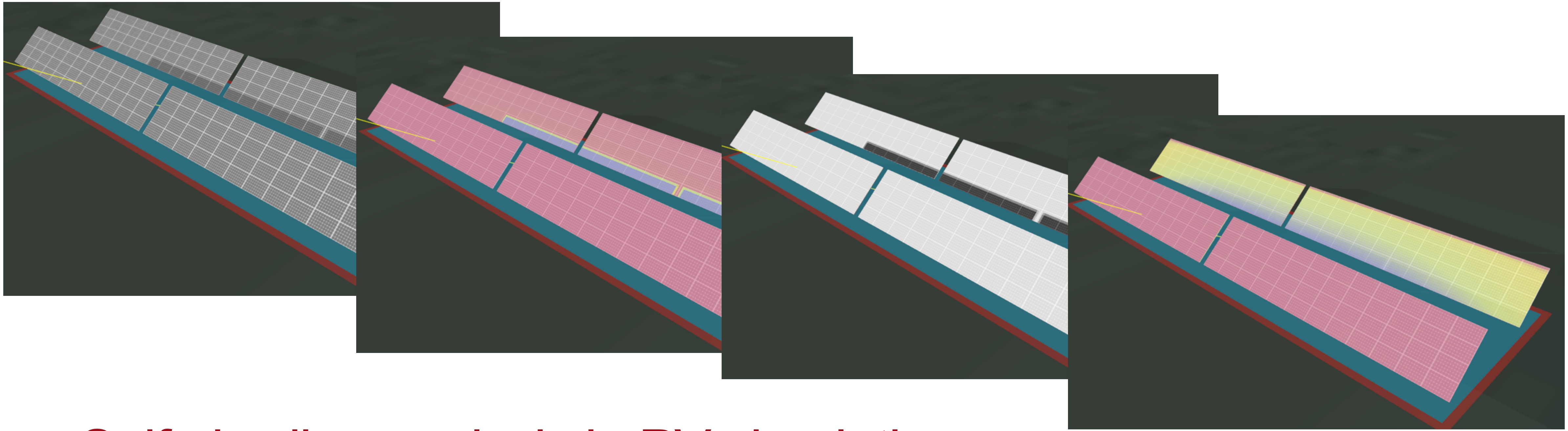
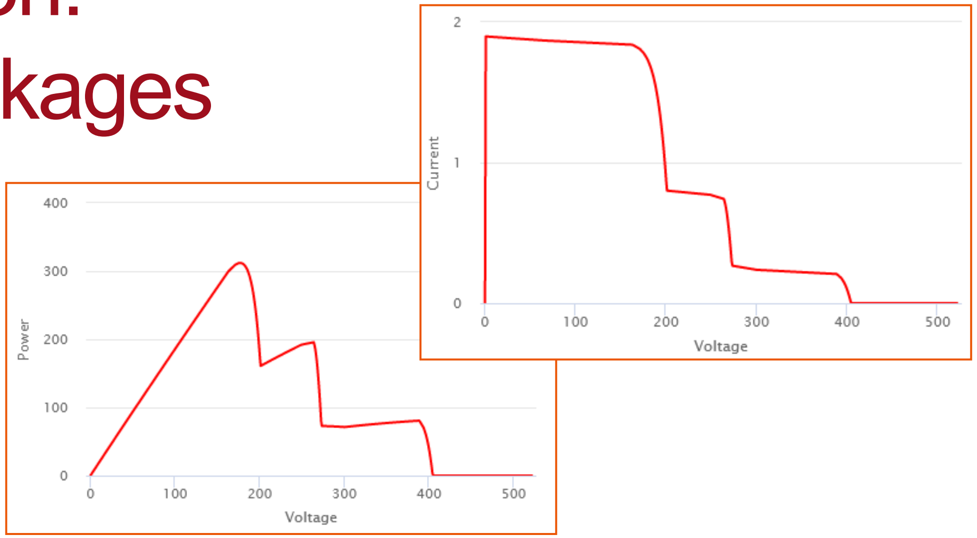


Self-shading analysis in PV simulation: comparison of different software packages



Peter Orosi, Artur Skoczek, Branislav Schnierer
Solargis, Slovakia

PVPMC Webinar series II, 5 August 2020

SOLARGIS

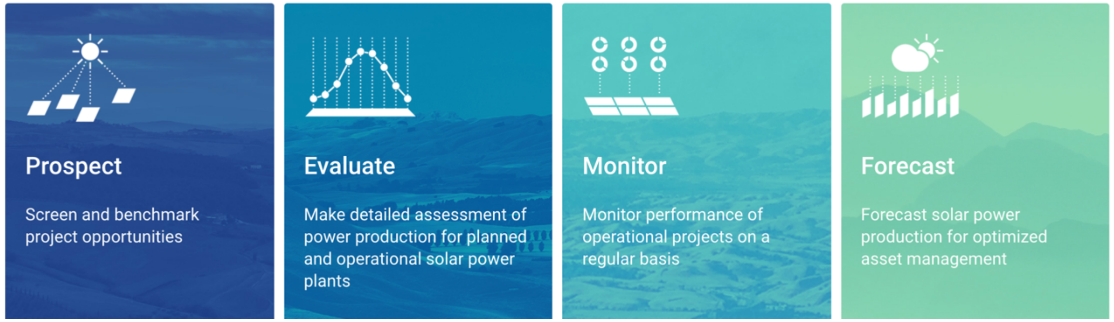
Agenda

- About Solargis
- PV simulation model development
- Visualization tool
- GTI and PVOUT shading simulation
- Verification of shading simulation
- Comparison to other software packages
- Conclusions and future work

About Solargis

Solar resource, meteorological and photovoltaic simulation data, software and expert services for power industry

- Prospection
- Project development
- Monitoring
- Forecasting



1000+ Customers

5000+ projects per year

100+ countries

20 years of experience in solar industry

SOLARGIS

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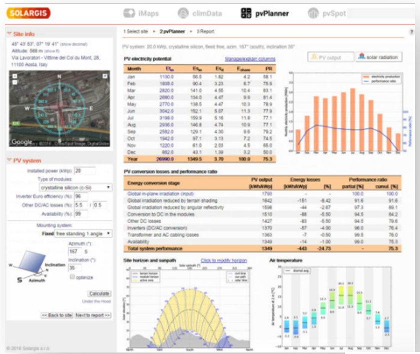
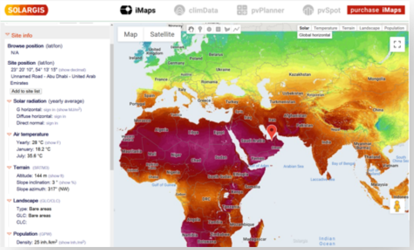
PV simulation model development





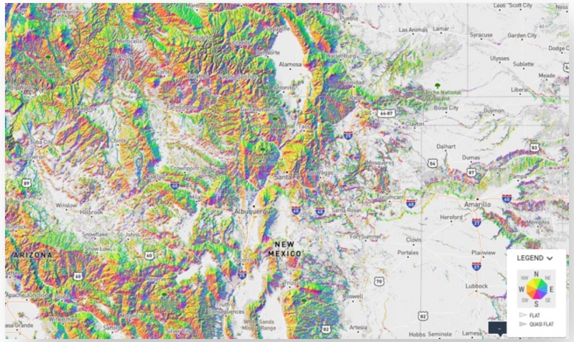
Current status of Solargis 1 model:

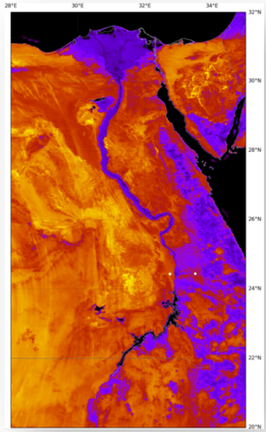
- In operation over 12 years
- Some parts are outdated
- Not easy to serve new or special requirements

New challenges:

- Improved input data
- Improved modelling capabilities
- Improved models – higher quality of simulation
- Collaboration in project development
- Improved PV knowledge – customers are asking more
- More detailed simulation in reasonable time

PV simulation model development

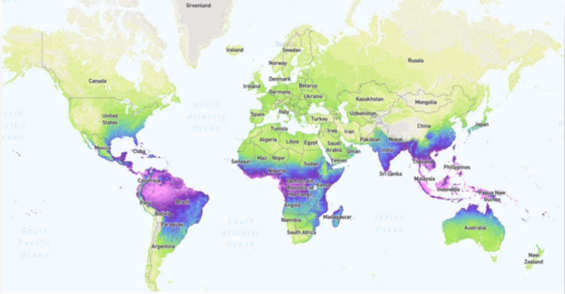


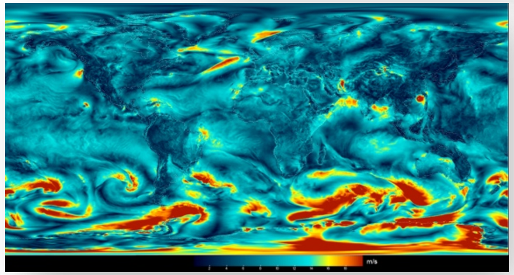


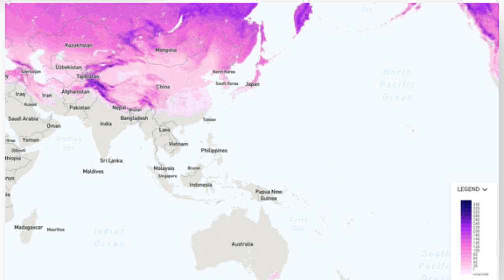
⇒ SG2 simulator is being developed

Requirements:

- Processing of 1-, 10-, 15-, or 30- minute data (full time series, customized data)
- Representing available period of data (26+ years)
- Using updated parameters (TEMP, WS, PWAT, AP), added more input parameters (ALBEDO, PREC, DUST, SNOW)
- High resolution digital elevation model
- Single diode model (PVLIB)
- SANDIA inverter model
- Simulate different hierarchical levels of PV power plant
- Supporting actual technical standards (ISO, IEC, …)
- Provide advanced graphical output
- Validation by independent software packages







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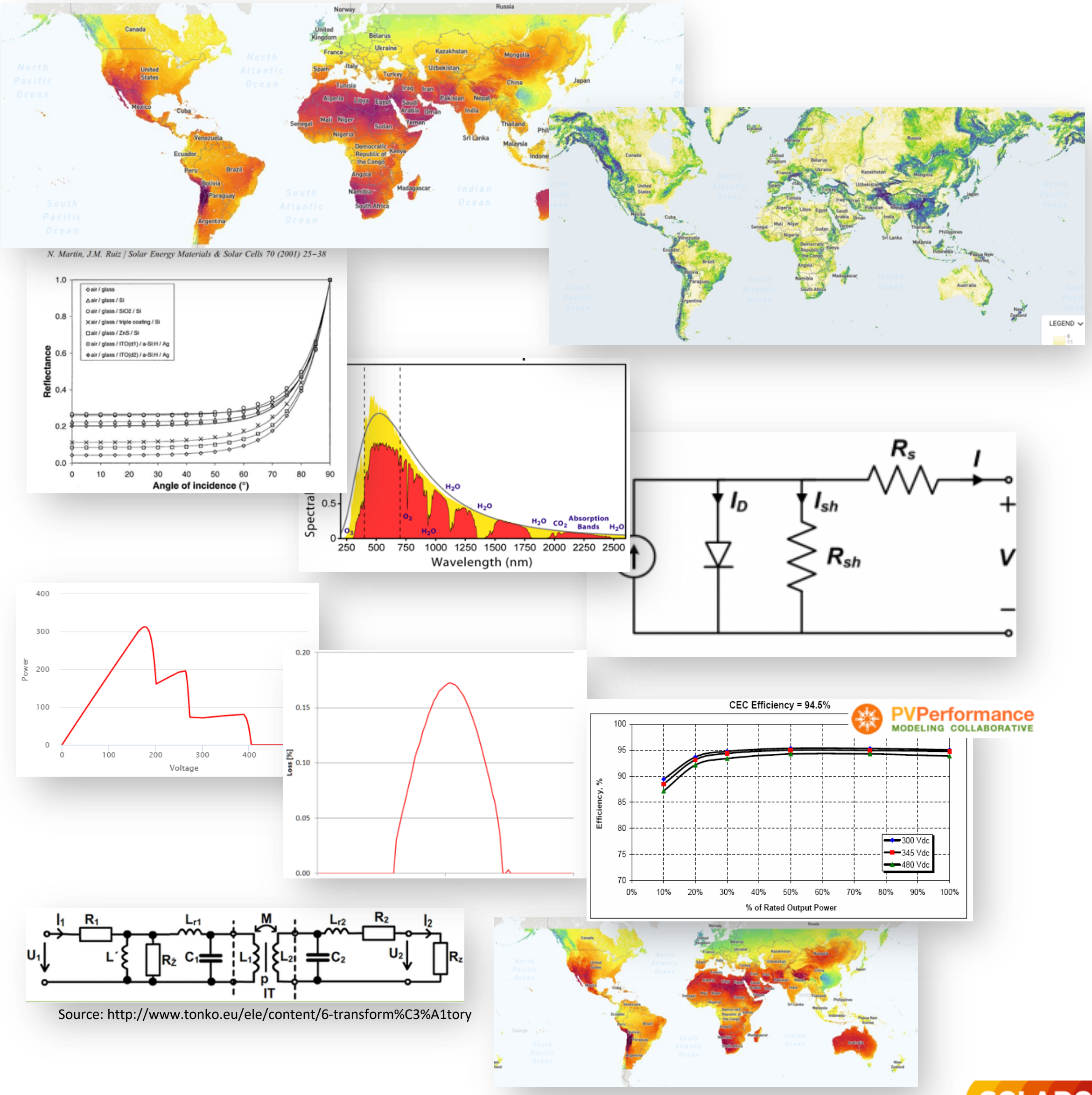
PV simulation model development

Simplified PV simulation chain

Global tilted irradiation (GTI)
↓
Shading by terrain
↓
Dirt, dust and soiling, snow
↓
Angular reflectivity
↓
Spectral correction
↓
Losses in the conversion of irradiance into DC in modules
↓
Inter-row shading losses
↓
Mismatch and cable losses
↓
Losses in the inverters
↓
Losses in transformers and AC
↓
Technical availability



Source: http://www.tonko.eu/ele/content/6-transform%C3%A1tory

SOLARGIS

PV simulation model development

Simplified PV simulation chain

Global tilted irradiation (GTI)
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Shading by terrain
↓
Dirt, dust and soiling, snow
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Angular reflectivity
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Losses in the conversion of irradiance into DC in modules
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Inter-row shading losses
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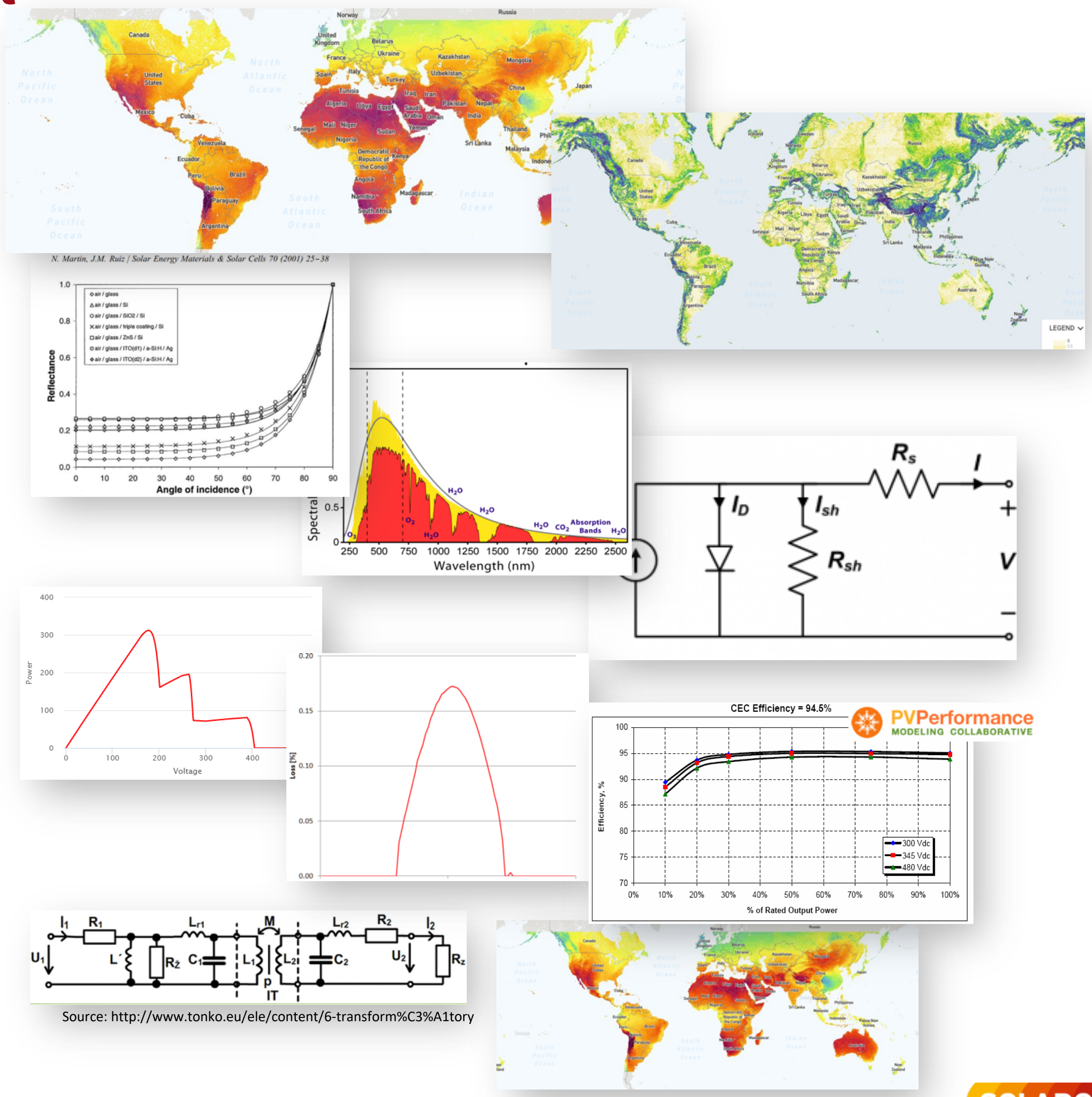
Mismatch and cable losses
↓
Losses in the inverters
↓
Losses in transformers and AC
↓
Technical availability

"GTI effective"

"Shaded DC PVOUT"



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SOLARGIS

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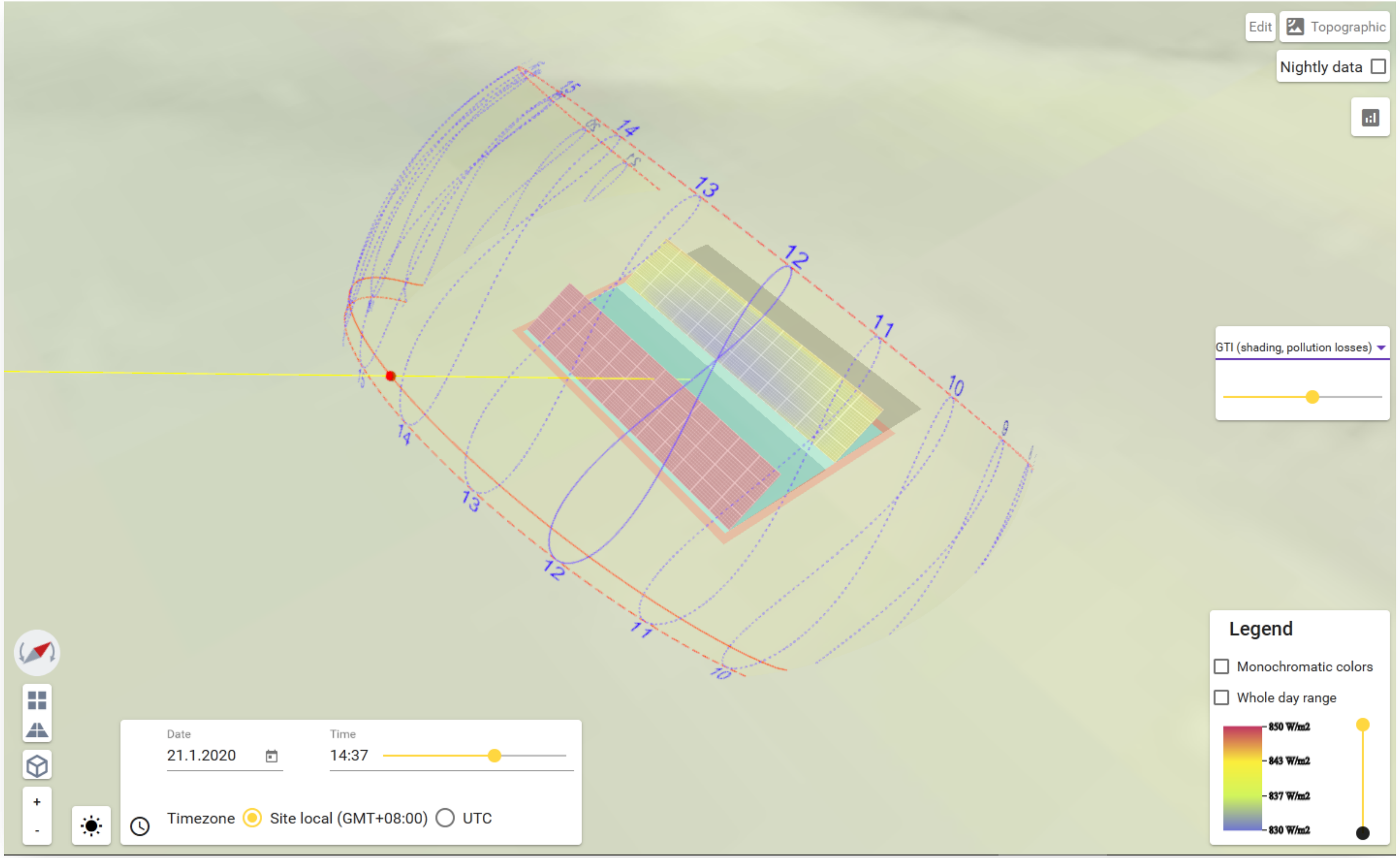
Visualization tool

- Detailed shading analysis of fix- and tracker-mounted systems
- Simulation for specific date
- Direct and diffuse shading
- Electric simulation of hierarchical levels of power plant down to cells
- Various strings layouts
- Modules orientation (vertical/horizontal)



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Visualization tool

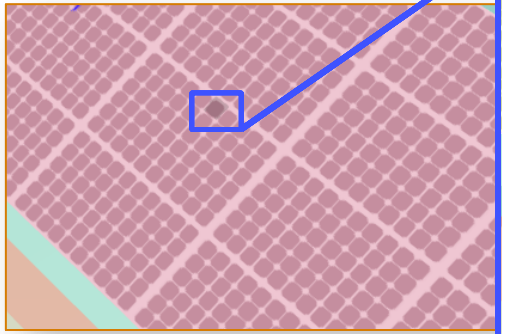
Results available in:

- Large number of parameters
- Interactive graphs
- Visual presentation

Solar, meteo and electric outputs of PV simulation

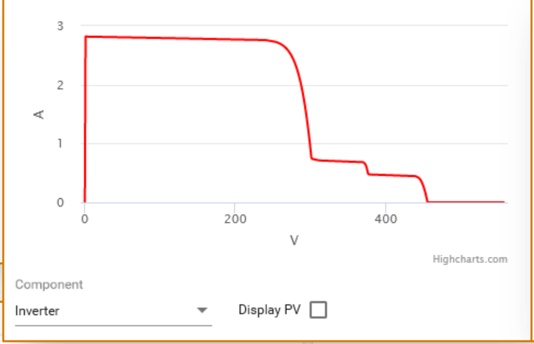
System data

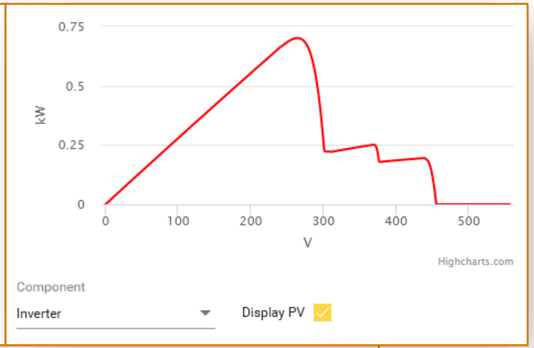
Solar Azimuth	181.47 °
Solar Elevation	30.89 °
Inc Angle	29.13 °
GHI	519 W/m2
DNI	755 W/m2
DIF	131.37 W/m2
Albedo	0.28
Soiling Losses	0
Temperature	-1.5 °C
Precipitable water	3.4 kg/m2
Shadow Ratio	0
GTI Without Losses	849.8 W/m2
GTI With Shading & Pollution Losses	842.36 W/m2
GTI With Shading & Pollution & Angular Losses	835.72 W/m2
GTI With Shading & Pollution & Angular & Spectral Losses	822.63 W/m2
Diffuse GTI With Shading & Pollution & Angular & Spectral Losses	78.08 W/m2
Disconnected Sub-Modules Ratio	0
PVOUT With All GTI Losses (specific)	838.19 W/Wp
PVOUT With All GTI Losses & DC Losses (specific)	831.5 W/Wp
PVOUT With All GTI Losses & DC & Inverter Losses (specific)	666.67 W/Wp
PVOUT With All GTI Losses & DC & Inverter & AC Losses (specific)	657.36 W/Wp

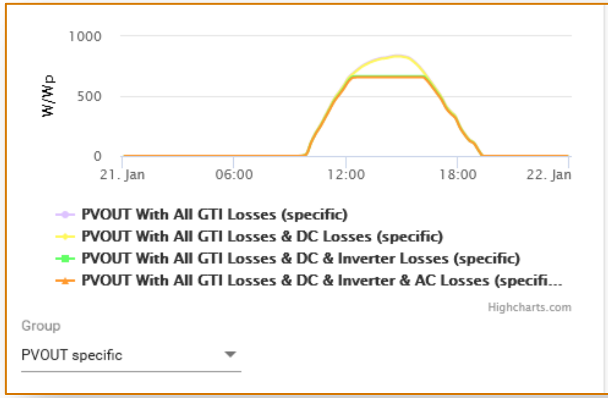


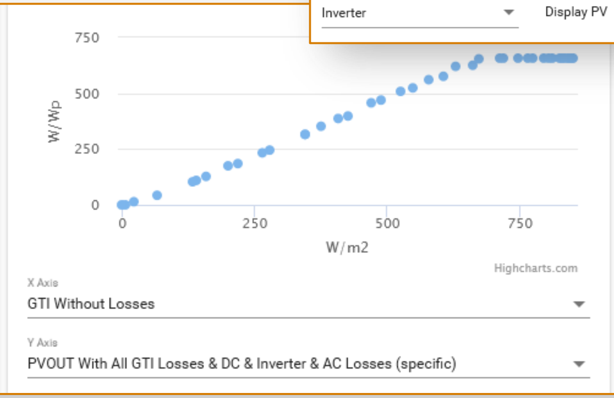
Cell data

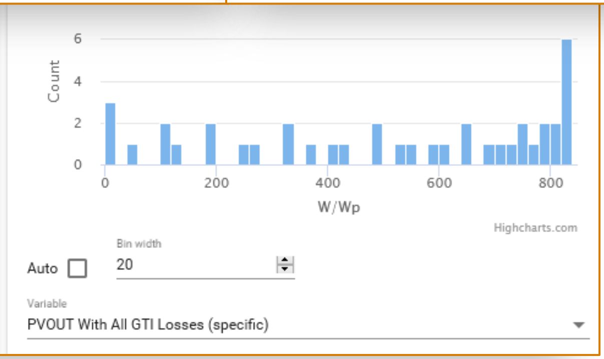
Coordinates	[T: 0, M: 21, SM: 2, C: 15]
Electric coordinates	[I: 1, S: 0]
GTI (shading, pollution losses)	849.78688 W/m2
GTI (shading, pollution, angular losses)	842.349594 W/m2
GTI (shading, pollution, angular, spectral losses)	829.158729 W/m2
Diffuse GTI (shading, pollution, angular, spectral losses)	84.604633 W/m2
Temperature	21.585646 °C
Shadow ratio	1
Voltage	0.522571 V
Current	6.73099 A
PV Out theoretical (with all GTI losses)	3.517425 W
PV Out effective (with all GTI losses)	3.517425 W
PV Out mismatch losses	0 W
PV Out contribution ratio	0.0173 %
Disconnected	0











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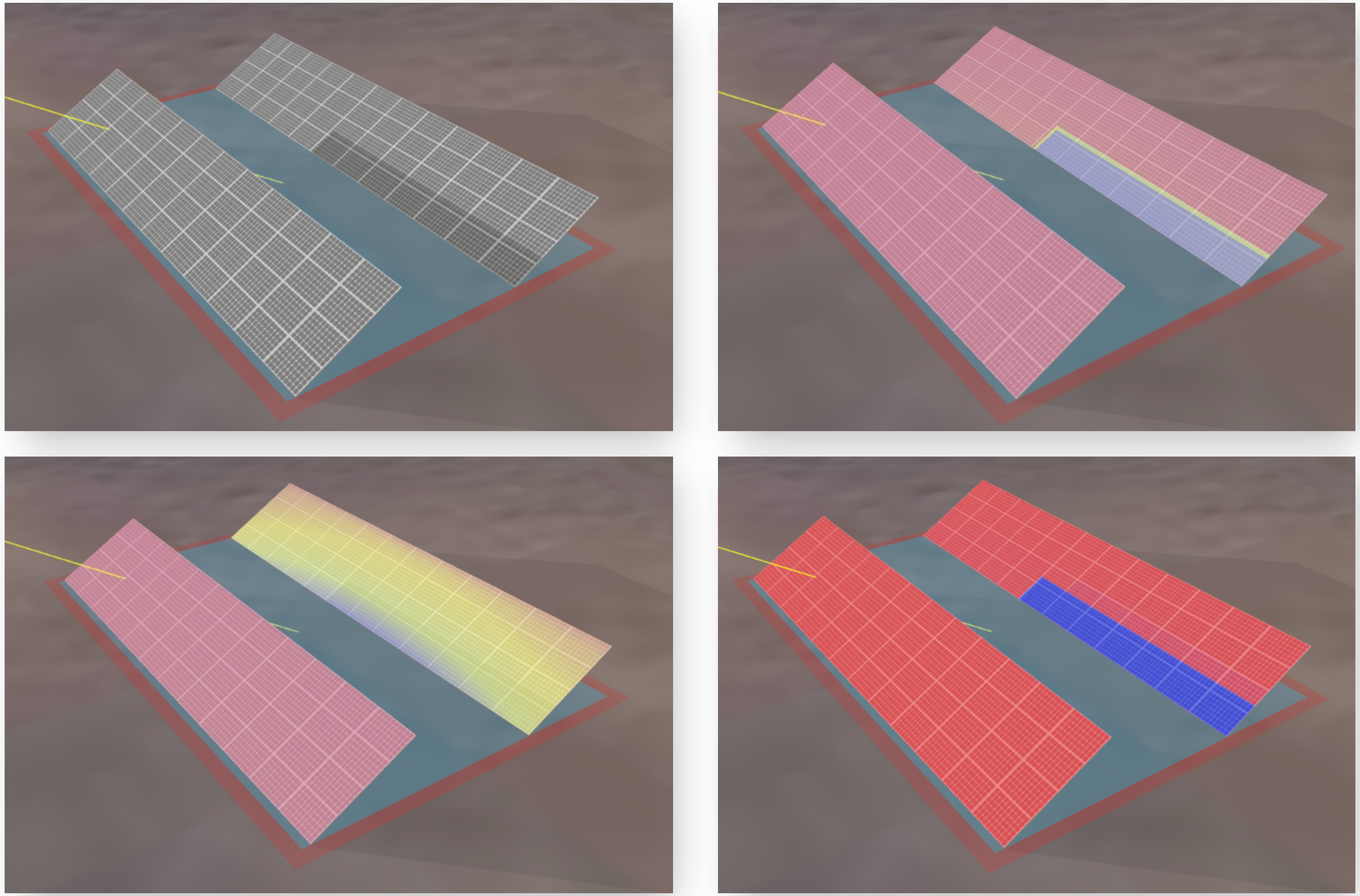
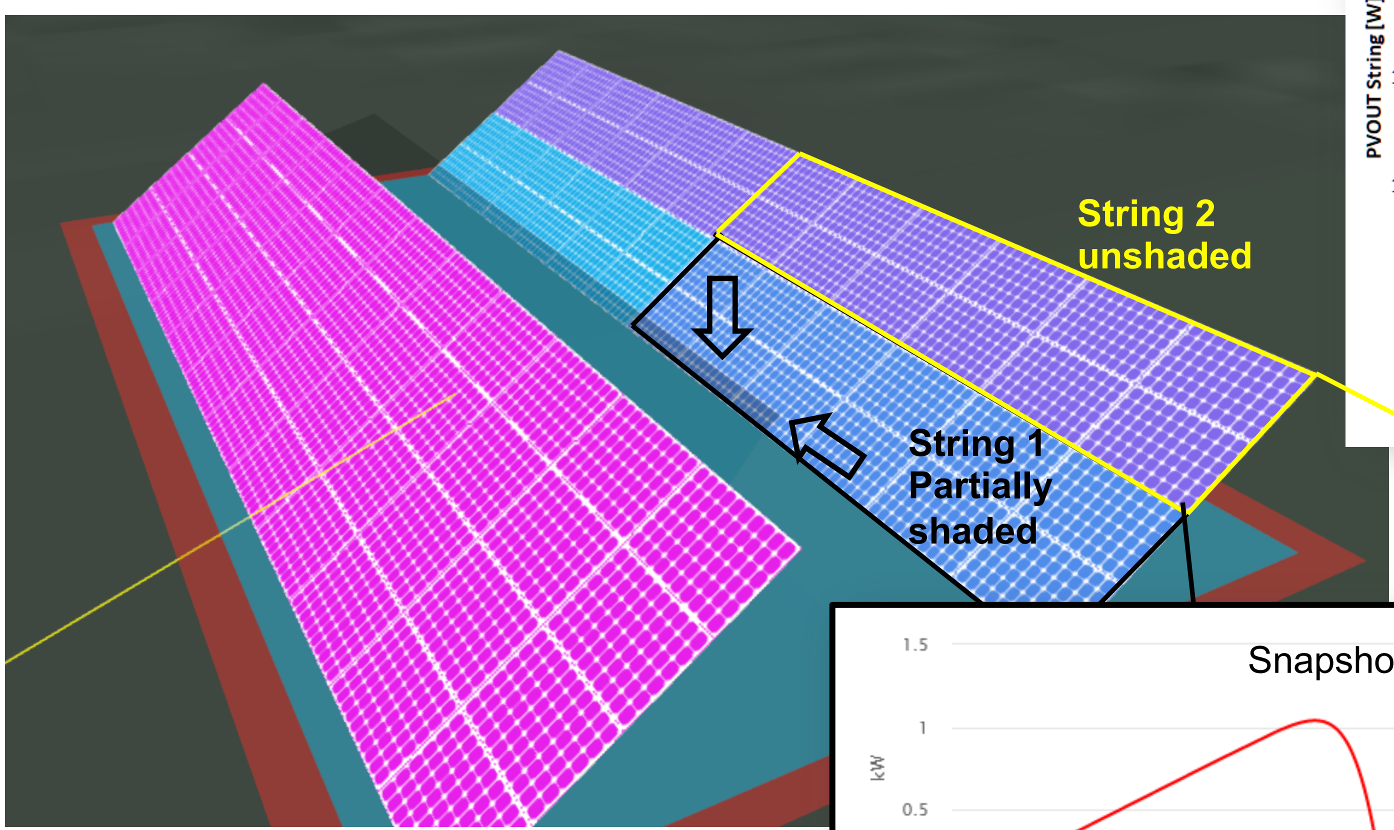
Visualization tool

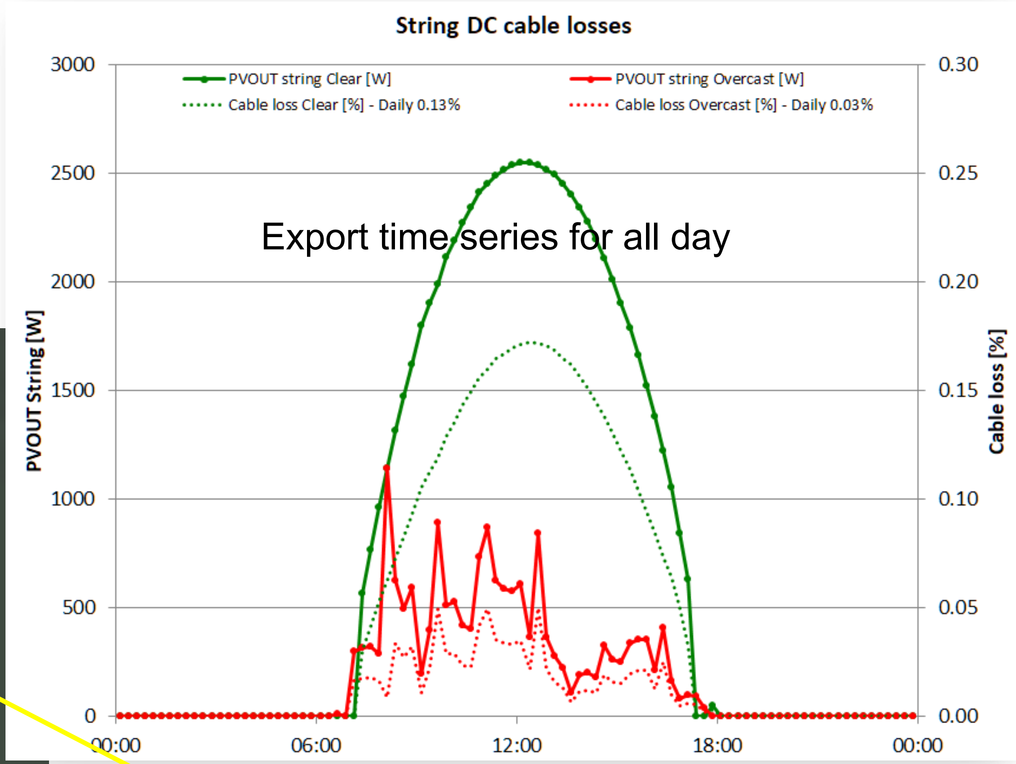
- Results available also in 3D view
- Diffuse part of shading
- Real shade vs. electrical effect
- Cell contribution to generated PVOUT
- Current, voltage, temperature, … all available operational parameters

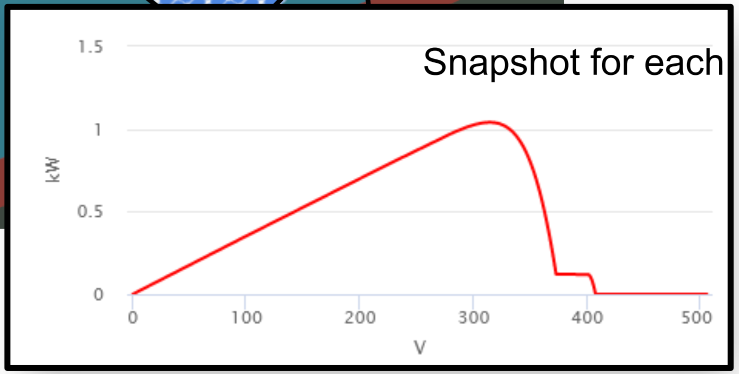


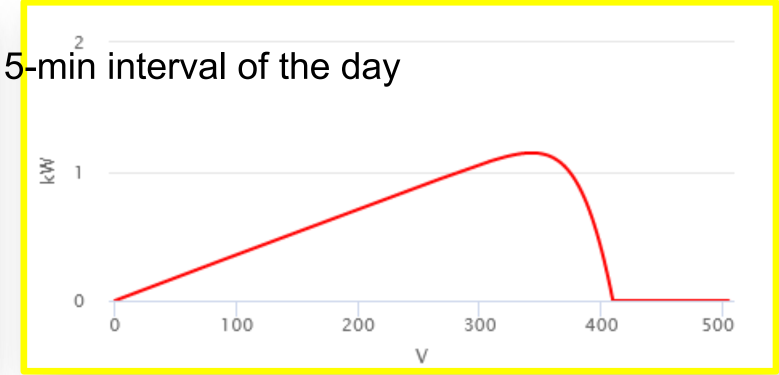
Visualization tool

- Example for strings









SOLARGIS

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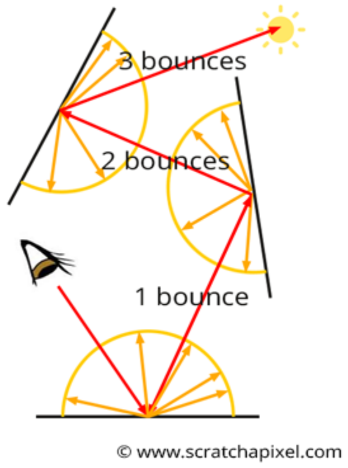
GTI and PVOUT Shading simulation

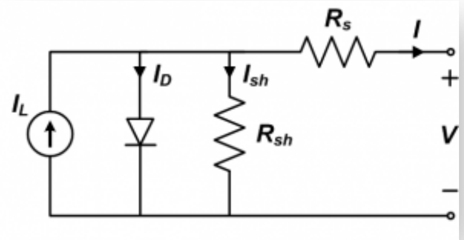


Raytracing method by Solargis

- Custom implementation
- Monte Carlo backward path-tracing
  (from cell to the source of light)
- Multiple bounces until the source of light is reached
- Fully converged unbiased per cell solution for Lambertian surfaces (no specular yet)
- Universal 3D scene (arbitrary panel placement)
- Sky model is adapted from Perez model (uses Solargis data):
  - Direct normal irradiance
  - Diffuse irradiance (sky isotropic)
- Easily extendable to more detailed models of sky (assuming the more detailed sky data is available)

GTI and PVOUT Shading simulation

- Single diode model



$$I = I_L - I_0\left[\exp\left(\frac{V + IR_s}{nV_T}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}$$

- De Soto model (Single diode model params calculated as function of cell temperature and irradiance)
  - $I_L = \frac{S}{S_{ref}}\frac{M}{M_{ref}}\left[I_{L,ref} + \alpha_{Isc}\left(T_c - T_{c,ref}\right)\right]$
  - $I_0 = I_{0,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left[\frac{1}{k}\left(\frac{E_g\left(T_{ref}\right)}{T_{ref}} - \frac{E_g\left(T_c\right)}{T_c}\right)\right]$
  - $E_g\left(T_c\right) = E_g\left(T_{ref}\right)\left[1 - 0.0002677\left(T_c - T_{ref}\right)\right]$
  - $R_s = \text{constant}$
  - $R_{sh} = R_{sh,ref}\frac{S_{ref}}{S}$
  - $n = \text{constant}$

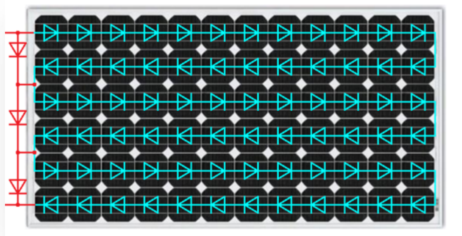
pvlib

PVPerformance MODELING COLLABORATIVE

- Algorithms inspired by Pvlib, but with custom implementation
- PV module parameters are from SAM (System Advisor Model) database

NREL NATIONAL RENEWABLE ENERGY LABORATORY

- Each cell is simulated
- Bypass diodes
- Blocking diodes (On/Off)



- Connections into substrings, strings, inverters – arbitrary layout

SOLARGIS

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Verification of shading simulation

- Main idea – to verify all possible simulator sections with independent software packages

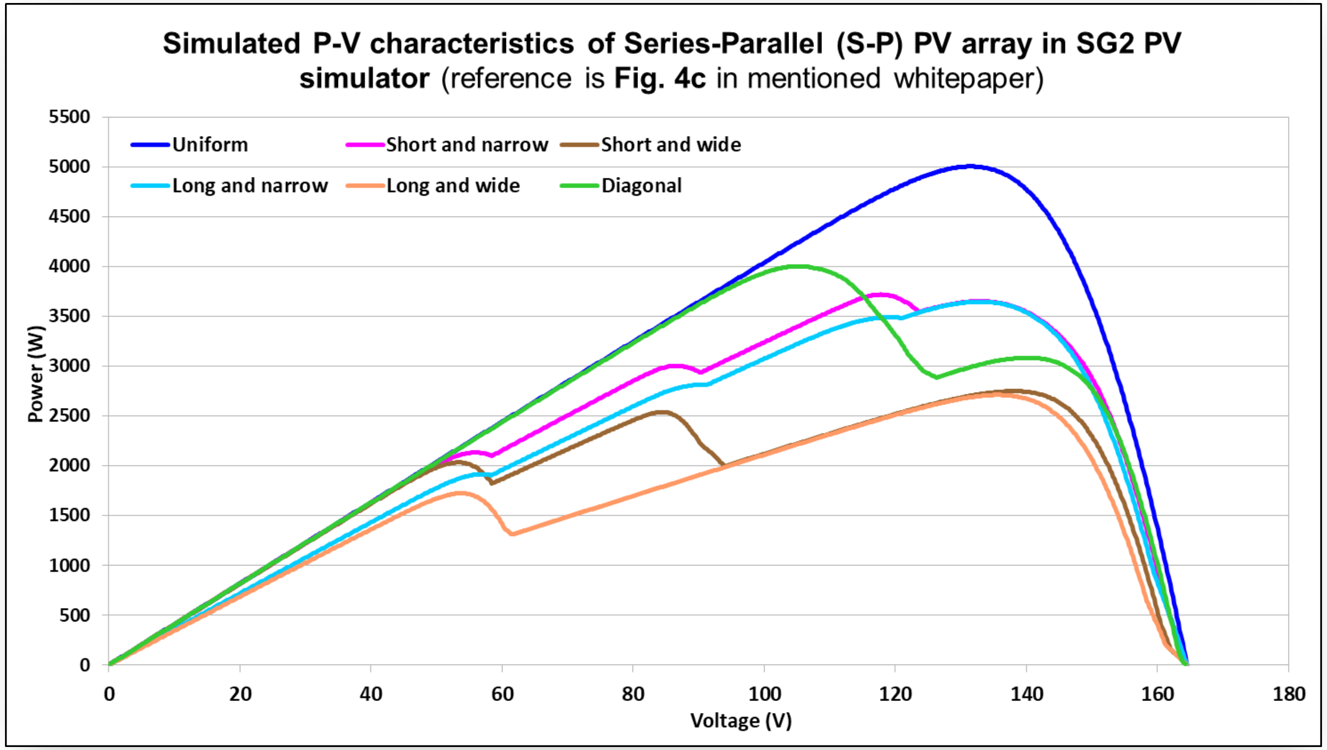
- Raytracing shading simulation – **bifacial_radiance**
  - Series of Python functions for RADIANCE (ray tracing lighting simulation tool) for photovoltaic (bifacial) simulations
  - Preparing for analysis

- Electrical effects of shading – **LTspice XVII**
  - Analog electronic circuit simulator/schematic capture/waveform viewer, based on SPICE (Simulation Program with Integrated Circuit Emphasis, Berkeley University of California) open source simulator
  - Started

Verification of shading simulation

- **Level of cells in a PV module**

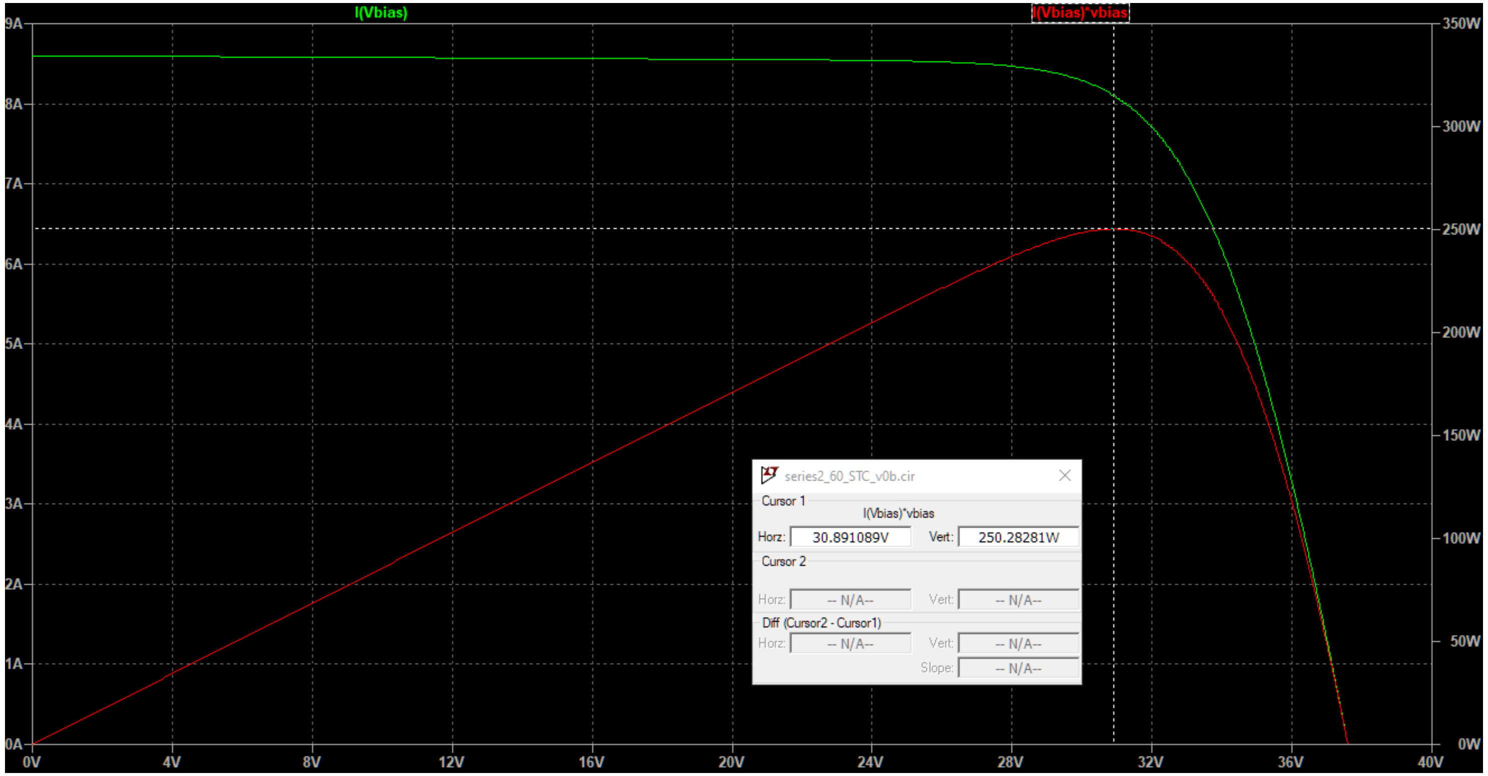
Suneel Raju Pendem, Suresh Mikkili: Modeling, simulation and performance analysis of solar PV array configurations (Series, Series–Parallel and Honey-Comb) to extract maximum power under Partial Shading Conditions (*https://www.sciencedirect.com/science/article/pii/S2352484717302378*)



- KYOCERA-KC200GT PV module
- Differences depending on shading situation
- In average 0.5%, maximum up to 1.0%
- Determined mainly by different Single-diode parameters (temp. coeff, Rs, Rsh) of used PV module (authors vs. SAM database)

Verification of shading simulation

- **Level of a single module at STC conditions**



- Hyundai HiS-M250MG PV module
- 60 cells simulation, 3 bypass diodes
- GTI = 1000 W/m^2, TEMP = 25°C

Simulation tool	P_{MPP} [W]
SG2	250.27
LTSPICE	250.2828
PVlib	250.2826
PVsyst 7.0.5	250.3
SAM 2020.2.29	250.29

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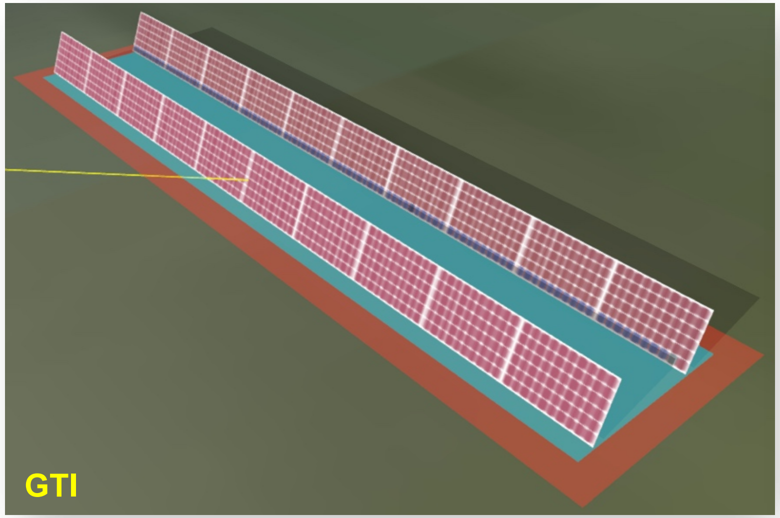
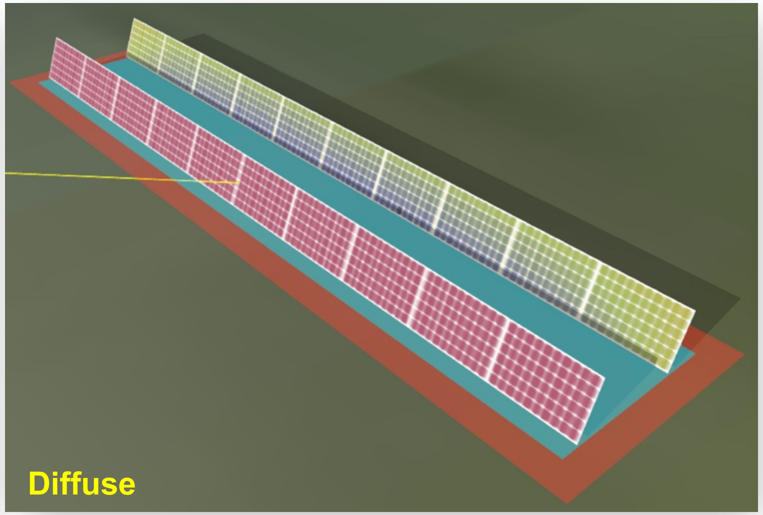
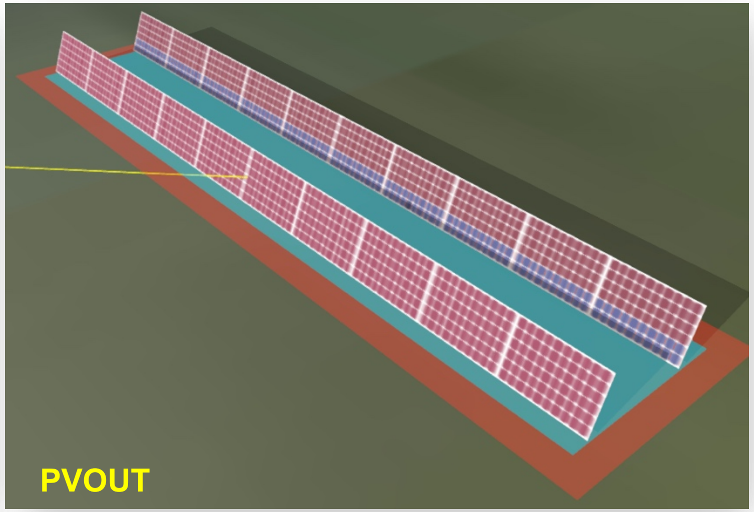
Verification of shading simulation

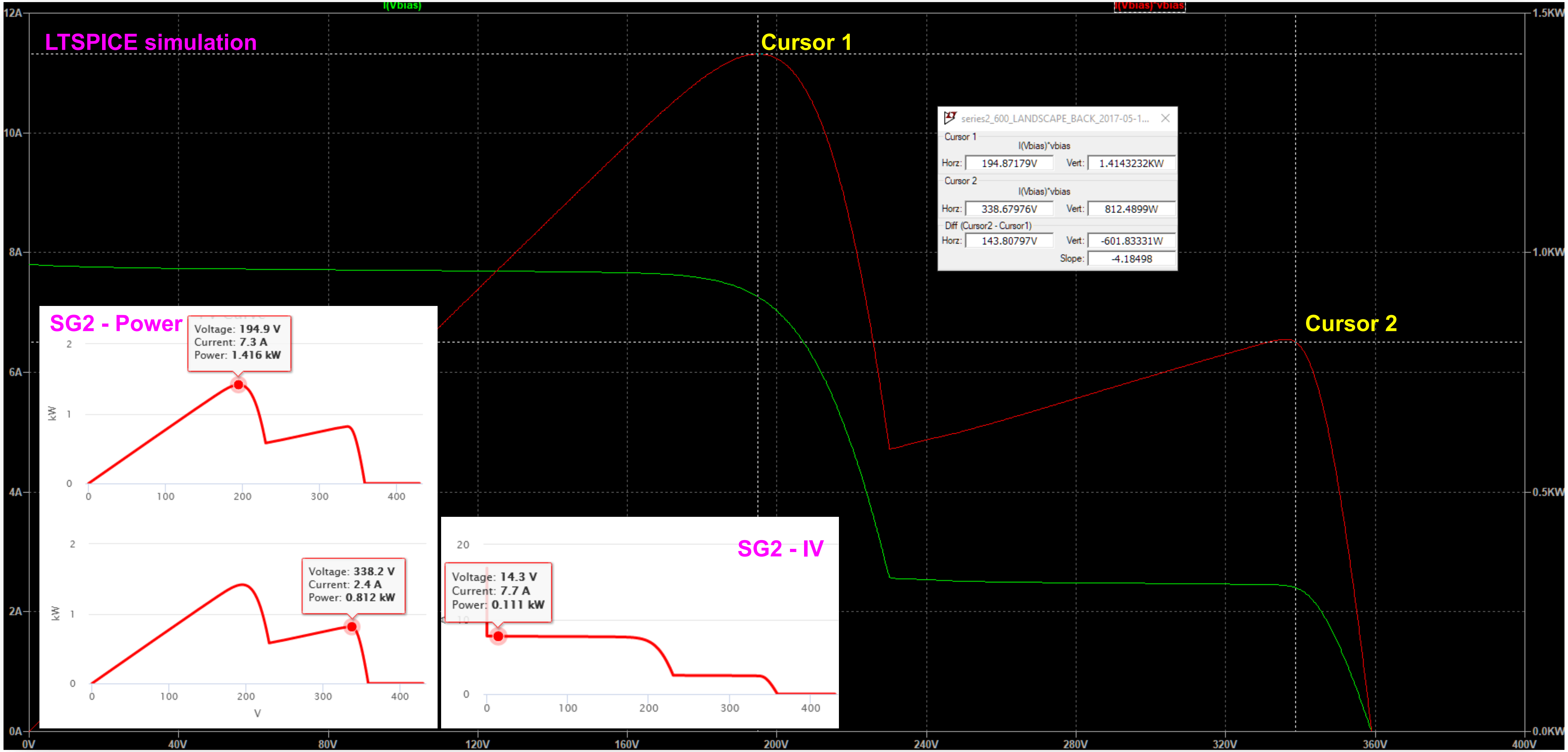
- **Level of a single string (shaded back row) – landscape orientation**
  - Siberia site (Lat: 59.878, Lon: 119.931), N-S tracker (GCR 50%), no backtracking
  - 10 modules in string (10 x 60 cells), **landscape** oriented, one string per row
  - No DC losses considered
  - Selected day – 12 May 2017, 16:37 local time
  - 600 GTI values fed into LTSPICE simulator and IV and Power curves calculated







Verification of shading simulation



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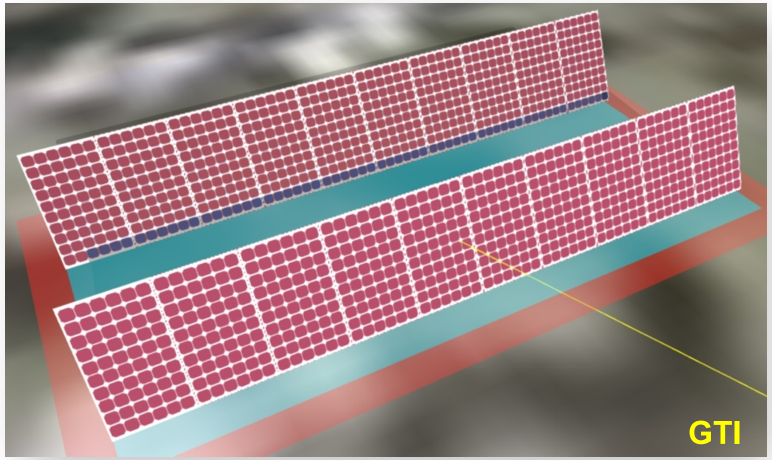
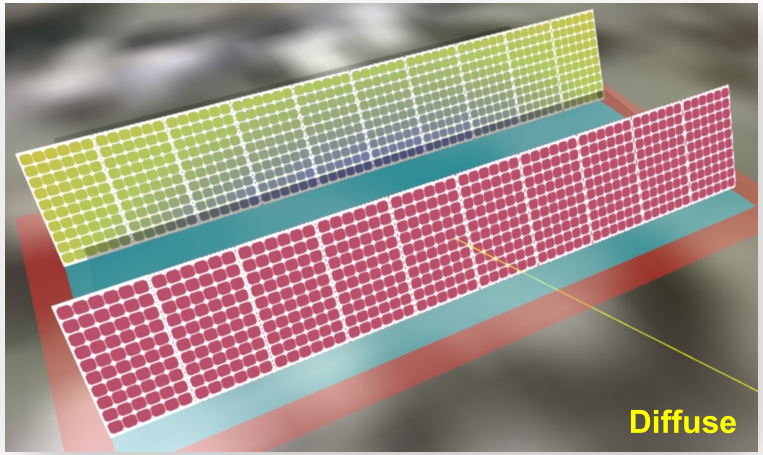
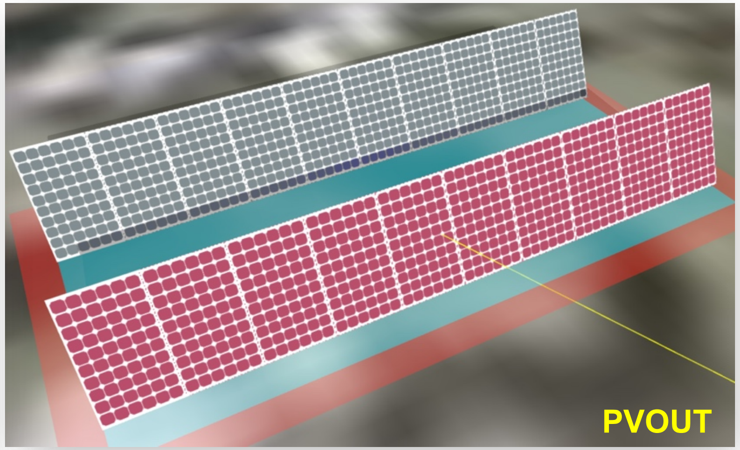
Verification of shading simulation

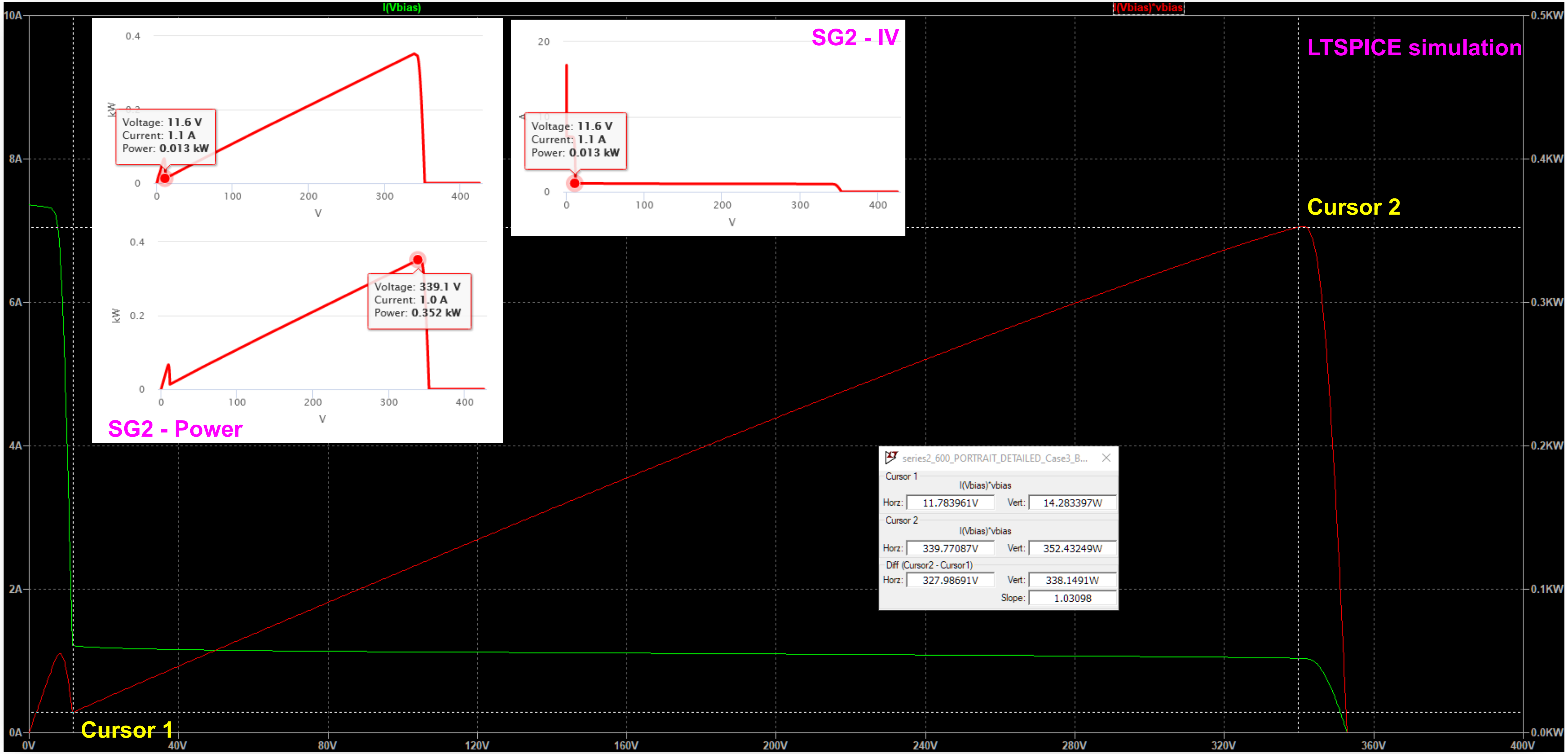
- **On a single string (shaded back row) – portrait orientation**
  - Finland site (Lat: 59.865, Lon: 23.172), N-S tracker (GCR 50%)
  - 10 modules in string (10 x 60 cells), **portrait** oriented, one string per row
  - No DC losses considered
  - Selected day – 26 July 2020, 8:52 local time
  - 600 GTI values fed into LTSPICE simulator and IV and Power curves calculated







Verification of shading simulation



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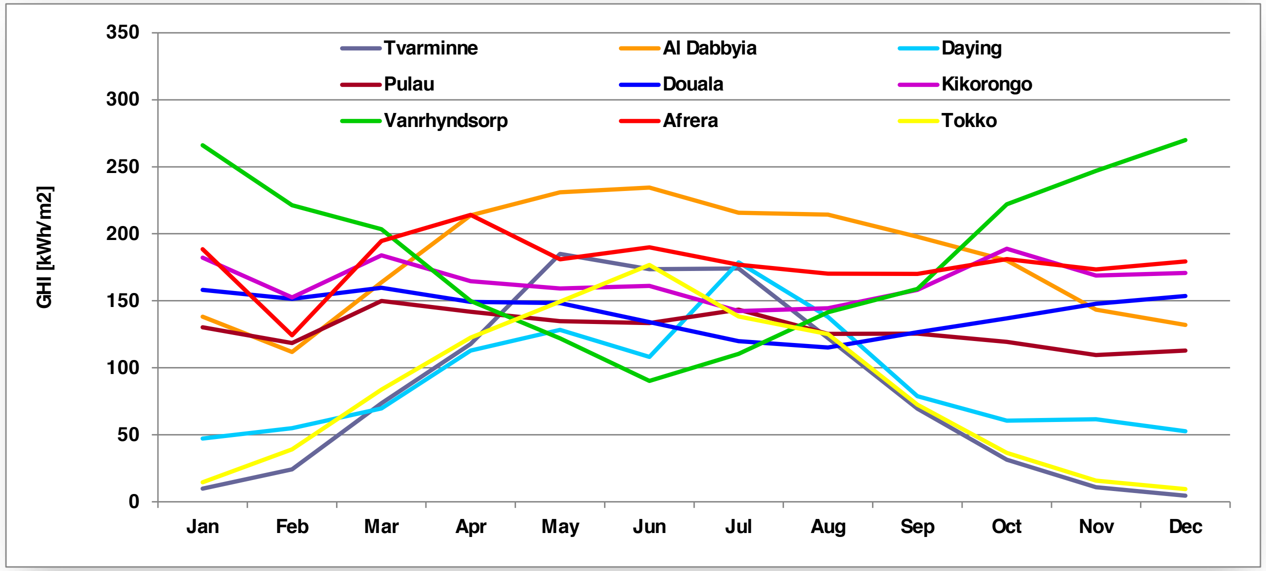
Comparison to other software packages

- 9 representative sites
- Sites should represent various climate conditions
- SAM and Pvsyst
- Year 2017, hourly data, exported in required format

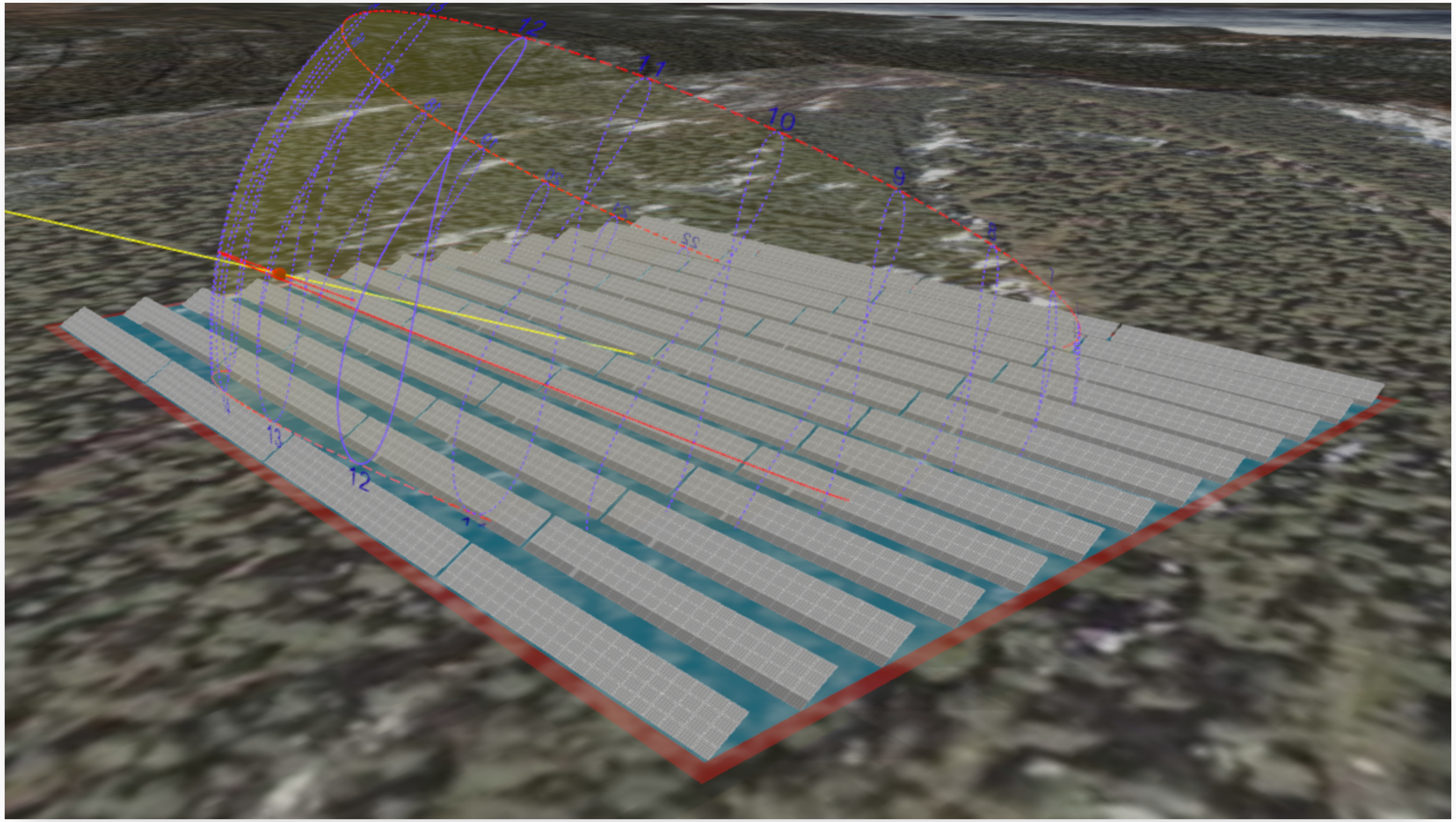
Site id	Site name	Country	Latitude [°]	Longitude [°]	Alt [m asl]	Azimuth [°]	Tilt [°]
1	Tvarminne	Finland	59.8651	23.1717	25	180	43
2	Al Dabbyia	Emirates	24.2569	54.1638	3	180	23
3	Daying	China	30.6231	105.1944	337	180	14
4	Pulau	Indonesia	3.8911	108.1786	19	180	2
5	Douala	Cameroon	3.7864	9.6543	5	180	5
6	Kikorongo	Uganda	0.0000	30.0000	1	0	1
7	Vanrhyndsorp	South Africa	-31.2780	18.6493	29	0	29
8	Afrera	Etiopia	12.9830	40.5880	15	180	15
9	Tokko	Russia	59.8779	119.9310	47	180	47



SOLARGIS

Comparison to other software packages

- Fixed tilt 1MWp installations
- Optimum tilt angle
- CSI modules, landscape
- Centralized inverter
- Where possible, other losses set to 0
- 20 PV modules in a string
- 4 strings on a table
- Variants with/without inter-row shading (no shading, GCR = 0.4, GCR = 0.5)



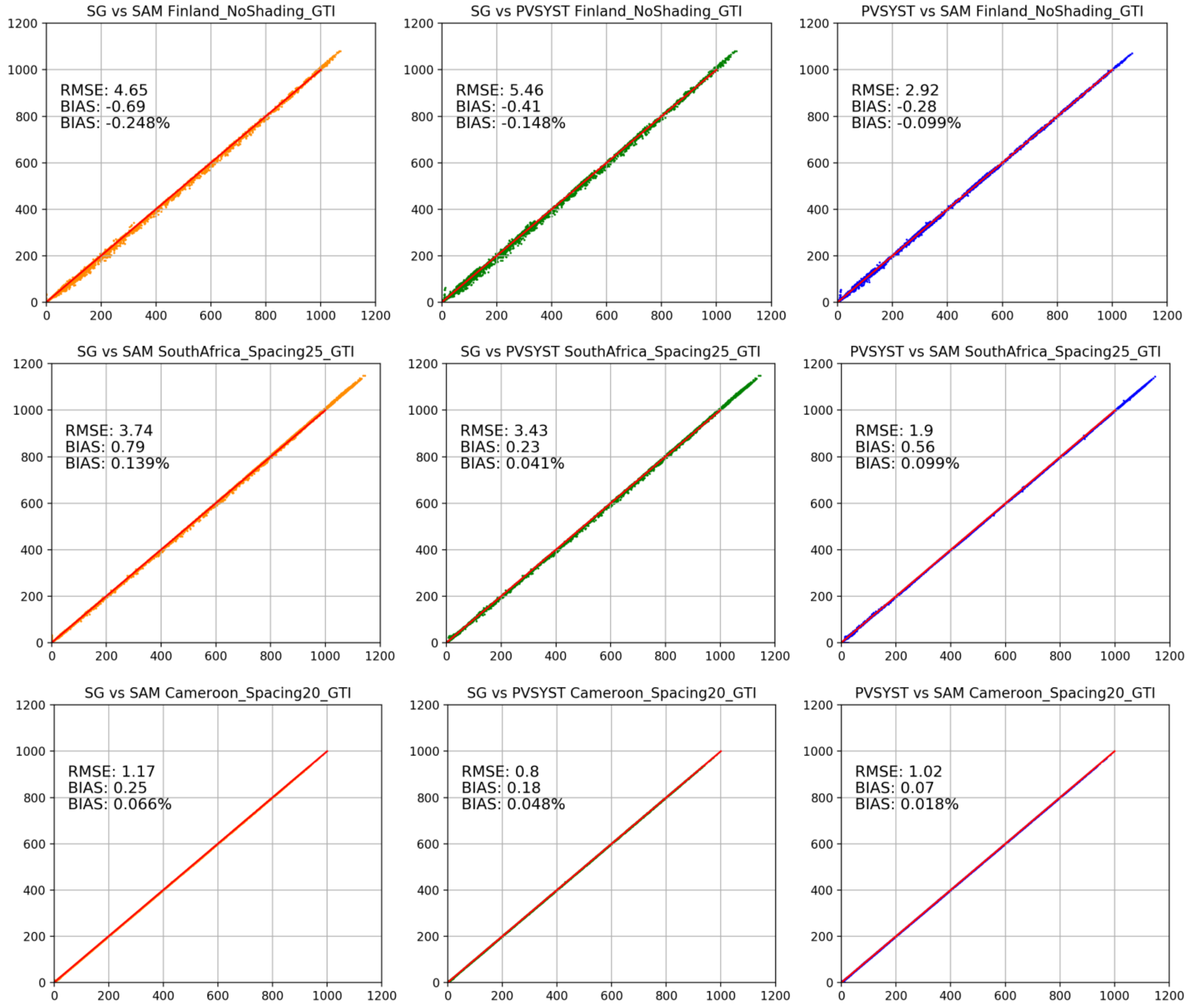
SOLARGIS

Comparison to other software packages

Global Tilted Irradiation (POA)

- Solargis exports GHI, DNI, DIF
- GTI is calculated inside of simulation SW with various models
- Albedo (!)
- Different approaches lead to different input data for simulation even after first step – preparation of data

Shading conditions	Yearly difference [%]
Not apply	-0.6 to +0.3

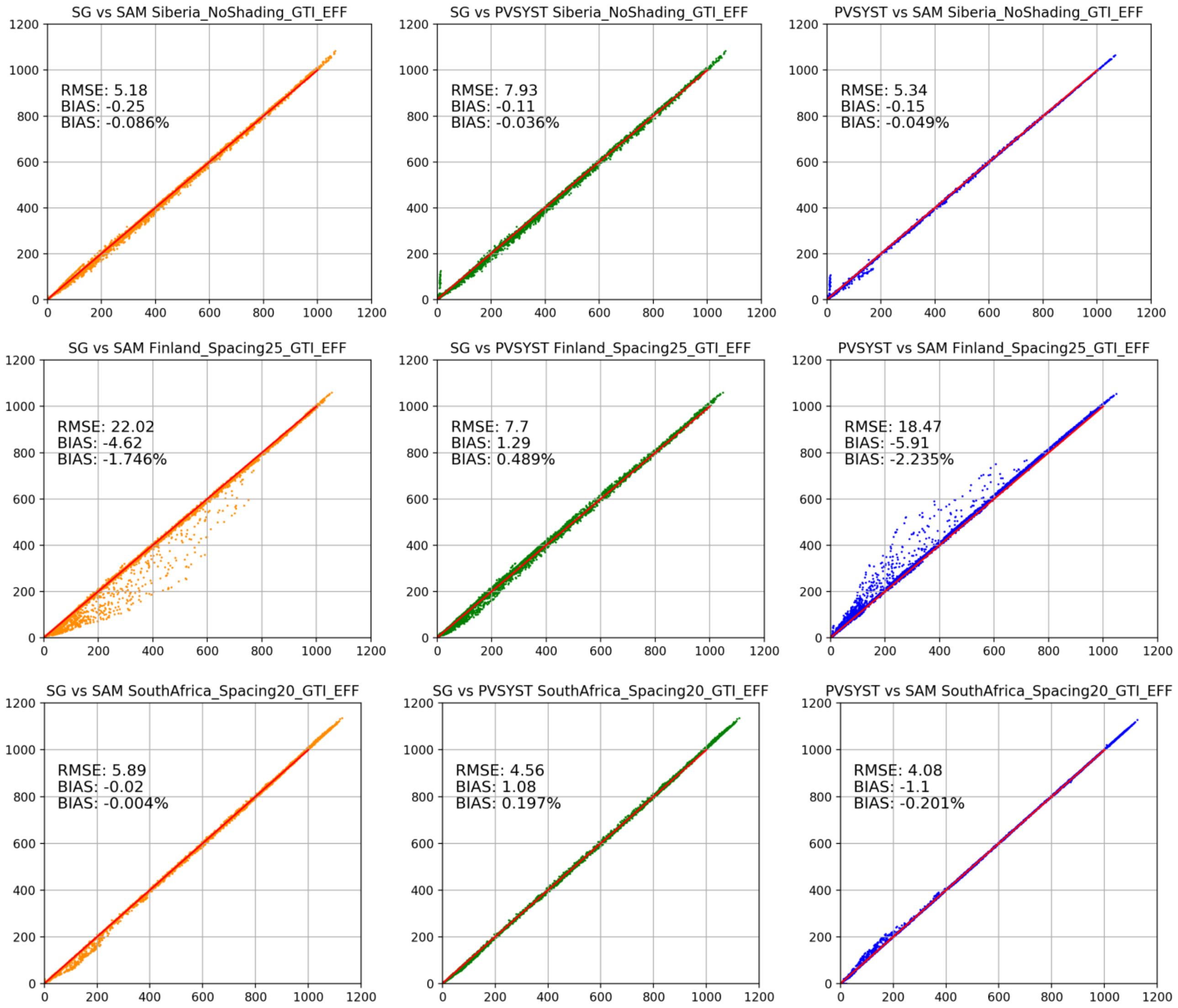


Comparison to other software packages

GTI effective

- GTI after shadings, soiling, incidence array losses
- Several IAM approaches exists, SG is using Martin & Ruiz model, which is not implemented in Pvsyst/SAM
- Shading calculation methods, solar geometry, hourly data too rough

Shading conditions	Yearly difference [%]
No shading	-0.2 to +1.4
Rel. spacing 2.5 (GCR = 0.4)	-8.1 to +1.5
Rel. spacing 2.0 (GCR = 0.5)	-10.5 to +1.6

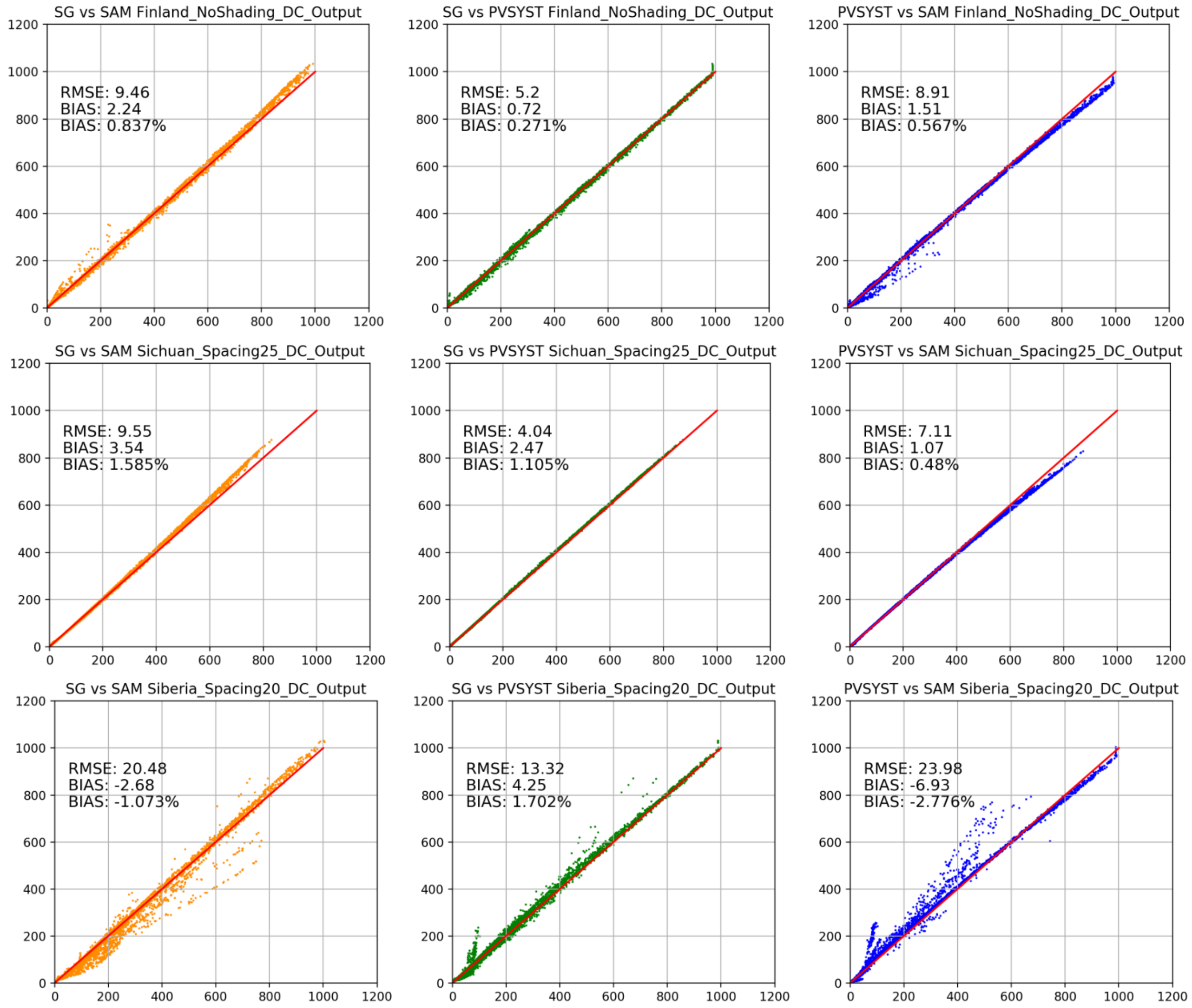


Comparison to other software packages

Shaded DC PVOUT

- DC output after conversion, with electrical effect of shading
- Several approaches exists, GTI and TEMP are main inputs (more approaches also for TEMP)
- User knowledge, skills and practice

Shading conditions	Yearly difference [%]
No shading	+0.4 to +4.6
Rel. spacing 2.5 (GCR = 0.4)	-2.1 to +4.6
Rel. spacing 2.0 (GCR = 0.5)	-1.6 to +4.6



Agenda

- About Solargis
- PV simulation model development
- Visualization tool
- GTI and PVOUT shading simulation
- Verification of shading simulation
- Comparison to other software packages
- Conclusions and future work

Conclusion and future work 1/2

Simulator

- Add and verify all currently used installation types (Fix tilt, Trackers, Bifacial, Floating)
- First version for internal consultancy work Q1 2021
- Public online version Q2 2021*

**Note: Electrical part of simulator is already available in Prospect (on irradiation side high quality view factor model is used as excellent trade-off of speed vs. precision for simple systems with regular layout)*

Verification of simulation

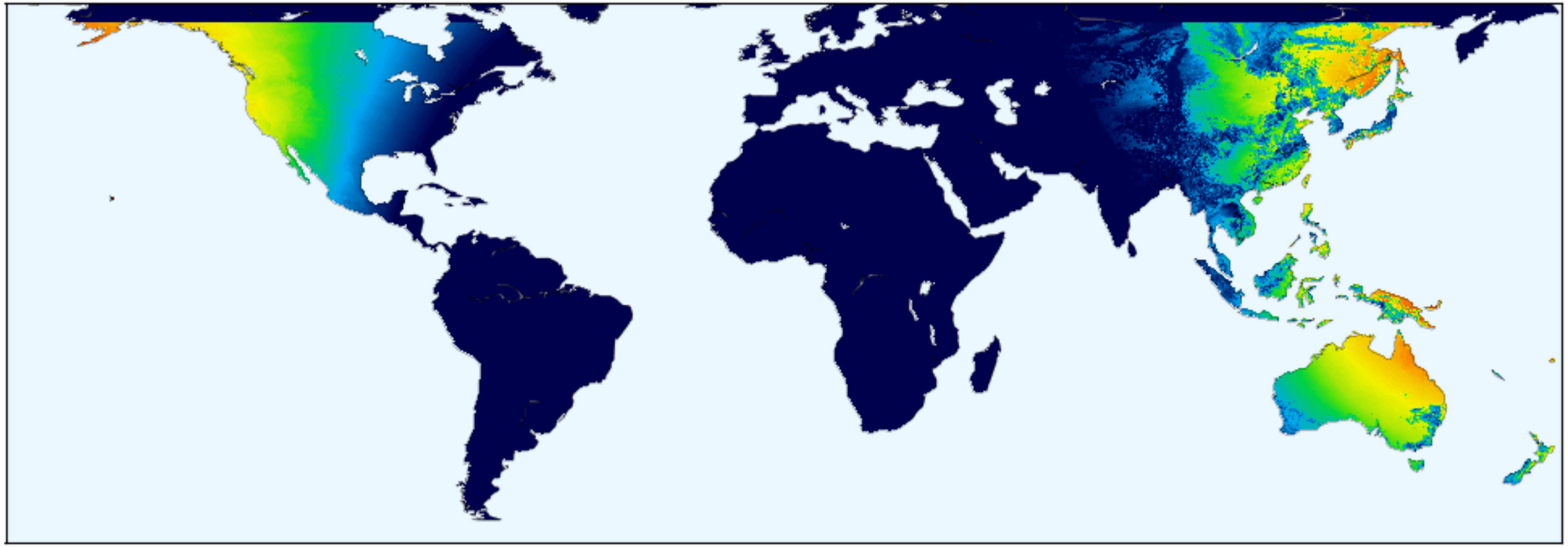
- Raytracing check with Radiance
- More combinations of string connections with LTSPICE
- Cable losses, inverters, transformers check with LTSPICE

Conclusion and future work 2/2

Comparison with other simulation tools

- Differences are in solar radiation models, solar geometry calculations - this introduces error even at the beginning of simulation chain
- Further differences are introduced by different PV parameters and problematic matching of them between simulators
- Add more simulation tools to comparison (Plant predict, …) and prepare analysis of each level of energy conversion chain

Thank you for attention!



Solargis http://solargis.com