Comparison of different bifacial systems
Design parameters influence analysis

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BIFI Workshop KONSTANZ October 2017

OUTLINE

1. Introduction-Definitions
2. Bifacial Space Systems
3. Design Factors for Terrestrial Bifacial Arrays
4. Experimental Analysis of Design Factors
5. System Test Results
6. Conclusions

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1. Introduction-Definitions

MODULE GAIN, BIFACIAL FACTOR AND EQUIVALENT EFFICIENCY

Bifacial Gain: The additional energy contribution due to the bifacial module's rear side collection is defined by:

$$G_{absolute} = \frac{E_b}{P_{fb}} - \frac{E_m}{P_{fm}}$$

Where E_b and E_m are respectively the Energy yield of bifacial and monofacial module and P_{fb} and P_{fm} the Power (at standard conditions) of front and back illuminated bifacial module

$$G_{relative}\ (\%) = \{ [E_b / P_{fb}] / [E_m / P_{fm}] - 1 \} \times 100$$

Bifacial Cell Equivalent Efficiency: The efficiency of a mono-facial cell required for generating the same energy as the bifacial cell, under the same operating conditions:

$$\text{Equivalent Efficiency} = \text{Front Efficiency} \times (1 + G_{relative})$$

Bifacial Factor: Back to front short circuit currents ratio:

$$BF = I_{sc,back} / I_{sc,front}$$

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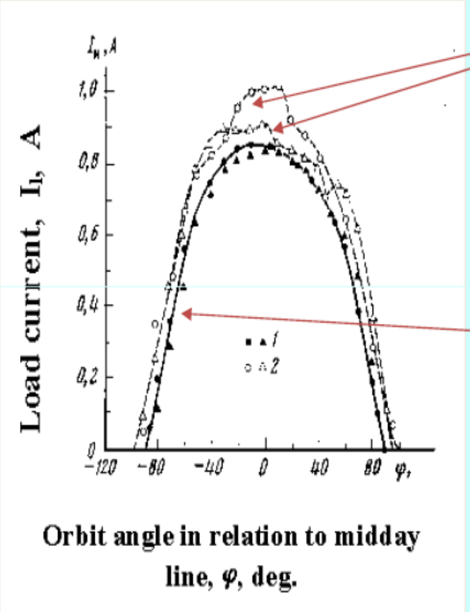
2. Bifacial Space Systems

BIFACIAL SYSTEMS in SPACE



A BIFACIAL ARRAY ON THE SALUT-5 SPACE STATION AT 350 KM ALTITUDE GENERATED ON AVERAGE~ 17% MORE POWER THAN A CONVENTIONAL PANEL.

Bifacial Factor: 75 %

Spacecraft name	Launch year	Orbit type	Power generation gain, %
Salut-3	1974	LEO	17 – 34
Salut-5	1976	LEO	17-45
Kosmos-1870	1987	LEO	12
Almaz	1991	LEO	10-20
Electro	1993	GEO	Reliability improved
Zarya (ISS section)	1998	LEO	10-20
Zvezda (ISS section)	2000	LEO	10-20

DESIGN PARAMETERS: HEIGHT OF ORBIT
ORBIT INCLINATION RELATIVE TO EQUATORIAL PLANE
EARTH ALBEDO
MODULE ORIENTATION

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BIFACIAL SYSTEMS in SPACE

Bifacial Si solar arrays were mounted on spacecrafts "Zarya" and "Zvezda" of Russian segment of the ISS.

Total Equivalent Efficiency of Bifacial Si Solar Cell with AM0 Front and Back Efficiencies 18 and 13.5 %

Full two-axis sun tracking			One-axis sun tracking			Feathered solar array to minimize drag		
Altitude of circular orbit, km								
200	600	1000	200	600	1000	200	600	1000
Equivalent efficiency								
21.5	21.0	20.5	21.2	20.5	20.3	24.3	24.6	25.0

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3. Design Factors For Terrestrial Bifacial Arrays

DESIGN FACTORS AFFECTING THE BACK CONTRIBUTION IN TERRESTRIAL BIFACIAL SYSTEMS

1. ILLUMINATION CONDITIONS

- Sun elevation
- Diffused/global radiation ratio

2. MODULE AND SYSTEM PARAMETERS

- Bifaciality Factor
- Module inclination (tilt)
- Distance between rows
- Module elevation above underlying surface
- Distance between modules in the row
- Albedo of underlying surface

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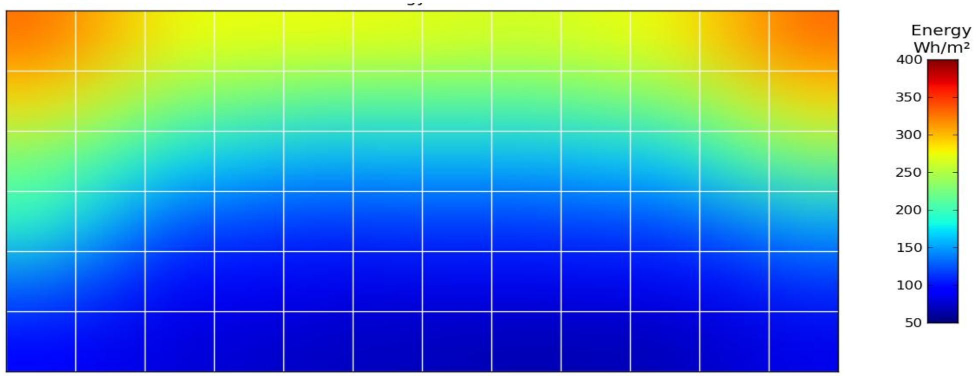
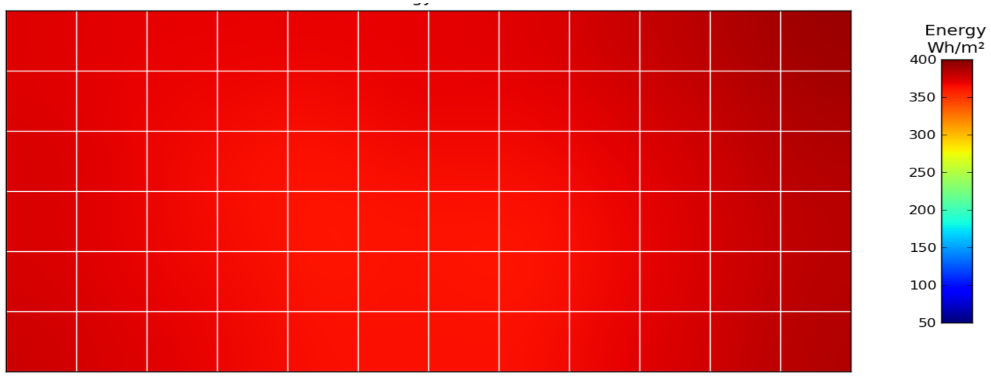
4. Experimental Analysis of Design Factors

INFLUENCE OF PANEL ELEVATION ON BACK IRRADIANCE

NON UNIFORMITY OF BACK IRRADIANCE VS. PANEL ELEVATION



Elevation 8 cm



Elevation 108 cm

Measured back side irradiance for a 30º tilted stand alone module

Albedo: 0.55
Global Irradiation: 1006 W/m^2
Diffuse Irradiation: 111 W/m^2
Panel size: 80x160 cm^2

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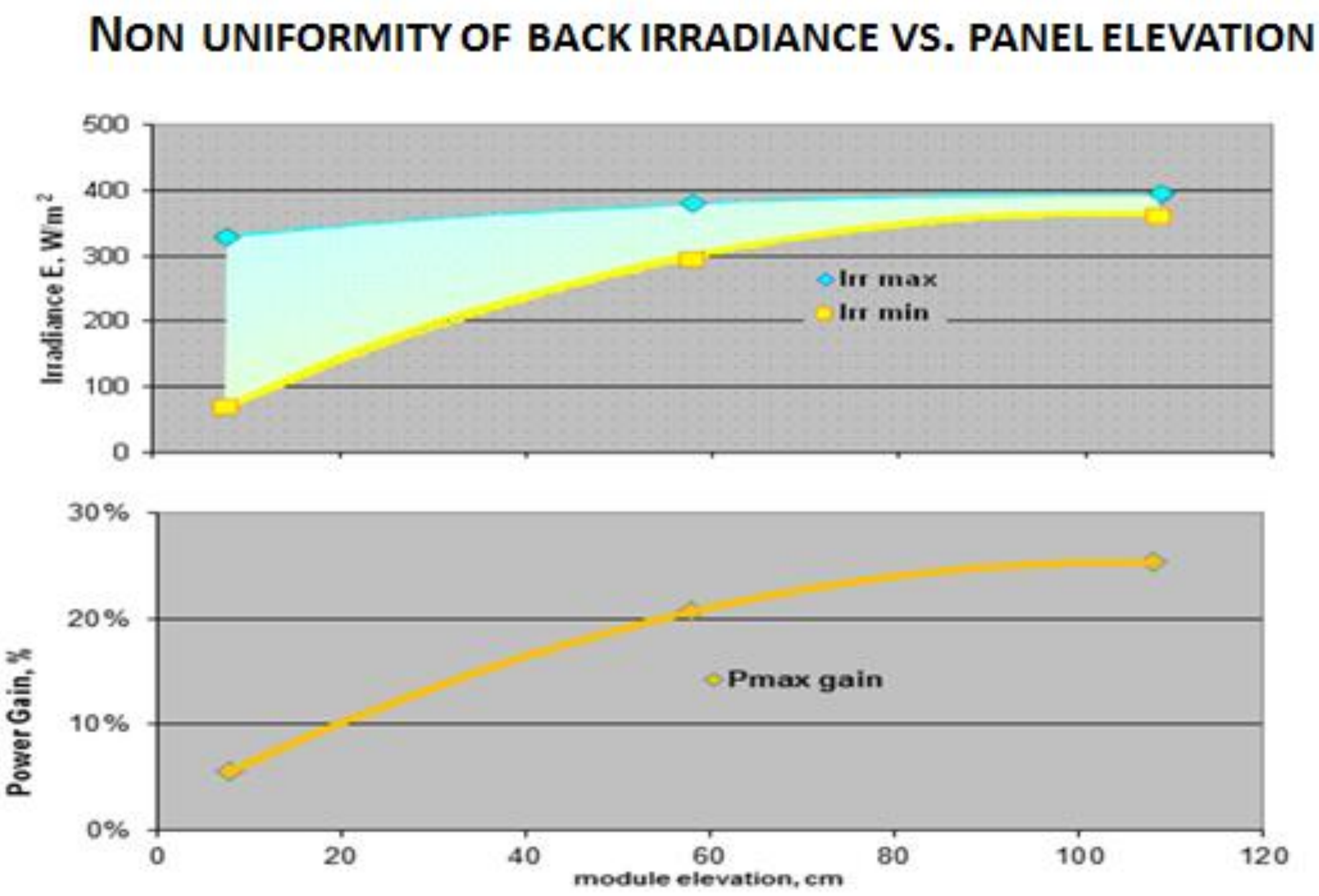
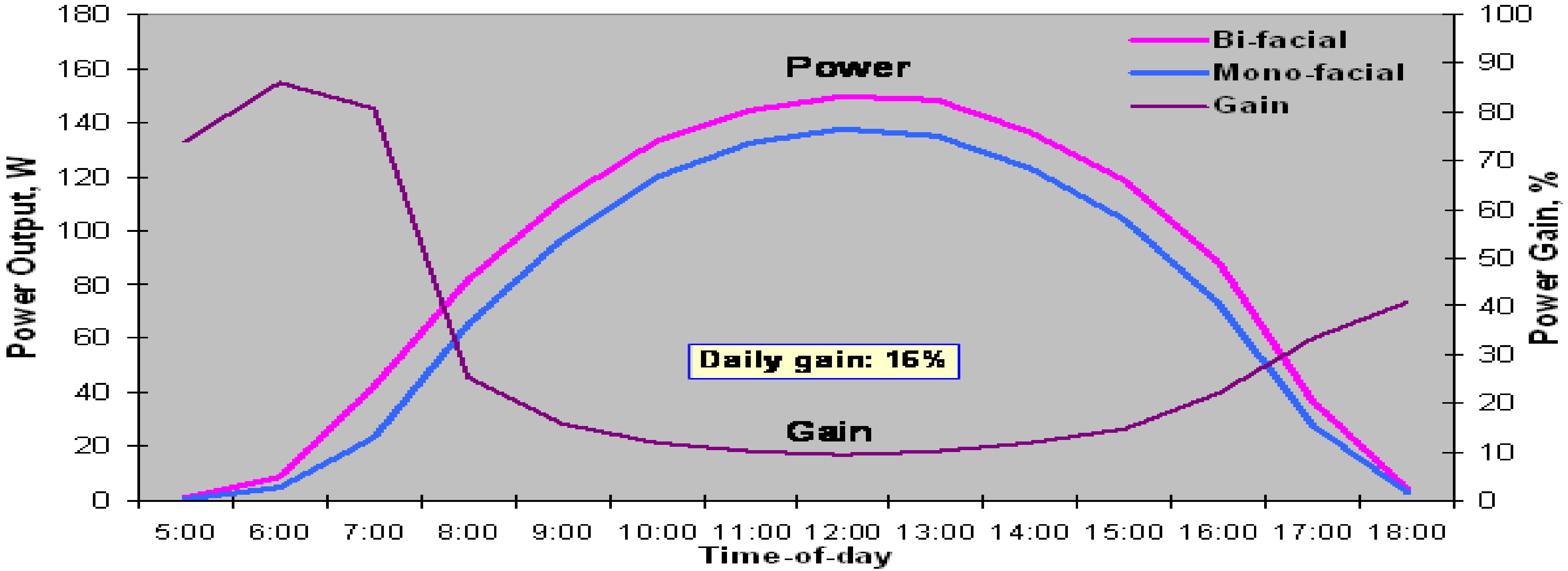
INFLUENCE OF PANEL ELEVATION ON GAIN



Back side irradiance E (min, max) and max power gain vs. module elevation

INFLUENCE OF WEATHER CONDITIONS ON GAIN

HOURLY DEPENDANCE OF ENERGY OUTPUT FOR MONO AND BIFACIAL MODULES IN A FIELD



Monitoring for sunny day with diffused/global radiation ratio: 11 % at noon

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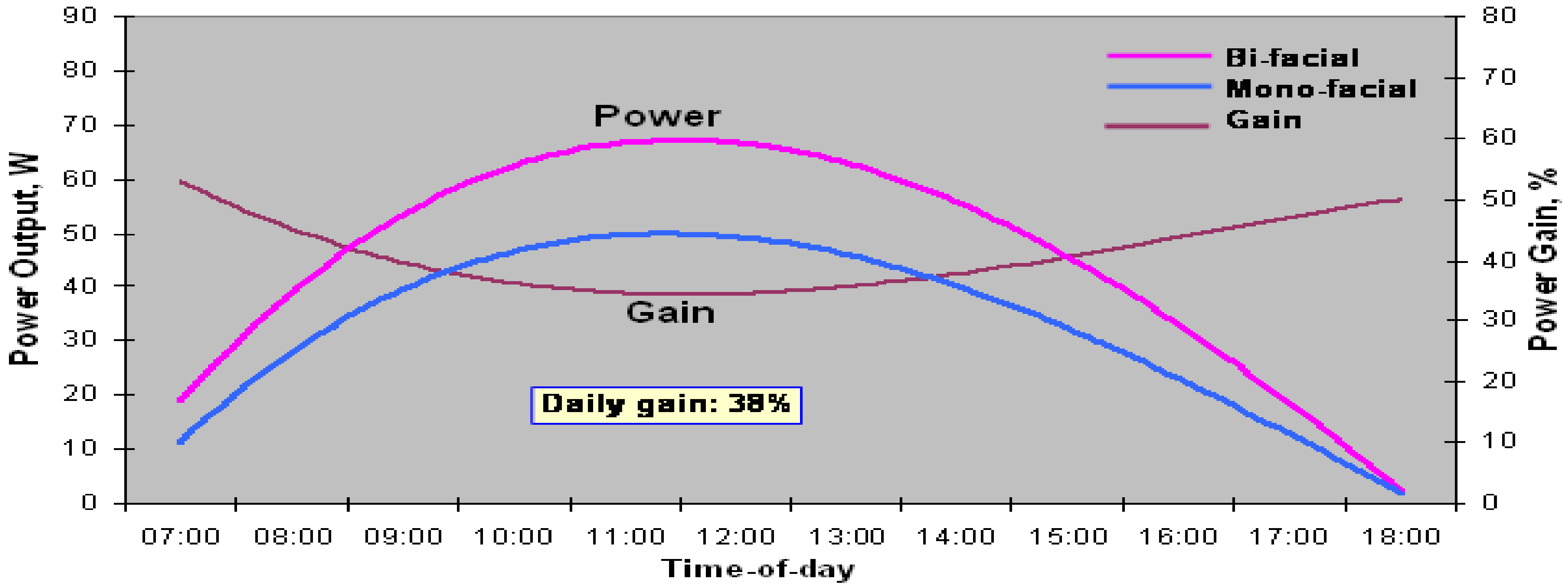
INFLUENCE OF WEATHER CONDITIONS ON GAIN

HOURLY DEPENDANCE OF ENERGY OUTPUT FOR MONO AND BIFACIAL MODULES IN A FIELD



Monitoring for cloudy day with diffused/global radiation ratio: 88 % at noon

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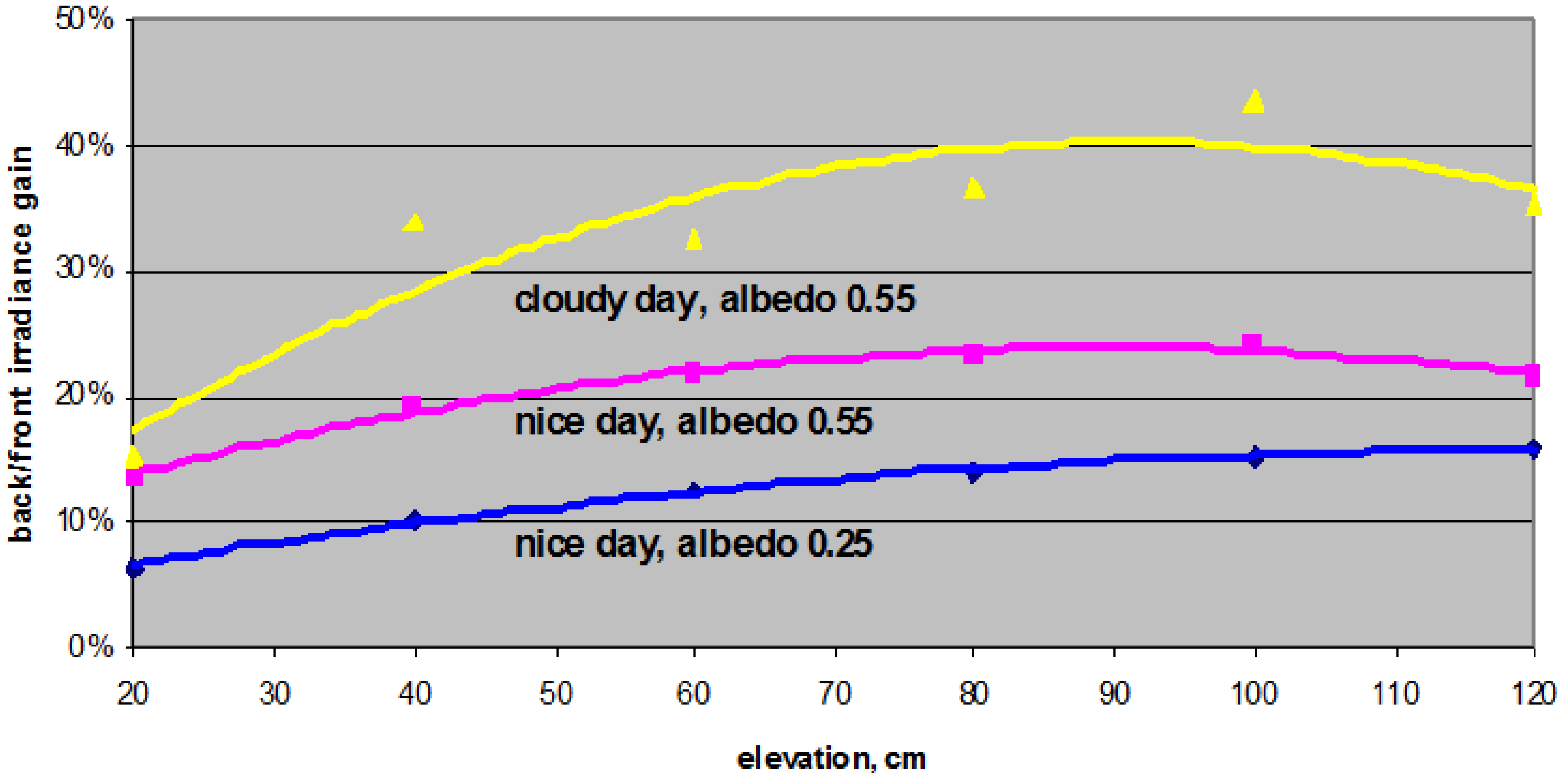
INFLUENCE OF ALBEDO AND WEATHER ON BACK IRRADIANCE



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5. System Test Results

Annual Bifacial Gain and Equivalent Cell Efficiency for various Field Designs
Simulated vs. Measured Results

ROOFTOP TEST FIELD IN GEILENKIRCHEN/GERMANY

Test field monitored by Fraunhofer ISE

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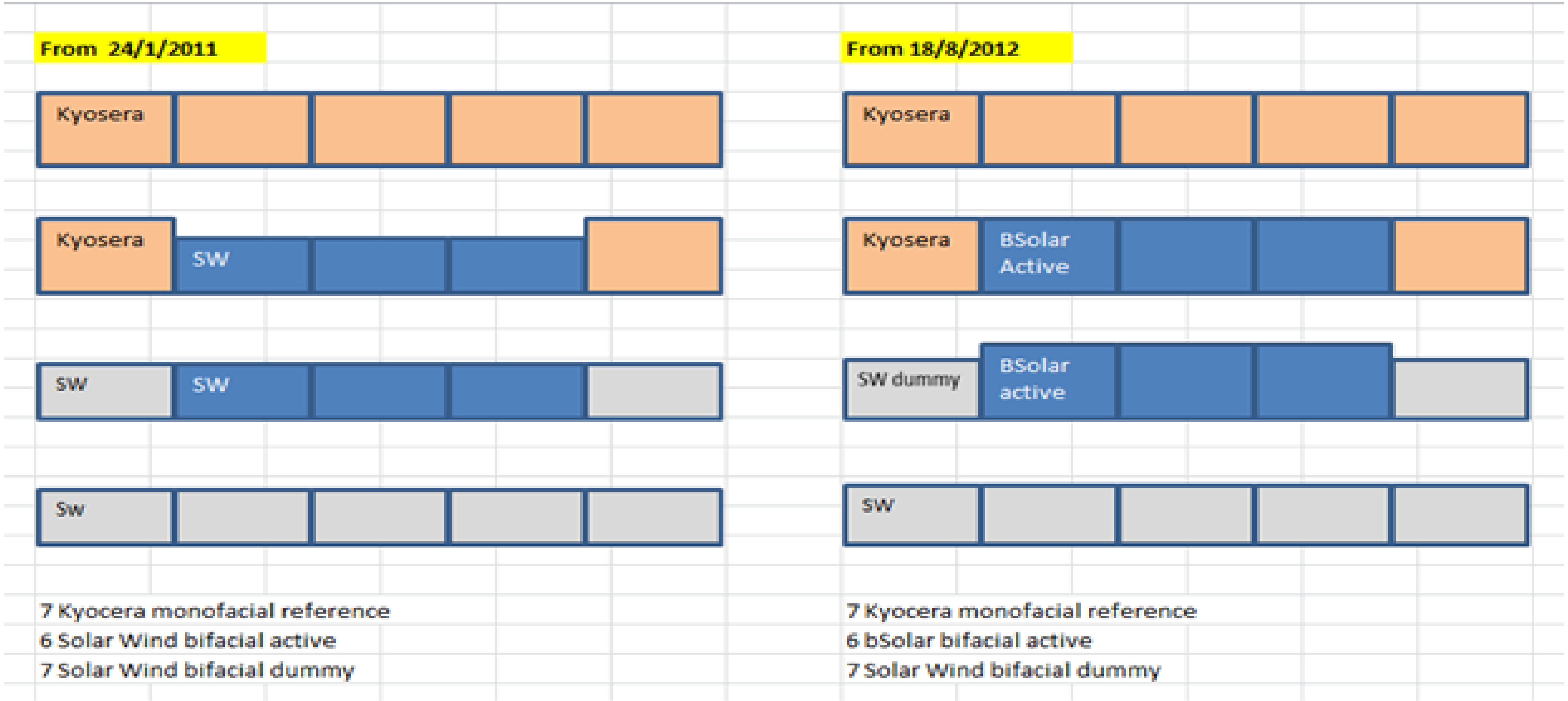
ROOFTOP TEST FIELD IN GEILENKIRCHEN/GERMANY



TEST FIELD LAYOUTS

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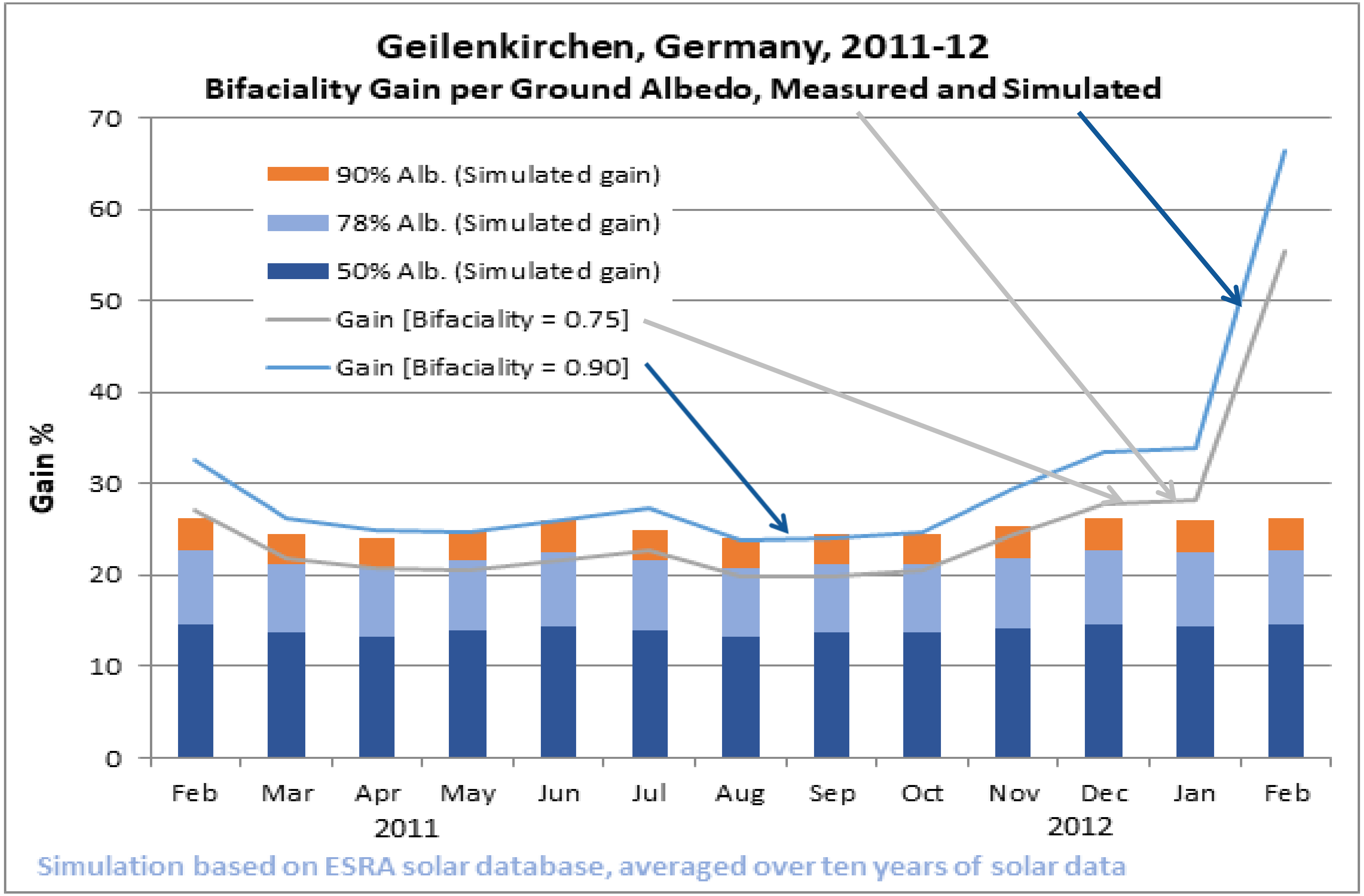
ROOFTOP TEST FIELD IN GEILENKIRCHEN/GERMANY



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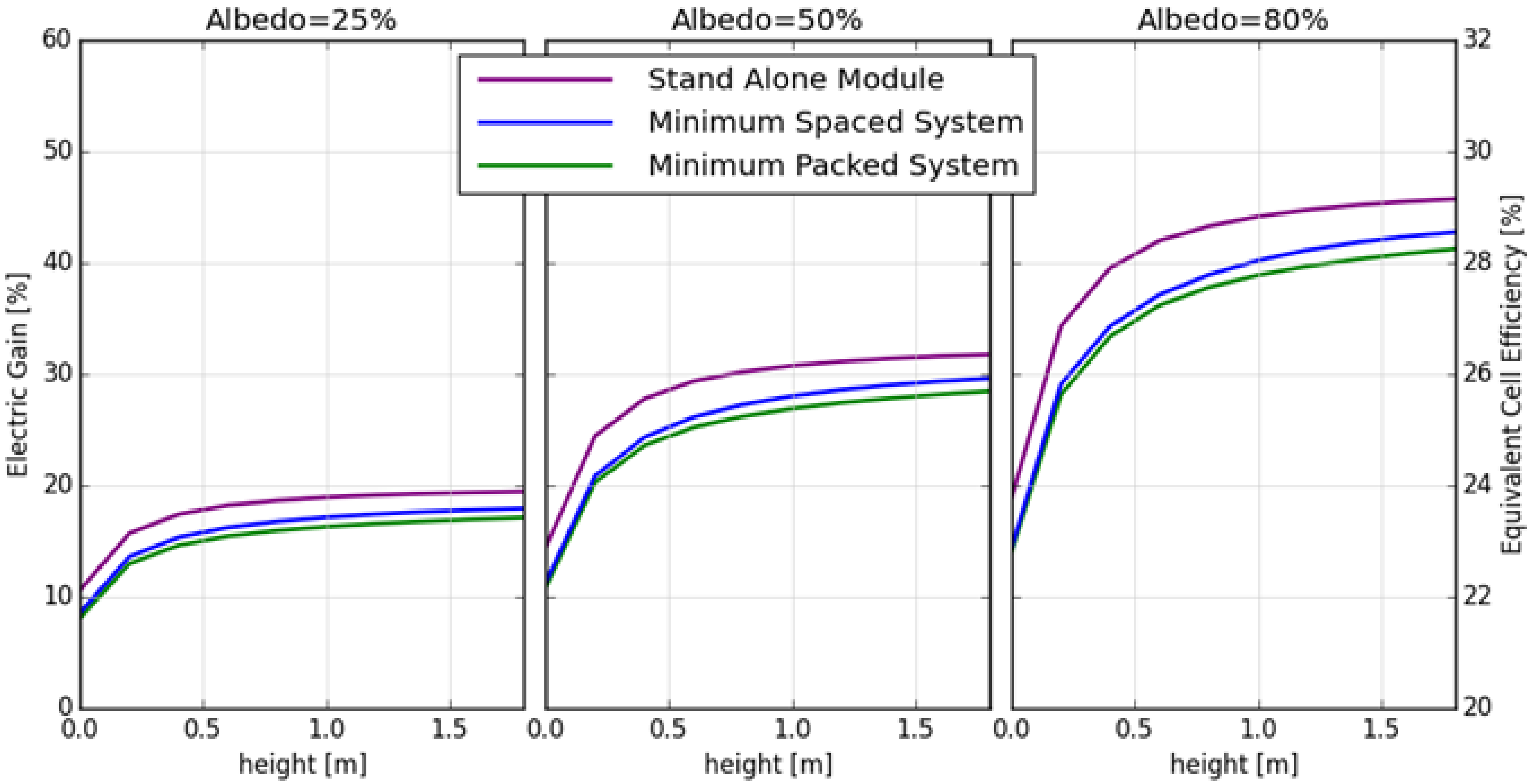
ROOFTOP TEST FIELD IN GEILENKIRCHEN/GERMANY



Electric Gain and Equivalent Efficiency Simulation
North Germany

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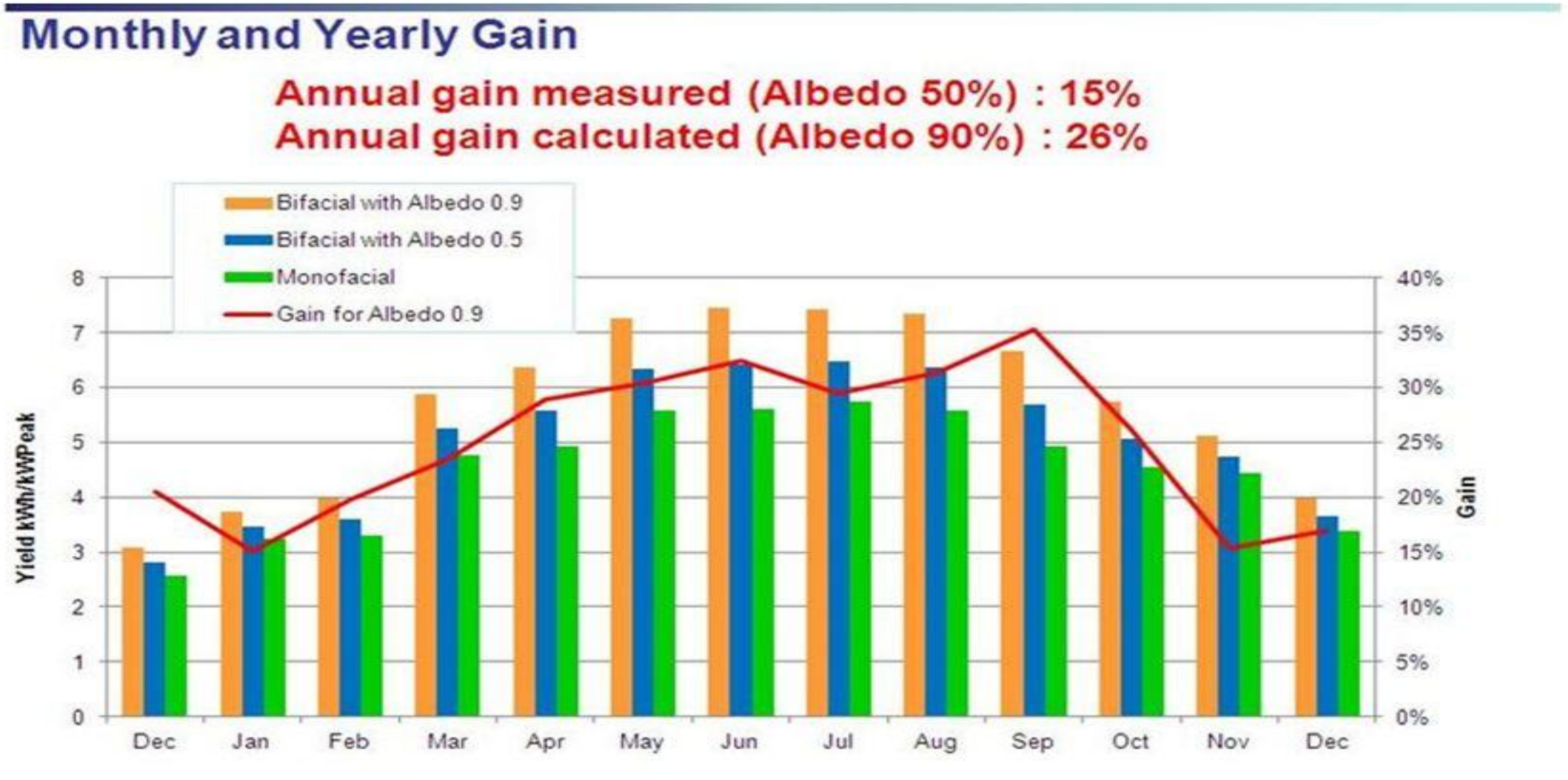
ROOFTOP TEST IN JERUSALEM/ISRAEL

- Solar field of 3x4 modules
- bSolar 170Wp module vs. Suntech 175 Wp module
- Bifaciality gain based on KWh/KWp comparisons
- Site parameters:
  - Ground reflectance (Albedo): ~50%
  - North-South (NS) distance (distance between rows, panel-panel center): 1.5m
  - East-West (WE) distance (panel-panel edge): 0.2m
  - Height (panel lower edge): 0.7m

ROOFTOP TEST IN JERUSALEM/ISRAEL



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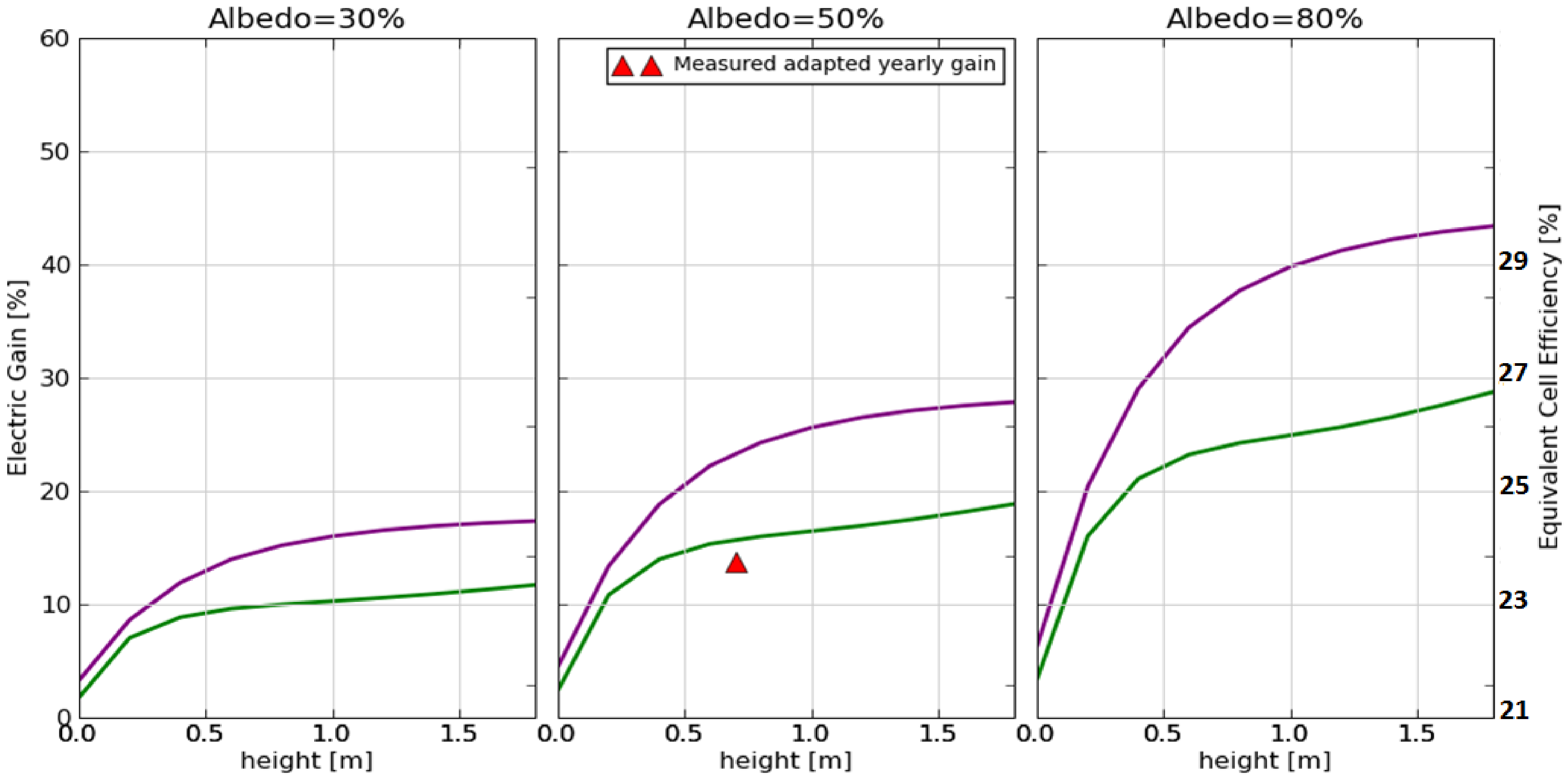
ROOFTOP TEST IN JERUSALEM/ISRAEL



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6. CONCLUSIONS

CONCLUSIONS

CAREFUL DESIGN AND PARAMETERS CHOICE OF BOTH MODULES AND FIELD INSTALLATION WILL INSURE BIFACIALITY GAIN OF 30-40 %

THE MOST IMPORTANT PARAMETERS UNDER CONTROL ARE:

- Module Bifaciality Factor
- Albedo of underlying surface
- The Height of the module is a critical factor too

BIFACIALITY GAIN PROVIDE ENERGY GENERATED DENSITY NOT ACHIEVABLE BY HIGHEST EFFICIENT MONO-FACIAL SILICON CELLS

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