University of Stuttgart
IER Institute of Energy Economics
and Rational Energy Use

BiFi-PV Workshop 2017
Constance

Development of an optical model for simulating energy yield of a bifacial PV array

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Ludger Eltrop

25-26.10.2017

Picture: http://www.desertmodule.cl/

Agenda

1. Introduction into bifacial PV
2. Methodology for energy yield modelling
3. Results

PV electricity market prices set new world record in 2016 in Chile

… with monofacial PV (!)

Renewables sweep Chile's electricity market and set historic low prices [1]

Solarpack marca record histórico en licitaciones con 29,1 $/MWh en Chile [2]

Imagine, how much more efficient could PV become

(even in less sunny regions than Chile)

if using both sides of the module!!!

1: https://www.pv-magazine.com

2: https://www.pv-magazine-latam.com

Utility-scale bifacial power plants

Hokuto PV Power Plant (test facility), Japan[1]

- P_{el}= 1.25 MW
- Inauguration: 2013
- Fixed tilt

$$\text{Bifacial Gain} = \frac{\text{Energy}_{\text{rear}}}{\text{Energy}_{\text{front}}}$$

La Hormiga PV Power Plant (commercial), Chile[2]

- P_{el}= 2.5 MW
- Inauguration : 2016
- Fixed tilt

Sunpreme PV Power Plant (commercial), USA[3]

- P_{el}= 12.8 MW
- Inauguration : 2016
- Fixed tilt

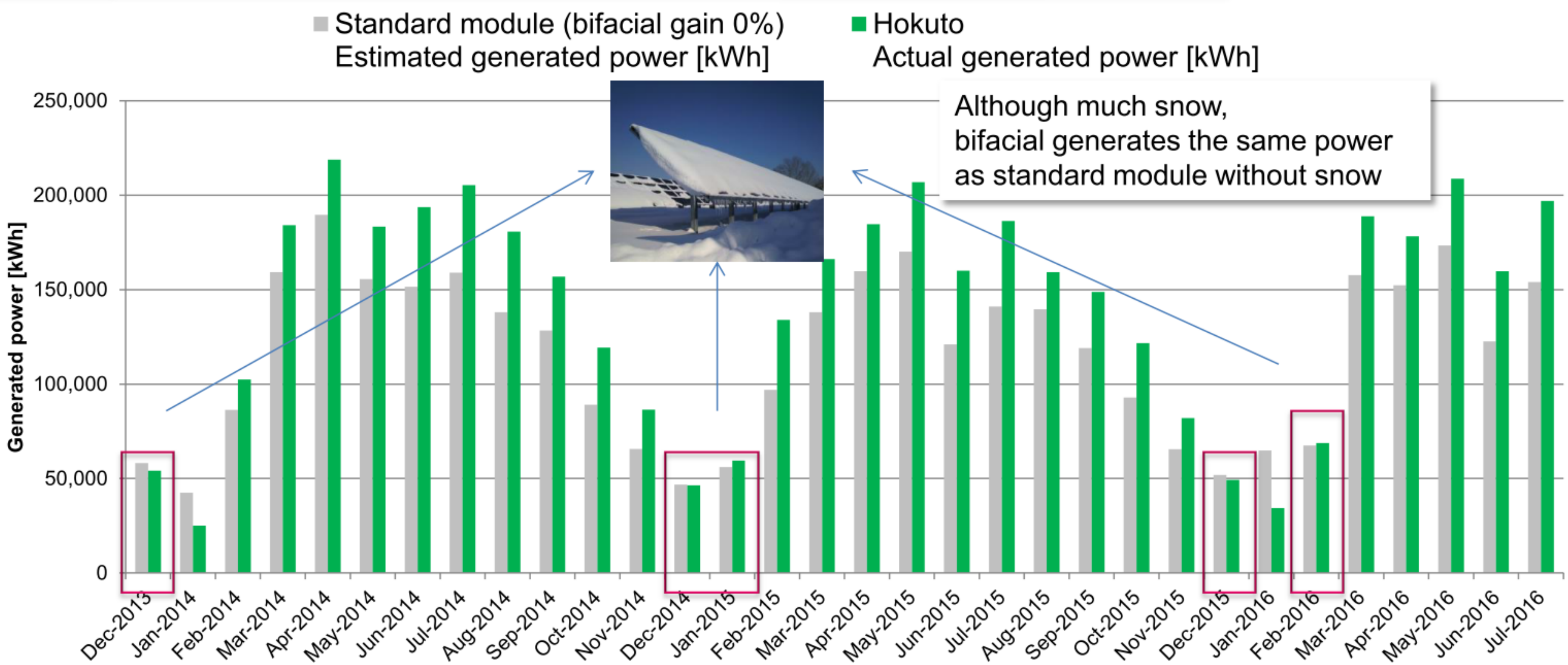
1: Photovoltaic Technical Solutions Presentation, 2016

2: isc-konstanz.de

3: pv-magazine.com

Which bifacial gain can one expect from bifacial PV plants?

Hokuto bifacial PV Power Plant, fixed-tilt, 1.25 MW[1]

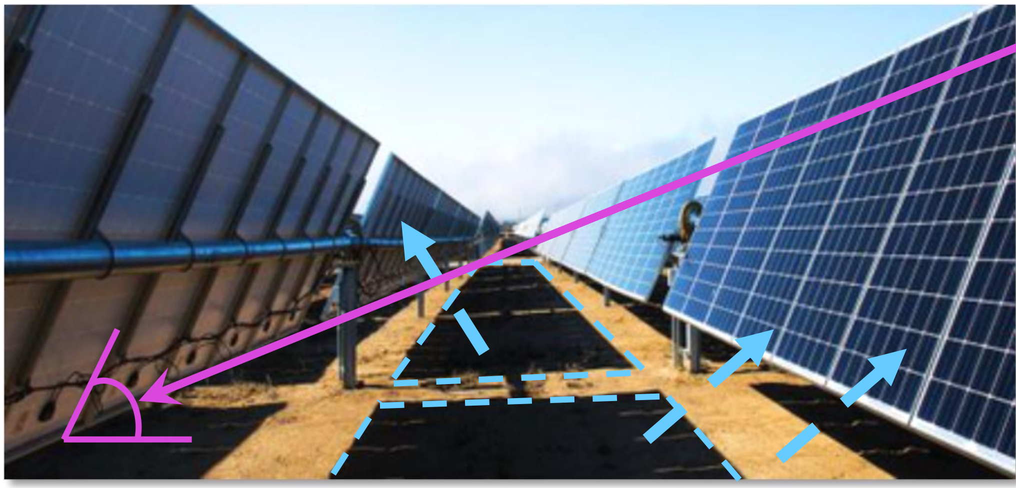


From Dec-13 to Jul-16 32 months	Generated power (Accumulated) [kWh]	Generated power (yearly per kW(front)) [kWh/kW/year]	Bifacial gain [%] = 1 - (Hokuto / BFgain0%)
Hokuto solar power plant	4,450,668	1,235	19.8%
Estimated by STEP-PV (bifacial gain 0%)	3,714,303	1,031	-

1: World First Large Scale 1.25MW Bifacial PV Power Plant on Snowy Area in Japan, 3rd bifi PV workshop in Miyazaki, Japan, 2016

Influencing factors on absorbed irradiation

SunEdison PV Power Plant, Chile[1]



1. Location

- Weather conditions
- Ground albedo factor

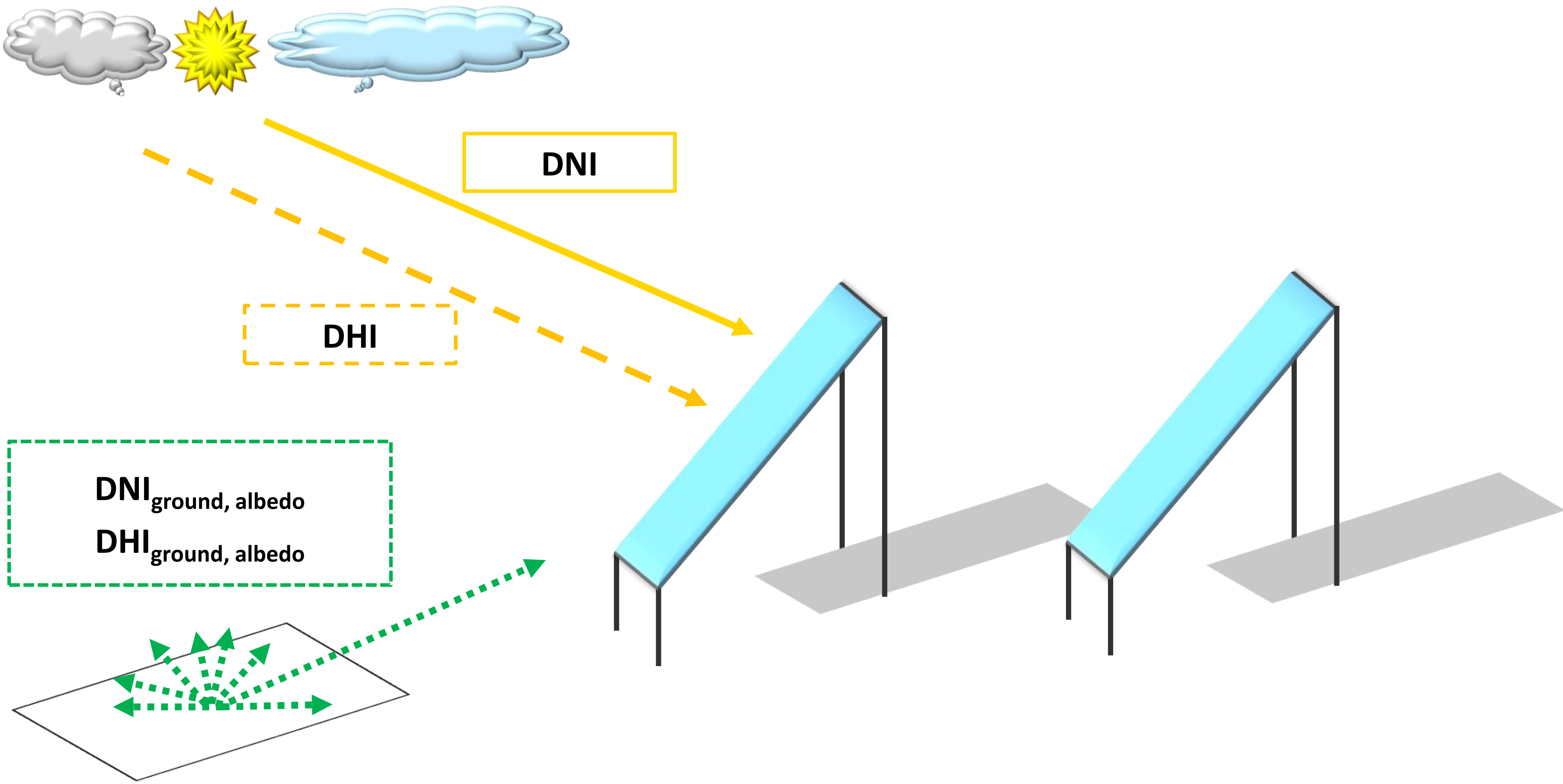
2. Field layout

- Elevation (installation height)
- Orientation
- Row spacing
- Slope

These factors directly influence the shading constellation and thus the ground-reflected irradiation from DNI & DHI (albedo)

1: pv-magazine.com

Absorbed irradiation by conventional (monofacial) PV

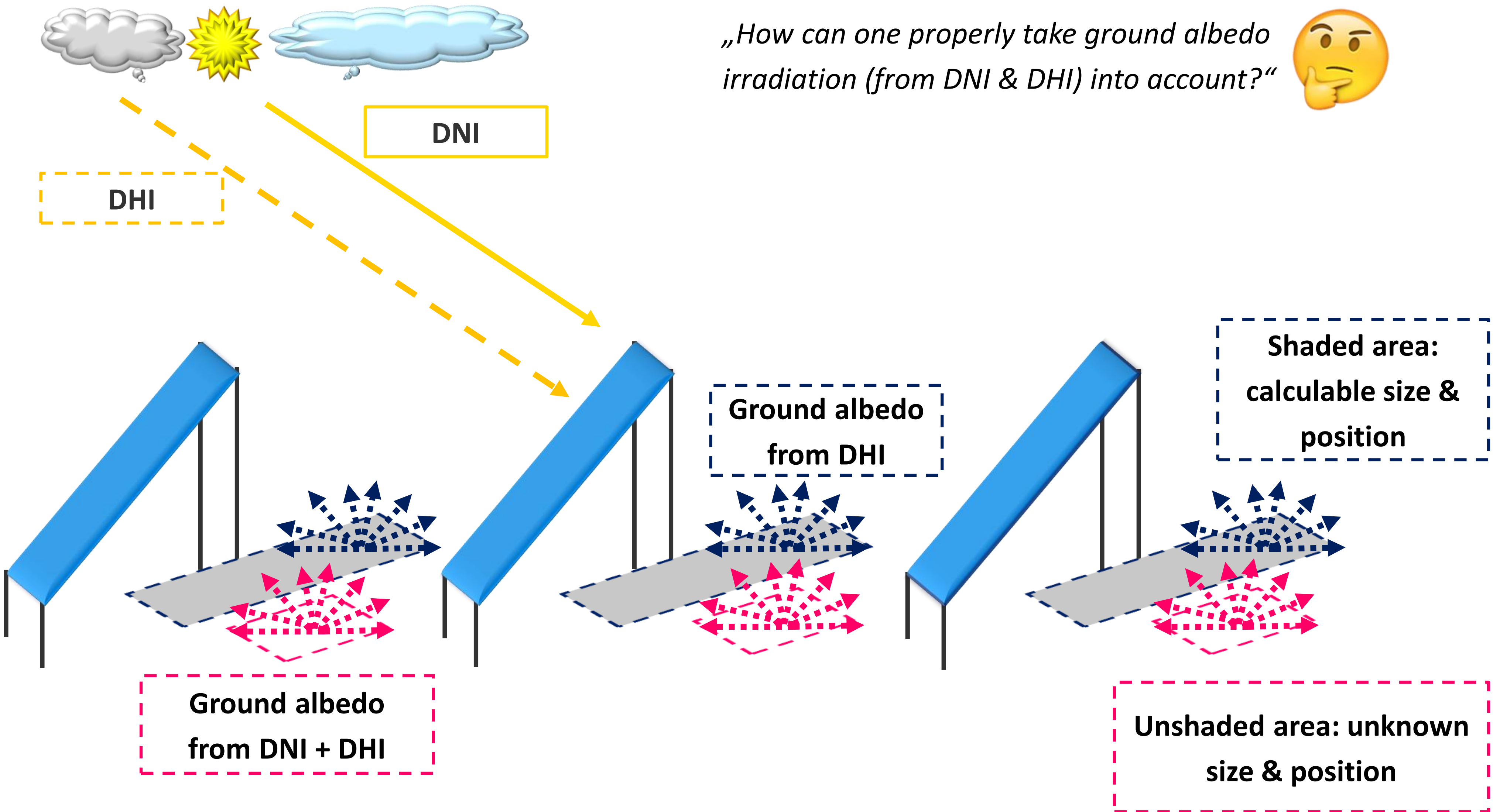


DNI: Direct Normal Irradiation

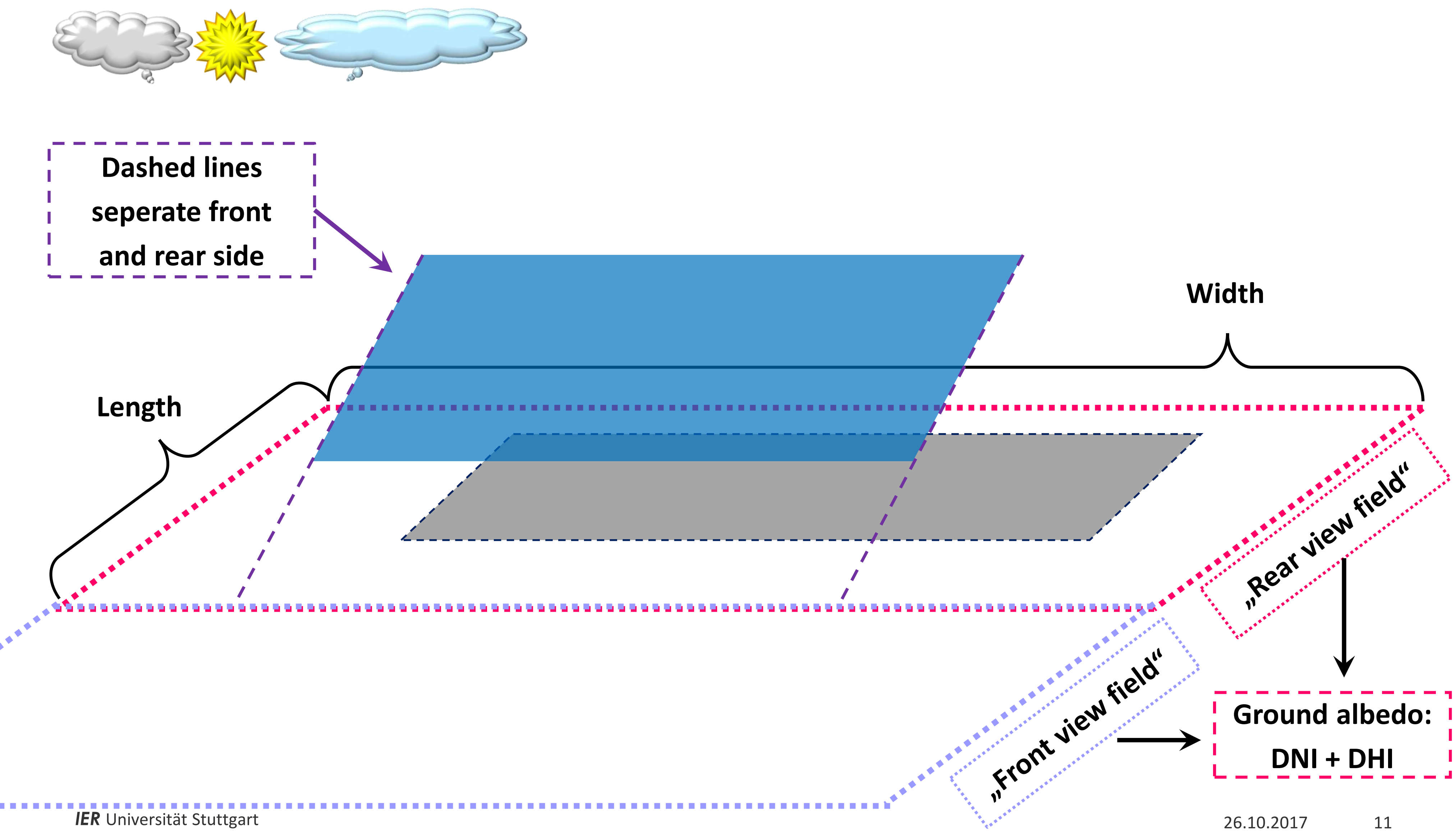
DHI: Diffuse Horizontal Irradiation

Absorbed irradiation by bifacial PV

„How can one properly take ground albedo irradiation (from DNI & DHI) into account?“



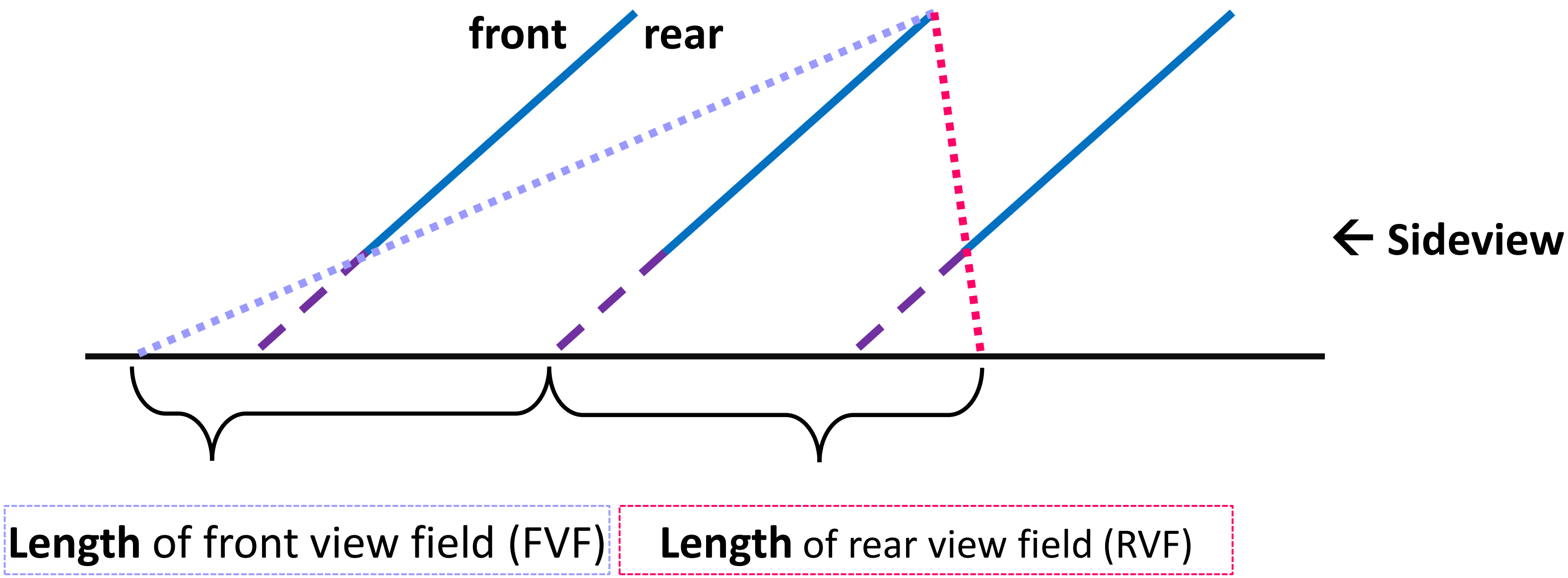
Definition of „view fields“



Definition of „view fields“

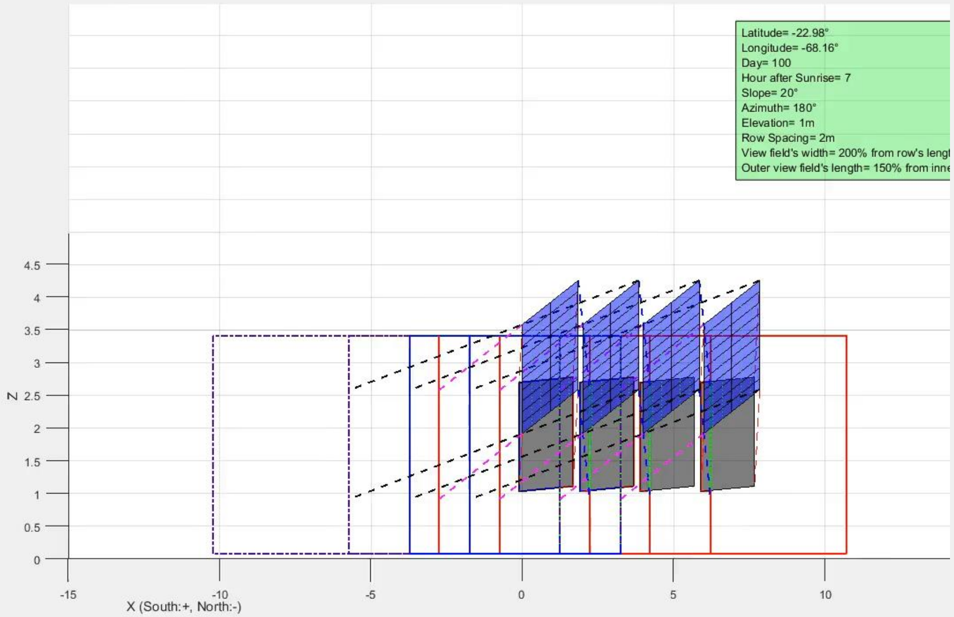
- **Length** of front and rear view fields depends on row spacing, elevation and slope
- FVF of first and RVF of last row are treated differently
- **Width** of view fields is defined exogeneously:
  - Higher width → more albedo energy (how much more?), but also higher land purchase costs

→ For a fixed-tilt configuration, the view fields are **time-invariant**

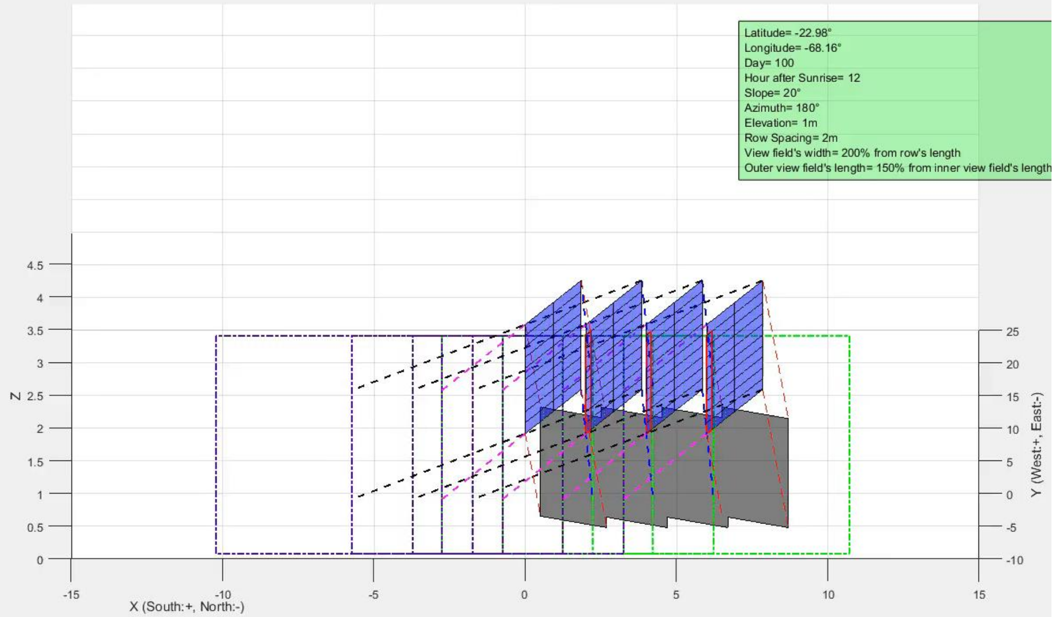


View fields implemented in Matlab

Here **no self-shading** occurs (7h after sunrise)



Here **self-shading** occurs (12h after sunrise)



View fields implemented in Matlab

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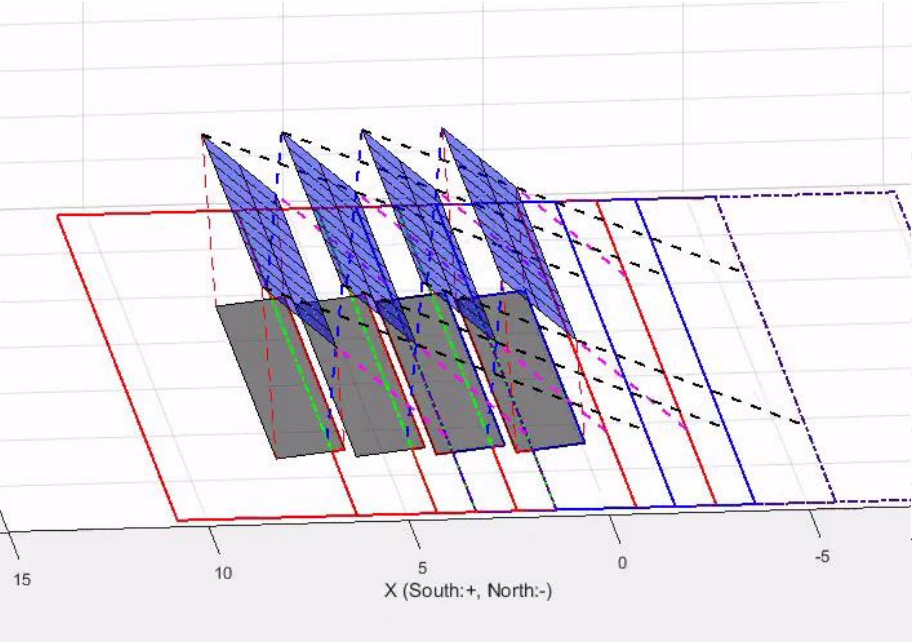

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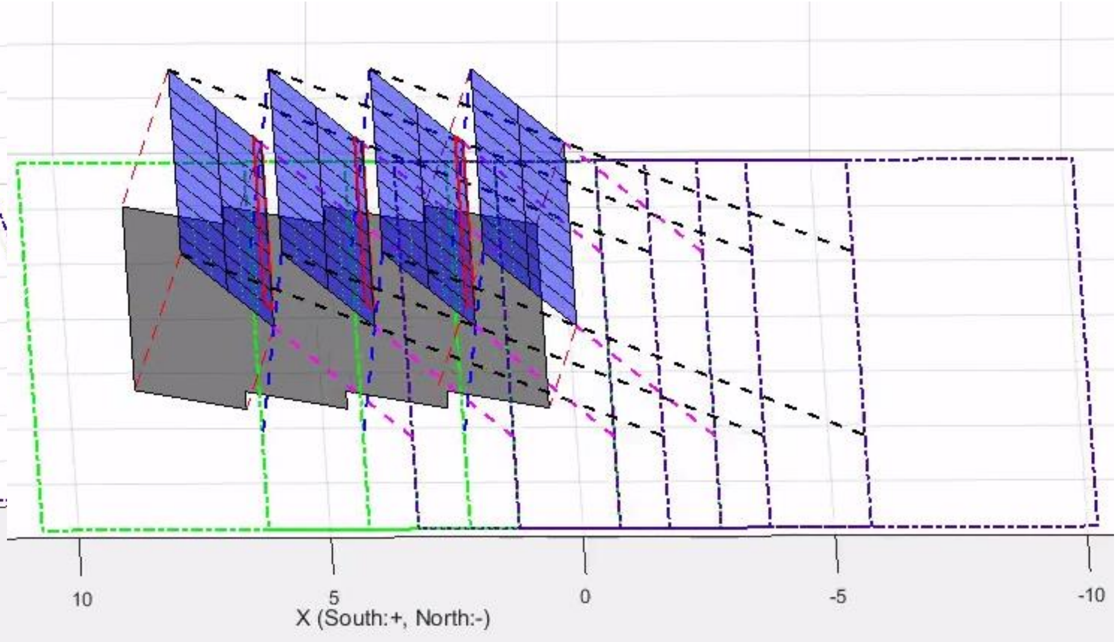


Recap of developed methodology

„How can one properly take ground albedo irradiation (from DNI & DHI) into account?"

Definition of *view fields*

+

using theory of *view factors* to compute share of ground albedo irradiation that hits the module's surfaces

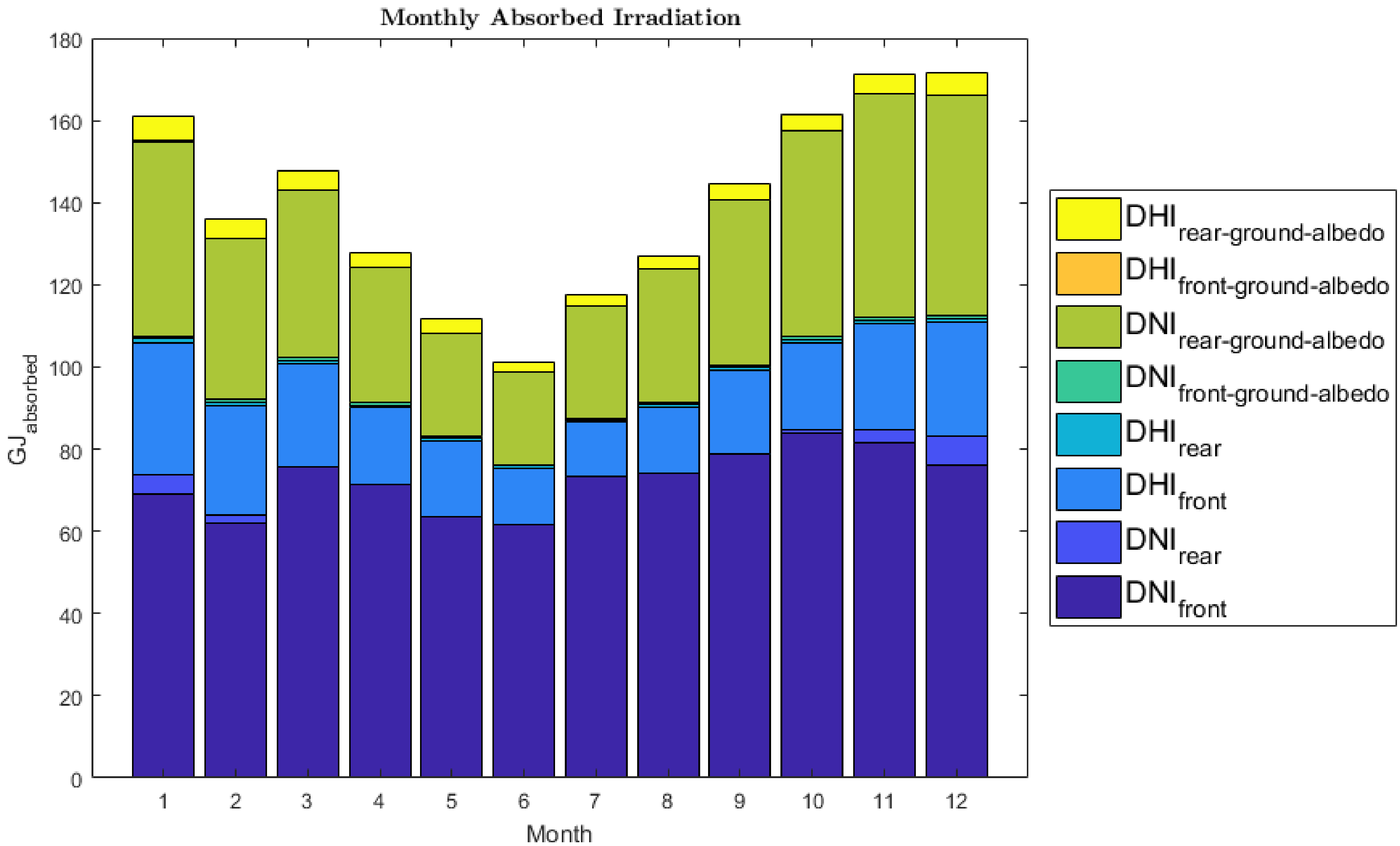
Simulation set-up

- Location: Atacama Desert, Chile
- Weather data in hourly resolution
- Computation resolution: 20 min
- PV Array: 80 modules in 4 rows (≈21 kW_{el})
- Ground reflectivity: 20%

Google

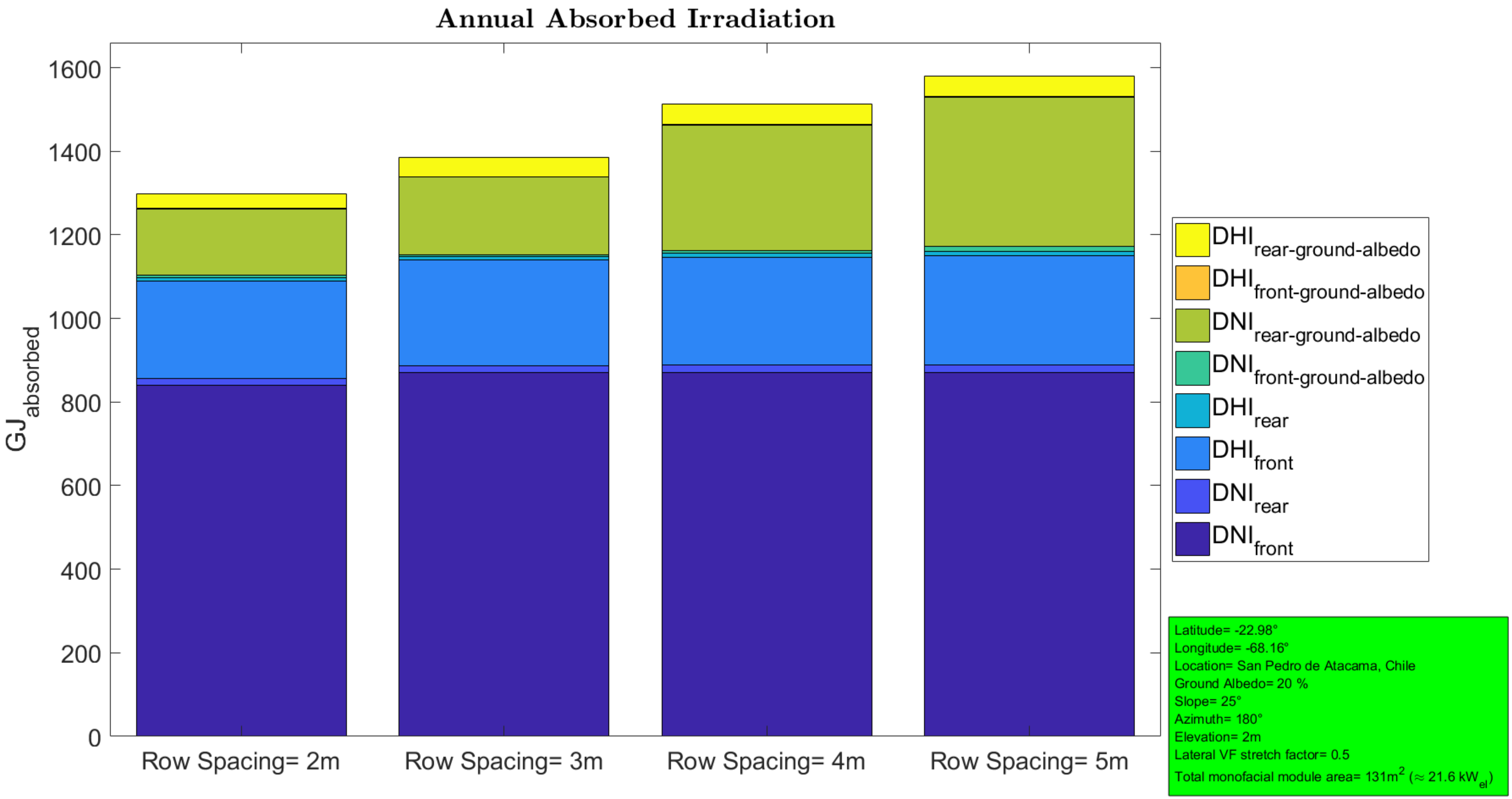
Monthly absorbed irradiation

Slope=25°, elevation= 3.5m, row spacing=4m



Annual absorbed energy

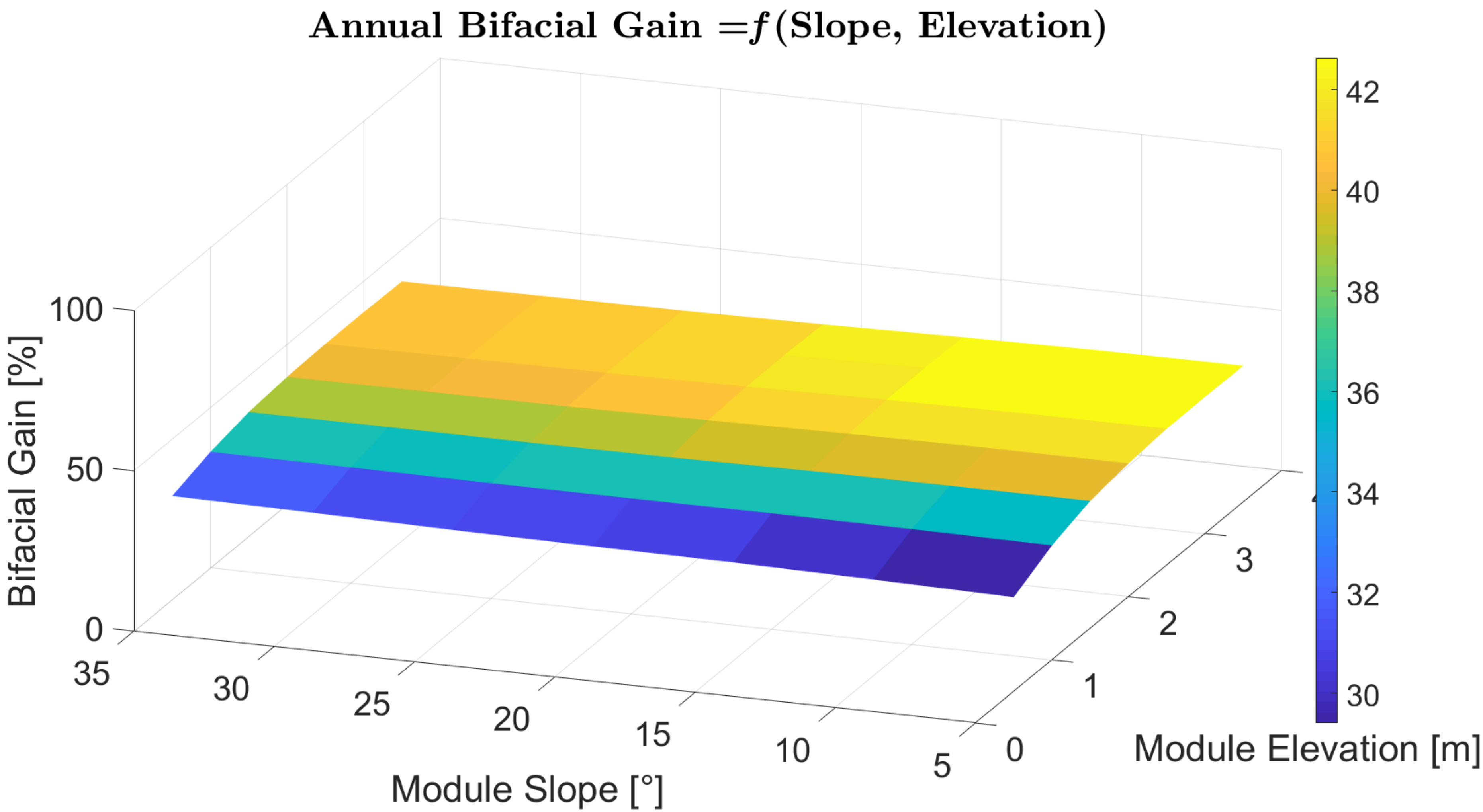
Slope=25°, elevation=2m, variation of row spacing



Annual bifacial gain of absorbed irradiation (AI)

Row spacing=5m, variation of slope and elevation

$$\text{Bifacial Gain}_{\text{AI}} = \frac{\text{Absorbed Irradiation}_{\text{rear}}}{\text{Absorbed Irradiation}_{\text{front}}}$$



Conclusions

- The definition and implementation of „**view fields**“ for both sides of a module is suitable to take into account different irradiance contributions
- Bifacial gain highly depends on **array desing**
  (slope, elevation, row spacing, assumed width of view fields)
  - Simulations show that a **bifacial gain** of over 40% of absorbed energy is possible
- Next step is to implement a submodel to calculate produced electric energy

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Muchas Gracias!

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Annex

Theory of „view factors“

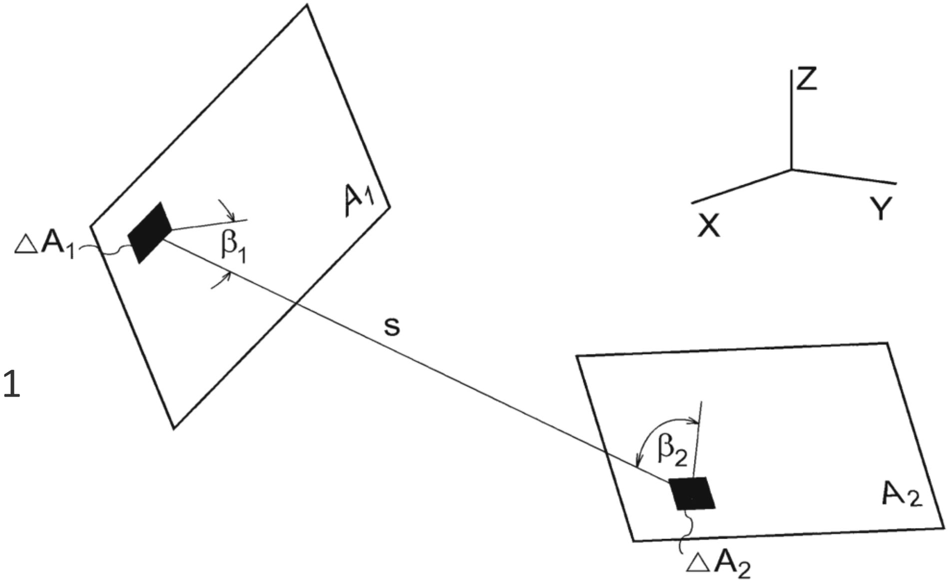
$$\phi_{12} = \frac{\text{diffuse energy leaving } A_1 \text{ directly toward and intercepted by } A_2}{\text{total diffuse enrgy leaving } A_1}$$ [1]

$$\phi_{12} = \frac{1}{\pi A_1} \int_{A_1} \int_{A_2} \frac{\cos(\beta_1) \cdot \cos(\beta_2)}{s^2} dA_1 dA_2$$ [1]

Assumption: All surfaces radiate diffusely

→ View factor is a solely geometric quantity

→ Sum of all view factors for one surface is always 1 (conservation of energy)



Theory of „view factors“ [2]

1: Heat Transfer Handbook, 2003

2: VDI Wärmeatlas, 2013

Calculation of „view factors“

- The **time-variant** view factors from *„ground shadow → module row“* and *„view field → module row“* are calculated using an algorithm in Matlab, developed by Nicolas Lauzier[1]
- **Time-invariant** view factors *„module row → sky“* (Perez model) are calculated using methodologies from:
  - **For inner rows:** *View factors of photovoltaic collector systems, Maor, T.; Appelbaum, J., 2012*

The view factor to the sky for collectors deployed in rows, excluding the first row, mounted on a horizontal plane (see Fig. 5) is derived by the cross-string rule and is:

$$F_{C\to sky} = \frac{H + D - \sqrt{(H\cdot\sin\beta)^2 + (D - H\cdot\cos\beta)^2}}{2\cdot H} \qquad (9)$$

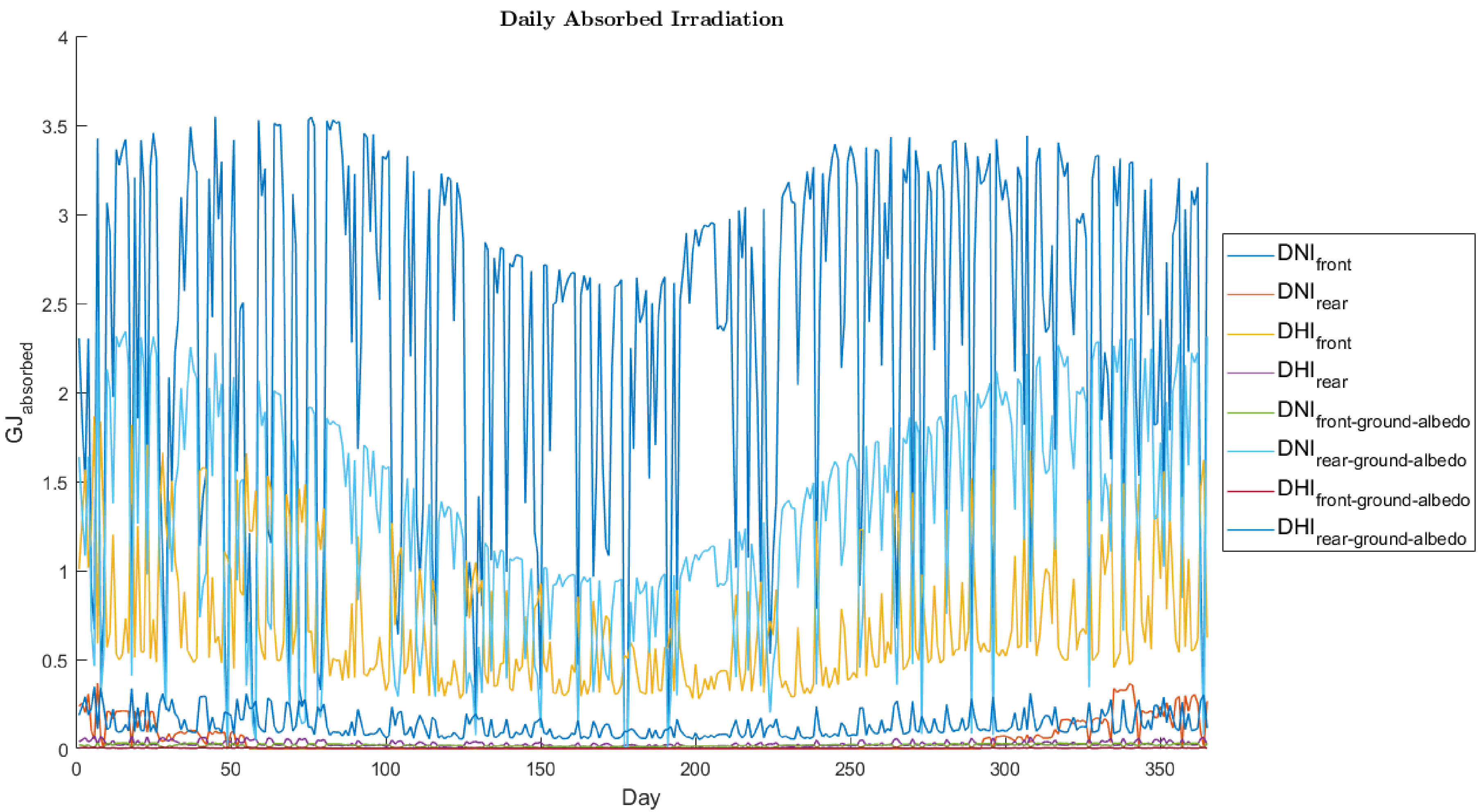
  - **For outer rows:** $F_{C\to sky} = \frac{1+\cos(\beta)}{2}, \beta = module's\ slope$

(Both approaches for **time-invariant** view factor calculation assume infinitely long module rows)

1: https://de.mathworks.com/matlabcentral/fileexchange/5664-view-factors

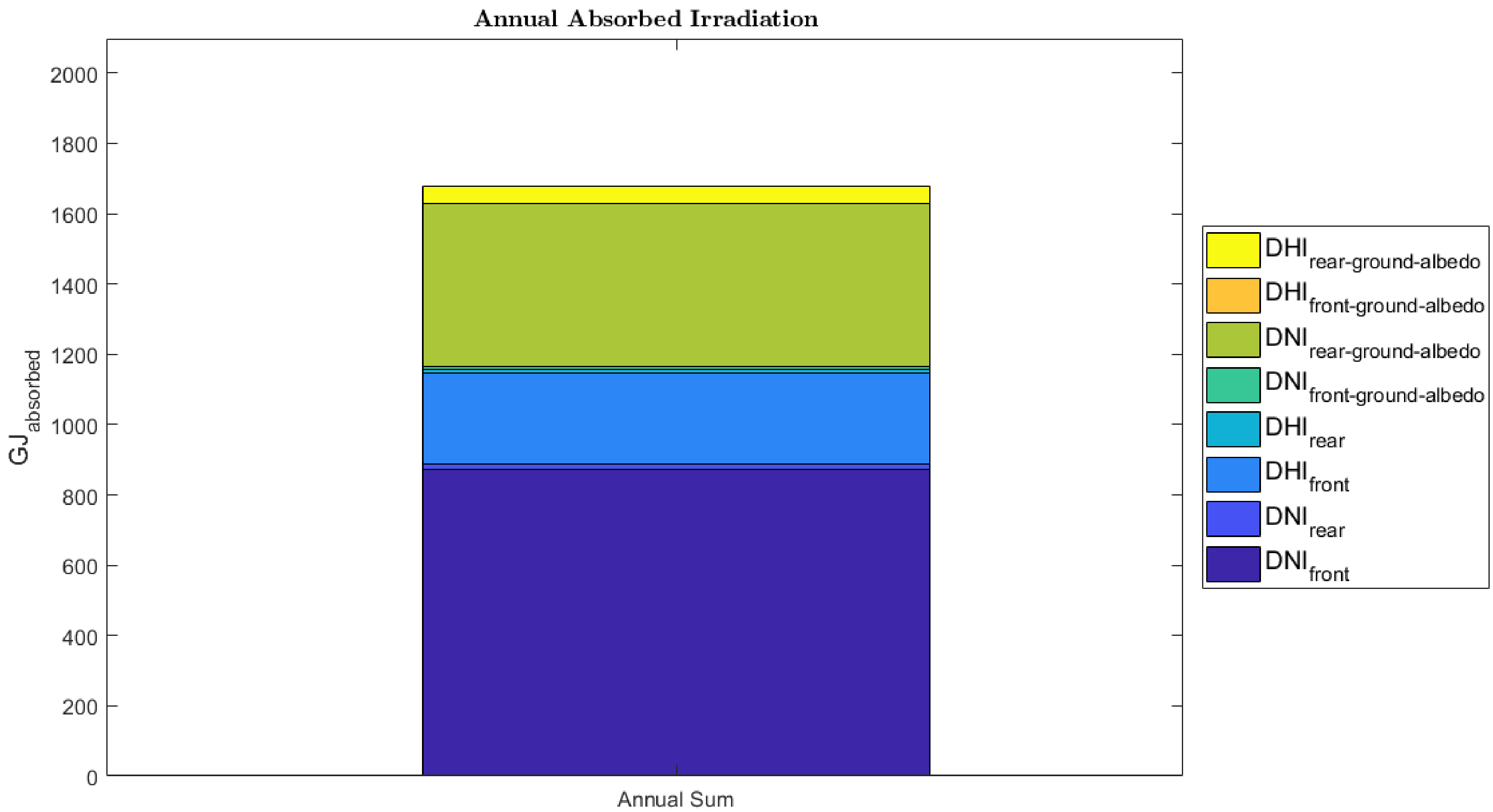
Daily absorbed energy

San Pedro de Atacama, slope=25°, elevation=3.5m, row spacing=4m

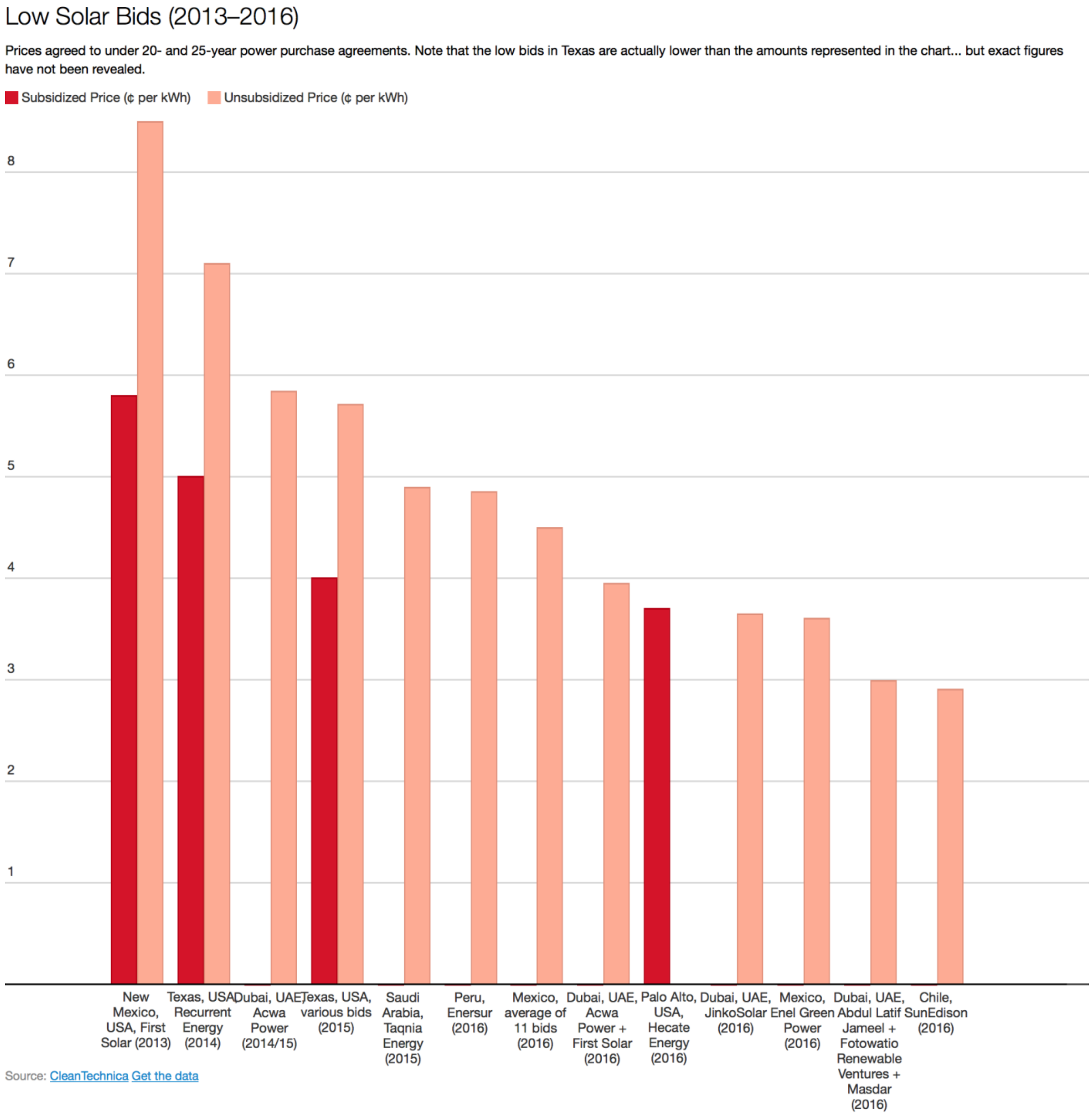


Annual absorbed energy

Slope=25°, elevation=3.5m, row spacing=4m



Low Solar Bids



https://c1cleantechnicacom-wpengine.netdna-ssl.com/files/2016/08/low-solar-bids.png

Annual bifacial gain of absorbed energy

Row spacing=4m, variation of slope and elevation

$$\text{Bifacial Gain}_{\text{AI}} = \frac{\text{Absorbed Irradiation}_{\text{rear}}}{\text{Absorbed Irradiation}_{\text{front}}}$$