The Energy Gain Provided by 4 and 6-Terminal Bifacial Tandem PV Cells, with a High Efficiency Bifacial Silicon p-PERT Sub-Cell

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Presentation Outline

- Technological considerations – Introduction
- Si sub-cell and bifacial tandem cell design
- Outdoor experiments as a basis for predictive calculation
- Example of the energy gain calculation
- Conclusions

Bifacial Tandem Cell Design - Advantage of 4 Terminal (or 6 Terminal) Over 2 Terminal

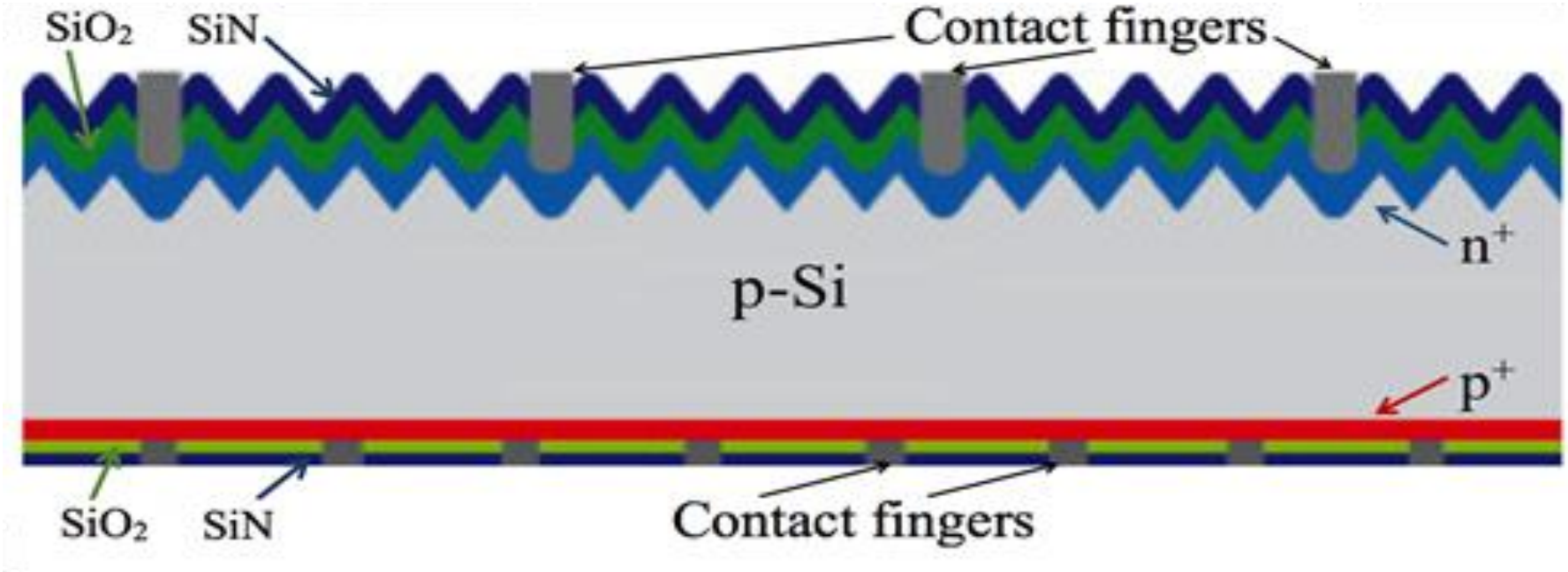
- The possibility of implementing a bifacial structure without of the need for balancing the currents of both sub-cells;
- High efficiency of the tandem cell, weakly dependent on the forbidden energy band gap width of the upper sub-cell semiconductor;
- Technological independence of sub-cells fabrication;
- Stability independence of the top and bottom sub-cells;
- The possibility of independent tests of each sub-cells

SolAround's Sub-Cell Structure - Highlights

- Use of high carrier lifetime p-type mainstream silicon.
- The cell's structure is a p-PERT, with full boron doped BSF.
- Bulk minority currier lifetime, after boron doping, is kept above 0.5 ms, (depending on starting lifetime)
- Back Seff is lower than 15 cm/s.
- Implied Voc is in the range 700 - 717 mV
- Bifaciality factor is 90 - 92%.

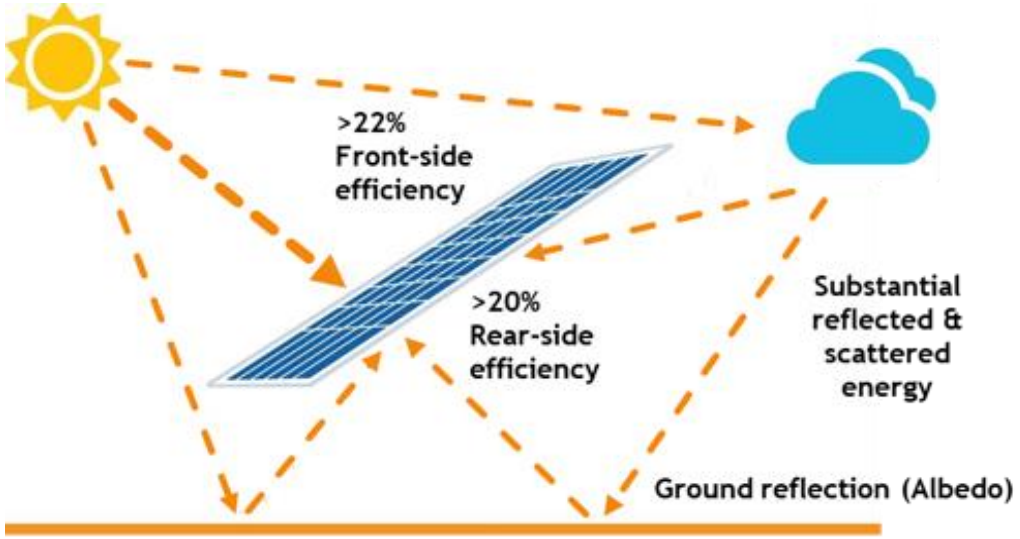
SolAround p-PERT – Cell Design

- ✓ Front side is textured;
- ✓ Rear side is chemically flat etched;
- ✓ Both sides are covered by SiO_2/SiN passivating and AR coating



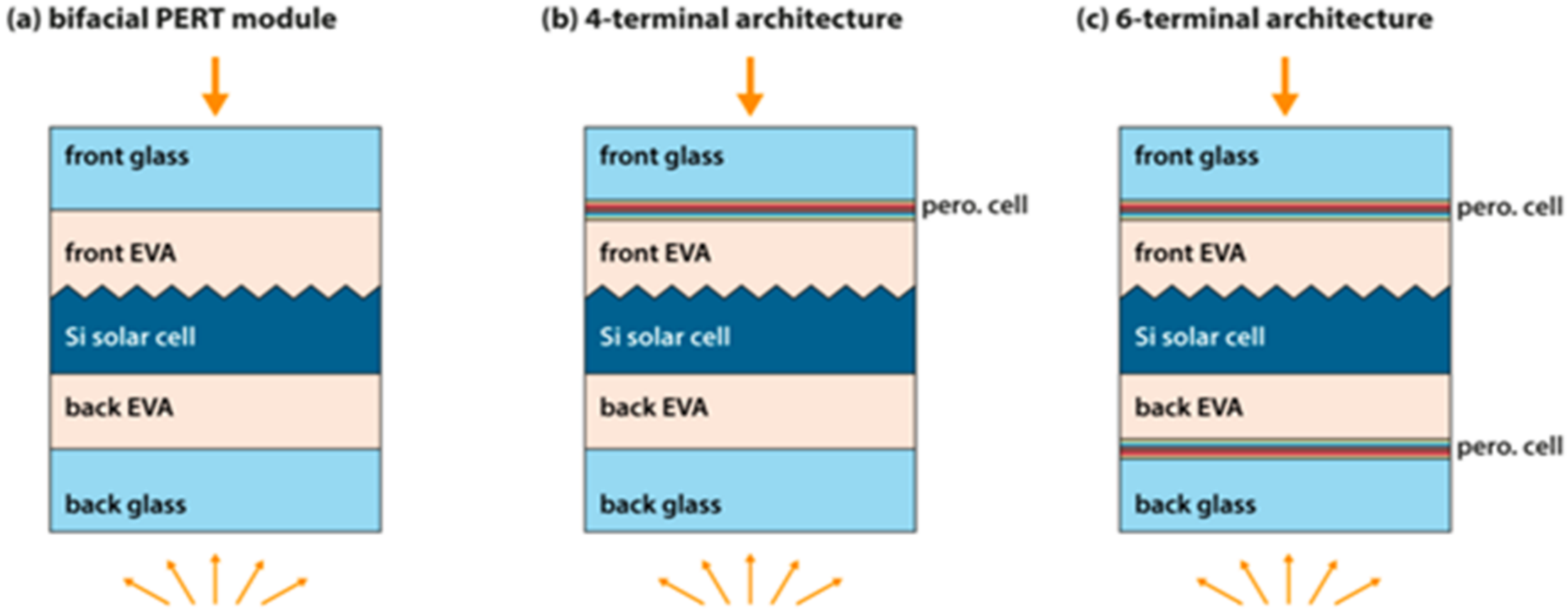
Operational Advantages of Si p-PERT Bifacial Cell

- Additional 20% to 40% Energy
- Equivalent efficiency: **27% to 31%**
- High stability, low aging
- LCOE (Cost of Energy): **-10% to -25%**
- A simple line retrofit
- Higher IRR, Shorter ROI in solar projects
- Highly profitable for **vertical** manufacturers



- Ideal for utility scale ground installations,
  flat white rooftops, sound barriers, carports, BIPV
- Enhanced yield gain in foggy, cloudy, northern, snow and desert conditions

Integration of Perovskite Sub-cells in 4 or 6 Terminal Tandem Solar Cells*



*K. Jäger et al, "Optical assessment of perovskite-enhanced bifacial silicon solar modules", 36 EUPVSEC Proceedings 2019

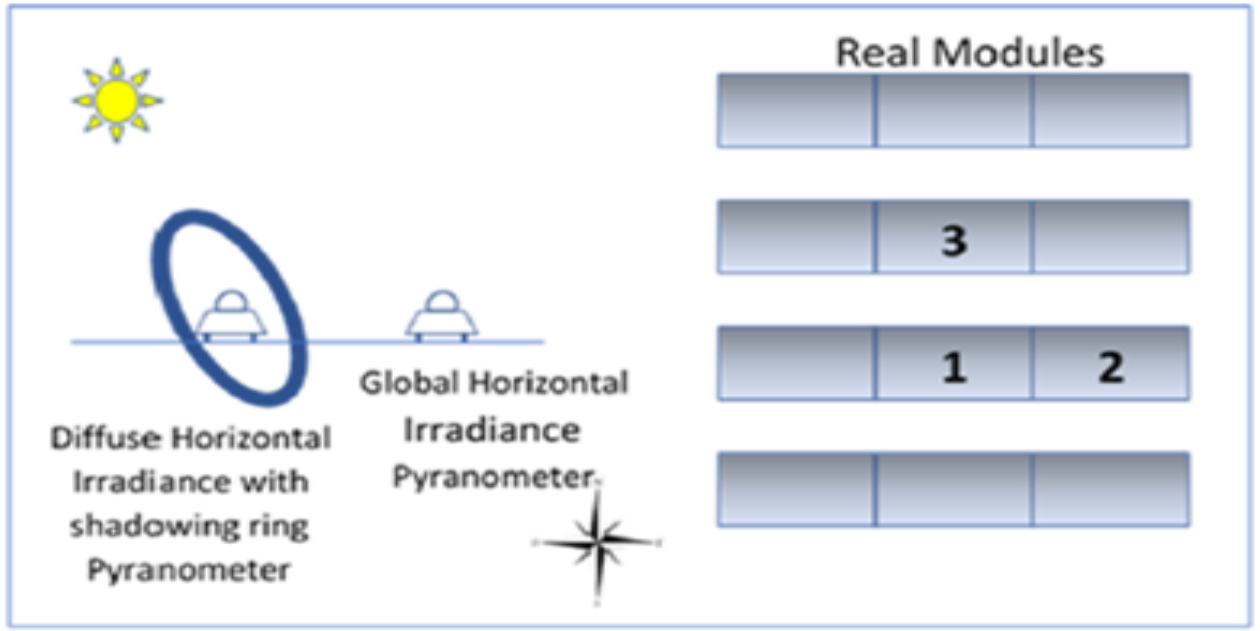
Experimental Verification of Simulation Model for Bifacial Module Energy Generation Gain

Object of the experimentation:
Comparative analysis of calculated and measured energy gain of bifacial modules over monofacial ones, in solar field conditions:

Method:

1. Measure the gain in energy of a bifacial module over a monofacial module, due to the added rear illumination.
2. Measure the added rear illumination and correlate with the electrical energy gain.
3. Compare and correlate both results with Solaround simulation tool.

The Bifacial Module Test Setup



EXPERIMENTAL "FIELD" LAY OUT

1. Continually measured bifacial module
2. Continually measured monofacial module
3. Bifacial module for measurements of rear and front irradiance (with 6 detectors)

Rooftop Test Field

Test Conditions:

- **Installation type**: Flat white rooftop
- **Ground Albedo** ~ 57.5±2.5%
- **Test configuration**: SolAround's prototype BIFACIAL panel, monitored in parallel to a few surrounding MONOFACIAL panels, in same operating terms
- **Test period**:
  A few days each month since mid. 2019.

Validation of Simulation Model

- **Optical validation:** correspondence of calculated and experimental front and back irradiance data. Effective cell irradiance is:

$$Ir_{eff} = Ir\ (Front) + Ir(Back)*(Bifacialty\ Factor)$$

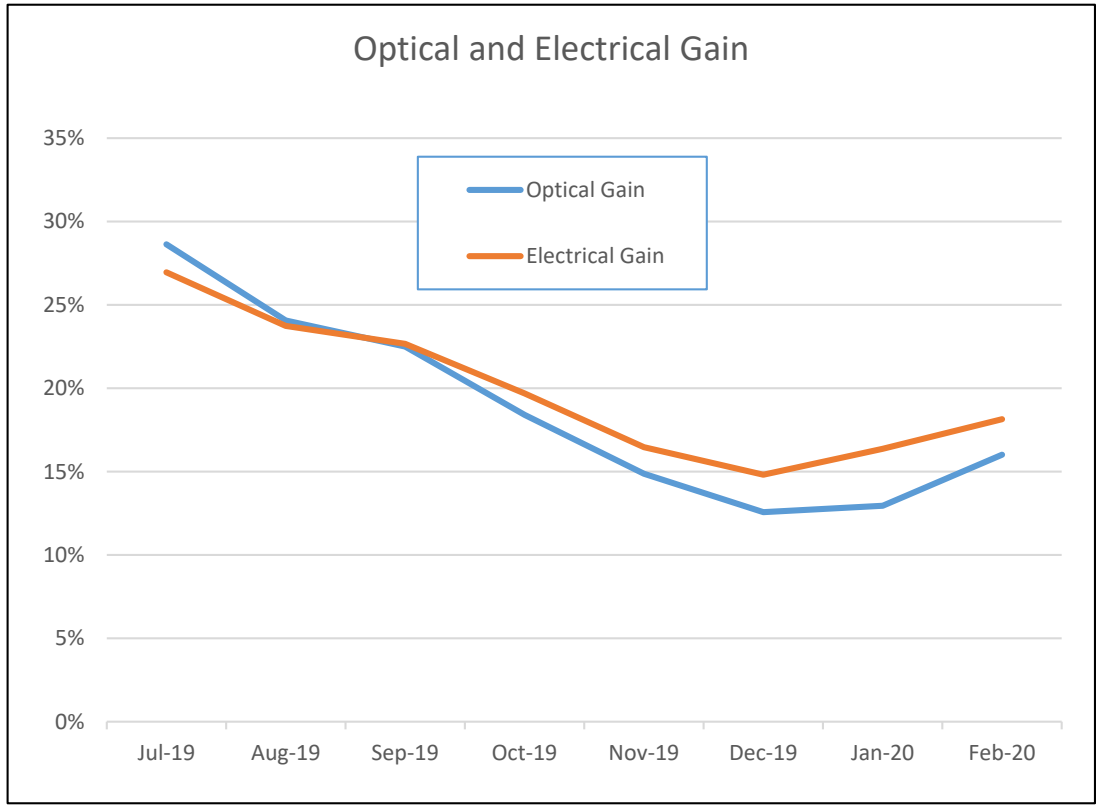
- **Electrical validation:** correspondence of calculated and experimental electrical data

$$\text{Bifacial Gain \%} = \frac{En\ (Bifacial) - En\ (Monofacial)}{En\ (Monofacial)}$$

where E_n is normalized module energy:

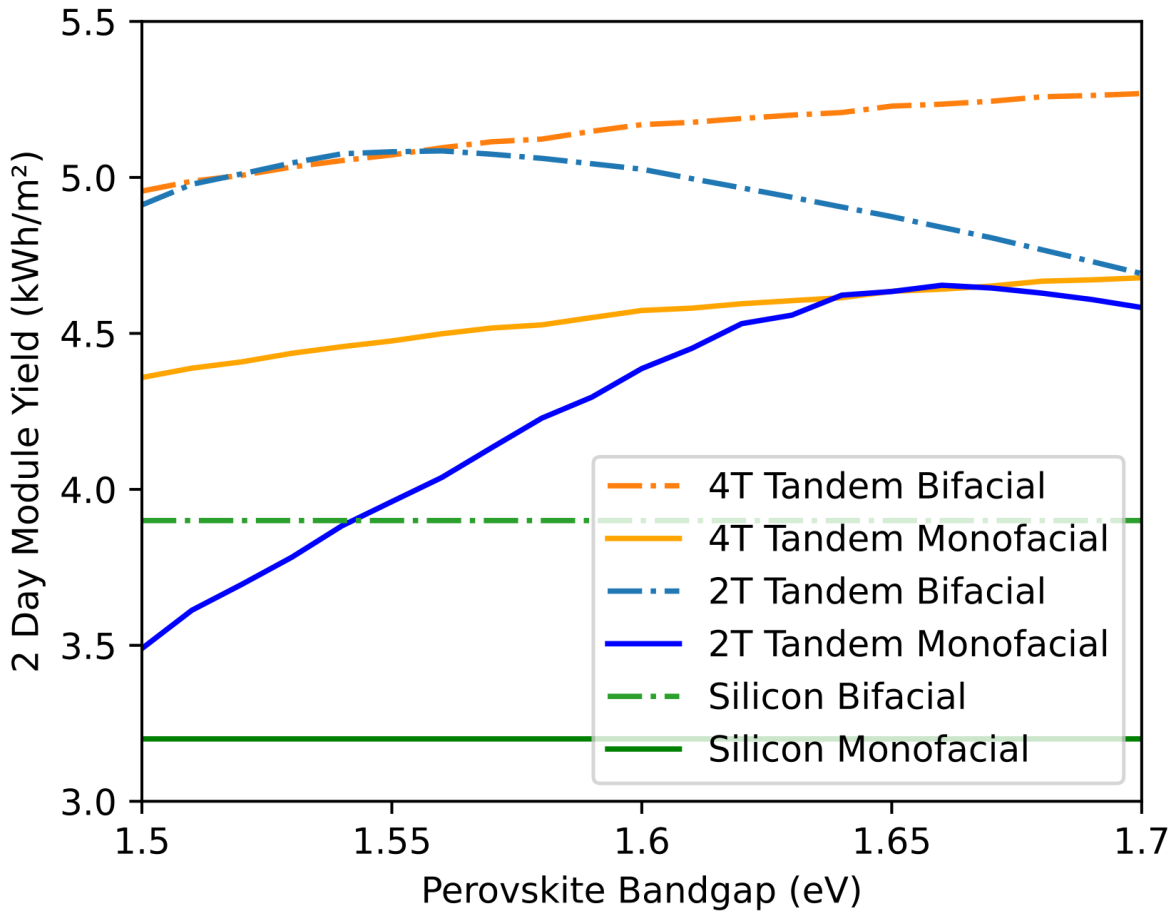
E_n = module generated energy **E**/ Front P_{max}, at STC

Experimental Verification of Simulation Model
Irradiance and energy gain values



month	Optical Gain	Electrical Gain
Jul-19	28.6%	27.0%
Aug-19	24.1%	23.7%
Sep-19	22.5%	22.7%
Oct-19	18.4%	19.7%
Nov-19	14.9%	16.5%
Dec-19	12.6%	14.8%
Jan-20	13.0%	16.4%
Feb-20	16.0%	18.1%

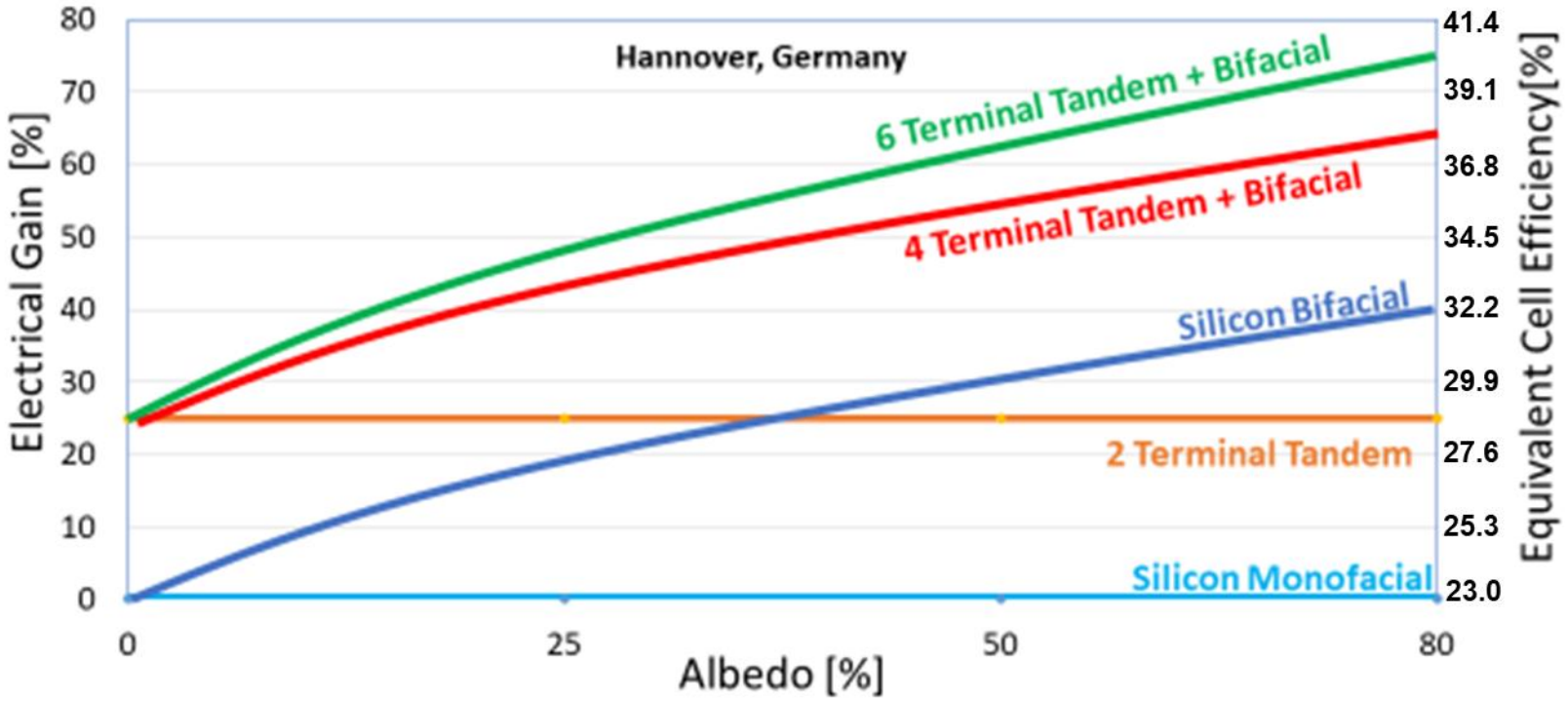
Simulation of Two-Day Energy Generation for a Modules of Various Designs (26.08.19 and 15.02.20)



Solar Input Data Used for the Simulation Tool

- **ESRA** (European Solar Radiation Atlas / Ecole Des Mines De Paris),for 500 available locations in Europe
- **US NREL database** for US locations.
- **METEONORM** (8,055 Stations worldwide, based on GEBA by World Meteorological Org (WMO/OMM) and the Meteo-Swiss DB).
- **ESRA interpolations** for other locations

Electrical Gain and Equivalent Efficiency of Silicon Perovskite Tandem Bifacial Cell



Summary

- **High efficiency bifacial Si p-PERT cell** is a candidate sub-cell for the silicon/perovskite tandem cell
- Careful outdoor experiments provide optical and electrical validation of the bifacial gain simulation model
- Combination of bifacial sensitivity and tandem design allows to maximize solar cell energy generation
- Strongly varying rear illumination does not allow for the best use the bifaciality factor in the 2-terminal tandem cell
- According to simulation, 4-terminal bifacial tandem cell can achieve the equivalent efficiency of ~37% comparing to 32% for bifacial Si cell with front efficiency 23%.
- Simulation for 6-terminal bifacial tandem cell results in equivalent efficiency ~39%

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