

Module losses due to cell-level EQE variation

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Introduction

- ▶ Module → **series-connected** cells
- ▶ Output limited by the **cell with lowest current** → **mismatch loss**
- ▶ **Reduced cell performance** can arise from:
 - ▶ Fabrication: manufacturing inconsistencies
 - ▶ Operation: degradation (long-term) / localised defects (e.g. cracking)
 - ▶ Environment: partial shading / non-uniform illumination
- ▶ Cell characterisation using **EQE**
- ▶ **Up to 10%** annual module spectral effect [1]

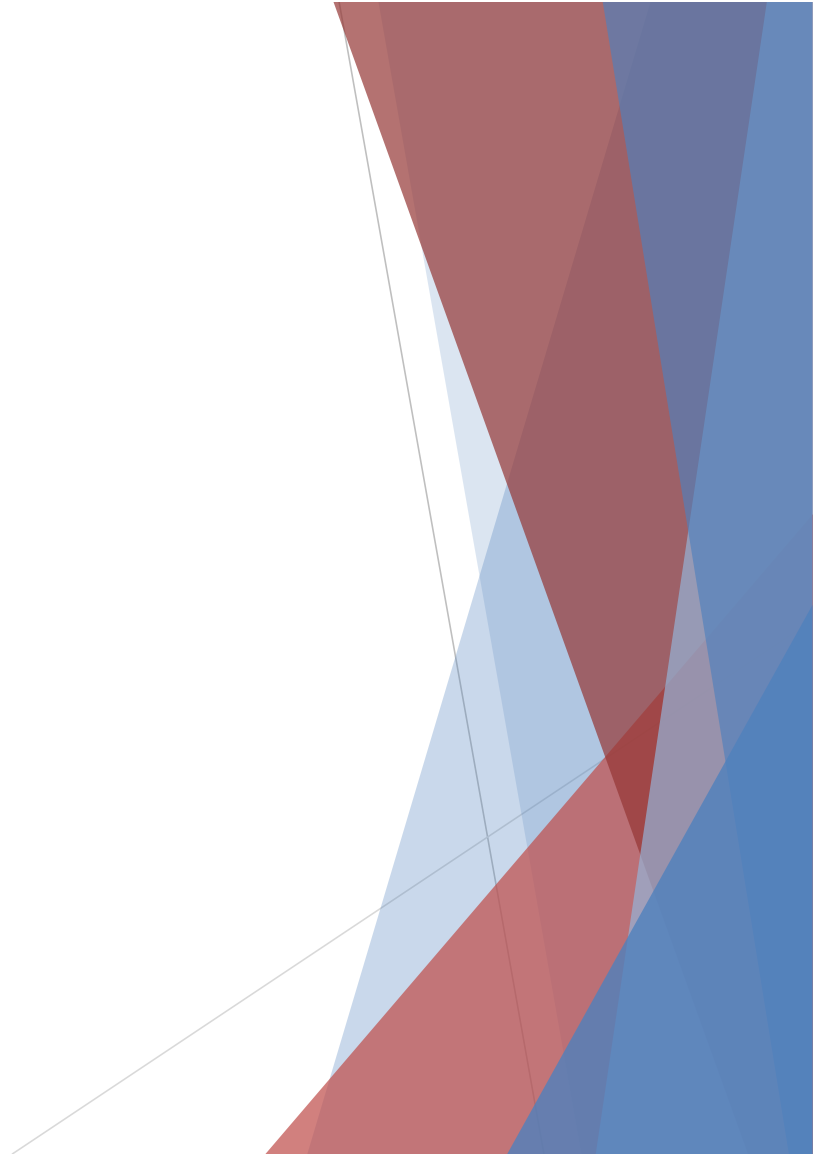
Questions

- ▶ What is the **scale of intracell EQE variation** in a PV module?
- ▶ **How much energy is lost** due to intracell EQE variation?
- ▶ How does the energy loss vary with **season and location**?



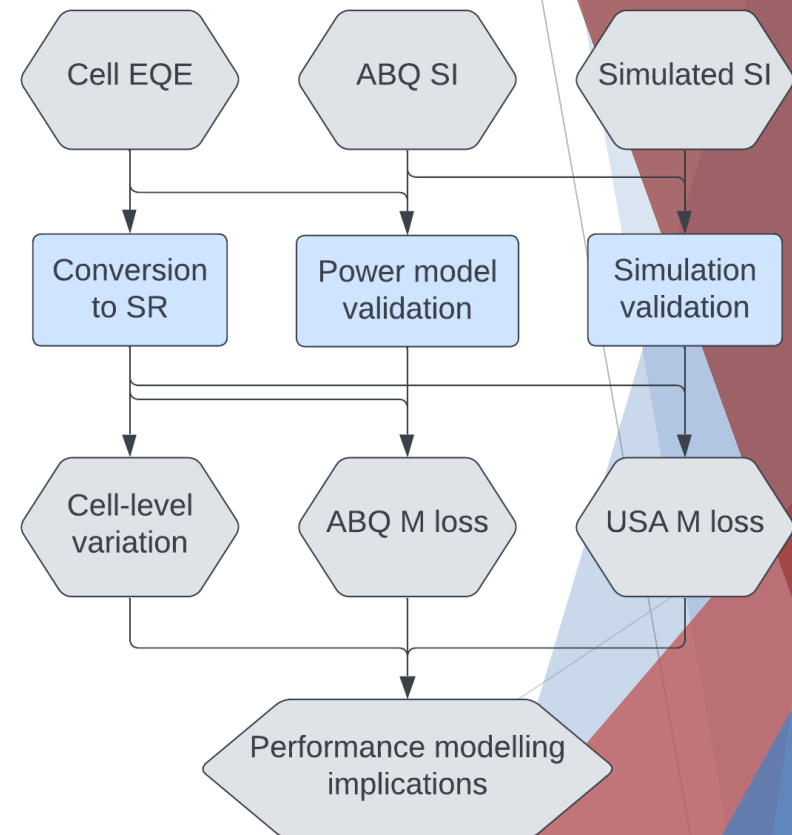
Methods

Research framework → Data → Power model



Data and research framework

- ▶ 12 commercial modules [2, 3]
- ▶ Cell EQE measurements [4]
- ▶ Weather and spectral data, measured [5] and simulated [6, 7]
- ▶ Output: mismatch loss across the contiguous USA



Research framework → Data → Power model

Data and metrics

- ▶ Range of PV technologies and architectures
- ▶ IEC 61853-1/2 characterisation by CFV labs
- ▶ Spectral mismatch:

$$UF_1 = \frac{\int_{300}^{1200} E_1(\lambda) SR_1(\lambda) d\lambda}{\int_{300}^{1200} E_1(\lambda) d\lambda}$$



Useful fraction of the prevailing spectrum

$$UF_2 = \frac{\int_{300}^{1200} E_0(\lambda) SR_1(\lambda) d\lambda}{\int_{300}^{1200} E_0(\lambda) d\lambda}$$



Useful fraction of the reference spectrum

$$M = \frac{UF_1}{UF_2}$$

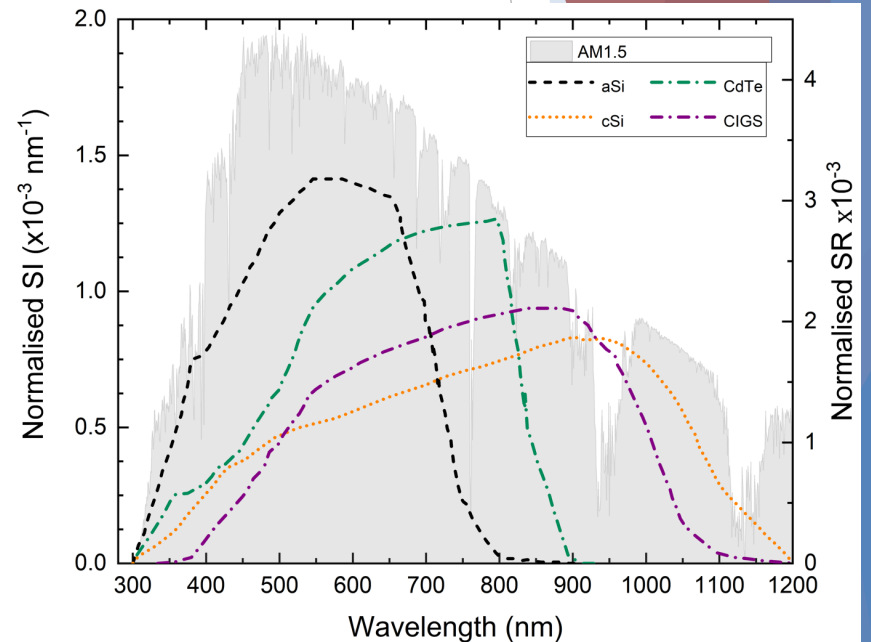


Spectral mismatch

Manufacturer	Type	P _{mp} (W)
Canadian Solar	poly-Si	267.53
Itek Energy	mono-Si PERC	354.70
LG	mono-Si N-type PERT	320.32
Mission Solar	mono-Si PERC	285.91
Panasonic	mono-Si HIT	322.30
Qcells	poly-Si PERC	277.92
Qcells	mono-Si PERC	289.88

Power model (Principles)

- ▶ Interaction between SR and SI
- ▶ Spectral mismatch:
Performance shift due to non-reference spectrum
- ▶ Intracell mismatch effect:
Difference between mismatch and non-mismatch scenarios



Power model (Equation)

- Realistic solar panel P :

$$P_1^{\text{mod}} = P_{STC}^{\text{mod}} \cdot (1 + \gamma(T - T_0)) \cdot \frac{G_T}{G_0} \cdot \left[\frac{\min[M^{\text{cell}} I_{sc,0}^{\text{cell},i}]}{\min[I_{sc,0}^{\text{cell},i}]} \right]$$

- Idealistic solar panel P , assuming uniform cell performance:

$$P_2^{\text{mod}} = P_{STC}^{\text{mod}} \cdot (1 + \gamma(T - T_0)) \cdot \frac{G_T}{G_0} \cdot M^{\text{mod}}$$

- P_{loss} due to intracell spectral mismatch:

$$P_{\text{loss}} = P_2 - P_1 = P_{tr} \cdot \left[M^{\text{mod}} - \frac{\min[M^{\text{cell}} I_{sc,0}^{\text{cell},i}]}{\min[I_{sc,0}^{\text{cell},i}]} \right]$$

Modelling assumptions:

$$I_{sc} = A \int E_{\lambda} \cdot SR_{\lambda} d\lambda$$

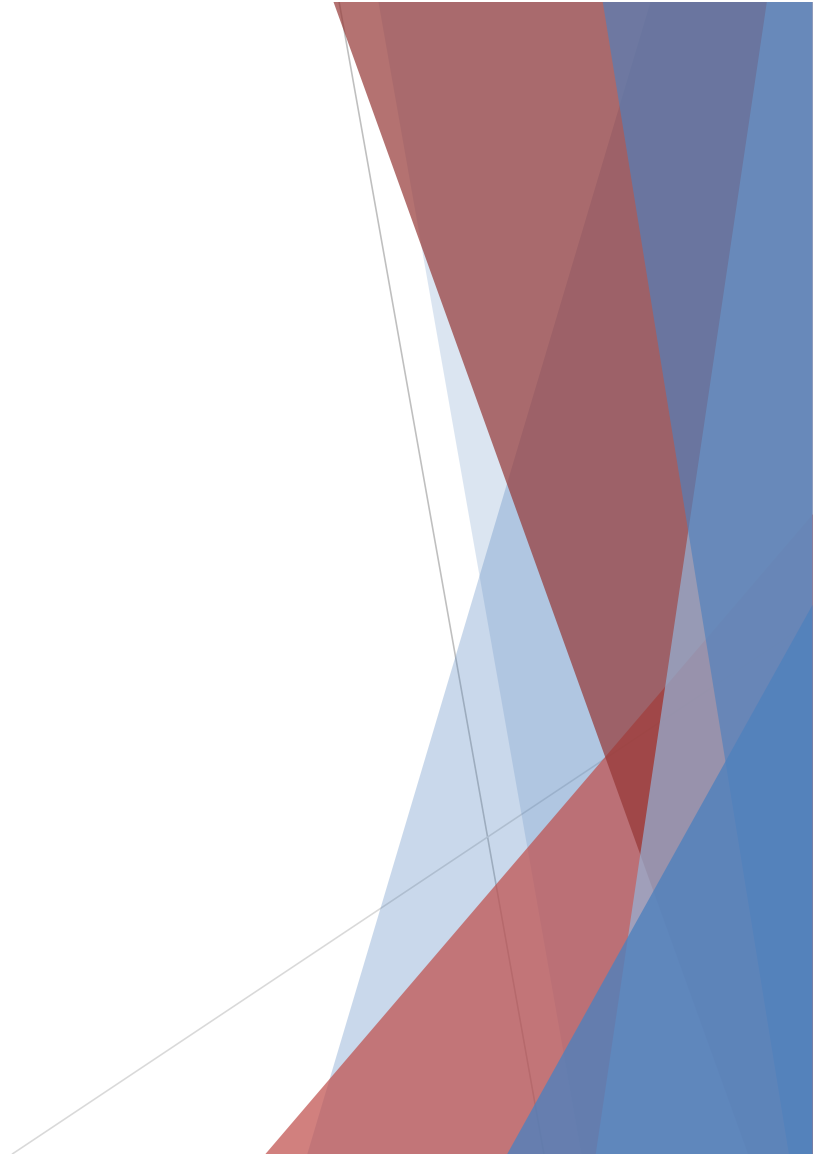
$$I_{mp} \propto I_{sc}$$

$$V_1 = V_2 = V_3 = \dots = V_n$$

$G_T \rightarrow$ Perez, Martin & Ruiz

Results

EQE variation → Power variation (location) → Discussion



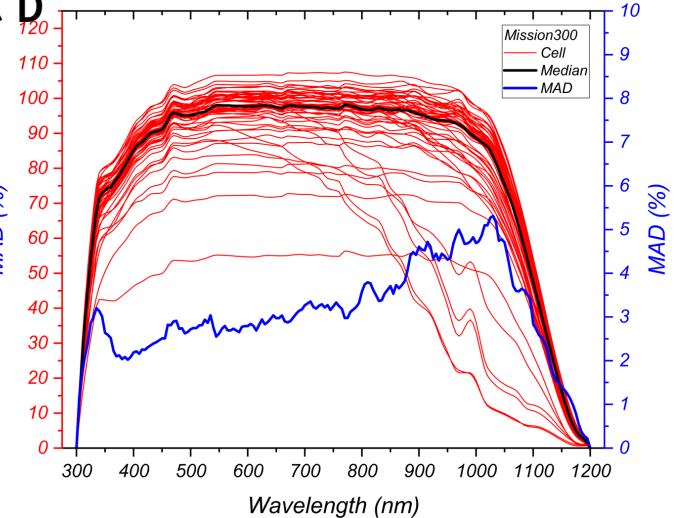
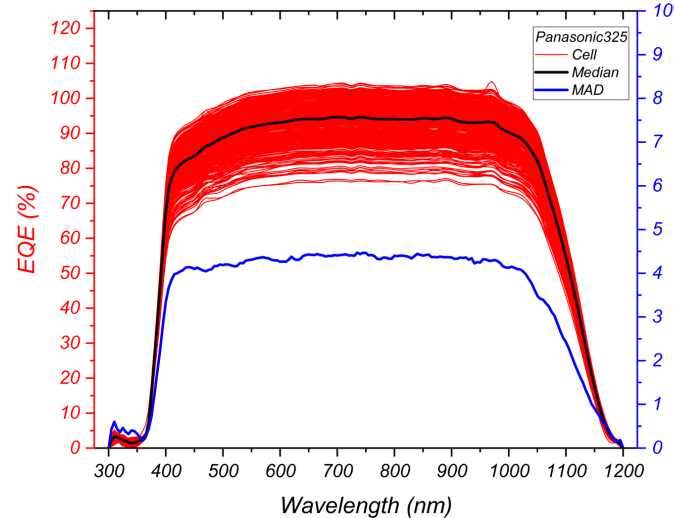
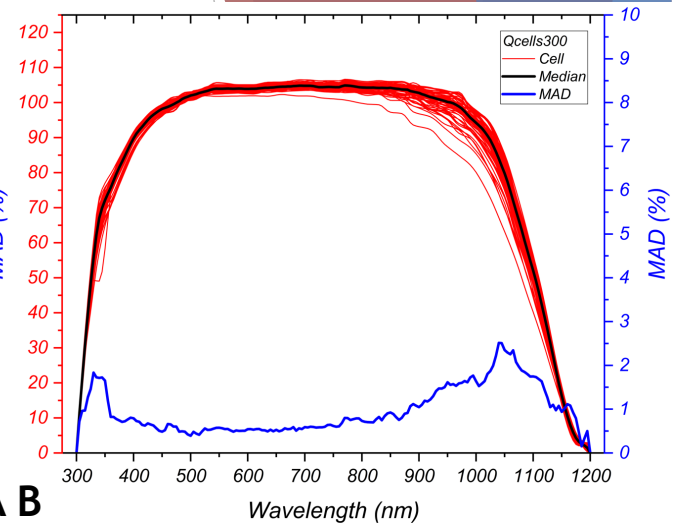
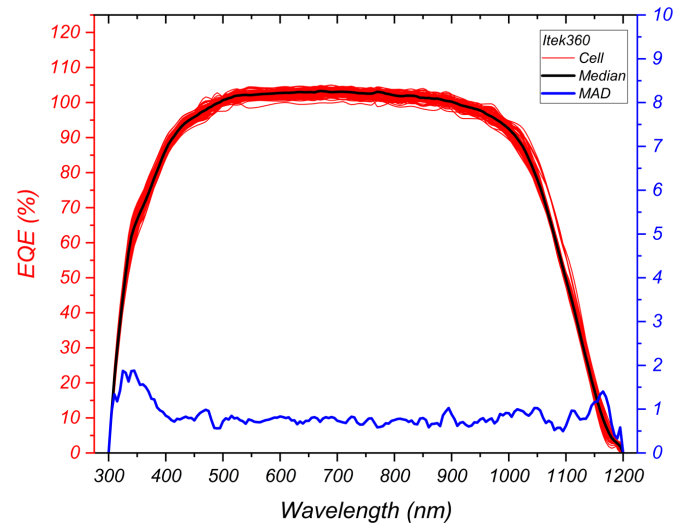
EQE variation

Four types of variation:

1. Negligible (A)
2. Wavelength (B)
3. Amplitude (C)
4. Mixed (D)

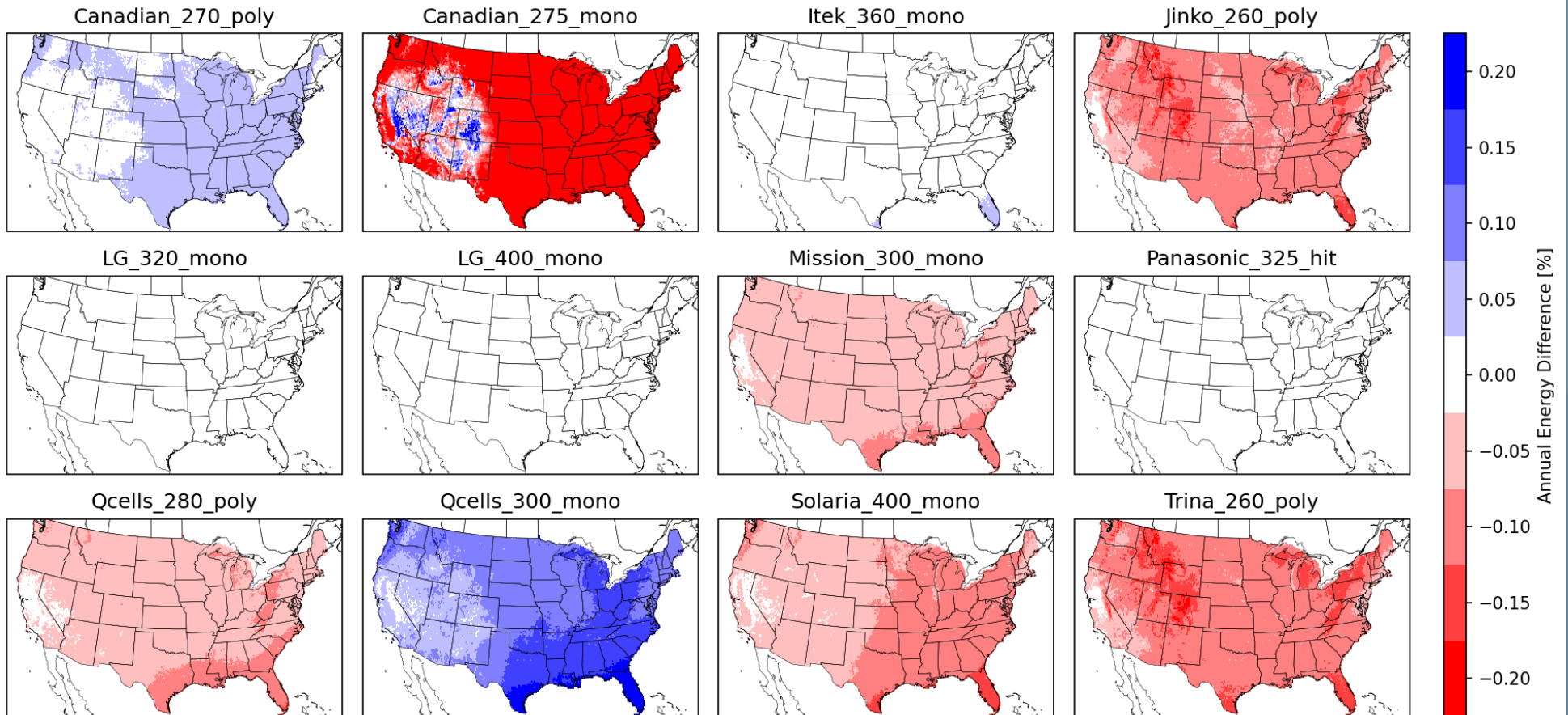
Interpretation:

- ▶ HIT: 450–1050nm, defect density in HIT structures [8]
- ▶ Wavelength: front/rear surface recombination [9]
- ▶ Effects of passivation



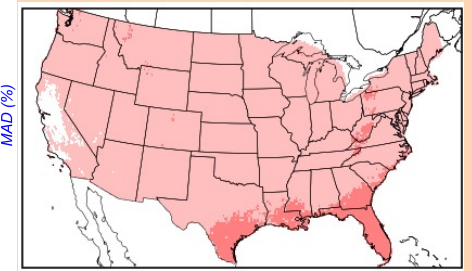
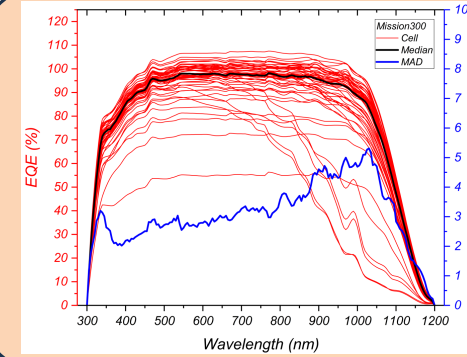
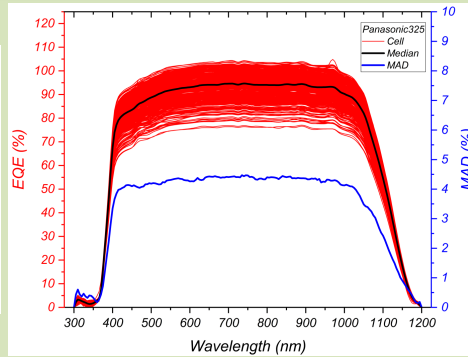
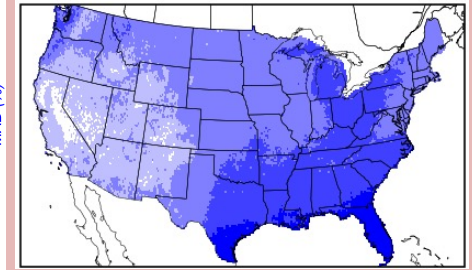
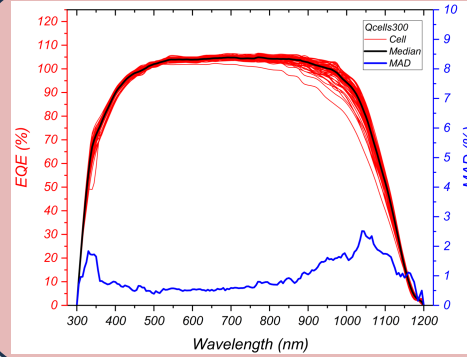
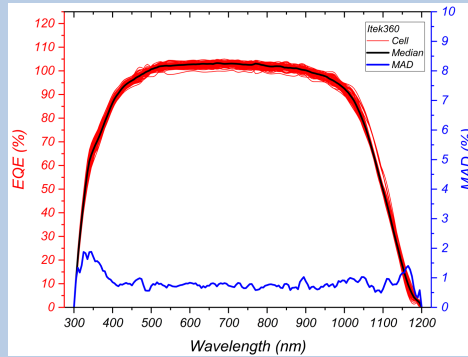
EQE variation → Power variation (location) → Discussion

Difference in annual energy, ΔE



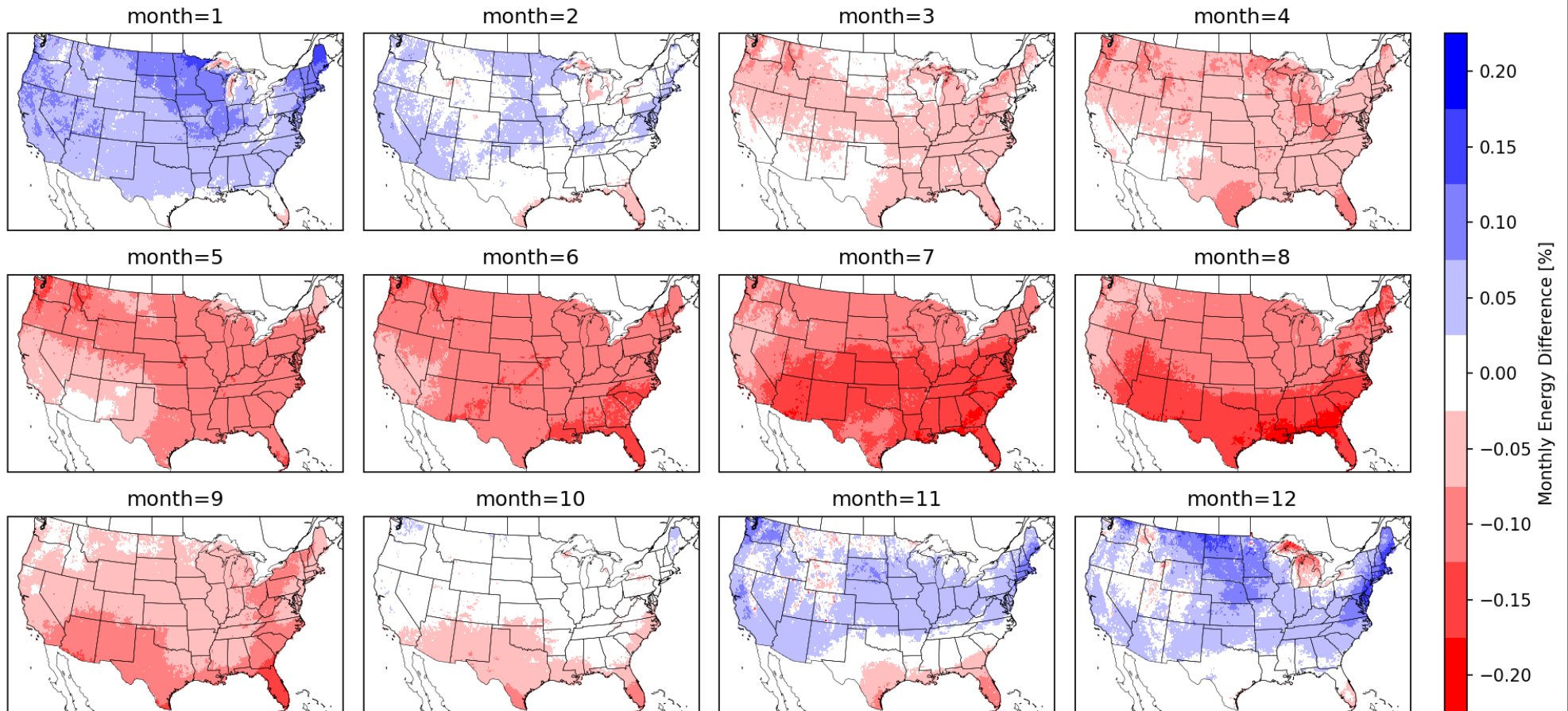
EQE $\longleftrightarrow$ ΔE relationship

- ▶ Different *shape* (not scale) matters
- ▶ Different shape $\rightarrow$ different SMM larger change in EMM



EQE variation $\rightarrow$ Power variation (location) $\rightarrow$ Discussion

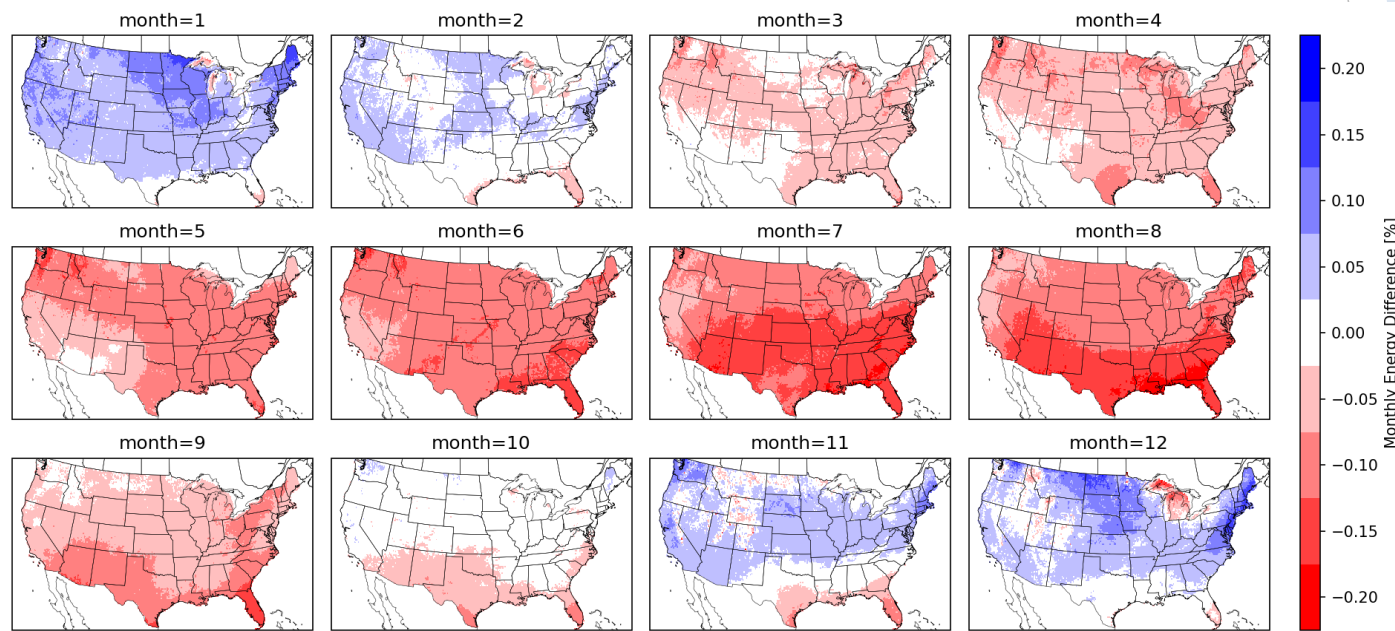
Seasonality – Mission 300



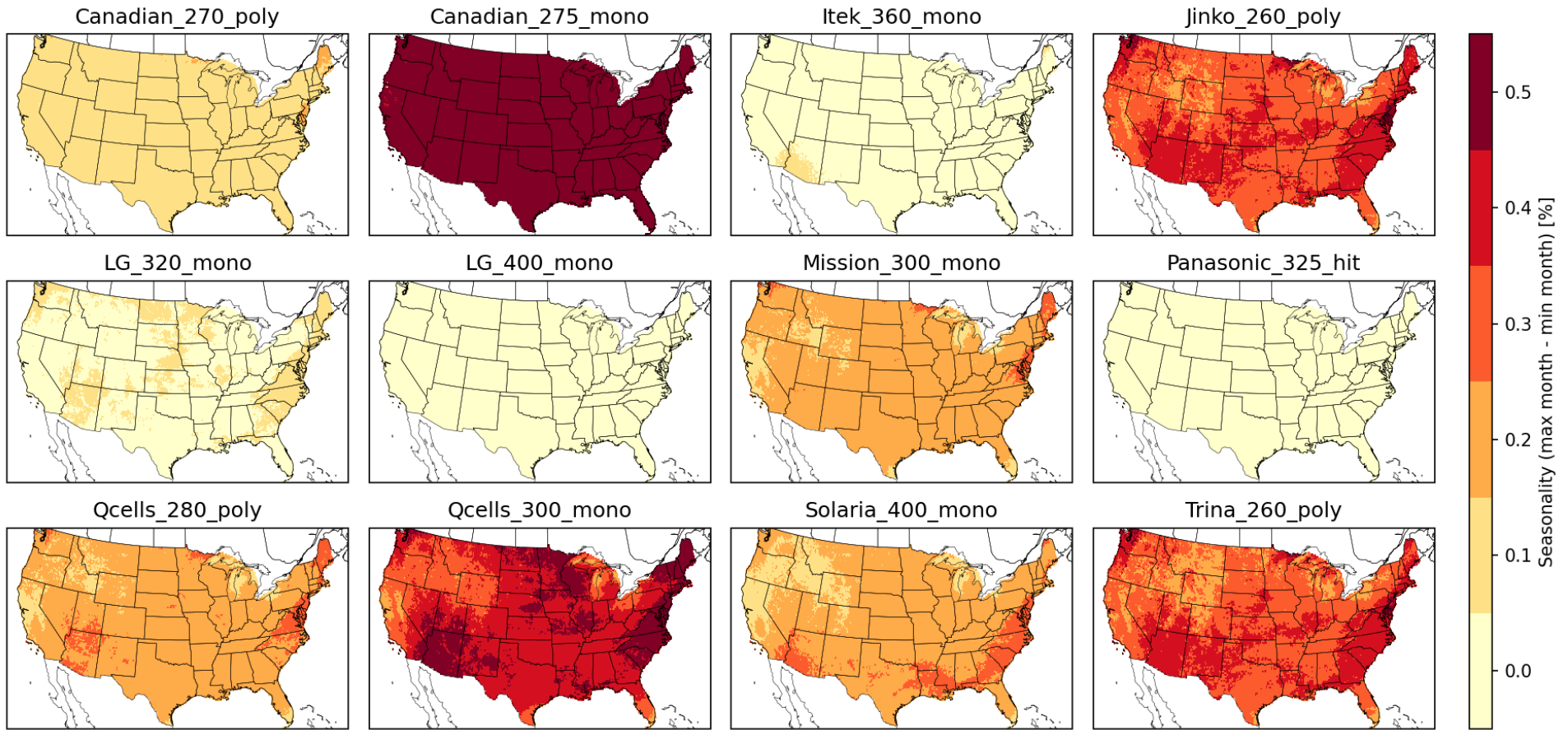
EQE variation → Power variation (location) → Discussion

Seasonality – Mission 300

- ▶ Approx half/half positive/negative
- ▶ Almost cancels annually, but any month could have a larger error
- ▶ Implications for **capacity testing**



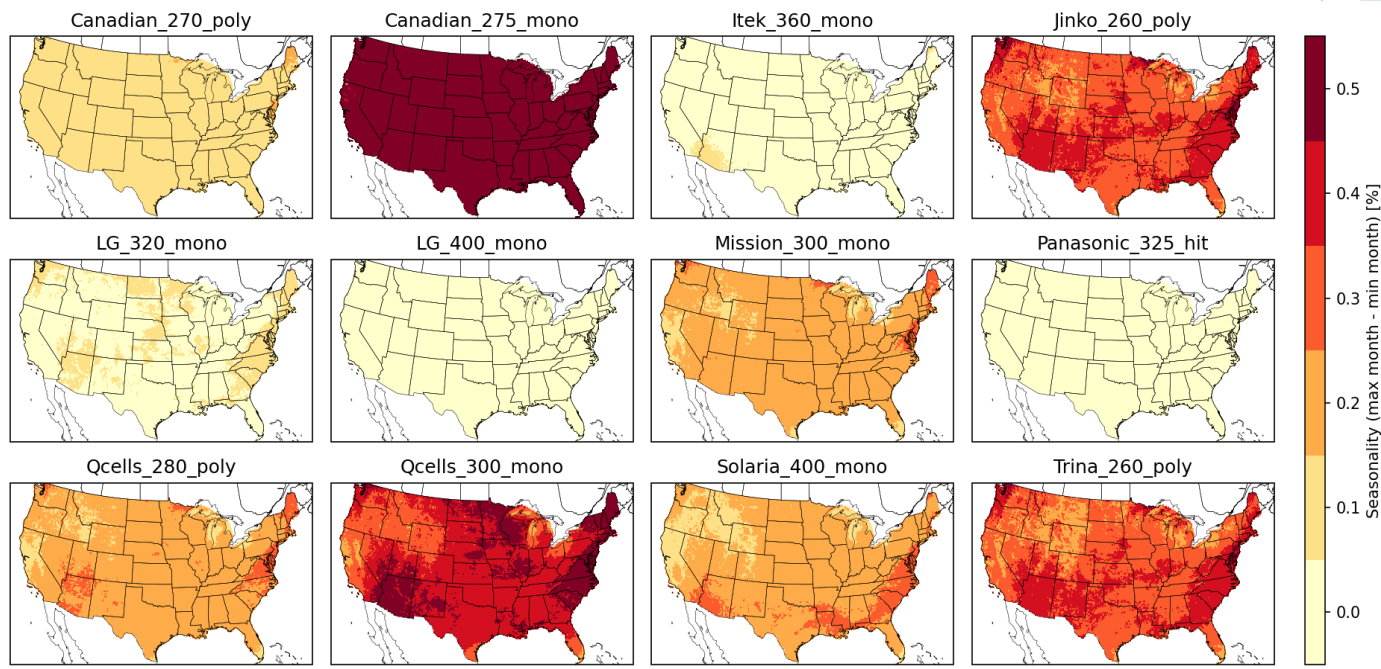
Seasonality – all modules



EQE variation → Power variation (location) → Discussion

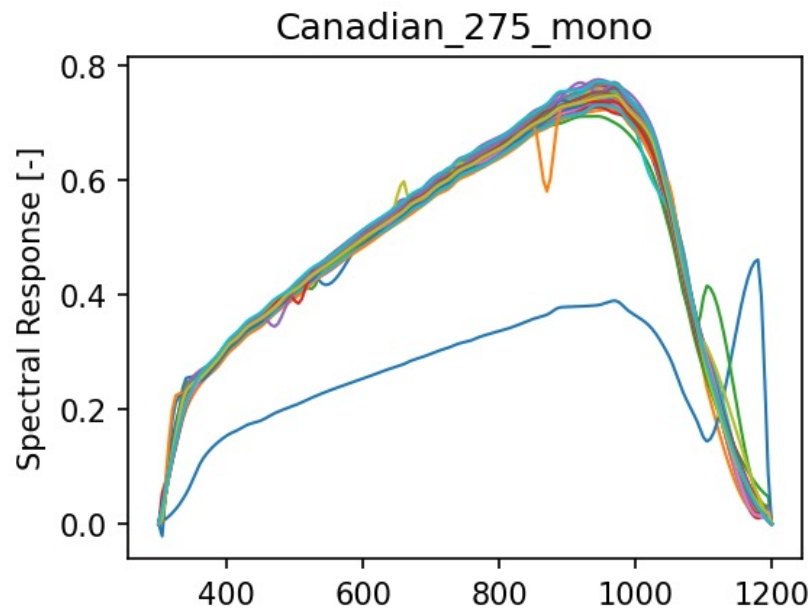
Seasonality – all modules

- ▶ Overall, low annual error is correlated with low seasonality
- ▶ The seasonality itself cannot be ignored for those modules where it present
- ▶ Extreme Canadian 275 result



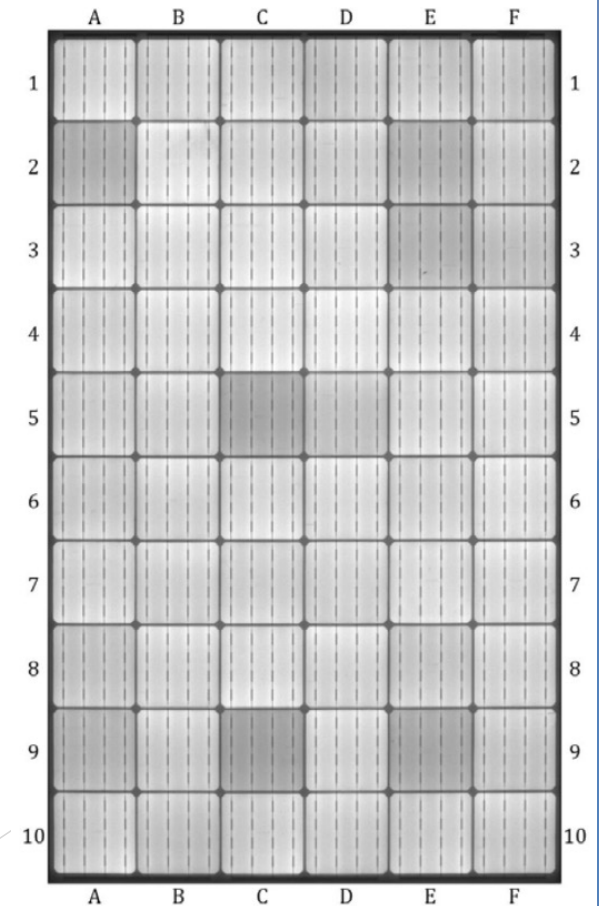
What's up with Canadian 275?

- ▶ Clean EL image suggests possible SR measurement error
- ▶ Illumination over bus bar rather than active cell area?
- ▶ Warrants further investigation



EQE variation → Power variation (location) → Discussion

19074-005: Initial



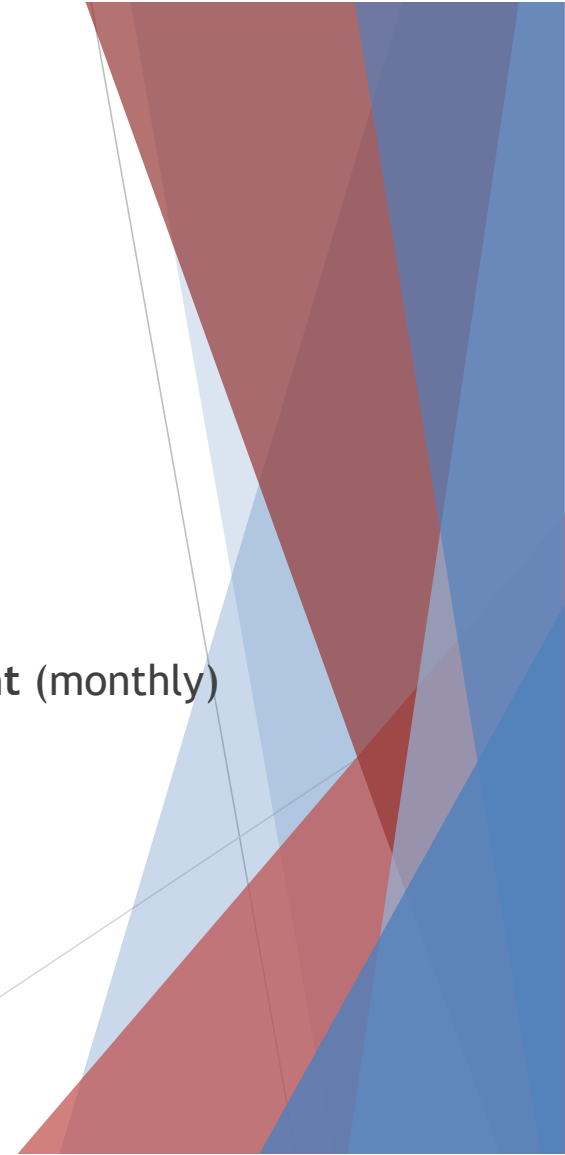
Conclusion

Observations:

- ▶ Four types of cell-to-cell EQE variation:
Negligible, *Wavelength*, Amplitude, *Mixed*
- ▶ EQE **shape** rather than scale is **important**
- ▶ Absolute (%) ΔE is **low** ($<0.2\%$), relative (%) **seasonality** is **significant** (monthly)

Future considerations:

- ▶ Sub-annual modelling applications
- ▶ Cell EQE measurement may require refinement
- ▶ Future measurements following multi-year degradation



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Spectral response curves are freely available from Sandia National Laboratories' PVPMC and SLTE projects: <https://datahub.duramat.org/dataset/module-sr-library>



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Ride with me next time?

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(until June only)



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