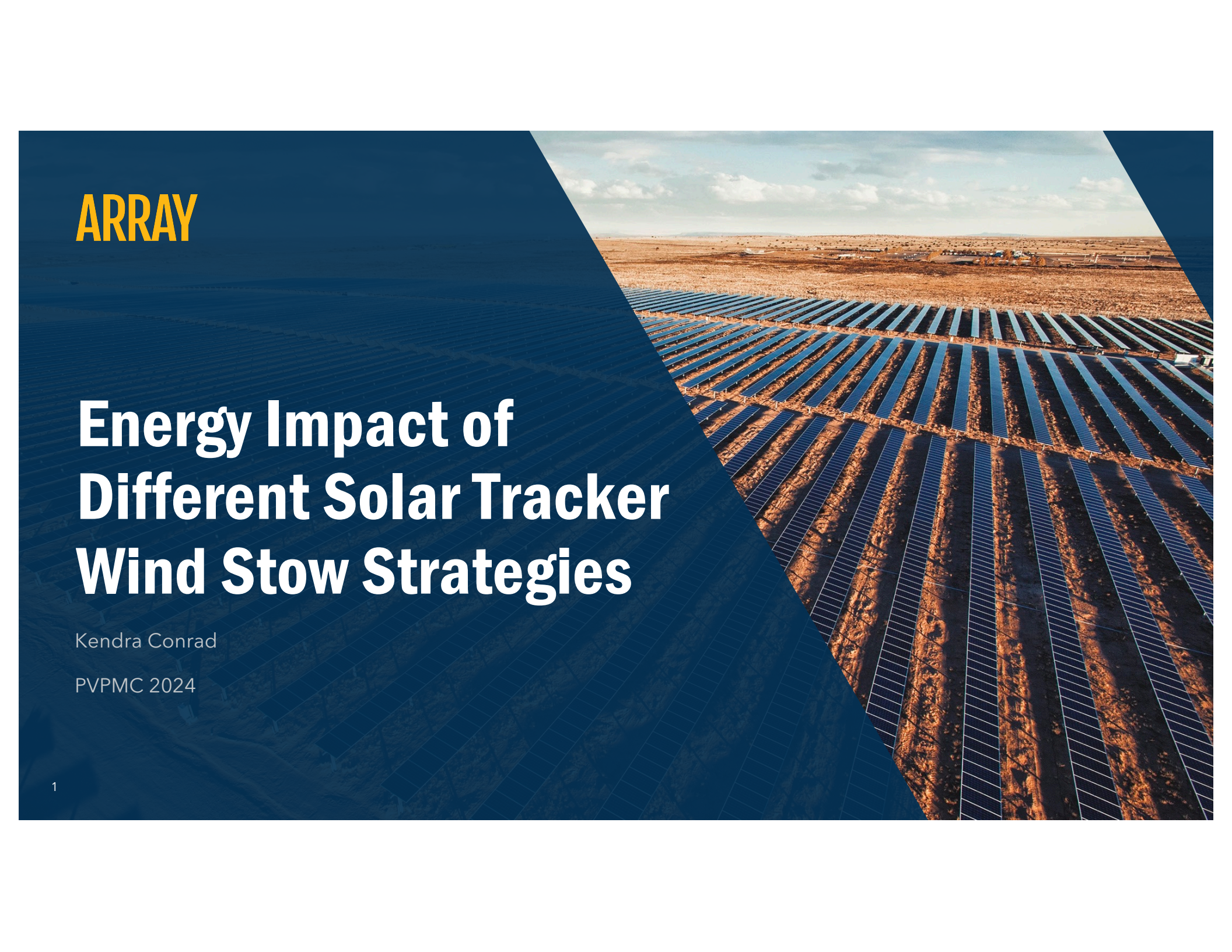




ARRAY

Energy Impact of Different Solar Tracker Wind Stow Strategies

Kendra Conrad

PVPMC 2024



→ Introduction

→ Modeling Methodology

- Wind Preprocessing
- Stow Analysis
- Energy Modeling

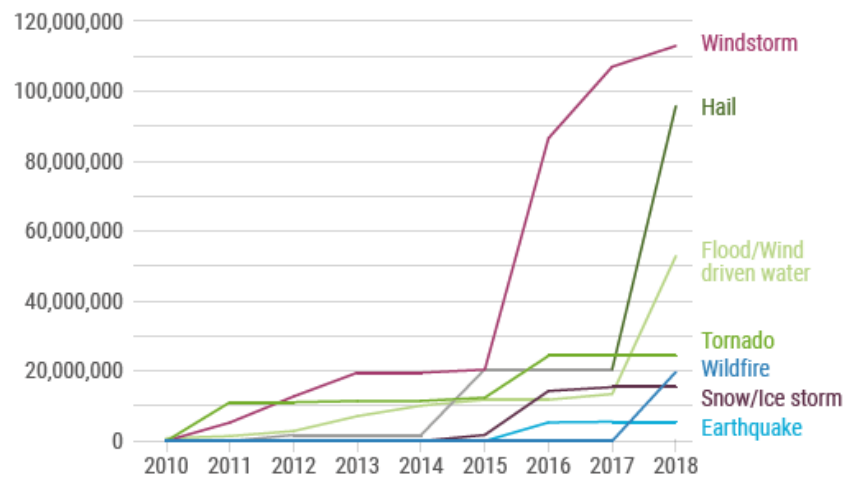
→ Results

→ Conclusions and Future Work

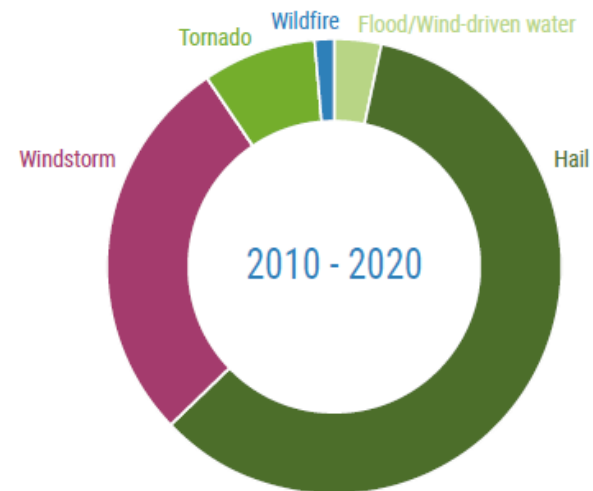


Cost of Extreme Weather

GCube - Hail or High Water Q1 2021 Report



Nat Cat and Extreme Weather, incurred cumulative total (USD)



Severity of Nat Cat and Extreme Weather by solar claim

System Cost vs. Energy Loss



ion

Wind Data Preprocessing

A stacked bar chart titled 'Wind Data Preprocessing' showing wind speed data by month. The y-axis is labeled 'Wind Speed (mph)' and ranges from 0 to 60 in increments of 10. The x-axis is labeled 'Months' and lists the twelve months of the year. Each bar is stacked with an orange bottom section representing 'Average' and a blue top section representing 'Peak'. The total height of each bar represents the combined value of the average and peak wind speeds for that month.

Month	Average (mph)	Peak (mph)	Total (mph)
January	10	48	58
February	14	34	48
March	15	39	54
April	18	37	55
May	17	31	48
June	17	23	40
July	17	18	35
August	16	34	50
September	16	30	46
October	14	35	49
November	10	47	57
December	10	34	44



Stow Angle Calculation



Energy Simulation

Wind Data for Stow Analysis

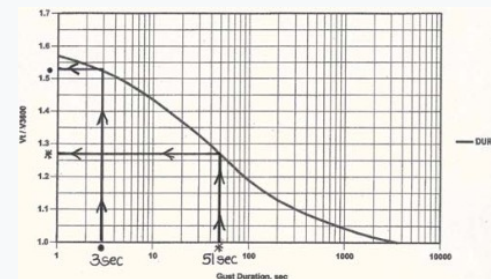
On-Site Wind Measurements

- ▶ Typical mounting sensor height is at 10m, but if necessary, sensor height can be corrected using the power law
- ▶ Wind speed measurements are instantaneous, but what is stored?
 - ▶ Average values (ex. 3 second mav)?
 - ▶ Peak values for the samples in the recording interval?
- ▶ What data is required by the stow strategy? Is wind direction even considered?



Included with Satellite Irradiance Dataset

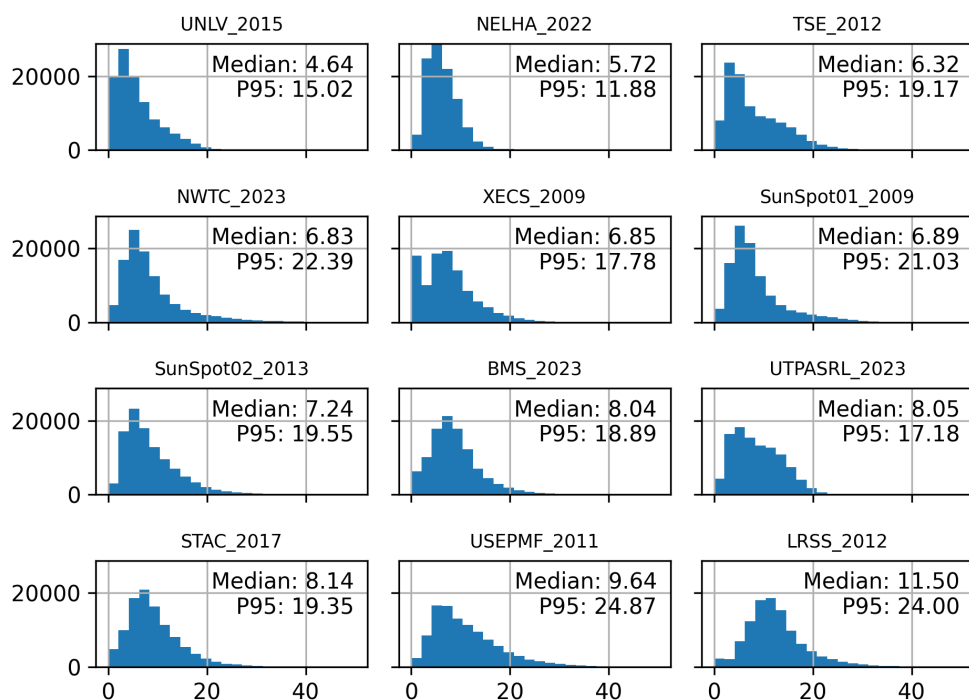
- ▶ TMY data (hourly resolution) is not sufficient for detailed wind analysis
 - ▶ Lengths of stow periods, relaxation times, etc. are often less than 1 hour
- ▶ 5-minute historical sources are available, but gust/peak wind speeds are not provided
- ▶ Durst curves (1960) or similar are often used to estimate peak gust wind speeds from a longer term mean wind speed



Source Data for the Study

NREL Measurement and Instrumentation Data Center (MIDC)

5-Min Average Wind Speed



- High-temporal-resolution ground-measured weather dataset, publicly available at <https://midcdmz.nrel.gov/>; 17 sites are currently active.
- We selected 12 sites that provide data with 1-minute recording interval:
 - » Global Horizontal Irradiance
 - » Air Temperature
 - » Wind Speed (Average and Peak)
 - » Wind Direction (Average)
- Wind data was processed into the format required by the various stow strategies, then the maximum value over each 5-minute window was used.

tion

Wind Data Preprocessing

A stacked bar chart titled 'Wind Data Preprocessing' showing wind speed data by month. The y-axis is labeled 'Wind Speed (mph)' and ranges from 0 to 60 in increments of 10. The x-axis is labeled 'Months' and lists the twelve months of the year. Each bar is stacked with an orange bottom section representing 'Average' and a blue top section representing 'Peak'. The total height of each bar represents the combined value of average and peak wind speeds for that month.

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Stow Angle Calculation



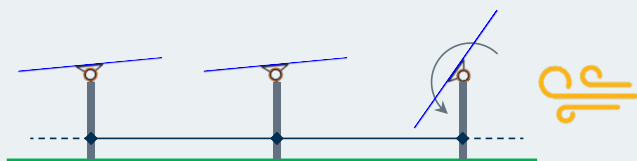
Energy Simulation

Wind Slow Energy Loss [%]

Model	Year	Wind Slow Energy Loss [%]
UNIV	2015	-0.1
UNIV	2017	-0.1
UNIV	2019	-0.1
UNIV	2021	-0.1
UNIV	2023	-0.1
UNIV	2025	-0.1
UNIV	2027	-0.1
UNIV	2029	-0.1
UNIV	2031	-0.1
UNIV	2033	-0.1
UNIV	2035	-0.1
UNIV	2037	-0.1
UNIV	2039	-0.1
UNIV	2041	-0.1
UNIV	2043	-0.1
UNIV	2045	-0.1
UNIV	2047	-0.1
UNIV	2049	-0.1
UNIV	2051	-0.1
UNIV	2053	-0.1
UNIV	2055	-0.1
UNIV	2057	-0.1
UNIV	2059	-0.1
UNIV	2061	-0.1
UNIV	2063	-0.1
UNIV	2065	-0.1
UNIV	2067	-0.1
UNIV	2069	-0.1
UNIV	2071	-0.1
UNIV	2073	-0.1
UNIV	2075	-0.1
UNIV	2077	-0.1
UNIV	2079	-0.1
UNIV	2081	-0.1
UNIV	2083	-0.1
UNIV	2085	-0.1
UNIV	2087	-0.1
UNIV	2089	-0.1
UNIV	2091	-0.1
UNIV	2093	-0.1
UNIV	2095	-0.1
UNIV	2097	-0.1
UNIV	2099	-0.1
UNIV	2101	-0.1
UNIV	2103	-0.1
UNIV	2105	-0.1
UNIV	2107	-0.1
UNIV	2109	-0.1
UNIV	2111	-0.1
UNIV	2113	-0.1
UNIV	2115	-0.1
UNIV	2117	-0.1
UNIV	2119	-0.1
UNIV	2121	-0.1
UNIV	2123	-0.1
UNIV	2125	-0.1
UNIV	2127	-0.1
UNIV	2129	-0.1
UNIV	2131	-0.1
UNIV	2133	-0.1
UNIV	2135	-0.1
UNIV	2137	-0.1
UNIV	2139	-0.1
UNIV	2141	-0.1
UNIV	2143	-0.1
UNIV	2145	-0.1
UNIV	2147	-0.1
UNIV	2149	-0.1
UNIV	2151	-0.1
UNIV	2153	-0.1
UNIV	2155	-0.1
UNIV	2157	-0.1
UNIV	2159	-0.1
UNIV	2161	-0.1
UNIV	2163	-0.1
UNIV	2165	-0.1
UNIV	2167	-0.1
UNIV	2169	-0.1
UNIV	2171	-0.1
UNIV	2173	-0.1
UNIV	2175	-0.1
UNIV	2177	-0.1
UNIV	2179	-0.1
UNIV	2181	-0.1
UNIV	2183	-0.1
UNIV	2185	-0.1
UNIV	2187	-0.1
UNIV	2189	-0.1
UNIV	2191	-0.1
UNIV	2193	-0.1
UNIV	2195	-0.1
UNIV	2197	-0.1
UNIV	2199	-0.1
UNIV	2201	-0.1
UNIV	2203	-0.1
UNIV	2205	-0.1
UNIV	2207	-0.1
UNIV	2209	-0.1
UNIV	2211	-0.1
UNIV	2213	-0.1
UNIV	2215	-0.1
UNIV	2217	-0.1
UNIV	2219	-0.1
UNIV	2221	-0.1
UNIV	2223	-0.1
UNIV	2225	-0.1
UNIV	2227	-0.1
UNIV	2229	-0.1
UNIV	2231	-0.1
UNIV	2233	-0.1
UNIV	2235	-0.1
UNIV	2237	-0.1
UNIV	2239	-0.1
UNIV	2241	-0.1
UNIV	2243	-0.1
UNIV	2245	-0.1
UNIV	2247	-0.1
UNIV	2249	-0.1
UNIV	2251	-0.1
UNIV	2253	-0.1
UNIV	2255	-0.1
UNIV	2257	-0.1
UNIV	2259	-0.1
UNIV	2261	-0.1
UNIV	2263	-0.1
UNIV	2265	-0.1
UNIV	2267	-0.1
UNIV	2269	-0.1
UNIV	2271	-0.1
UNIV	2273	-0.1
UNIV	2275	-0.1
UNIV	2277	-0.1
UNIV	2279	-0.1
UNIV	2281	-0.1
UNIV	2283	-0.1
UNIV	2285	-0.1
UNIV</		

Mechanical vs. Sensor-Based Wind Stow Strategies

Mechanical Stow

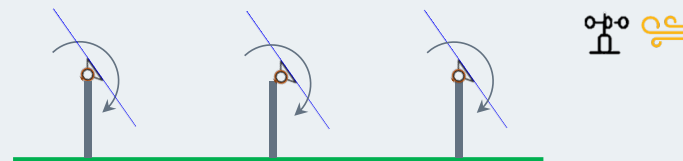


Fully mechanical, passive wind-load mitigation system. Each row has an integrated torque-limiting mechanical clutch that allows the row to stow automatically when the mechanical load threshold is exceeded.

Individual row stow maintains generation in unaffected rows.

Doesn't require power source or additional components/sensors.

Sensor-Based Stow



Uses on-site wind speed measurements to determine when wind speeds exceed predetermined thresholds to command the row(s) to stow.

Stow strategies are specific to each tracker product and stow parameters can vary widely based on project-specific design and conditions.

Requires uninterrupted power source or battery backup in addition to wind sensors.

Mechanical Stow Video

NREL Flatirons Campus

How do we model this behavior?

- Function to calculate clutch-triggering wind speed derived from model of mechanical system combined with wind tunnel test data.
 - » Wind Speed Threshold =
 $f(\text{row length, module size, module mass, ext/int, wind direction, current tilt angle})$
- Number of rows that stow based on NREL test site
 - » (8 108m rows) → 17% interior rows stow as a conservative estimate

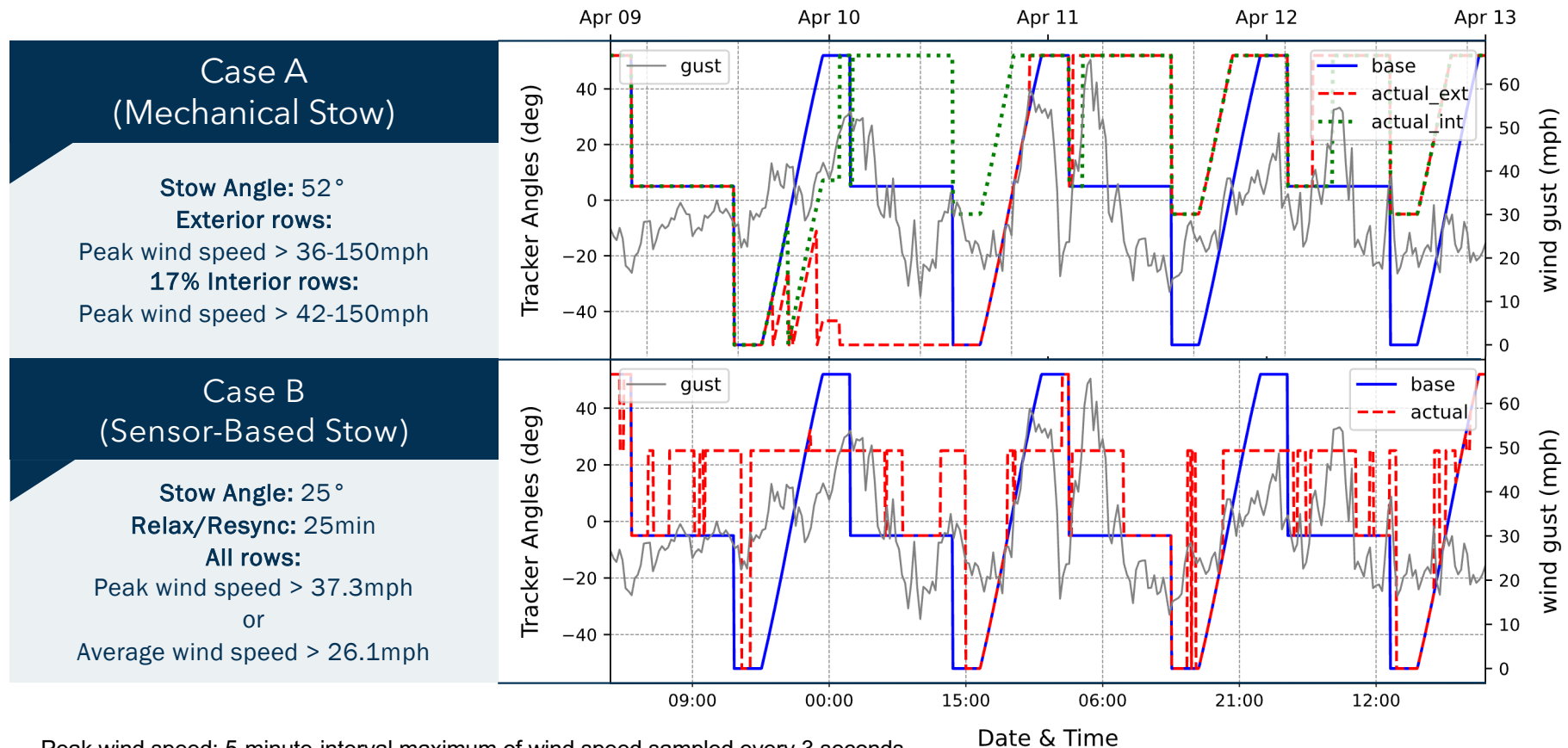


Stow Strategies Considered

Case	Mechanical or Sensor-Based	Relaxation + Resync Time (min)	Stow Angle (deg)	Windspeed Thresholds
A	Mechanical	N/A	52	Exterior rows: Peak wind speed > 36-150mph 17% Interior rows: Peak wind speed > 42-150mph
B	Sensor-Based	25	25	All rows: Peak wind speed > 37.3mph or Average wind speed > 26.1mph
C	Sensor-Based	N/A	60	Exterior rows + 25% interior rows: Normal component of average wind vector @ 3m > 21mph (exit 16mph) All rows: Normal component > 25mph (exit 20mph)
D	Sensor-Based	35	60	25% rows: Peak wind speed > 30mph All rows: Peak wind speed > 35mph

~~Peak wind speed: 5-minute-interval maximum of wind speed sampled every 3 seconds~~
 Average wind speed: 5-minute-interval average of wind speed sampled every 3 seconds

Stow Strategy Comparison Example (Case A vs. Case B)



Peak wind speed: 5-minute-interval maximum of wind speed sampled every 3 seconds
 Average wind speed: 5-minute-interval average of wind speed sampled every 3 seconds

ion

Wind Data Preprocessing

A stacked bar chart titled 'Wind Data Preprocessing' showing wind speed data by month. The y-axis is labeled 'Wind Speed (mph)' and ranges from 0 to 60 in increments of 10. The x-axis is labeled 'Months' and lists the twelve months of the year. Each bar is composed of two segments: an orange segment at the bottom representing the 'Average' wind speed and a blue segment on top representing the 'Peak' wind speed. The total height of each bar represents the combined value of the average and peak speeds for that month. The data shows that January has the highest peak speed (around 48 mph) and the highest average speed (around 10 mph), while July has the lowest peak speed (around 18 mph) and the lowest average speed (around 17 mph).

Month	Average (mph)	Peak (mph)	Total (mph)
January	10	48	58
February	14	34	48
March	15	39	54
April	18	37	55
May	17	31	48
June	18	23	41
July	17	18	35
August	16	34	50
September	16	30	46
October	14	35	49
November	10	47	57
December	10	34	44



Stow Angle Calculation

The graph displays the relationship between Tracker Angles and wind gusts over a four-day period. The 'base' line represents the intended or calculated angles, while the 'actual_ext' and 'actual_int' lines represent measured values. The 'gust' line shows the wind speed in mph, which is correlated with the changes in the angle lines.

Date & Time	base (deg)	actual_ext (deg)	actual_int (deg)	gust (mph)
Apr 09 04:00	-40	-40	-40	~10
Apr 09 14:00	-40	-40	-40	~10
Apr 09 16:00	0	0	0	~10
Apr 09 18:00	0	0	0	~10
Apr 09 20:00	0	0	0	~10
Apr 09 22:00	0	0	0	~10
Apr 10 00:00	40	40	40	~10
Apr 10 02:00	40	40	40	~10
Apr 10 04:00	40	40	40	~10
Apr 10 06:00	40	40	40	~10
Apr 10 08:00	40	40	40	~10
Apr 10 10:00	40	40	40	~10
Apr 10 12:00	40	40	40	~10
Apr 10 14:00	40	40	40	~10
Apr 10 16:00	40	40	40	~10
Apr 10 18:00	40	40	40	~10
Apr 10 20:00	40	40	40	~10
Apr 10 22:00	40	40	40	~10
Apr 11 00:00	40	40	40	~10
Apr 11 02:00	40	40	40	~10
Apr 11 04:00	40	40	40	~10
Apr 11 06:00	40	40	40	~10
Apr 11 08:00	40	40	40	~10
Apr 11 10:00	40	40	40	~10
Apr 11 12:00	40	40	40	~10
Apr 11 14:00	40	40	40	~10
Apr 11 16:00	40	40	40	~10
Apr 11 18:00	40	40	40	~10
Apr 11 20:00	40	40	40	~10
Apr 11 22:00	40	40	40	~10
Apr 12 00:00	40	40	40	~10
Apr 12 02:00	40	40	40	~10
Apr 12 04:00	40	40	40	~10
Apr 12 06:00	40	40	40	~10
Apr 12 08:00	40	40	40	~10
Apr 12 10:00	40	40	40	~10
Apr 12 12:00	40	40	40	~10
Apr 12 14:00	40	40	40	~10
Apr 12 16:00	40	40	40	~10
Apr 12 18:00	40	40	40	~10
Apr 12 20:00	40	40	40	~10
Apr 12 22:00	40	40	40	~10



Energy Simulation

Model/Year	Wind Slow Energy Loss [%]
UNIVL 2015	-0.1
UNIVL 2017	-0.1
NELMVA 2012	-0.1
WATC 2009	-0.1
WATC 2015	-0.1
SumSim0001 2009	-0.1
SumSim0001 2015	-0.1
UTM0001 2015	-0.1
UTM0001 2023	-0.1
UTM0001 2033	-0.1
UTM0001 2043	-0.1
UTM0001 2053	-0.1
UTM0001 2063	-0.1
UTM0001 2073	-0.1
UTM0001 2083	-0.1
UTM0001 2093	-0.1
UTM0001 2103	-0.1
UTM0001 2113	-0.1
UTM0001 2123	-0.1
UTM0001 2133	-0.1
UTM0001 2143	-0.1
UTM0001 2153	-0.1
UTM0001 2163	-0.1
UTM0001 2173	-0.1
UTM0001 2183	-0.1
UTM0001 2193	-0.1
UTM0001 2203	-0.1
UTM0001 2213	-0.1
UTM0001 2223	-0.1
UTM0001 2233	-0.1
UTM0001 2243	-0.1
UTM0001 2253	-0.1
UTM0001 2263	-0.1
UTM0001 2273	-0.1
UTM0001 2283	-0.1
UTM0001 2293	-0.1
UTM0001 2303	-0.1
UTM0001 2313	-0.1
UTM0001 2323	-0.1
UTM0001 2333	-0.1
UTM0001 2343	-0.1
UTM0001 2353	-0.1
UTM0001 2363	-0.1
UTM0001 2373	-0.1
UTM0001 2383	-0.1
UTM0001 2393	-0.1
UTM0001 2403	-0.1
UTM0001 2413	-0.1
UTM0001 2423	-0.1
UTM0001 2433	-0.1
UTM0001 2443	-0.1
UTM0001 2453	-0.1
UTM0001 2463	-0.1
UTM0001 2473	-0.1
UTM0001 2483	-0.1
UTM0001 2493	-0.1
UTM0001 2503	-0.1
UTM0001 2513	-0.1
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UTM0001 2573	-0.1
UTM0001 2583	-0.1
UTM0001 2593	-0.1
UTM0001 2603	-0.1
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UTM0001 2623	-0.1
UTM0001 2633	-0.1
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UTM0001 2663	-0.1
UTM0001 2673	-0.1
UTM0001 2683	-0.1
UTM0001 2693	-0.1
UTM0001 2703	-0.1
UTM0001 2713	-0.1
UTM0001 2723	-0.1
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UTM0001 2783	-0.1
UTM0001 2793	-0.1
UTM0001 2803	-0.1
UTM0001 2813	-0.1
UTM0001 2823	-0.1
UTM0001 2833	-0.1
UTM0001 2843	-0.1
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UTM0001 2883	-0.1
UTM0001 2893	-0.1
UTM0001 2903	-0.1
UTM0001 2913	-0.1
UTM0001 2923	-0.1
UTM0001 2933	-0.1
UTM0001 2943	-0.1
UTM0001 2953	-0.1
UTM0001 2963	-0.1
UTM0001 2973	-0.1
UTM0001 2983	-0.1
UTM0001 2993	-0.1
UTM0001 3003	-0.1
UTM0001 3013	-0.1
UTM0001 3023	-0.1
UTM0001 3033	-0.1
UTM0001 3043	-0.1
UTM0001 3053	-0.1
UTM0001 3063	-0.1
UTM0001 3073	-0.1
UTM0001 3083	-0.1
UTM0001 3093	-0.1
UTM0001 3103	-0.1
UTM0001 3113	-0.1
UTM0001 3123	-0.1
UTM0001 3133	-0.1
UTM0001 3143	-0.1
UTM0001 3153	-0.1
UTM0001 3163	-0.1
UTM0001 3173	-0.1
UTM0001 3183	-0.1
UTM0001 3193	-0.1
UTM0001 3203	-0.1
UTM0001 3213	-0.1
UTM0001 3223	-0.1
UTM0001 3233	-0.1
UTM0001 3243	-0.1
UTM0001 3253	-0.1
UTM0001 3263	-0.1
UTM0001 3273	-0.1
UTM0001 3283	-0.1
UTM0001 3293	-0.1
UTM0001 3303	-0.1
UTM0001 33	

Wind Stow Energy Modeling Overview

All steps executed using the PlantPredict SDK (python)

Import Time Series Data

- 5 minute resolution:
- ▶ Weather data
 - ▶ GHI, Tamb
 - ▶ Tracker wind stow angles



Run Predictions

- ▶ Reference prediction based on customer site
 - ▶ Modules: FS
 - ▶ GCR: 40%
 - ▶ DC:AC: 1.25
- ▶ Run baseline and stow cases
 - ▶ Tiered stow strategies require multiple cases



Calculate Wind Stow Loss

$$\text{Wind Stow Loss} = \frac{P_{stow,agg}}{P_{base}}$$

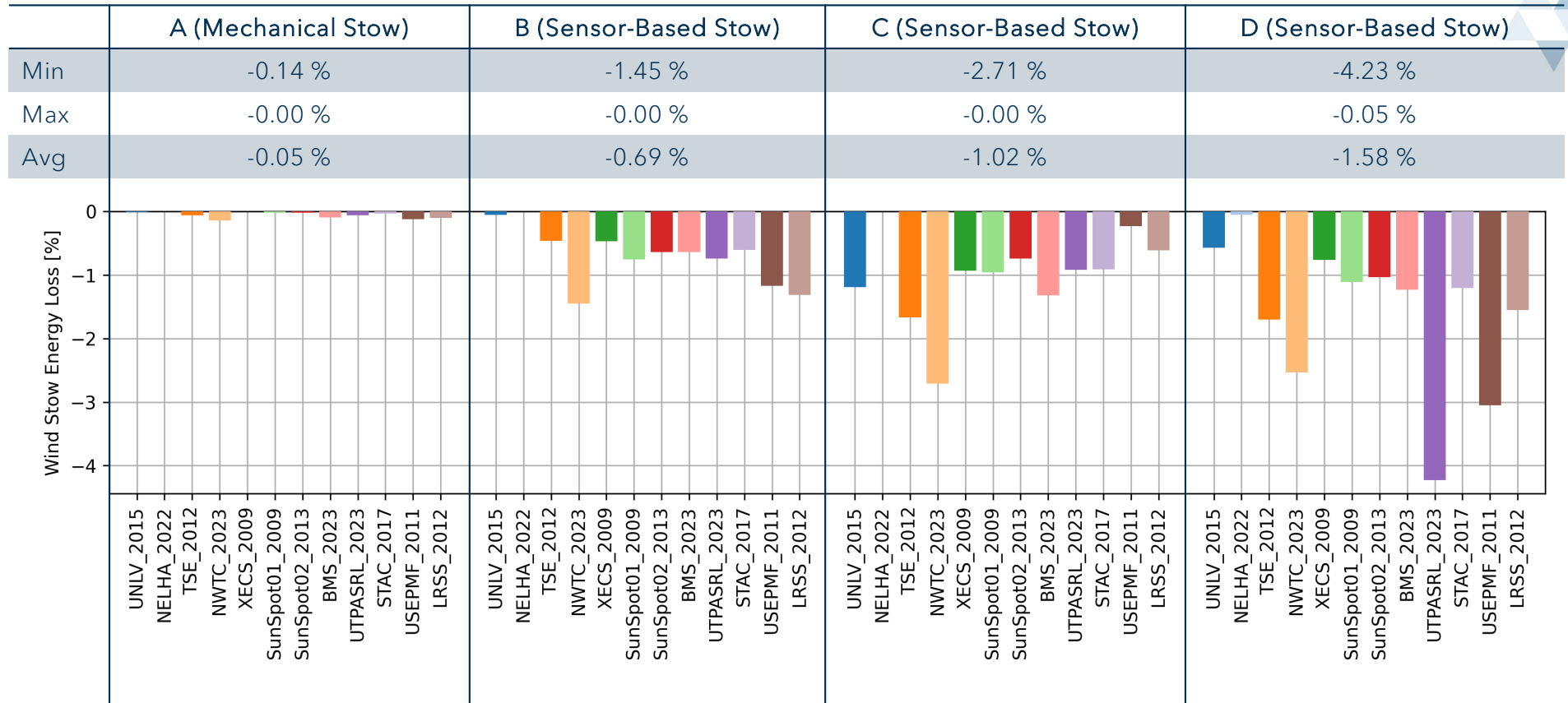
Calculate aggregate stow power for tiered cases using weighted average

▶ *Mechanical Stow* ex:

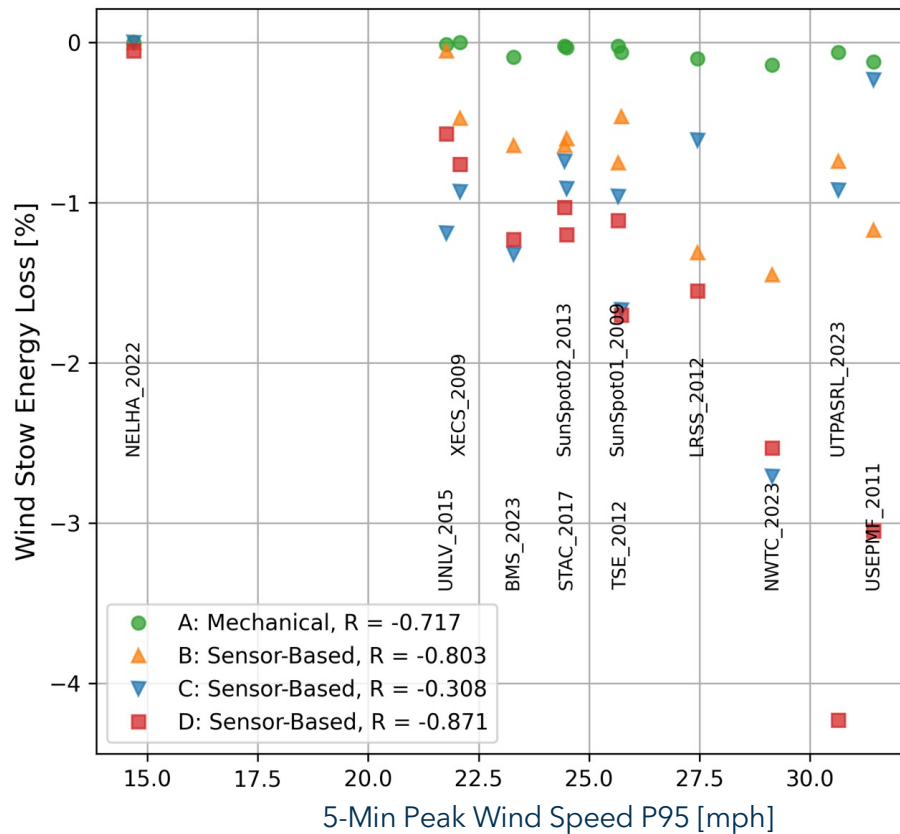
$$P_{stow,agg} = W_{int}P_{int} + W_{ext}P_{ext} + W_{base}P_{base}$$

$$W_{int}, W_{ext}, W_{base} = 0.164, 0.018, 0.818$$

Results

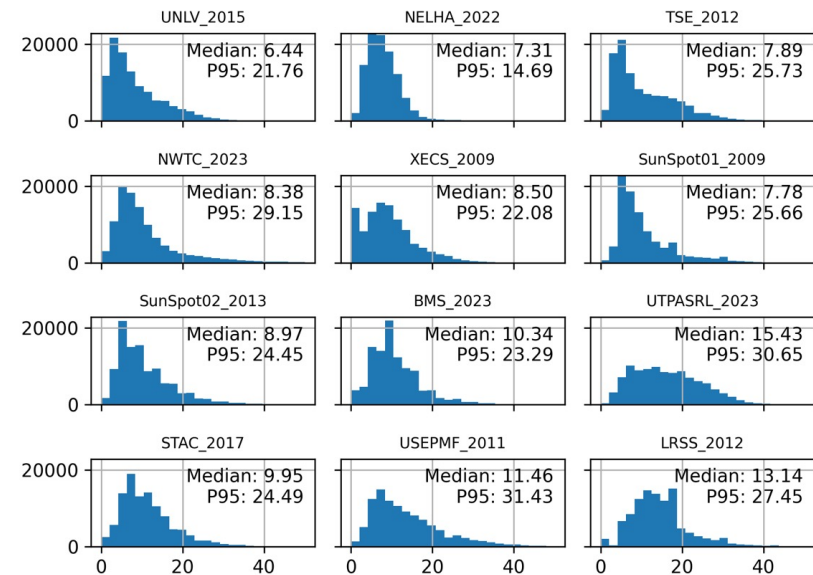


Correlation with Wind Speed



- As expected, wind stow energy loss is correlated with how windy a site is, except for Case C.
- Case C has the most sophisticated strategy of using the normal component of the wind vector.

5-Min Peak Wind Speed (3s Sampling) @ 10m Height [mph]





Conclusions and Future Work

- Reviewed wind stow modeling methodology:
 - » Wind data pre-processing
 - » Stow analysis (tracker angle calculation)
 - » Energy modeling
- Results
 - » Mechanical stow generally gives smaller wind stow energy loss (0.00% to -0.14%) than sensor-based stow (0.00% to -4.23%).
 - » Wind stow energy loss is correlated with wind speed; sites with higher winds tend to show bigger wind stow losses.
 - » Energy losses from different sensor-based strategies can be significantly different.
- Future Work
 - » Build tool to quickly estimate mechanical stow losses based on site metrics
 - » Compare to methods using hourly data + DURST curves
 - » Further validation of mechanical stow assumptions at customer sites

Thank you

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