Transient weighted moving average model of photovoltaic module back-surface temperature

PVPMC Webinar 2020

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Agenda

- Motivations
- FEA Modeling approach
- Moving-average Model Development
- Model Validation
- Conclusions

Motivation

- PV performance: typically 1-hour models
- Steady-state temperature models standard
- Steady-state models do not account for thermal mass of module
- Interest in finer data resolution:
    - Underestimation of low irradiance performance
    - Inverter clipping
    - Battery storage/dispatch modeling

Transient Models

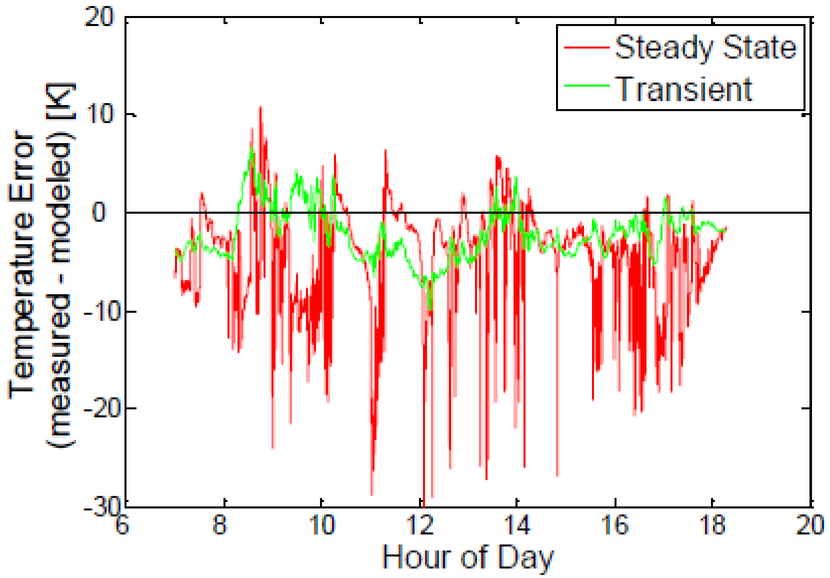
- Jones and Underwood:

Jones, Underwood, “A thermal model for photovoltaic systems”, *Solar Energy*, Vol. 70, 2001, p. 349-359.

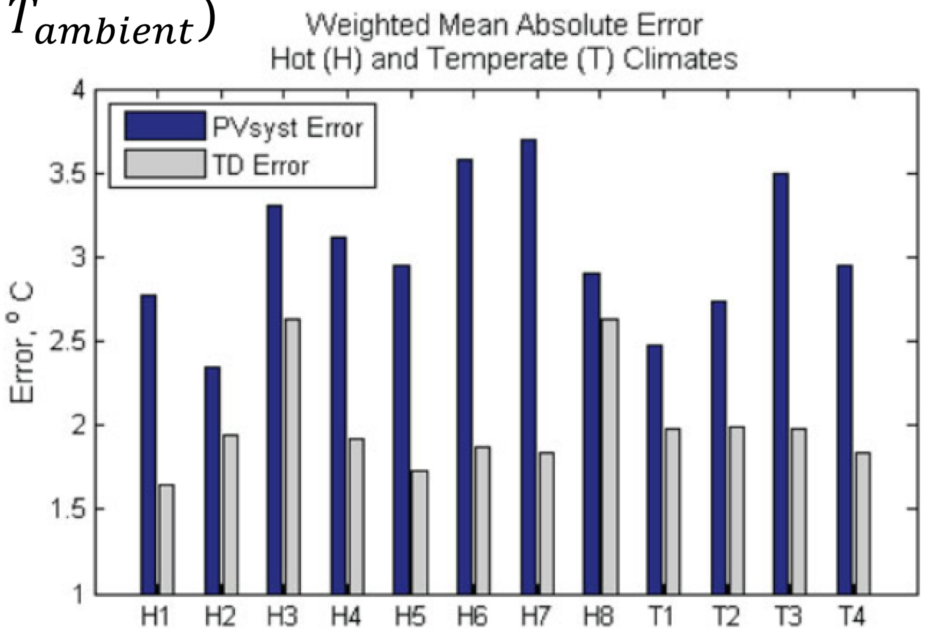
$$C_{module}\frac{dT_{module}}{dt} = \sigma * A * \left(\varepsilon_{sky}(T_{ambient} - \partial T)^4 - \varepsilon_{module}{T_{module}}^4\right)$$

$$\alpha * \Phi * A - \frac{C_{FF} * E * \ln(k_1 E)}{T_{module}} - \left(h_{c,forced} + h_{c,free}\right) * A * \left(T_{module} - T_{ambient}\right)$$

- Stein, Luketa-Hanlin: optimized for Hawaii
- Hayes, Ngan: Similar model for CdTe
- Steady-state models not accounting for thermal mass of module
- Need: Accuracy of transient models with few accessible input parameters



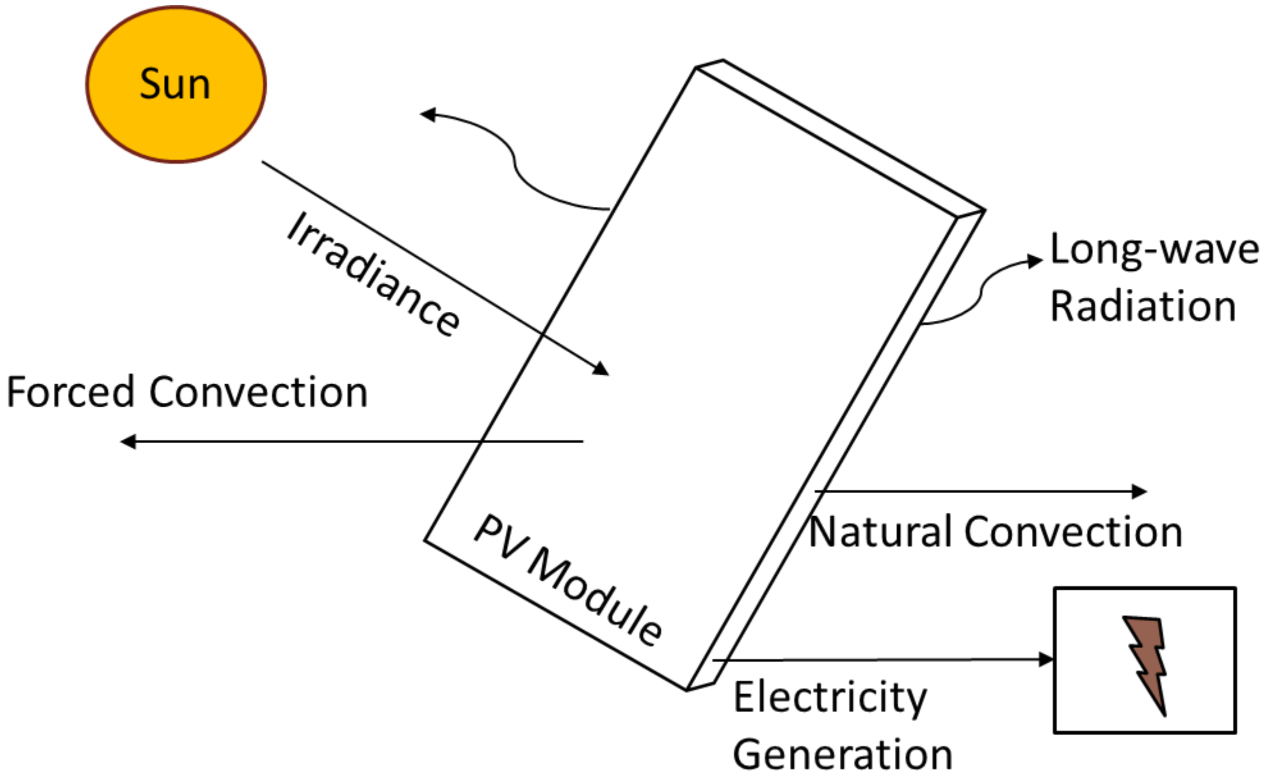
Stein, Luketa-Hanlin, *Improvement and Validation of a Transient Model to Predict Photovoltaic Module Temperature*.



Ngan, Hayes, “A Time-Dependent Model for CdTe PV Module Temperature in Utility-Scale Systems,” *IEEE Journal of Photovoltaics*, 2015, Vol. 5, p. 238-242.

FEA Simulations

- Finite Element Analysis (FEA) of simulated module
- Physical Heat transfer balance
  - Convection
  - Radiation
  - Irradiance
  - Conduction
  - Electricity Generation

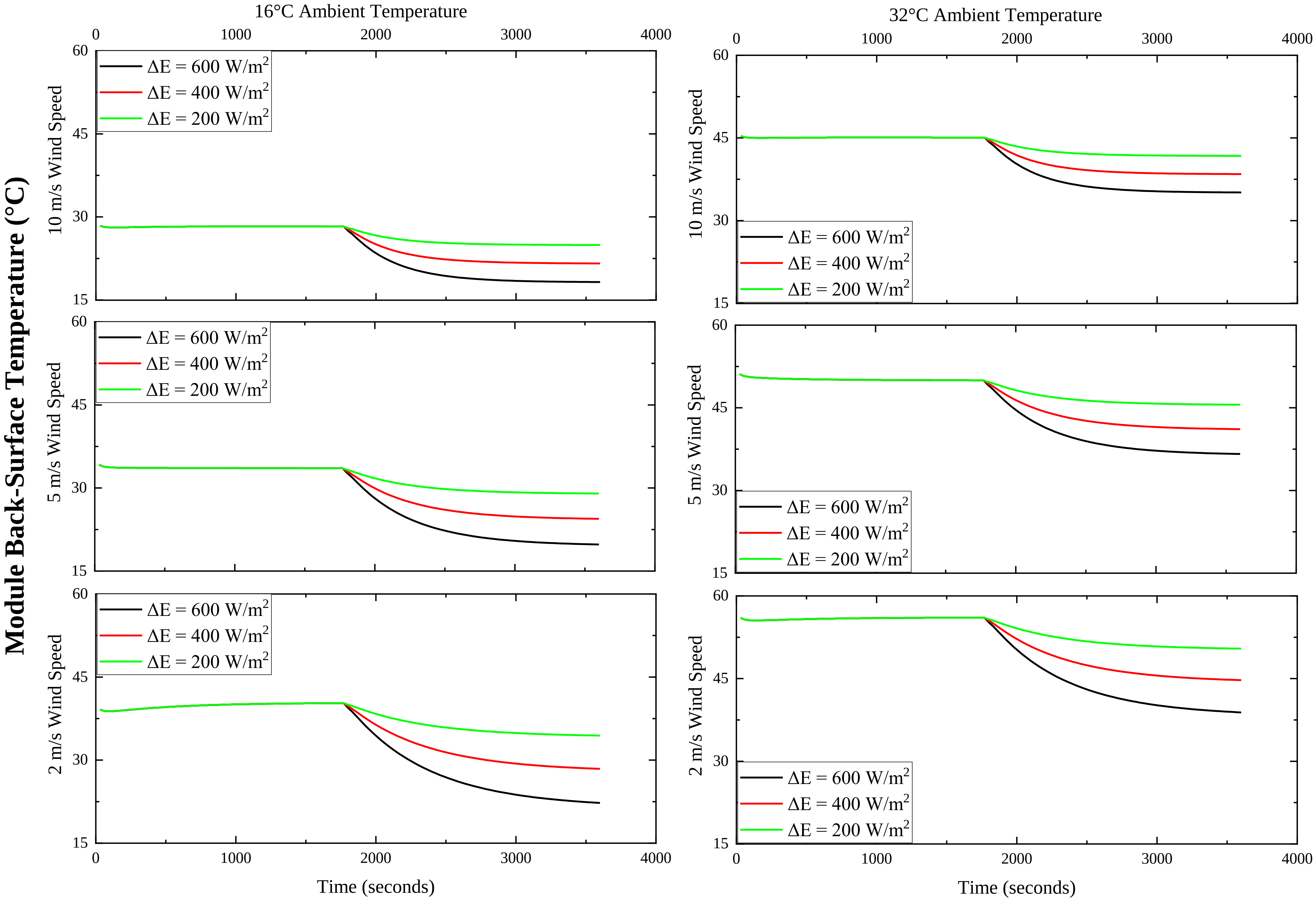


Steady-state FEA

- Within inherent inaccuracy of Sandia steady-state model
- Convergence tests
  - 3 ambient conditions
  - Range of wind speeds

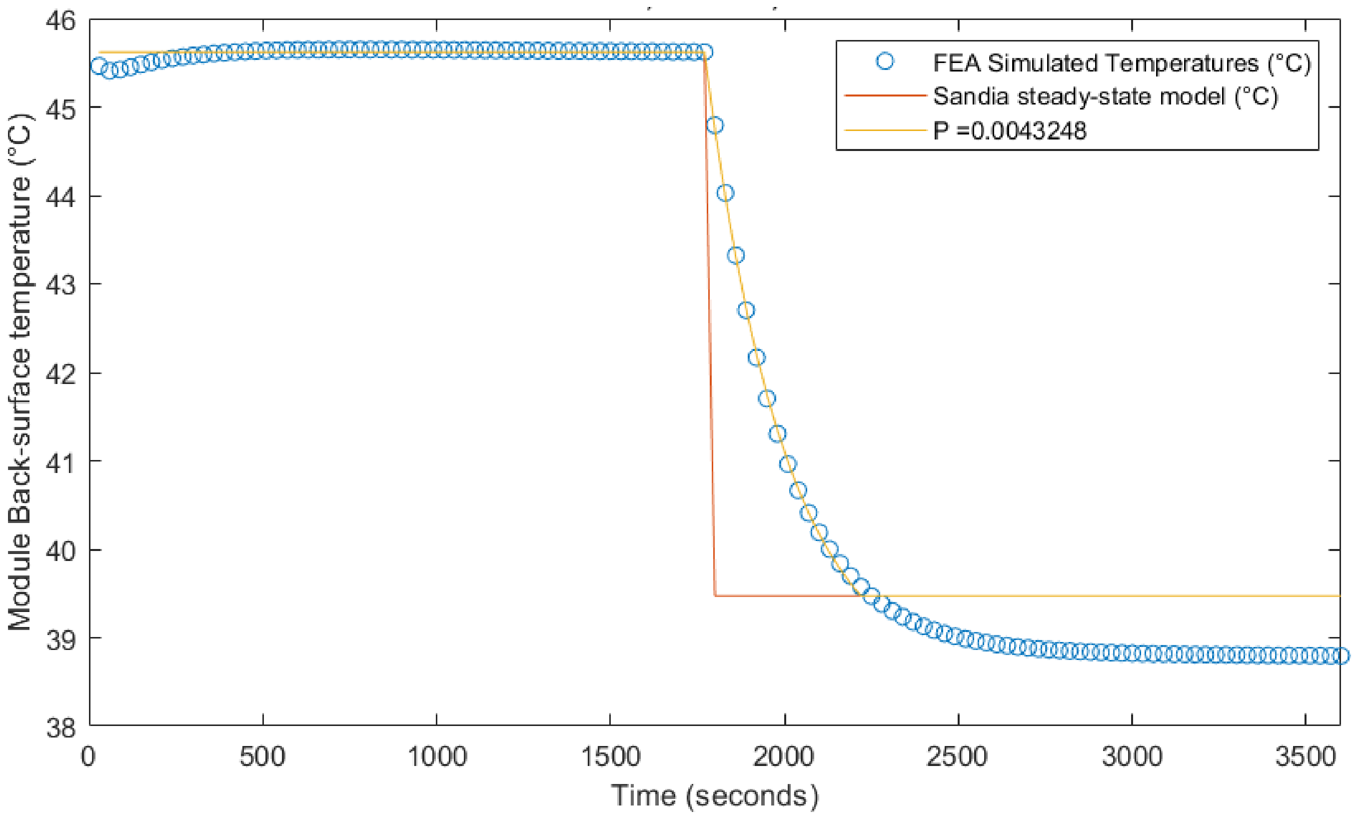
-6.7°C Ambient					15.6°C Ambient					32.2°C Ambient				
Wind speed (m/s)	1	3	5	10	Wind speed (m/s)	1	3	5	10	Wind speed (m/s)	1	3	5	10
Steady-state model (°C)	19.7	16.0	12.8	6.7	Steady-state model (°C)	42.0	38.3	35.1	29.0	Steady-state model (°C)	58.6	54.9	51.7	45.6
FEA Temperature (°C)	23.9	18.3	14.9	8.2	FEA Temperature (°C)	40.7	38.2	34.1	28.7	FEA Temperature (°C)	57.9	54.3	50.6	45.5
FEA - Steady (°C)	**4.2**	**2.3**	**2.1**	**1.5**	FEA - Steady (°C)	**-1.3**	**-0.2**	**-1.1**	**-0.3**	FEA - Steady (°C)	**-0.7**	**-0.6**	**-1.1**	**-0.1**

Transient FEA



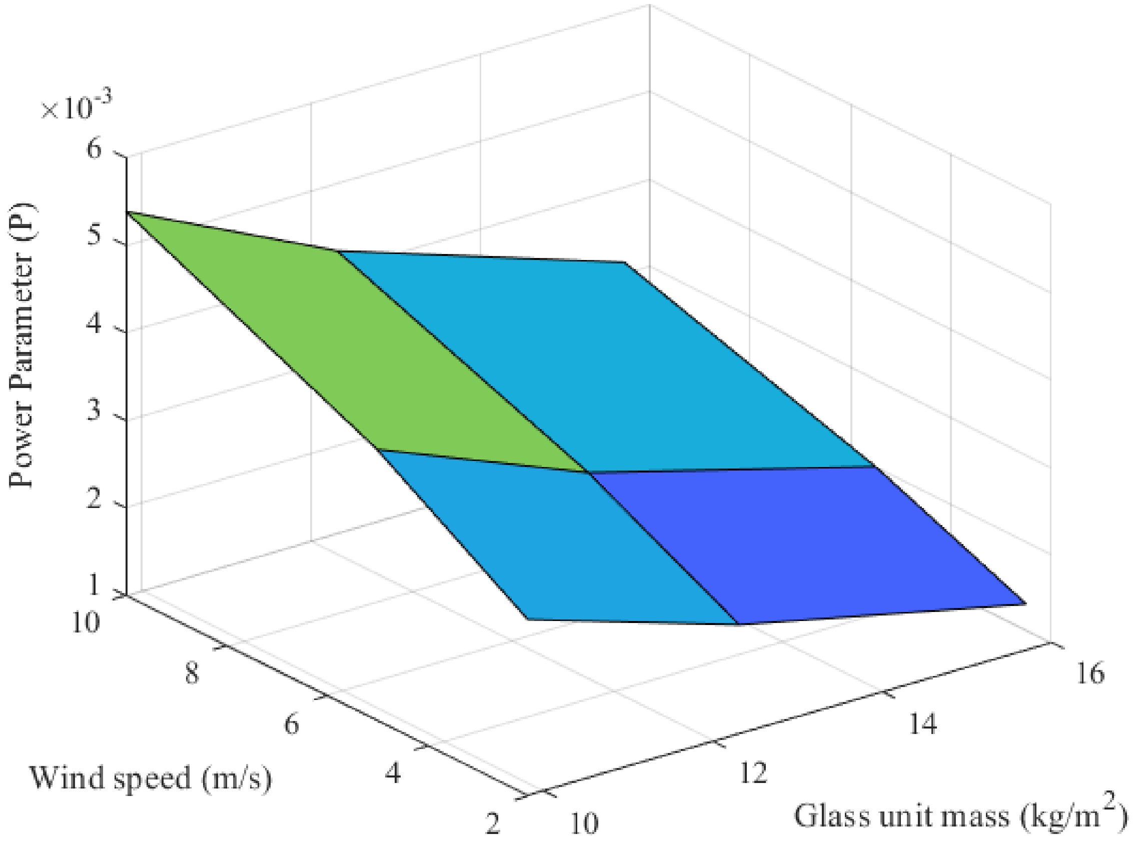
Model Development

- Take weighted average of steady-state predictions
- Optimize weighting parameter for best fit between SS weighted-average and FEA temperature curve
- Repeat for each FEA dataset, evaluate P as function of environmental variables



Model Development

- Exponential power parameters equally dependent on wind speed, unit mass
- Bilinear Interpolation



$$\begin{bmatrix} 1 & WS_1 & mu_1 & (WS_1 mu_1) \\ 1 & WS_1 & mu_2 & (WS_1 mu_2) \\ 1 & WS_2 & mu_1 & (WS_2 mu_1) \\ 1 & WS_2 & mu_2 & (WS_2 mu_2) \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} P_{11} \\ P_{12} \\ P_{21} \\ P_{22} \end{bmatrix}$$

$$P = a_0 + a_1 * WS + a_2 * m_u + a_3 * WS * m_u$$

Coefficient	Value
a0	0.0046
a1	0.00046
a2	-0.00023
a3	-1.6E-05

Model Equation

- Forward-facing model: describes time following the given index
- Takes moving-average of all times within 20 minutes prior to current index
- Matches ramp rate of actual module thermal behavior

$$T_{MA,i} = \frac{\sum_{i=2}^{t_i \leq 1200} \left(T_{SS,i} * e^{-P*t_i}\right)}{\sum_{i=2}^{t_i \leq 1200} \left(e^{-P*t_i}\right)}$$

Model Example

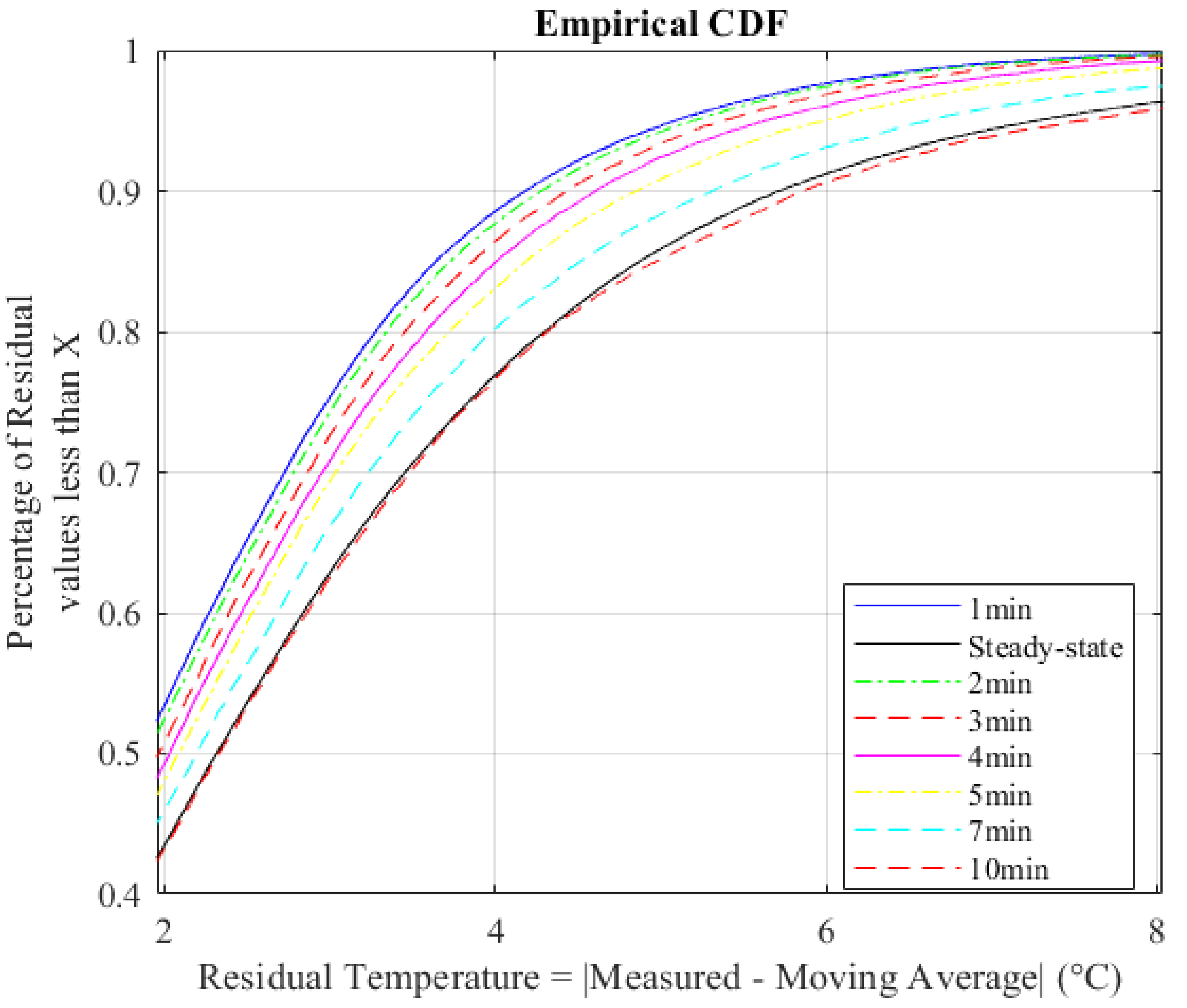
- Calculation for index 1
- Wind speed measured at height of 2 meters
- Unit mass from module spec sheet

Time index, *i*	**Seconds before t=0, t_i**	**Steady State Temp. $T_{SS,i}$ (°C)**	**2-meter Wind Speed (m/s)**	**P_i**	**$T_{MA,\,i}$ (°C)**
1	0	32.5	5.0	0.0032	22.5
2	120	22.5	N/A	N/A	N/A
3	240	26.2	N/A	N/A	N/A
4	480	28.7	N/A	N/A	N/A
5	840	19.0	N/A	N/A	N/A
6	960	18.2	N/A	N/A	N/A
7	1080	18.3	N/A	N/A	N/A
8	1200	19.0	N/A	N/A	N/A

$$T_{MA} = \frac{[22.5e^{-P*120}] + [26.2e^{-P*240}] + [28.7e^{-P*480}] + \cdots [19.0e^{-P*1200}]}{[e^{-P*120}] + [e^{-P*240}] + [e^{-P*480}] + \cdots [e^{-P*1200}]}$$

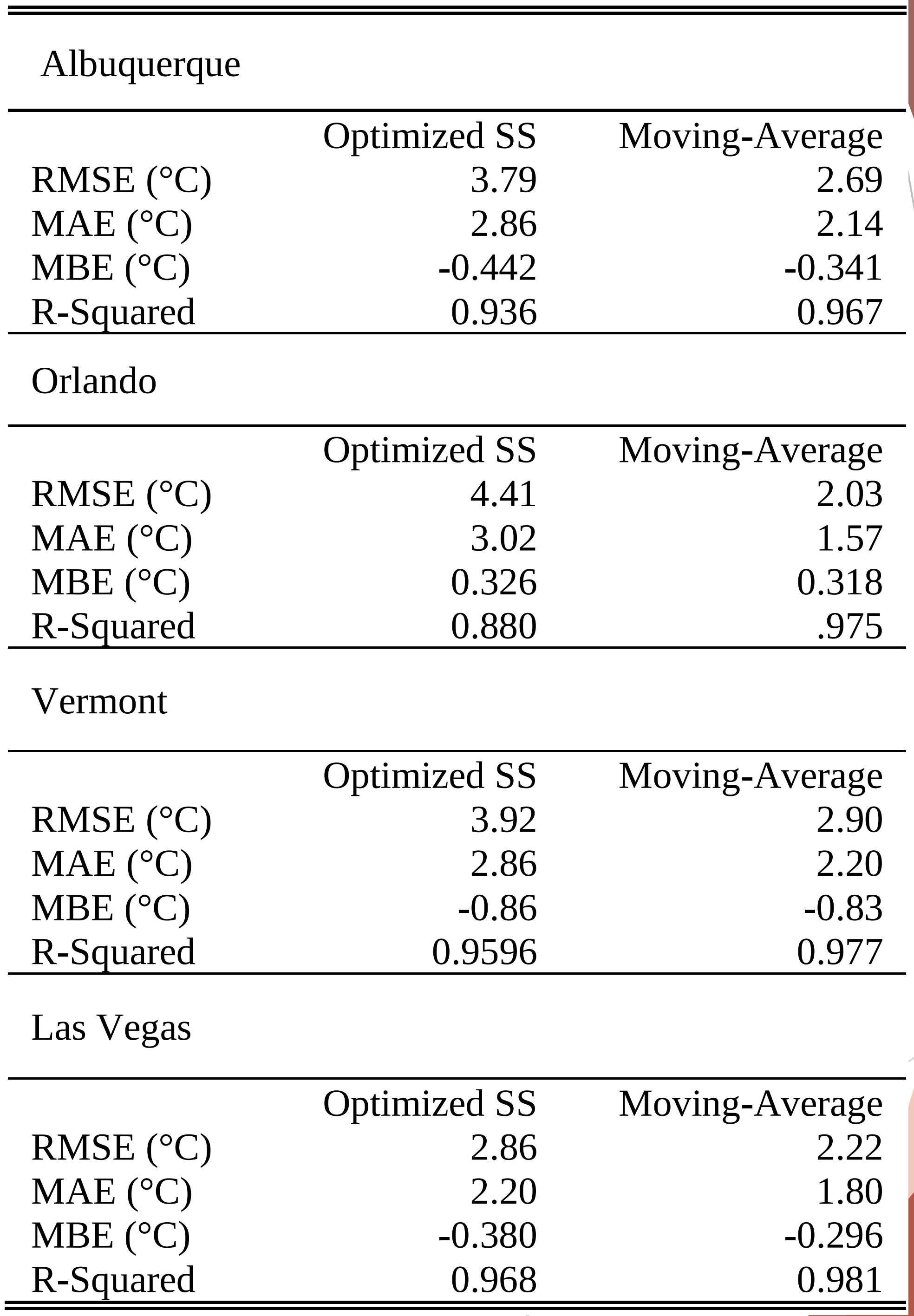
Model Validation

- Improves performance for finer data intervals
- Empirical cumulative distribution function: shows probability of residual occurrences



Model Validation

- Annual 1-minute datasets
- Statistical Metrics
  - RMSE
  - MAE
  - MBE
  - R-squared
- 4 Unique climates
  - Albuquerque (dry, warm)
  - Orlando (tropical, warm)
  - Las Vegas (hot, dry)
  - Vermont (cold)



Albuquerque

	Optimized SS	Moving-Average
RMSE (°C)	3.79	2.69
MAE (°C)	2.86	2.14
MBE (°C)	-0.442	-0.341
R-Squared	0.936	0.967

Orlando

	Optimized SS	Moving-Average
RMSE (°C)	4.41	2.03
MAE (°C)	3.02	1.57
MBE (°C)	0.326	0.318
R-Squared	0.880	.975

Vermont

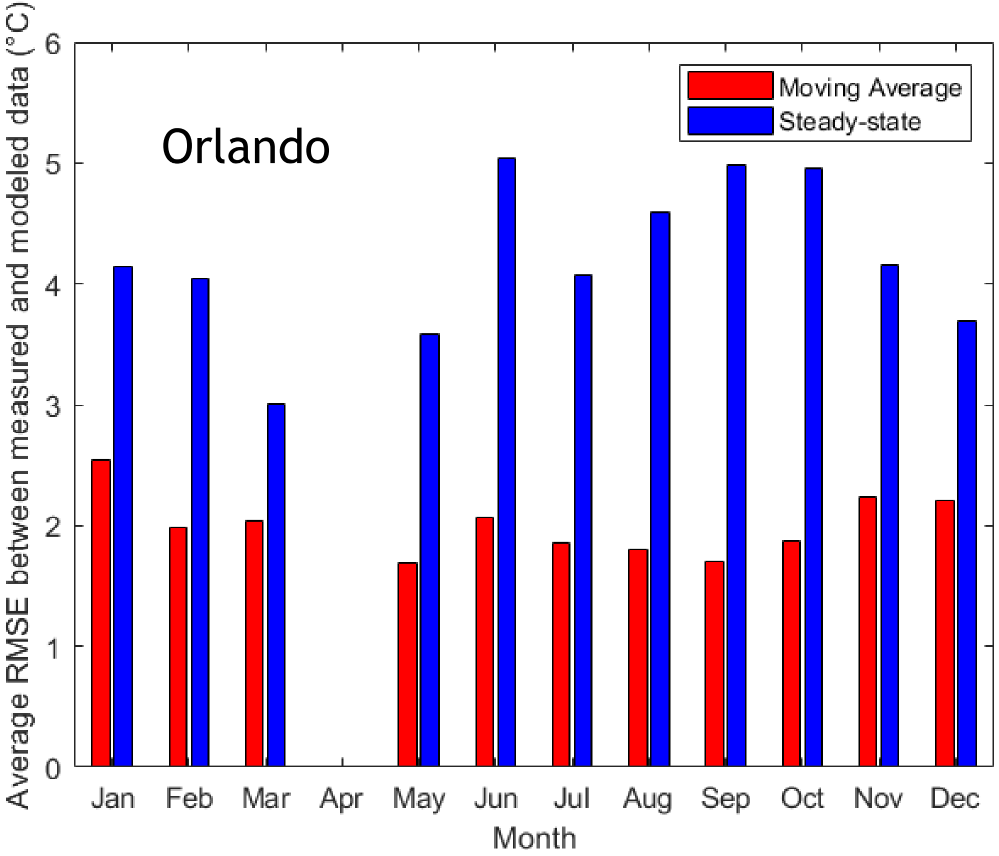
	Optimized SS	Moving-Average
RMSE (°C)	3.92	2.90
MAE (°C)	2.86	2.20
MBE (°C)	-0.86	-0.83
R-Squared	0.9596	0.977

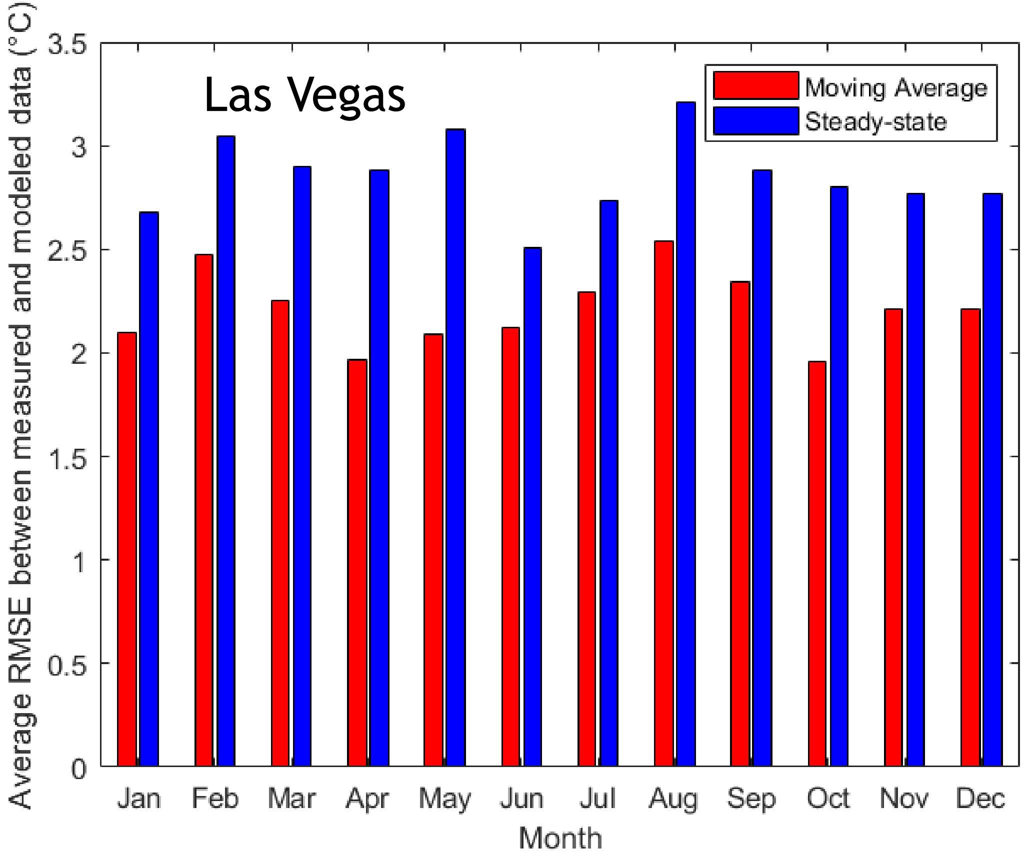
Las Vegas

	Optimized SS	Moving-Average
RMSE (°C)	2.86	2.22
MAE (°C)	2.20	1.80
MBE (°C)	-0.380	-0.296
R-Squared	0.968	0.981

Model Validation

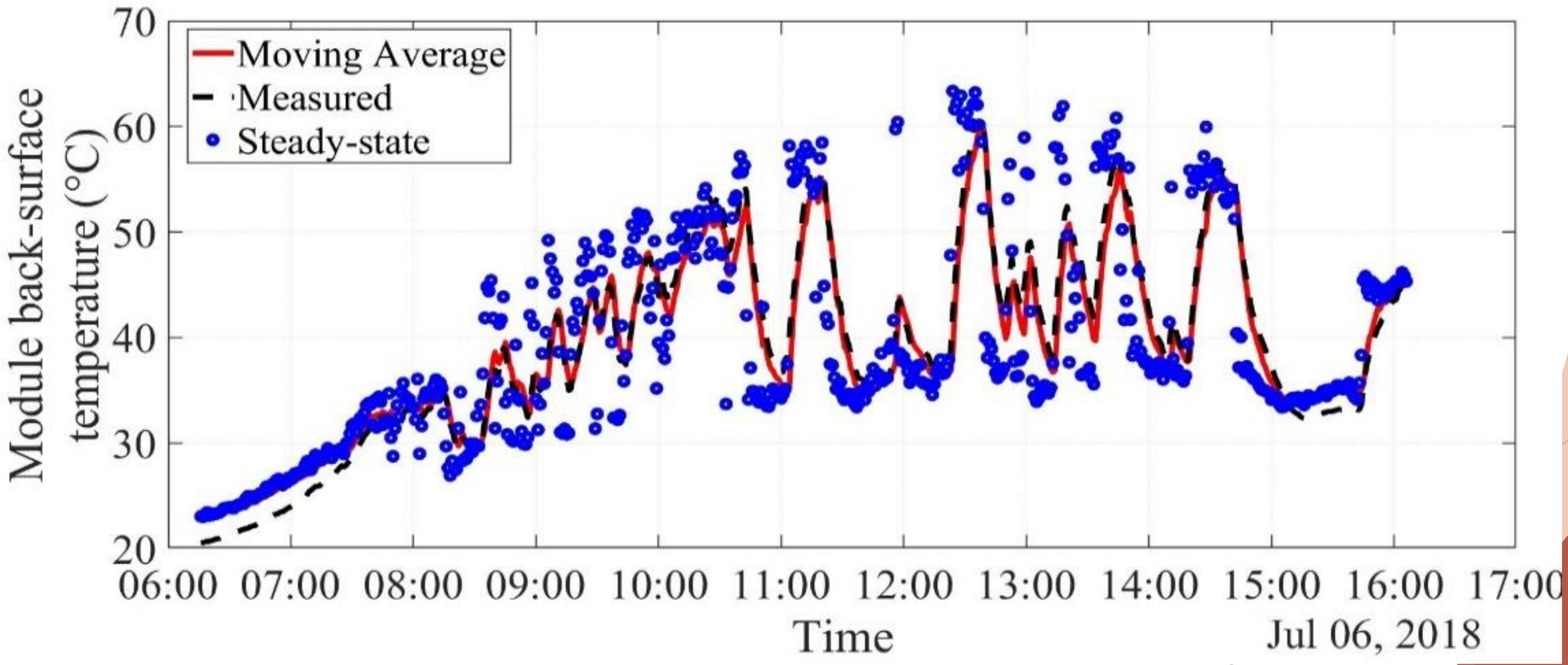
- Monthly RMSE values show greatest accuracy improvements occur in summer
- Model has less effect in desert climates with clear skies





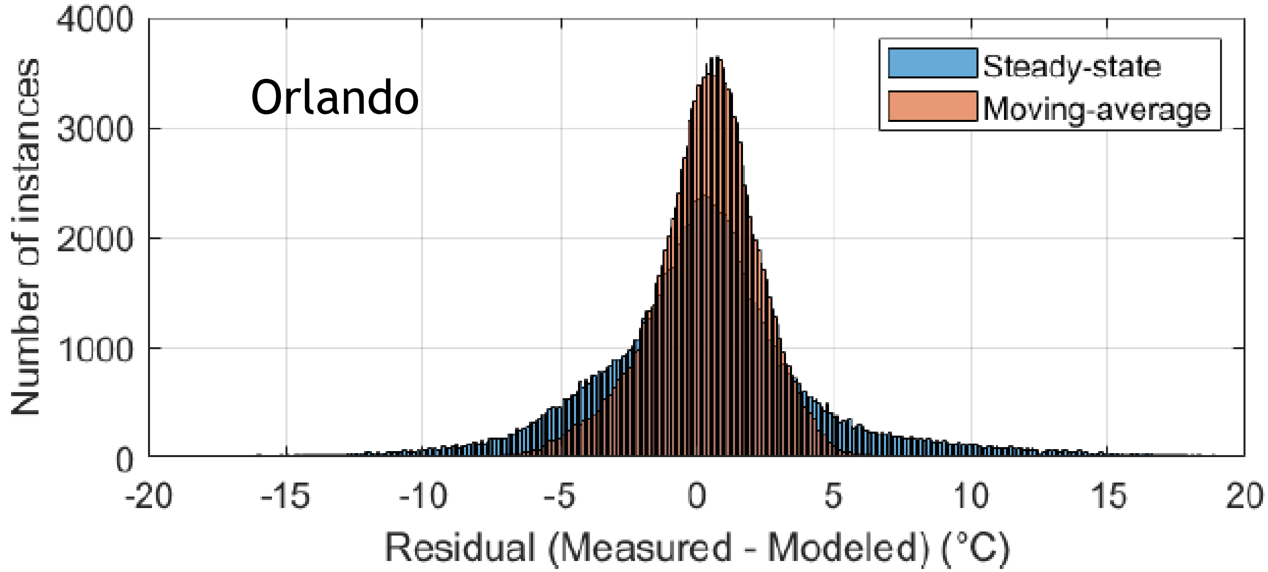
Model Validation

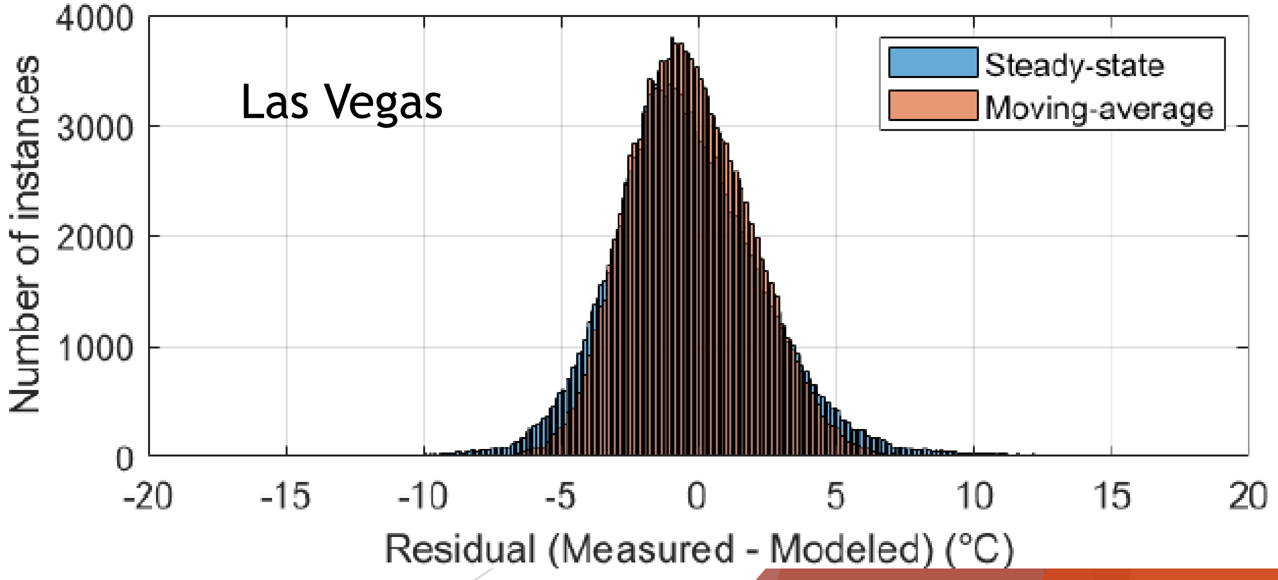
- Model matches the shape of the temperature curve
- Some instances of residuals, but shape still matches



Model Validation

- Histograms: MA model reduces extreme residual values
  - Increases instances of 0-2°C residuals for 1-minute data
  - Much larger effect for climates with more intermittency





Model Benefits

- Annual Energy Performance Improvements: upwards of a 0.58% on energy performance accuracy for 1-minute data
- Effect is greater on a minute basis where energy modeling accuracy can vary with changes in irradiance

	Albuquerque	**Orlando**	**Vermont**	**Las Vegas**
MAE (Moving Average - Steady-state) (°C)	0.72	1.45	0.66	0.4
Energy Accuracy Improvement	0.29%	0.58%	0.26%	0.16%

Conclusions

- Industry need for transient model based on simple input parameters
- Model can be based on database of module thermal behavior developed through FEA
- Led to weighted average of steady-state temperatures within 20 minutes of given index
- To accuracy improvements as high as 1.45°C over steady-state models for 1-minute data
- Can offer benefits to performance modeling for variety of applications

Questions?

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IEEE Journal of Photovoltaics Paper:
https://ieeexplore.ieee.org/document/9095219

ASU Master's Thesis:
https://repository.asu.edu/items/57328