Packaging Technology for Ultrathin Silicon Solar Cells: Improved Packing Density and Achieving Over 10 Years Lifespan in Space with Minimum Degradation

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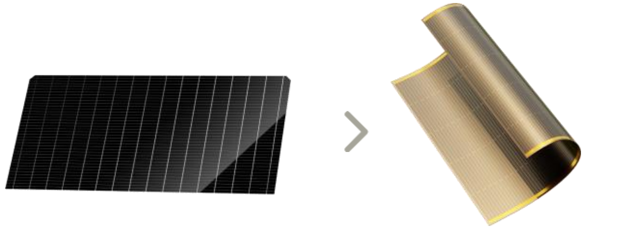
40th Space Power Workshop, 2023
Torrance, CA

Contents

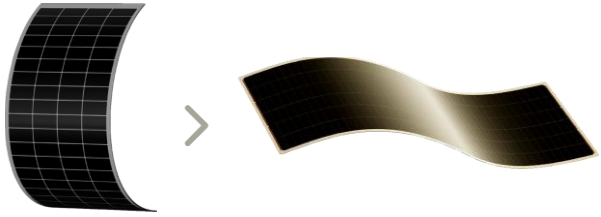
Introduction

- Small business based in Tempe, AZ
- 20 full-time employees
- Product: silicon solar cells and SPMs (blankets) optimized for space
- 100% US made / Si wafer
- 10 MW/year production starting 2025
- <$20/W blanket level cost
- >10 years lifespan

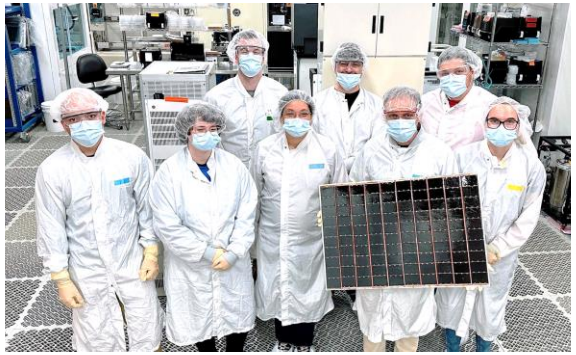
- Previously known as Regher Solar



Terrestrial Si solar cell → solestial



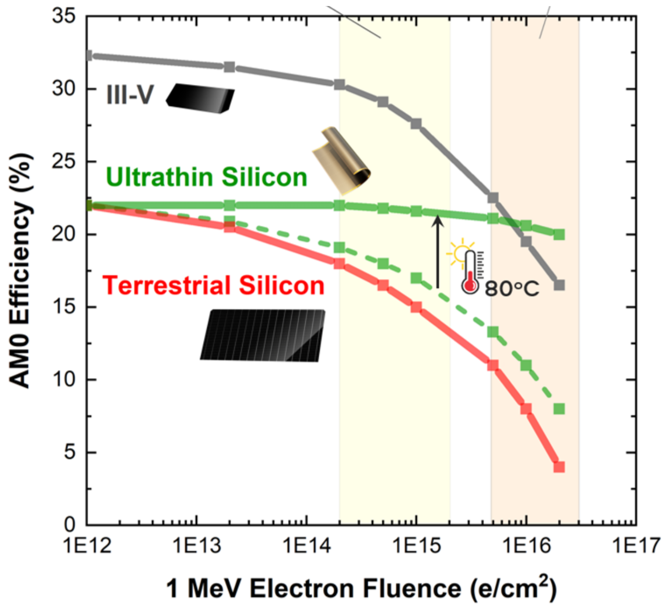
Terrestrial Si solar blanket → solestial

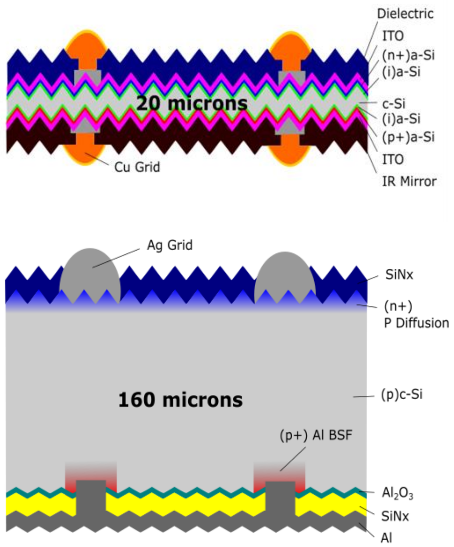


Why thin silicon heterojunction solar cells?

- Radiation damage can be annealed at 80ºC.
- Can self-cure radiation damage at normal operation conditions.
- **Need 20-micron-thick cells.**

- Other advantages:
  - Low weight
  - Low temperature coefficient
  - Robust electroplated metallization



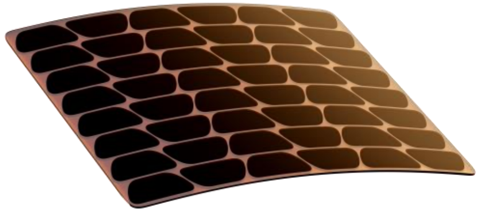


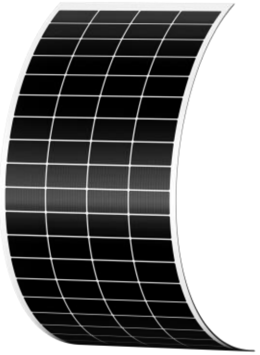
Thin Silicon Heterojunction

Terrestrial Silicon (PERC)

Packaging challenge

- Existing packaging processes are not suitable for 20-micron-thick silicon cells.

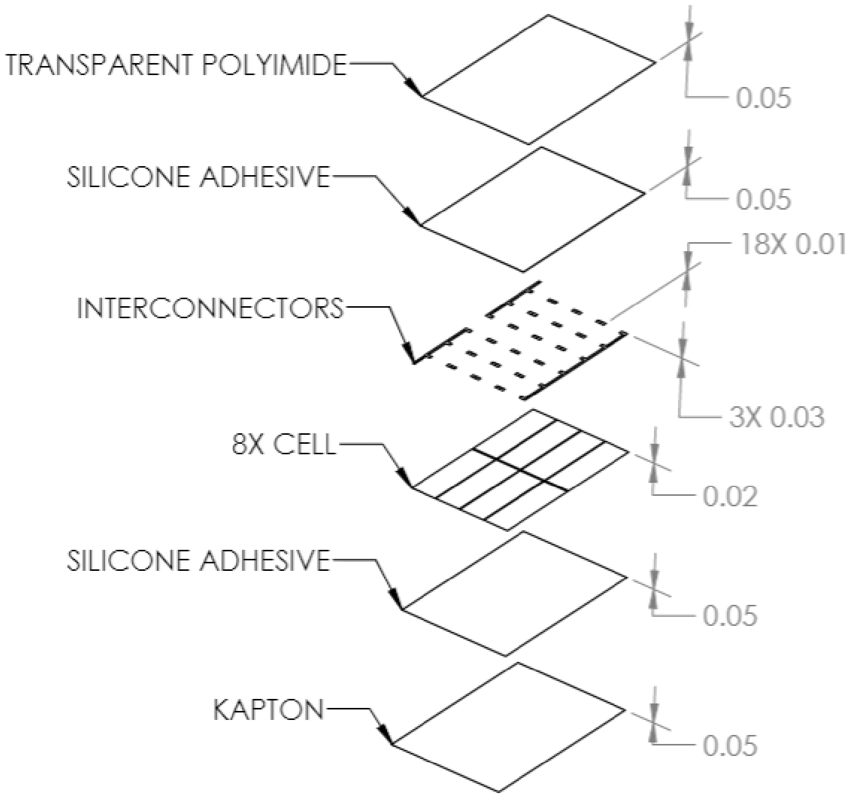




Technology Component	State of Practice Space Solar Blanket	Terrestrial Solar Blanket
Process flow	Individual cell lamination, stringing, lay-down	Stringing, full module lamination
Interconnects	Welding, 3-5 interconnects, joints at the edge	Soldering, 9-12 wires, multiple joints across cell
Transparent cover	Quartz glass, 50 um	ETFE, 1-2 mm
Encapsulants	Silicone	EVA/Polyolefin
Substrate	Polyimide	PVF, PVDF, etc.
Expected lifespan	>20 years	2-4 years
Cost	$100-$300/W	$0.1/W
Automation	1-2 MW	1,000 MW

New lamination & interconnection process for thin Si solar cells

- Concept: full lamination first, form joints after
- Process flow:
  - Apply rear silicone
  - Cells and interconnectors lay-down
  - Apply front silicone
  - Laminate
  - Open interconnectors
  - Form metal joints
  - Deposit capping layers



Flexible cell sizing and integrated processing

- Key capability – cell size variability

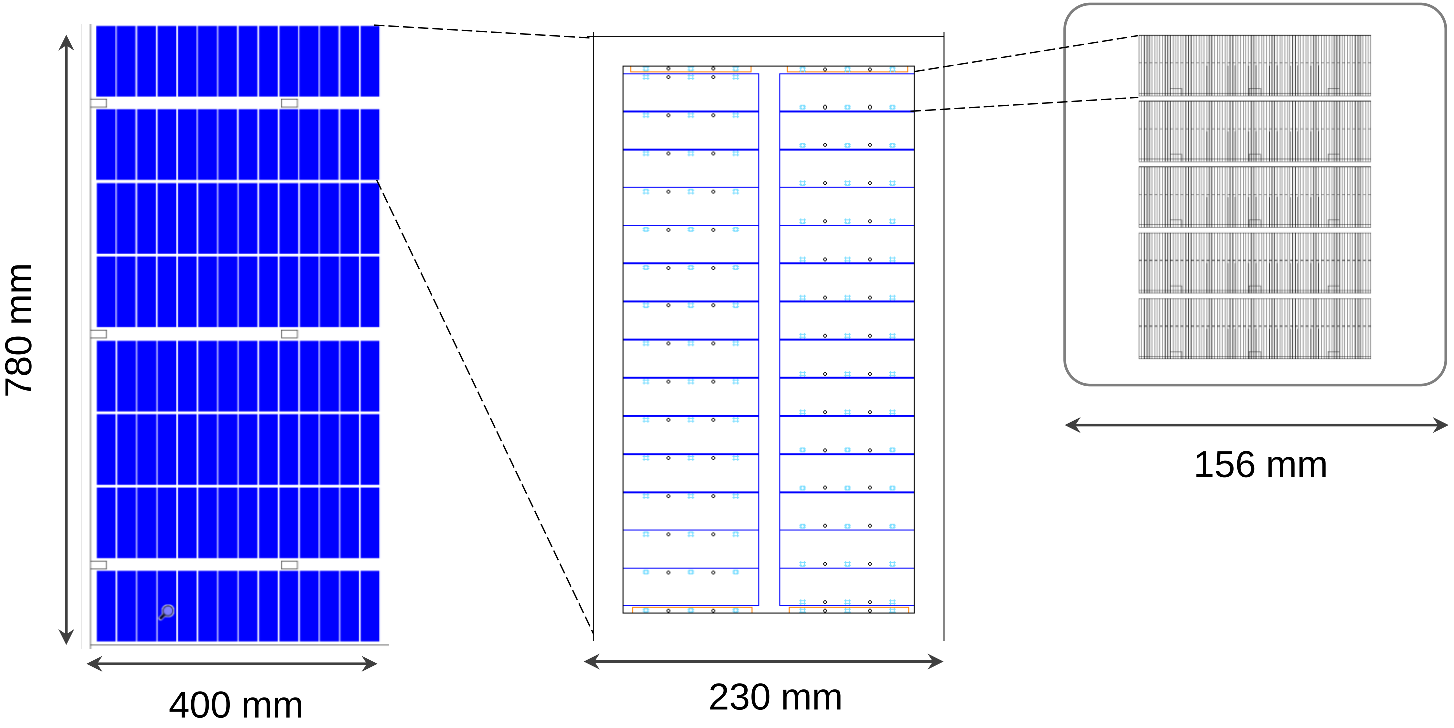
- Panel design is defined by 6 drawings:
  - Laydown of cells and interconnectors
  - Substrate cutting pattern
  - Cell metal mask
  - Cell dicing pattern
  - Interconnectors
  - Films openings

- Make cells, substrates, interconnectors and assemble in-house

Step 1
Panel design

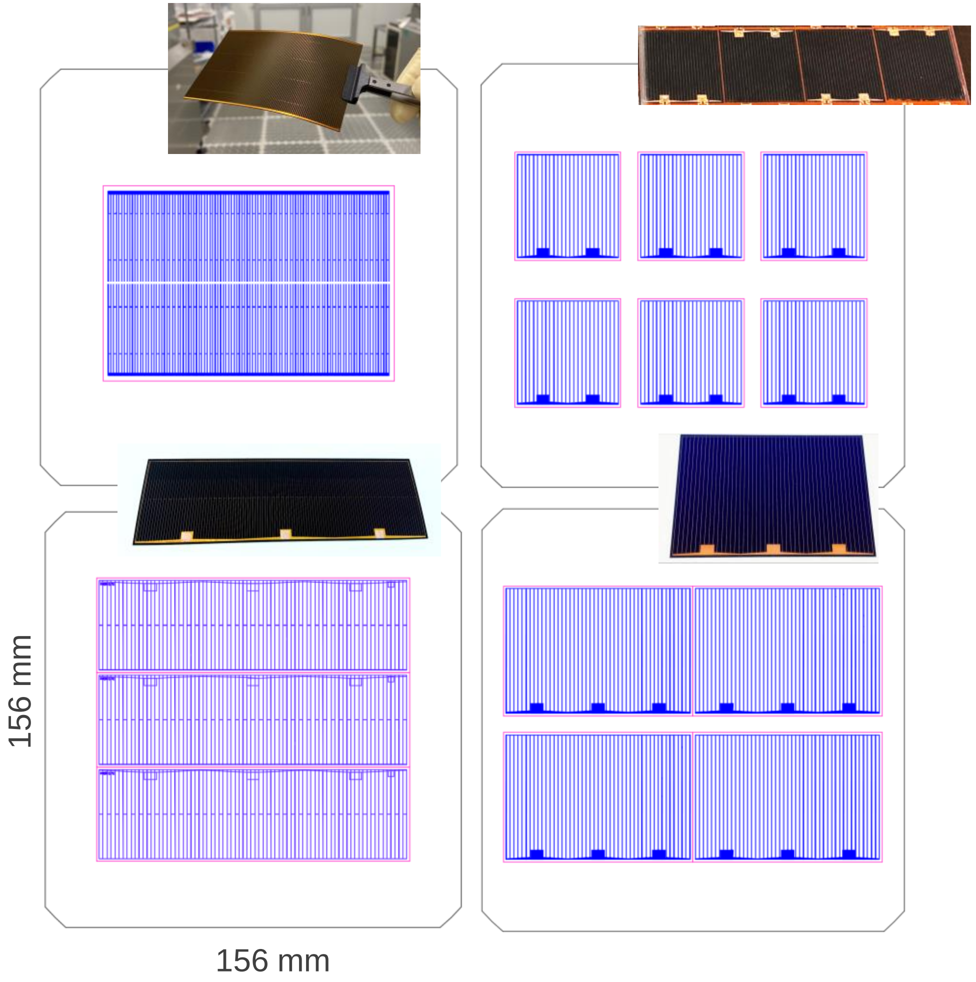
Step 2
Blanket design

Step 3
Cell design



Flexible cell sizing examples

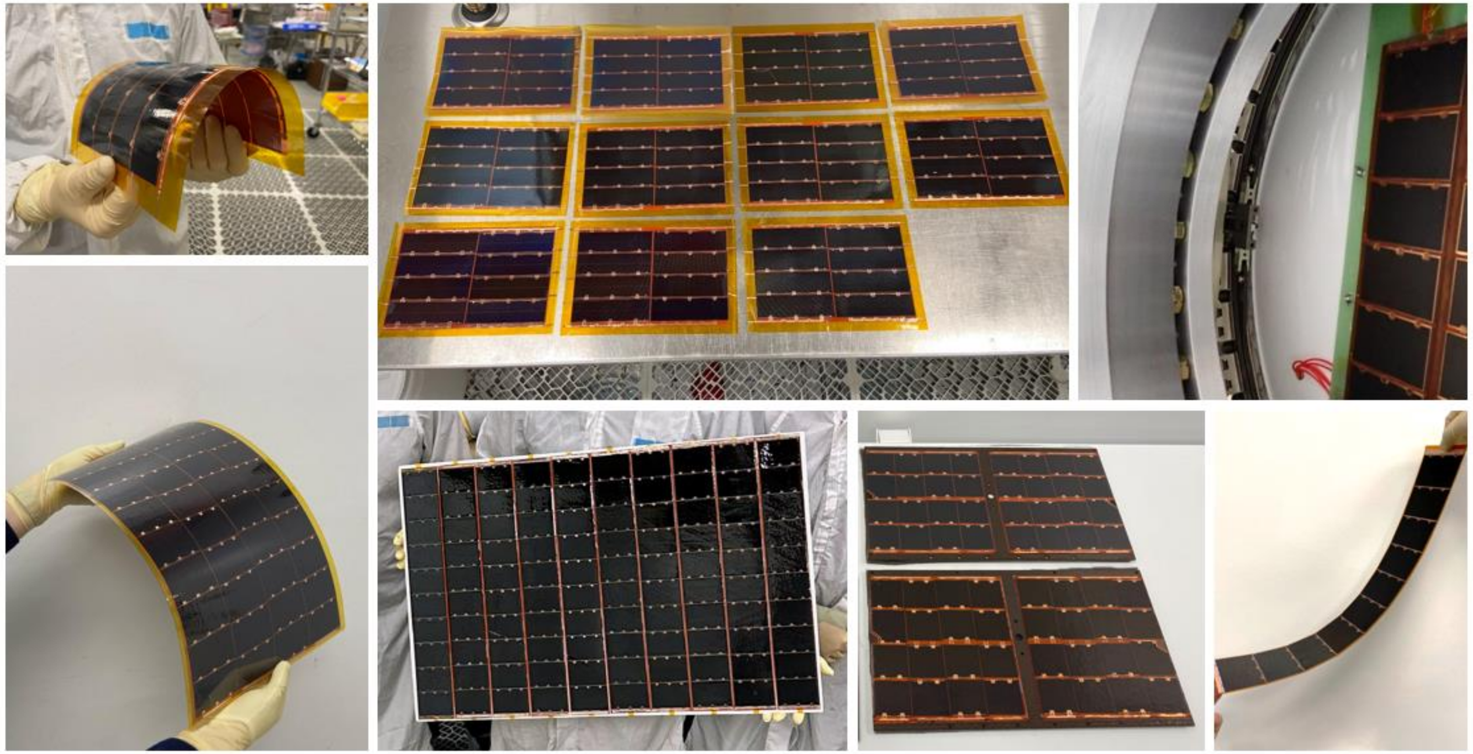
- Demonstrated multiple cell design in pilot production.
- No tradeoffs with cost due to low Si wafer cost ($1-2 per piece).



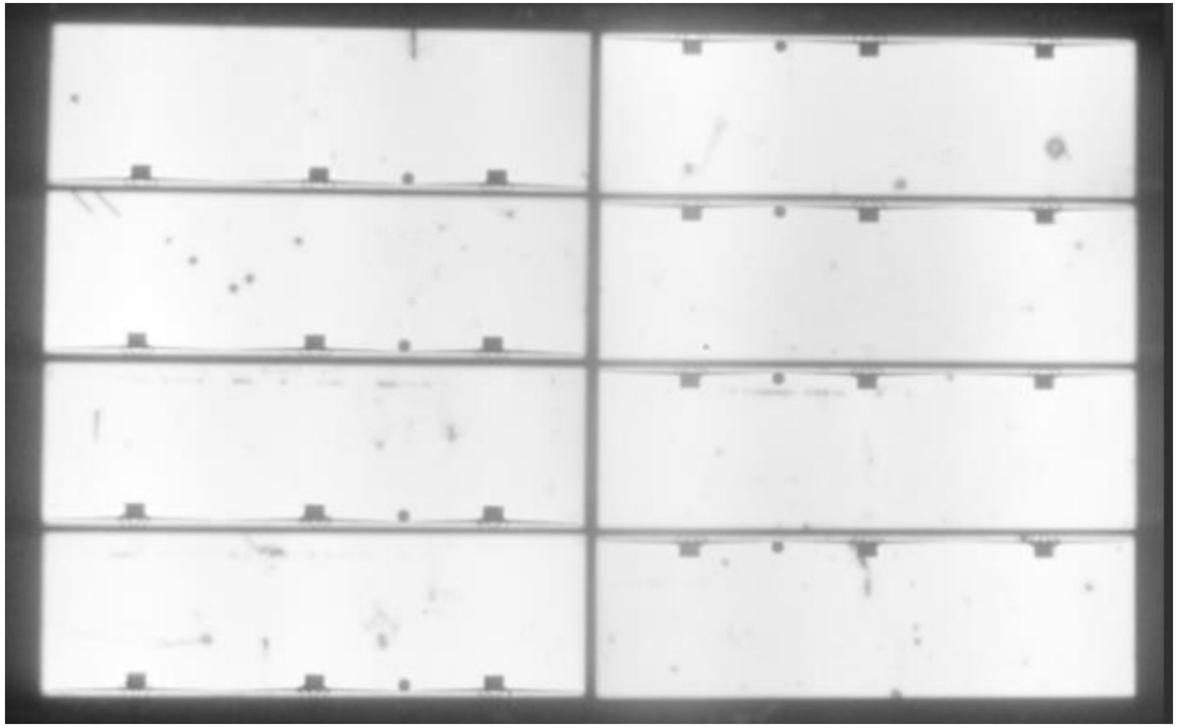
Demo blankets

- Demonstrated the blankets with a variety of form-factors.
- No air trapped, passed Tvac.
- Presently testing for silicone outgassing.

- 3 mini blankets flew on Transporter 6 in Jan 23.
- 3 sets of blankets delivered to development partners, integrated and waiting for flights.

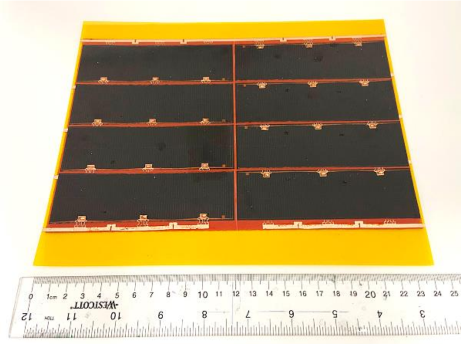


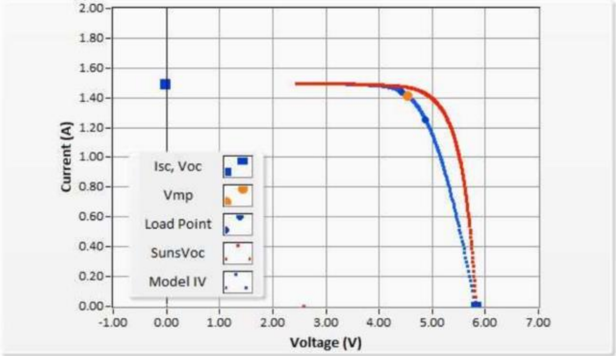
Blanket performance



Electroluminescence image

Parameter	Output	Parameter	Normalized Output
Isc (A)	1.498	Jsc (A/cm2)	0.03653
Voc (V)	5.825	Voc (V/cell)	0.7281
Imp (A)	1.419	Jmp (A/cm2)	0.03461
Vmp (V)	4.513	Vmp (V/cell)	0.5642
Pmp (W)	6.405	Pmp (W/cm2)	0.01953
FF (%)	73.41	Efficiency (%)	19.53 / 17% AM0

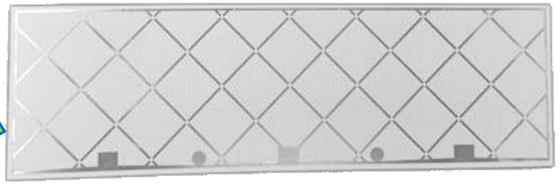


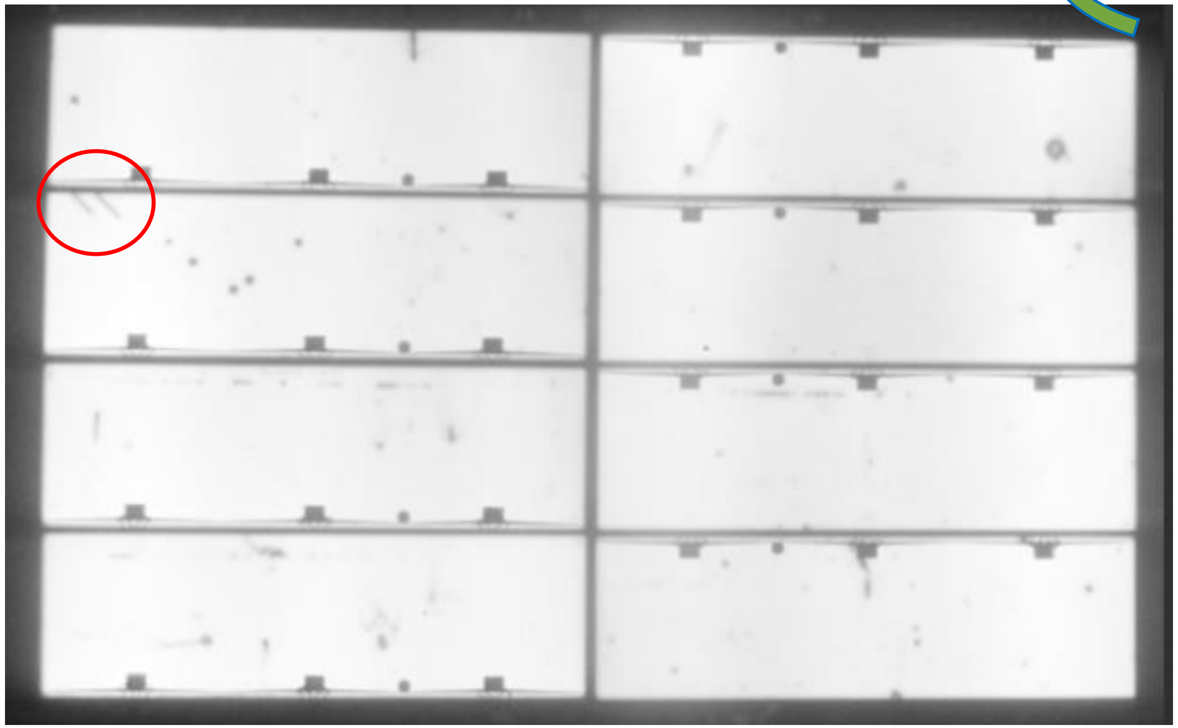


AM 1.5 IV of the best blanket produced as of Feb 2023

Blanket performance – crack mitigation

Rear side of the cell reinforced with metal





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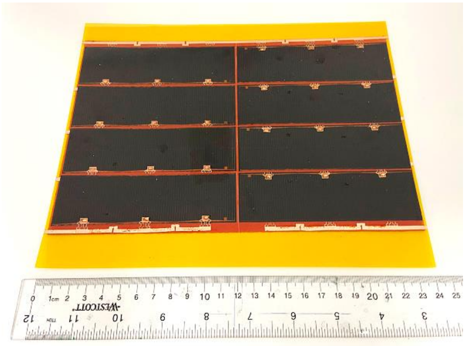
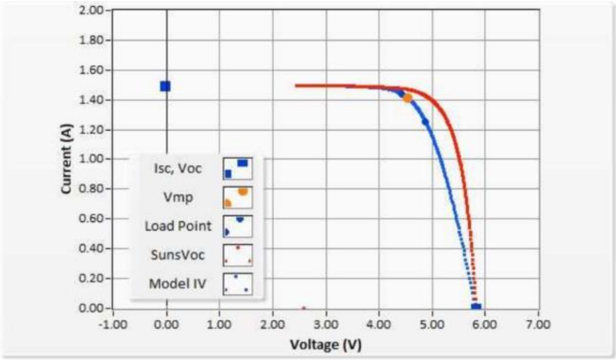
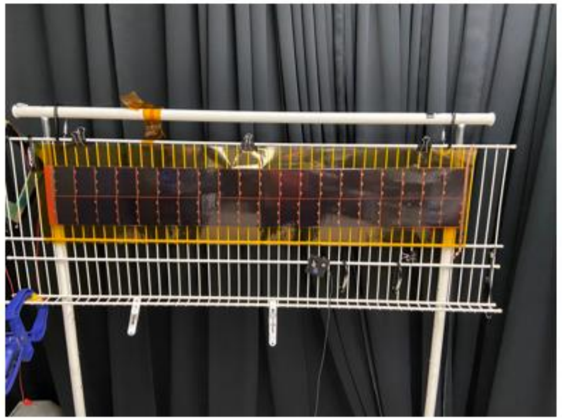


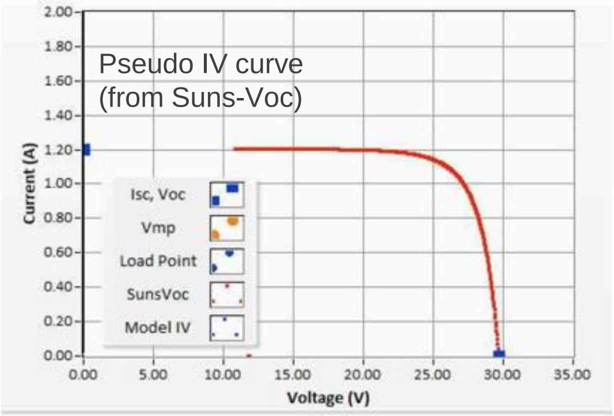


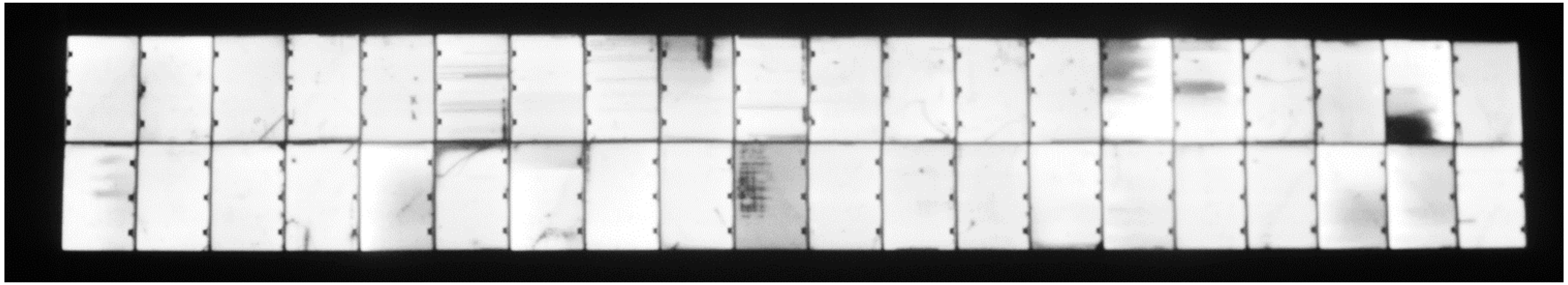
Electroluminescence image

AM 1.5 IV of the best blanket produced as of Feb 2023

1 meter processing capability



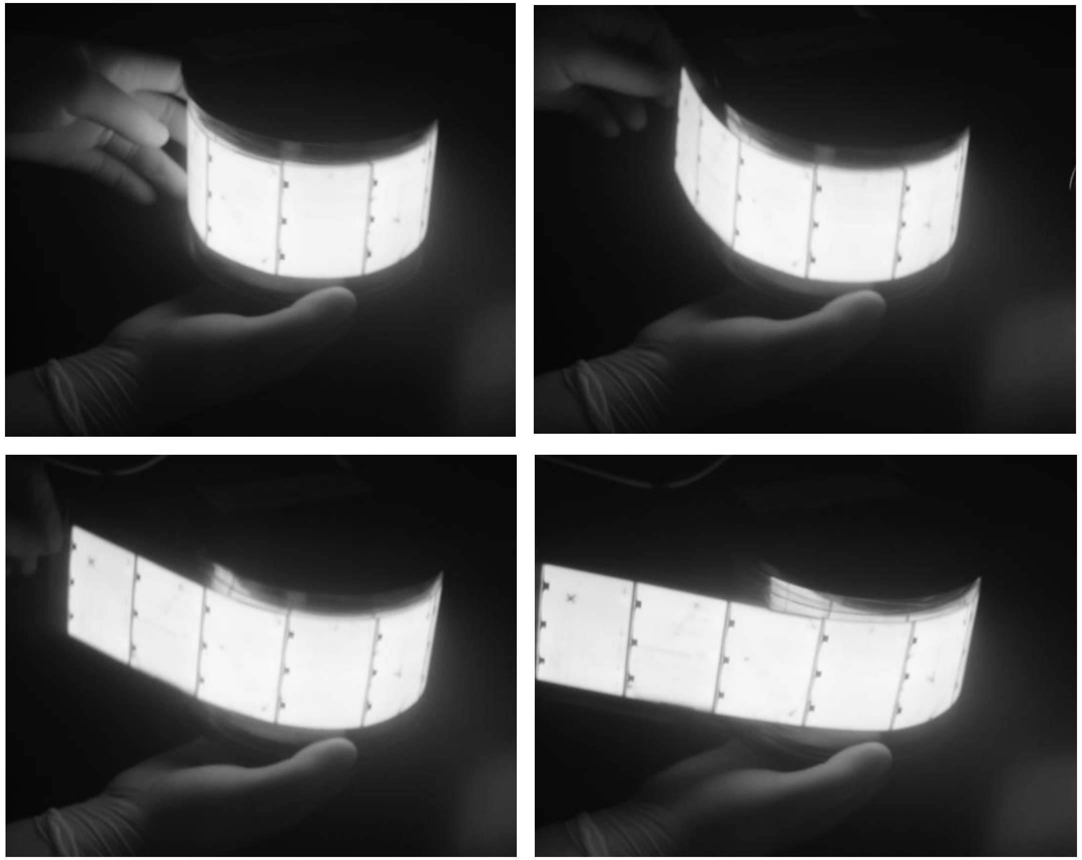




Electroluminescence image

Flexibility

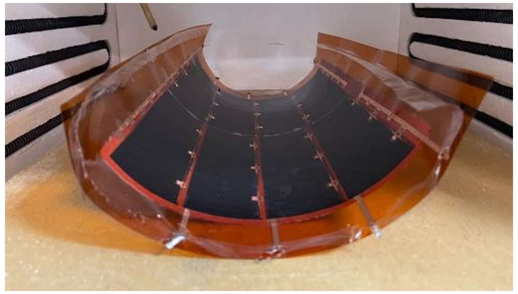
20 um device	Bending diameter
Bare wafer	Sharpie
Cell with metal	3 cm
Blankets	10 cm
Blanket, 60 um cells	15 cm



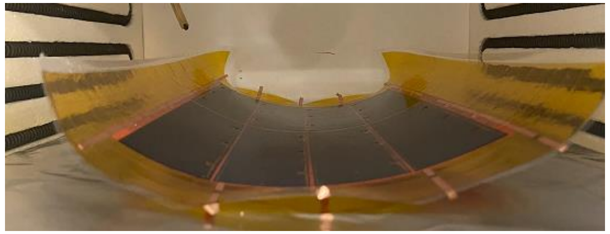
Electroluminescence images

Temperature cycling of thin Si blankets

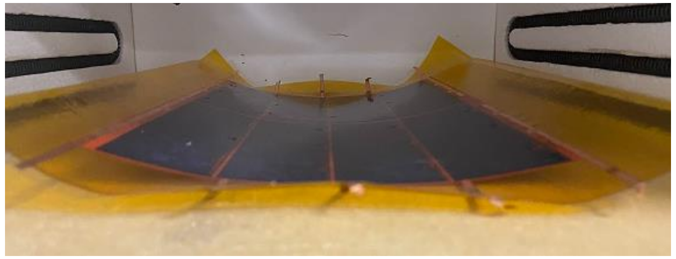
- Started -170º/+150ºC cycling
- Free-standing blankets failed due to bowing and cells cracking
- Three ways to mitigate the bow:
  - Thinner Kapton
  - Thermal treatment of Kapton



5 mil Kapton HN



2 mil Kapton HN

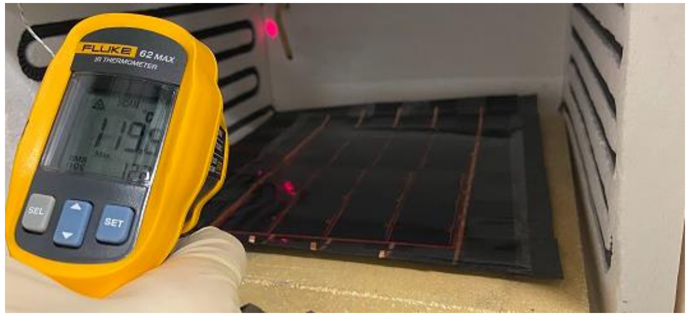


2 mil Kapton HN after thermal treatment at 150ºC for 1 hour

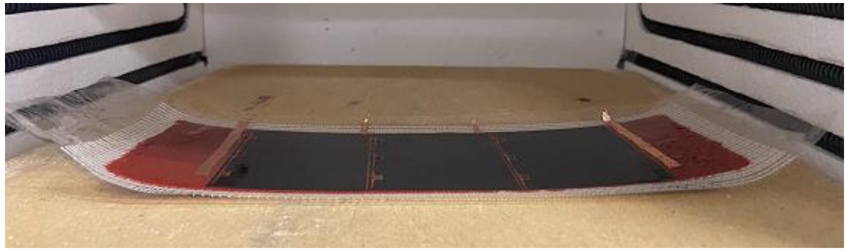
Photos of the blankets in the muffle furnace at 120ºC

Temperature cycling of thin Si blankets

- Replace polyimide substrates with carbon fiber fabric and fiberglass mesh.



Cells on a carbon-fiber fabric substrate with a 2 mil Mylar cover having acceptable stress.

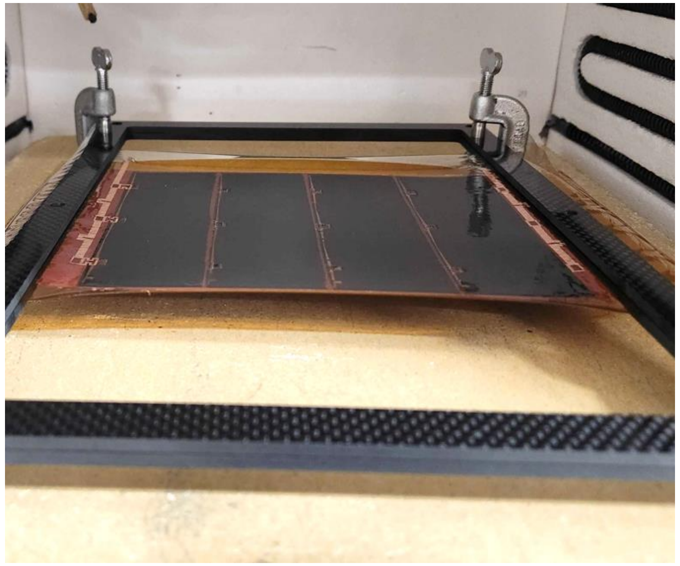


A ‘thick’ fiberglass substrate with minimum stress.

Photos of the blankets in the muffle furnace at 120^{o}C

Temperature cycling of thin Si blankets

- Framing the blankets.
- Blankets remain flat at both hot and cold temperatures.
- T cycling data is being collected at the moment.

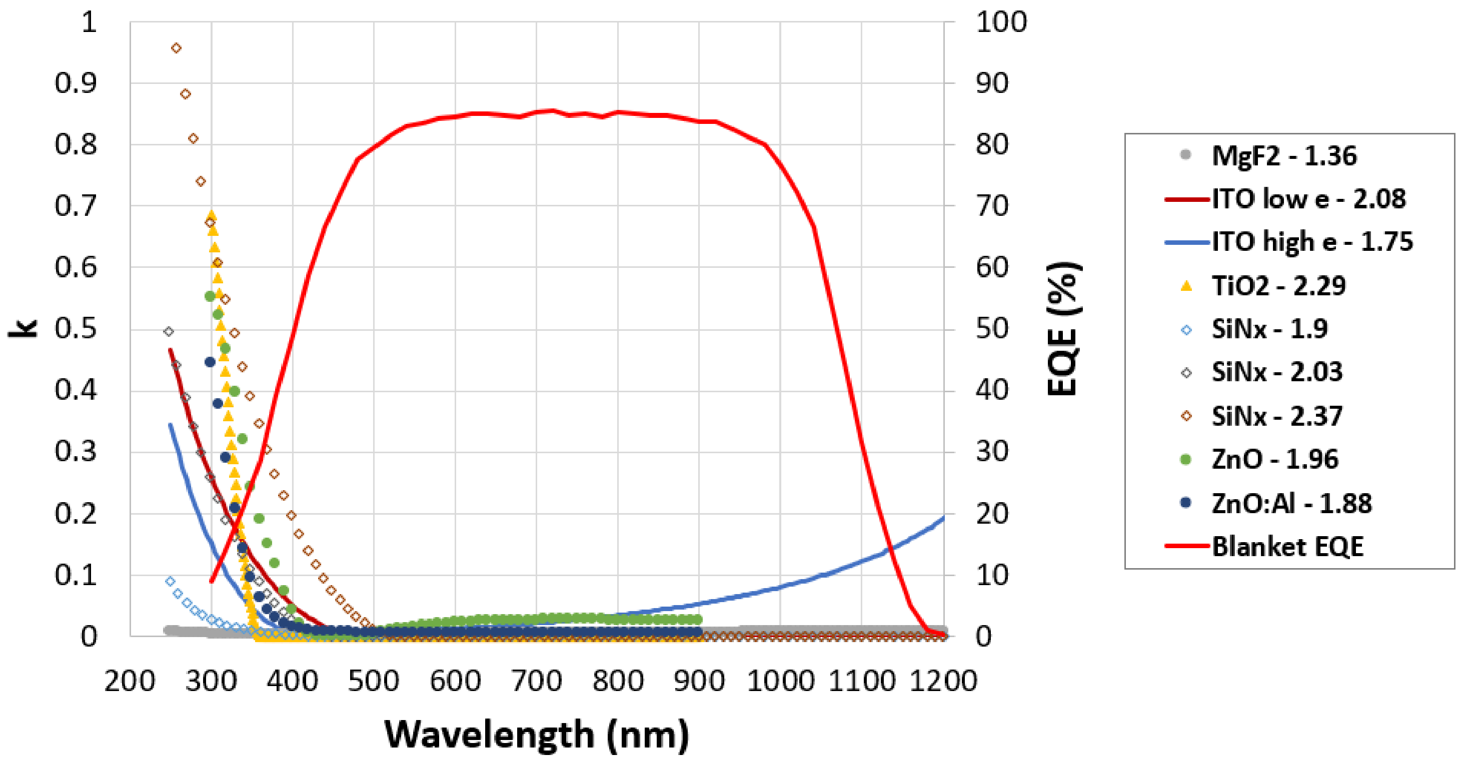


Blankets in the muffle furnace at 120ºC

Blanket submerged in liquid nitrogen.

Front transparent coating

- Need UV and AO protection.
- Good UV filters: TiO_2, SiN_x, ZnO
- Good AO barriers: SiO_x, Al_2O_3
- Also need good index matching
  - 100 nm nm TiO_2 – 6 mA/cm^2 loss.
  - 100 nm ZnO:A – 3 mA/cm^2 loss.
- There is no protection from electrons.
- Possible solution – reduce the thickness of polymers to minimum needed for mechanical stability.



Mass

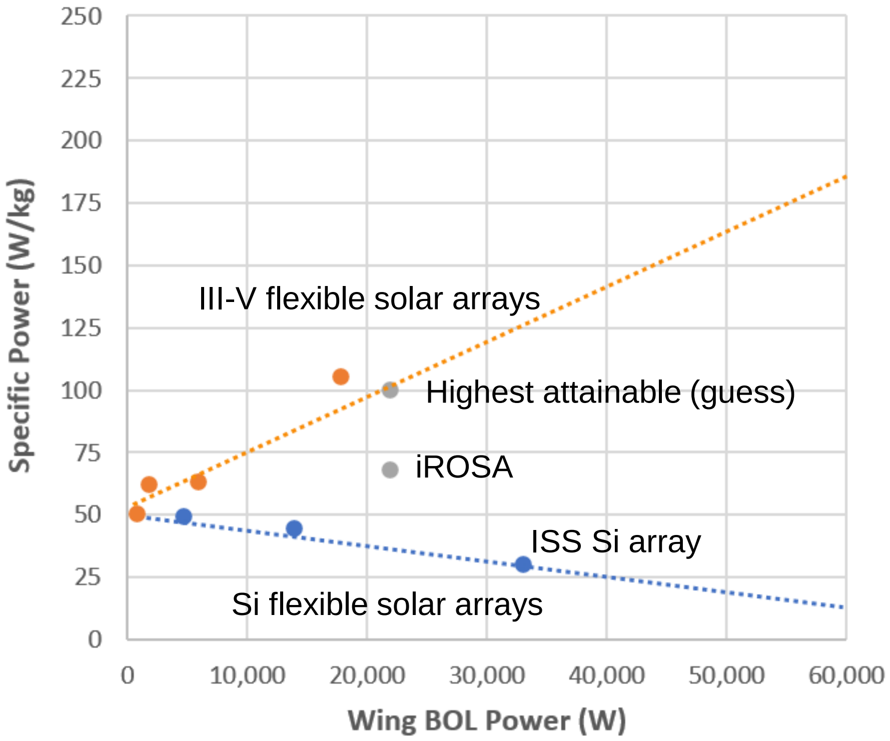
- 500-600 g/m² blanket mass density
- 270-300 W/m² blanket power density
  - 22% AM0 cells
  - 0.95 packing density
- 500-600 W/kg blanket specific power

Layer	Thickness (μm)	Mass area density (g/m²)
Front cover	50	68
Front encapsulant	50	53
Front metal	10	6
Silicon	20	47
Rear metal	10	9
Rear encapsulant	50	63
Rear substrate	50	71
Interconnectors	25	44
Total		**361**

Breaking through silicon array mass trend

- Increasing the size of silicon array compromises its mass.
- Large size III-V arrays are challenging because of cost and CIC mass.

- Solestial blanket
  - 500-600 W/kg
  - 270-300 W/m^2



Data: J. Gibb, IEEE 2018
iROSA datapoint: Solestial internal estimate from public data (22 kW, 325 kg)

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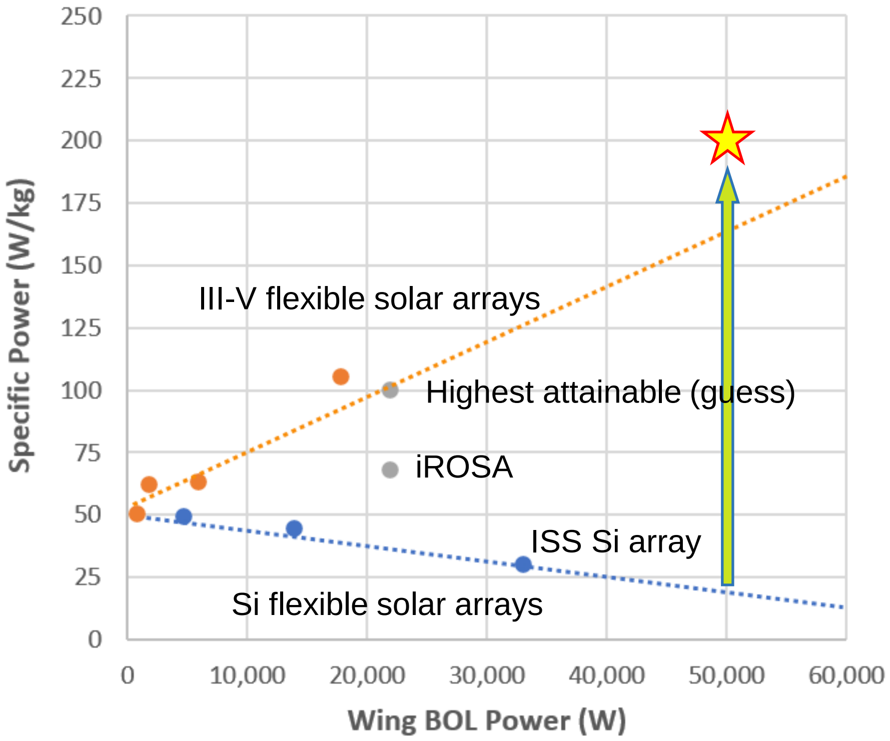

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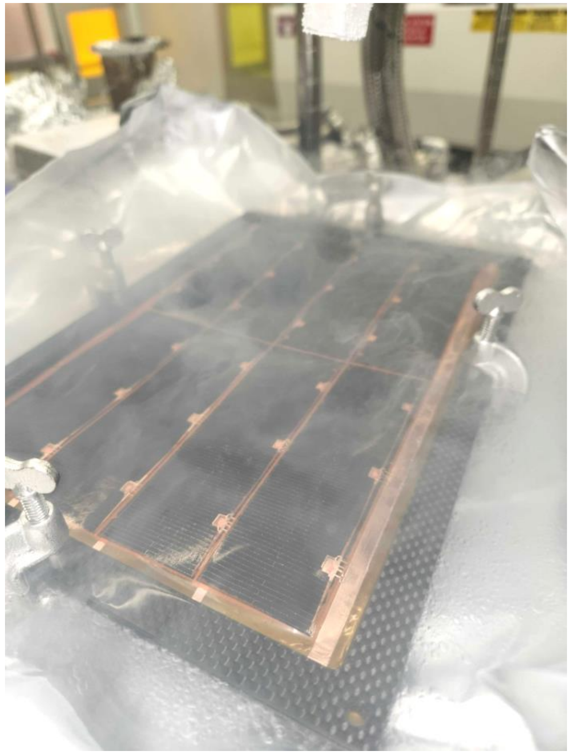
Conclusion

- Solestial developed a novel way to interconnect and laminate thin silicon solar cells which can be fully automated and achieve $20/W blanket cost.
- We used the combination of materials and techniques that can achieve over 10 years lifespan in space with minimum degradation. We will publish the results of accelerated stress testing later in 2023.
- The developed blanket design relies on superior radiation hardness of thin silicon solar cells. Solestial is working on third-party verification of low temperature annealing feature of our solar cells.
- If coupled with advanced solar array deployment system thin Si blankets with 500-600 W/kg specific mass and 270-300 W/m^2 can enable very large size solar arrays with up to 200 W/kg array level specific power.



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Thank you!