International Solar Energy Research Center Konstanz

Overview: energy yield simulations and calculation of LCOE for bifacial PV systems

J.Libal, D. Berrian, R. Kopecek

International Solar Energy Research Center (ISC), Konstanz, GERMANY

Bifacial economics

International Solar Energy
Research Center Konstanz

"We need to replace the old-fashioned Euro/Wp mentality by the more suited Euro/kWh mentality"

- "euro": concept for LCOE-calculation

- "kWh": simulation of bifacial energy yield

Introduction: basic LCOE Definition

International Solar Energy Research Center Konstanz

- Cost of the electricity (euro/kWh) produced by a given PV system is the <u>final criterium for its economical feasibility</u>

- The levelized cost of electricity (LCOE) :

  - **total cost** for building and operating a power plant during its complete life cycle

  - **total electricity produced** during its life cycle:

$$LCOE = \frac{total\ life\ cycle\ cost}{total\ lifetime\ electricity\ generation} = \frac{Euro}{kWh}$$

A little bit of financial mathematics

International Solar Energy Research Center Konstanz

- The **LCOE** can also be defined as the **minimum price** at which the electricity generated by the power plant must be sold in order to achieve the **economic break even** of the power plant project during its lifetime:

total revenues from electricity sales
=
total cost for building and running the power plant

- In order to obtain a fair evaluation – in terms of financial profitability – of the power plant project compared to other investment opportunities, when calculating the LCOE, the **discounted cash flow** (DCF) method has to be applied.

- The DCF method is a concept from financial mathematics and consists in attributing a lower („discounted“) value to future expenses and revenues compared to those that are due in the present.

  This discounted value is called „**net present value**“

Some more financial mathematics

International Solar Energy Research Center Konstanz

- The weighted average cost of capital (**WACC**) of a project is determined by its financing structure, .i.e. the ratio of equity and debt financing and the respective interest rates

$$WACC = e \times i_e + b \times i_b$$

with

e and b	*share of equity (e) and share of debt (b)*
i_e *and* i_b	*interest rates for equity (*i_e *)and for debt (*i_b*)*

- Accordingly in many cases, the WACC is used as the discount rate ***d*** for calculation of the net present value.

- In this way, the net present value of the expenses $\boldsymbol{C_t}$ in year ***t*** is as follows:

$$\frac{C_t}{(1+d)^t}$$

- In the same way, the revenues from electricity sales have to be discounted accordingly

$$LCOE \times \left(\frac{E_t}{1+d} \right)^t$$

Complete LCOE definition

International Solar Energy Research Center Konstanz

The condition of break-even and considering the complete lifetime of the plant implies:

$$\sum_{t=1}^{N}\left(\frac{LCOE_t}{(1+d)^t}\times E_t\right)=\sum_{t=1}^{N}\frac{C_t}{(1+d)^t}$$

Which can be translated to

$$LCOE=\sum_{t=1}^{N}\frac{\left(\frac{C_t}{(1+d)^t}\right)}{\left(\frac{E_t}{(1+d)^t}\right)} \quad = \frac{Euro}{kWh}$$

with

- t year of lifetime of the power plant (1 ... N)
- N economic lifetime of the power plant
- d real discount rate (without inflation)
- E_t energy (kWh) produced in year t (from modelling or monitoring)
- C_t Total expenditures (debt and equity service, O&M, ...) in year t

Bifacial system cost

International Solar Energy Research Center Konstanz

- **PV modules price:** depending on specific bifacial technology (PERC+, nPERT, pPERT, HJ, ...)

- **Balance of system cost :** mounting racks, cabling, inverters
  → nominal *inverter capacity must be adapted to the expected additional energy yield*

- **land cost:** *optimum row-to-row distance tends to be higher for bifacial compared to monofacial PV systems, leading to a lower ground cover ratio for bifacial PV systems*

- **operation and maintenance (O&M):** *if measures have been taken to artificially increase the ground albedo, CAPEX and O&M cost might be increased*

- **financing:** *depending on the maturity (and track record) of a given bifacial PV technology (and the specific module supplier), the **financing terms** (discount rate - see above) **can be less beneficial for PV system based on bifacial modules** compared to a system using standard monofacial modules* → ***higher discount rate for bifacial ?***

- same as for monofacial:
  - **installation, land preparation**
  - **project development**

Bifacial energy yield

- geographic location (yearly solar irradiance and temperatures, albedo, soiling): ***ground albedo*** *has a significant impact on the energy yield of a bifacial system, also diffuse irradiance fraction has an increased impact*

- module technology (efficiency, temperature behaviour, bifacial factor, yearly degradation rate): ***the additional energy yield is directly proportional to the bifaciality factor of the module***

- system configuration (tracking/fixed tilt, row-to-row distance, mounting height, tilt, azimuth, ...): ***Module mounting height is crucial for the energy yield of bifacial systems***

- considered system lifetime: *the useful* ***system lifetime*** *is determined by the* ***yearly degradation rate which in turn depends strongly on the bill of materials of the module****.*

→ ***a meaningful comparison between monofacial and bifacial technology will consider the same laminate structure for both****; i.e. either glass/glass or glass/backsheet for both technologies.*

→ ***the same lifetime should be considered for bifacial and monofacial PV systems.***

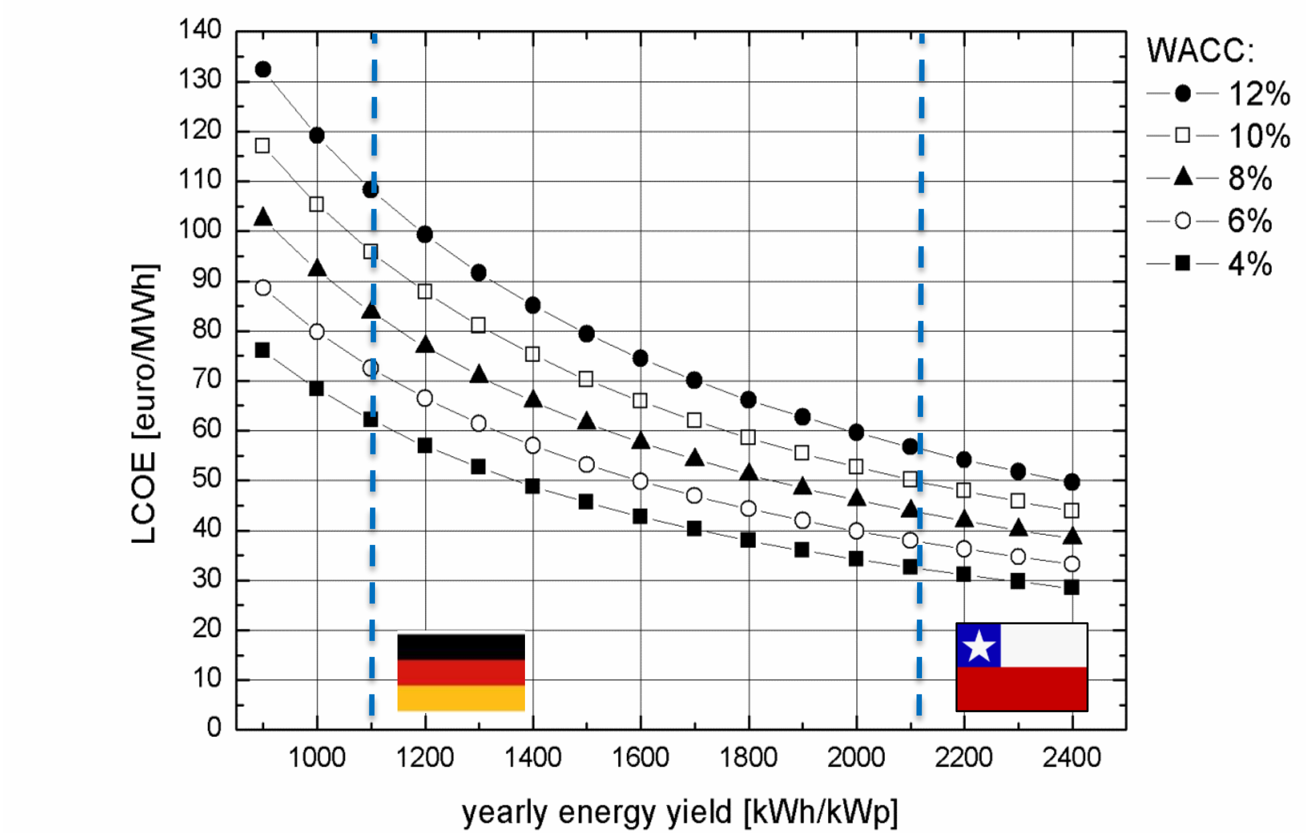
Assumptions for LCOE calculations

International Solar Energy Research Center Konstanz

- module price: 0.31 €/Wp (**monofacial** Cz-Si PERC cells)
- module Pmpp at STC (60 cells module): 300 Wp
- CAPEX for installed, **monofacial** utility scale PV system: 0.79 €/Wp
- system lifetime: 25 years (glass-backsheet modules)
- performance ratio of the system: 0.82
- yearly degradation rate for Pmpp: 0.4%
- yearly operating and maintenance (O&M) expenditures: 15 €/Wp
- considered locations (and respective irradiance/monofacial yield):
  - Germany and Chile

Monofacial LCOE vs WACC

International Solar Energy Research Center Konstanz

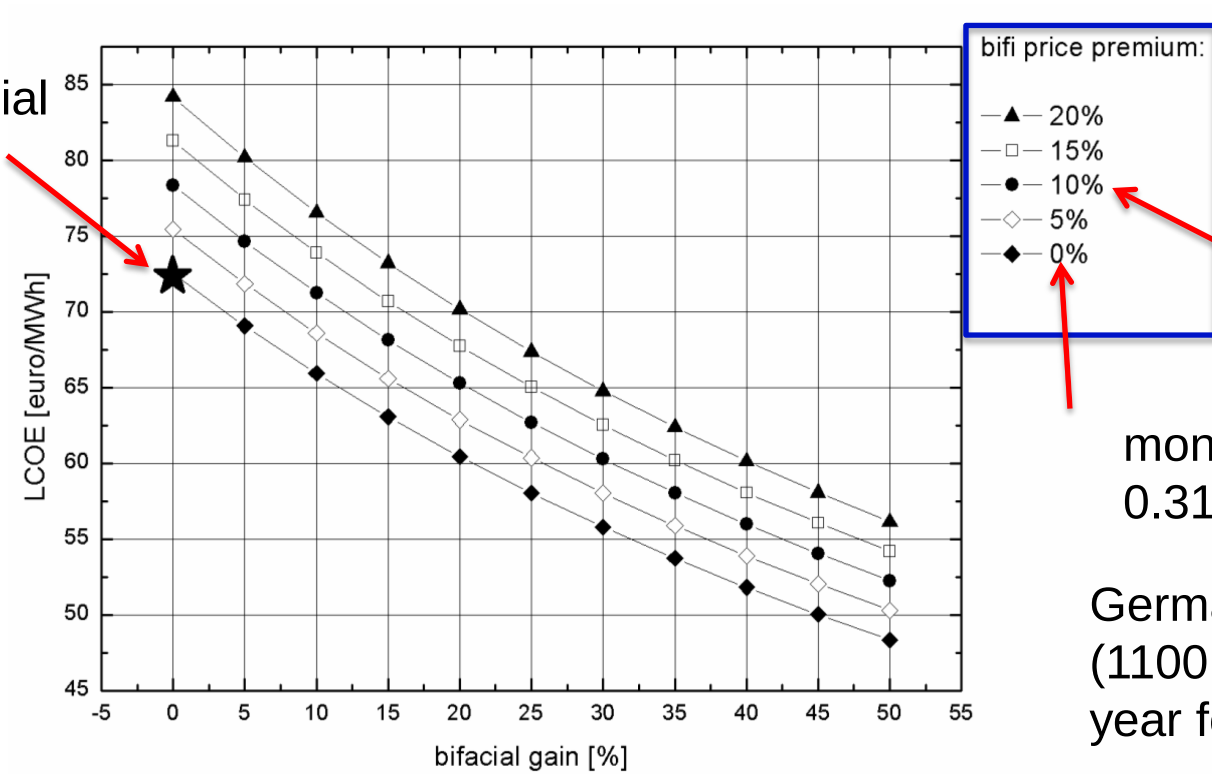


Calculated LCOE for fixed tilt, **monofacial** (utility scale, ground mounted) PV system for various WACC and different energy yields corresponding to different geographic locations.

LCOE vs module cost and bifacial gain

International Solar Energy Research Center Konstanz

monofacial LCOE



on system level

bifi module:
0.39 €/Wp
(+25%)

monofacial module:
0.31 €/Wp

Germany
(1100 kWh/kWp per year for monofacial)

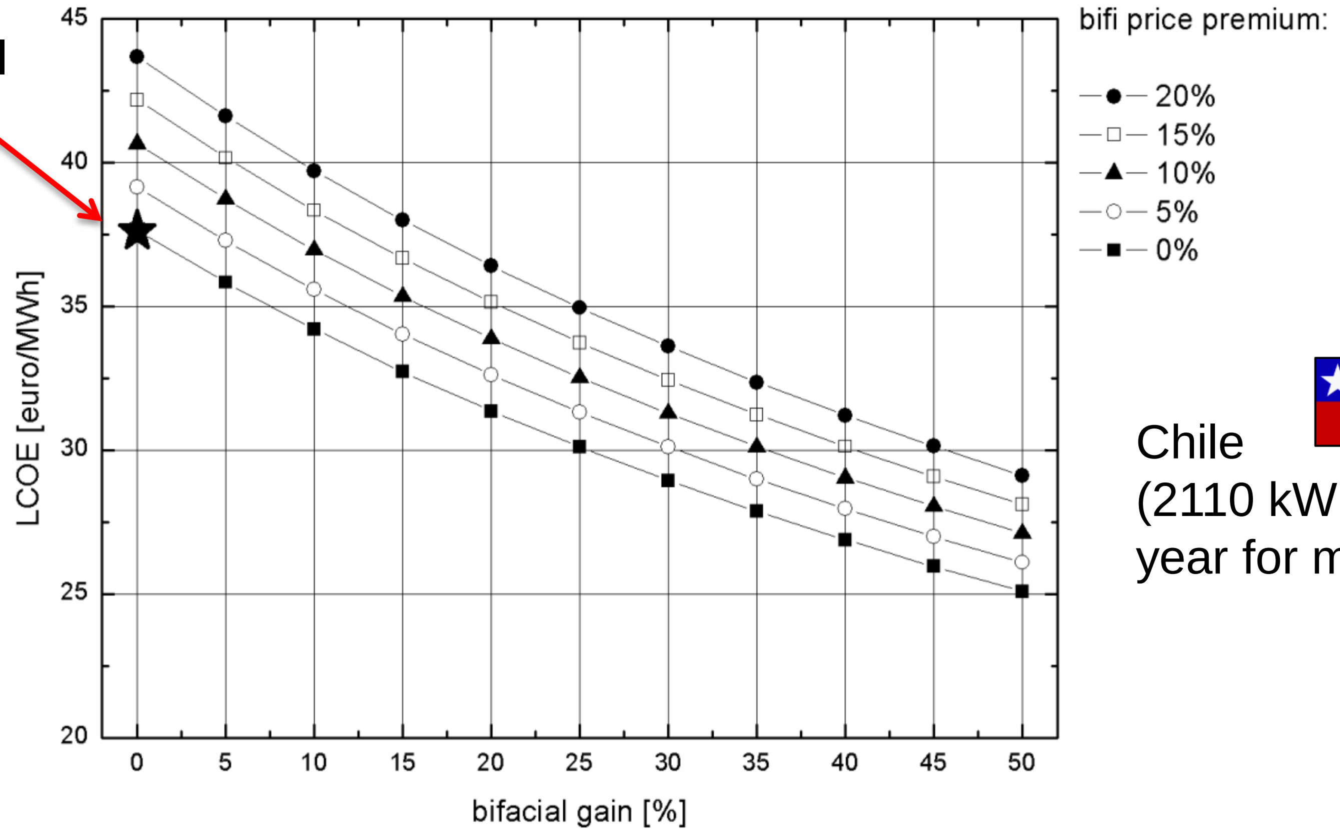
LCOE calculations for **bifacial** fixed tilt, utility scale, ground mounted PV system

6% WACC has been used for monofacial as well as for bifacial systems.

LCOE vs module cost and bifacial gain

International Solar Energy Research Center Konstanz

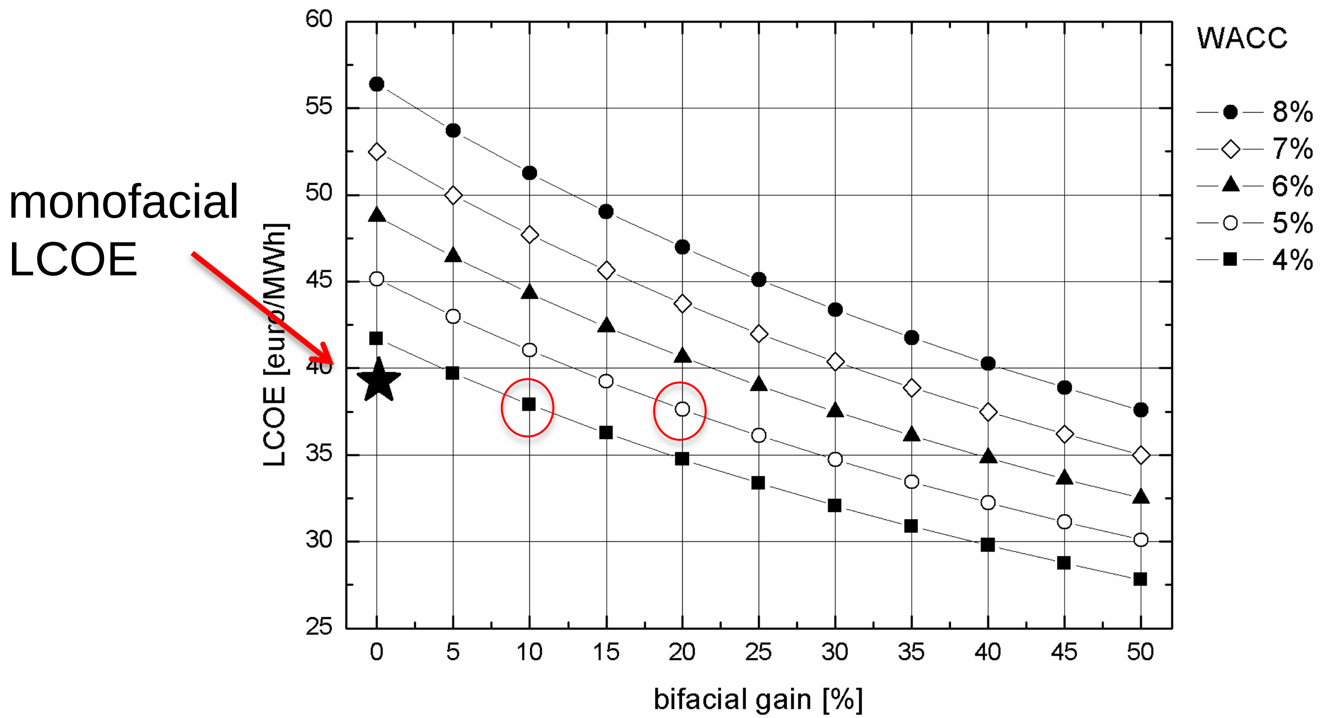
monofacial LCOE



Chile
(2110 kWh/kWp per year for monofacial)

LCOE vs. WACC for bifacial PV

International Solar Energy Research Center Konstanz



– monofacial system CAPEX:0.79 €/Wp , WACC of 4%, 1700 kWh/kWp per year.

– bifacial PV system CAPEX: 0.83 €/Wp (= 6% price premium compared to monofacial system)

Conclusions - LCOE

ISC International Solar Energy Research Center Konstanz

– **LCOE is reduced by more than 50%** when moving the installation site from a region with low irradiance (e.g. north of Germany with 1100 kWh/kWp yearly energy yield) **to a region with highest iradiance** (e.g. Atacama desert in Chile with 2100 kWh/ kWp monofacial yearly energy yield)

→ **strong potential of bifacial PV to reduce the LCOE** of PV generated electricity: a 10% price premium (on system CAPEX) **requires the bifacial energy yield gain just to exceed 10%** in order to reduce the bifacial LCOE below the level of the monofacial one.

– **The WACC attributed to attributed to a PV power plant project has a significant impact on the LCOE.** Consequently, the beneficial effects in terms of LCOE reduction of the use of bifacial modules can be only exploited if the WACC of bifacial PV projects is not higher than for standard technology.

→ the WACC is – amongst others - related to the perception of the **technological risk**

→ will be discussed this afternoon in the session about **bankability** *[Richter, Moser]*

Status of bifacial energy yield prediction

International Solar Energy Research Center Konstanz

- **For standard (monofacial) PV systems, very sophisticated tools for energy yield prediction are commercially available** and play a crucial role in calculation of the LCOE and consequently in the evaluation of the bankability of large PV systems

- For bifacial PV systems, in the last years, **more and more academic institutitions and companies** are working on the development of their own models and software tools. Meanwhile**, first commercial software with basic features** are now available.

List of “bifacial simulators”

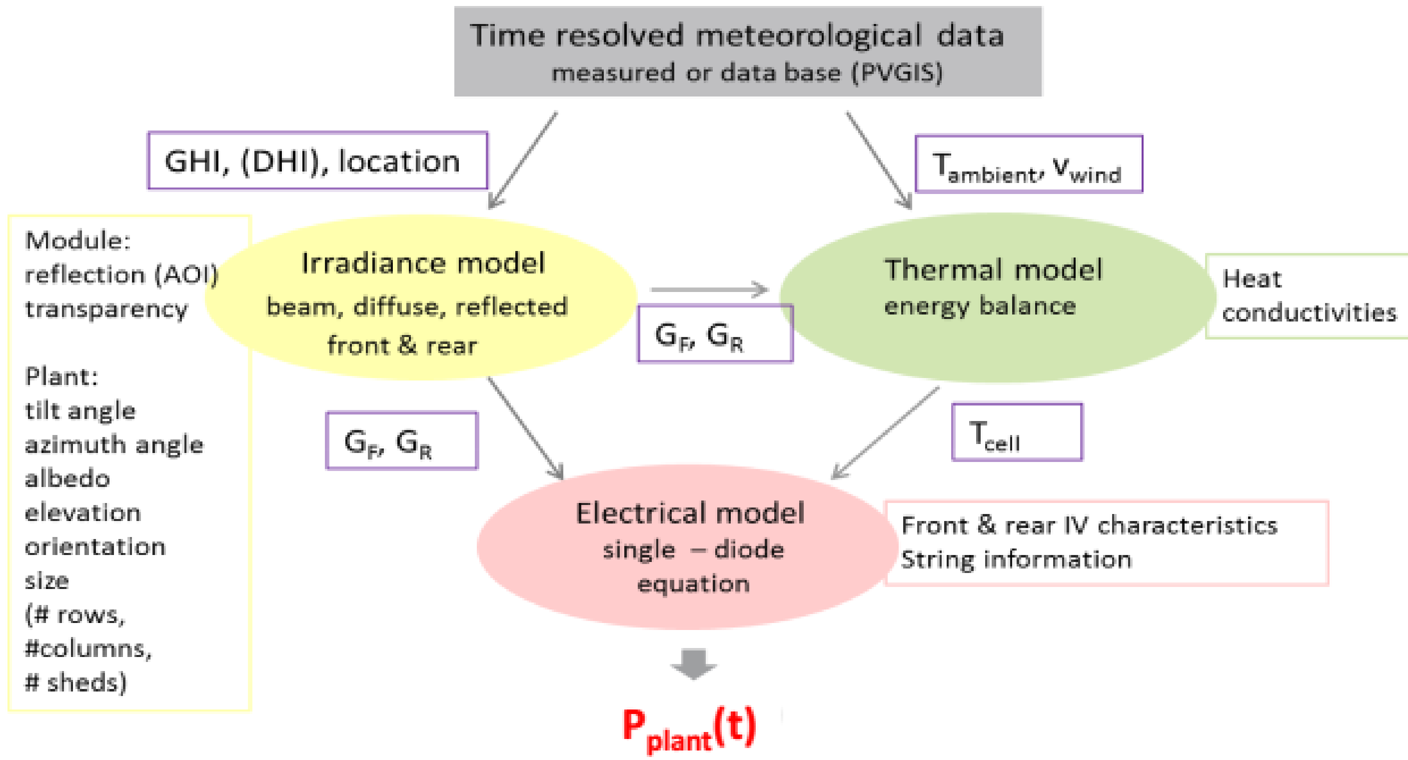
International Solar Energy Research Center Konstanz

- JCT
- ECN
- CEA INES
- ISC KONSTANZ
- REC
- SERIS
- Sandia
- NREL
- University of Iowa
- RTWH Aachen
- EDF
- Fraunhofer ISE
- Enel Green Power
- PVsyst
- Polysun
- University of Nevada
- Fraunhofer CSP
- ZHAW
- University of Stuttgart
- KAUST

and others …

Modelling of bifacial systems

International Solar Energy Research Center Konstanz



- All sub-models affected by bifaciality
- Resulting in time resolved power data → annual energy yield (AEY)

source: B. van Aken, bifi PV 2016

Irradiance model: options

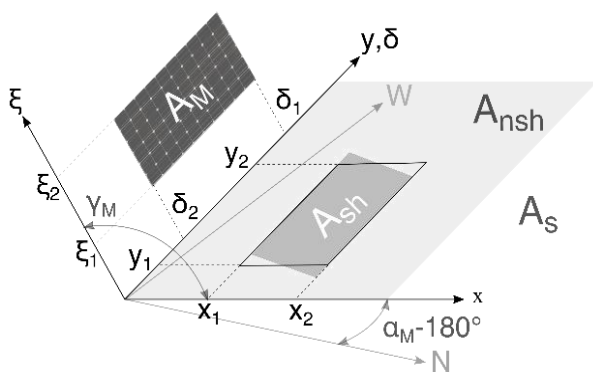
International Solar Energy Research Center Konstanz

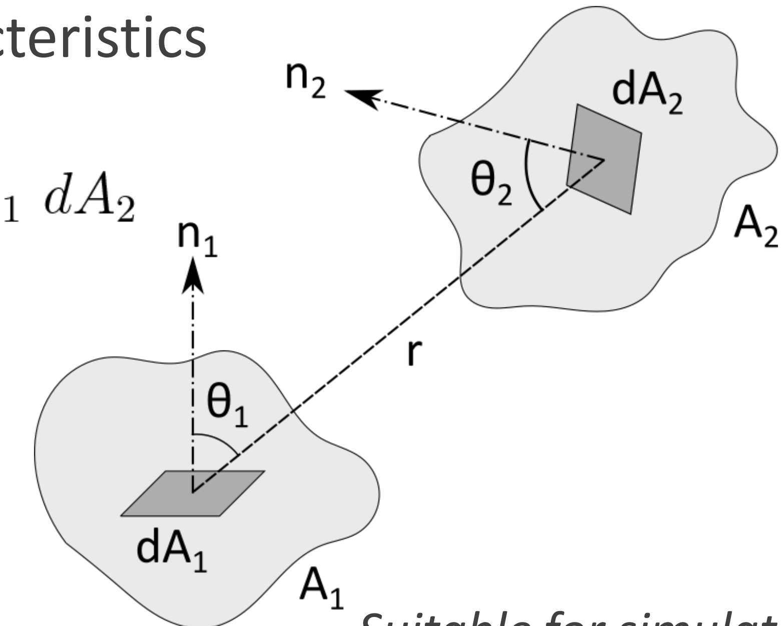
- Calculation of rear side irradiance using
  - Ray tracing or
  - View factor

View Factor

- geometric quantity, concept known from heat transfer theory
- irradiation leaving A_1, that reaches A_2
- inpedendent of surface characteristics

$$F_{A_1 \rightarrow A_2} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} \, dA_1 \, dA_2$$





Suitable for simulating effects from rear side mounting structures or module frame ?

$$I_{refl,r} = \alpha \; GHI \; F_{A_{nsh} \rightarrow A_M} + \alpha \; DHI \; F_{A_{sh} \rightarrow A_M}$$

Electrical model: options

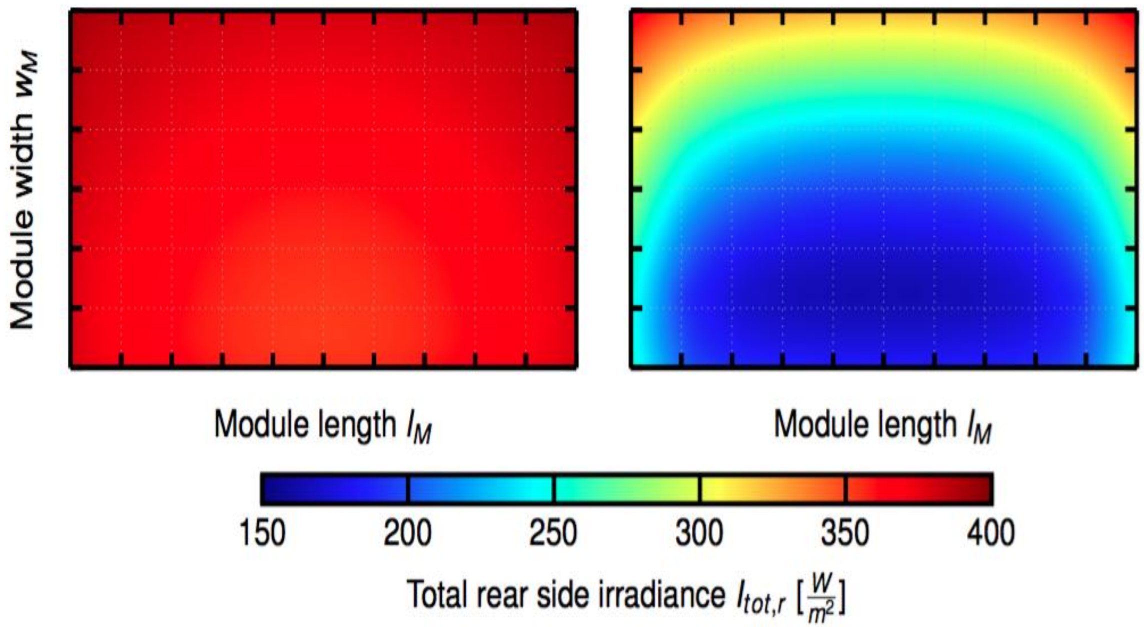
International Solar Energy Research Center Konstanz

For bifacial cell:

- weighted 2-diode model G.J.M. Janssen et al. *En.Proc.* **77** (2015) 364
- 1-diode model with effective irradiance
- 1-diode model with seperate front and rear I/V data @ STC

J.P. Singh et al. *Sol.En.Mat.Sol.Cells* **127** (2014) 136

Simulation results



a) El Gouna, 21.06.2005, noon, $\alpha = 0.5$, $h_M = 1\ m$

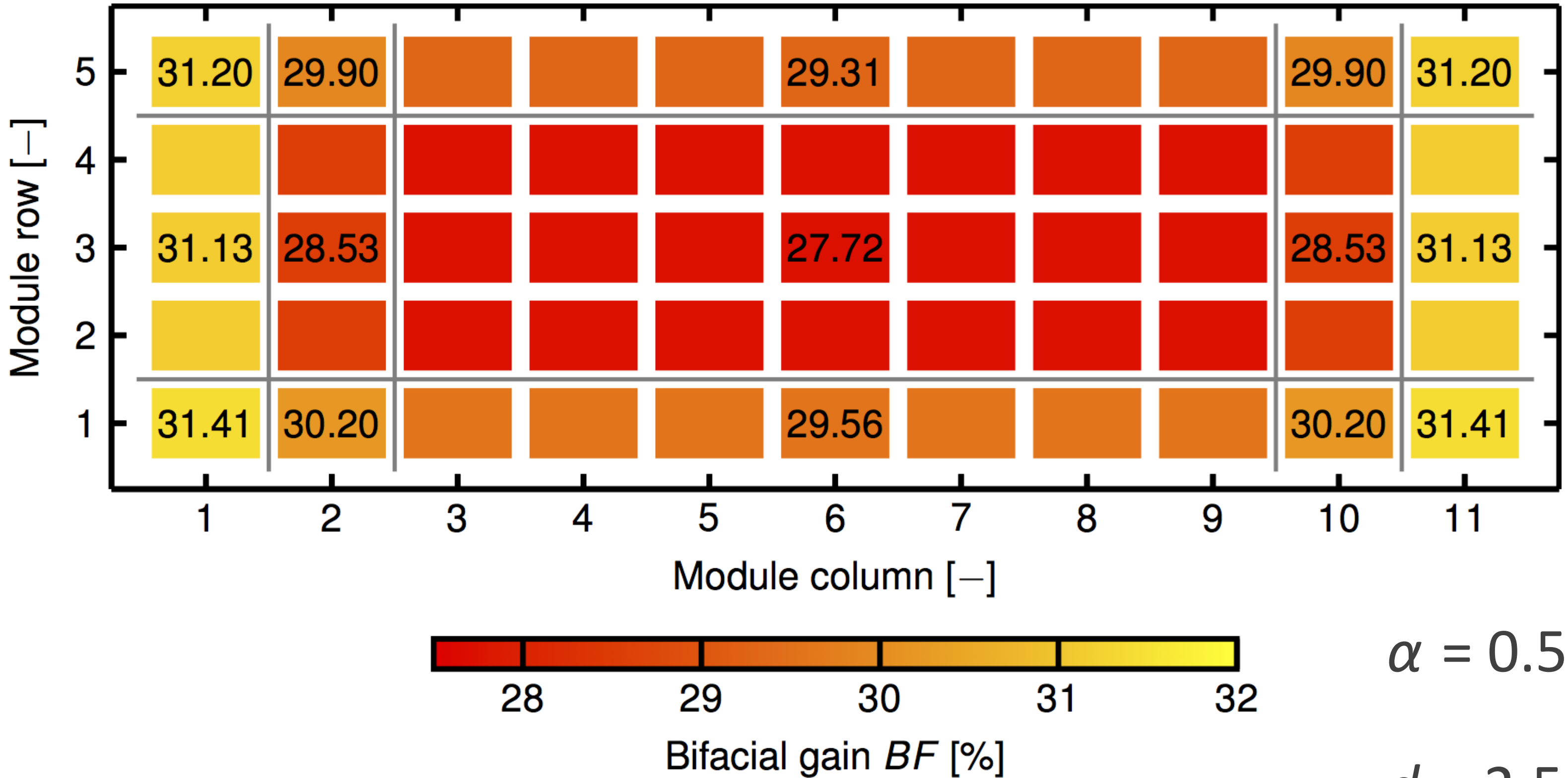
b) El Gouna, 21.06.2005, noon, $\alpha = 0.5$, $h_M = 10\ cm$

For low module elevations, rear side irradiance can be strongly inhomogeneous

→ module Impp will be limited to Impp of cell with lowest irradiance

Bifacial module inside module-field

International Solar Energy Research Center Konstanz



$\alpha = 0.5$

d_R=2.5 m

h_M=1.5 m

Single Module: *BF* = 34 %

Module field: *BF* = 27.72 % (worst)

BF = 31.41 % (best)

Energy yield of bifacial modules depends on position within the array

Summary – bifacial simulations

International Solar Energy Research Center Konstanz

- Increasing number of models and software tools for bifacial energy yield prediction are meanwhile under development at many institutes and companies

- Electrical and optical modelling of bifacial PV cell, modules and systems is more complex than for monofacial

- For bifacial modules, parameters such as ground albedo, diffuse irradiance fraction and module elevation have a much higher impact on energy yield than for monofacial

In general: validation of the models under development has started, but in order to increase the reliability of the models – and thus, to improve the trust of investors in the achievability of claimed bifacial energy yields - **validation with long-term monitoring data (meteo and electrical, during several years) from large bifacial systems in different geographic locations is required**

→ **more complete, high quality datasets, are needed – including, apart from the meteo data, the I/V data of single modules within an array, of strings and of the array (DC and AC)**

Thank you for your attention

This work has been partially funded by the EC (HORIZON 2020) and by the German BMWi (FKZ 0324088A) within the Solar-era.net project "Bifalo”

Federal Ministry
for Economic Affairs
and Energy

European
Commission