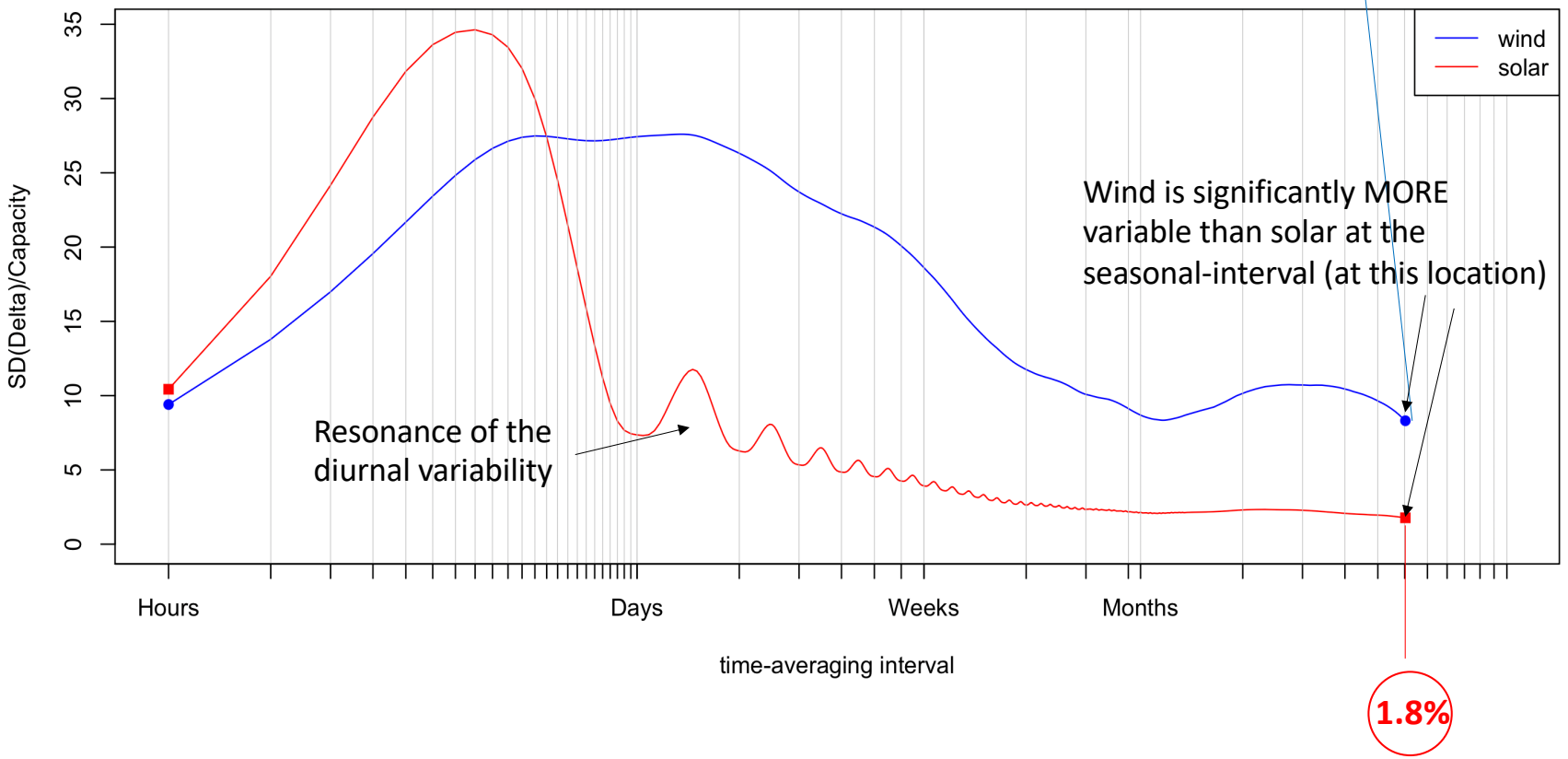


Seasonal Fluctuations ($\Delta W_{t=6mo}$)

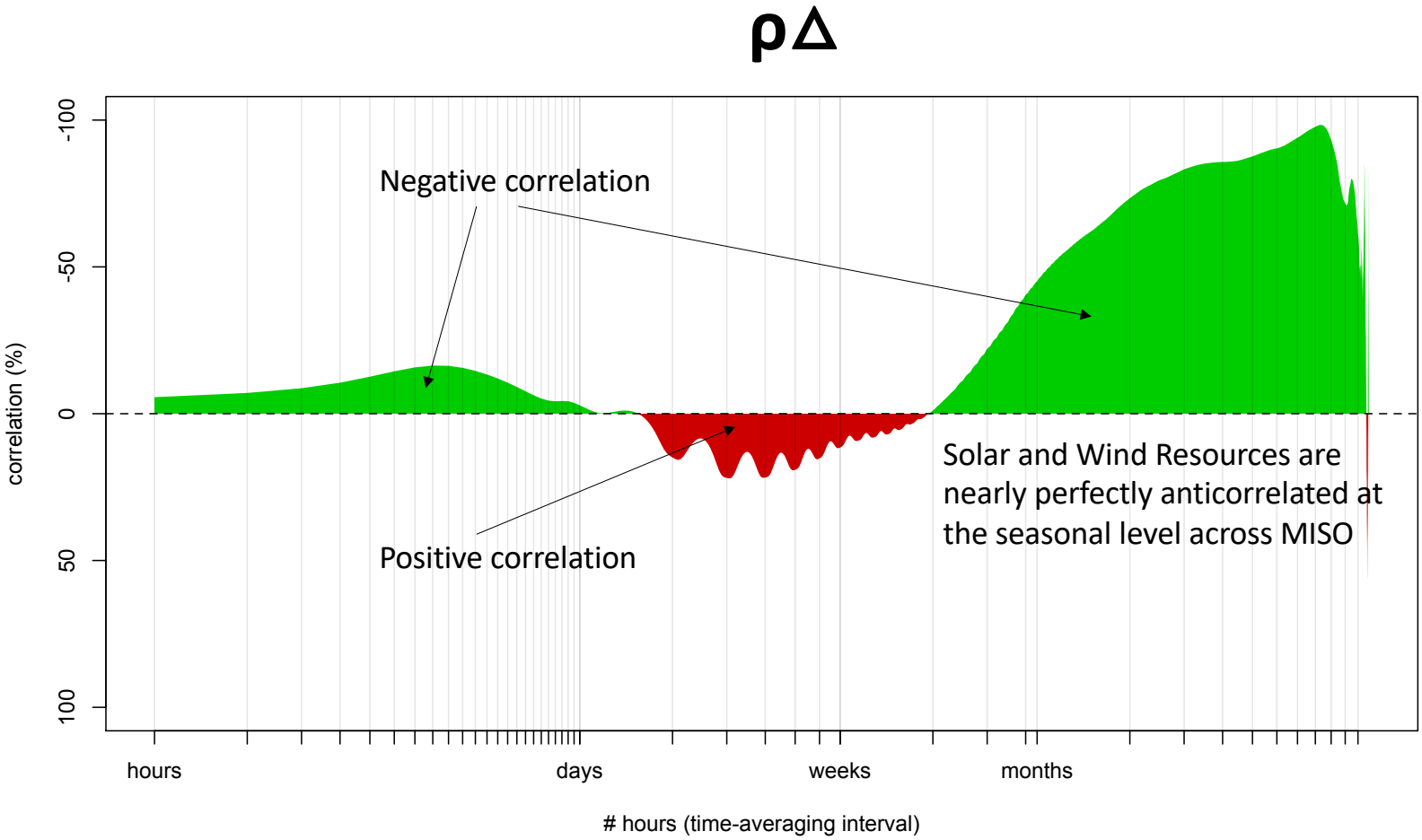


Seasonal fluctuations range between
+/- 12.54% of rated capacity

σΔ


8.4%
W
P
wind
solar
SD(Delta)/Capacity
0
5
10
15
20
25
30
35
Wind is significantly MORE variable than solar at the seasonal-interval (at this location)
Resonance of the diurnal variability
Hours
Days
Weeks
Months
time-averaging interval
1.8%

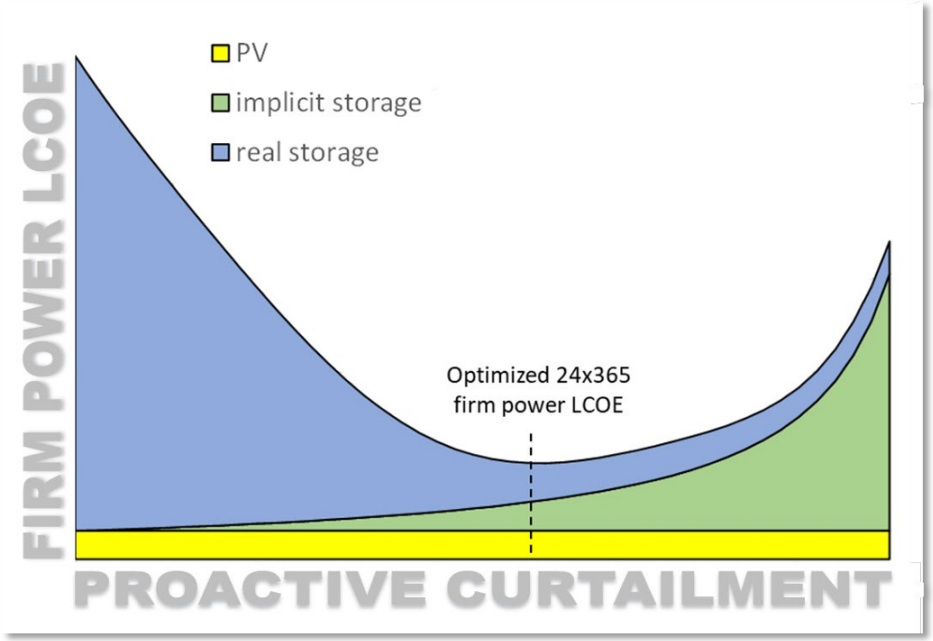
Correlation also plays a major role



Let's talk about implications for *firm power*

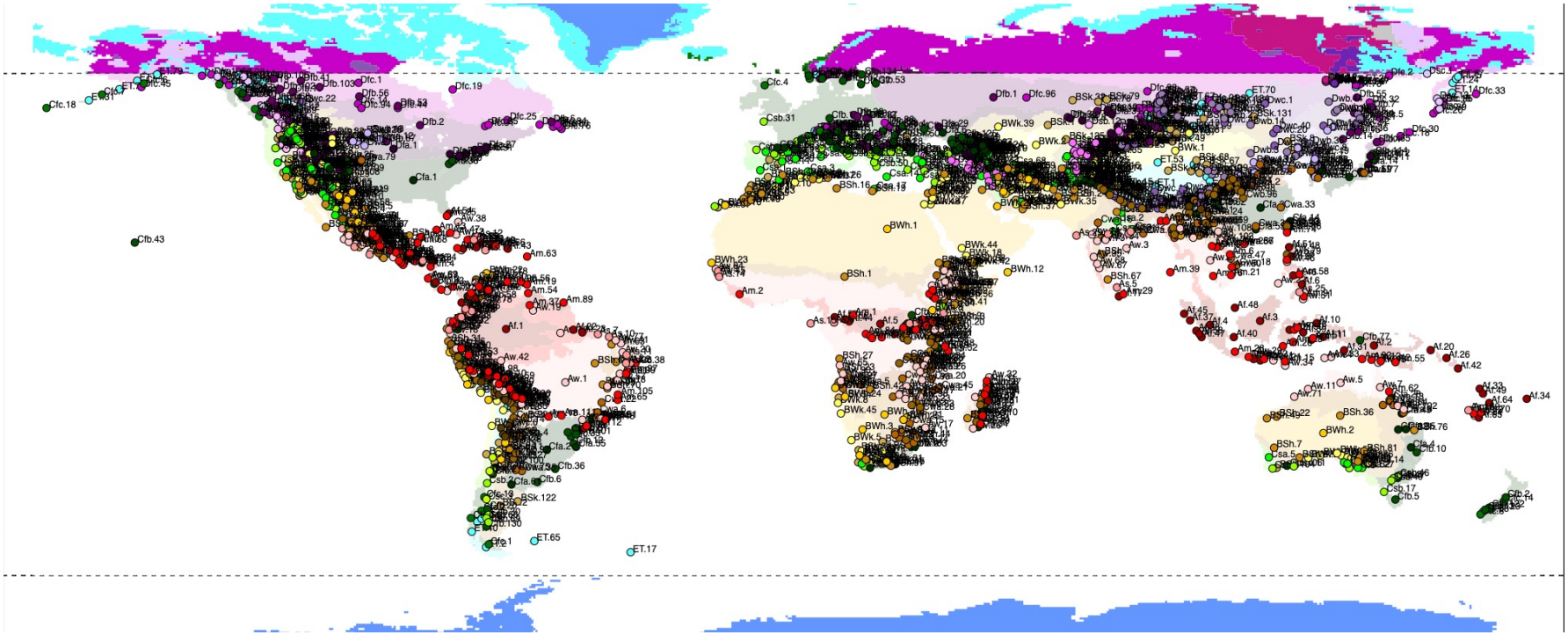
- Cost-minimization of solutions to guarantee 24/365 baseload:
  - implicit storage (overbuilding+curtailment)
  - Using efuel flexibility,
  - PV + wind hybridization

International Energy Agency
Photovoltaic Power Systems Programme

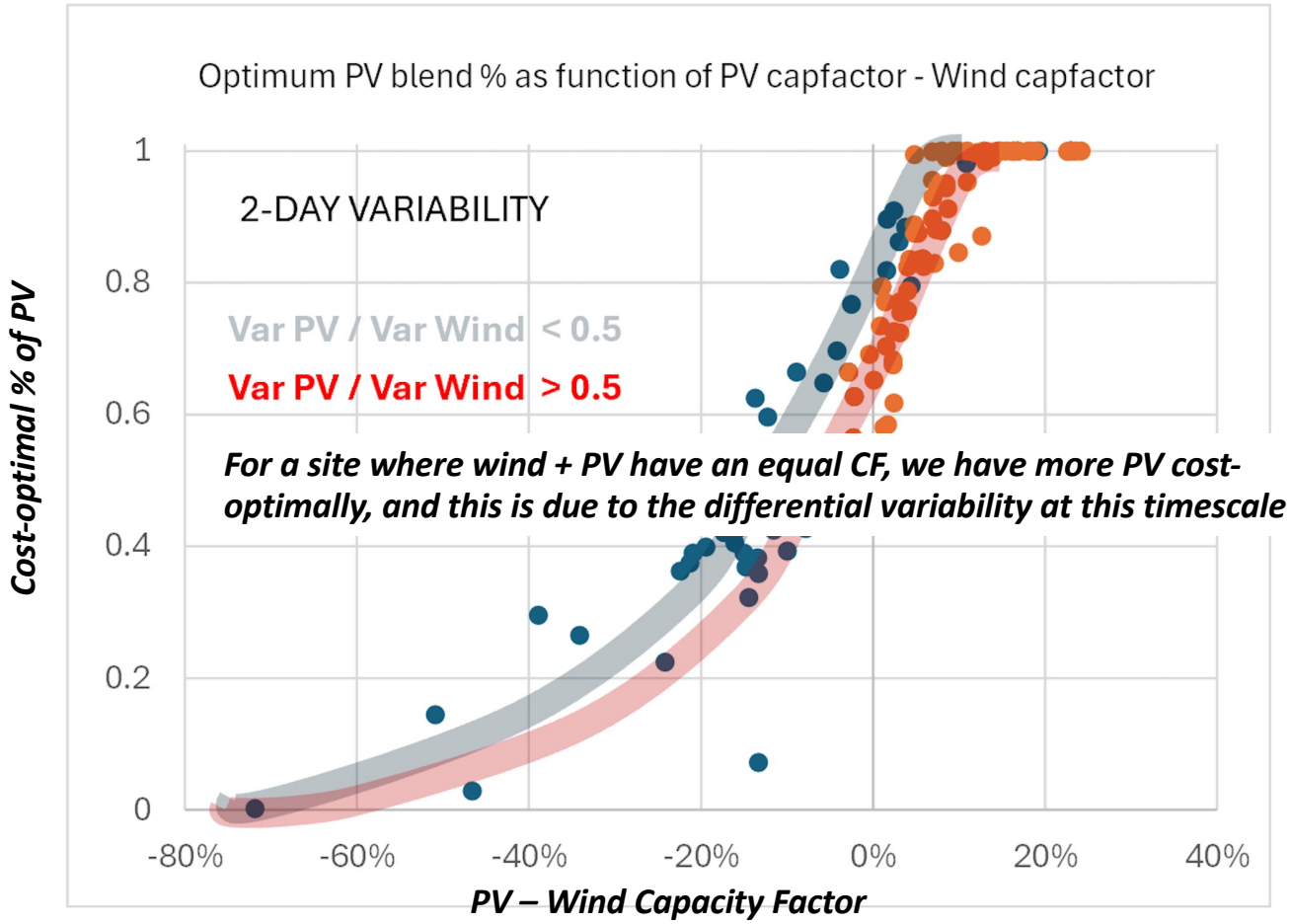


We looked at 290 sites around the world

- *Specifically, we looked at where the cost-optimum wind/PV blend sits across each of these sites with very different CF, variability and correlation*



Sneak preview of global analysis



Takeaways:

- PV is significantly more variable than wind at timescales <7-8h due to the deterministic diurnal variability of the solar resource
- Wind is significantly more variable than PV at timescales >12-15h as the solar resource at these timescales experiences variability that is more deterministically-and less stochastically-driven
- These characteristics depend heavily on location but follow this general rubric
- Grid integration implications are linked to both the magnitude of the resource variability at different timescales, the degree to which wind and PV are correlated at key timescales and their relative capacity factors.
- *Can hybrid PV systems reliably deliver the grid-support functions we model them for?* ***It depends on the location.*** ***Sometimes one or the other resource is preferred solely, but generally it's PV.***
- ***Solar is a more stable resource:*** ***PV's lower variability at key (longer) timescales (e.g. 2-day) leads to its preferential selection for hybrid plants, despite lower capacity factor.***

Next Steps:

- Synthesize the analysis performed at >250 sites globally across 29 Koppen Climate Zones

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Implications for Grid Integration

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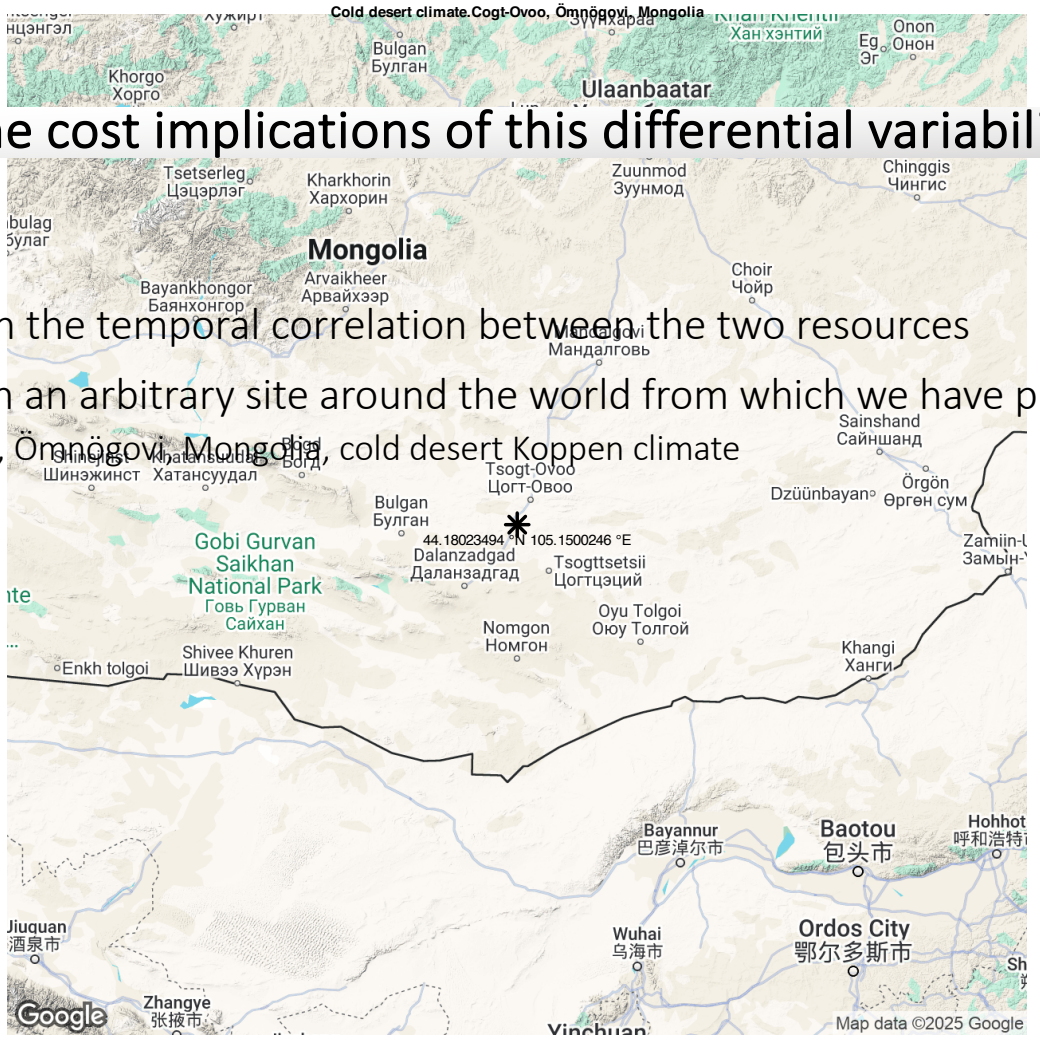
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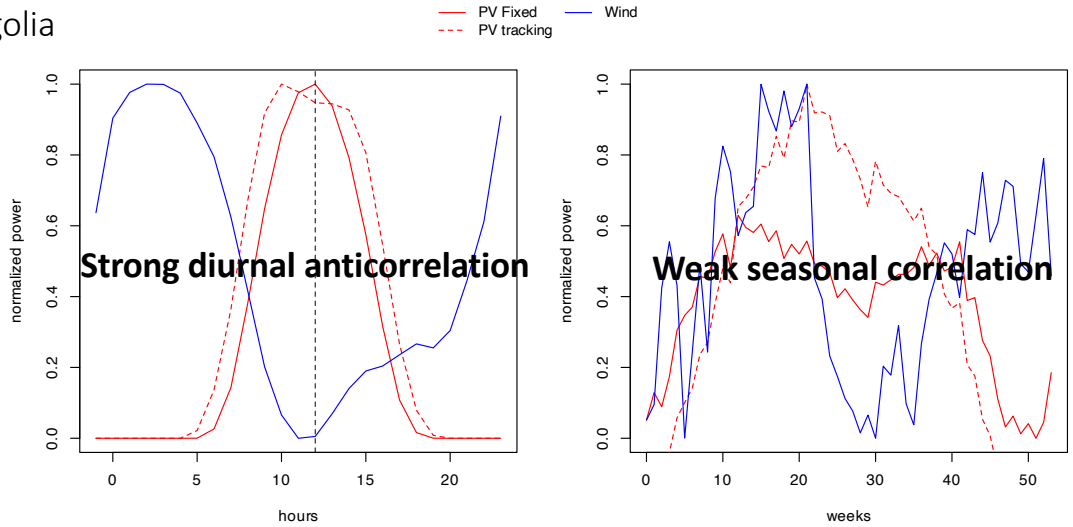
Appendix

What are the cost implications of this differential variability?

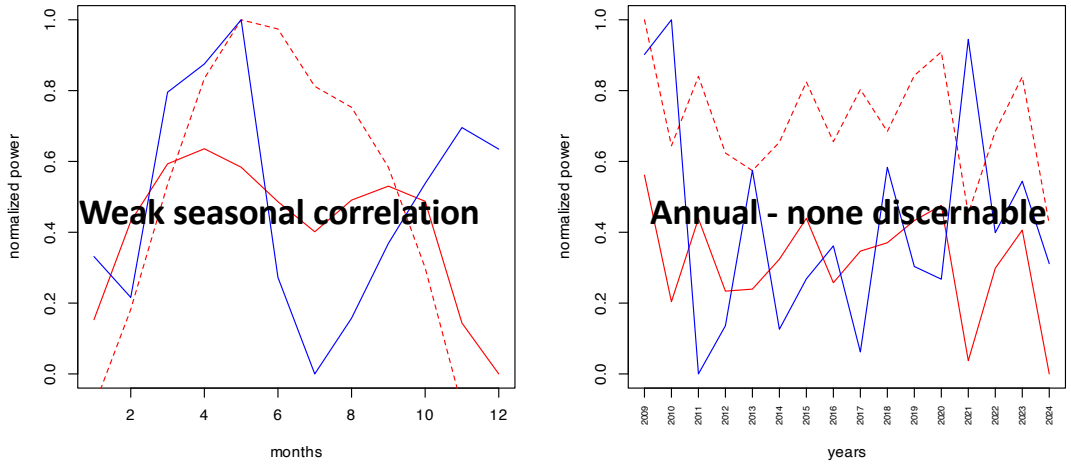
- It depends on the temporal correlation between the two resources
- Let's focus on an arbitrary site around the world from which we have pulled data:
  - Cogt-Ovoo, Ömnögovi, Mongolia, cold desert Koppen climate



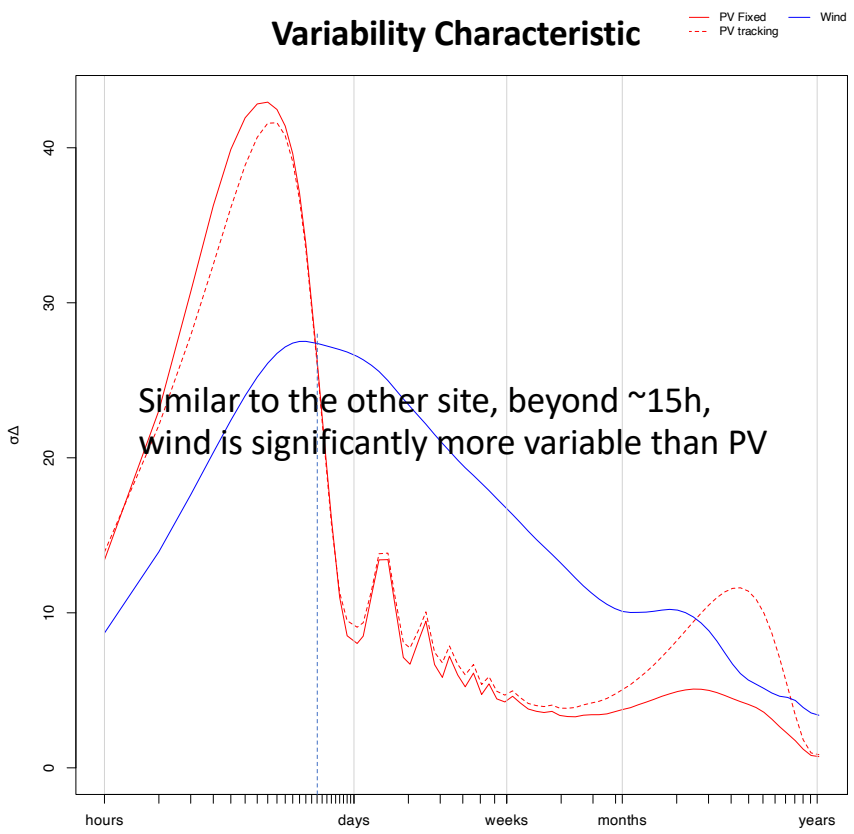
Cogt-Ovoo, Ömnögovi, Mongolia

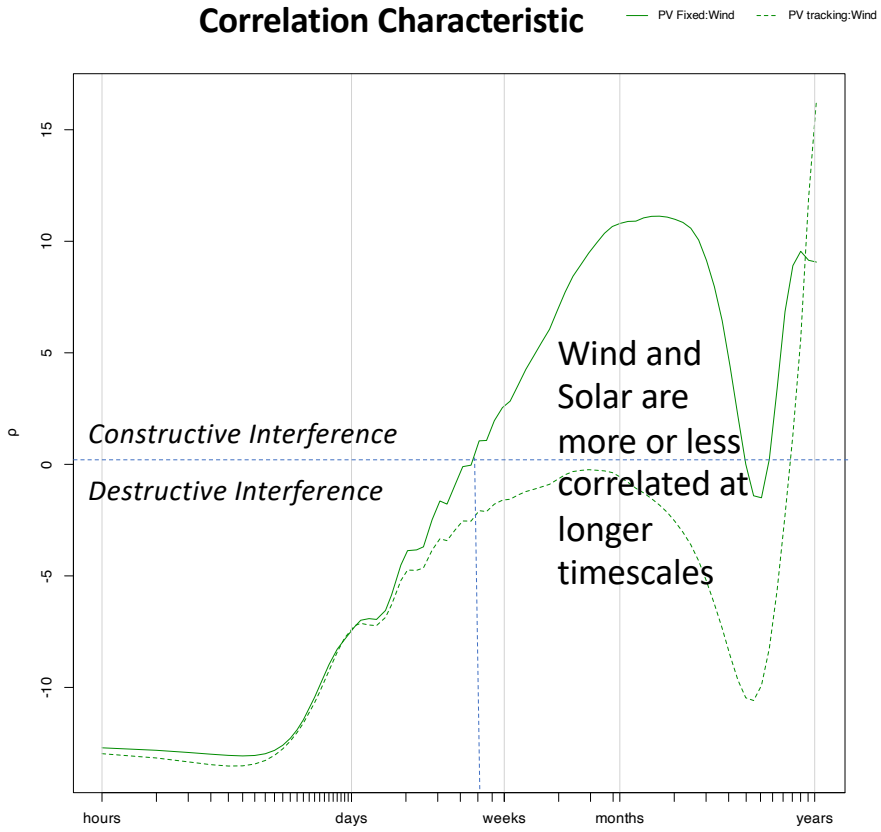


Visualizing Wind/Solar Correlation at different timescales



How do we quantify this correlation?

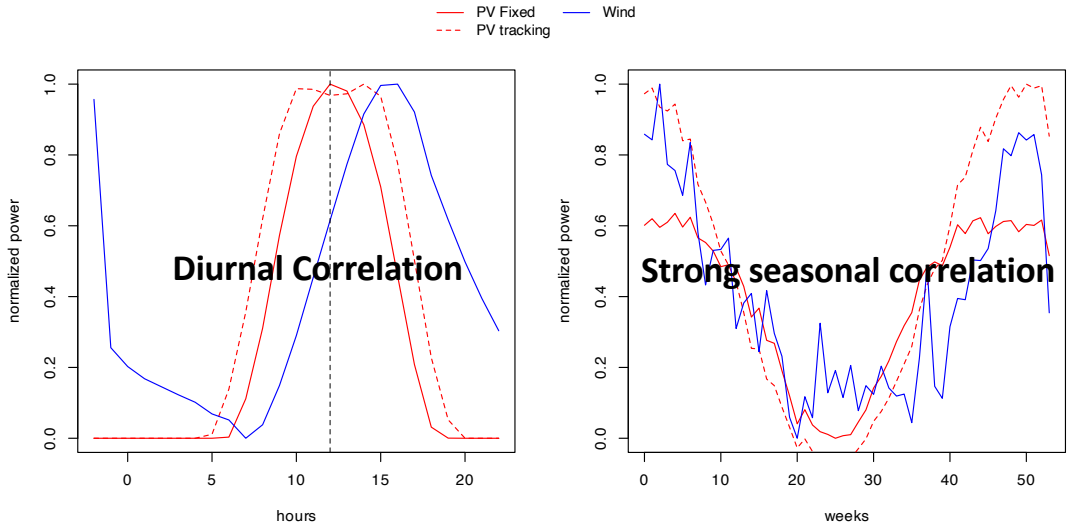




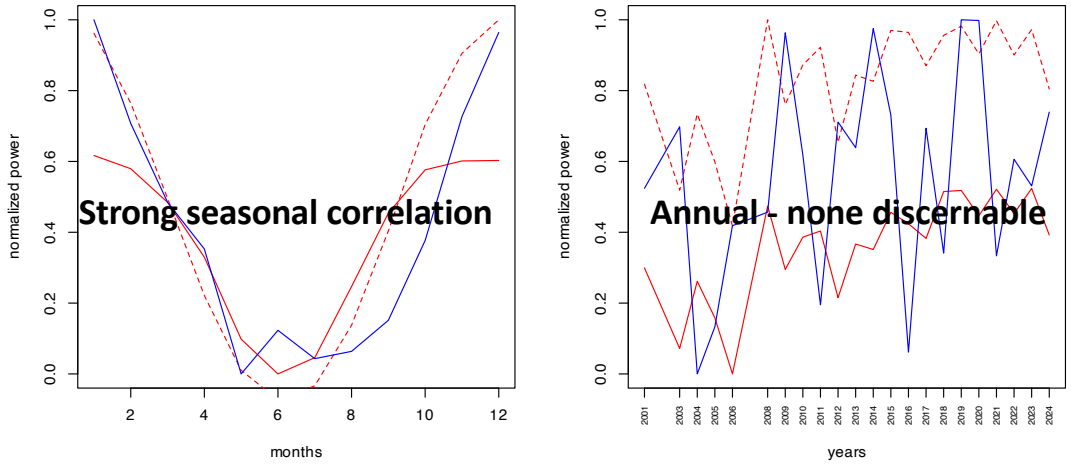
By contrast, let's look at a site in the Cold Summer Mediterranean Climate

- Lago Buenos Aires, Argentina

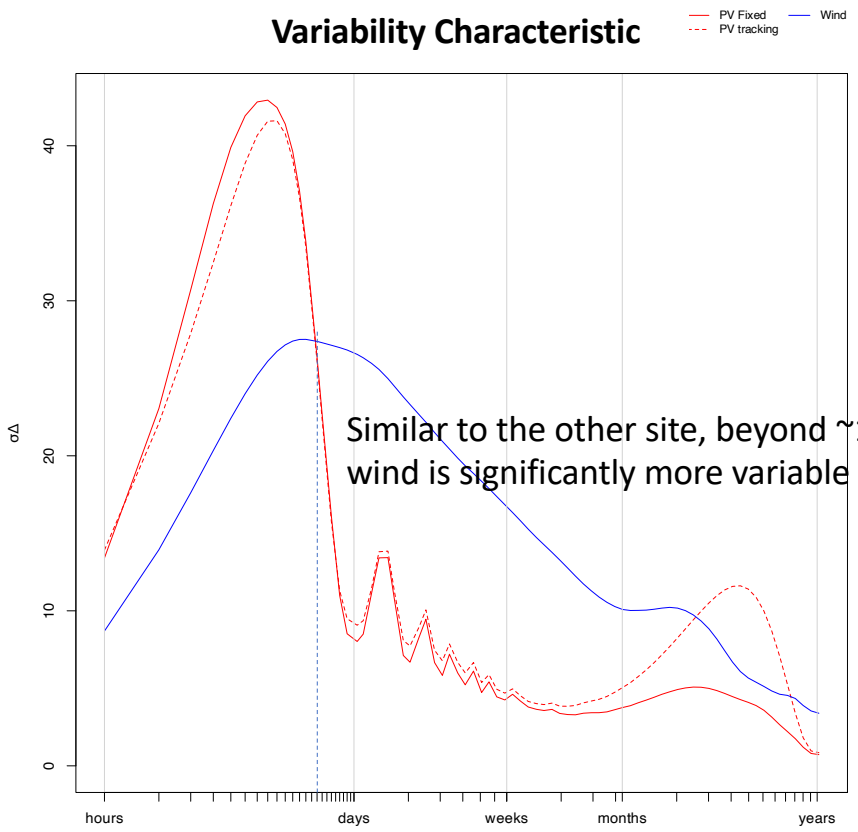




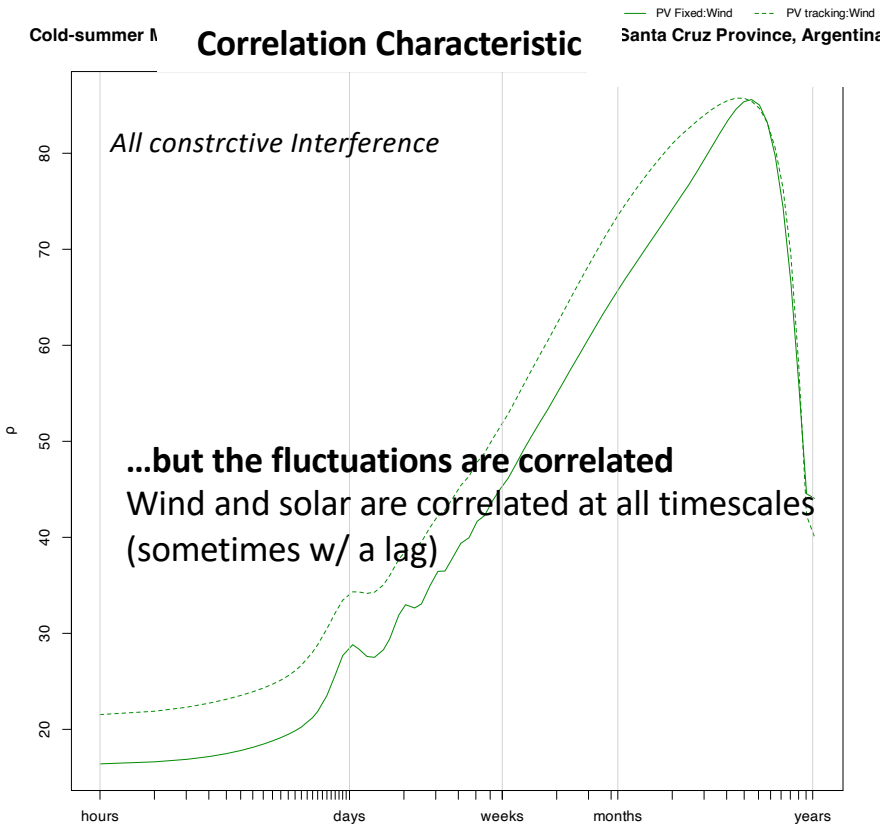
Visualizing Wind/Solar Correlation at different timescales



How do we quantify this correlation?



Similar to the other site, beyond ~15h, wind is significantly more variable than PV

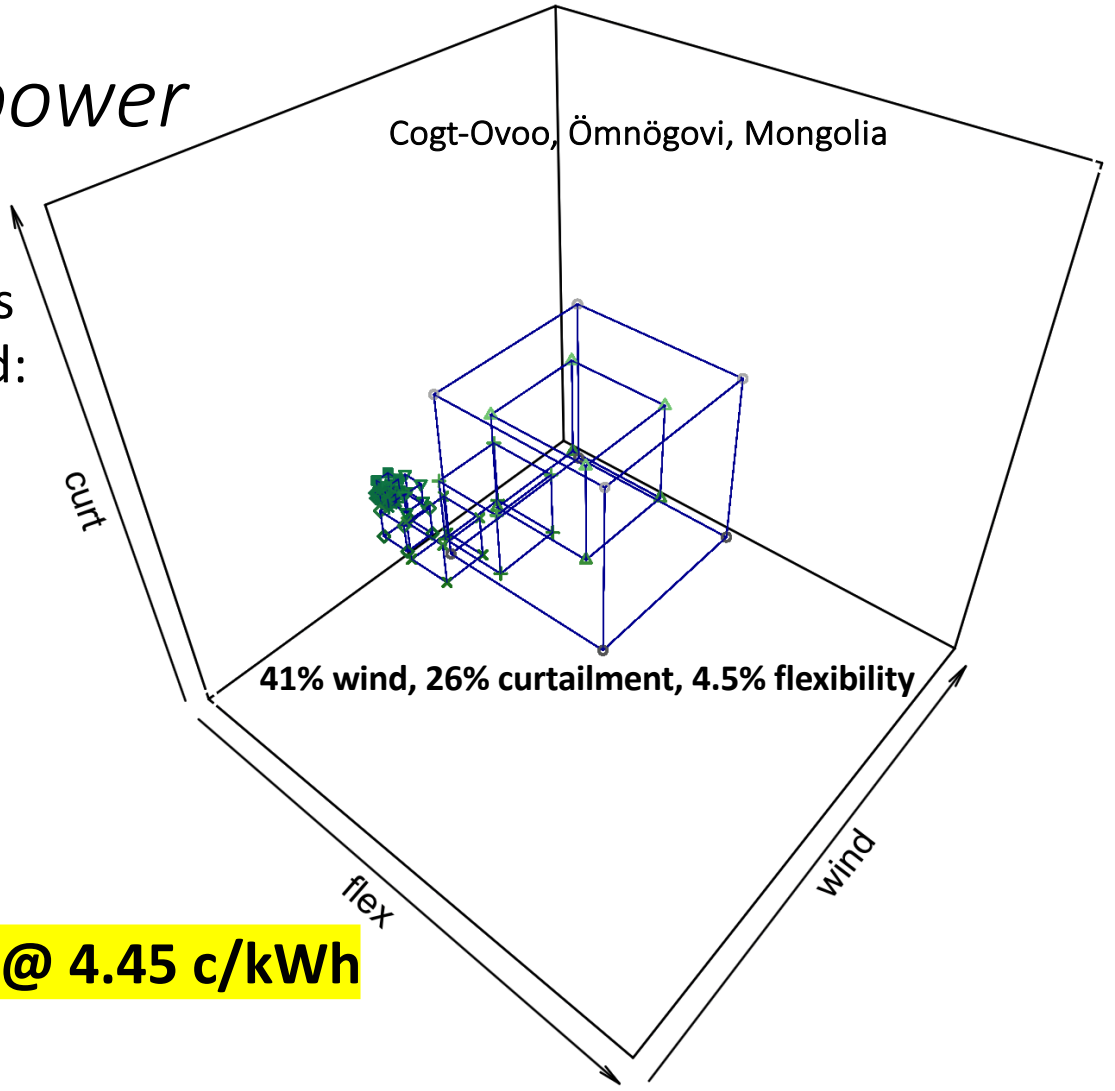


…but the fluctuations are correlated

Wind and solar are correlated at all timescales (sometimes w/ a lag)

Let's optimize *firm power*

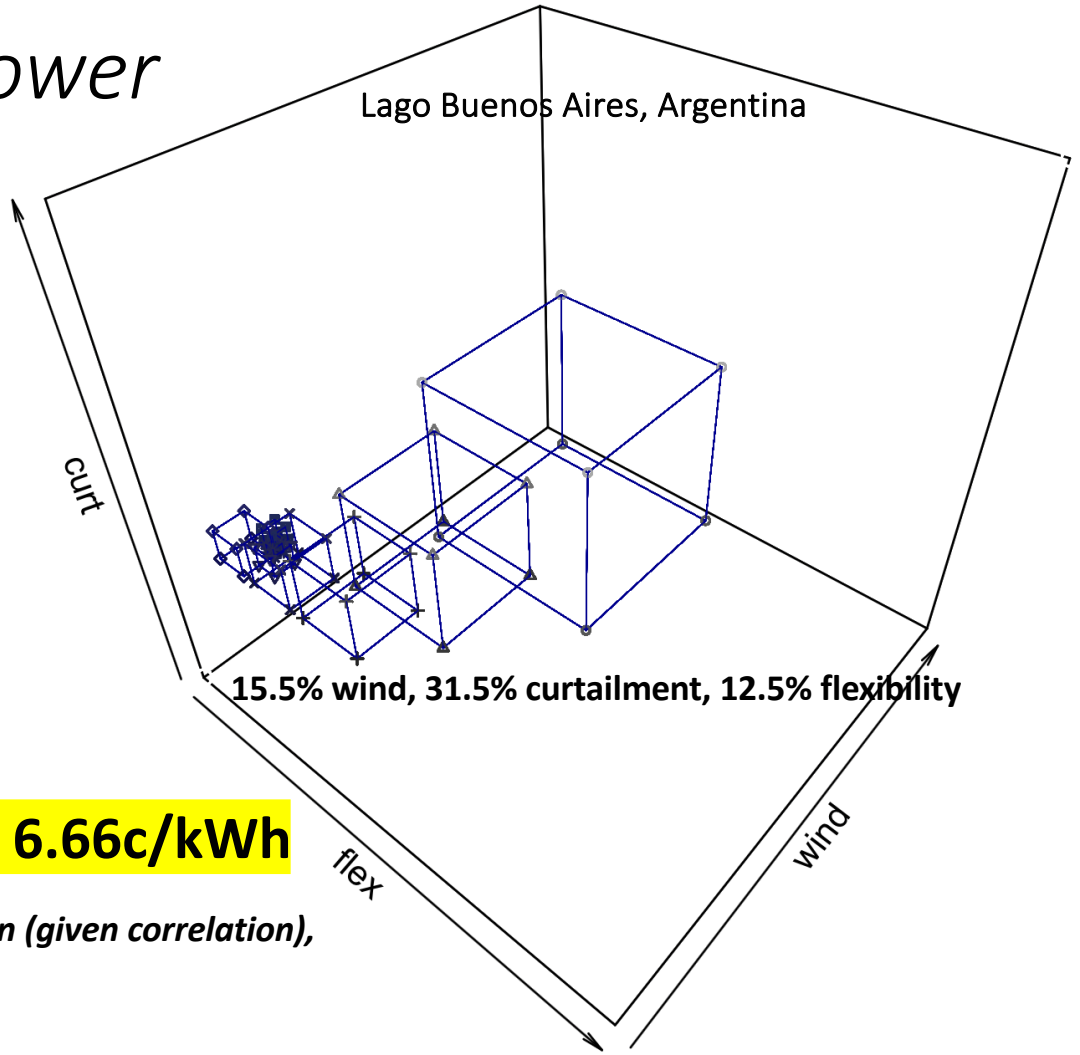
- Cost-minimization of solutions to guarantee 24/365 baseload:
  - implicit storage (overbuilding+curtailment)
  - Using efuel flexibility,
  - PV + wind hybridization



95.5% variable renewables @ 4.45 c/kWh

Let's optimize *firm power*

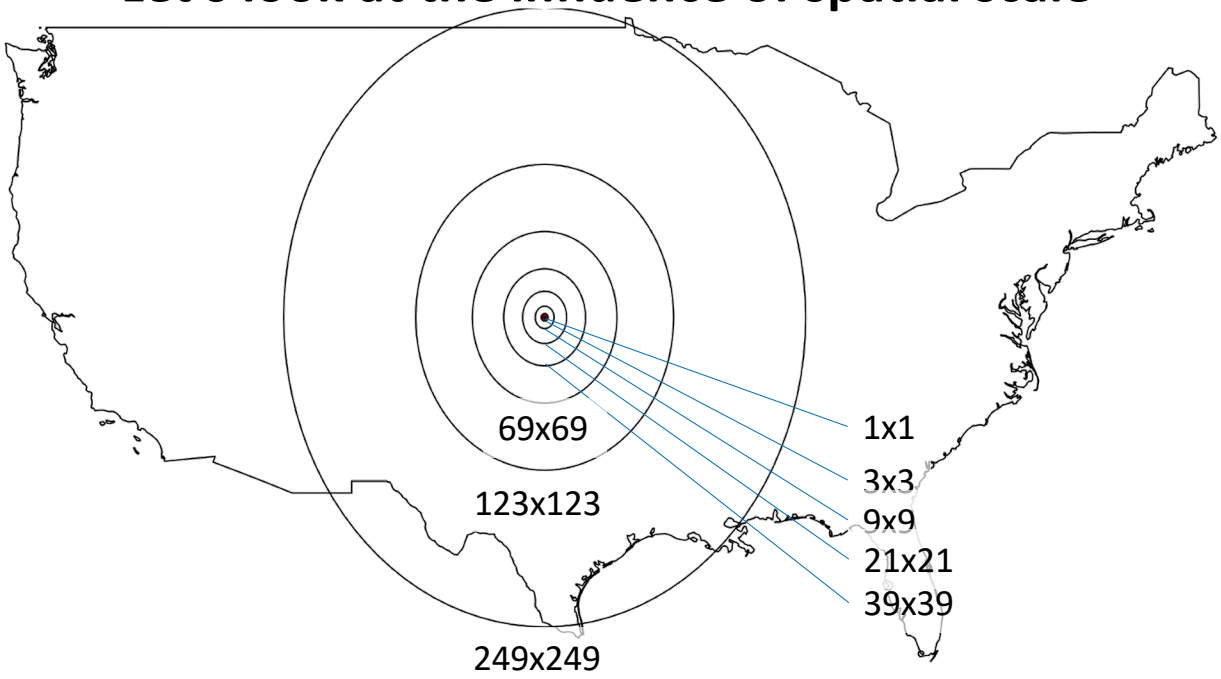
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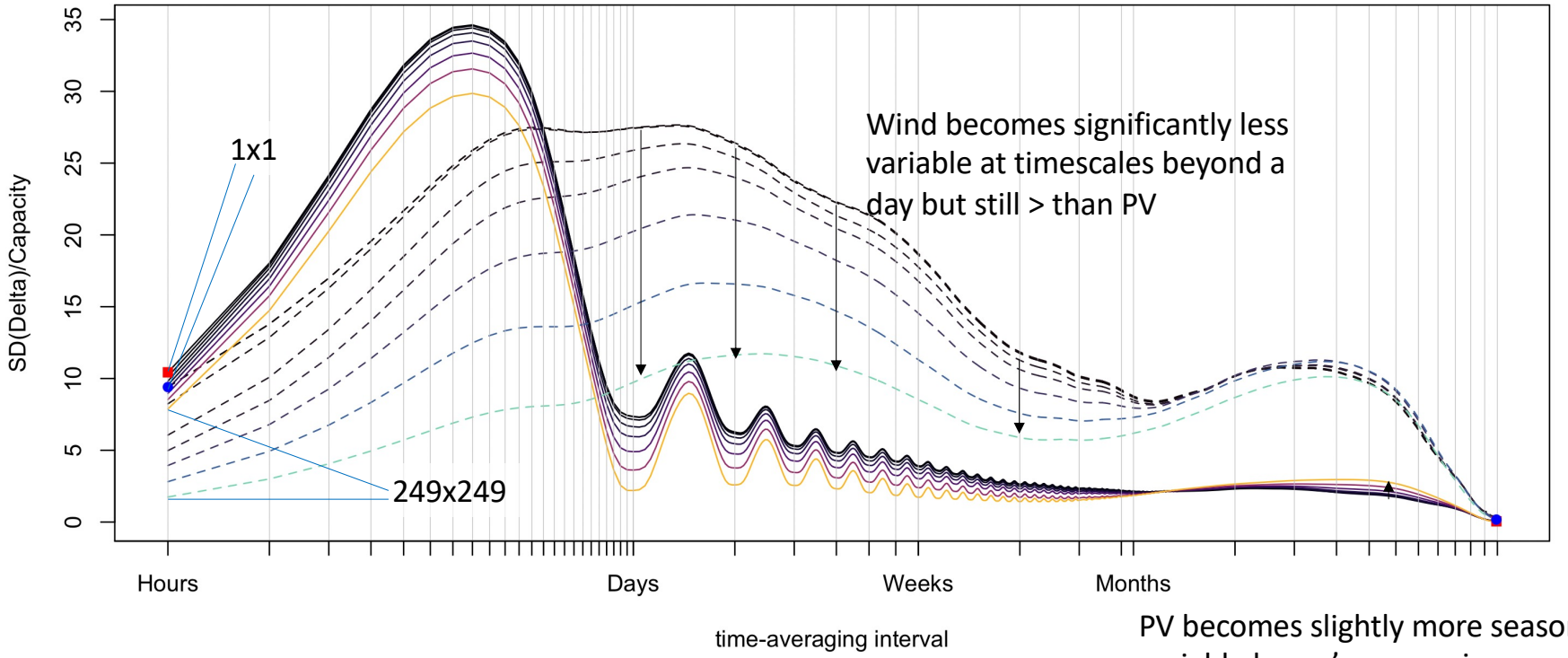
87.5% variable renewables @ 6.66c/kWh

This site in Argentina has less wind hybridization (given correlation), and more optimal curtailment and flexibility

Let’s look at the influence of spatial scale

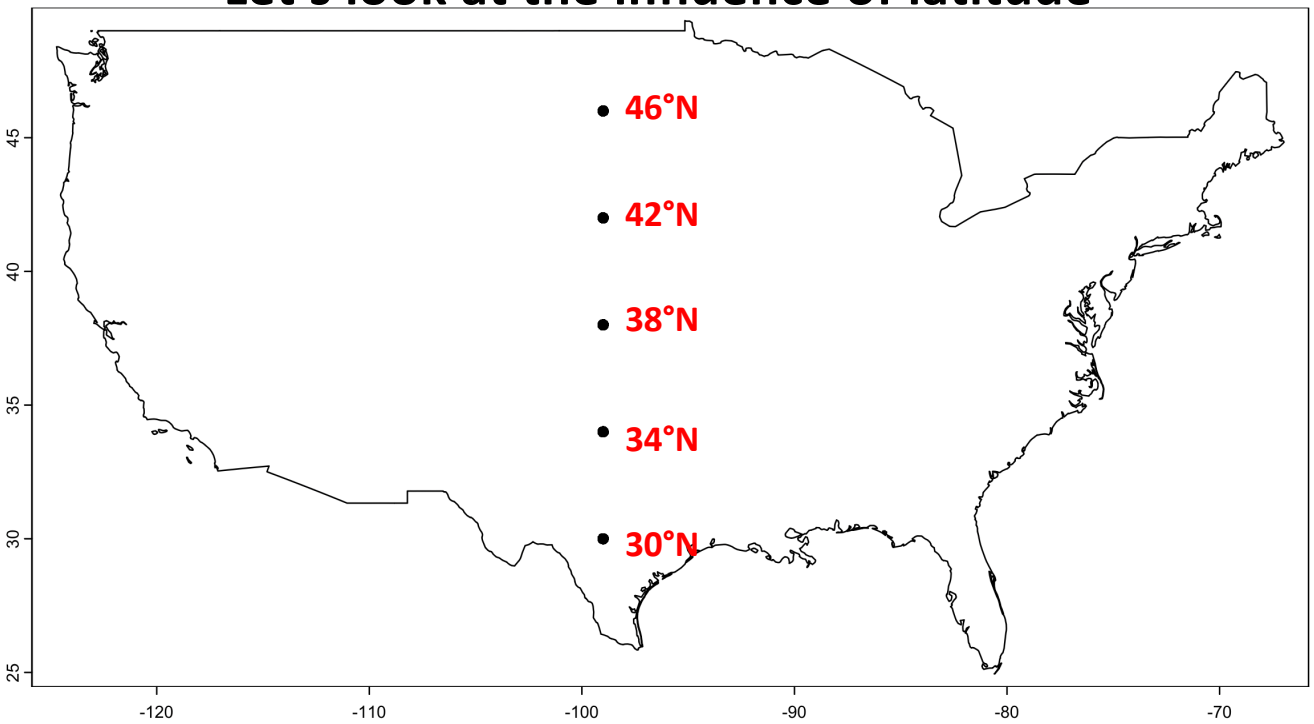


Let's look at the influence of spatial scale

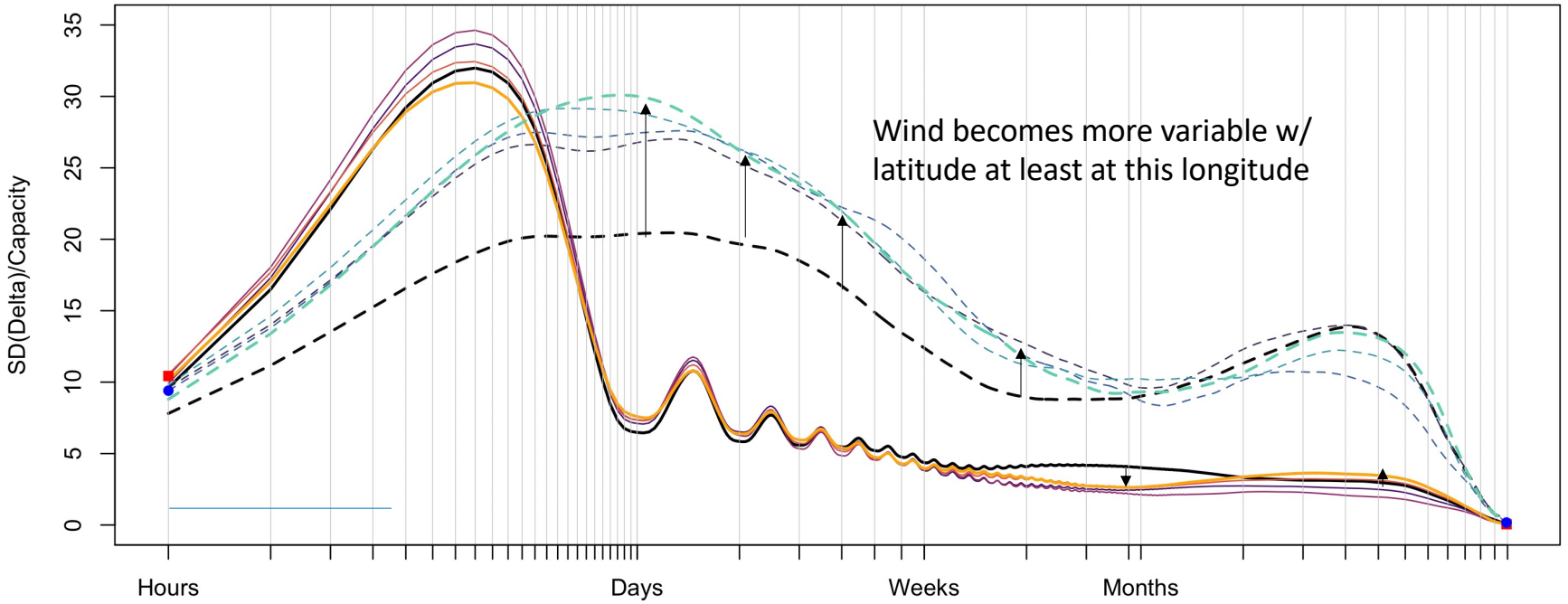


PV becomes slightly more seasonally variable bc we're averaging more northerly places but the diurnal signal is still strong.

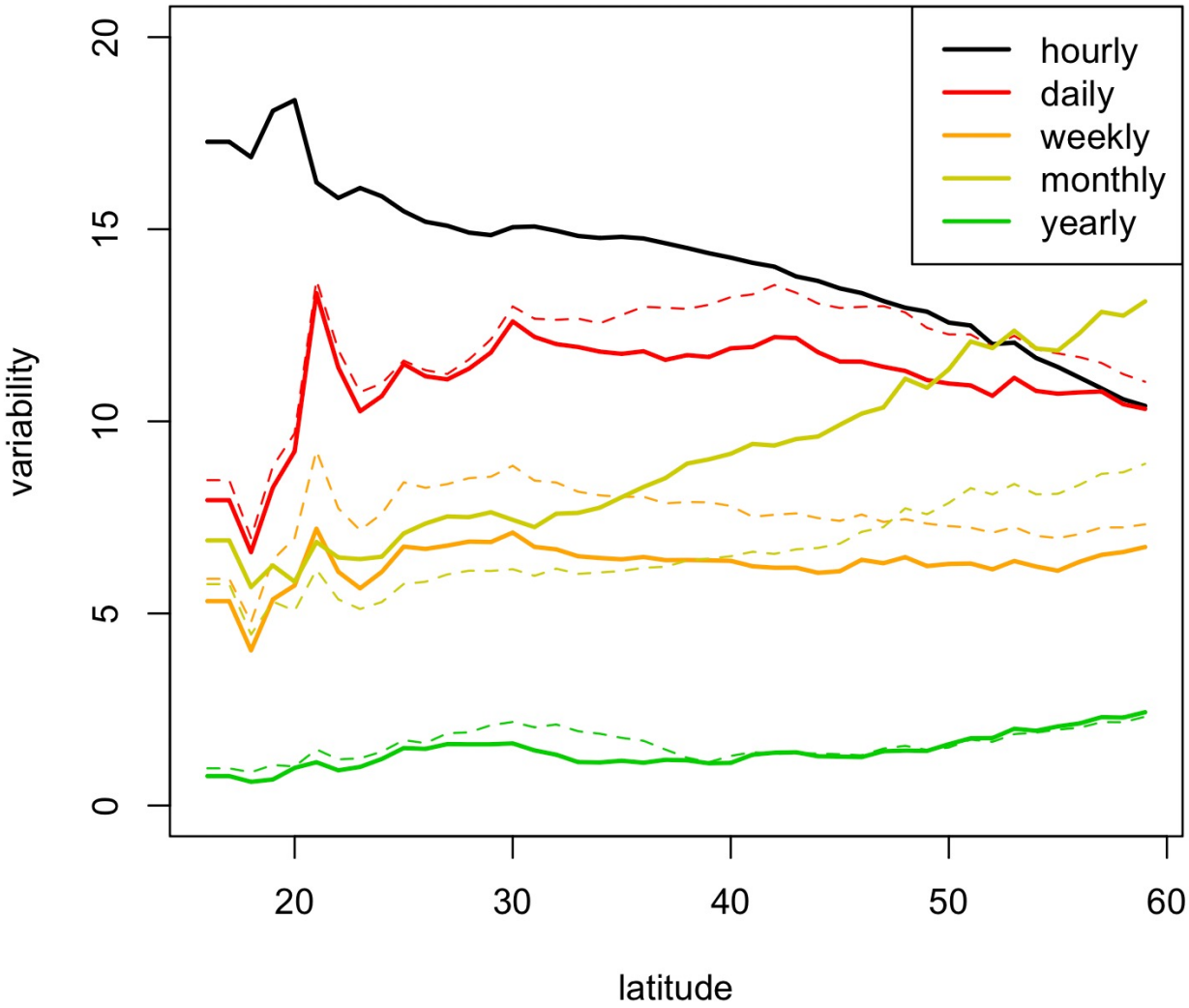
Let’s look at the influence of latitude

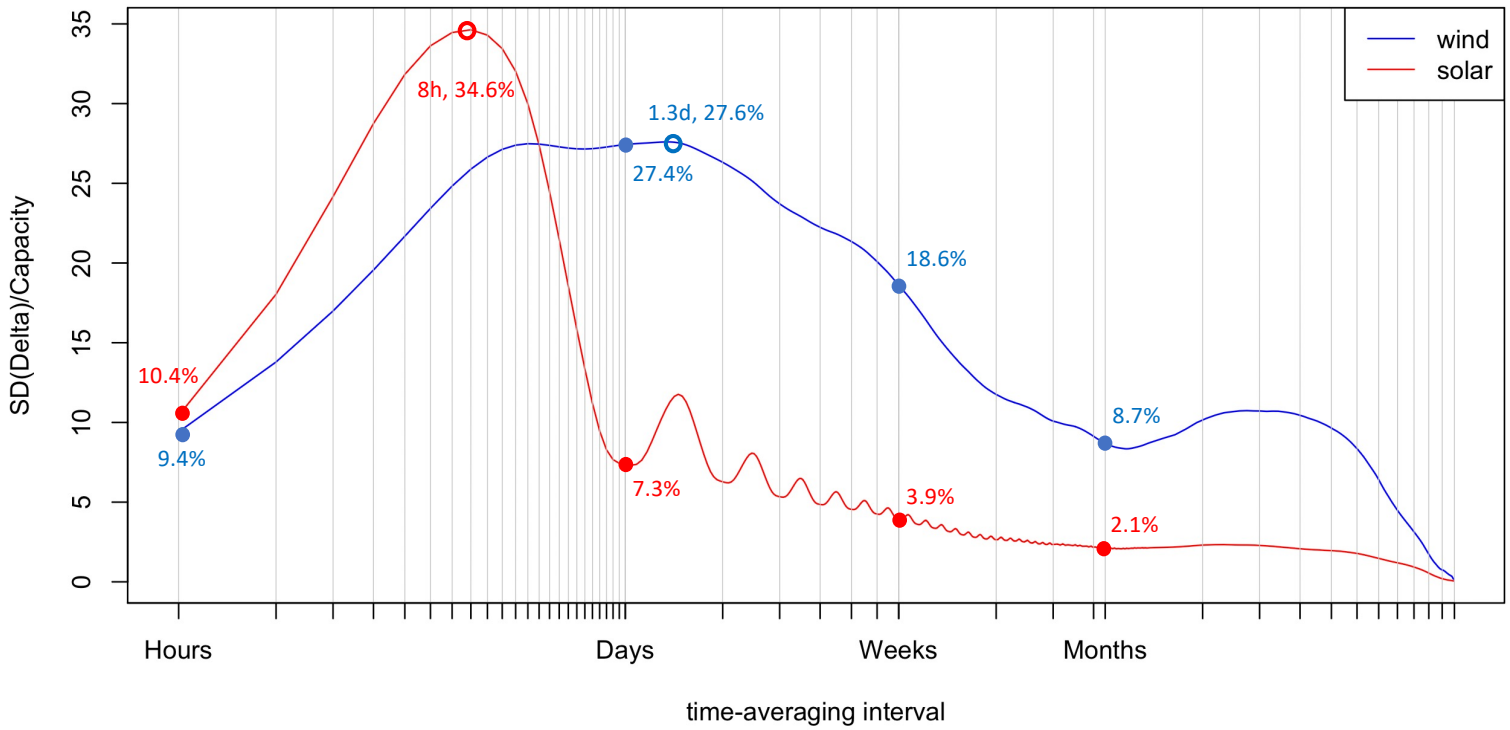


Let's look at the influence of latitude

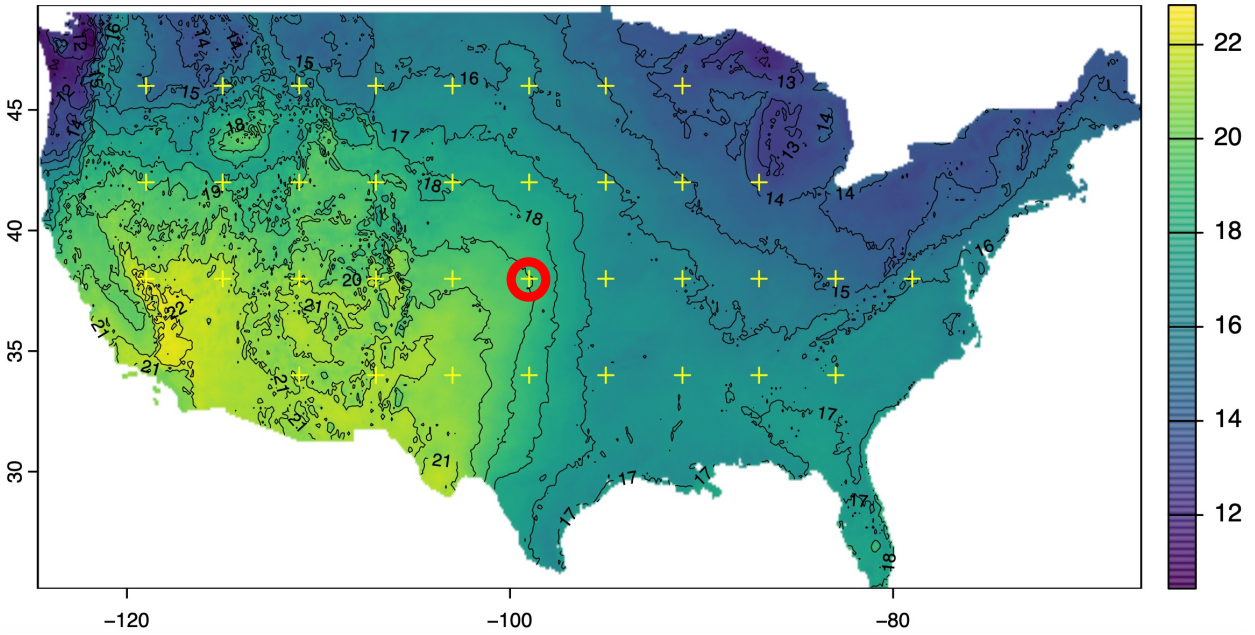


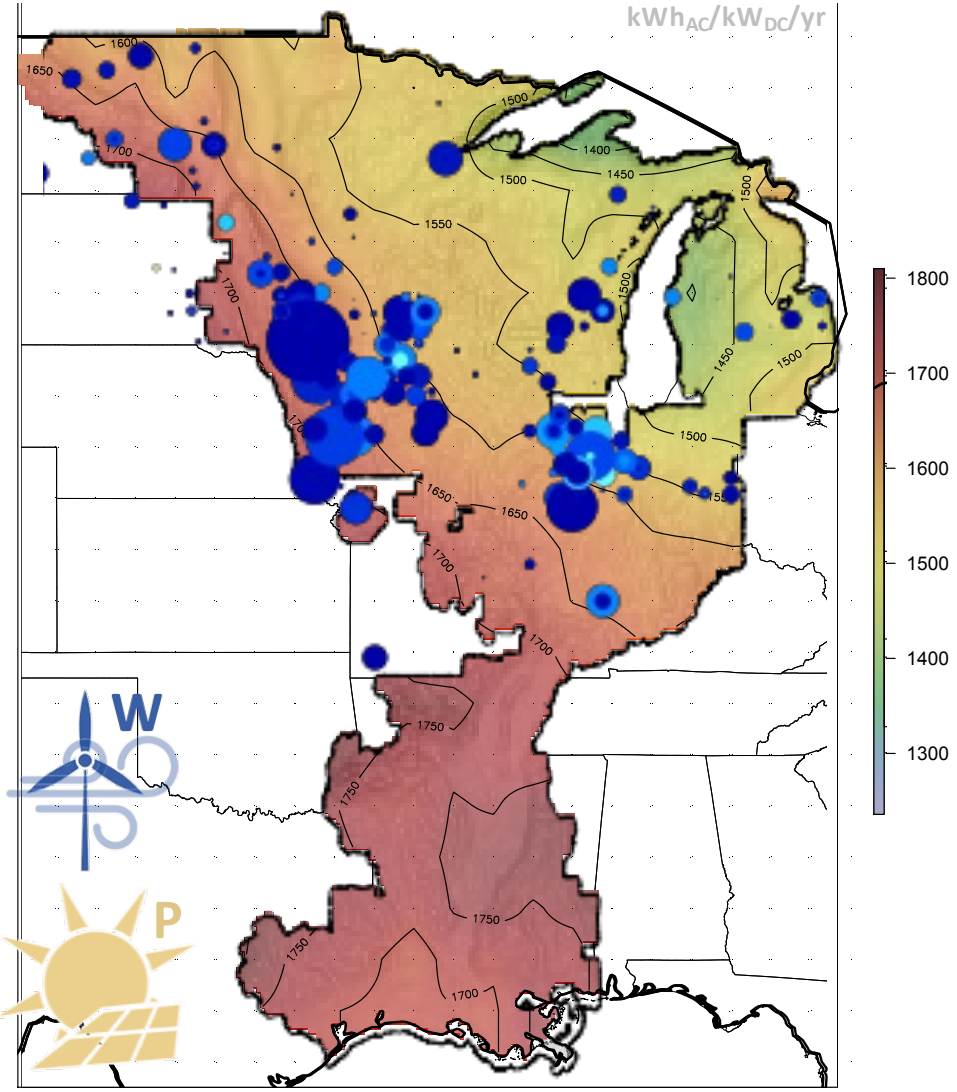
PV becomes slightly more seasonally variable bc we're heading further north but there are seasonal microclimate effects influencing variability on the order of months. The lowest latitude has > month-month variability than the highest


hourly
daily
weekly
monthly
yearly
variability
0
5
10
15
20
20
30
40
50
60
latitude


wind
solar
SD(Delta)/Capacity
0
5
10
15
20
25
30
35
Hours
Days
Weeks
Months
time-averaging interval
10.4%
8h, 34.6%
1.3d, 27.6%
27.4%
18.6%
8.7%
9.4%
7.3%
3.9%
2.1%

Let's Extend the temporal scope to see if we can pick up IAV signal

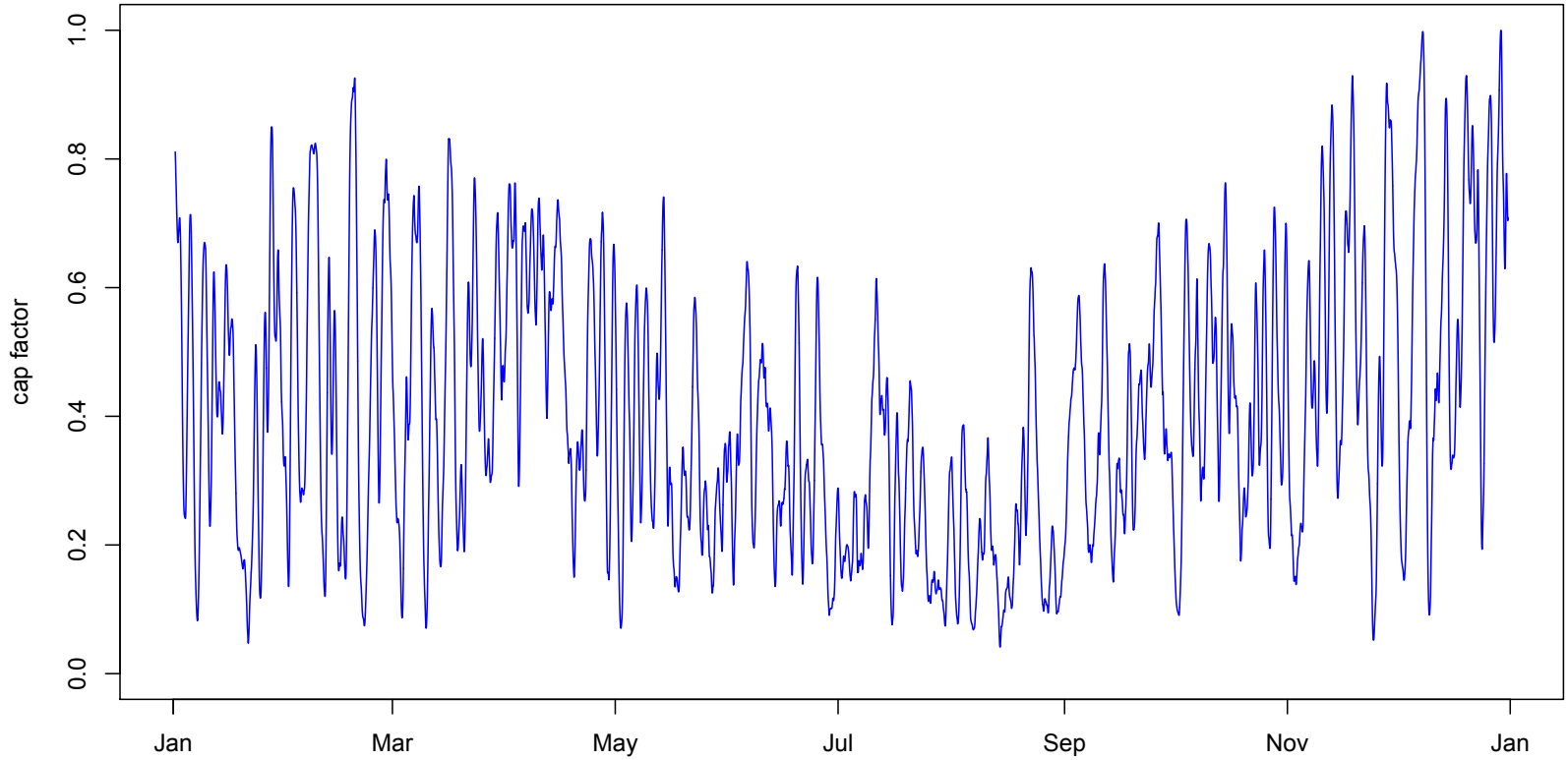




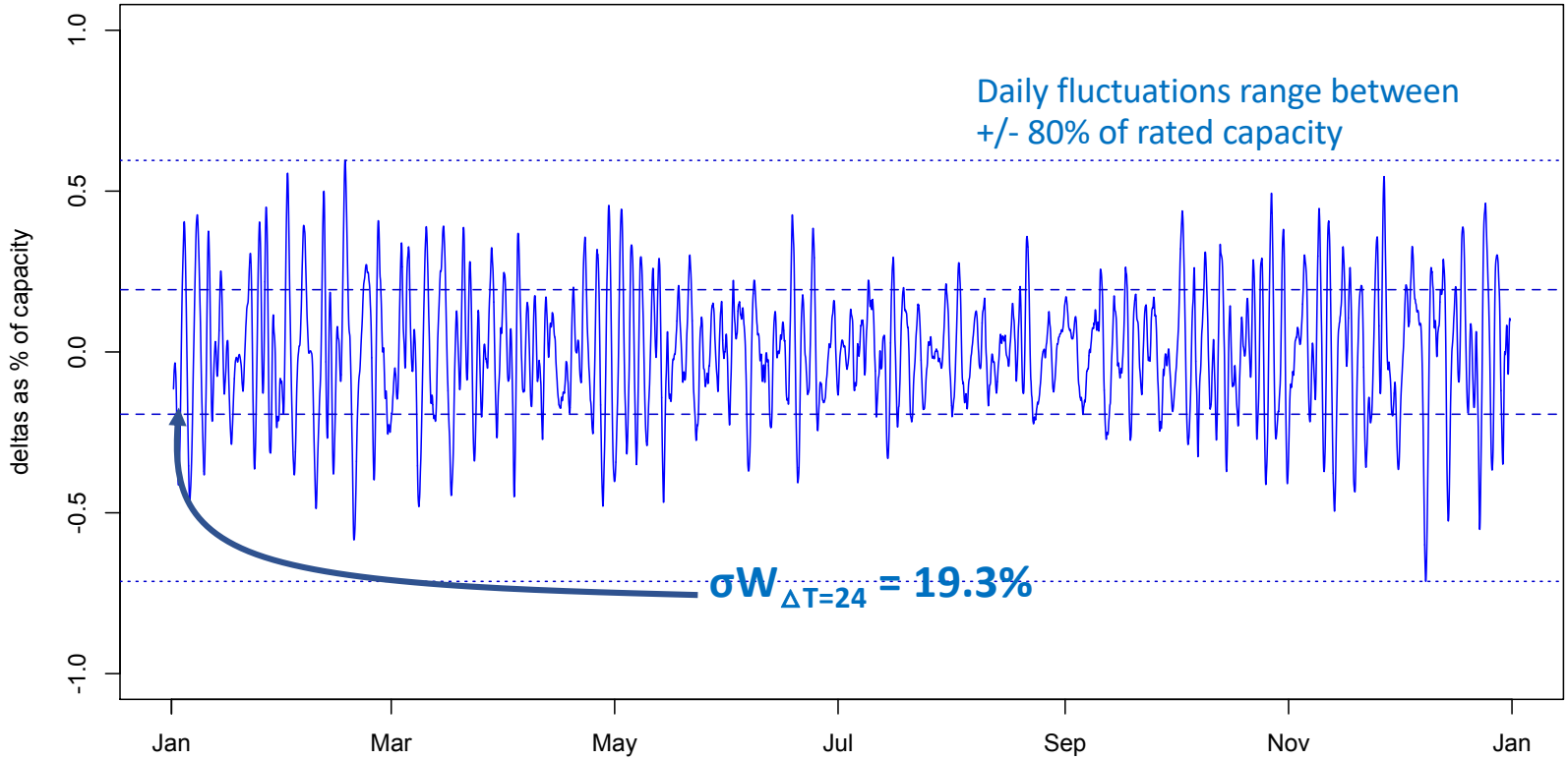
Daily-interval characterization

- The daily interval is of interest from an intermediate energy balancing perspective
- At the inter-day interval, the diurnality of the solar resource is no longer visible

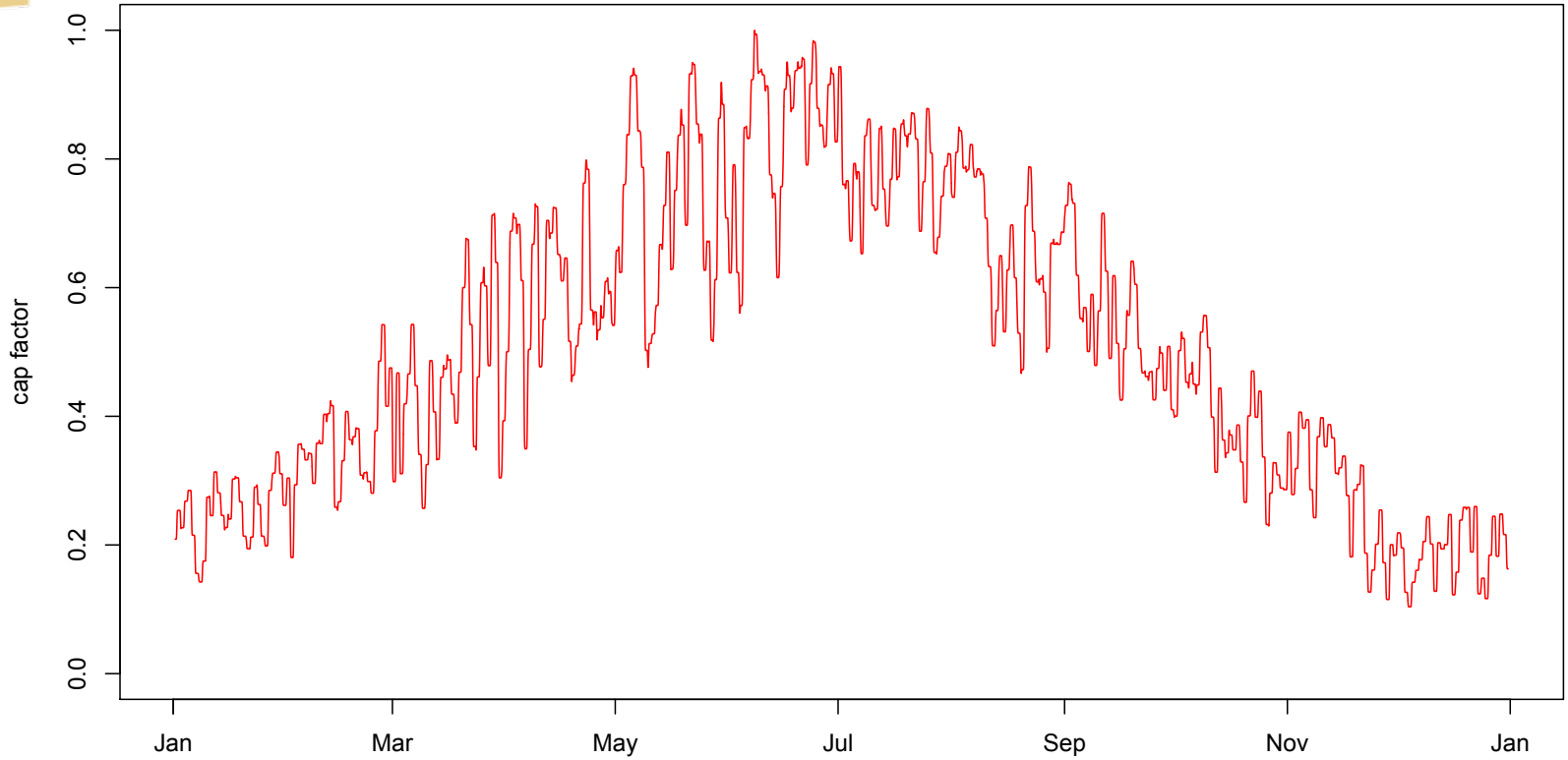
Normalized Daily Wind Power (W) across MISO



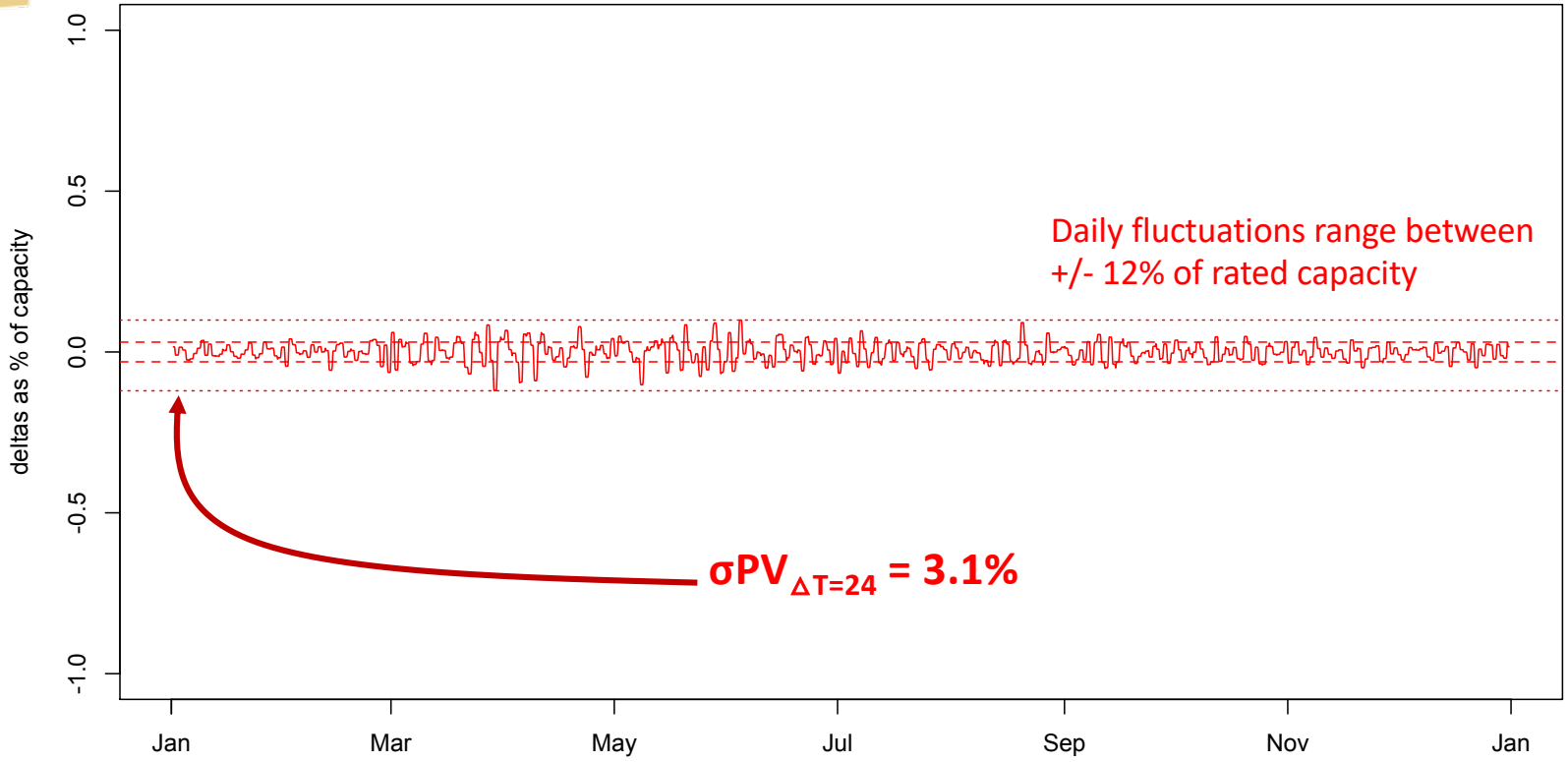
Daily Fluctuations ($\Delta W_{t=24h}$)



Normalized Daily GHI across MISO



Daily Fluctuations ($P_{\Delta T=24hr}$)



Solar variability at the daily interval is <u>much</u> lower than wind variability at the daily interval

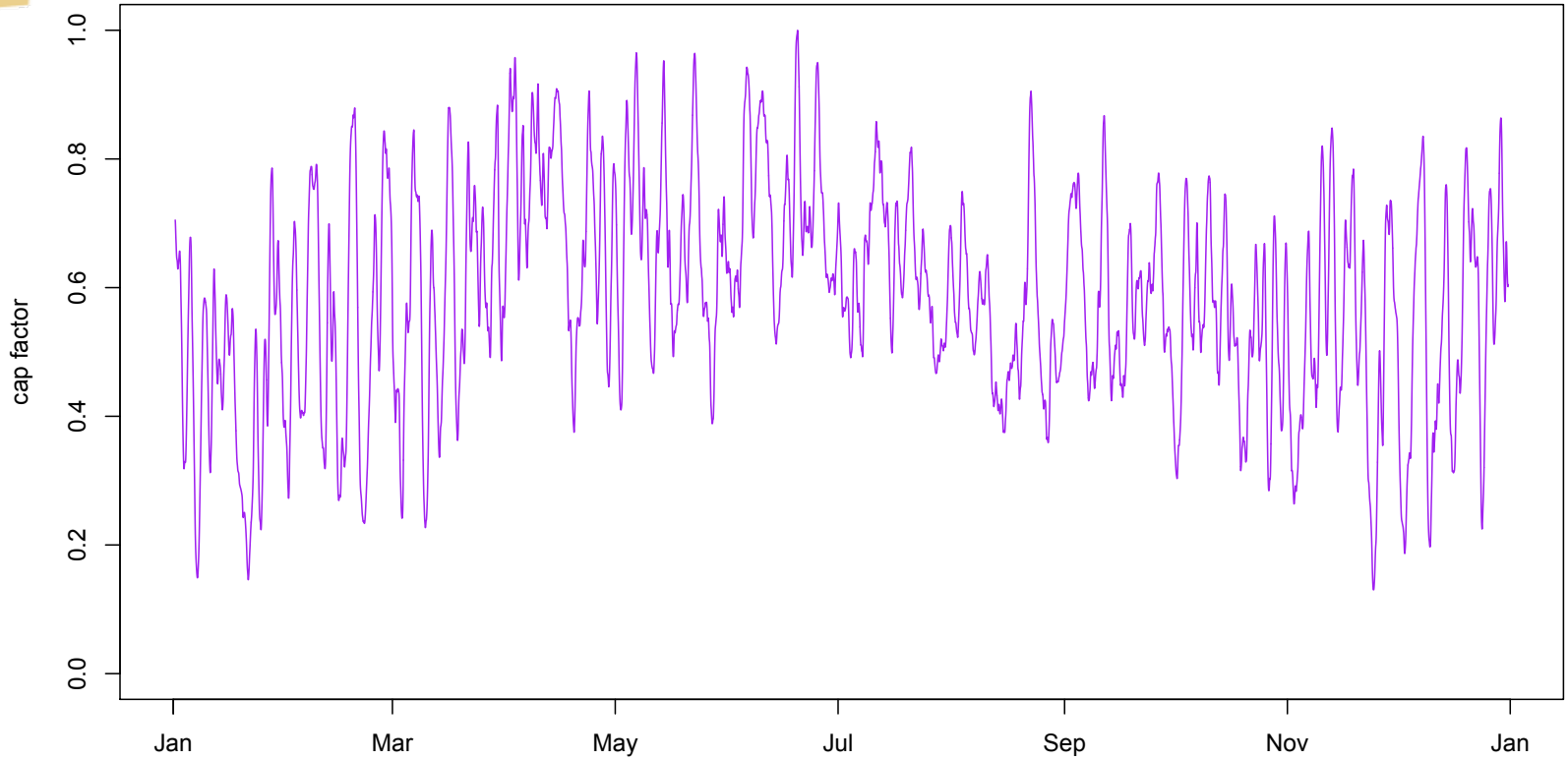
Wind/PV correlation

($PV_{\Delta T=24hr}$ vs $W_{\Delta T=24hr}$)

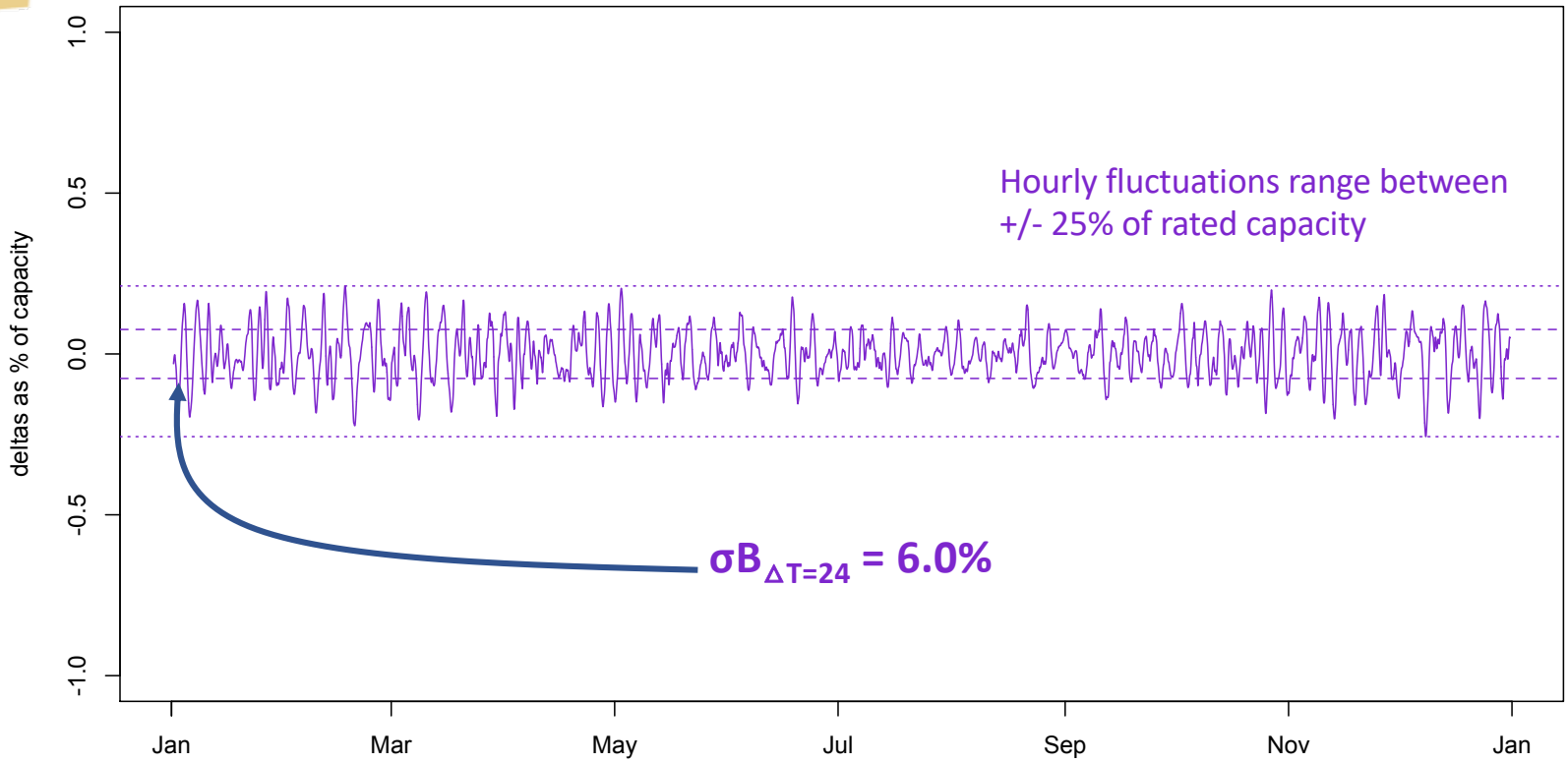
$$\rho = -2.9\%$$

Slight negative correlation

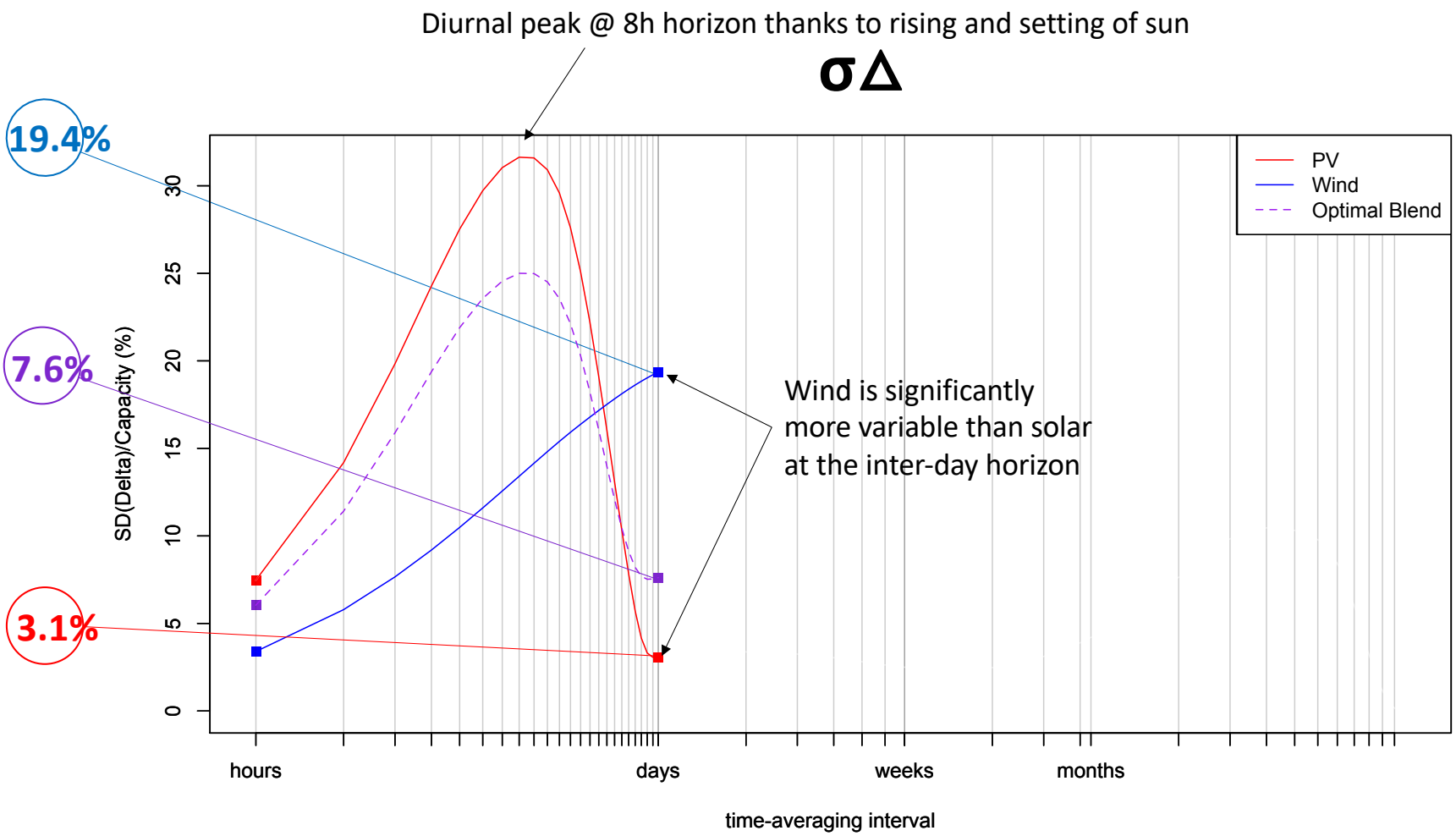
Normalized Daily 50/50 Blended Resource across MISO

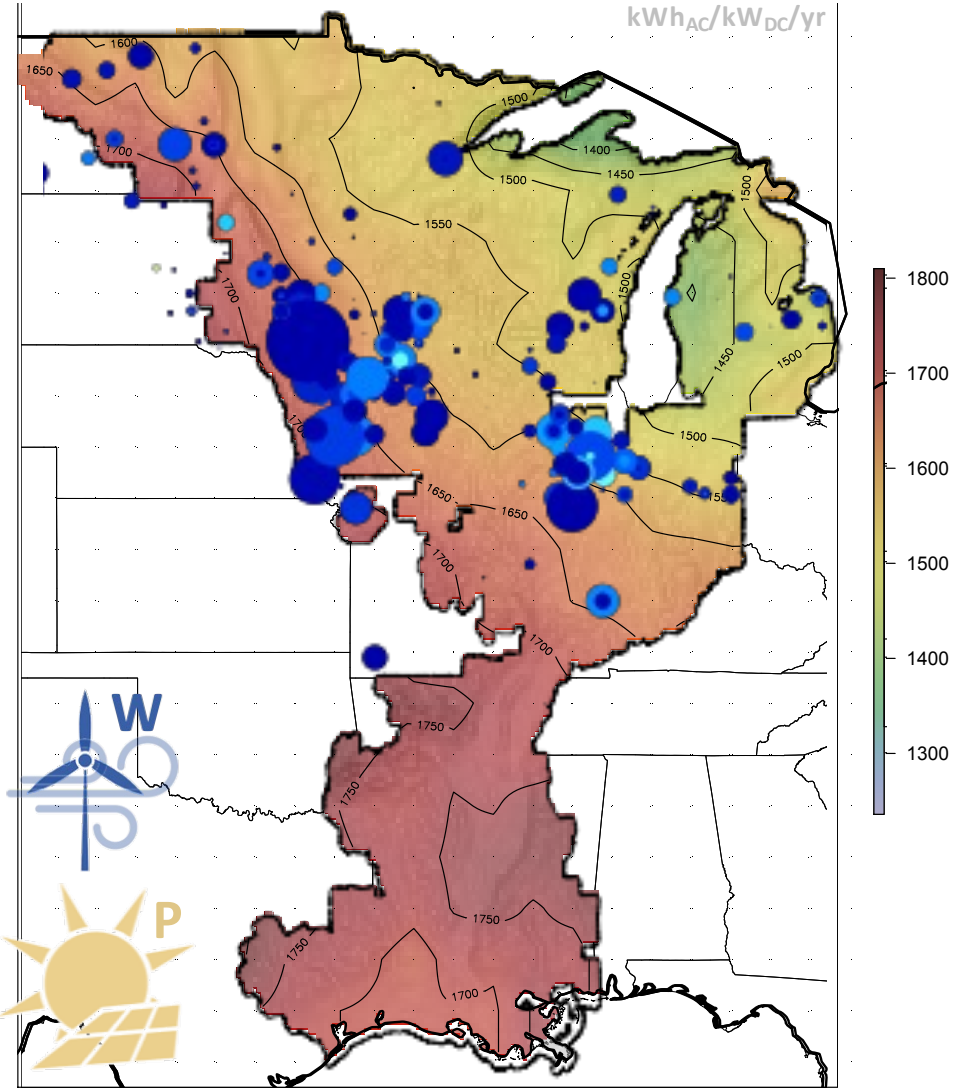


Daily Fluctuations ($\Delta B_{t=24h}$)



The hybrid wind + solar variability is much lower than wind alone but still higher than solar alone.

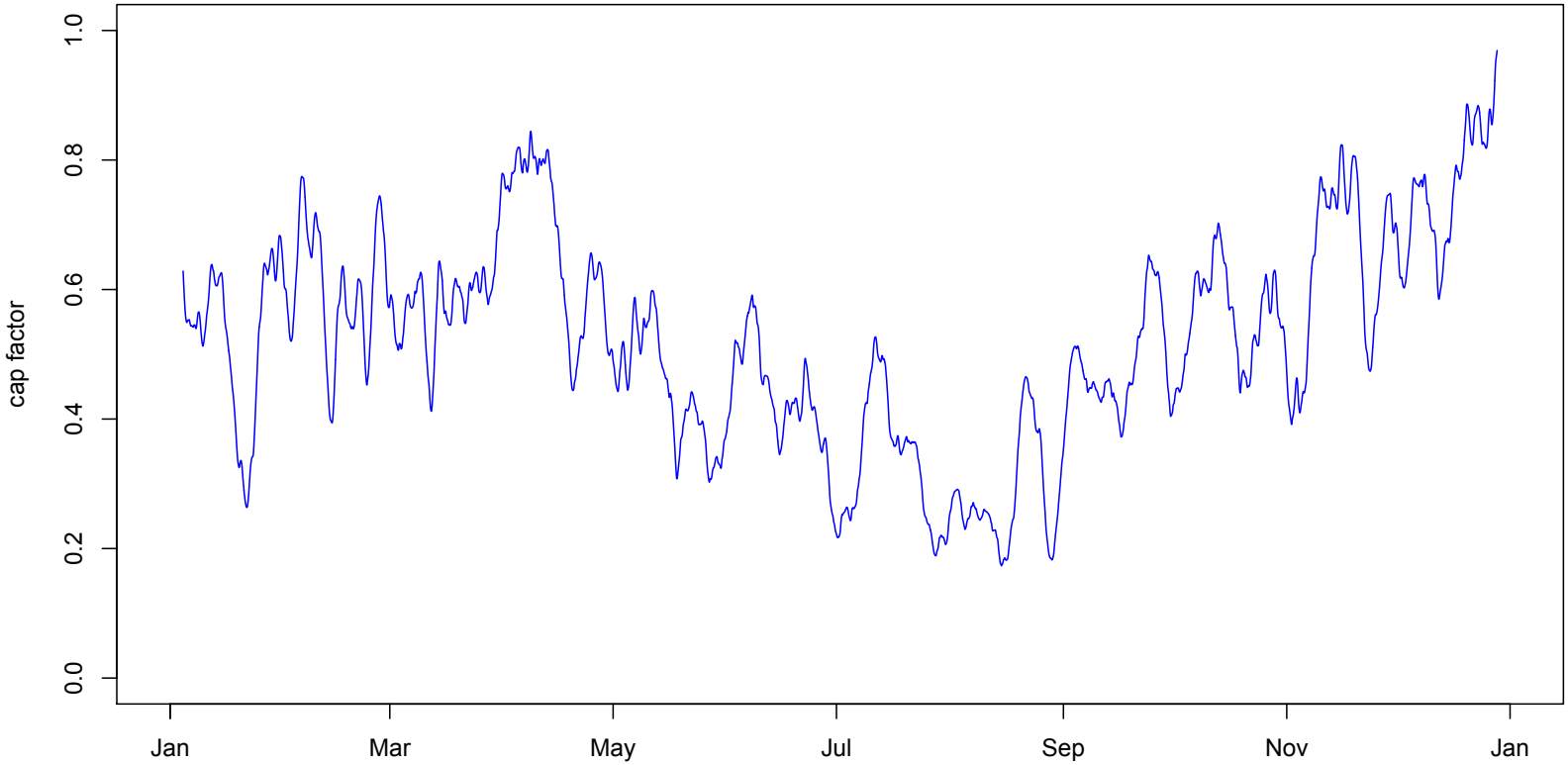

Diurnal peak @ 8h horizon thanks to rising and setting of sun
σΔ
19.4%
7.6%
3.1%
SD(Delta)/Capacity (%)
0
5
10
15
20
25
30
PV
Wind
Optimal Blend
Wind is significantly
more variable than solar
at the inter-day horizon
hours
days
weeks
months
time-averaging interval



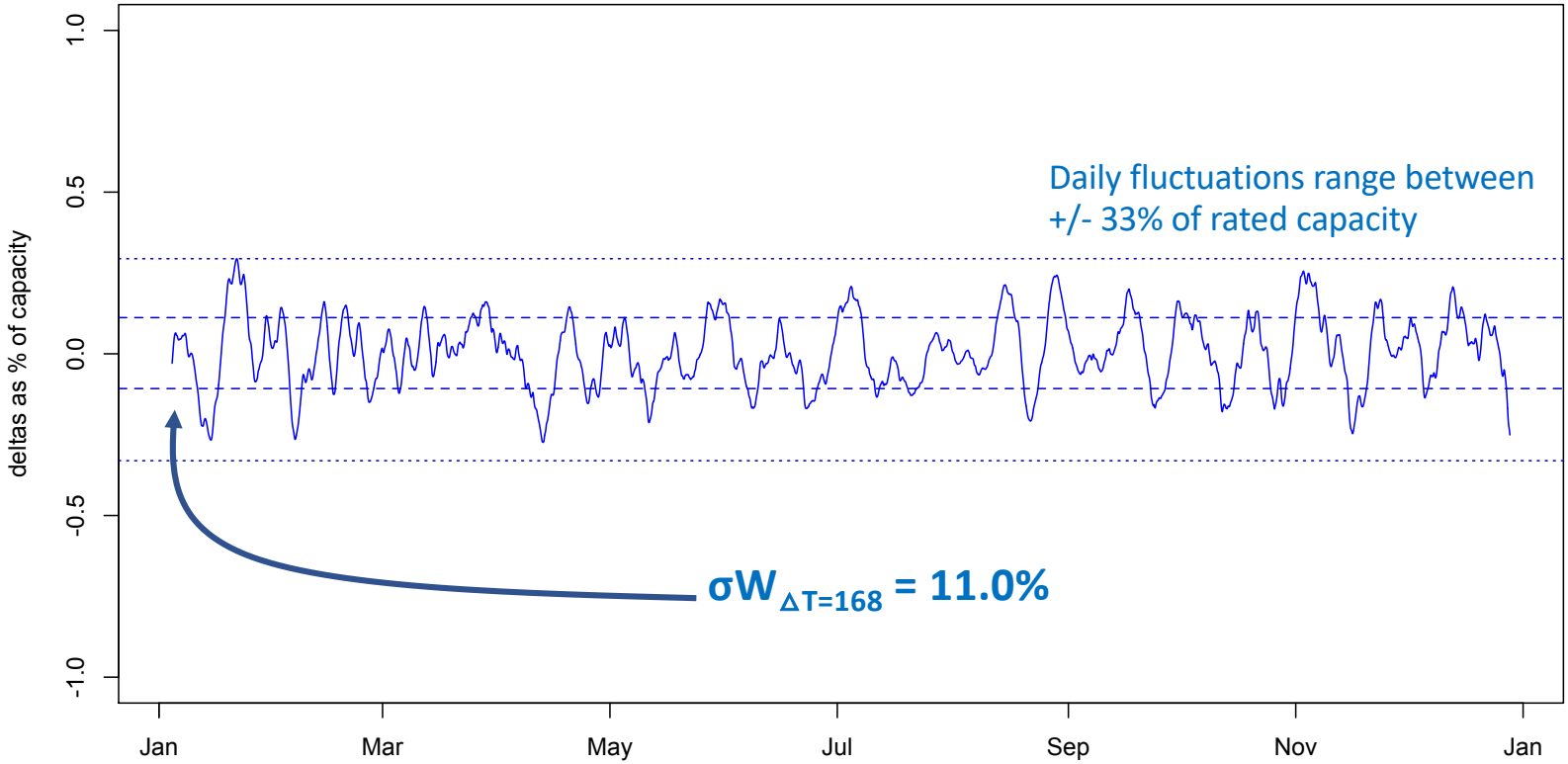
Weekly-interval characterization

- The weekly interval is of interest from a medium-term energy balancing perspective, load scheduling
- At the hebdomadary interval, things like macro-scale weather phenomena start to dominate the picture: weather fronts.

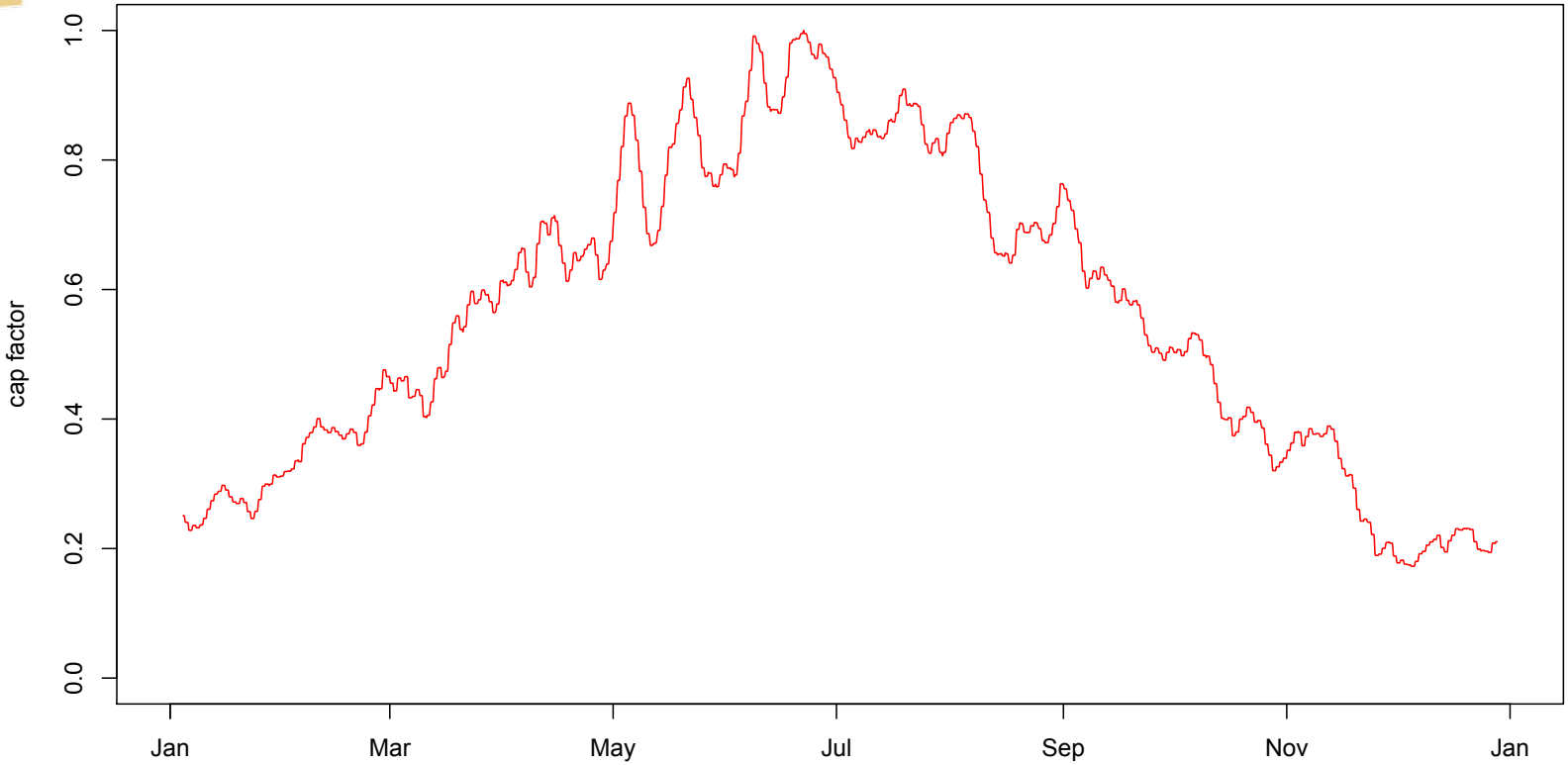
Normalized Weekly Wind Power (W) across MISO



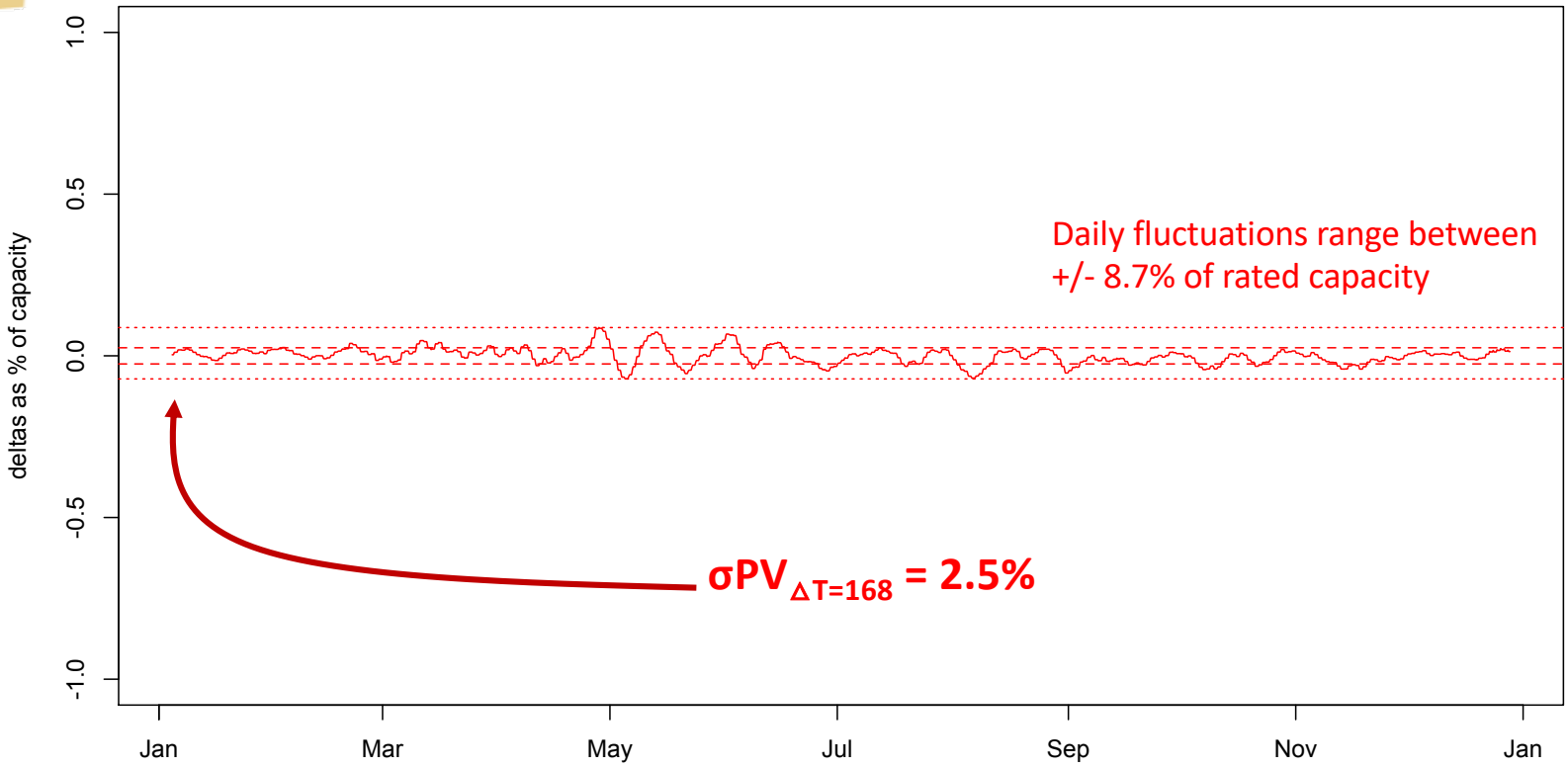
Weekly Fluctuations ($\Delta W_{t=168h}$)



Normalized Weekly GHI across MISO



Weekly Fluctuations ($P_{\Delta T=168hr}$)



Solar variability at the weekly interval is still lower than wind variability at the same interval

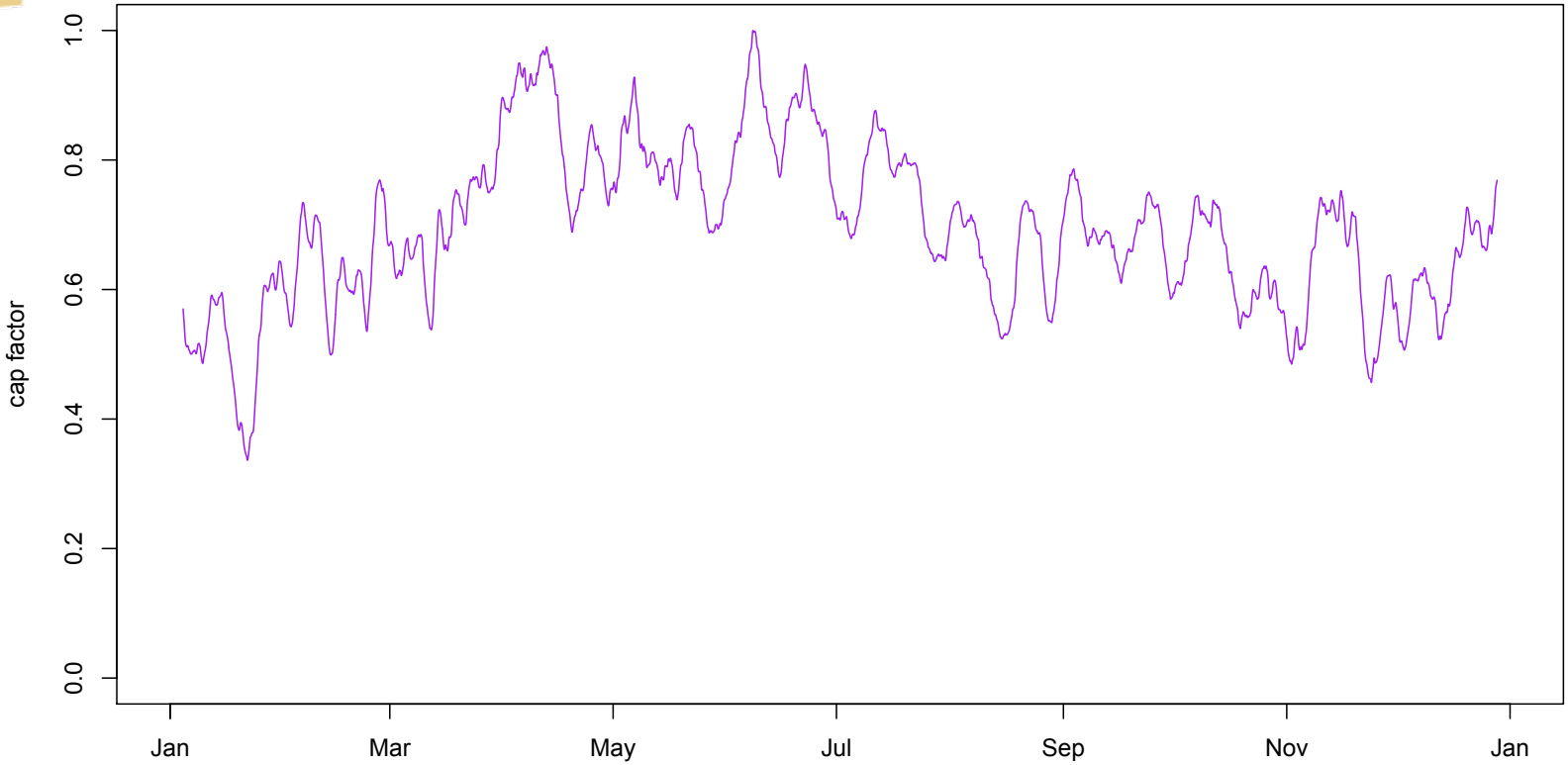
Wind/PV correlation

($PV_{\Delta T=168hr}$ vs $W_{\Delta T=168hr}$)

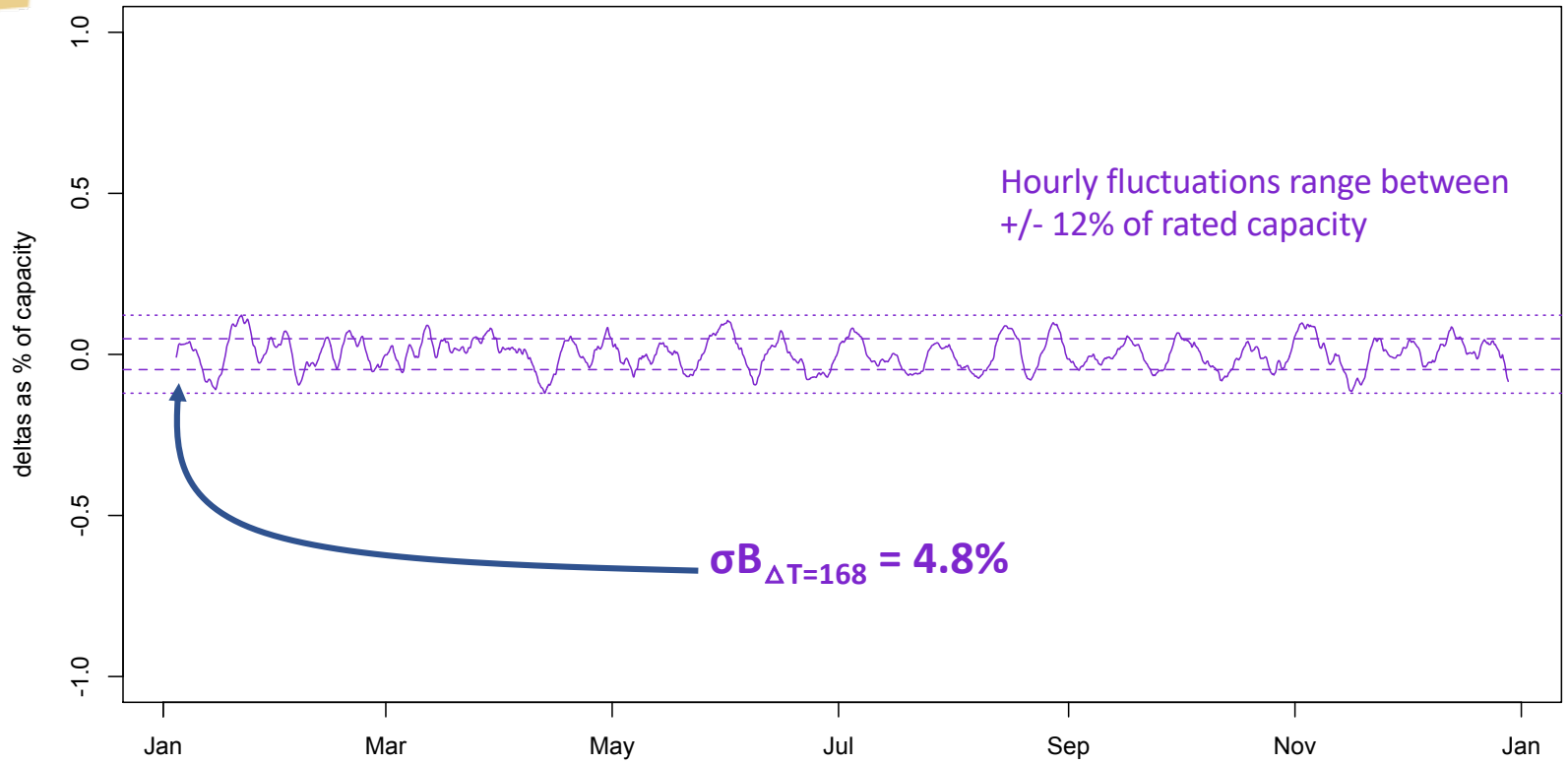
$$\rho = +11.5\%$$

Slight positive correlation

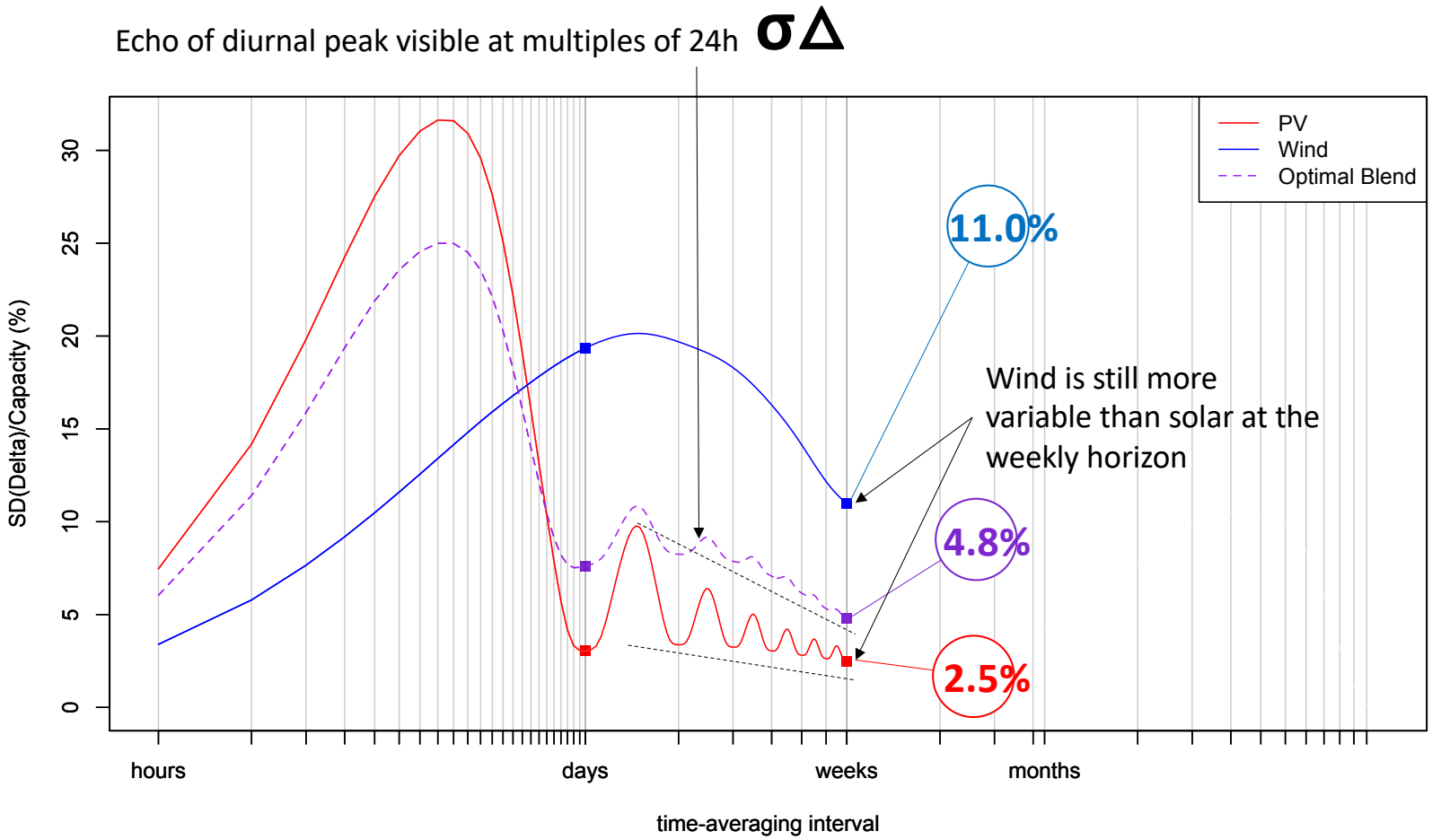
Normalized Weekly 50/50 Blended Resource across MISO

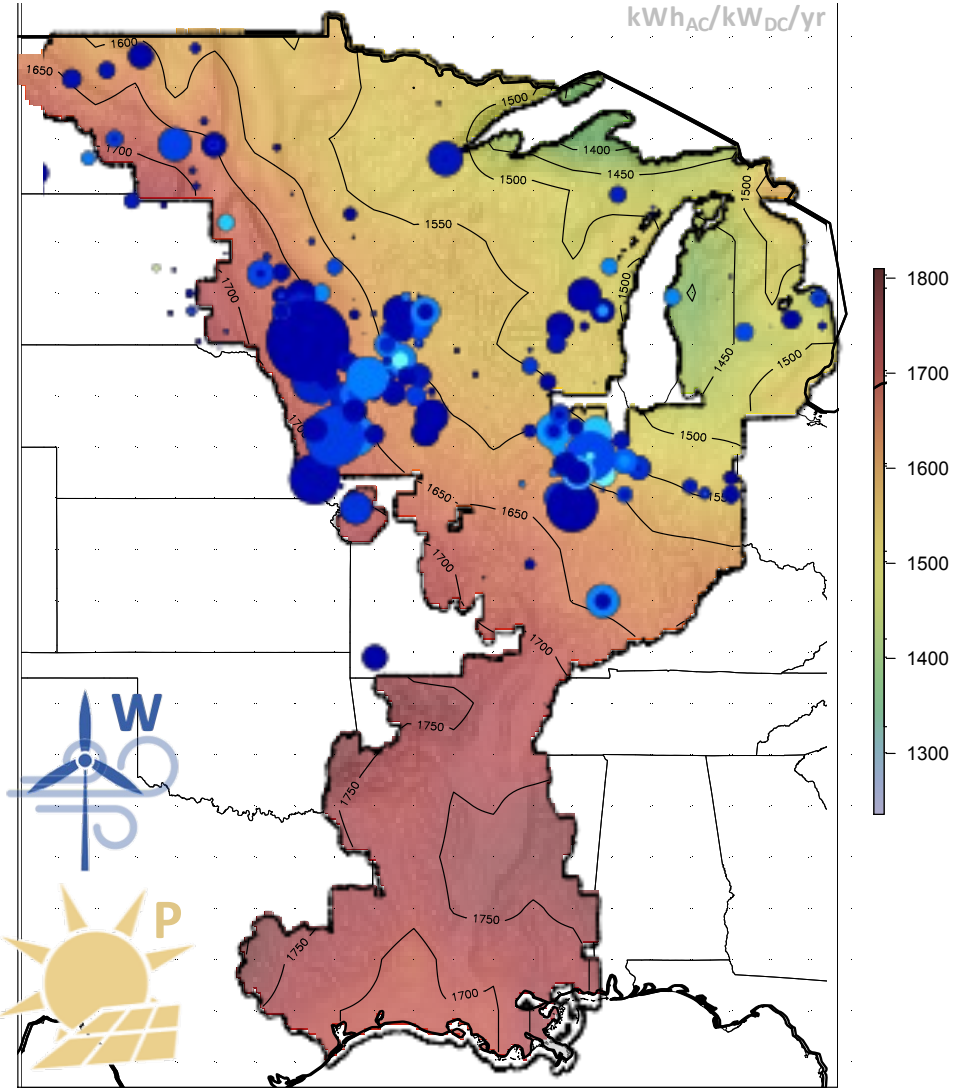


Weekly Fluctuations ($\Delta B_{t=168h}$)



Similar to the daily interval, at the weekly interval, the hybrid wind + solar variability is much lower than wind alone but still higher than solar alone.

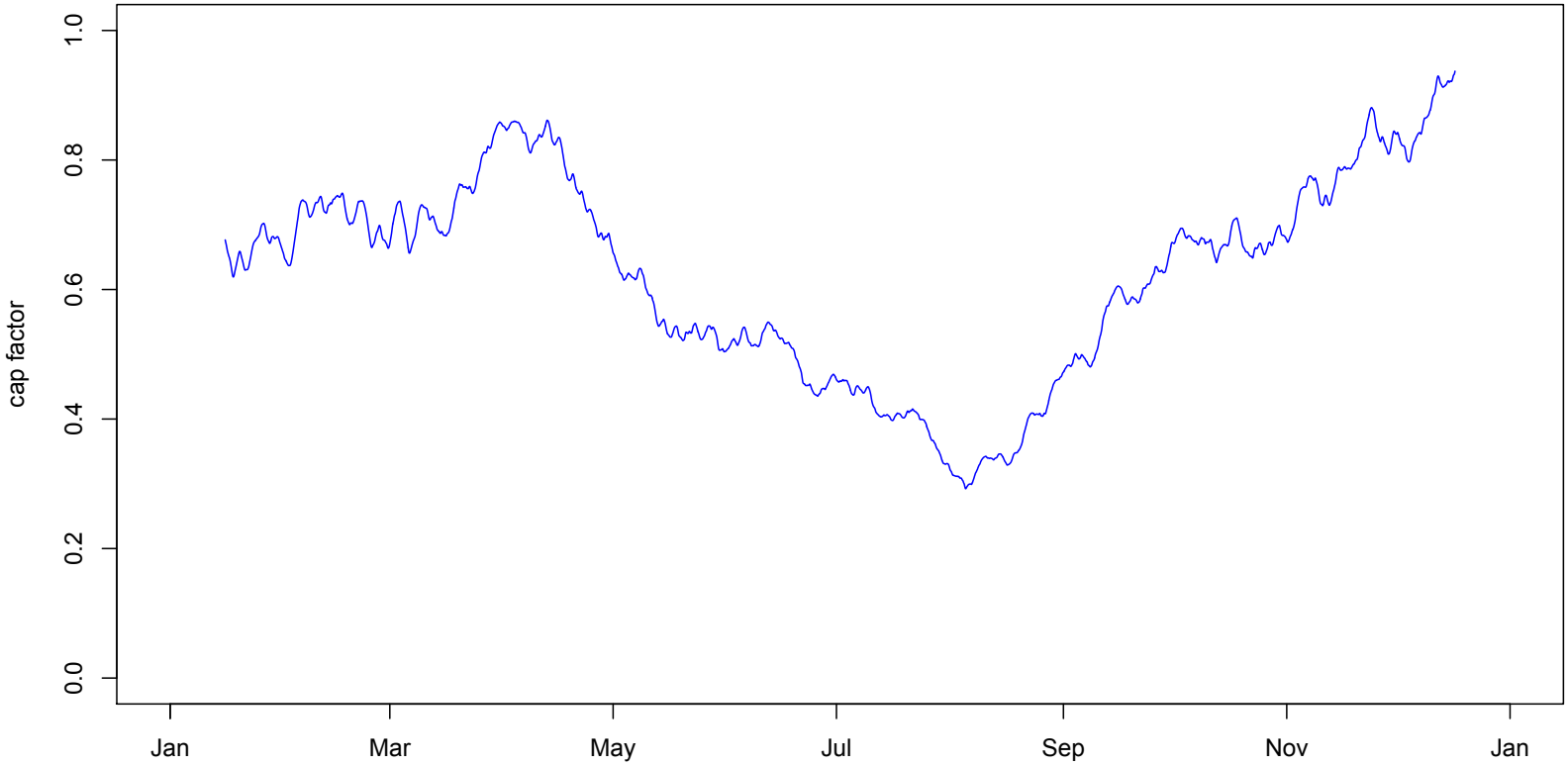

Echo of diurnal peak visible at multiples of 24h σΔ
PV
Wind
Optimal Blend
11.0%
Wind is still more variable than solar at the weekly horizon
4.8%
2.5%
SD(Delta)/Capacity (%)
0
5
10
15
20
25
30
hours
days
weeks
months
time-averaging interval



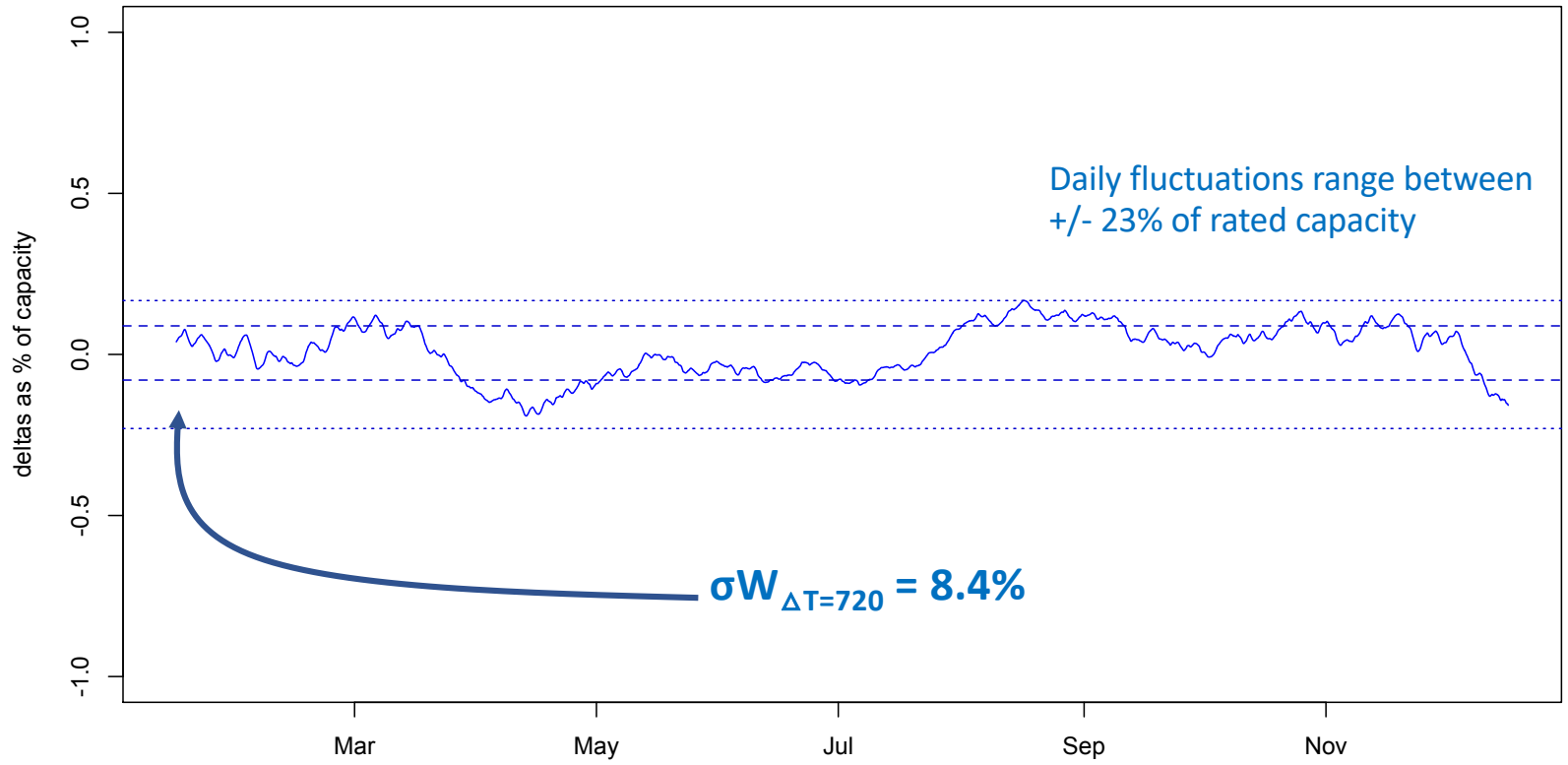
Monthly-interval characterization

- The monthly interval is of interest from a long-term perspective. Slow-moving resources like coal can be scheduled on this horizon. Cheap $/kWh energy storage is required (pumped hydro, CAES, etc)
- Month-to month variations are dominated by more-or-less deterministic seasonal effects linked to the earth's axial tilt and orbit around the sun

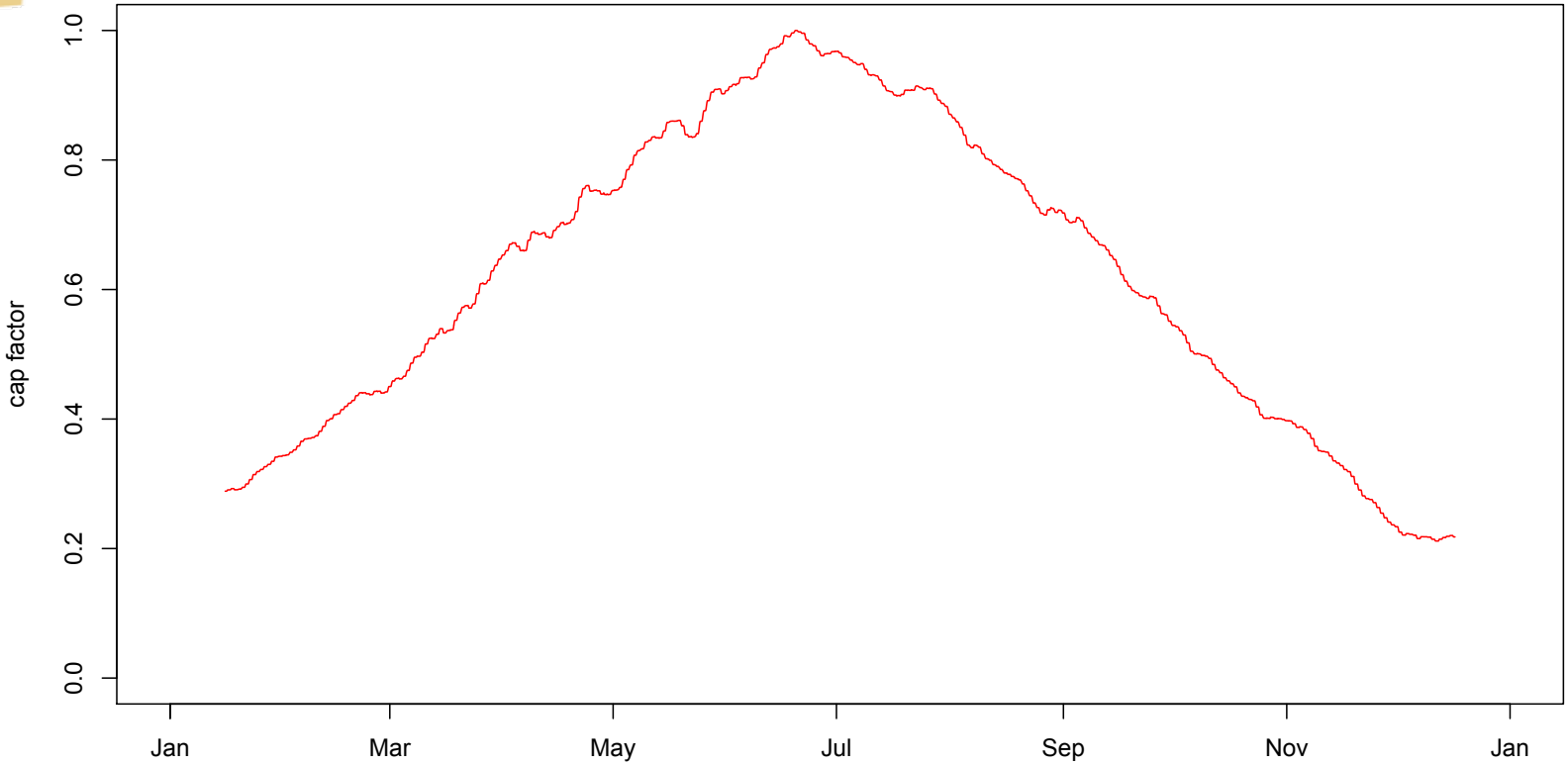
Normalized Monthly Wind Power (W) across MISO



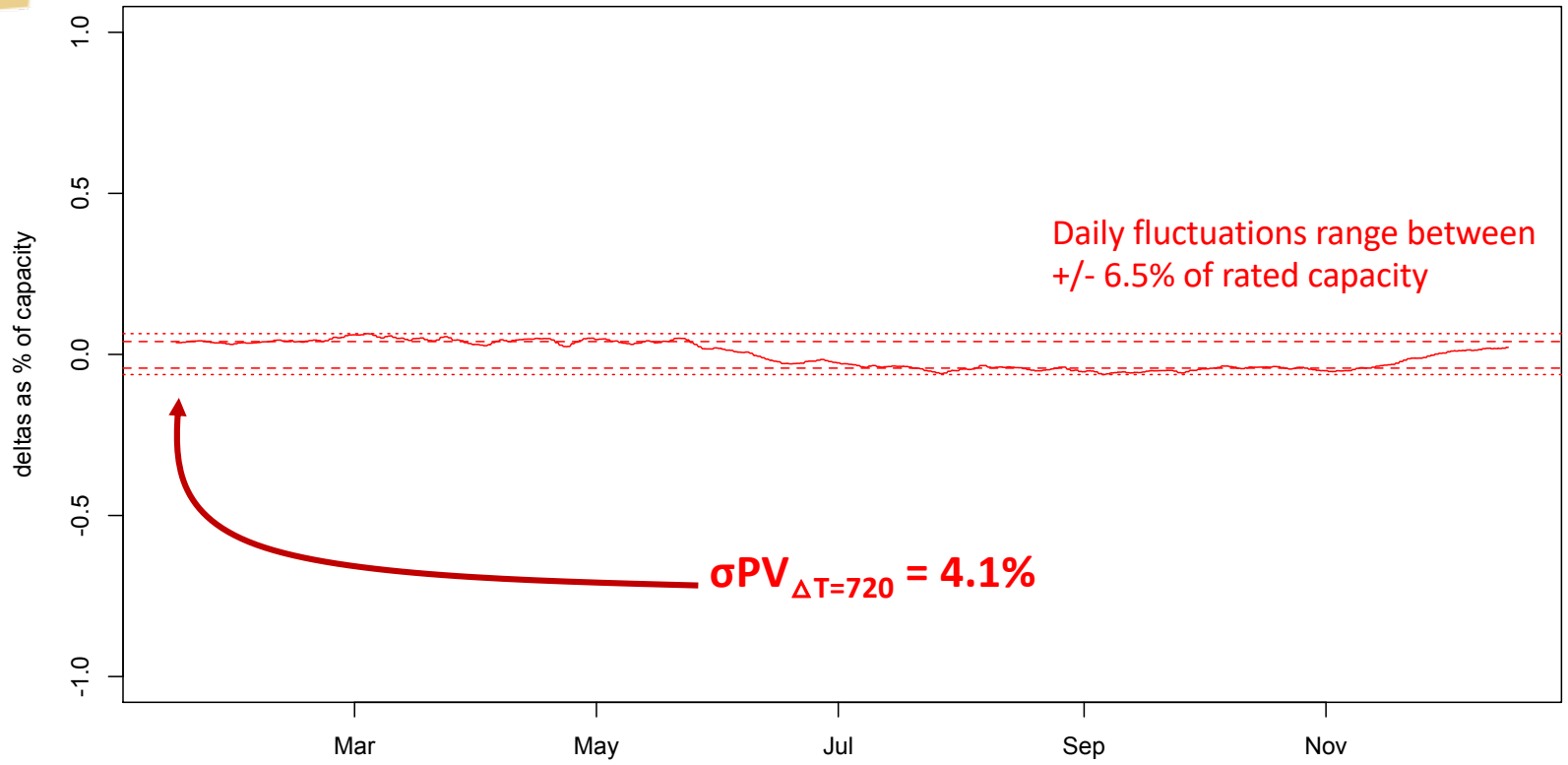
Monthly Fluctuations ($\Delta W_{t=720h}$)



Normalized Monthly GHI across MISO



Monthly Fluctuations ($P_{\Delta T=720hr}$)



Solar variability at the monthly interval is still lower than wind variability at the same interval, this is starting to become because of the seasonality of both resources

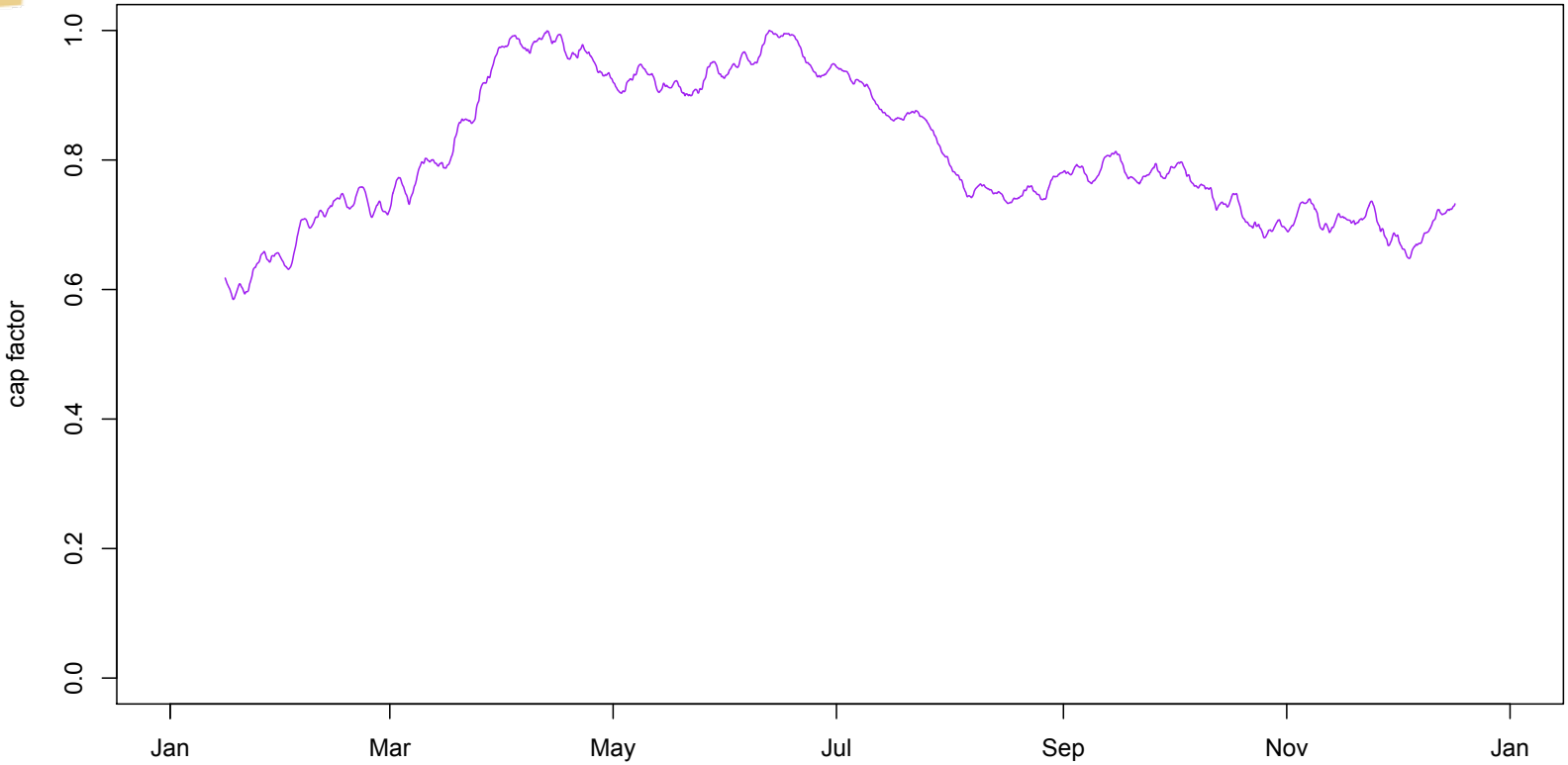
Wind/PV correlation

($PV_{\Delta T=720hr}$ vs $W_{\Delta T=720hr}$)

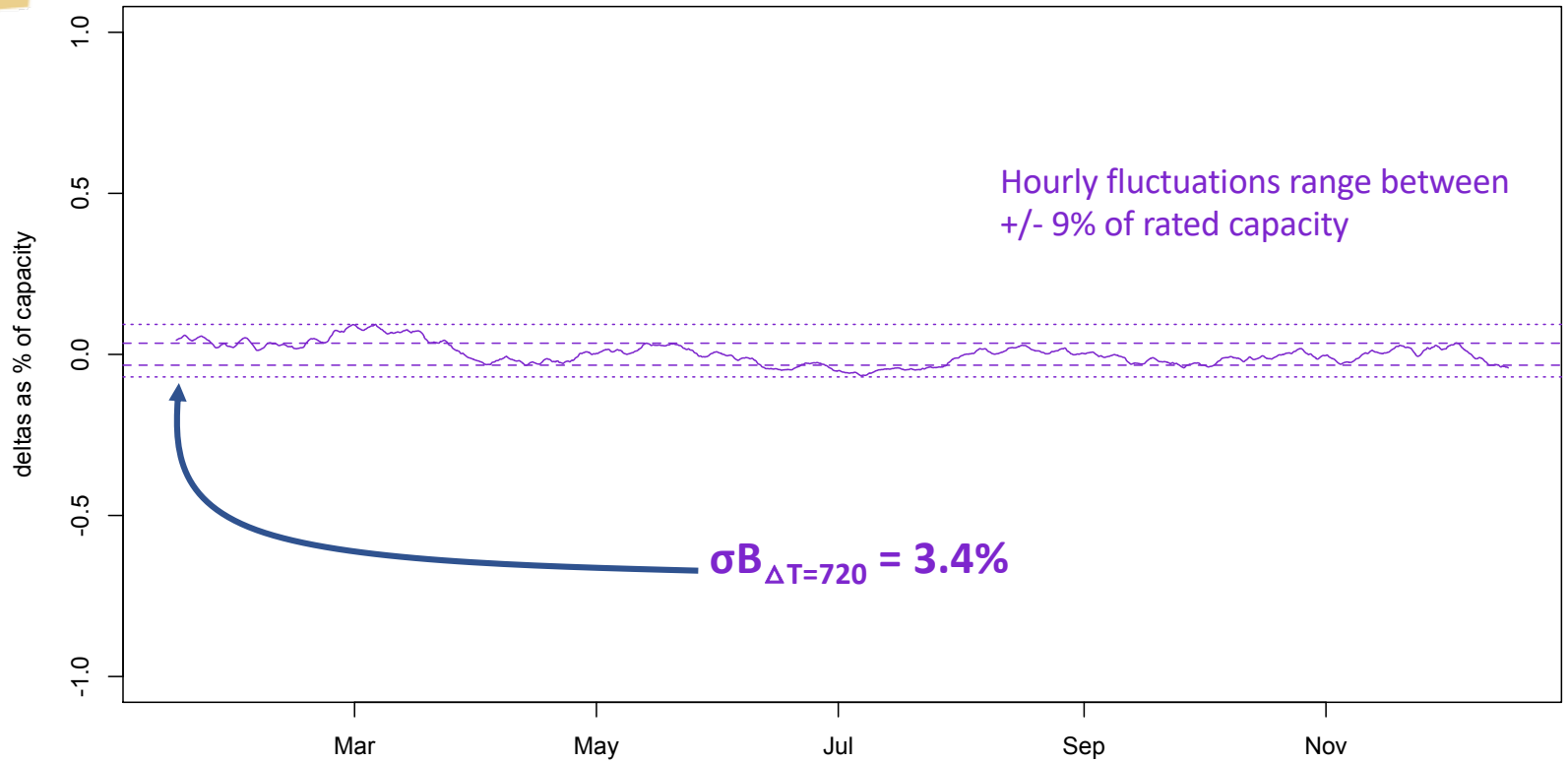
$$\rho = -44.3\%$$

A fairly strong anti-correlation exists between the two resources

Normalized Monthly 50/50 Blended Resource across MISO

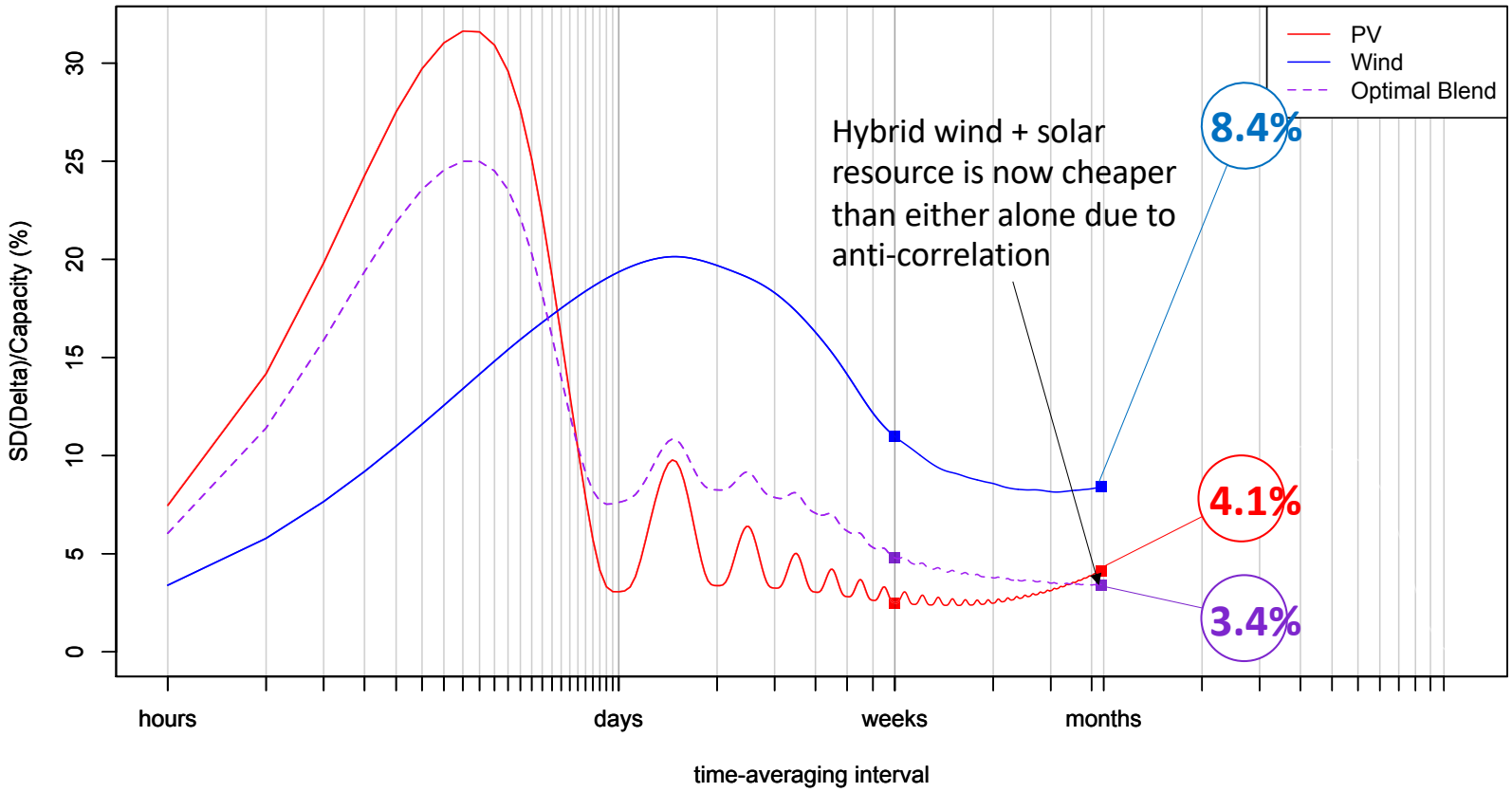


Monthly Fluctuations ($\Delta B_{t=720h}$)

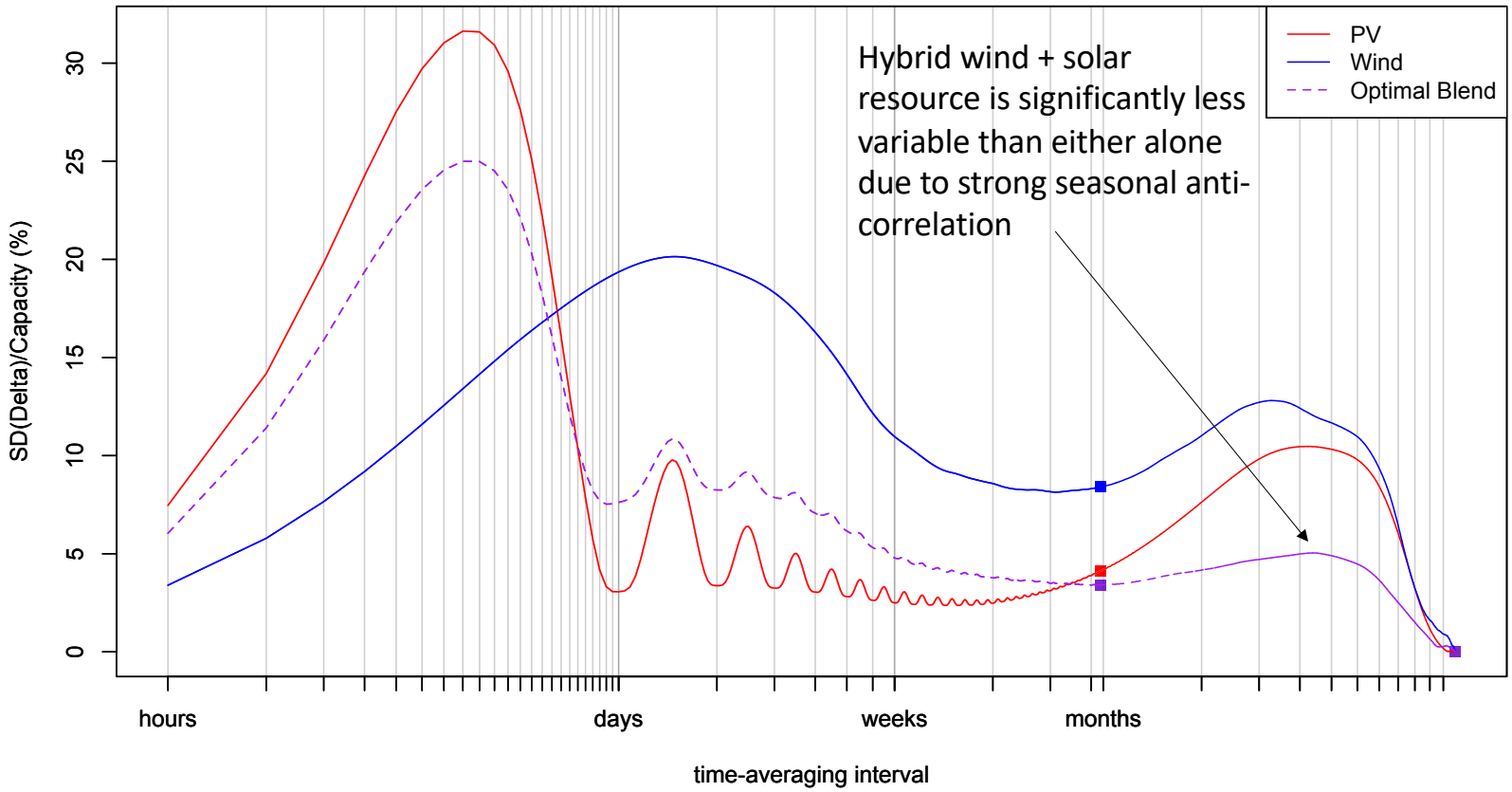


At the monthly interval, a hybrid wind + solar resource is **less variable** than either is individually

σΔ


PV
Wind
Optimal Blend
Hybrid wind + solar resource is now cheaper than either alone due to anti-correlation
8.4%
4.1%
3.4%
SD(Delta)/Capacity (%)
0
5
10
15
20
25
30
hours
days
weeks
months
time-averaging interval

σΔ


PV
Wind
Optimal Blend
Hybrid wind + solar resource is significantly less variable than either alone due to strong seasonal anti-correlation
SD(Delta)/Capacity (%)
0
5
10
15
20
25
30
hours
days
weeks
months
time-averaging interval

Takeaways:

- PV is significantly more variable than wind at timescales <16h due to the deterministic diurnal variability of the solar resource
- Wind is significantly more variable than PV at timescales >16h as the solar resource at these timescales experiences variability that is more deterministically-and less stochastically-driven
- The hybrid wind + PV resource is much less seasonally variable (at timescales > 3.5 weeks) than either resource individually thanks to the strong seasonal anti-correlation between the two resources.
- Negative correlation exists at both the seasonal and the diurnal levels but is much stronger (at least across MISO) at the seasonal level.
- This is somewhat unfair of an operational perspective for PV as we are using GHI as a benchmark. When all the PV is tilted at latitude, the PV variability at the seasonal level drops significantly.
- As seasonal variability is a significant cost-driver at high-penetrations (alleviated either through oversizing or storage), hybridizing assets where anti-correlated makes strong economic sense.



On the Complementary Variability of Wind & Solar Power

Marc Perez[1]

Apr. 1st, 2025

[1]*Clean Power Research, Napa, CA*

IEA 16[2]

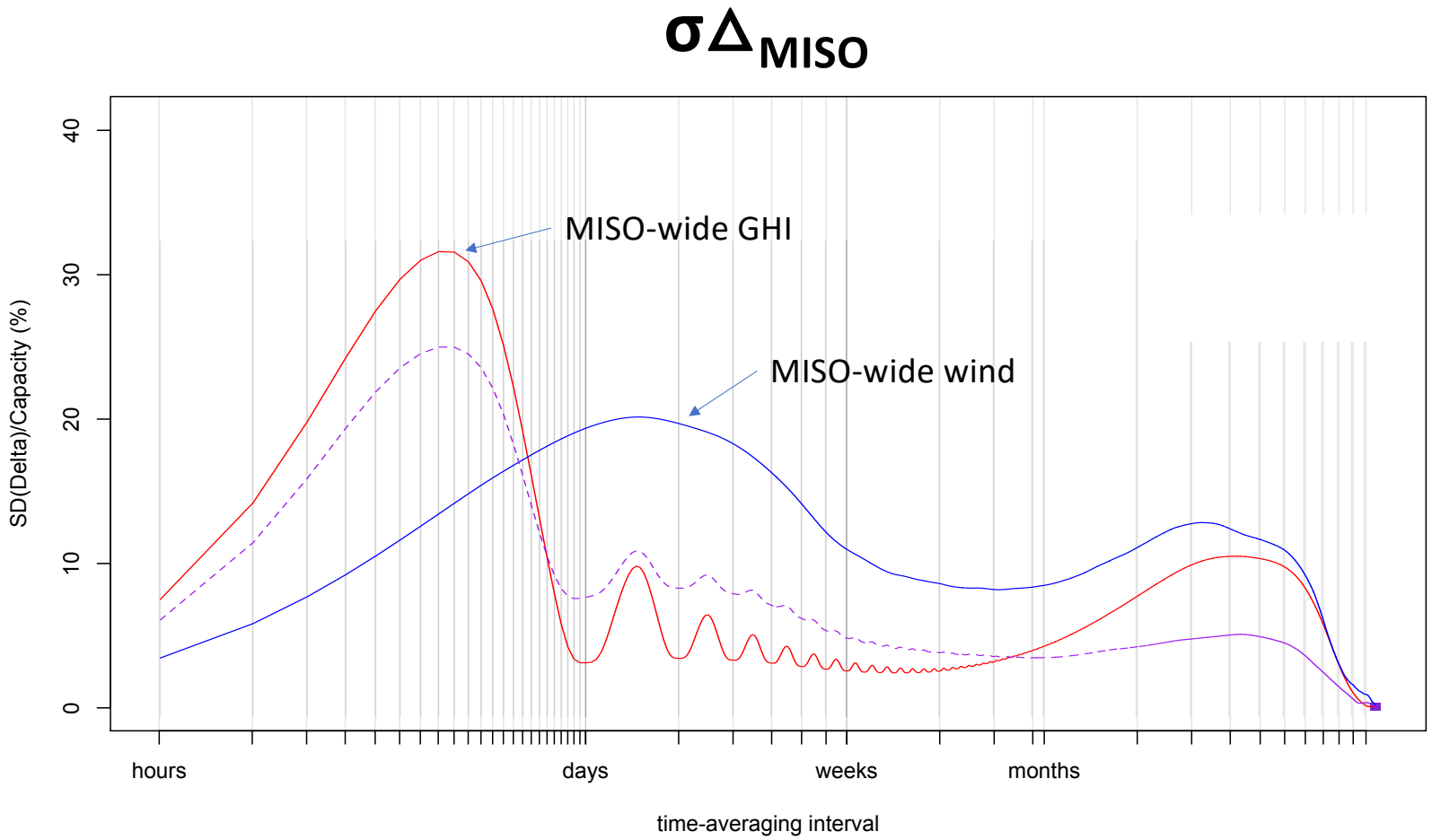
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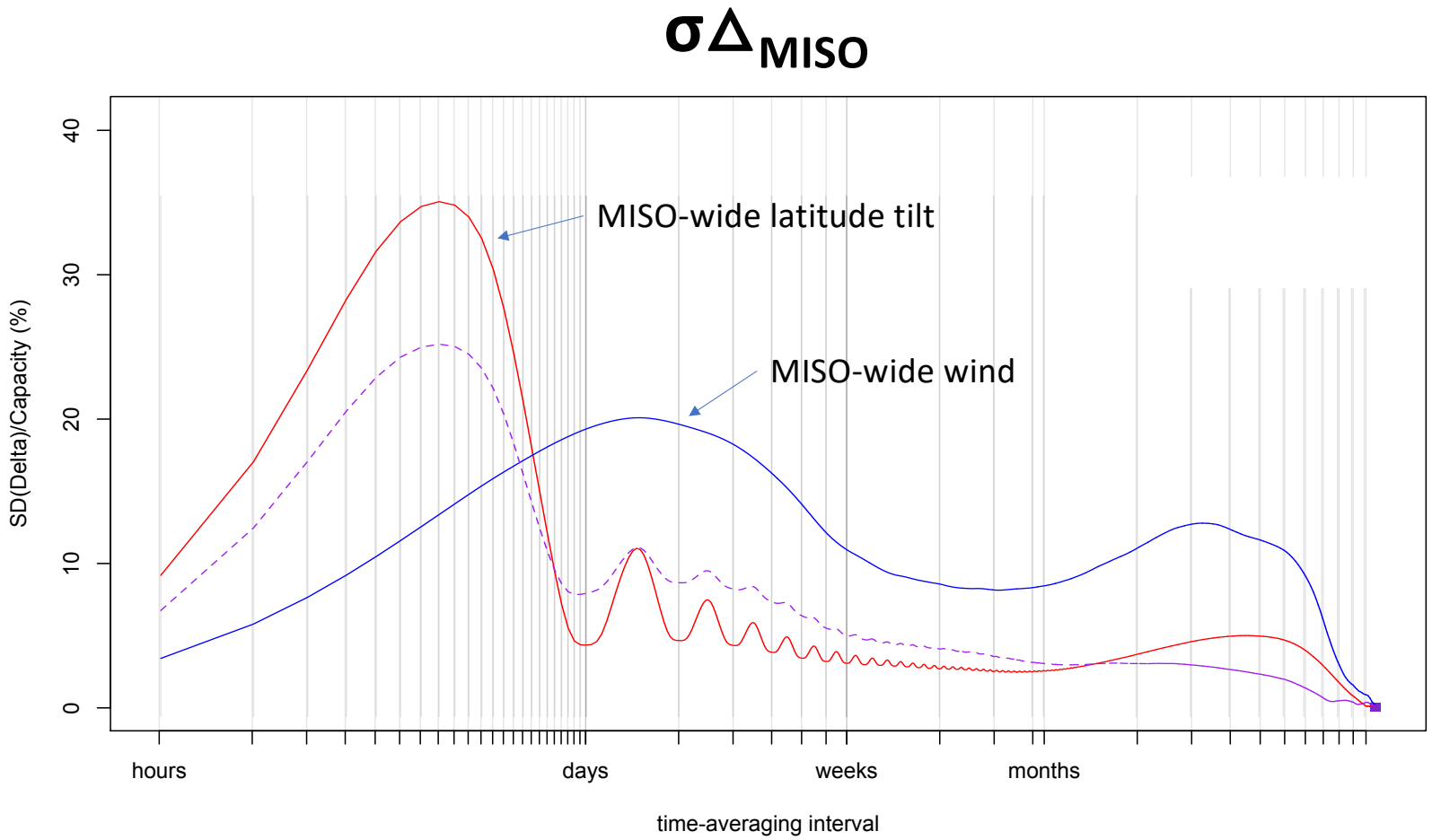
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Appendix

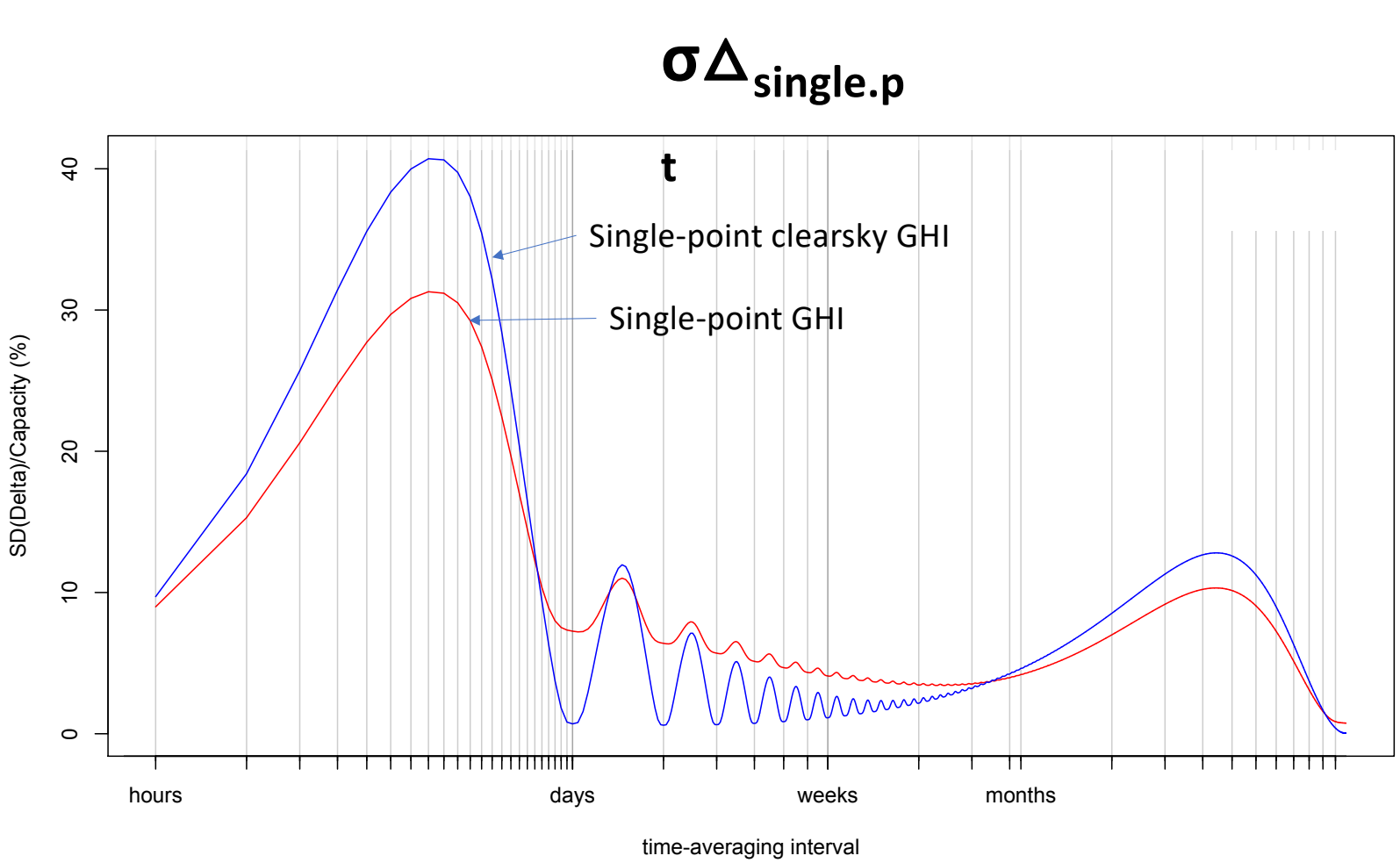
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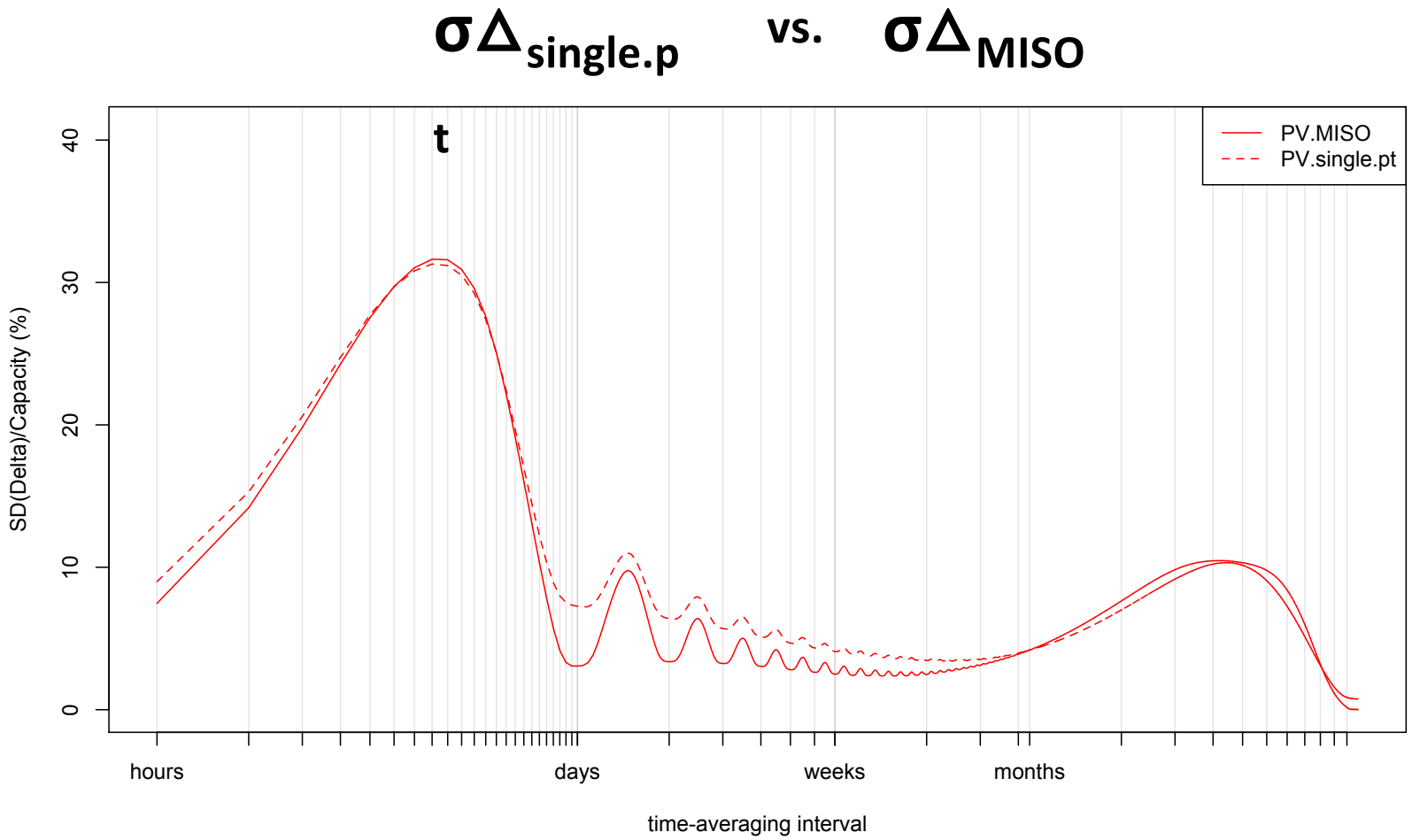
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σΔMISO
MISO-wide GHI
MISO-wide wind
SD(Delta)/Capacity (%)
0
10
20
30
40
hours
days
weeks
months
time-averaging interval


σΔMISO
MISO-wide latitude tilt
MISO-wide wind
SD(Delta)/Capacity (%)
0
10
20
30
40
hours
days
weeks
months
time-averaging interval

40.8,-91.1


σΔsingle.p
t
Single-point clearsky GHI
Single-point GHI
SD(Delta)/Capacity (%)
0
10
20
30
40
hours
days
weeks
months
time-averaging interval


σΔsingle.p vs. σΔMISO
t
PV.MISO
PV.single.pt
SD(Delta)/Capacity (%)
0
10
20
30
40
hours
days
weeks
months
time-averaging interval