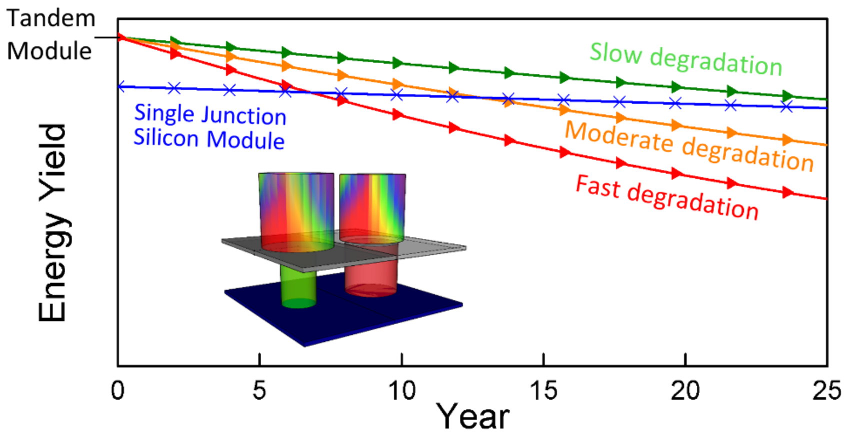
Long-Term Impact of Perovskite Solar Cell Degradation on Perovskite/Silicon Tandem Modules



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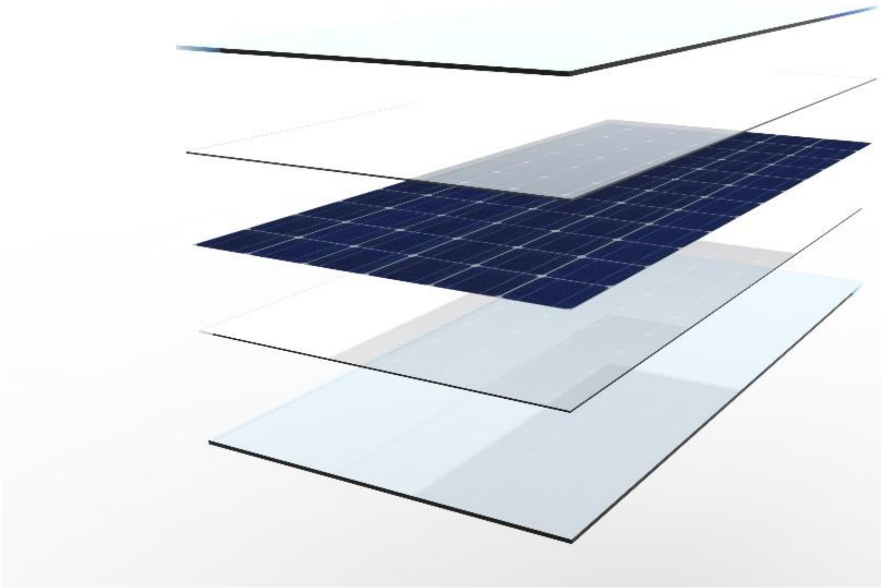
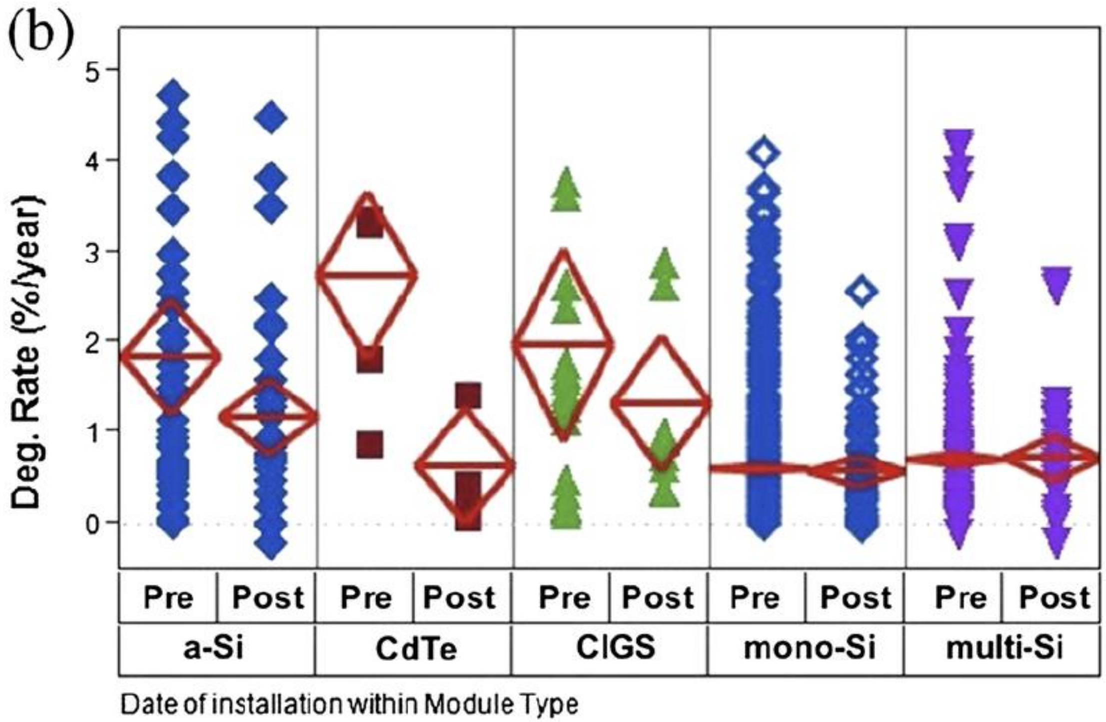
Solar module degradation

- **Degradation of short-circuit current (I_{SC})**
  - E.g. caused by delamination, discoloration, cracked cells, glass soiling
- **Degradation of open-circuit voltage (V_{OC})**
  - E.g. through increase in recombination (surface / bulk)
- **Degradation of fill-factor (*FF*)**
  - Increase in series resistance caused for instance by corrosion, solder bond weakening, or cracked cells.



Solar module degradation

- Decades of measurement data for long-term degradation of **single-junction solar modules** available

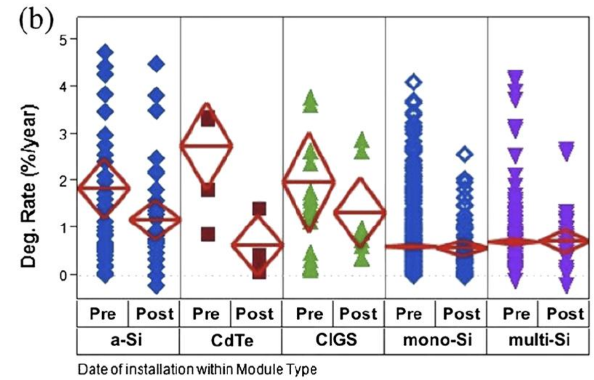


Source: D. C. Jordan and S. R. Kurtz, "Photovoltaic Degradation Rates-an Analytical Review," Prog. Photovolt: Res. Appl **21** (1), 12–29 (2013).

Solar module degradation

- Decades of measurement data for long-term degradation of **single-junction solar modules** available

- Long-term **perovskite solar module degradation** rates **not yet known**



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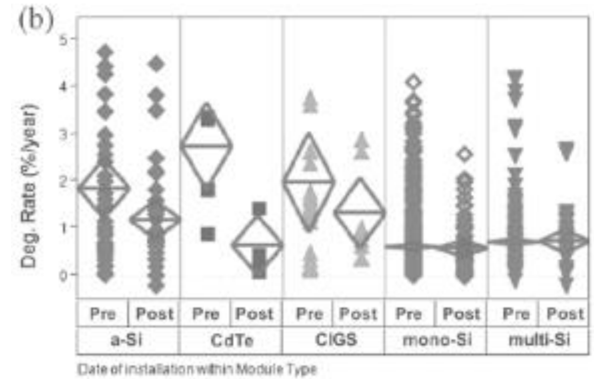

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? What are the requirements on **perovskite cell degradation** to enable **long-term performance** and **economic viability** of **silicon-based tandem modules**?

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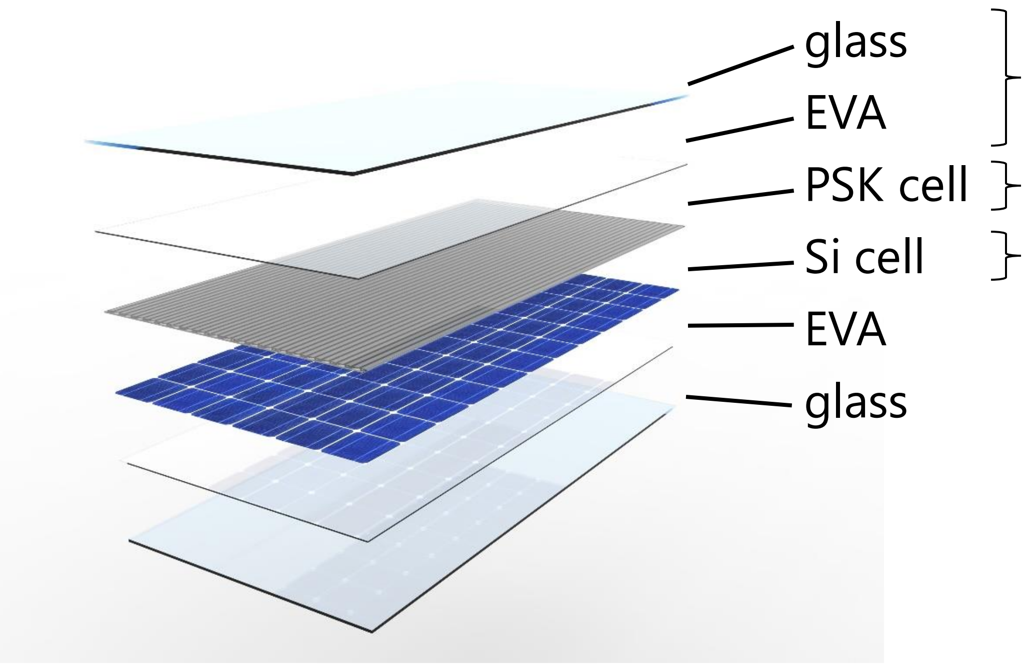
Tandem Modules

Degradation components considered separately

- Module encapsulation (constant): Reduction of encapsulation transmittance of EVA and glass impacting cell current of top and bottom cell
- Silicon cell degradation: Reduction of fill-factor and voltage (constant)
- PSK degradation scenarios and rate varied to analyse impact on tandem performance



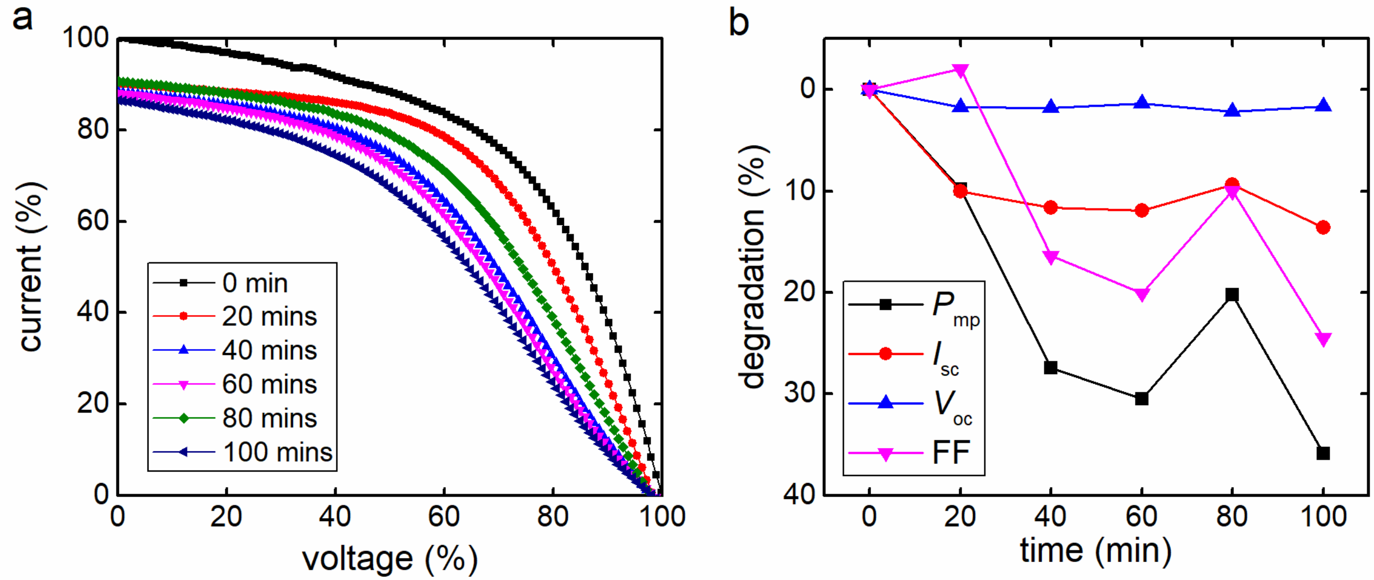
- 0.26% Module degradation affecting top and bottom cell I_{SC}
- **PSK cell degradation (varied)**
- 0.09% FF + 0.03% V_{OC} degradation

Si module degradation parameters from:
D. C. Jordan and S. R. Kurtz, IEEE J. Photovoltaics **4** (1), 317–323 (2014).

PSK cell degradation

Experimental degradation scenario

- Accelerated degradation experiment using an in-house solution-processed PSK cell.
- Degradation performed at 65°C in ambient atmosphere with 35% humidity.



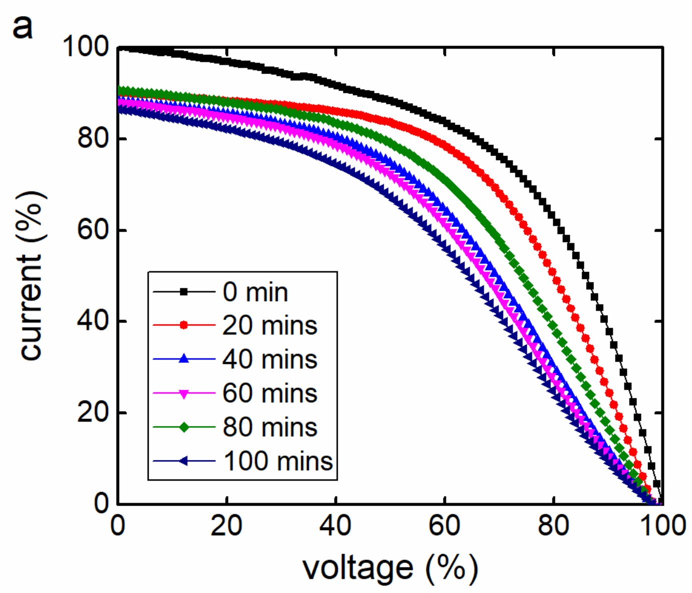
Cell details: Quadruple cation Rb-FA0.75MA0.15Cs0.1PbI2Br with a cell structure of FTO / compact TiO2 / mesoporous TiO2 / passivation layer (PCBM + PMMA) / perovskite / spiro-OMeTAD / Au

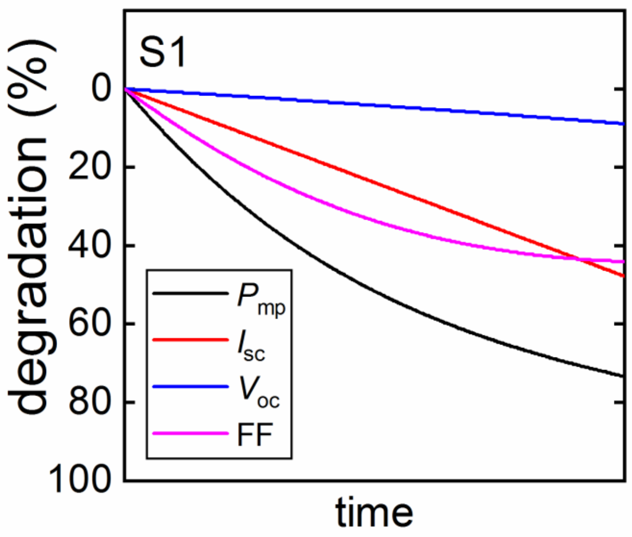
J. Qian et al., Sustainable Energy Fuels 3, 1439–1447 (2019).

PSK cell degradation

Experimental degradation scenario

- Accelerated degradation experiment using an in-house solution-processed PSK cell.
- Degradation performed at 65°C in ambient atmosphere with 35% humidity.
- *Experimental degradation scenario* based on measured degradation response





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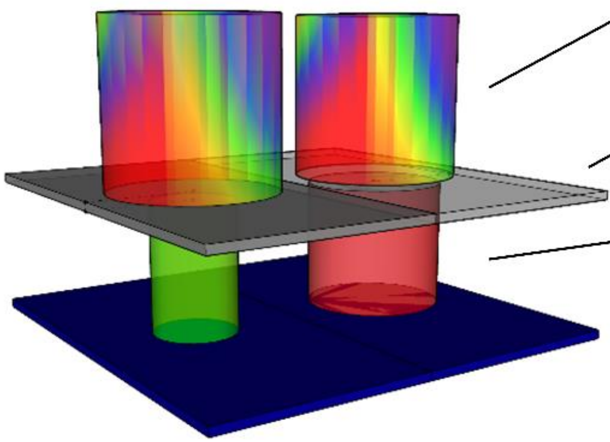
PSK current degradation

Correlation between current degradation and optical transmittance

- With degrading cell current, the PSK may become transparent or opaque
- f_τ is the fraction of current loss in the PSK cell that is transmitted to the silicon bottom cell



$$J^{t}_{\mathrm{sc(Si)}} = J^{0}_{\mathrm{sc(Si)}} \cdot (1 - t \cdot r_{\mathrm{enc}}) + f_\tau \cdot J^{0}_{\mathrm{sc(PSK)}} \cdot t \cdot r_{\mathrm{c(PSK)}}$$

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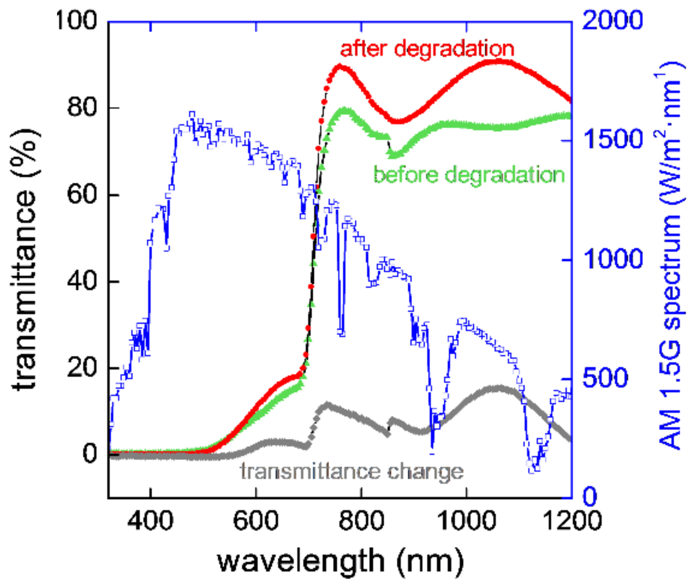
PSK current degradation

Correlation between current degradation and optical transmittance

- With degrading cell current, the PSK may become transparent or opaque
- Experiment: $f_\tau = 0.89$ (nearly all light from current reduction in PSK cell is transmitted to bottom cell)



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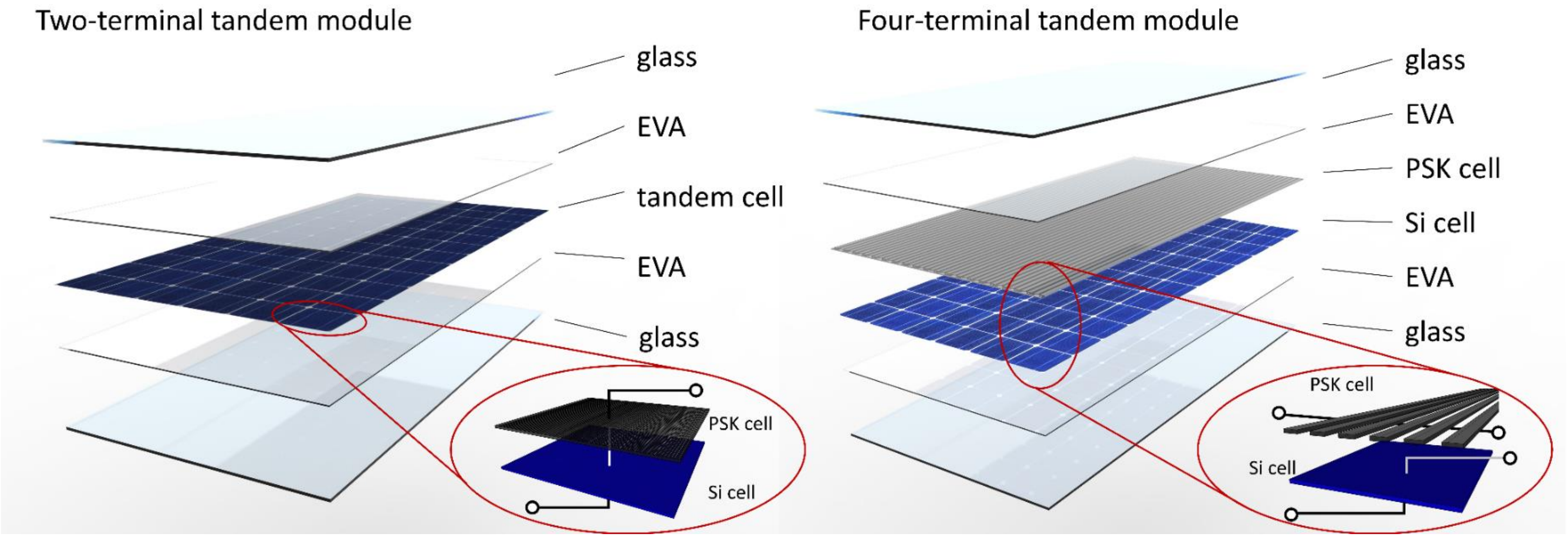
Tandem Modules

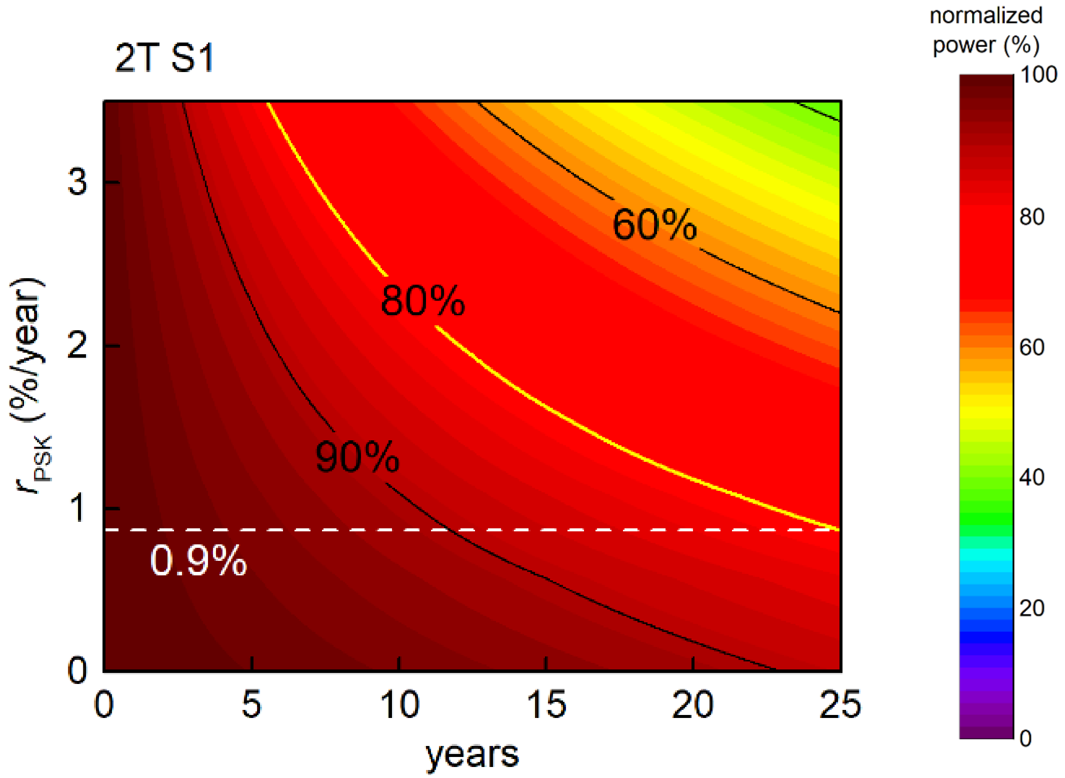
- **Assuming a conventional 72-cell c-Si PV module layout**
- **Case I: Perovskite/silicon two-terminal tandem module**
  - Based on 25.2% two-terminal tandem cell *(F. Sahli et al., Nat Mater 17 (9), 820–826 (2018).)*
  - Initial nominal module power rating of 442 W
- **Case II: Perovskite/silicon four-terminal tandem module**
  - Based on 26.7% four-terminal tandem cell *(C. O. R. Quiroz et al., J. Mater. Chem. A 6 (8), 3583–3592 (2018).)*.
  - Initial nominal module power rating of 467 W

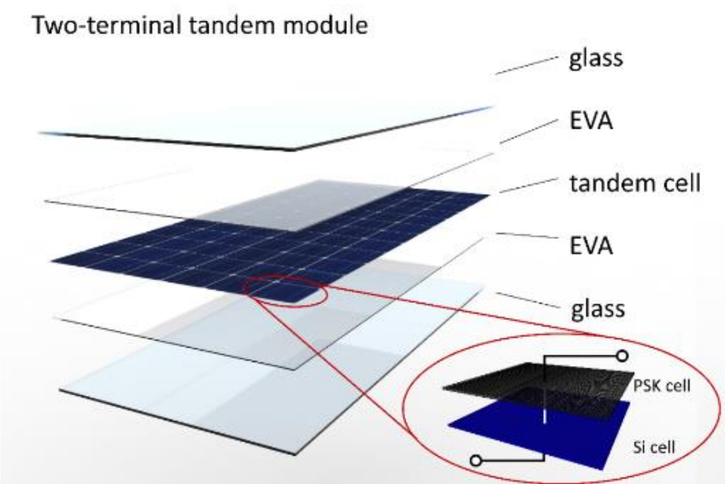


Tandem module power

Normalized tandem module power over 25 year lifetime

- Experimental degradation scenario in 2T configuration
- Assuming $f_\tau = 0.89$ from experiment
- Limiting PSK degradation determined for maintaining 80% power after 25 years

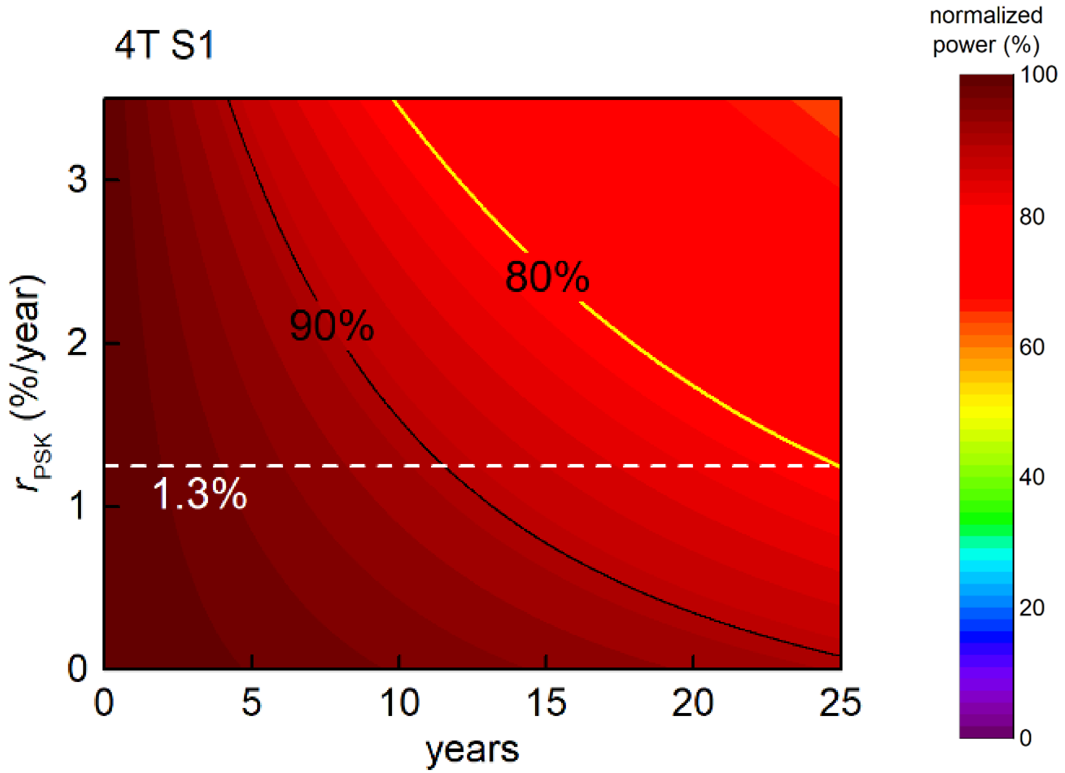


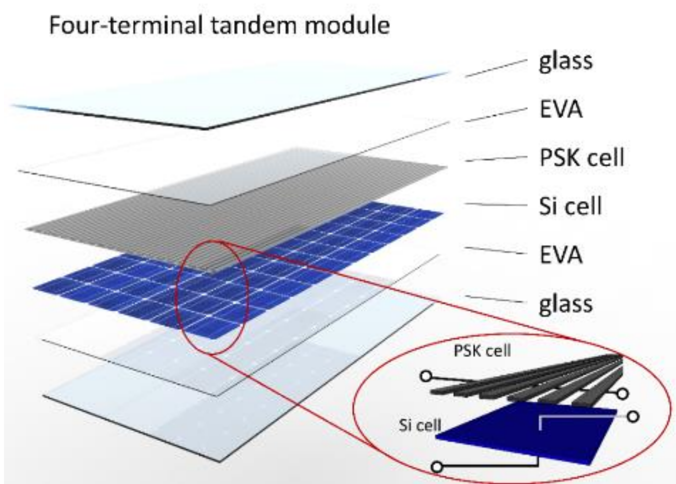


Tandem module power

Normalized tandem module power over 25 year lifetime

- Experimental degradation scenario in 4T configuration
- Assuming $f_\tau = 0.89$ from experiment
- Limiting PSK degradation determined for maintaining 80% power after 25 years

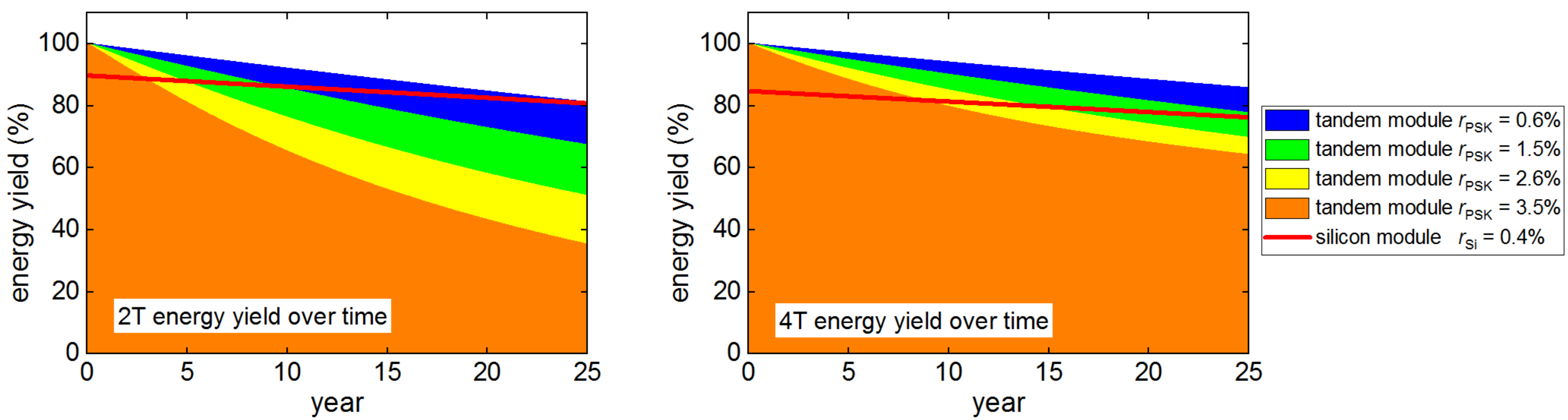




Energy yield

Normalized module yield over 25 year lifetime

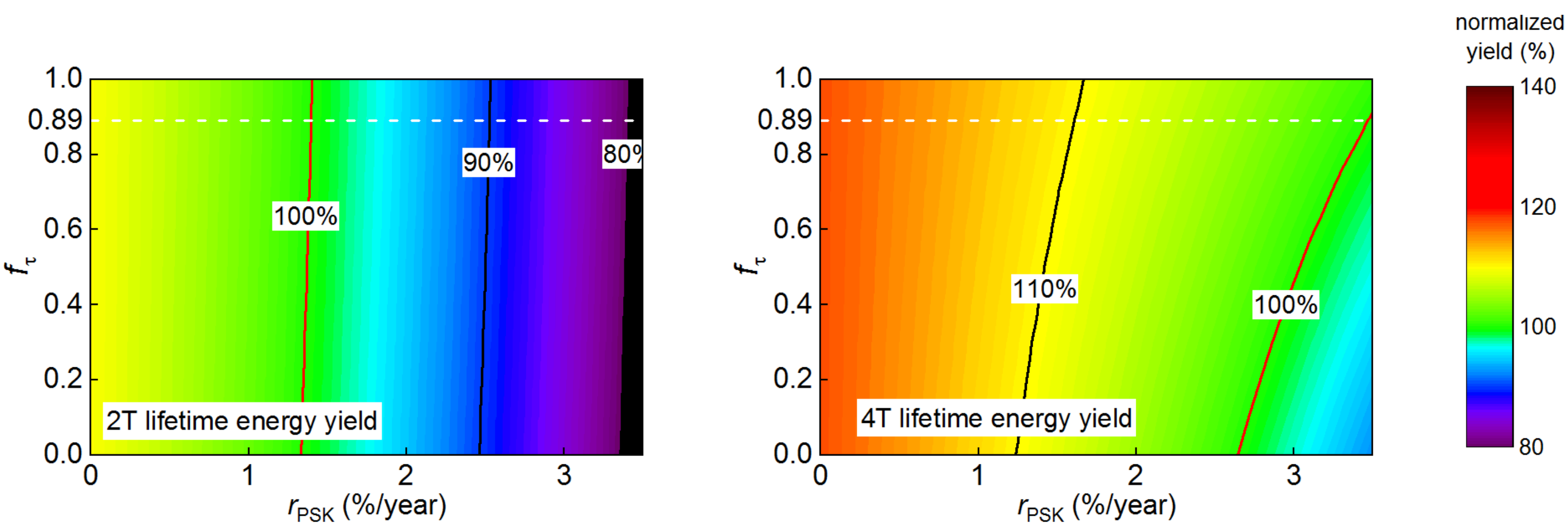
- Comparing annual energy yield for 2T and 4T setup
- Tandem module yield exceeds that of single-junction in early years
- Depending on PSK degradation rate, silicon module yield may exceed tandem module yield in later years



Energy yield

Normalized module yield over 25 year lifetime

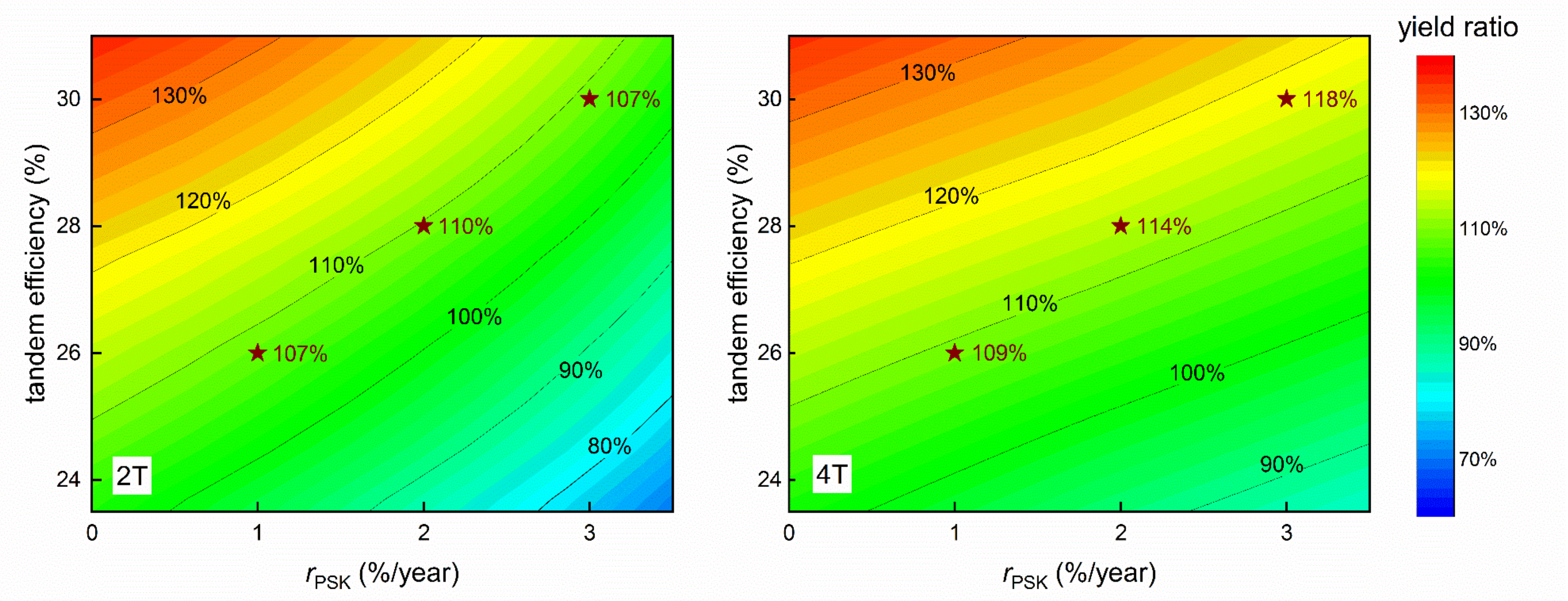
- Energy yield integrated over 25 years for varying PSK degradation rates show for ~1.5% annual PSK cell degradation rate the same total energy yield for a 2T module compared to a single-junction silicon module can be achieved.
- In 4T configuration, lifetime energy yield exceeds that of bare silicon module at the same degradation rates



Future tandem modules

Energy yield for projected PSK / Si PERC tandem in 2025

- Projected 72-cell PERC module assumed with 405 W in 2025
- 2T: A 1% gain in tandem efficiency can offset 0.5% increase in annual PSK degradation rate
- 4T: A 1% gain in tandem efficiency can offset 1% increase in annual PSK degradation rate



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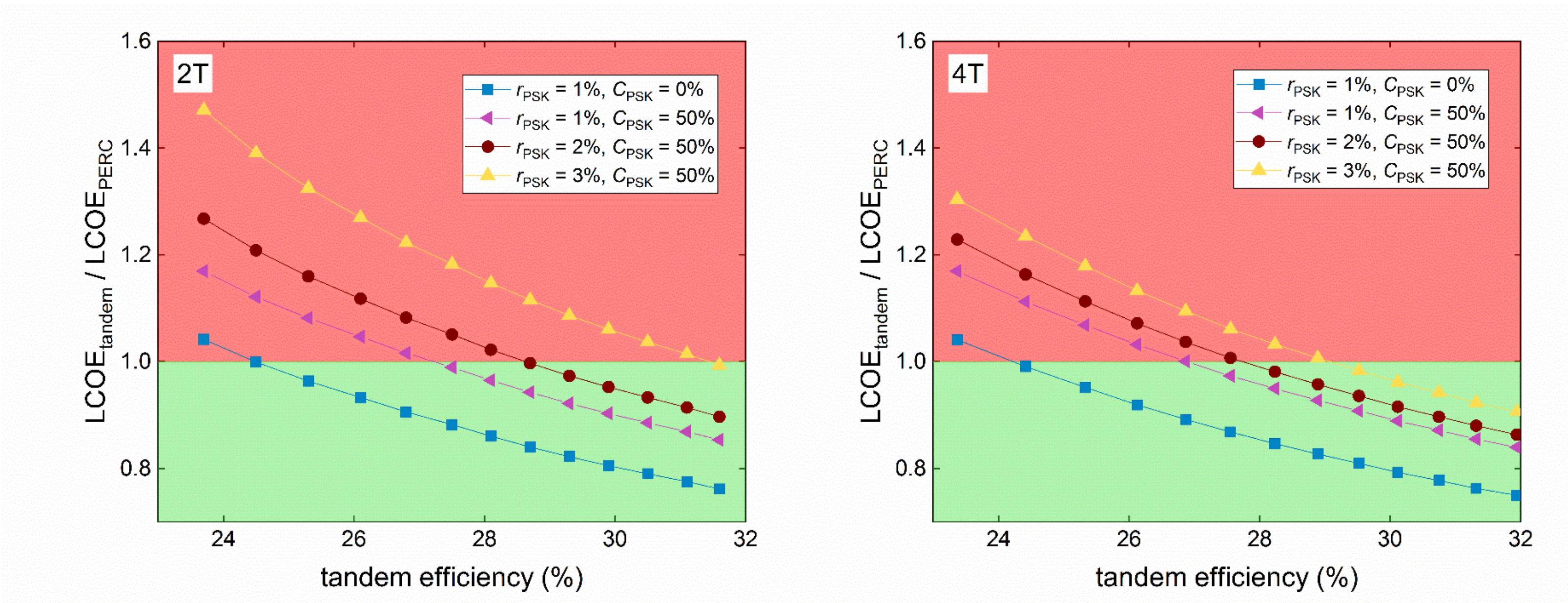
Economic viability

LCOE scenarios for PSK / Si PERC tandem in 2025

- LCOE considering capital and O&M cost and additional cost for PSK cell C_{PSK} in tandem module
- With 50% additional cost for PSK cell, a 28.7% efficient 2T or 27.6% efficient 4T tandem module can be economically competitive if PSK degradation is below 2%

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{t_s} \frac{C_t}{(1+d)^t}}{E_{\mathrm{tandem}}^{\mathrm{lifetime}}}$$

$$C_t \begin{cases} \text{capital cost} & t = 0 \\ \text{O\&M cost} & t > 0 \end{cases}$$



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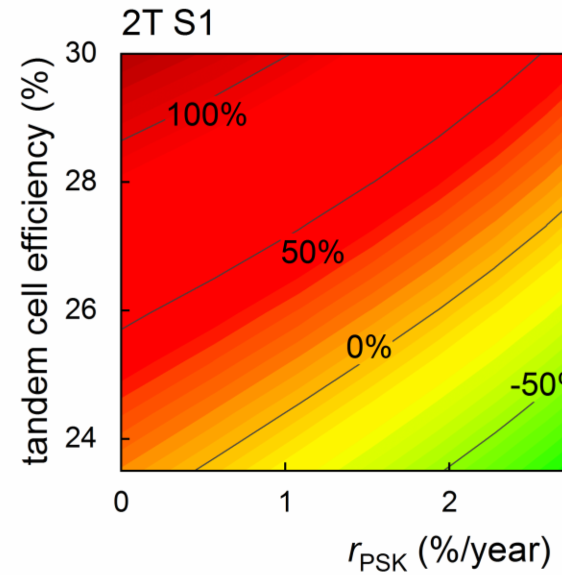
Economic viability

➔ LCOE scenarios for PSK / Si PERC tandem in 2025

- Permitted cost for PSK cell C_{PSK} in tandem module to achieve same LCOE as bare PERC module



Summary

What are the requirements on **perovskite cell degradation** to enable **long-term performance** and **economic viability** of **silicon-based tandem modules**?

- Based on **module power** after 25 years, PSK degradation must stay below **0.9% and 1.3%** for 2T and 4T PSK/Si tandem modules, respectively.
- A **2T PSK/Si tandem** module with **1.5% annual degradation rate** could produce the same **total energy** over a 25 year lifetime.
- A **1% increase in annual degradation rate offsets** the energy yield gains from **2% increase in tandem module efficiency** for a 2T tandem module.
- **Break-even** of **LCOE** could be achieved for a **28.7% efficient 2T or 27.6% efficient 4T tandem** module can be economically competitive if **PSK degradation** is **below 2%** and adding **maximum 50% additional cost** to PERC module production.

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Thank you for your attention

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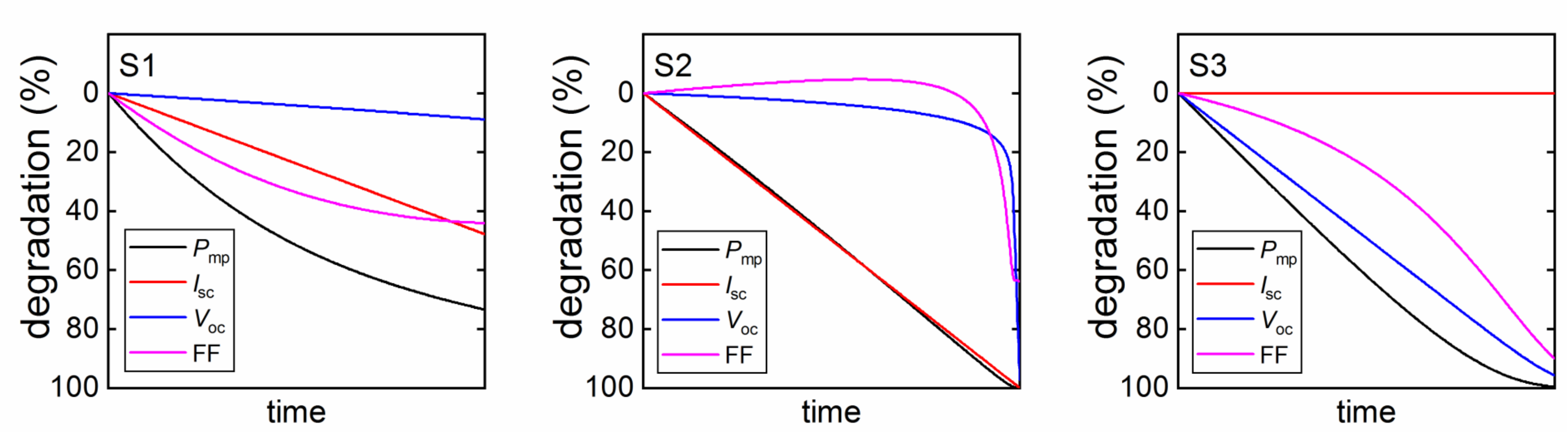
Responsibility for the views, information or advice expressed herein is not accepted by the Australian Government.

PSK cell degradation scenarios

Considering three scenarios

- Scenario S1: *Realistic degradation case* based on measured degradation response
- Scenario S2: *Extreme case* dominated by **current degradation**
- Scenario S3: *Extreme case* dominated by **voltage degradation**



Tandem module power

Normalized tandem module power over 25 year lifetime

- Comparing "realistic" degradation scenario S1 in 2T and 4T configuration
- S2 current-degradation and S3 voltage-degradation scenarios
- Assuming $f_\tau = 0.89$ from experiment