ARIZONA STATE UNIVERSITY
PHOTOVOLTAIC RELIABILITY LABORATORY

Finite Element Thermal Analysis Supporting a Transient Moving-Average Module Temperature Prediction Model

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Presented by Matthew Prilliman
Sponsors:
Joshua S. Stein
Daniel Riley
Dr. Govindasamy Tamizhmani

Sandia National Laboratories

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Agenda

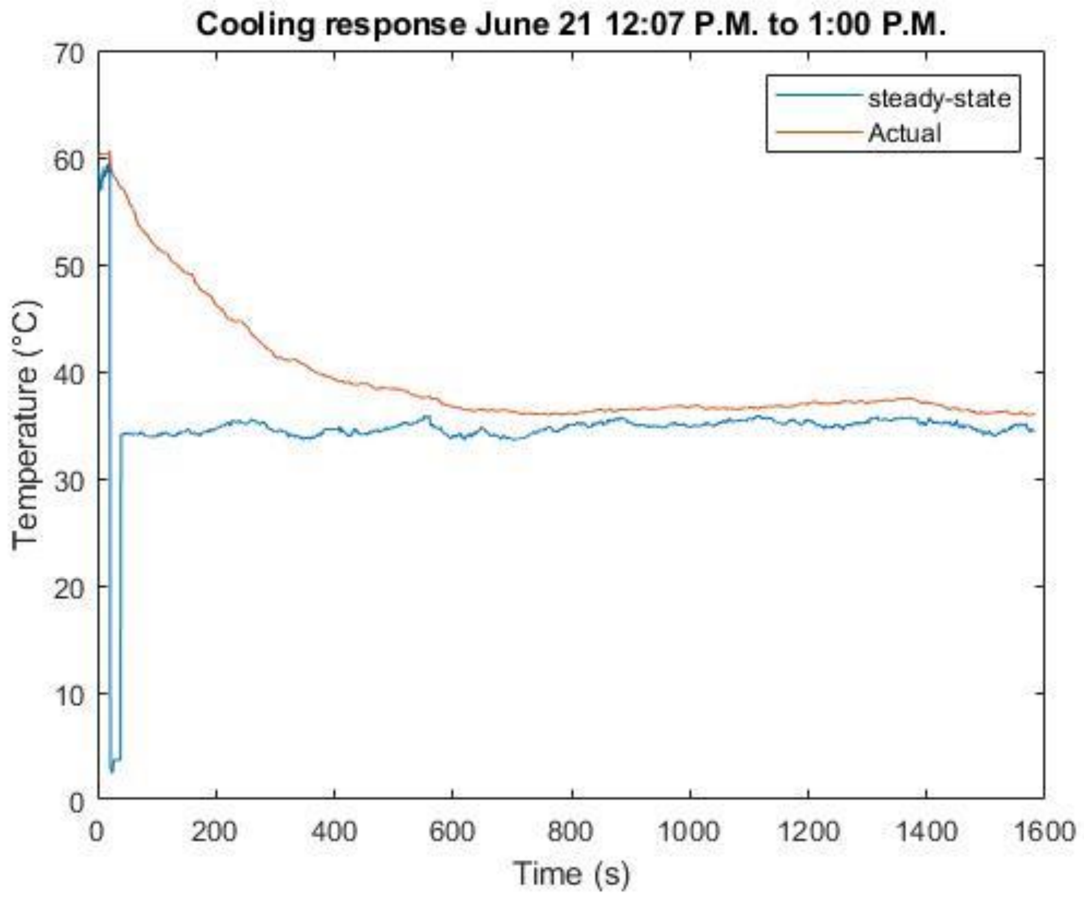
- Motivation
- Modeling Approach
- Simulation Results
- Early-stage moving-average model
- Next Steps

Motivation

- Shading tests show exponential thermal behavior for modules introduced to large step decrease in irradiance
- Current steady-state models cannot account for large changes in irradiance at fine time scales (< 60s)

$$T_m = E \cdot \left\{ e^{a+b \cdot WS} \right\} + T_a$$

Source: Sandia Array Performance Model

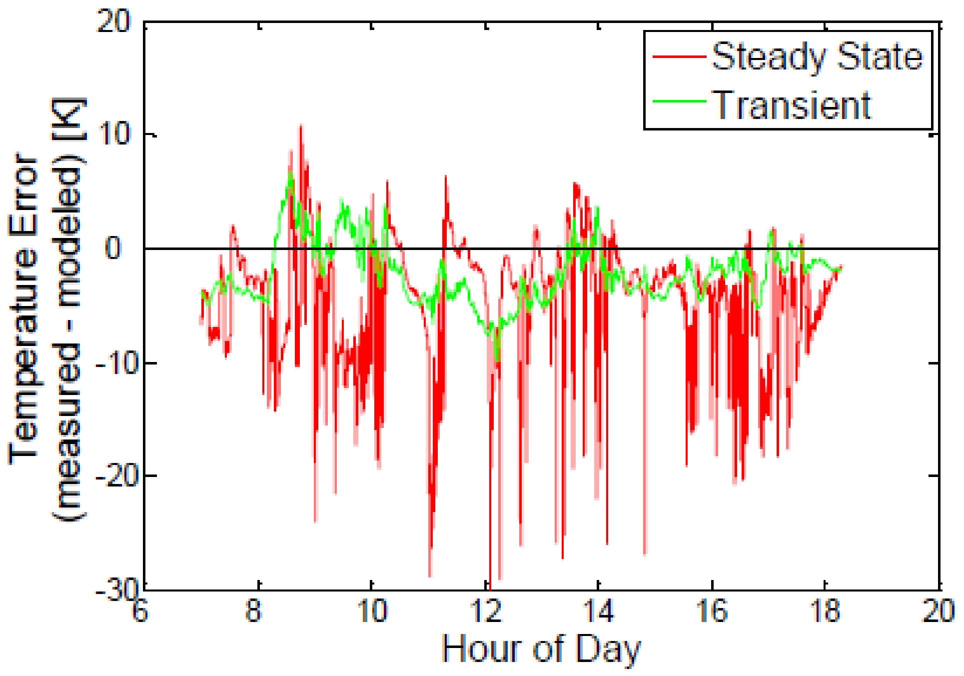


Motivation

- Previous transient models: physical heat transfer models
- Input parameters are not available and are challenging to estimate (requires empirical optimization).
- New model should be based on available parameters:
  - Parameters available on spec sheet (e.g., module mass and area)

$$C_{module}\frac{dT_{module}}{dt} = q_{lw} + q_{sw} + q_{conv} - P_{out}$$

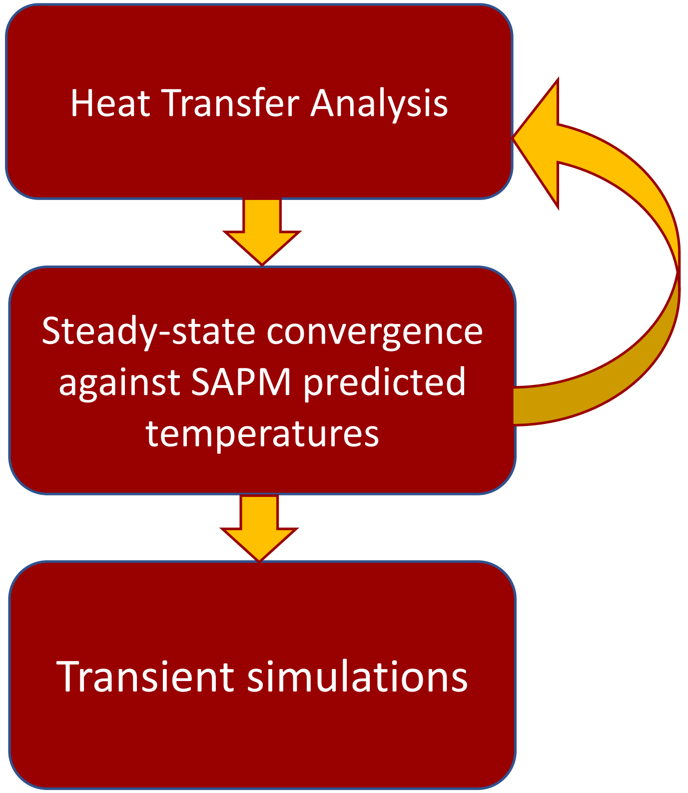
Source: Hayes, Ngan, "A time dependent model for CdTe PV module temperature in utility scale systems"



Source: Stein, Luketa-Hanlin, "Improvement and validation of a transient model to predict photovoltaic module temperature

FEA Validation

1. Heat transfer analysis of convection and radiation on module front and rear surfaces
2. Steady-state convergence tests against Sandia Array Performance Model predictions
3. Confidence to continue to transient simulations



FEA Approach-Steady-state and Transient

Convection

- Uniform turbulent wind convection across module front surface

$$Nu = .0308\,\mathrm{Re}^{\frac{4}{5}}\,Pr^{\frac{1}{3}}$$

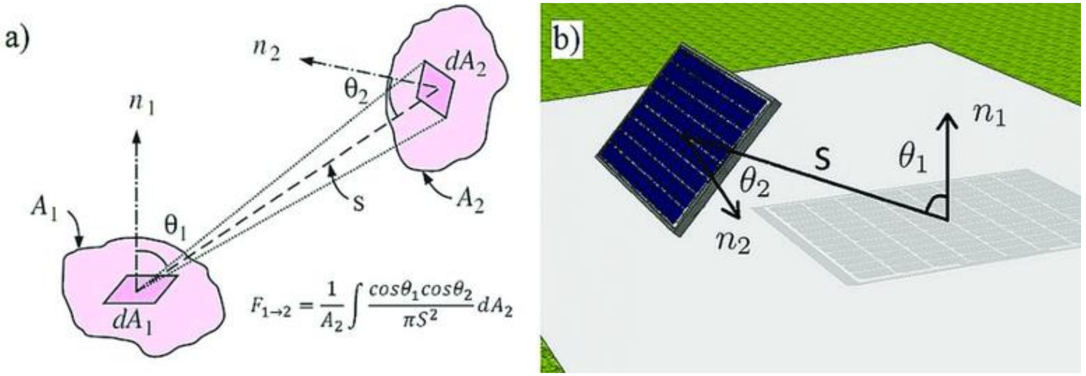
$$h = \frac{Nuk}{L}$$

- Natural air convection on module rear surface

$$Nu = \frac{.17\left(\left(9.8\cos(90-\theta)\cdot(1/T_f)\right)IL^4\right)}{(kv^2Pr^2)}\cdot k\cdot L$$

Radiation

- Solidworks calculates the view factors



Irradiance

- Adjusted for efficiency of module

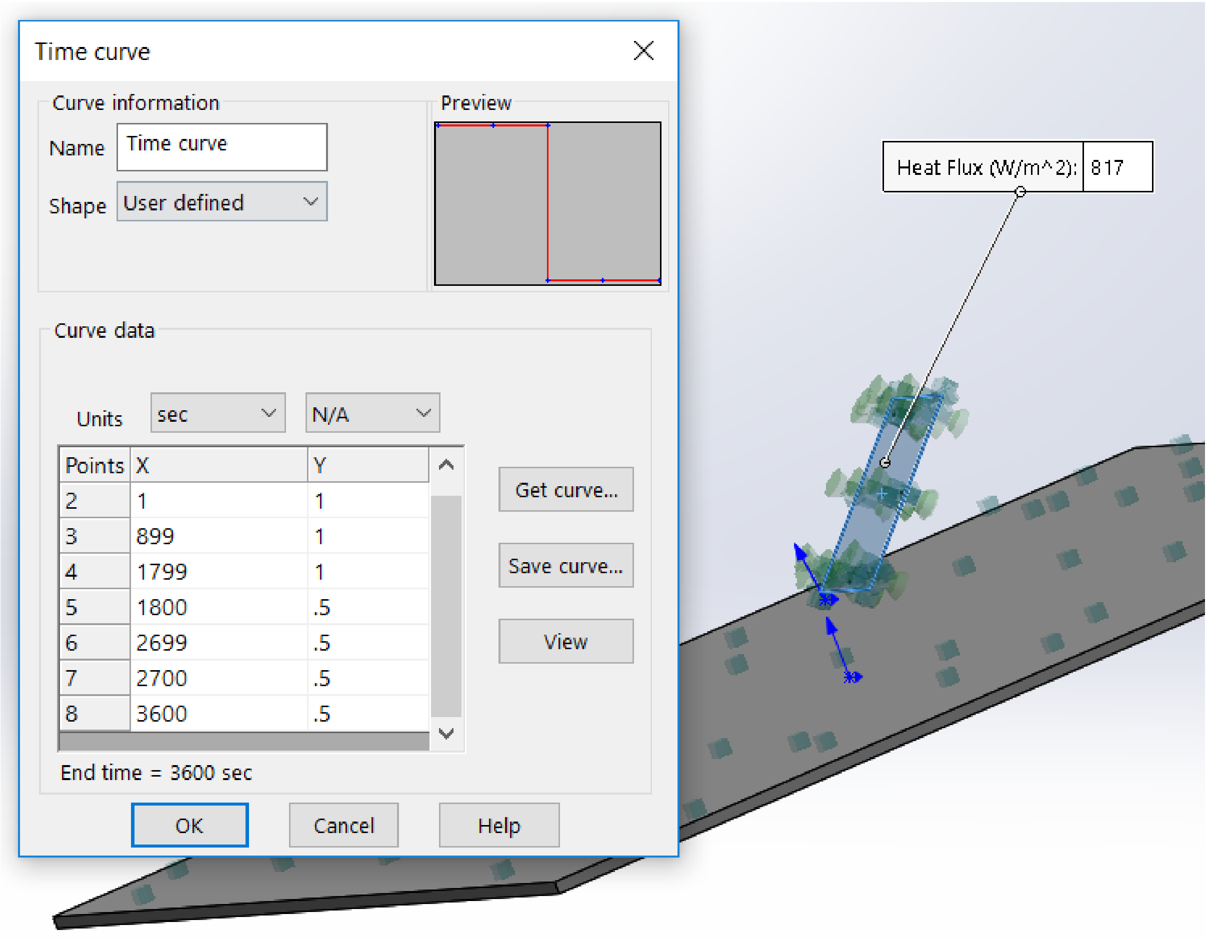
Source: Cengel and Ghajar, Heat and Mass Transfer

Validation Results

(-6.7°C) Ambient																
Wind speed (m/s)	**0.1**	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**6**	**7**	**8**	**9**	**10**
Steady-state model (°C)	21.5	20.7	19.7	18.7	17.8	16.9	16.0	15.2	14.4	13.6	12.8	11.4	10.1	8.9	7.8	6.7
FEA Simulated Temperature (°C)	26.8	24.4	23.9	23.1	22.6	20.1	18.3	18.5	17.1	15.9	14.9	13.1	11.6	10.2	9.2	8.2
FEA - Steady (°C)	**5.3**	**3.7**	**4.2**	**4.4**	**4.8**	**3.2**	**2.3**	**3.3**	**2.7**	**2.3**	**2.1**	**1.7**	**1.5**	**1.3**	**1.4**	**1.5**
15.6°C Ambient																
Wind speed (m/s)	**0.1**	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**6**	**7**	**8**	**9**	**10**
Steady-state model (°C)	43.8	43.0	42.0	41.0	40.1	39.2	38.3	37.5	36.7	35.9	35.1	33.7	32.4	31.2	30.1	29.0
FEA Simulated Temperature (°C)	45.0	42.2	40.7	41.5	41.1	39.5	38.2	36.4	36.0	35.0	34.1	32.6	31.4	30.4	29.4	28.7
FEA - Steady (°C)	**1.2**	**-0.8**	**-1.3**	**0.5**	**1.0**	**0.3**	**-0.2**	**-1.1**	**-0.7**	**-0.9**	**-1.1**	**-1.1**	**-1.0**	**-0.8**	**-0.7**	**-0.3**
32.2°C Ambient																
Wind speed (m/s)	**0.1**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**
Steady-state model (°C)	60.4	59.6	58.6	57.6	56.7	55.8	54.9	54.1	53.3	52.5	51.7	50.3	49.0	47.8	46.7	45.6
FEA Simulated Temperature (°C)	58.8	58.3	57.9	57.5	57.2	55.5	54.3	53.2	52.2	51.3	50.6	49.3	48.1	47.1	46.2	45.5
FEA - Steady (°C)	**-1.6**	**-1.3**	**-0.7**	**-0.1**	**0.5**	**-0.3**	**-0.6**	**-0.9**	**-1.1**	**-1.2**	**-1.1**	**-1.0**	**-0.9**	**-0.7**	**-0.5**	**-0.1**

Transient FEA Approach

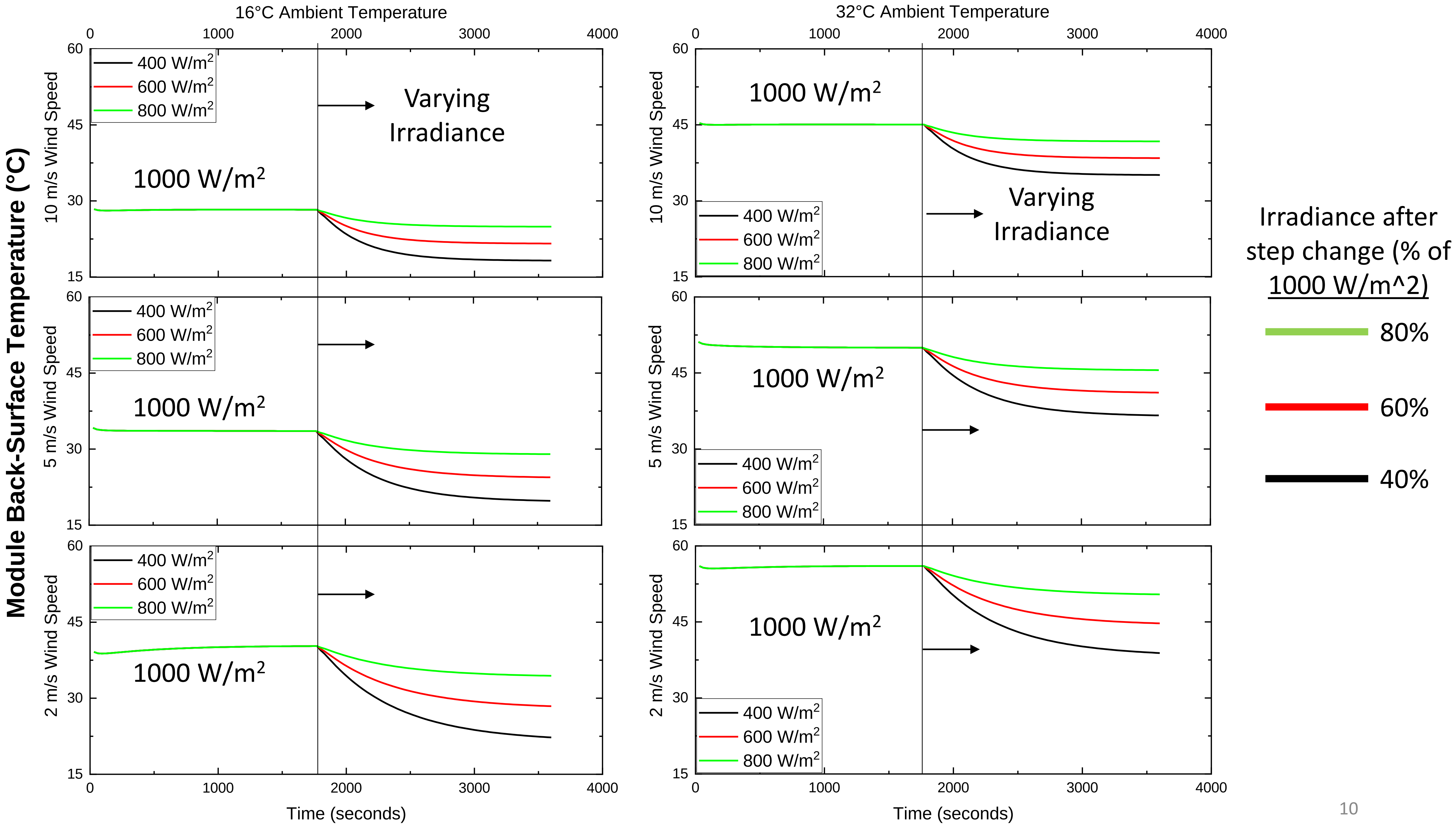
- Transient time series simulations: 1 hour simulation time, 30 second intervals
- Constant wind speed and ambient temperature throughout
- Begin with irradiance of 1000 W/m^2, introduce step decrease after module temp stabilizes (t = 1800s)
  - 20,40,60,80% decreases



Transient FEA Approach

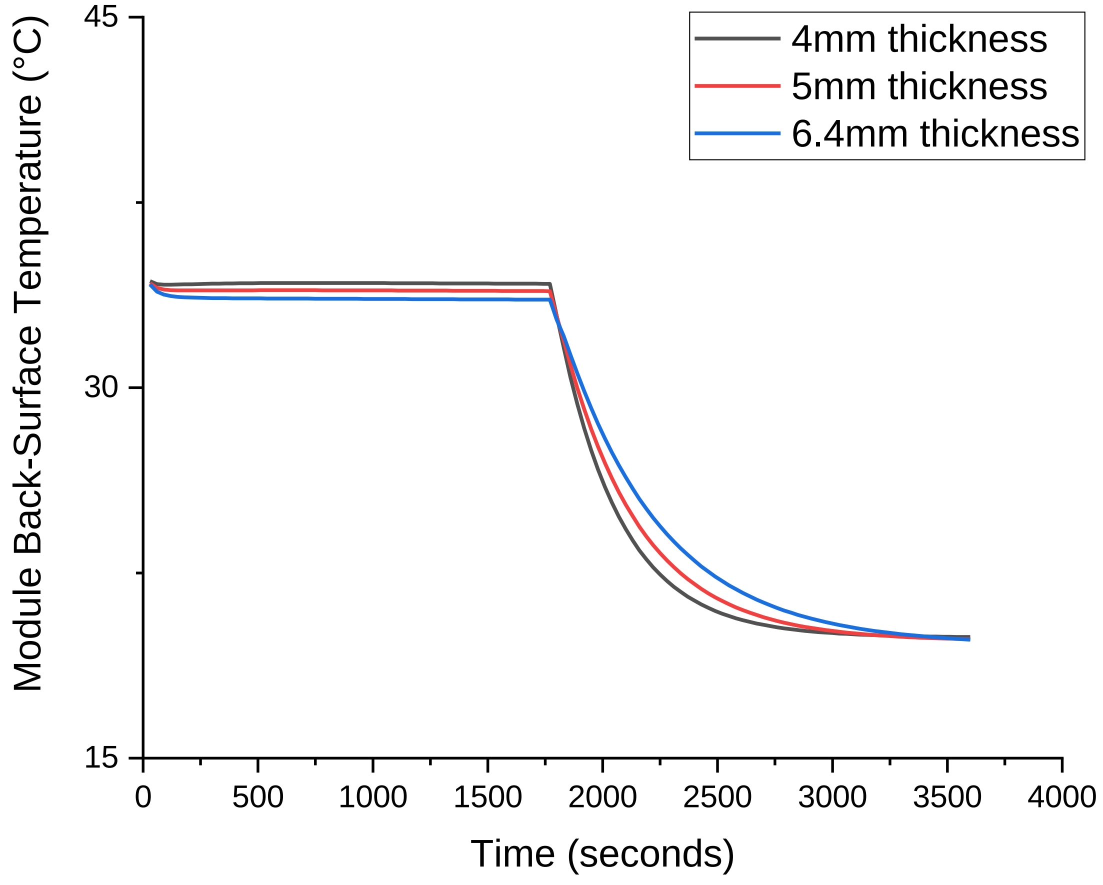
- **Ambient temperatures:**
  -6.7°C, 15.6°C, 32.2°C
- **Wind speeds:**
  2 m/s, 5 m/s, 10 m/s
- **Irradiance step sizes:**
  20%, 40%, 60%, 80%
- 3 ambient temps
  * 3 wind speeds
  * 4 irradiance step sizes
  = 36 simulations

Point	X	2ws16C	5ws16C	10ws16C	2ws32C	5ws32C	10ws32C	2ws-7C	5ws-7C	10ws-7C
1	30	39.127	34.175	28.371	56.029	51.109	45.339	17.324	12.322	6.4667
2	60	38.861	33.887	28.174	55.7	50.782	45.124	17.187	12.126	6.3248
3	90	38.806	33.766	28.11	55.585	50.625	45.045	17.26	12.091	6.3062
4	120	38.83	33.709	28.095	55.552	50.535	45.016	17.405	12.114	6.3307
5	150	38.883	33.678	28.098	55.551	50.475	45.008	17.574	12.157	6.3693
6	180	38.947	33.66	28.109	55.564	50.43	45.008	17.748	12.208	6.4117
7	210	39.014	33.648	28.122	55.583	50.392	45.012	17.921	12.26	6.4537
8	240	39.082	33.64	28.137	55.605	50.361	45.017	18.088	12.312	6.4939
9	270	39.148	33.634	28.151	55.629	50.333	45.023	18.249	12.361	6.5316
10	300	39.212	33.629	28.164	55.652	50.308	45.029	18.404	12.409	6.5665
11	330	39.274	33.626	28.176	55.675	50.286	45.035	18.551	12.454	6.5987
12	360	39.333	33.623	28.188	55.698	50.265	45.041	18.692	12.496	6.6281
13	390	39.389	33.62	28.198	55.72	50.247	45.046	18.826	12.536	6.6551
14	420	39.443	33.618	28.208	55.741	50.23	45.051	18.954	12.573	6.6798
15	450	39.494	33.616	28.217	55.761	50.214	45.055	19.075	12.608	6.7022
16	480	39.543	33.614	28.225	55.78	50.199	45.059	19.191	12.64	6.7226
17	510	39.589	33.613	28.232	55.798	50.186	45.062	19.301	12.671	6.7412
18	540	39.632	33.611	28.238	55.815	50.173	45.065	19.405	12.699	6.7581
19	570	39.673	33.61	28.244	55.831	50.162	45.068	19.504	12.725	6.7735


16°C Ambient Temperature
32°C Ambient Temperature
Module Back-Surface Temperature (°C)
10 m/s Wind Speed
5 m/s Wind Speed
2 m/s Wind Speed
400 W/m2
600 W/m2
800 W/m2
1000 W/m2
Varying Irradiance
Time (seconds)
Irradiance after step change (% of 1000 W/m^2)
80%
60%
40%

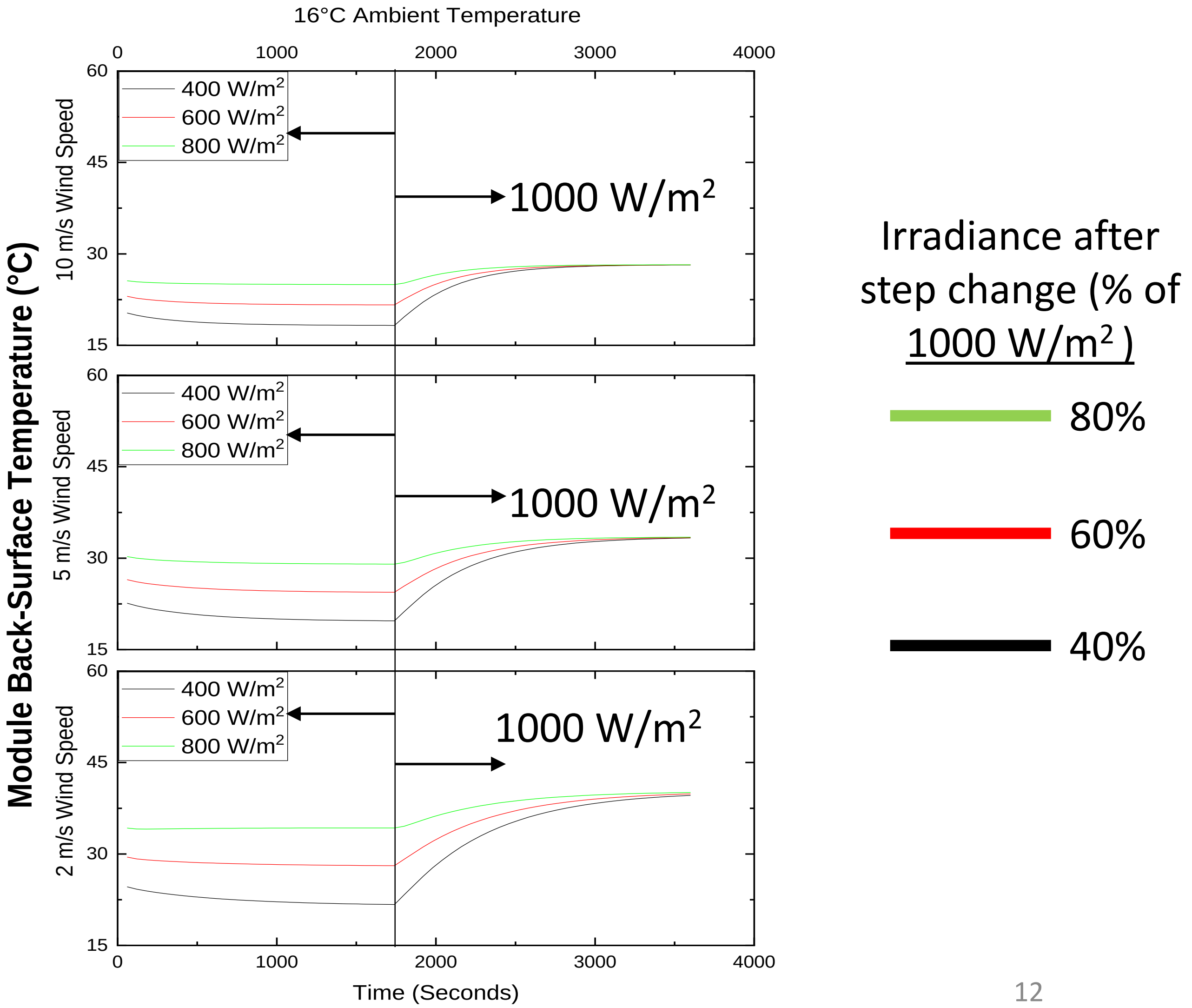
Transient FEA Results

- Repeated decreasing step changes at different module thicknesses
- Higher thickness = higher thermal mass
  - Slower temperature drop



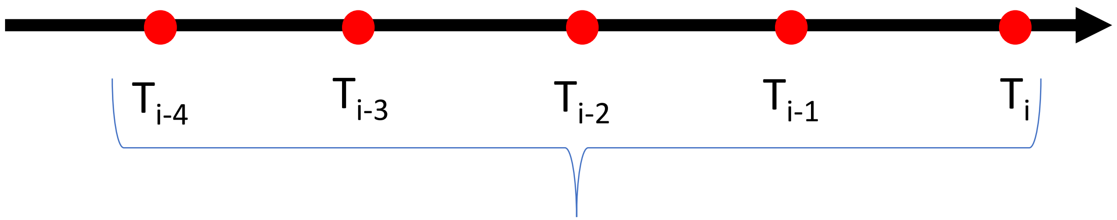
Transient FEA Results

- Repeated for increasing irradiance step changes
- Began at low irradiance, step change to 1000 W/m^2 irradiance
- To determine model changes for temperature increase rather than decrease



Moving-average model

- The Sandia module temperature model predicts the steady-state temp.
- A weighted moving average of these model estimates is proposed as a simple transient model.
- Models developed from FEA simulations are used to define:
  - Averaging window size
  - Weights for each point (a,b,c,d,…)

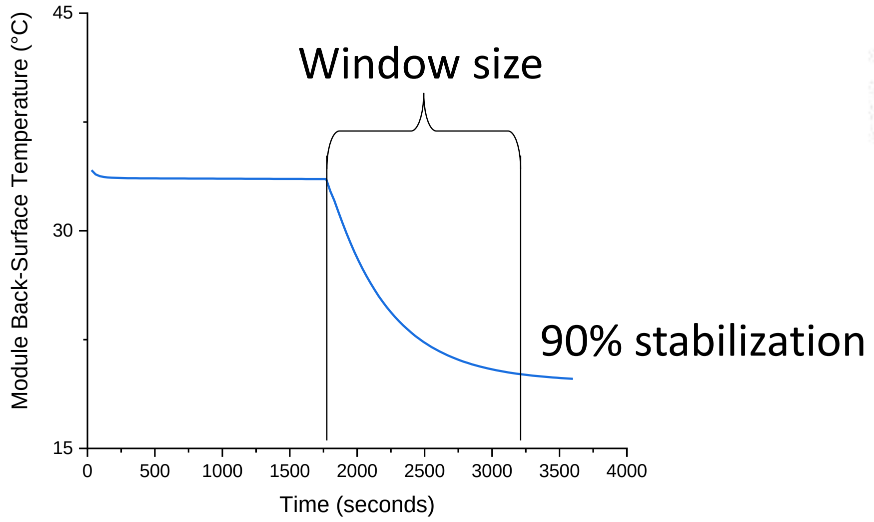


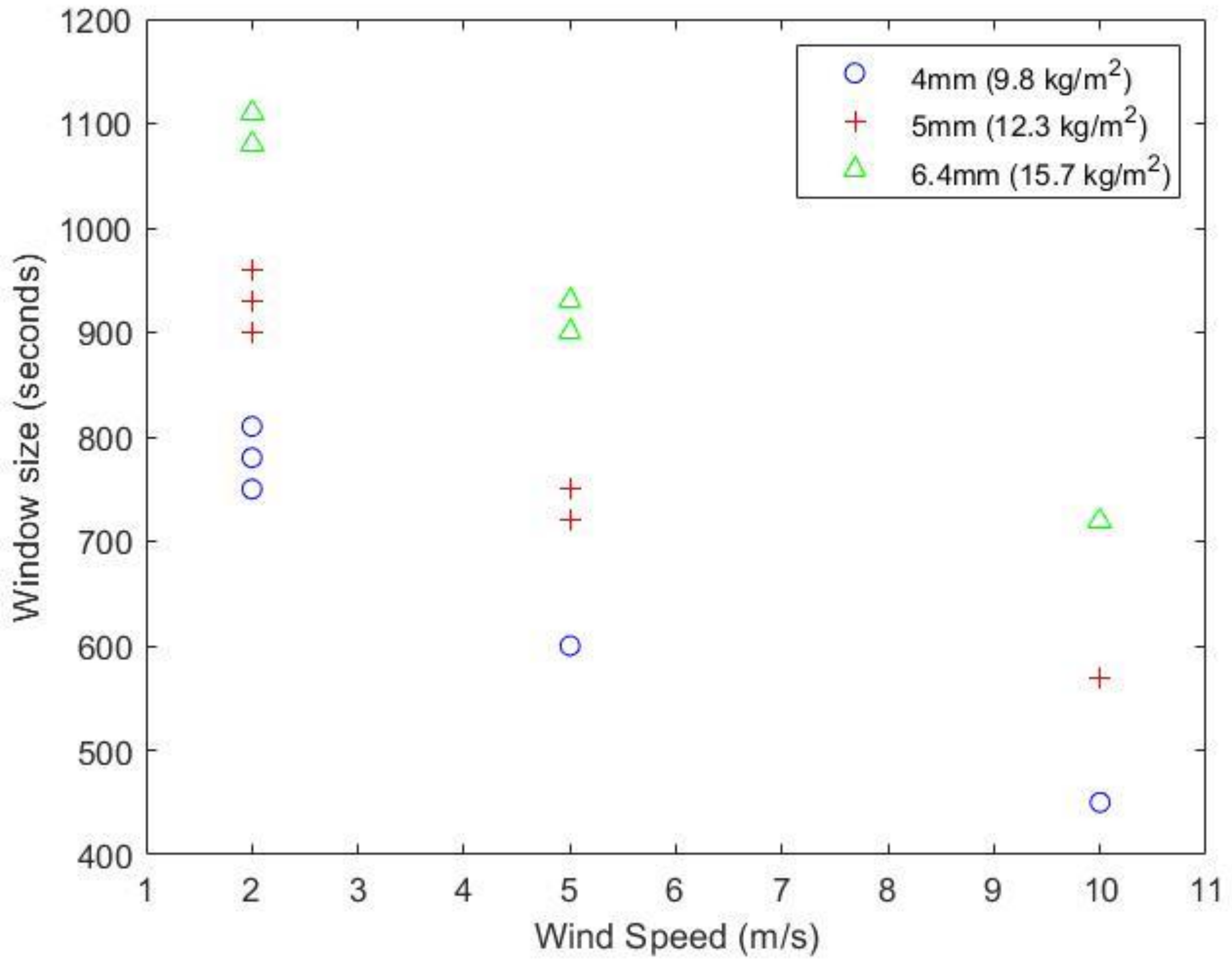
Window Size = fcn(Wind Speed, Weight/Area)
Wind Speed ↑ Window Size ↓
Weight/Area ↑ Window Size ↑

$$T_i = \frac{aT_{i-1} + bT_{i-2} + cT_{i-3} + dT_{i-4}}{a+b+c+d}$$

Moving-Average Window

- Window size: Time needed to reach 90% stabilization
- Varies with wind speed and thermal mass (not irradiance or ambient temperature)



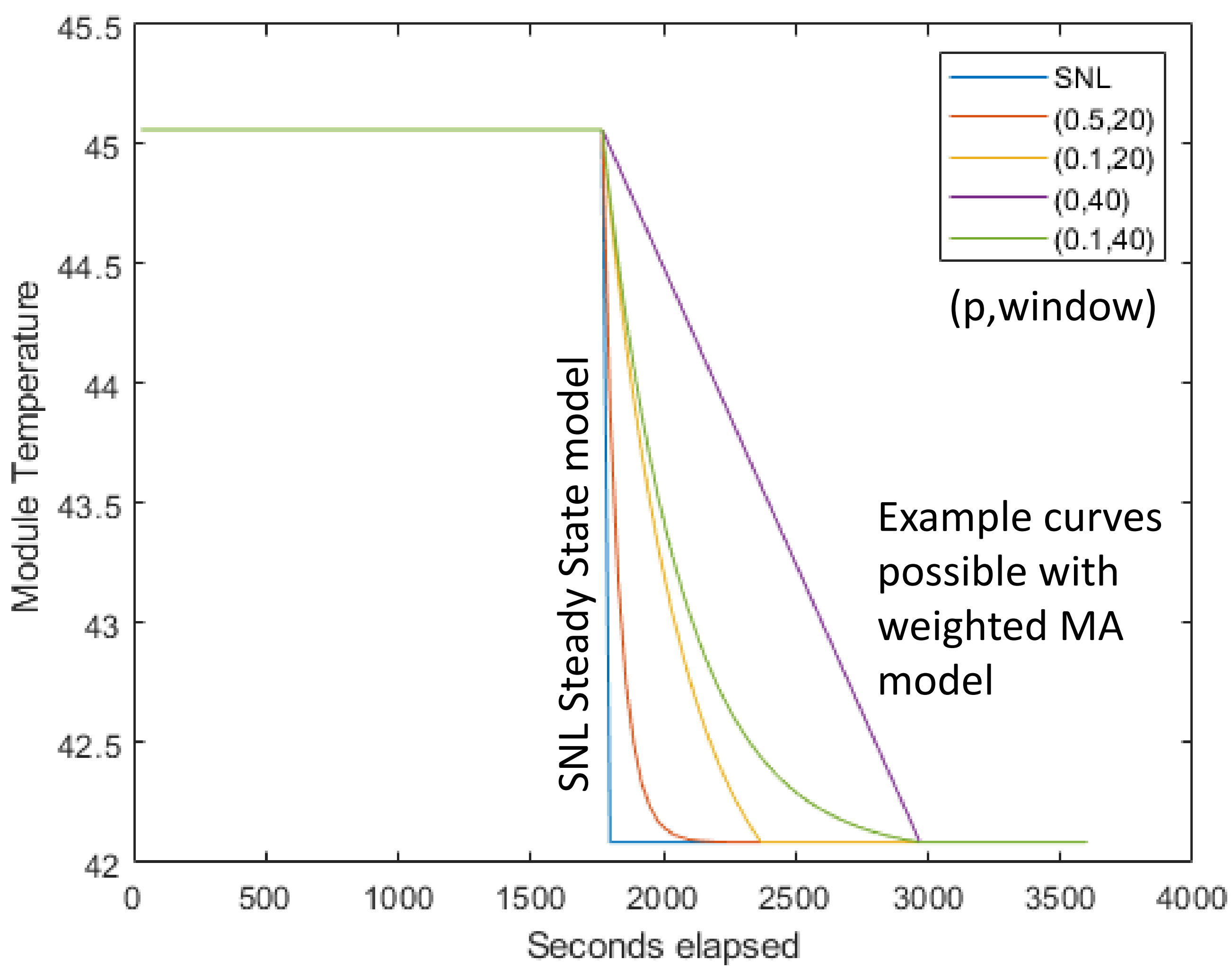


Moving-average Model

- Power function designed to make weighted moving-average of SAPM model temperatures align with FEA curves

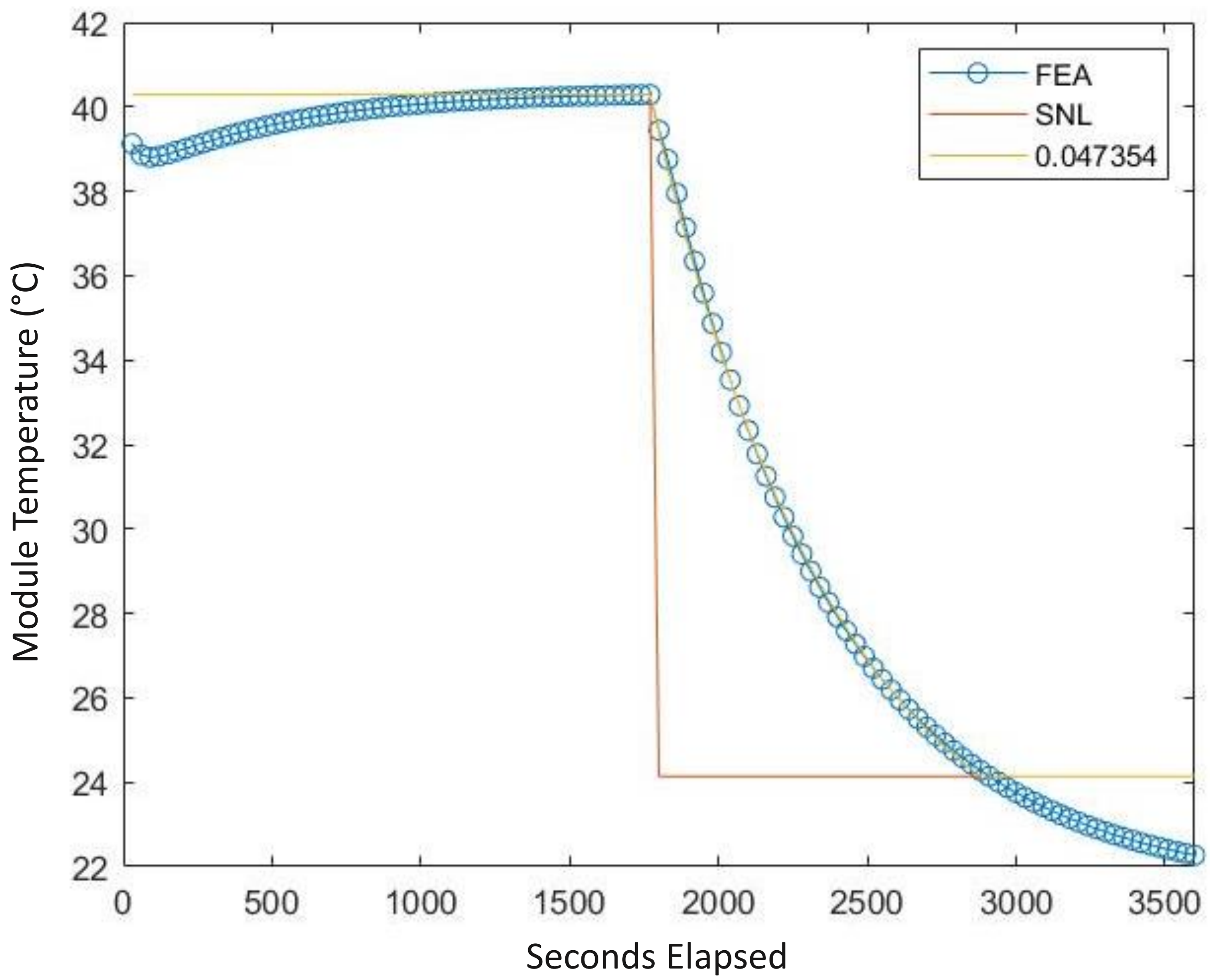
$$T_{MA} = \frac{\sum_{i=1}^{Window} \frac{1}{e^{ip}} T_{SAPM}}{\sum_{i=1}^{Window} \frac{1}{e^{ip}}}$$

- p : optimized for minimum $\sum\sqrt{(T_{MA} - T_{FEA})^2}$



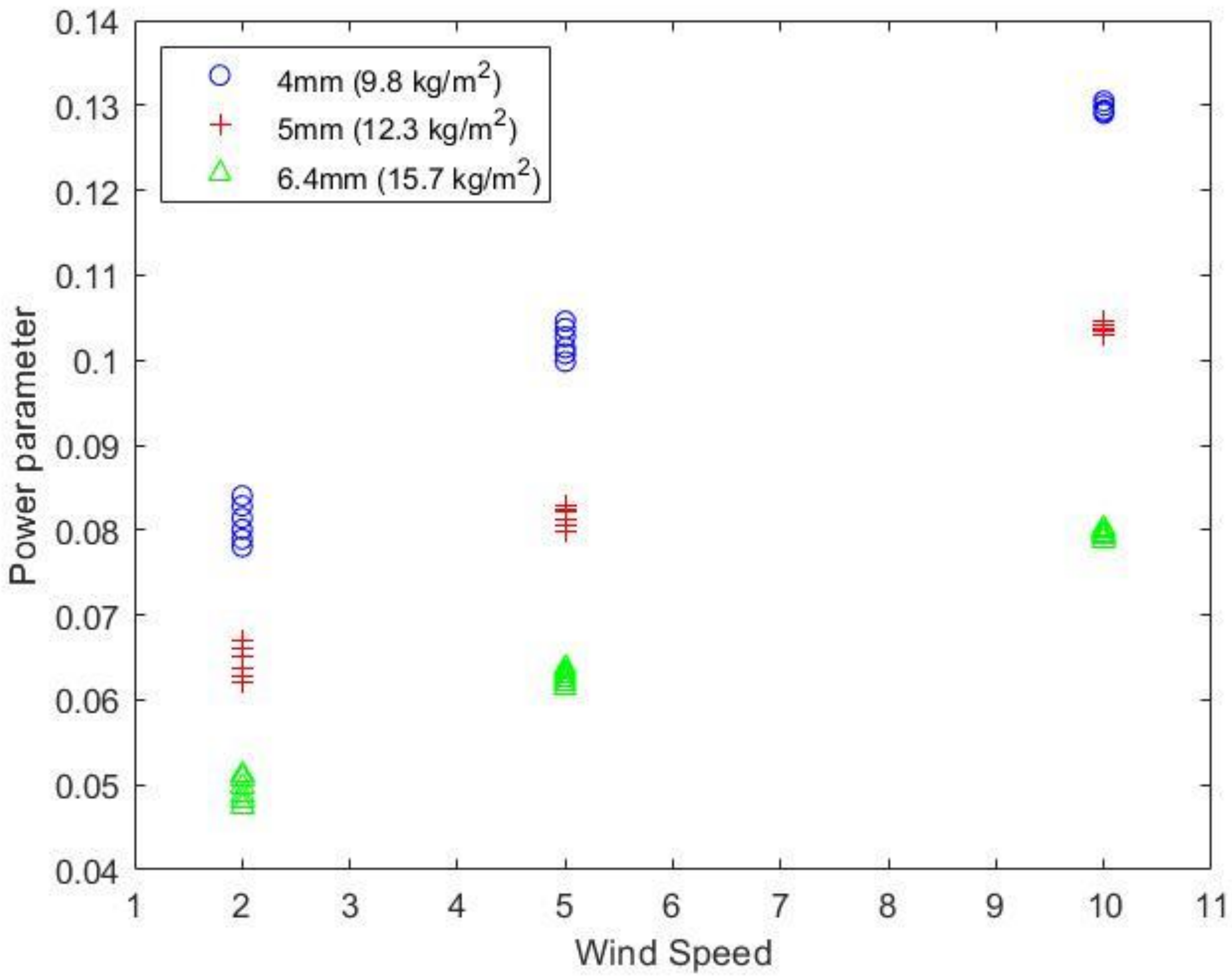
Fitting Model to FEA Results

Model is able to match the FEA results very closely!



Power Parameter

- Power parameter p increases for decreasing module weight
- Increases for increasing wind speed
- Temperature decreases quicker for modules with less thermal mass



Next Steps

- Optimize model for increasing irradiance FEA studies
- Evaluate against experimental data
- Correct for errors in empirical comparison
- Publish results

Thanks!

Questions?