NREL
Transforming ENERGY

Bifacial PV: de tudo um pouco

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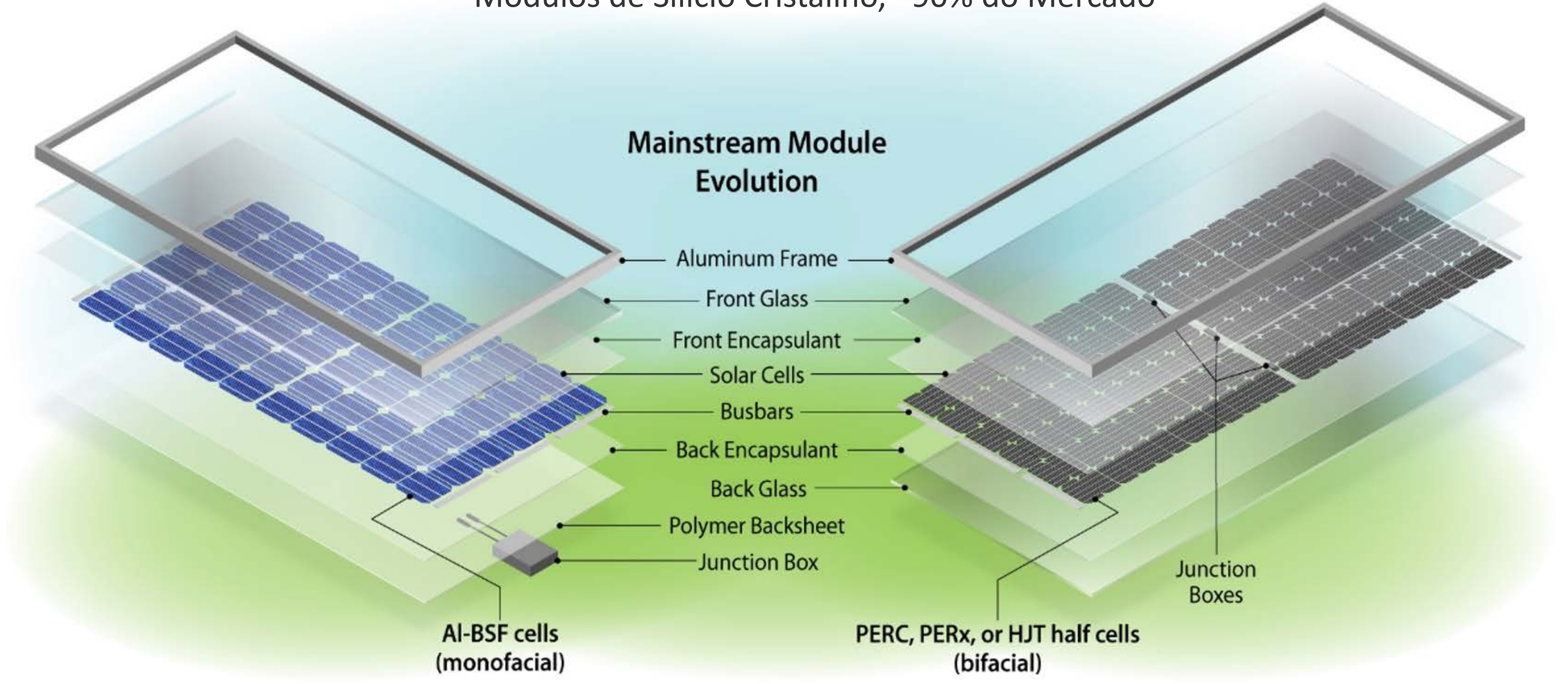
Seminário na Fotovoltaica-UFSC

Maio 23, 2024 Florianópolis, SC

A tecnologia fotovoltaica evolui constantemente

Módulos de Silício Cristalino, ~90% do Mercado

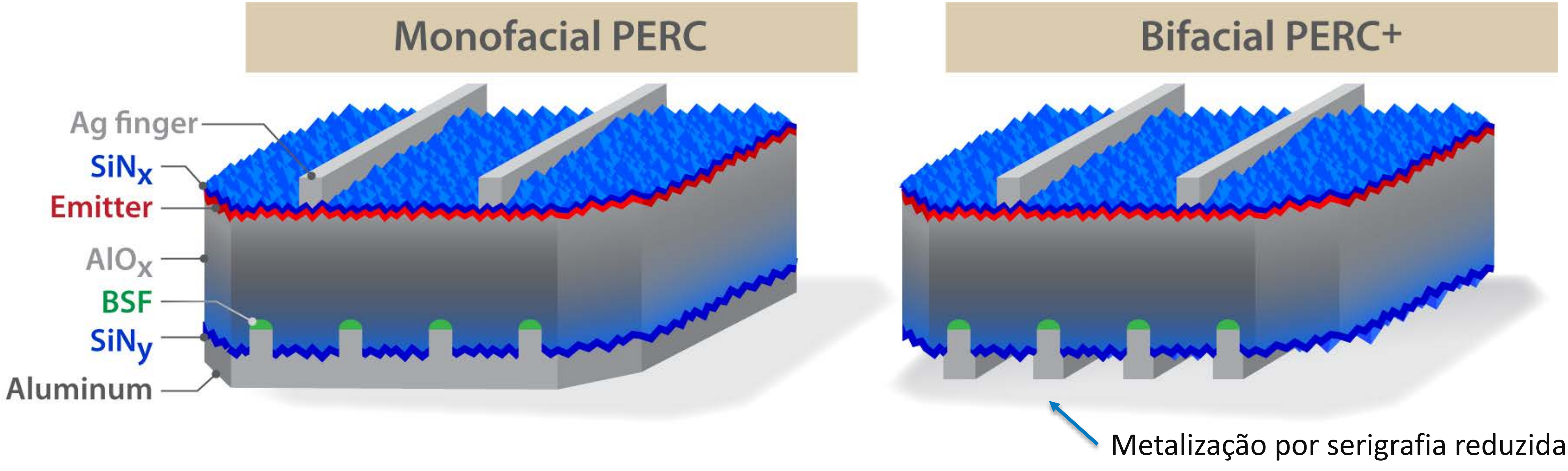


Módulo Pre-2015, vida útil de 20-25 anos

Módulo 2023, vida útil 35 anos

Ovaitt & Mirletz et al, 2022. "PV in the Circular Economy, A Dynamic Framework Analyzing Technology Evolution and Reliability Impacts." *ISCIENCE* https://doi.org/10.1016/j.isci.2021.103488.

Tecnologia de células PERC – transição chave para bifacial



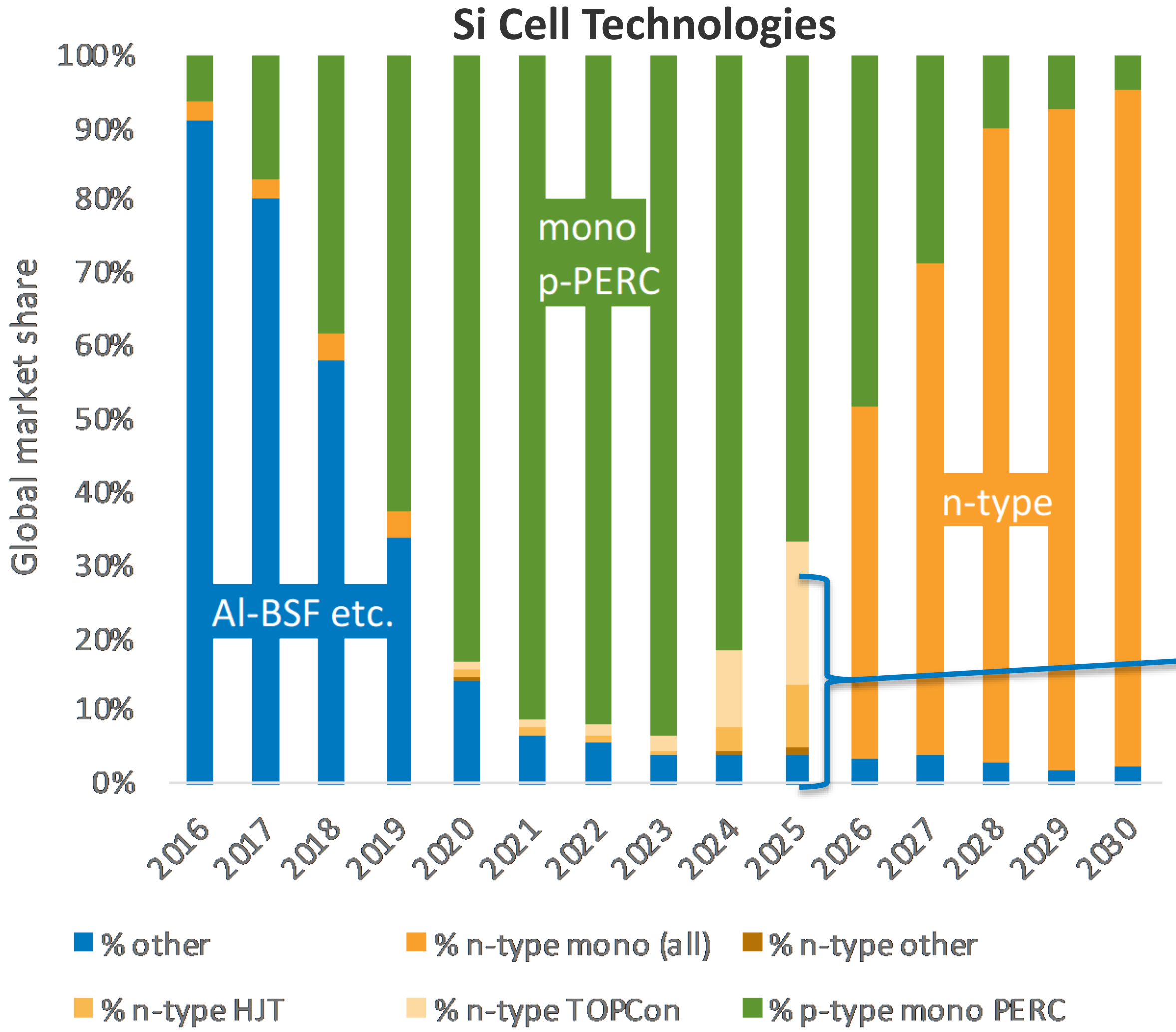
bifacialidade $\phi = \frac{P_{Rear}}{P_{Front}} =$

0.65-0.80 (p-PERC)	0.75-0.90 (n-PERT)	0.85 – 0.95 (Si Heterojunction)

Thorsten Dullweber et al. PERC+: industrial PERC solar cells with rear Al grid enabling bifaciality and reduced Al paste consumption, Prog. Photovolt: Res. Appl. (2015)

A evolução não termina

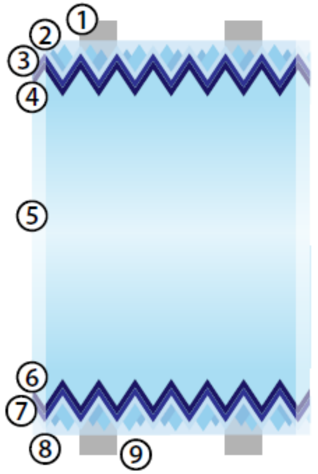
bifacialidade $\phi = \frac{P_{Rear}}{P_{Front}}$



HJT

23-25% cell efficiency

ϕ ~0.85 – 0.95

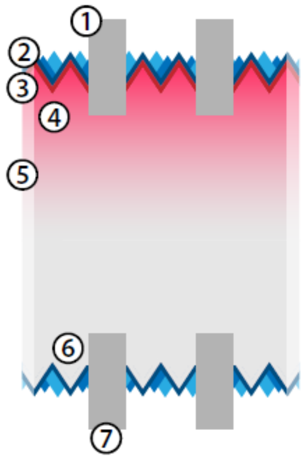


1. Frontside fingers (busbars optional) compromised of low-temperature screen-printed Ag pastes or electroplated Ni/Cu/Sn/Ag
2. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
3. p^+ doping and full-area emitter formation by PECVD of a-Si:H
4. Intrinsically doped a-Si:H by PECVD
5. High lifetime n-type base wafer
6. Intrinsically doped a-Si:H by PECVD
7. n^+ doping and full-area BSF formation by PECVD of a-Si:H
8. TCO by PVD (typically ITO for high optical transmission and low sheet resistance)
9. Backside fingers (busbars optional)

TOPCon

21-23% by SP, 21-26% by PVD

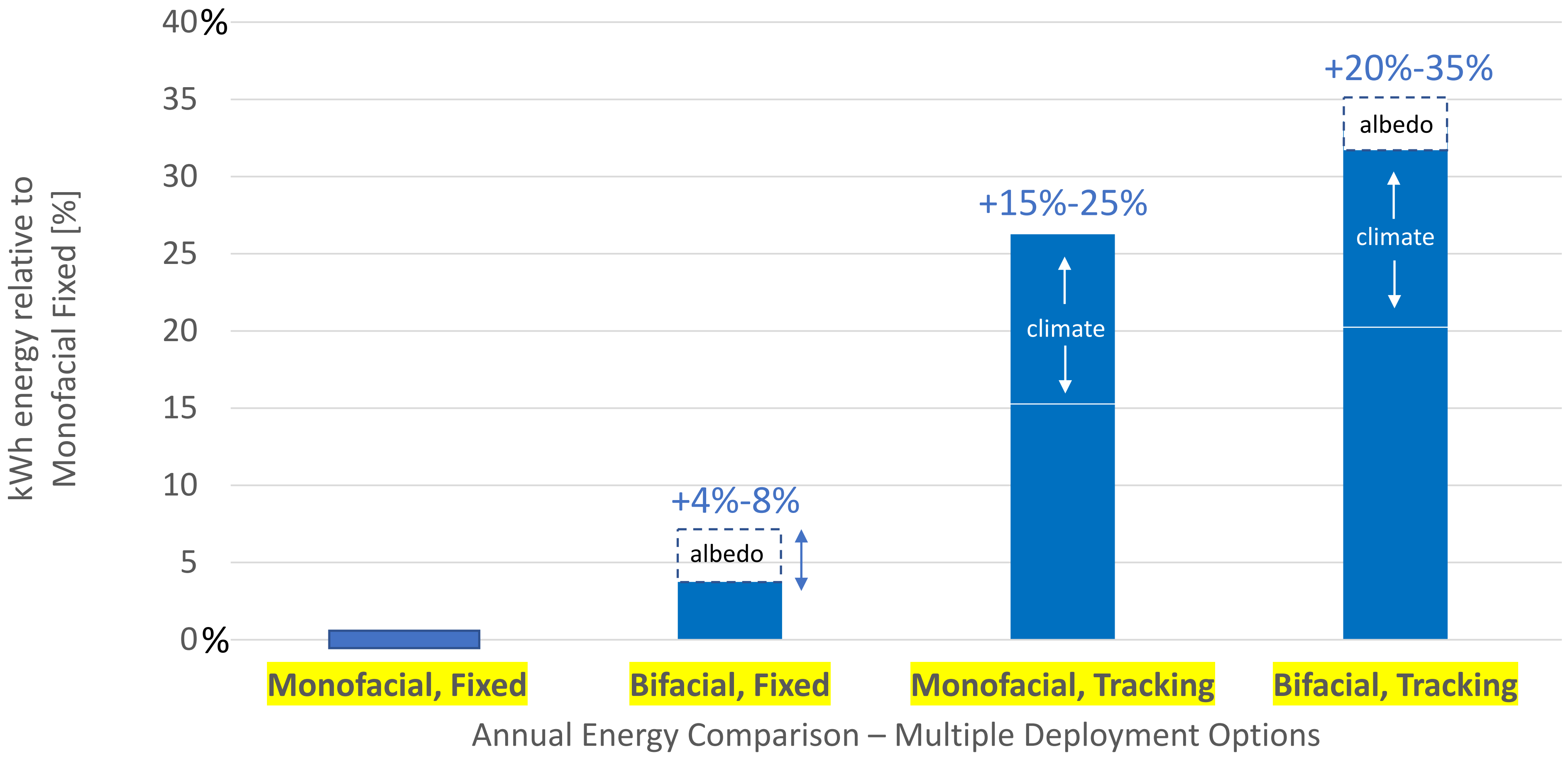
ϕ ~0.8



1. Ag and Al front metallization by screen-printing or PVD
2. SiN_x ARC and passivation layer by PECVD
3. PECVD or ALD of AlO_x surface passivation layer
4. p^+ doping and full-area emitter formation by ion implantation or BBr_3 diffusion
5. High lifetime n-type base wafer
6. Tunnel oxide passivated contact (TOPCon) layer formed by PECVD or LPCVD of doped a-Si or poly-Si layers
7. Ag rear metallization (sometimes full-area) by screen-printing or PVD

Jarett Zuboy. DuraMAT Tech Scouting 2022

Por que bifacial?
Grandes melhorias na produção de energia



*SAM simulation, range of scenarios

Agenda

1 Motivação

2 Pesquisa de PV bifacial no NREL

3 Como posicionar sensores de irradiância

4 Otimização do Albedo

5 AgriPV

6 Ferramentas de modelagem bifacial & AgriPV

7 Oportunidades no NREL


75 kW bifacial HSAT
5 tecnologias bifaciales

3 anos de datos Open-Source

https://datahub.duramat.org/dataset/best-field-data

Comparando PV bifacial com monofacial

O ganho para um Sistema bifacial é determinado comparando o rendimiento energético [kWh] ou o Performance Ratio [KWh/KW] de ambos sistemas

$$BG = \left(\frac{Y_{bifacial}}{Y_{monofacial}} - 1\right) \times 100\%$$

$$BG_{Medido} = \left(\frac{PR_{bifi}}{PR_{mono}} - 1\right) \times 100\%$$

Silfab module photo

Comparando PV bifacial com monofacial

$$BG_{Medido} = \left(\frac{PR_{bifi}}{PR_{mono}} - 1\right) \times 100\%$$

- Diferença de potência nominal
  Coeficiente de temperatura
- resposta à baixa luminosidade
- Orientação de montage
- Bifacialidade

$$BG_{\text{Medido},bifacialidade} = \left(\frac{PR_{bifi}}{PR_{mono}} \underbrace{\frac{PR_{mono,model}}{PR_{bifi,model}}}_{\text{Fator de Correção}} - 1\right) \times 100\%$$

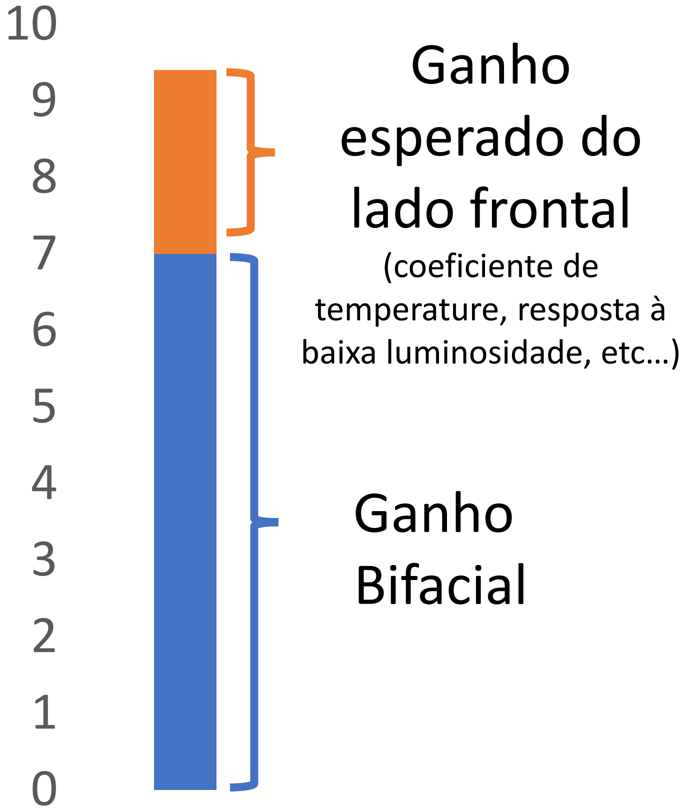
Ovaitt et al, Model and Validation of Single-Axis Tracking with Bifacial PV, JPV 2019. 10.1109/JPHOTOV.2019.2892872

Comparando PV bifacial com monofacial

100 kW Silfab HJT,
2-up horizontal

100 kW Trina mcSi,
1-up vertical

H = 0.75, GCR = 0.35, Albedo = 0.2 (short grass)



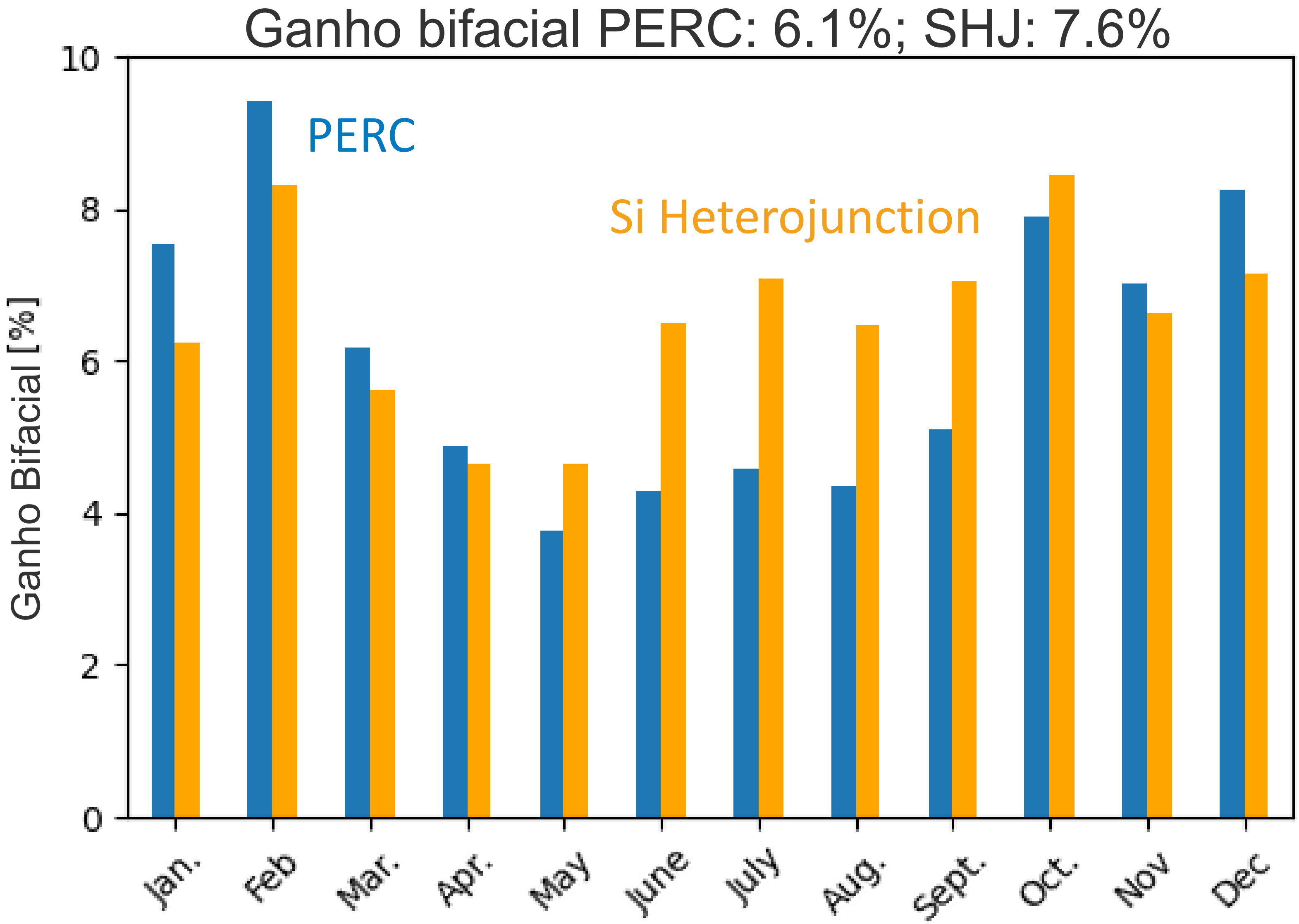
$$BG_{\text{Medido},bifacialidade} = \left(\frac{PR_{bifi}}{PR_{mono}} \frac{PR_{mono,model}}{PR_{bifi,model}} - 1 \right) \times 100\%$$

Ovaitt et al, Model and Validation of Single-Axis Tracking with Bifacial PV, JPV 2019. 10.1109/JPHOTOV.2019.2892872

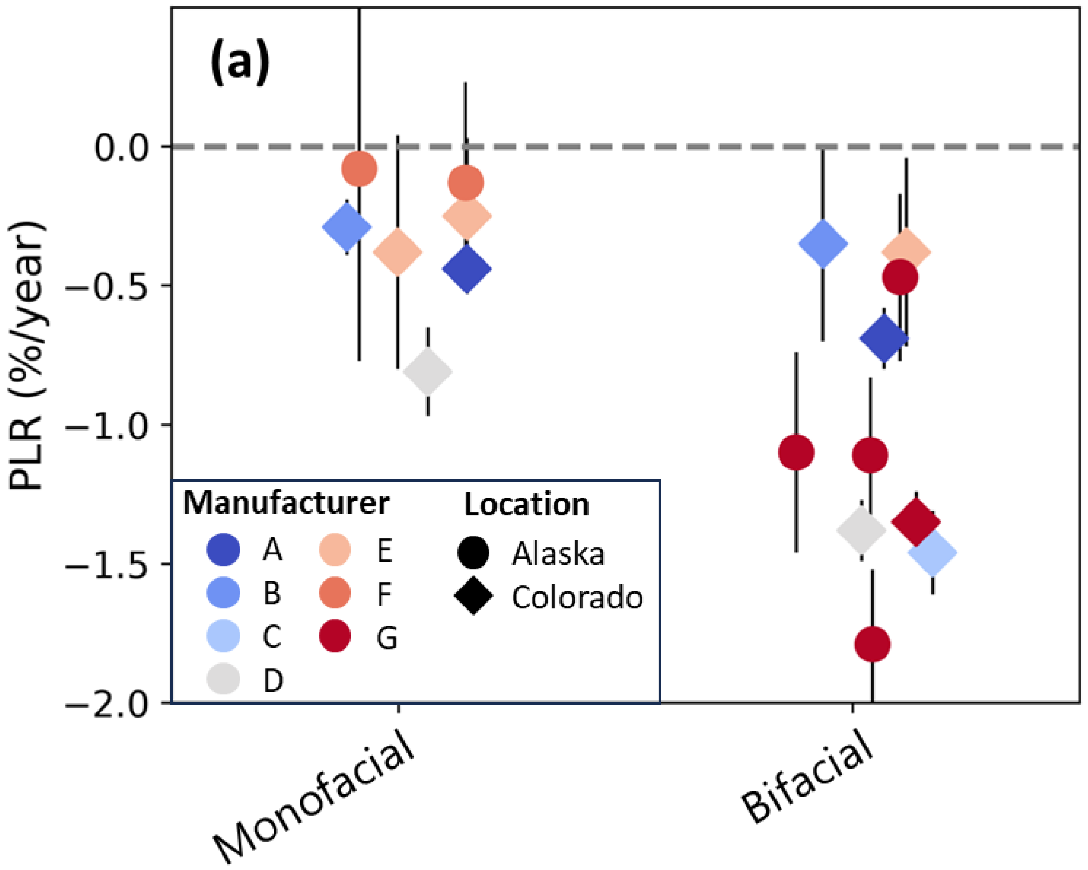
Ganho bifacial

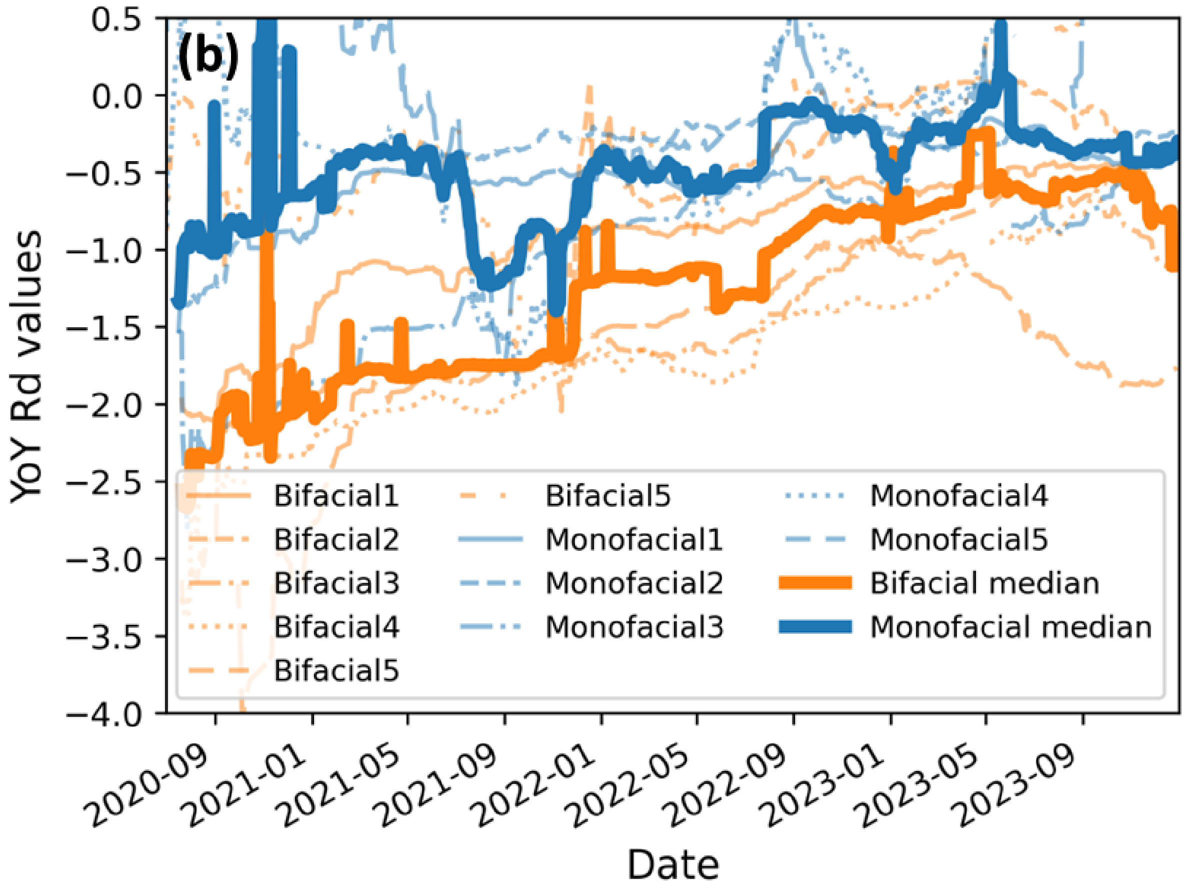
$$\frac{Energia\ bifacial}{Energia\ monofacial} - 1\quad [\%]$$

*Ganho de 3-anos, agrupado por mês



Degradação



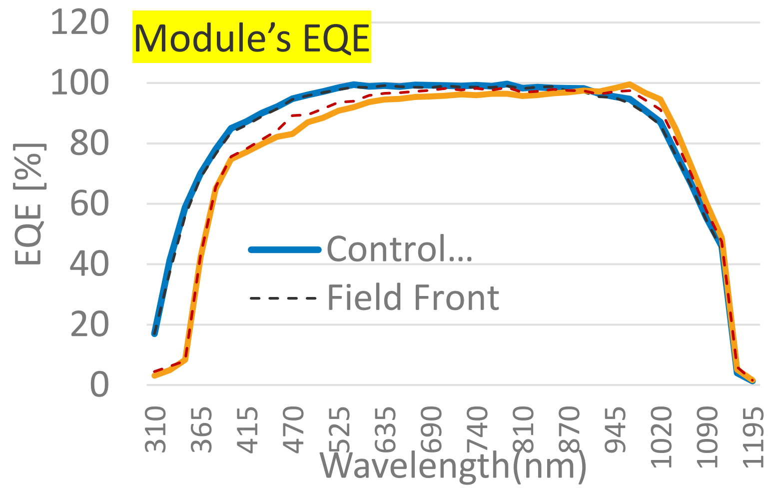


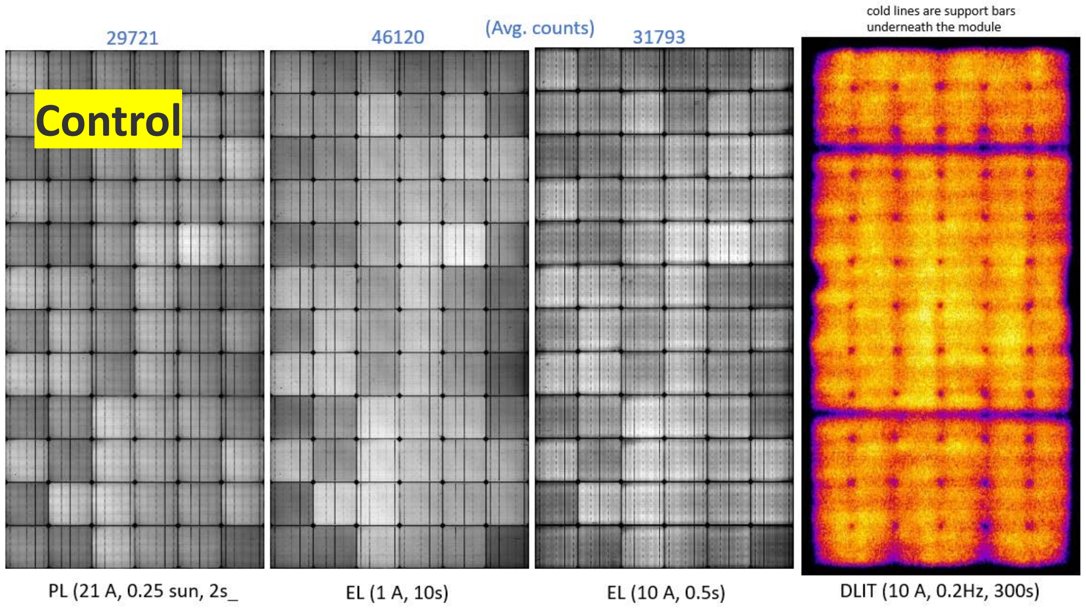
Done: IV Curves, Field IR, EL, PL, Low temp PL, Module QE Measurements, Hanheld Raman, Hanheld AR Coating
Destructive next: Hydrogen traces through d-SIMS, or Glow Discharge Optical Emissions Spectroscopy

MFG A

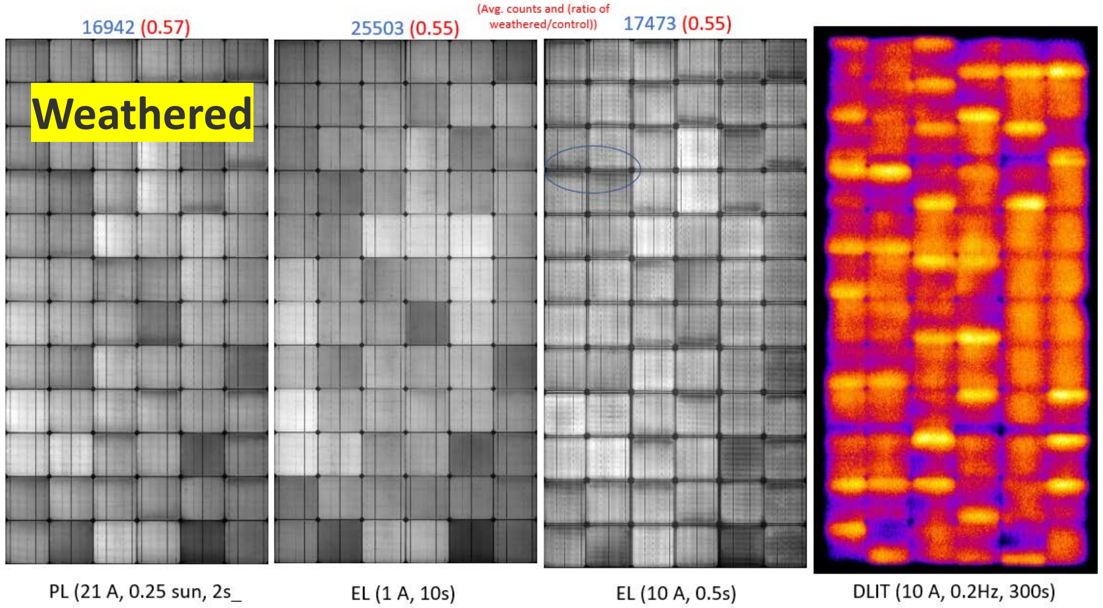
pPERC, G/G, Full cell, Top JB, EVA

IV Curves Results	% Change
ISC Loss Front	-0.35%
ISC Loss Back	2.15%
Voc Loss Front	-1.39%
Voc Loss Back	-1.41%
FF Loss Front	-0.45%
FF Loss Back	-0.88%
Pmp Loss Front	-2.17%
Pmp Loss Back	-0.13%





For weathered module compared to control, overall luminescence intensity is down to about 55% of the control, suggesting a loss in voltage



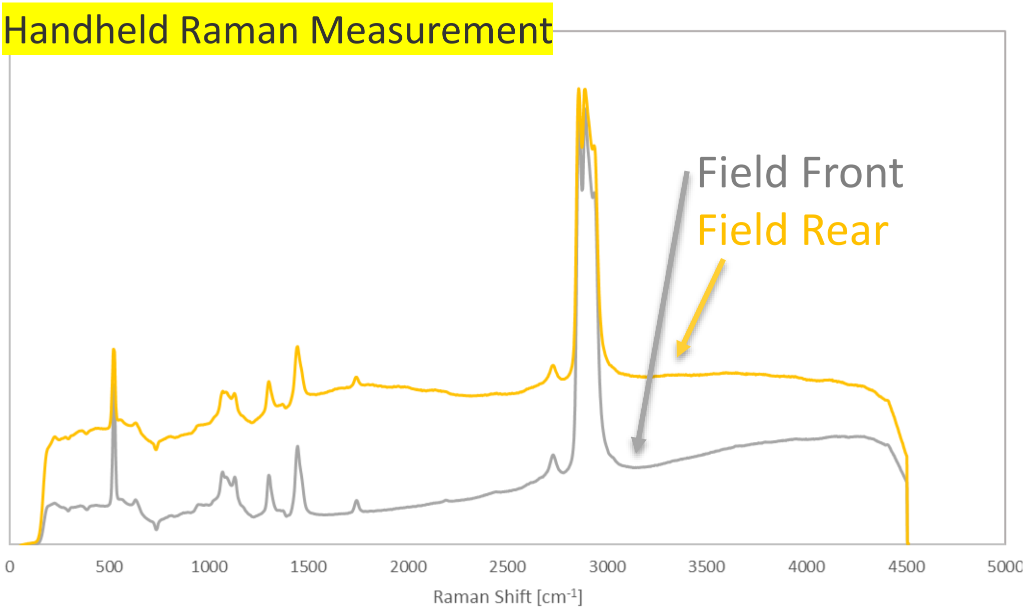
. There are dark edge patterns (either top or bottom of cells) in high-current EL and PL, and hotter DLIT, suggesting these are areas with increased carrier recombination, perhaps loss of passivation.

MFG C

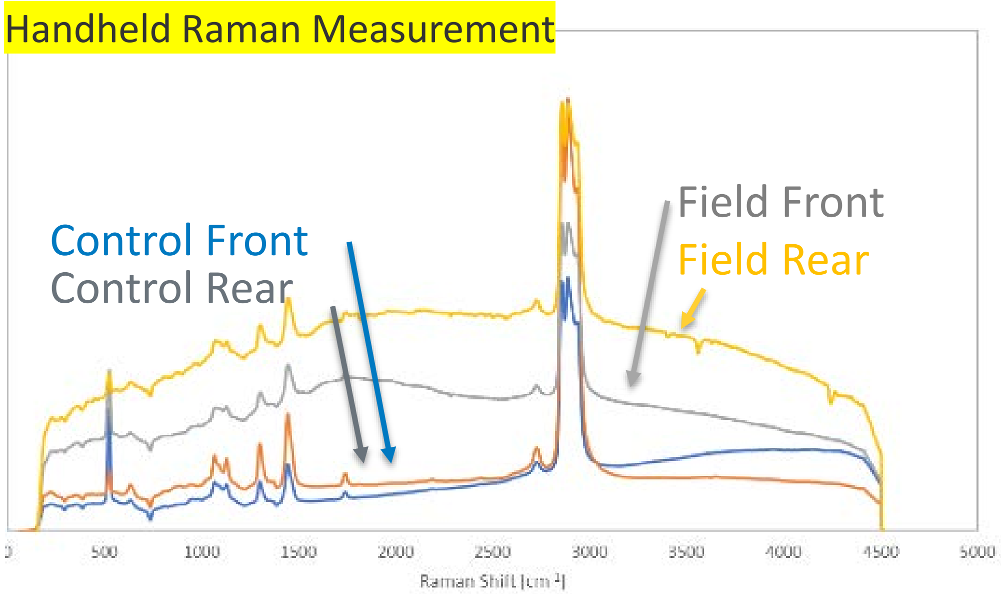
pPERC, G/G, Half-cell, Center JB, EVA

IV Curves Results	% Change
ISC Loss Front	-0.30%
ISC Loss Back	-1.86%
Voc Loss Mono	-2.93%
Voc Loss Front	-1.92%
Voc Loss Back	-2.70%
FF Loss Mono	-2.81%
FF Loss Front	-0.34%
FF Loss Back	-1.00%
Pmp loss Mono	-2.27%
Pmp Loss Front	-2.54%
Pmp Loss Back	-5.45%

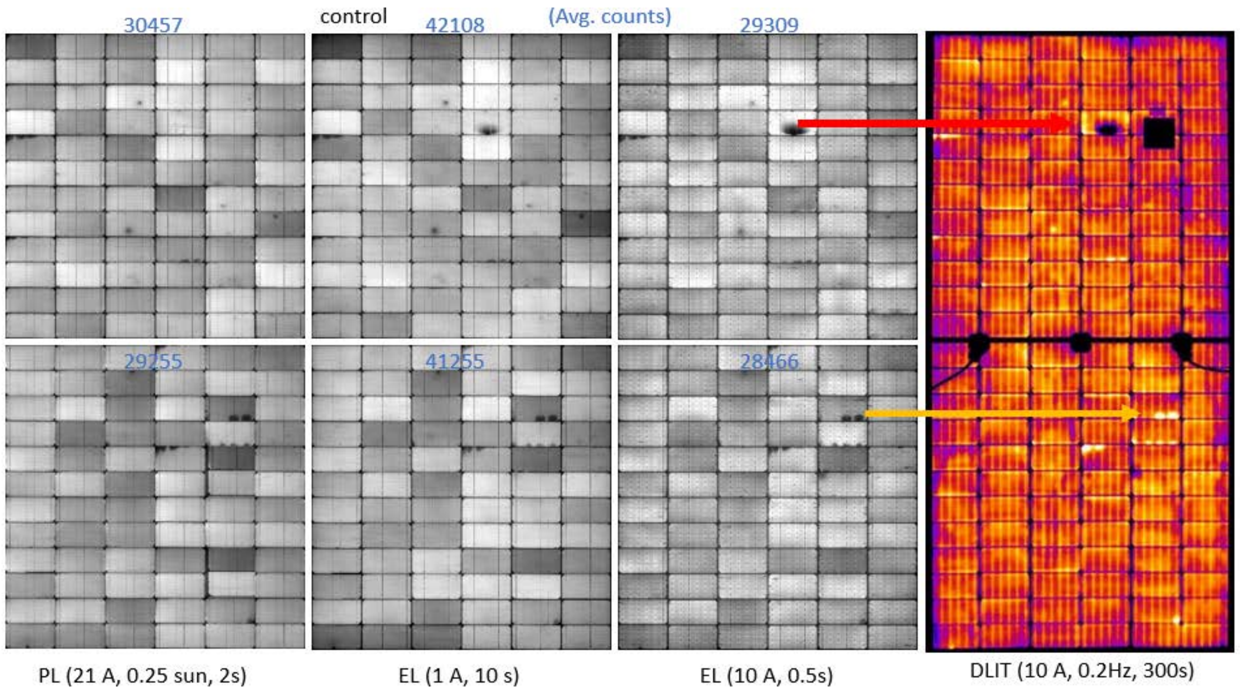
Monofacial



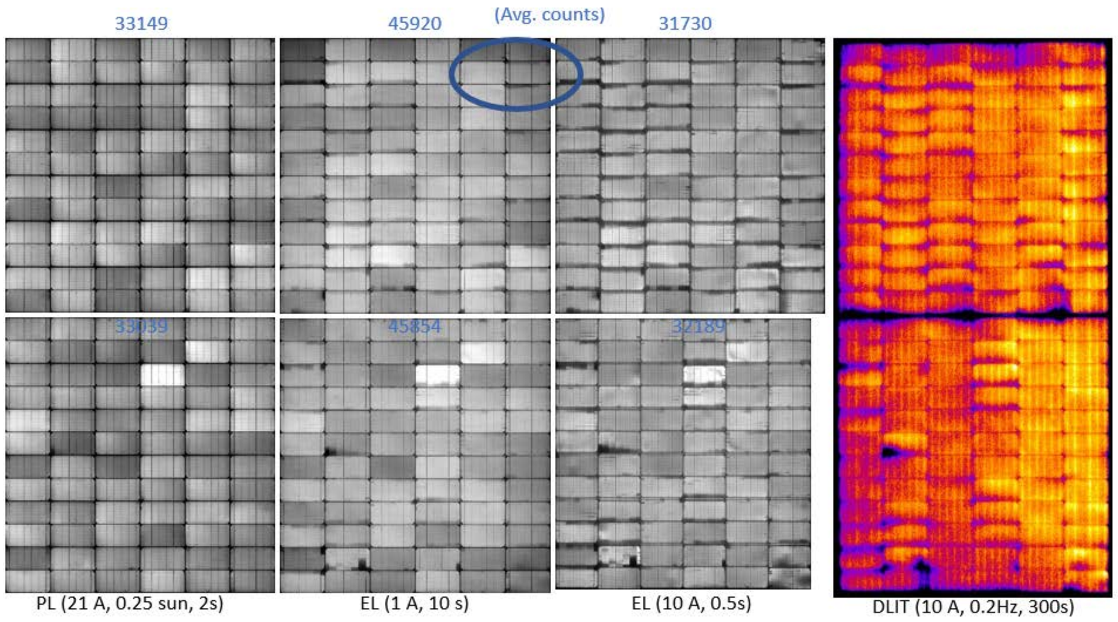
Bifacial



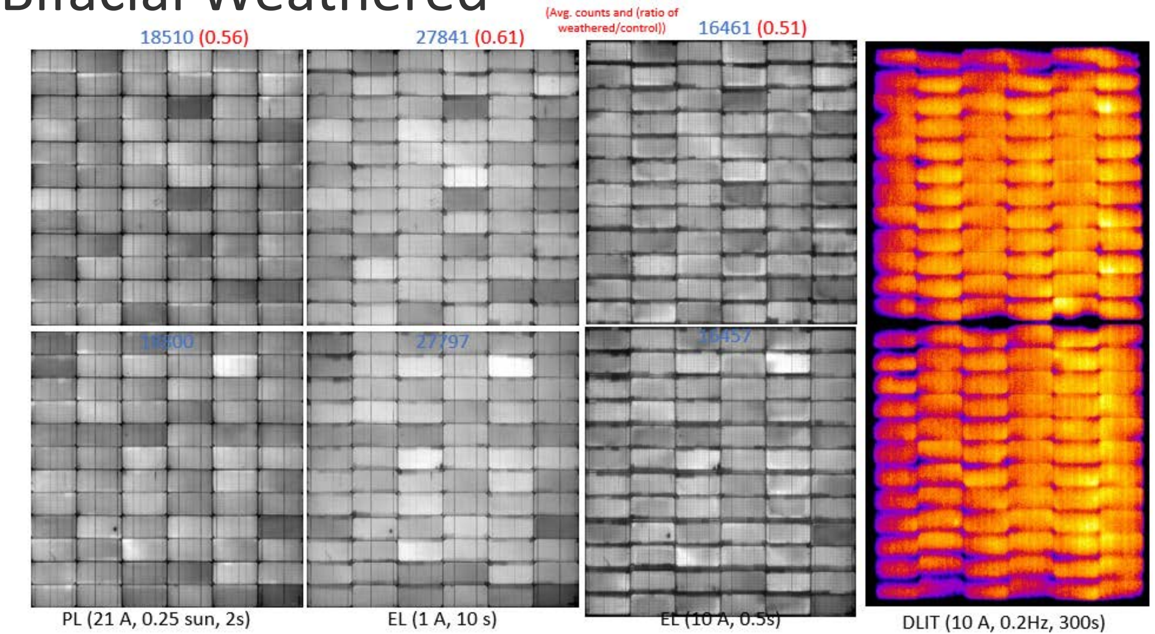
Monofacial Control



Bifacial Control



Bifacial Weathered



For weathered module compared to control, overall luminescence intensity is down to about ~¾ of the control, suggesting a loss in voltage. There are a few patterns in high-current EL showing dark areas of higher resistance. DLIT dark areas here too, suggesting lower current density or broken grid fingers – possibly leading to reduced fill factor.

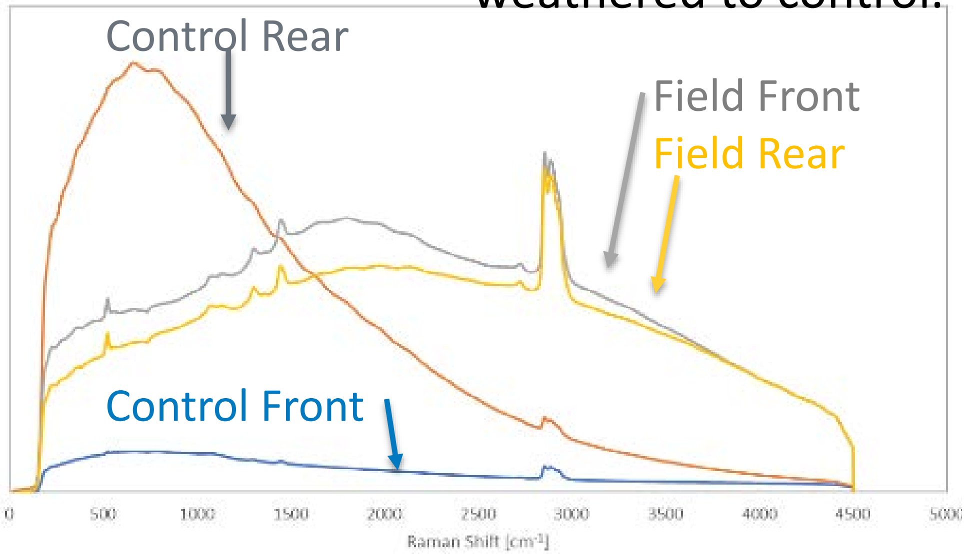
MFG E

HJT, G/G, Half cell, JB center, “PE/EBA”

IV Curves Results	% Change
Perdida ISC Front	-6.43%
Perdida ISC Back	-3.22%
Voc Loss Front	-1.19%
Voc Loss Back	-0.89%
FF Loss Front	-0.02%
FF Loss Back	-0.93%
Pmp Loss Front	-7.53%
Pmp Loss Back	-4.96%

For weathered module compared to control, overall luminescence intensity is down to about ~¾ of the control, suggesting a loss in voltage. No other obvious patterns or observations when comparing weathered to control.

Handheld Raman Measurement



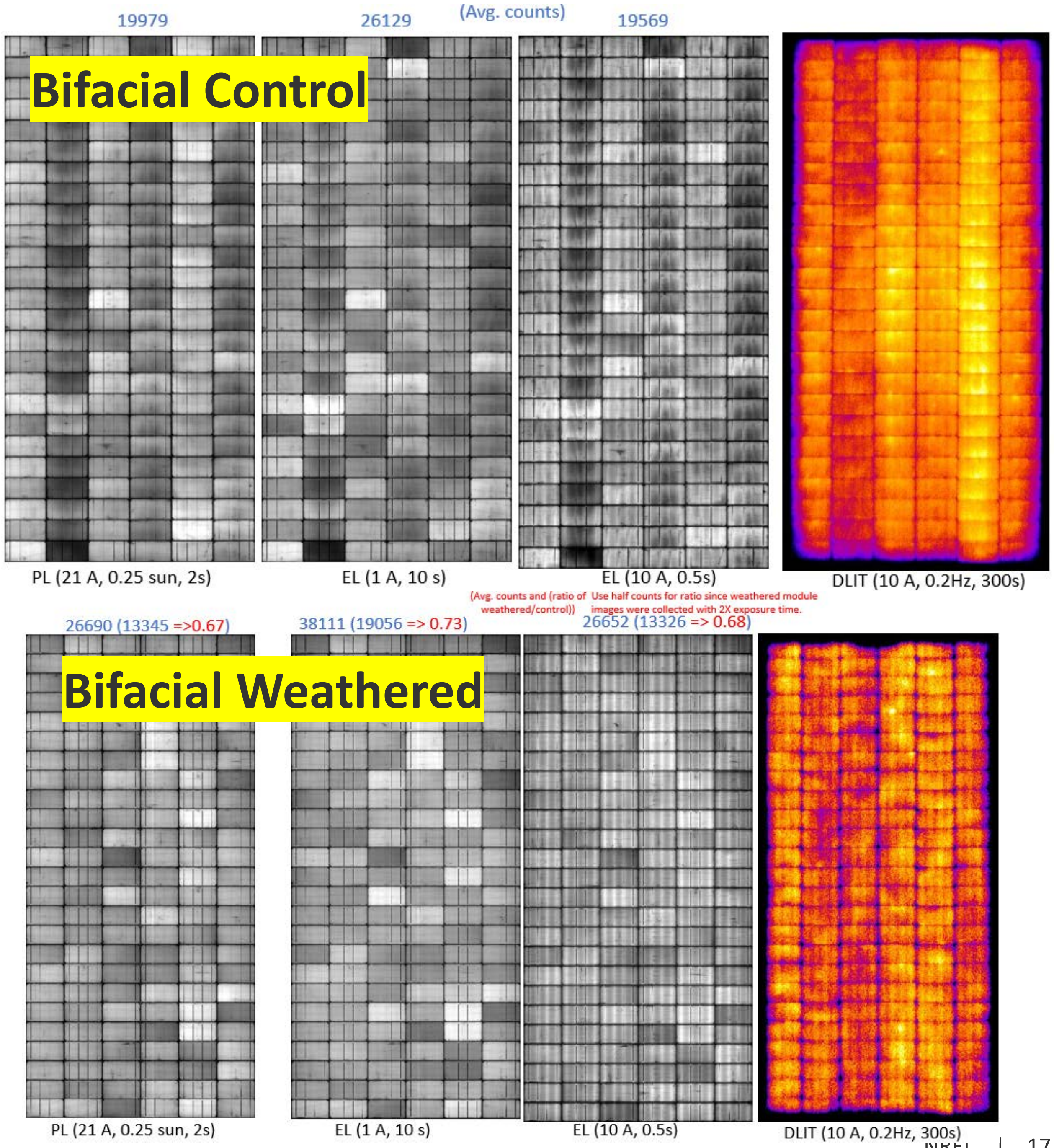
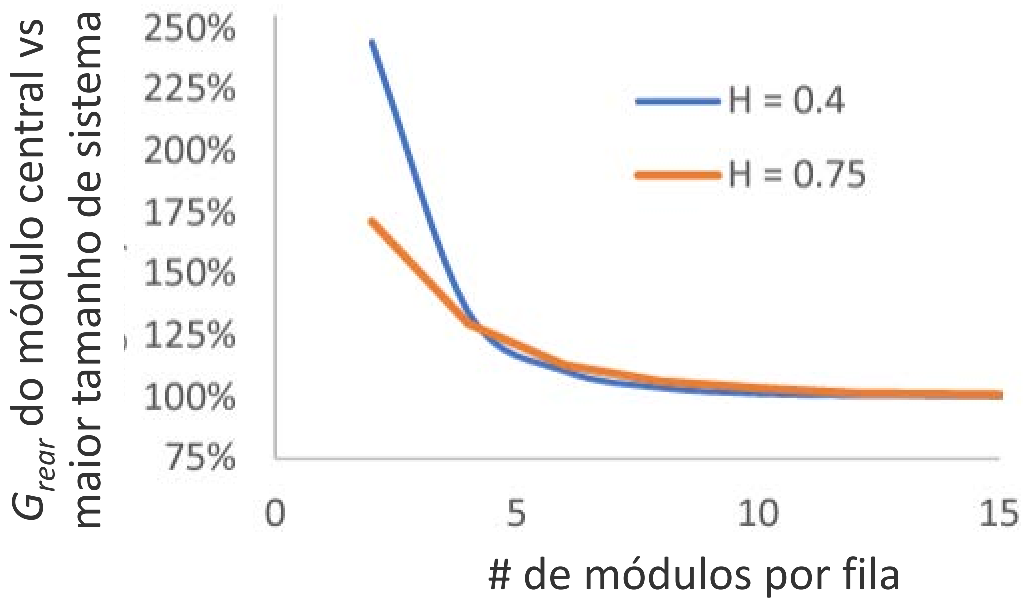
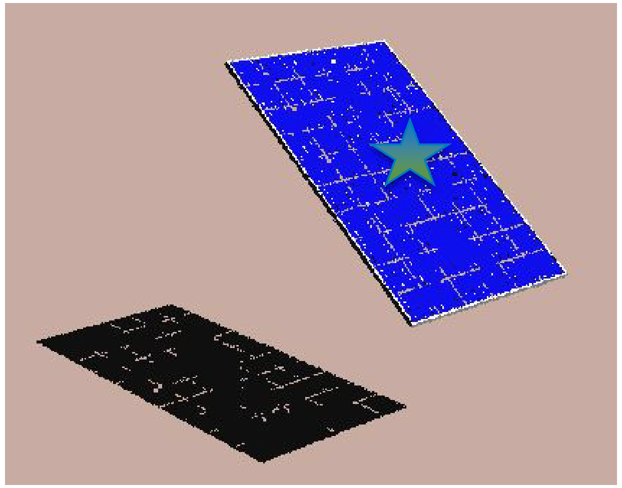


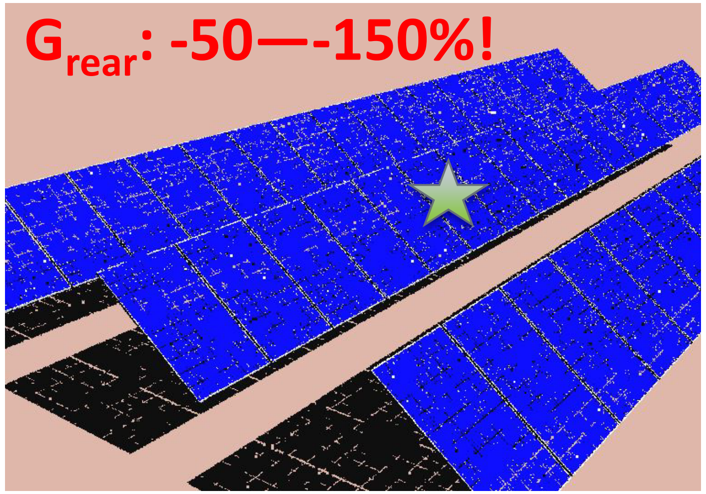
Photo: EDF

A irradiação no rear-side é muito não uniforme

Tamanho do sistema para estado estável da irradiação

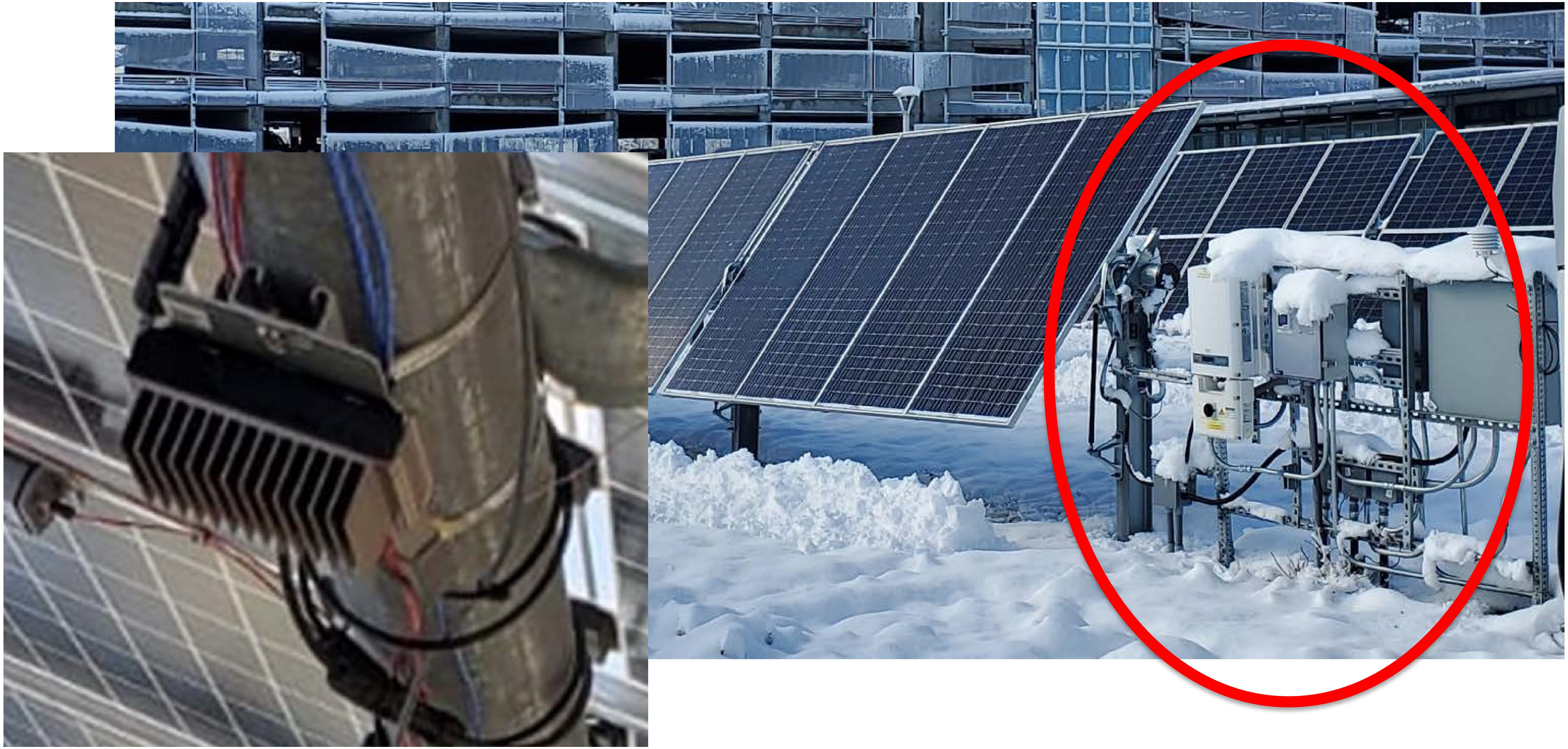






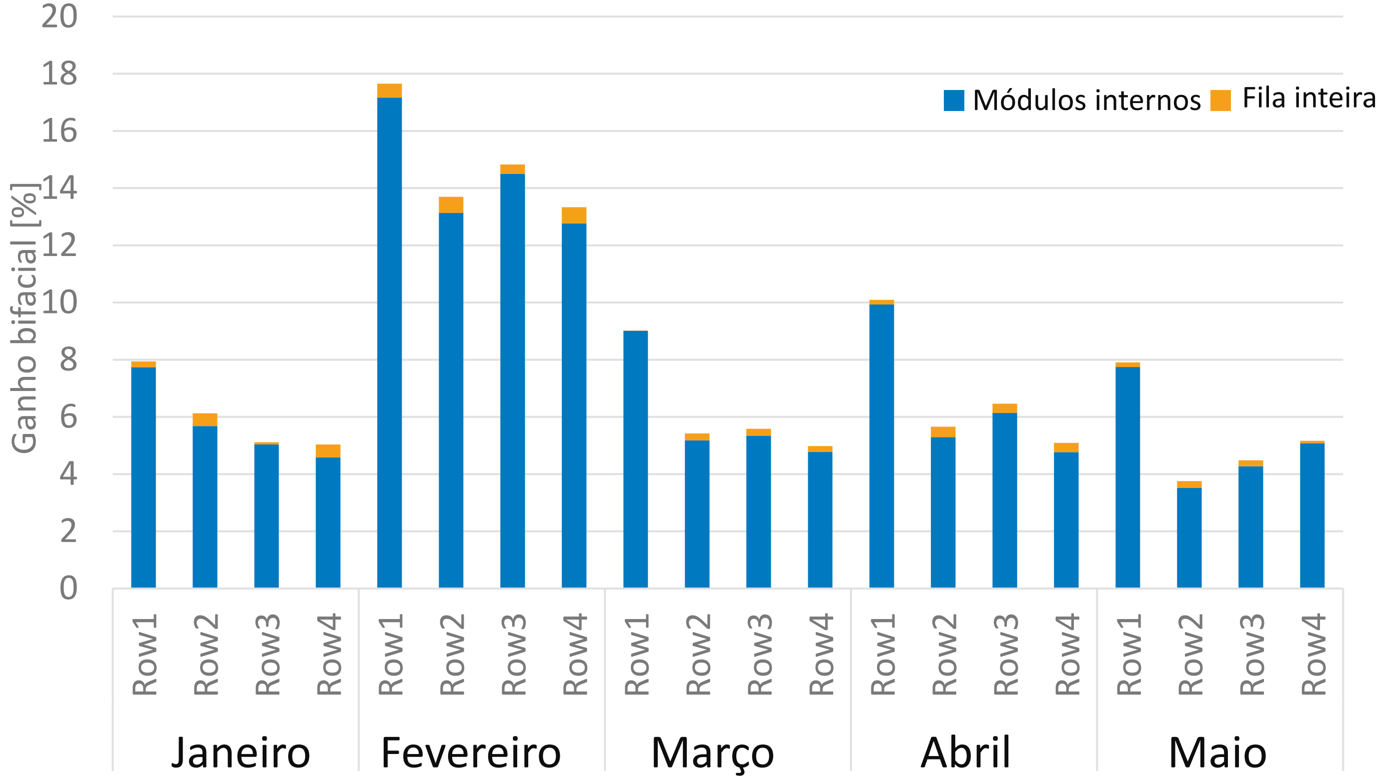
C. Deline et al., Assessment of Bifacial Photovoltaic Module Power Rating Methodologies – Inside and Out, J. Photovoltaics **7,** 2017
Ovaitt et al, Model and Validation of Single-Axis Tracking with Bifacial PV, JPV 2019. 10.1109/JPHOTOV.2019.2892872

Dados de desempeho ao nivel do módulo e da fila

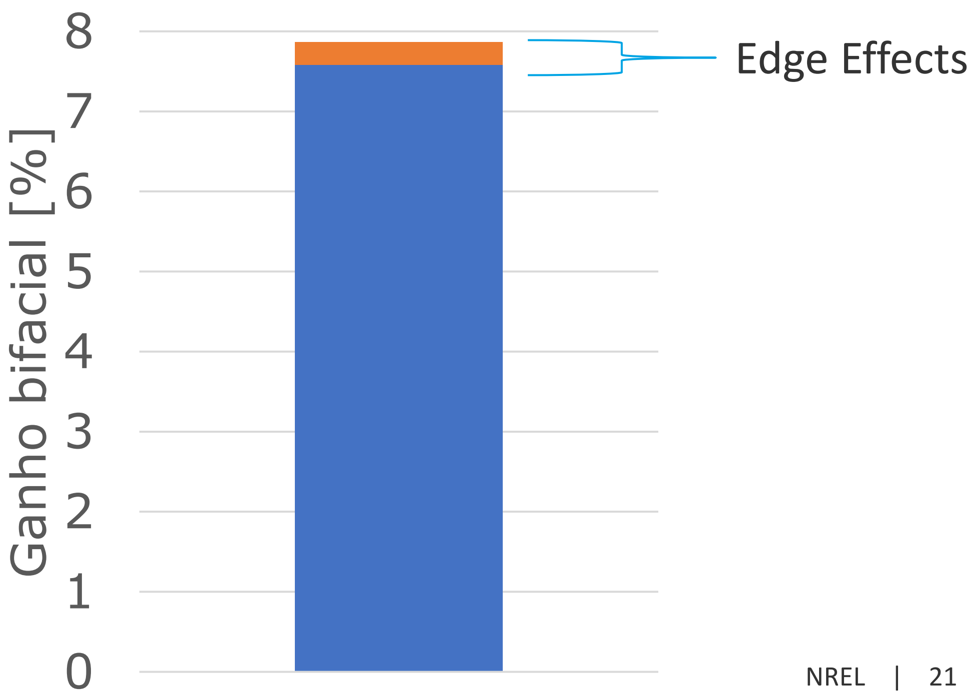


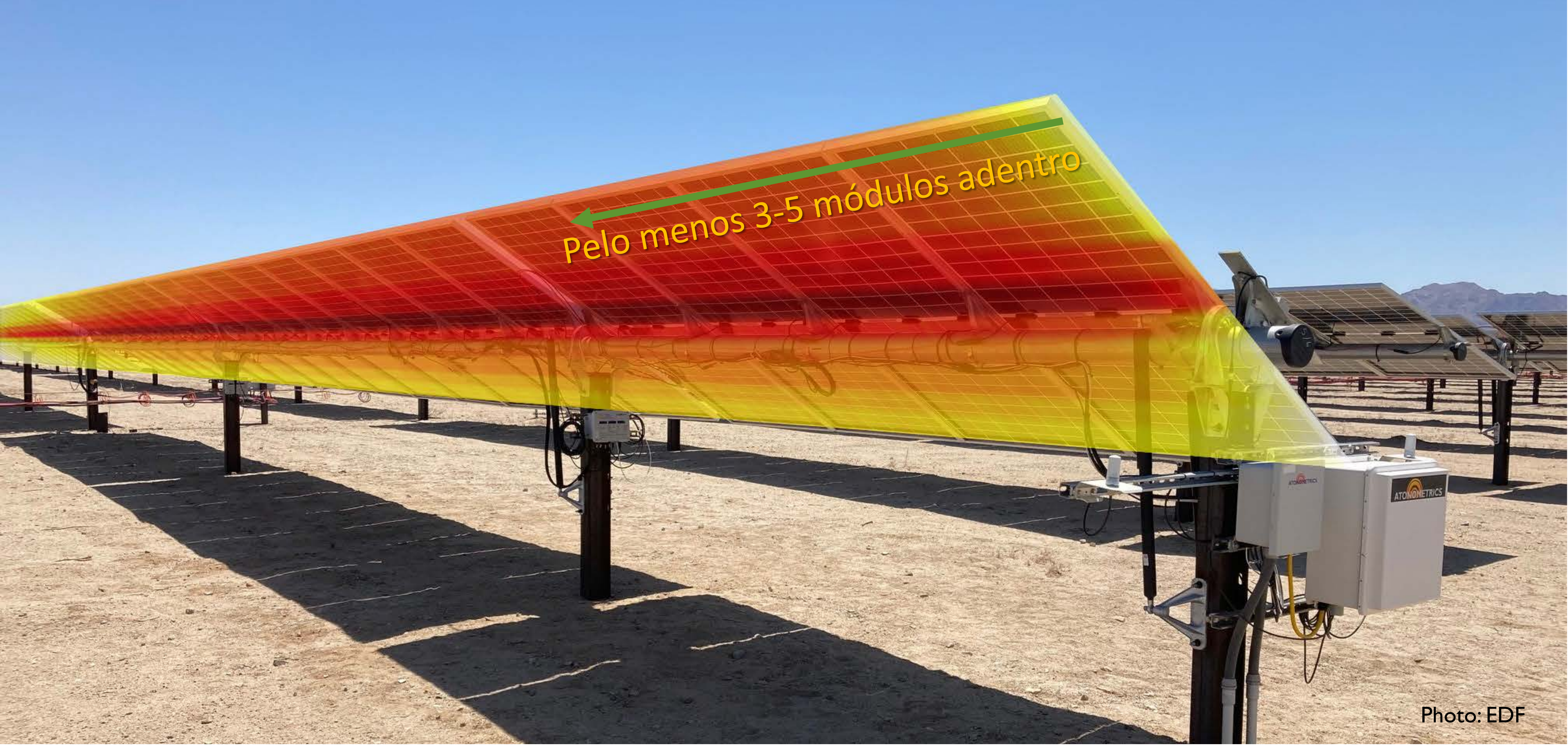
Edge effects incrementam o ganho bifacial em 0.28%

Por fila, por mes



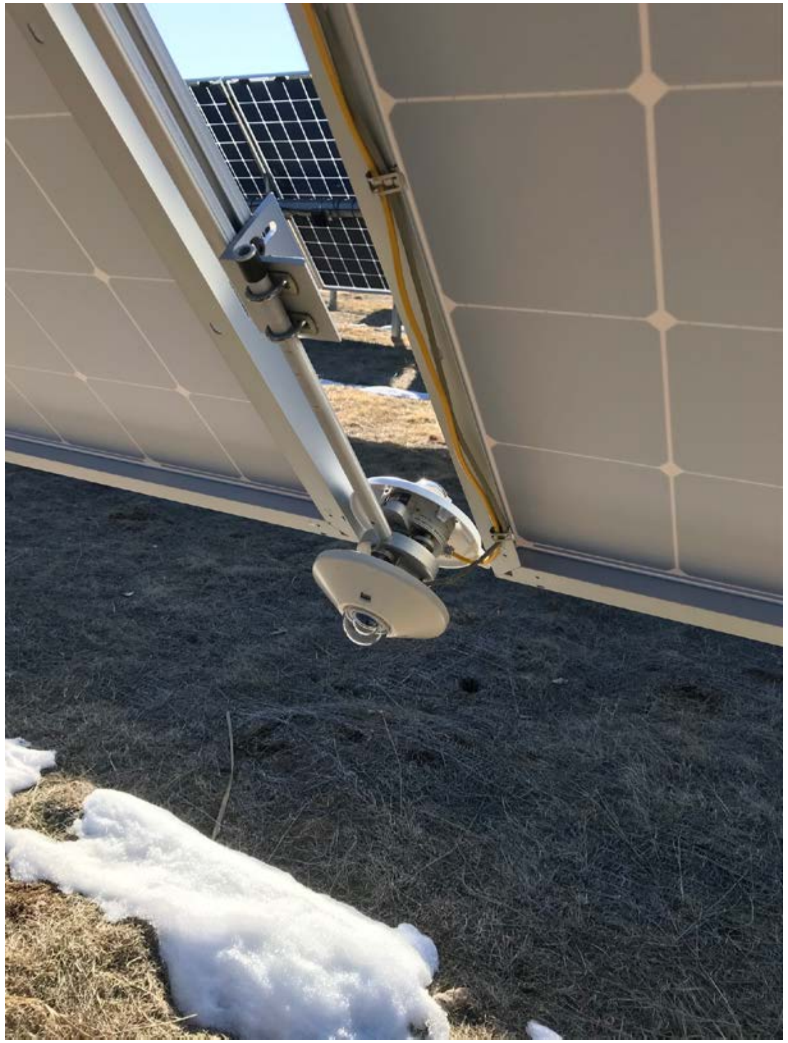
Efeito cumulativo





A irradiação no rear-side é muito não uniforme

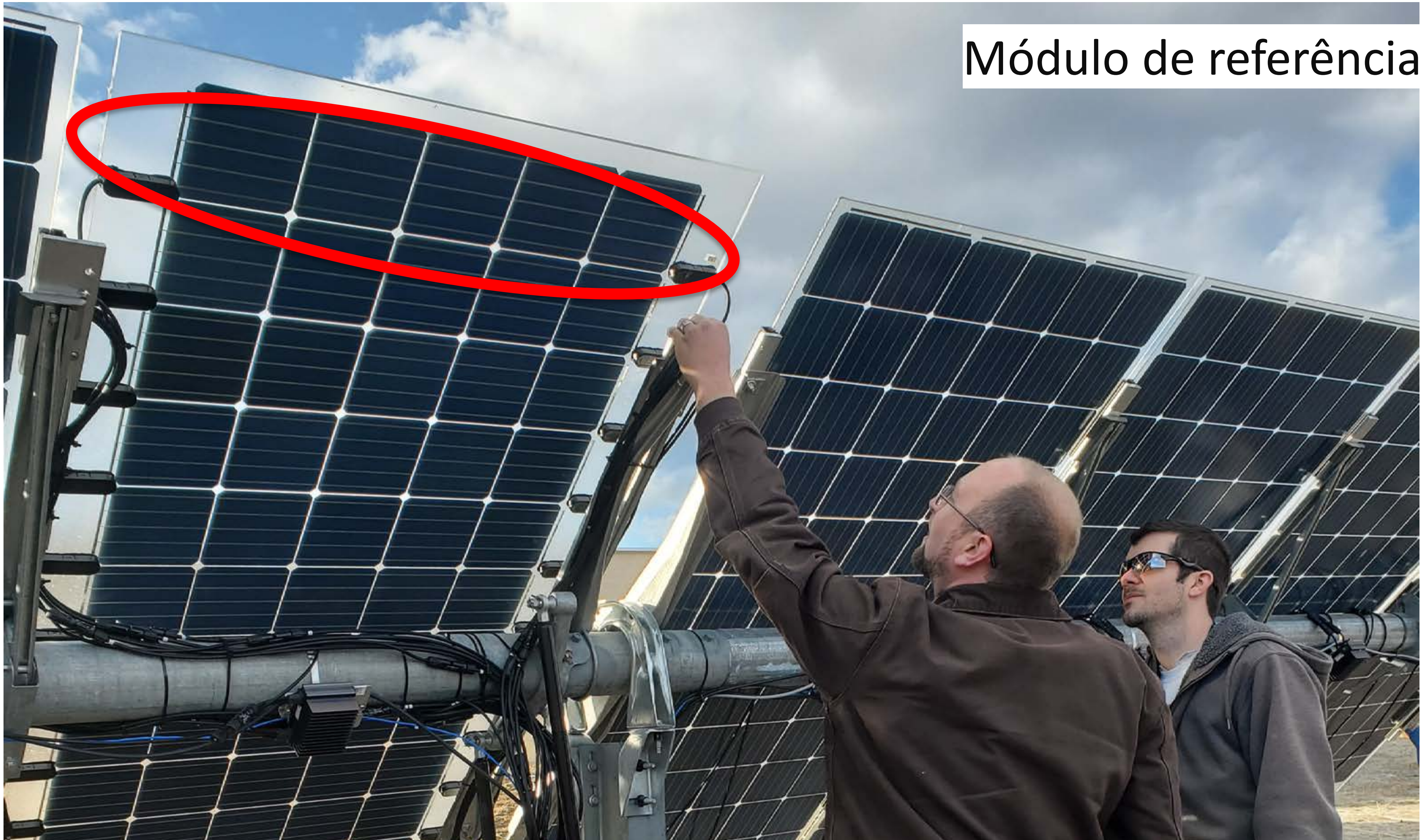
Como medir a distribuição de irradiância no módulo



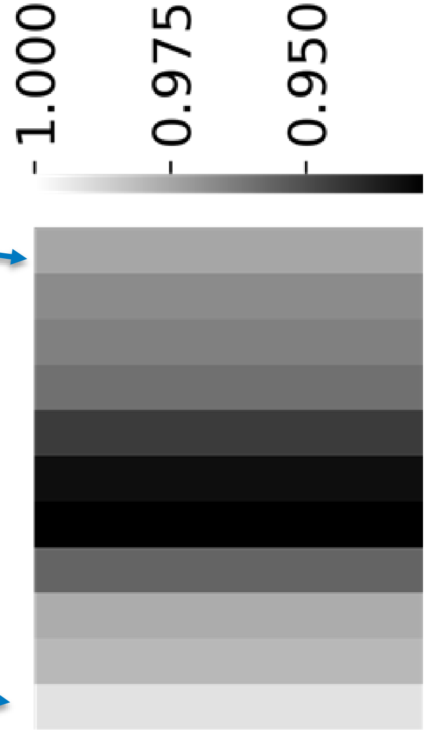
Sensores de irradiância de banda larga

Células de referência

Como medir a distribuição de irradiância no módulo



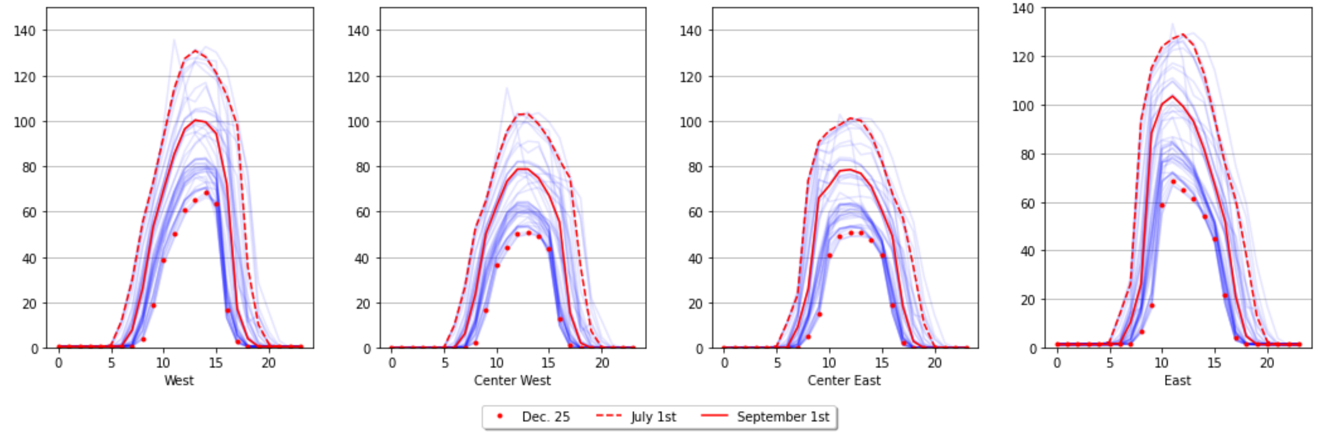
Como medir a distribuição de irradiância no módulo



Este módulo customizado e utilizado para medir o fator de sombreamento (shading factor), e como módulo de referencia para testes de capacidade

Posicionamiento dos sensores

Dias clear-sky, Outubro 2019-2021



% Diferença com a média das medições das células de referência

Ref. Cell (WEST)	**7**	**-12**	**-8**	**13**	**Ref Cell (EAST)**
K&Z CM11	13			30%	Licor

Usar uma combinação de sensores ao longo do módulo pode ajudar a reduzir o desvio das medições

SENSOR A

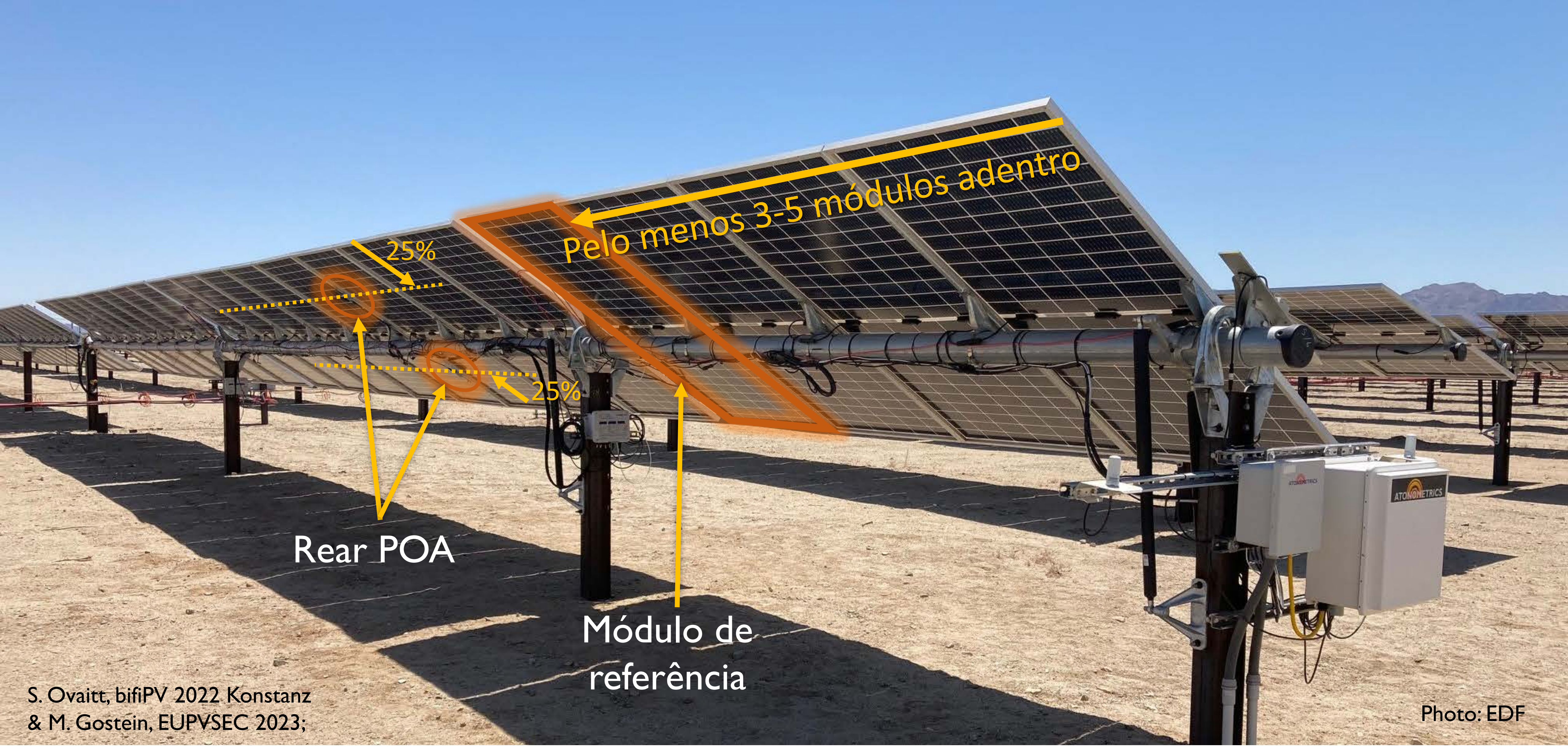
SENSOR B

	1	2	3	4	5	6	7	8	9	10	11
2	0.10										
3	0.08	0.07									
4	0.07	0.07	0.06								
5	0.06	0.06	0.06	0.07							
6	0.05	0.05	0.05	0.06	[illegible]						
7	0.04	0.03	0.04	0.05	[illegible]	[illegible]					
8	0.03	0.02	0.02	0.04	0.06	0.07	0.08				
9	0.04	0.03	0.01	0.02	0.04	0.05	0.06	0.06			
10	0.05	0.04	0.02	0.01	0.03	0.04	0.05	0.05	0.06		
11	0.07	0.05	0.03	0.02	0.02	0.04	0.05	0.06	0.06	0.07	
12	0.08	0.07	0.05	0.04	0.03	0.04	0.05	0.06	0.08	0.09	0.10

Desvio padrão da media do módulo customizado

Gostein, Ovaitt et al PVSC 2021 https://ieeexplore.ieee.org/document/9518601

A irradiação no rear-side é muito não uniforme



Posicionamento dos sensores para medir a irradiância no Rear-side

Otimização do albedo

Artificial ground reflector size and position effects on energy yield and economics of SAT bifacial PV
PinPV 2024 http://doi.org/10.1002/pip.3811

Otimização do albedo

+5% de ganho no desempenho bifacial

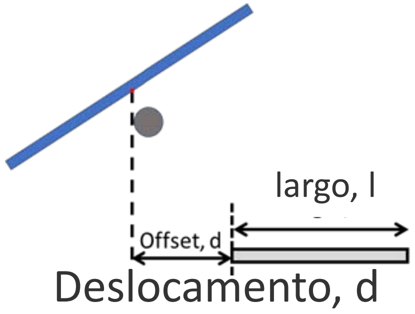
http://doi.org/10.1002/pip.3811

Otimização do albedo

http://doi.org/10.1002/pip.3811

Passo 1: Ganho com os refletores na irradiância

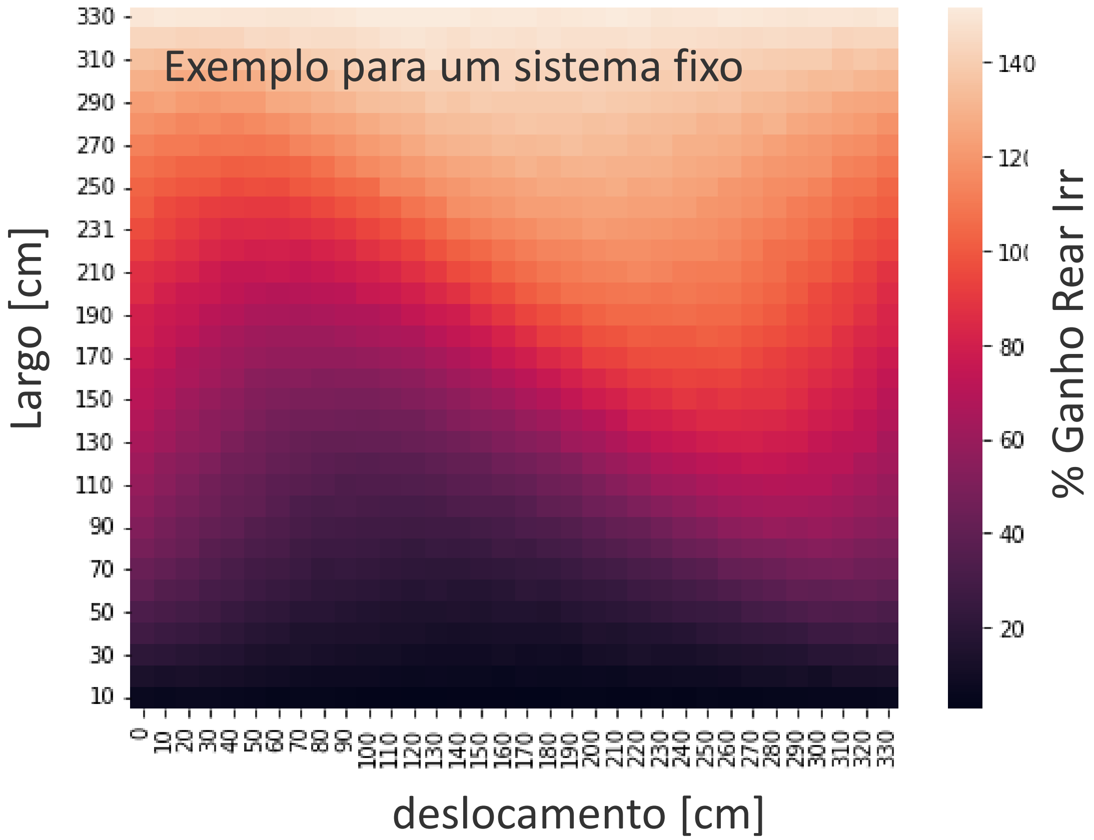
O deslocamento ideal varia com o largo do refletor



Rear Irr. (com reflector)

$$\% \, Ganho \, Rear \, Irr. = \frac{G_{rear} - G_{ref}}{G_{ref}}$$

Rear Irr. (sem reflector)



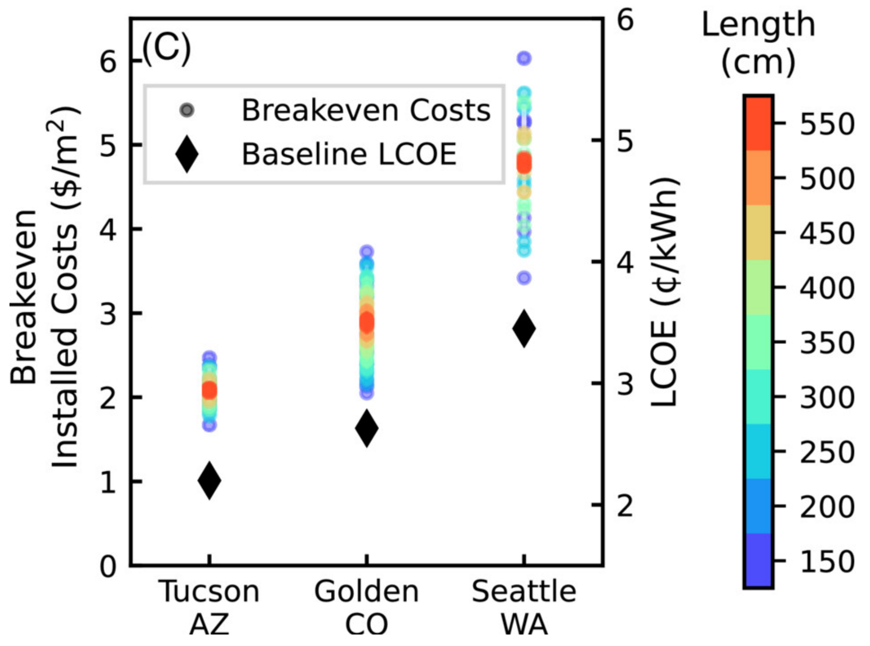
Passo 2: LCOE

$$\text{LCOE}\ (\%) = \frac{(\text{CAPEX Total}\ (\$) * \text{CRF}) + \text{O\&M Anual}\ (\$)}{\text{CF}(\%) * 8760\ {}^{\text{hrs}}/_{\text{yr}} * \text{Tamanho do Sistema (W)}}$$

Análise do Ponto de Equilíbrio

$$\text{LCOE}\left({}^{\text{com}}/_{\text{reflector}}\right) = \text{LCOE (referência)}$$

$$\text{CAPEX do Material} = \frac{\text{LCOE}\left(\frac{\$}{\text{Wh}}\right) * \text{CF}(\%) * 8760\ {}^{\text{hrs}}/_{\text{yr}} * \text{Tamanho do Sistema (W)} - \text{O\&M Anual}\ (\$)}{\text{CRF}} - \text{PV CAPEX}$$

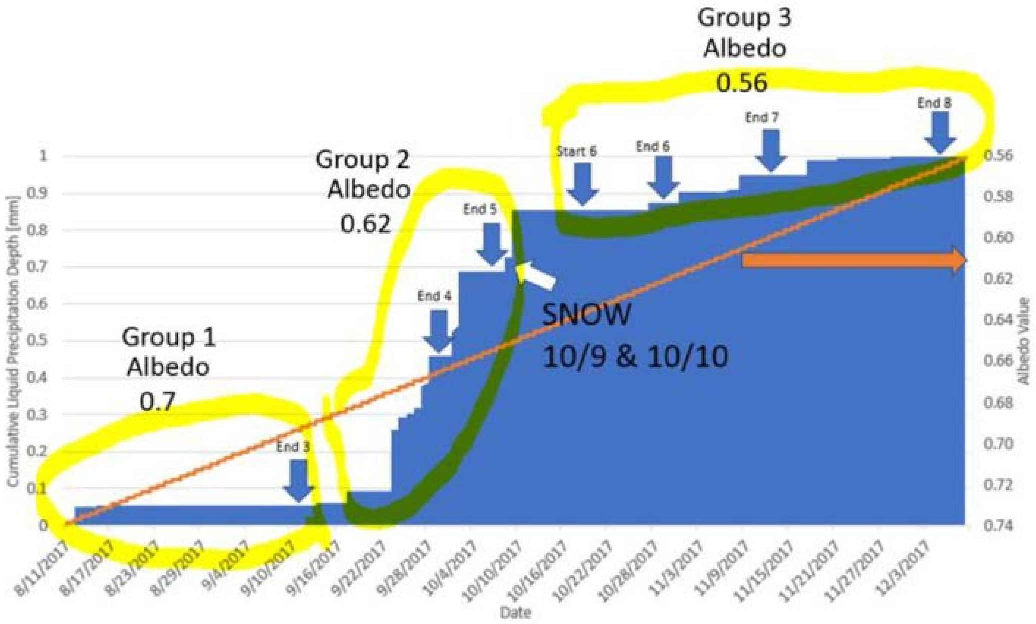


- O posicionamento ideal do refletor é centralizado diretamente sob o tubo de torque
- Em Golden, CO, o ponto de equilíbrio para refletores artificiais é de \$2.50–4.60 /m².
- Custos de material mais altos são possíveis em sistemas com LCOE inicial mais alto, por exemplo \$3.40–6.00/m² para Seattle, WA.
- "Clipping Losses," o corte do inversor impacta significativamente os sistemas que incorporam refletores artificiais, reduzindo o ganho de energia anual e deslocando o posicionamento ideal dos refletores.

http://doi.org/10.1002/pip.3811

Durabilidade do Albedo

Membrana spray-on, foto original de
https://www.nrel.gov/docs/fy21osti/80863.pdf
e 2 anos depois



Membrana de silicone de alta refletividade para telhados
A sujidade reduziu o albedo de 0.7 pra 0.56 em 4 meses
(S. Ayala Pelaez, JPV 2019)

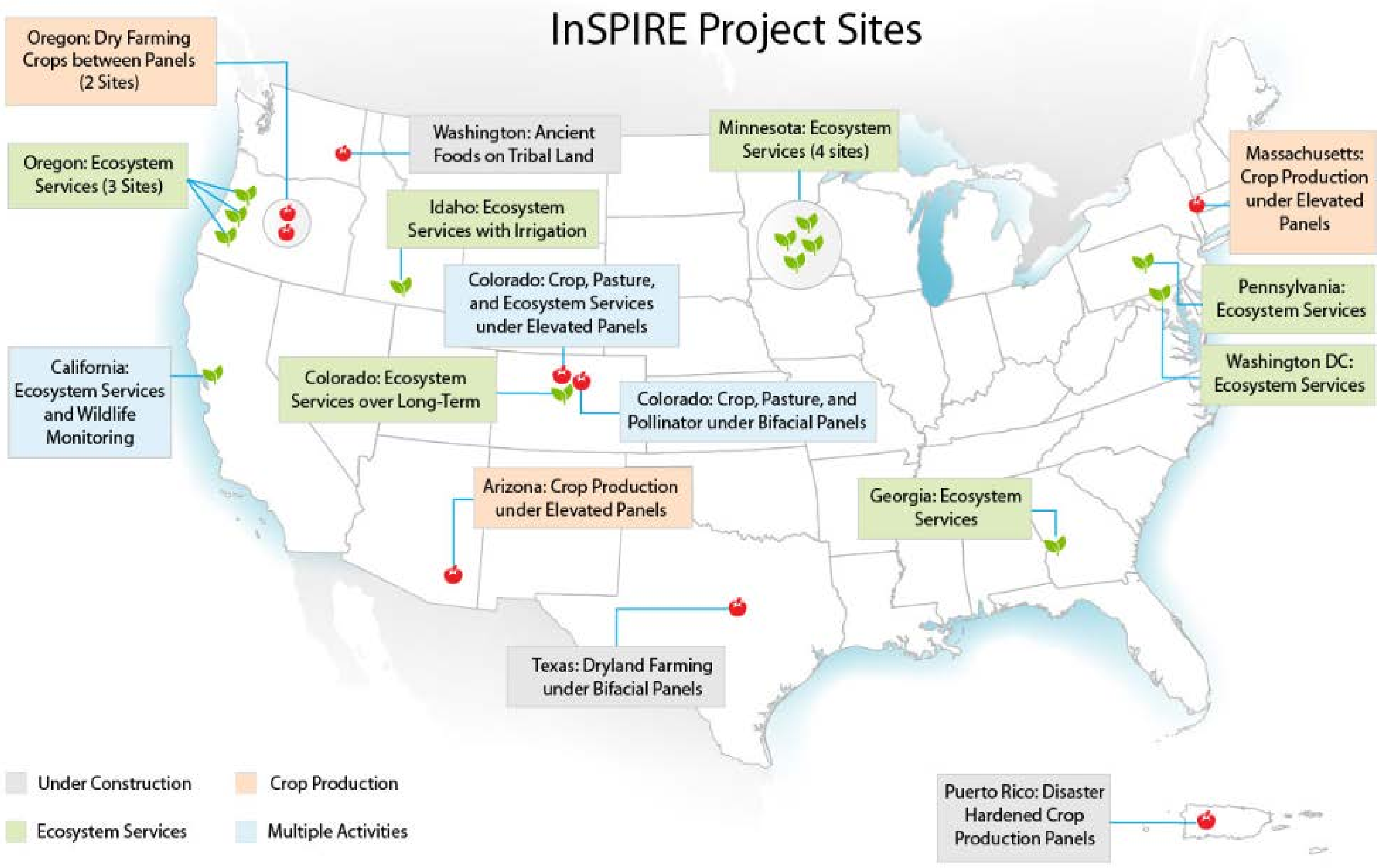
AgriPV no NREL

Verãos 2022, 2023, 2024

Projeto InSPIRE

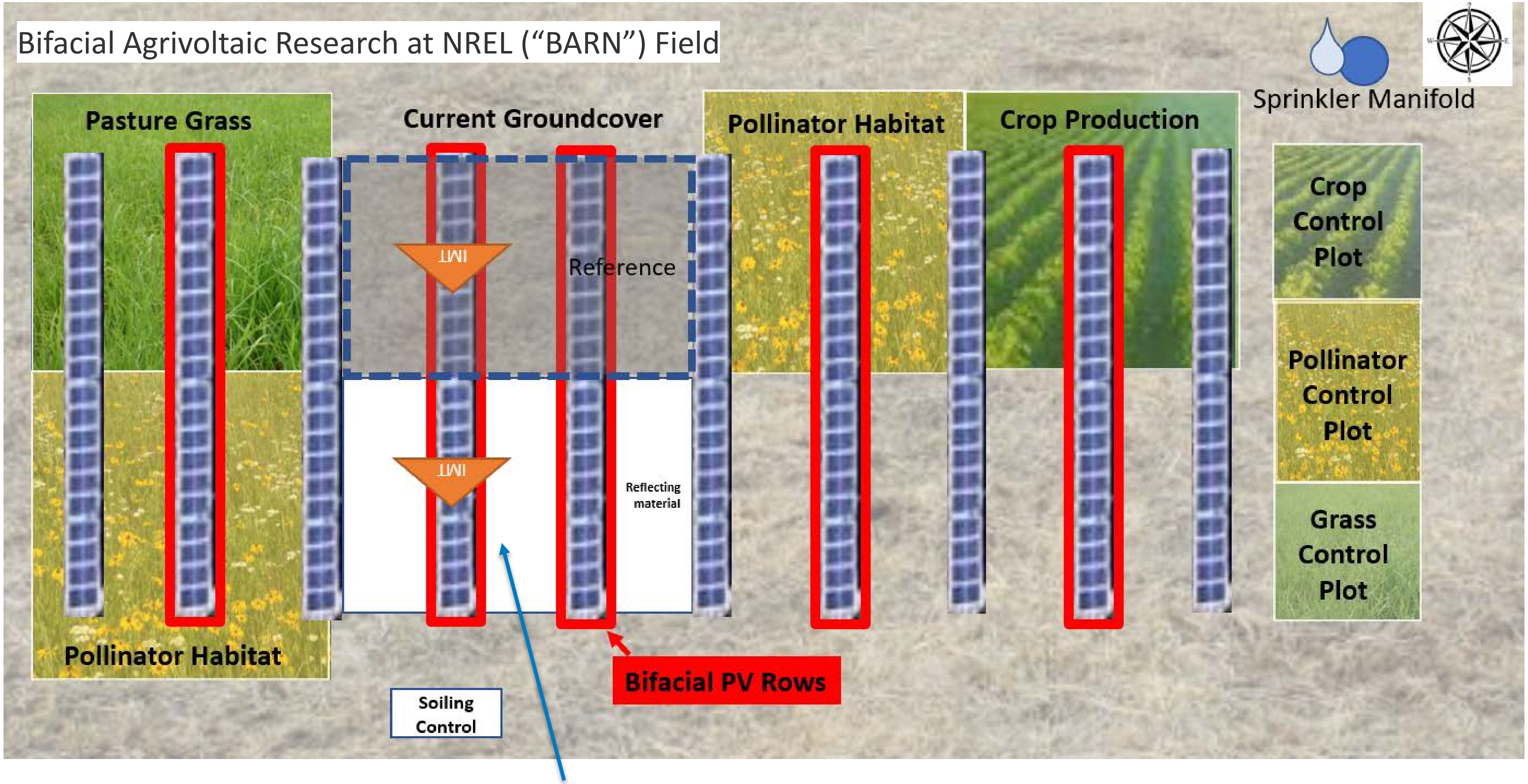
Innovative **S**olar **P**ractices **I**ntegrated with **R**ural Economies and **E**cosystems

- 24+ projetos de pesquisa de campo ativos
- Mapa interativo rastreia 6+ GW de projetos agriPV nos EUA
- World Agrivoltaic Conference: Denver, Colorado, Jun 19-14



https://openei.org/wiki/InSPIRE

AgriPV no campo bifacial de NREL



Test de Albedo

Verão 2023: Resultados

Melhor Desempenho com Base no Peso da Produção

	Controle	Canteiro Leste	Central	Canteiro Oeste
Acelga			x	
Couve		x		
alfavaca				x
Cenoura	x			
Tomate 1		x		
Tomate 2		x		
Pimentão 1				x
Pimentão 2			x	

- A maioria das plantas teve desempenho pelo menos igual entre os painéis solares em comparação com o controle. As cenouras foram as únicas culturas que apresentaram desempenho distintamente melhor no controle.
- O tomate 1 foi colhido mais cedo no controle do que os tomates sob os painéis.
- A alfavaca também floresceu mais cedo no controle

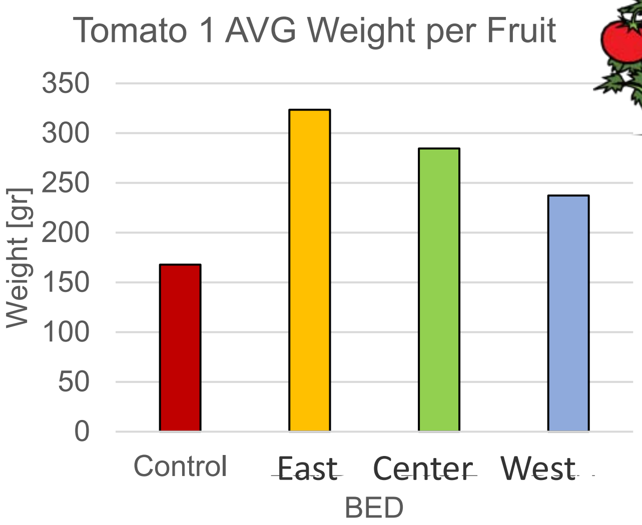


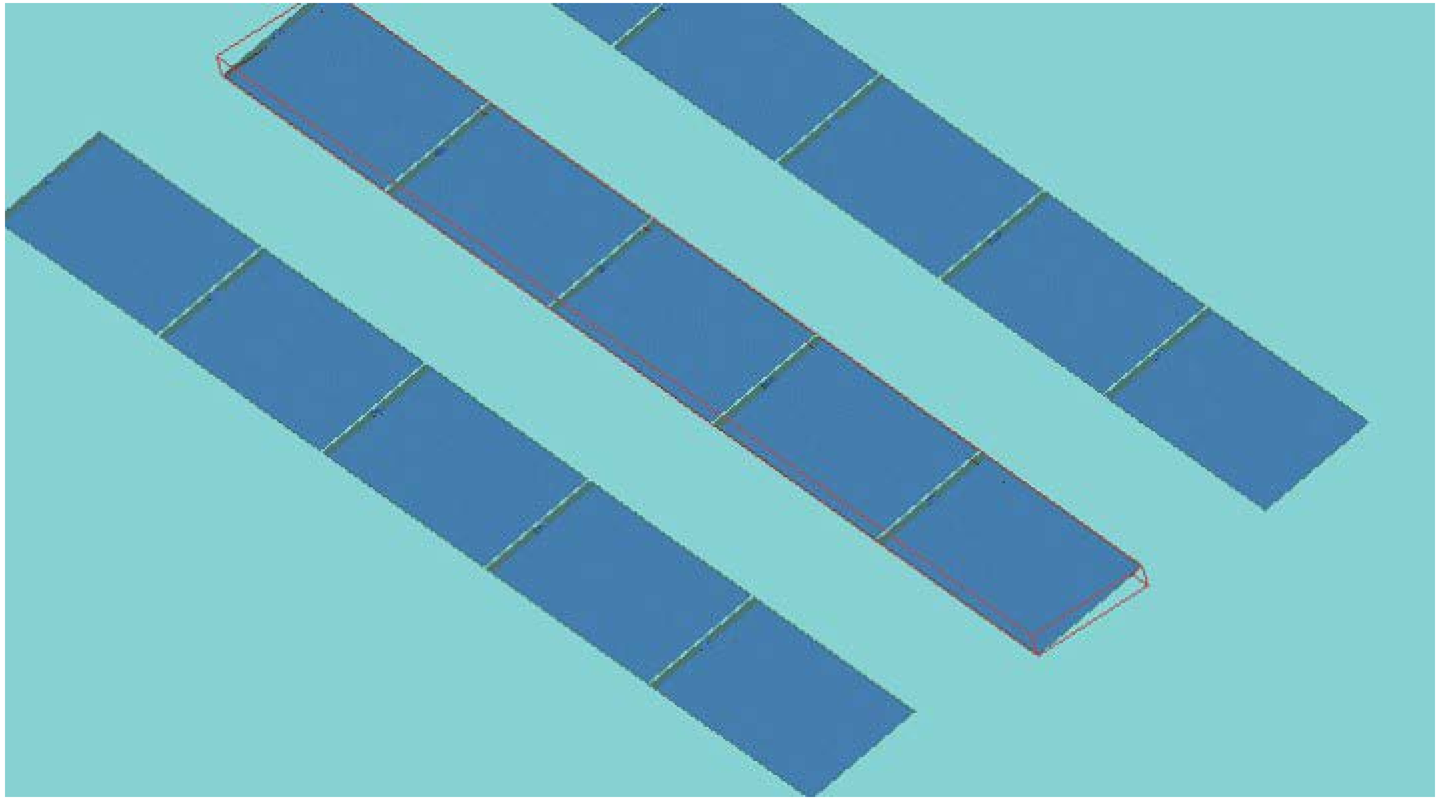
Foto de C. Deline

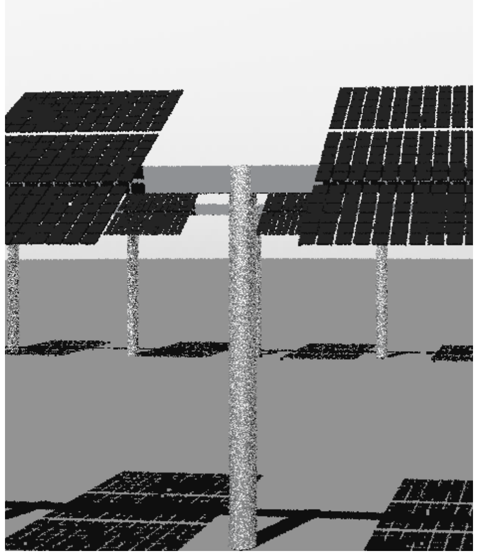
Ferramentas de Modelagem

Bifacial & AgriPV

Ferramenta: Raytracing

https://github.com/NREL/bifacial_radiance



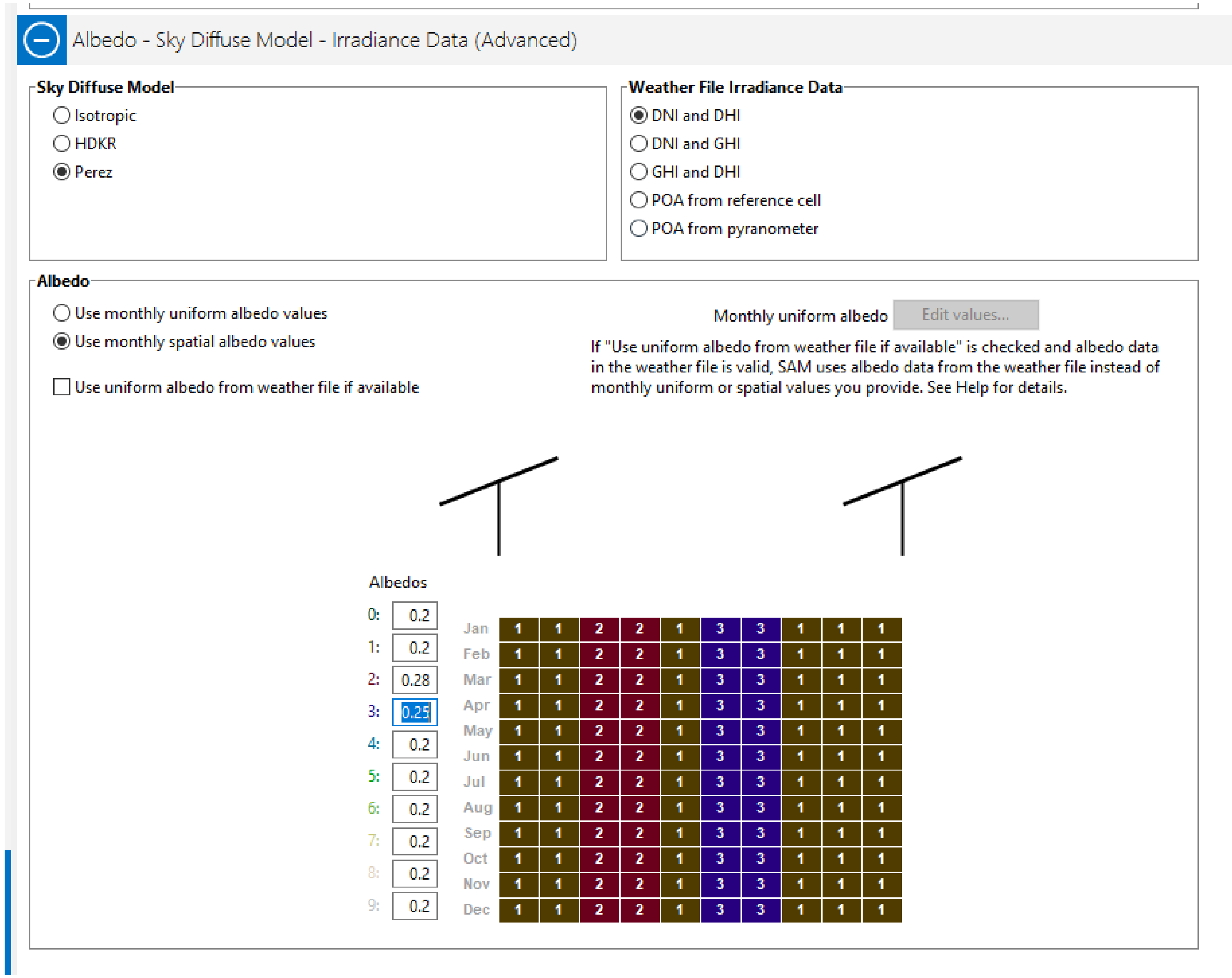


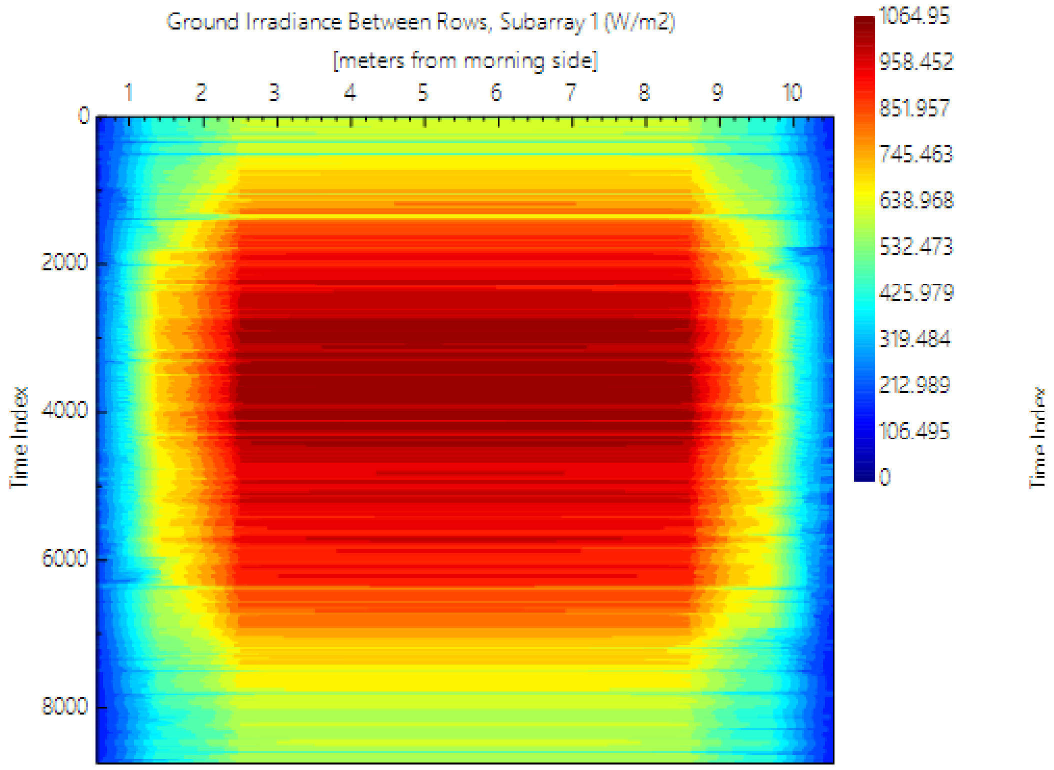
Exemplos AgriPV:

bifacial_radiance

- Peer-reviewed, open source!
- Usa rastreamento de raios para avaliar a irradiância (W/m^2) em qualquer lugar, com muita customização!
- Clima → Irradiância → Energia do Módulo com PVlib

Ferramentas: System Advisor Model (SAM)





Due diligence software para PV

Accesso programático com pySAM

National Renewable Energy Laboratory

Golden CO, Boulder CO, Washington, DC & Alaska, Fairbanks – +3900 trabalhadores

Photo by Werner Slocum, NREL 66364

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- Eólica
- Hídrica
- Geotérmica

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- Bioenergia
- Hidrogênio e Células de Combustível (Fuel Cells)
- Transporte e Mobilidade

Edifícios e Indústria

- Edifícios
- Eficiência Industrial e Descarbonização
- Materiais Avançados e Manufatura
- Governos Estaduais, Locais e Tribais

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- Soluções Energéticas Integradas

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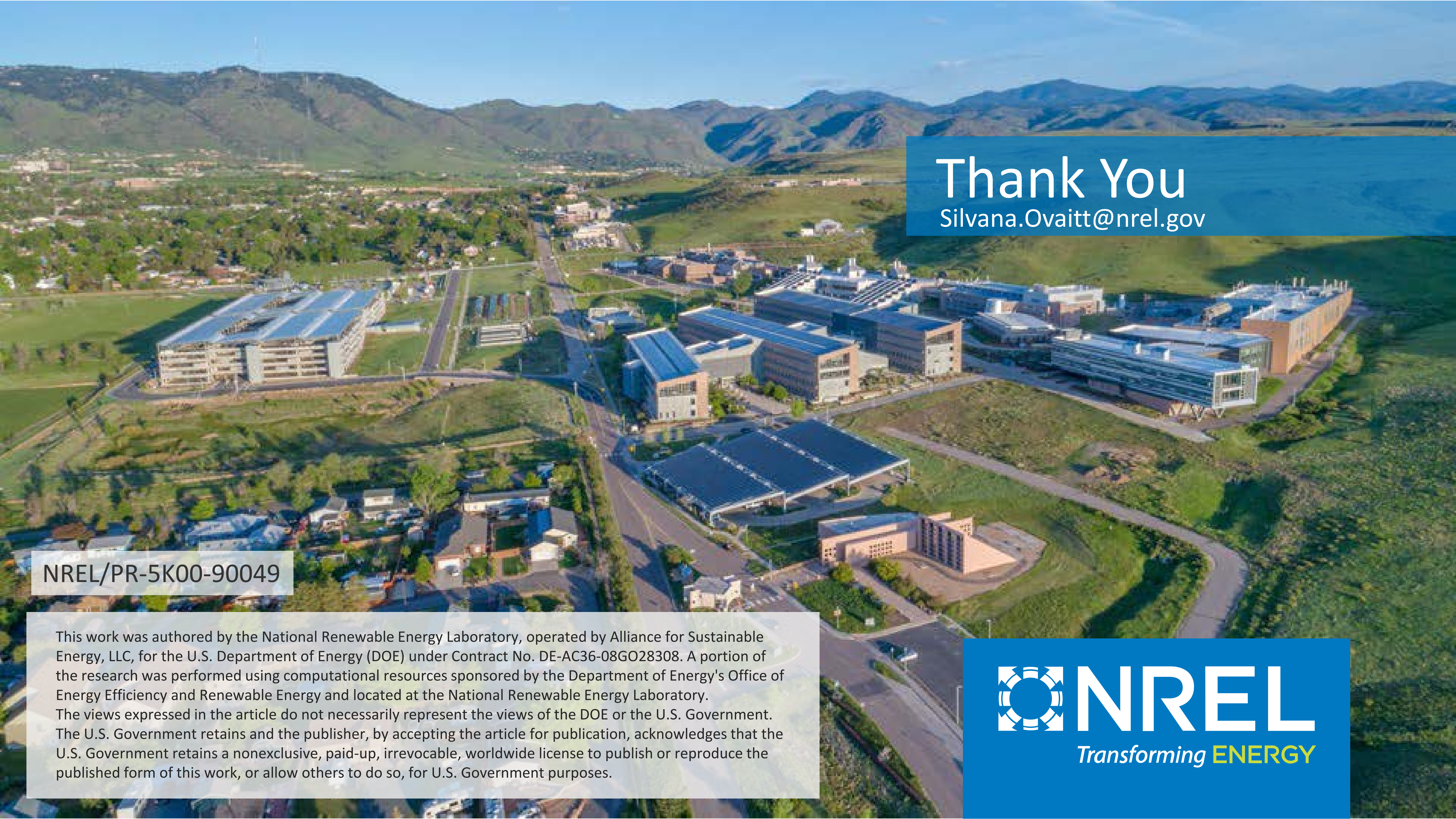

Thank You

Silvana.Ovaitt@nrel.gov

NREL/PR-5K00-90049

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