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Supplementary Information for

Impact of Perovskite Solar Cell Degradation on the Lifetime Energy Yield and Economic Viability in Perovskite/Silicon Tandem Modules

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Table S1 Electrical properties of two-terminal and four terminal PSK/Si solar cells and the module configuration used for simulation.

	Cell	Jsc ($mA \cdot cm^{-2}$)	Isc (A)	Voc (V)	FF (-)	PCE (%)
2T[1]	PSK	19.5	4.77	1.05	0.68	14.1
	Si	19.5	4.77	0.73	0.79	11.2
	Tandem					25.3
4T[2]	PSK	21.0	8.39	1.10	0.74	17.1
	Si	17.7	4.32	0.67	0.80	9.6
	Tandem					26.7

Simulation method

One-diode equation

$$J = J_{ph} - J_0\left(e^{\frac{V + J \cdot R_s}{nV_T}} - 1\right) - \frac{V + J \cdot R_s}{R_{sh}}$$

J is the cell current density, J_{ph} is the photo-generated current density, J_0 is the dark-saturation current, *V* is the voltage at the cell, R_s is the series resistance, *n* is the ideality factor at the p-n junction, V_T is the thermal voltage calculated as $\frac{kT}{q}$, where *k* is the Boltzmann constant, *T* is the cell temperature and *q* is the electron charge, R_{sh} is the shunt resistance.

Explicit solution to the one-diode equation using Lambert *W* function[3]

$$V = (J_{ph} + J_0) \cdot R_{sh} - J \cdot (R_s + R_{sh}) - nV_T W\left[\frac{R_{sh} J_0}{nV_T} e^{\frac{R_{sh}(J_{ph} + J_0 - J)}{nV_T}}\right]$$

V_{oc} degradation by degrading J_0

$$J_0^t = J_0^0 \cdot r_v$$

r_v is a coefficient to adjust the open-circuit voltage.

FF degradation by increasing R_s

$$R_s^t = R_s^0 \cdot r_{FF}$$

r_{FF} is a coefficient to adjust the fill factor.

Perovskite cell J_{sc} degradation

$$J_{ph(PSK)}^{t} = J_{ph(PSK)}^{0}(1 - tr_{c(PSK)})(1 - tr_{encp})$$

$J_{ph(PSK)}^{t}$ is the photo-generated current at time *t* with a current degradation rate of $r_{c(PSK)}$ of the perovskite cell and annual optical degradation rate of r_{encp} for the encapsulation.

Silicon cell J_{sc} degradation

$$J_{ph(Si)}^{t} = J_{ph(Si)}^{0}(1 - tr_{c(Si)})(1 - tr_{encp}) + f_\tau(J_{ph(PSK)}^{0} - J_{ph(PSK)}^{0}(1 - tr_{c(PSK)})) \quad (5)$$

$J_{ph(Si)}^{t}$ is the photo-generated current at time *t* with a current degradation rate of $r_{c(Si)}$ of the perovskite cell and annual optical degradation rate of r_{encp} for the encapsulation. Coefficient f_τ represents the correlation between the current degradation at the perovskite top cell and the current increase at the silicon bottom cell due to increased light transmitted. The coefficient f_τ can be calculated as following.

$$f_\tau = \frac{\Delta J_{sc(PSK)}}{\int_{\lambda_{min}}^{\lambda_{max}} \Delta\phi(\lambda) \cdot EQE(\lambda) \cdot d\lambda}$$

$\Delta J_{sc(PSK)}$ is the short-circuit current degradation in the perovskite top cell. $\Delta\phi(\lambda)$ is the photon flux increase at the silicon bottom cell due to the perovskite optical degradation. $EQE(\lambda)$ is the spectral external quantum efficiency of the silicon cell. $\Delta\phi(\lambda)$ can be calculated as:

$$\Delta\phi(\lambda) = \frac{\Delta T(\lambda) \cdot G_{AM1.5g}(\lambda)}{E(\lambda)}$$

$\Delta T(\lambda)$ is the transmittance change of the perovskite cell during degradation, and is measured for a sample cell $G_{AM1.5g}(\lambda)$ is the AM 1.5g spectral irradiance and $E(\lambda)$ is the photon energy, which equals to $\frac{h \cdot c}{\lambda}$, where *h* is Planck's constant and *c* is the speed of light.

Table S2 Simulated degradation rates for encapsulation, Si cell and PSK cell.

	Degradation rate (%/year)				
Parameter	Encapsulation	Si cell	PSK cell		
			S1	S2	S3
I_{sc}	0.3	0			
FF	0	0.09			
V_{oc}	0	0.03			
P_{mp}	N/A	0.3	0-4.7	0-4.5	0-3.5

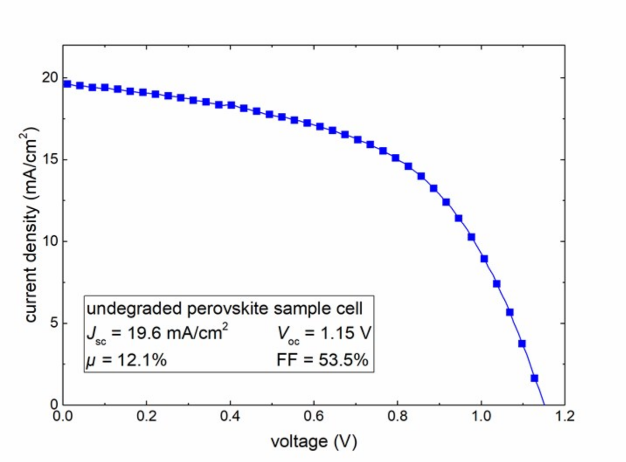

Figure S1 Figure of merit of the perovskite solar cell used for extracting the realistic degradation scenario.

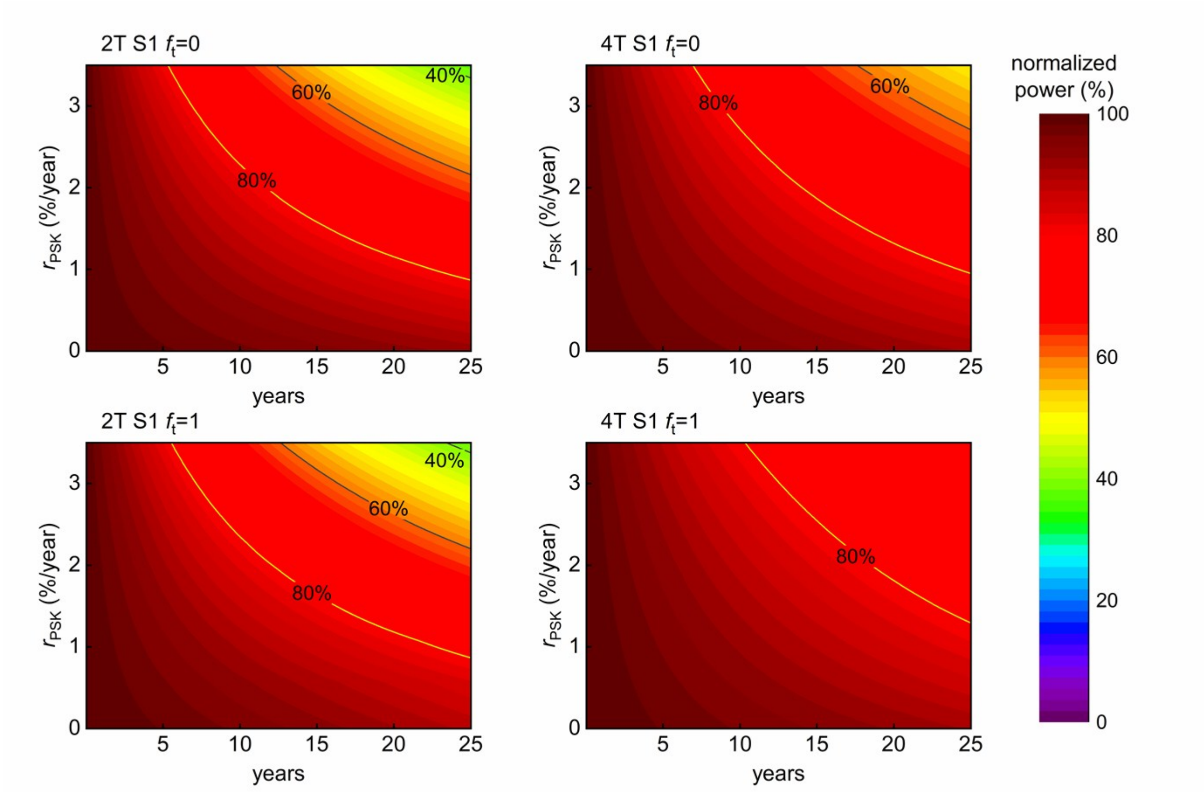

Figure S2 Tandem module power degradation impacted by varying PSK top cell degradation rate over 25 years in Scenario 1, with f_τ= 0 and 1.

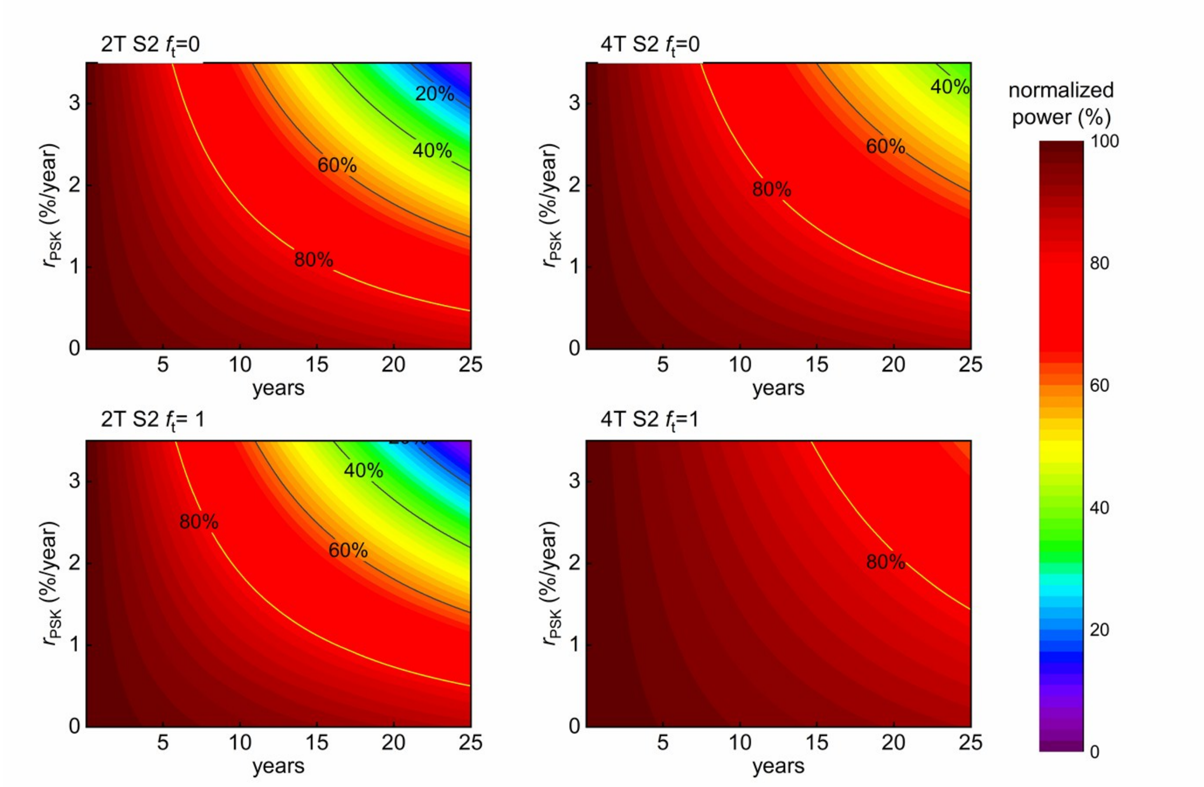

Figure S3 Tandem module power degradation impacted by varying PSK top cell degradation rate over 25 years in Scenario 2, with f_τ = 0 and 1.

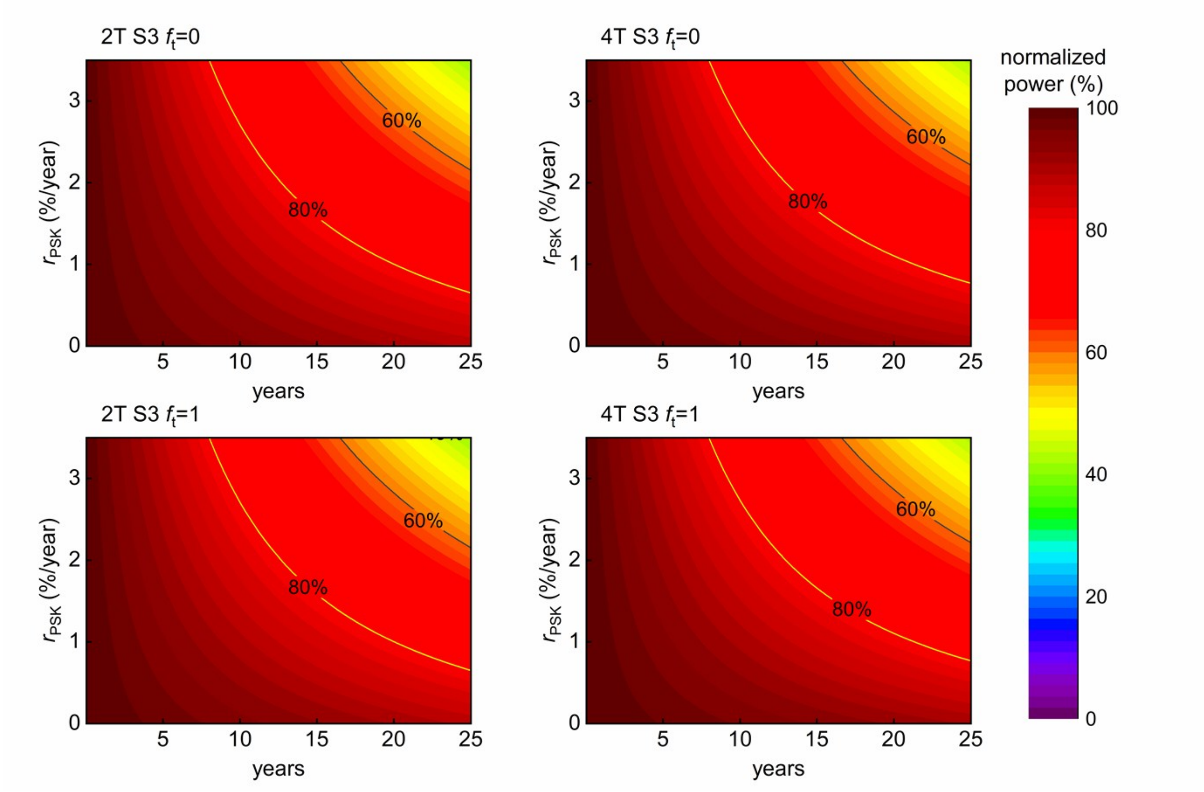

Figure S4 Tandem module power degradation impacted by varying PSK top cell degradation rate over 25 years in S2, with f_τ equals to 0 and 1.

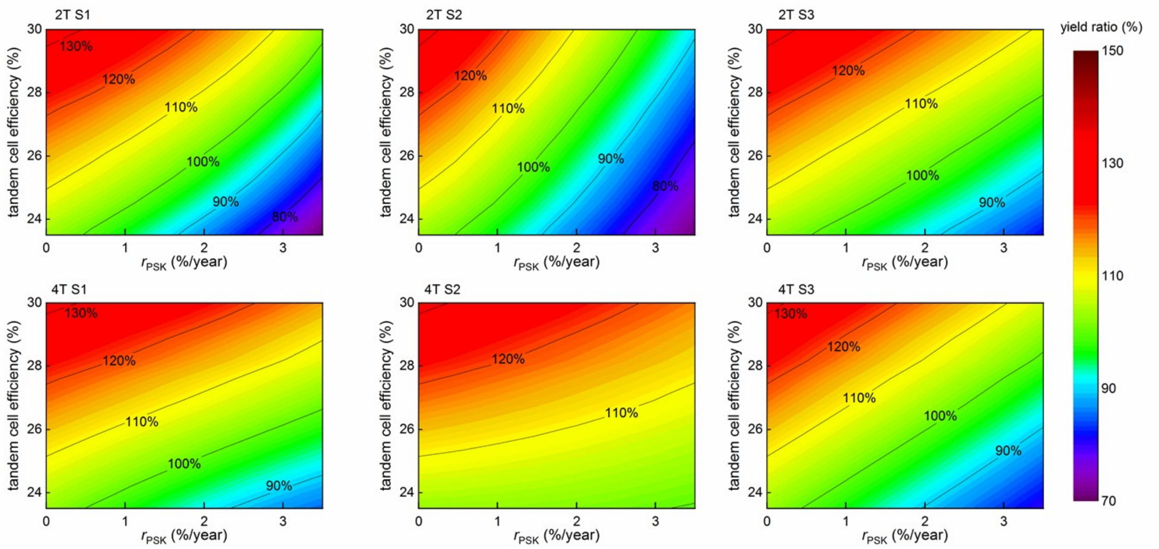

Figure S5 Ratios between the lifetime energy yield of the 2T and 4T tandem modules in S1, S2 and S3 and the projected lifetime energy yield of a 405 W mono c-Si PERC module in 2025. The encapsulation and Si cells in tandem modules and the 2025 PERC modules are assumed to degradation be 0.4%/year. A future energy discount rate of 5%/ year and constant f_τ = 0.89 is used.

Table S3 Cost components used to simulate the LCOE of PSK/Si tandem modules and the mono c-Si PERC module in 2025.[4]

			Unit Cost	PERC module in 2025	PSK/Si tandem module
Additional cost of tandem processing				0	C_{PSK}
Module power				405	P_{tandem}
Category		Sub-category	Cost ($/W)	Cost ($/module)	Cost ($/module)
Module type dependent cost	Capital Cost				
	Soft cost		0.25	101	
	System cost				
	Module	encapsulation	0.096	39	
		Si cell	0.057	23	
		Si wafer	0.047	19	
		Si material	0.06	24	
		total	0.26	104	104+C_{PSK}
	Inverter		0.05	20	$0.05 \times P_{tandem}$
Module type independent cost	Wiring		0.12	50	
	Mounting		0.091	37	
	Ground		0.050	20	
	O&M cost per year		0.0065	2.6	
	Total O&M cost over 25 years		0.23	92	
Total Cost ($)			1.05	425	$\underline{405 + 0.05 \times P_{tandem} + C_{PSK}}$

Table S4 Latitude and annual solar insolation in Perth in comparison with other cities in the world[5].

City	Latitude	Annual Solar Insolation (kWh·m^2)
Perth, Australia	31.953° S	2133
Los Angeles, US	34.054° N	2239
Denver, US	39.739° N	1940
Mexico City, Mexico	19.433° N	2187
Berlin, Germany	52.5200° N	1284
Paris, France	48.857° N	1369
Qinghai, China	36.000° N	1921
Singapore, Singapore	1.290° N	1735
Riyadh, Saudi Arabia	24.632° N	2494
New Delhi, India	28.614° N	2139

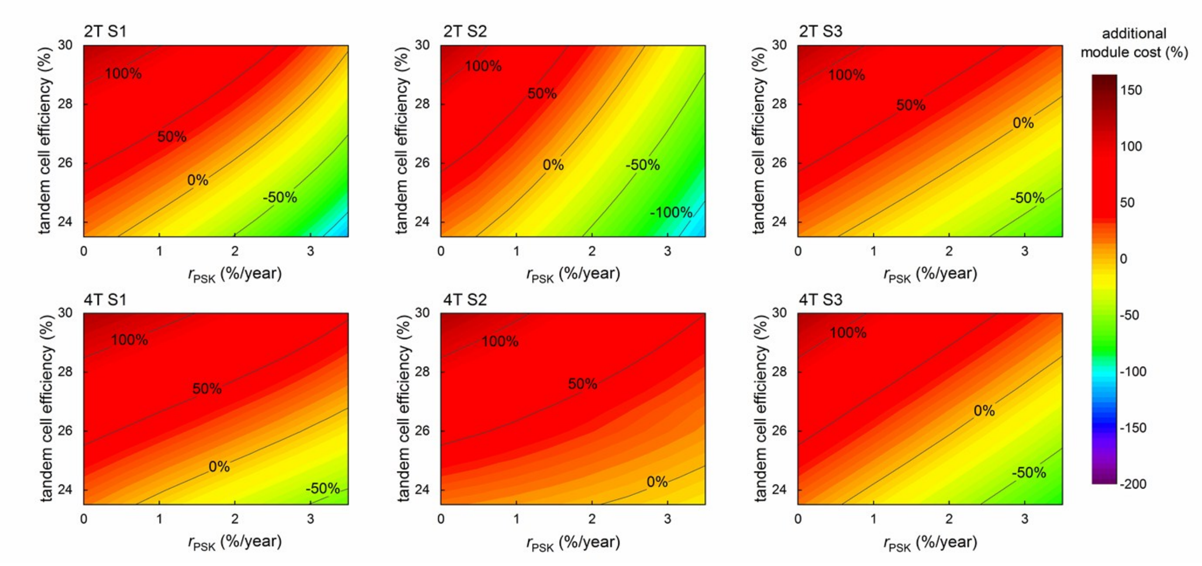

Figure S6 Simulated permissible C_{PSK} for 2T and 4T tandem modules in the three degradation scenarios (S1, S2 and S3) to breakeven with the mono c-Si PERC module in 2025. The encapsulation and Si cells in tandem modules and the 2025 PERC modules are assumed to degradation be 0.4% per year. A future energy discount rate of 5%/ year and a fixed f_{τ} value of 0.89 is used.

Reference

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3 A. Jain and A. Kapoor, *Sol. Energy Mater Sol. Cells*, 2004, **81**, 269-277.

4 ITRPV working group International technology roadmap for photovoltaic (ITRPV) - 2017 Results, Technical Report (March, 2018)

5 Photovoltaic Geographical Information System, http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#HR, accessed March 2019