A new thermal model for ground and offshore PV installations

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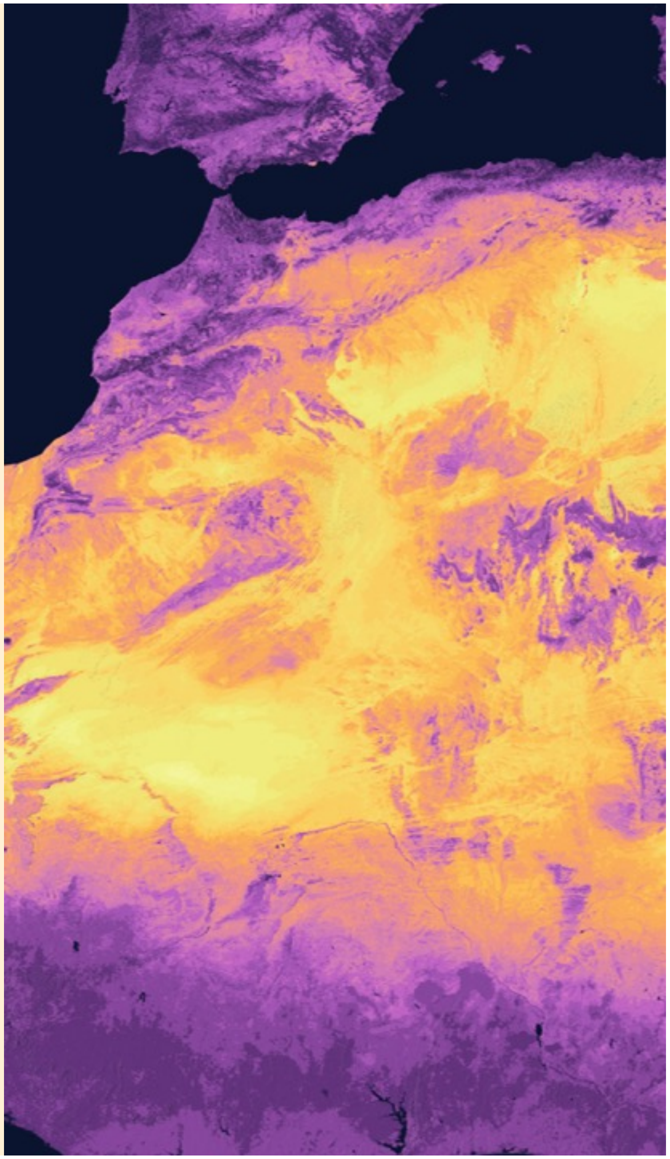
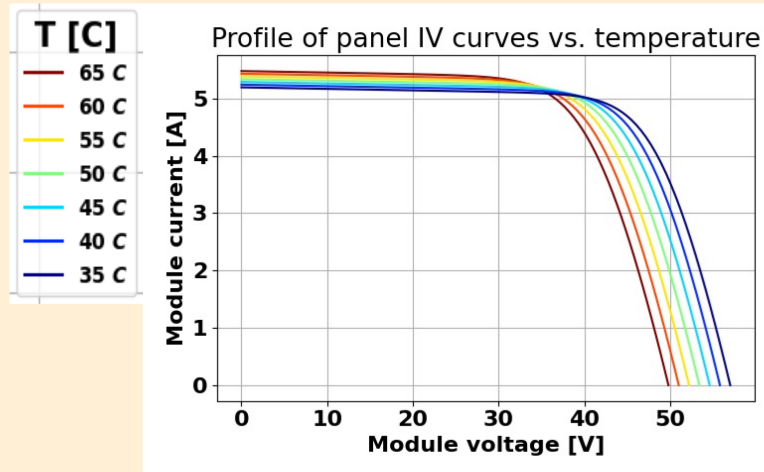


Agenda

- Impact of temperature on PV modules
- Motivation for a new temperature model
- Approach to solution
- Model structure
- Preliminary results and verification
- Proposed next steps

Impact of temperature on PV modules

	Environmental effect
1	Global tilt irradiance G [W/m^2]
2	**Temperature T [°C]**
3	Albedo [-]
4	Pollution, Dust

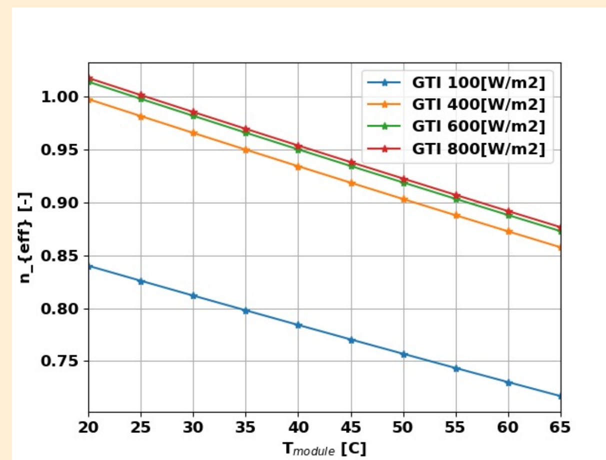


Effects on PV panel

- Open circuit voltage V_{OC} is decreased
- Output DC power and P_{MP} is decreased
- Short circuit current I_{SC} is increased

Models for temperature efficiency μ

- Huld's model – simplified King's model (King et al., 2004)
- Explicit linear models $\mu = \mu_{ref}\left(1 - \beta_{ref}\left(T - T_{ref}\right) + \gamma\, ln(I)\right)$



Why new temperature model

SAPM, PVsyst, Faiman and SAM-NOCT

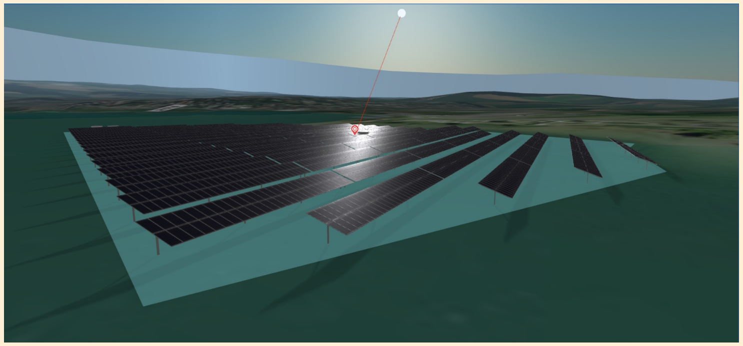
- Based on stationary heat balance equation

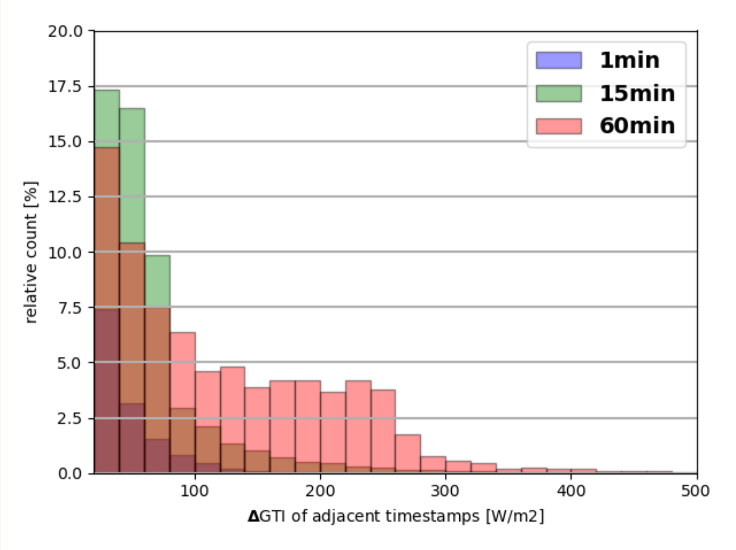
$$q_{GTI} - q_{electric} - q_{covection} - q_{coduction} - q_{radiation} = 0$$

- Solution in case of all 4 models is straightforward and explicit formula for module temperature => low calculation costs
- Models are based on a coefficients with constant values for calculated system (even in case of trackers)
- Basic inputs come from fit of ground measured data
- Does not reflect heat capacity of PV modules

Transient weight moving average model (Prilliman et al., 2020)

- Previous module temperature is considered via moving average





New temperature model approach

- Work package in SERENDI-PV project – Floating simulation improvements
- Heat transfer is a more general issue than PV industry covers
- Approach motivated by (Choi et al., 2021)

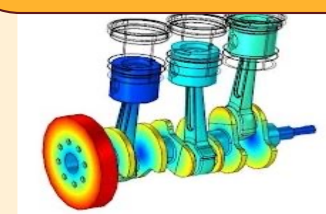
Model accuracy: Low → High
Calculation requirements: Low → High

NOCT 1st version
- Actual panel Temp

Models based on measured data
(currently used)
- General tool
- Usable accuracy
- Partially validated

Characteristic equations and numbers
(Re, Gr, Pr,...)
- Thermal physics included
- Solve heat transfer tasks
- Validates in wide range of cases in industry
- Time dependent

CAE models
(FEM,CFD,..)
- Improved physical models (automotive, aviation design,..)
- Diff. equation solvers
- Spatial distribution
- Benchmarking
- Current state of the art



Basic model structure

- As simple as the solution of heat balance equation (time dependent)
- Explicit or straightforward calculation except the *h* value.

***h* – convective heat transfer coefficient**

- Involves differences between laminar and turbulent flow
- Depends on material properties of air
- Semi empirical method for *h.*

- Panel tilt
- Panel temperature
- Panel dimensions

- Air viscosity
- Air density
- Air thermal conductivity
- Air temperature
- Wind speed

$$C\,\frac{dT_{module}}{dt} = P_{in} - P_{electr} - P_{convect} - P_{rad}$$

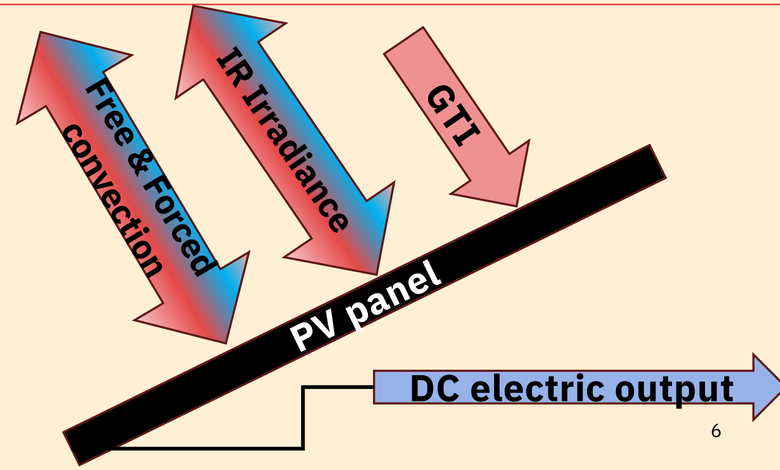
$P_{in} = A * G * \mu\ [W]$ – Power to module surface

$P_{electr} = U * I\ [W]$ – Outflow DC power

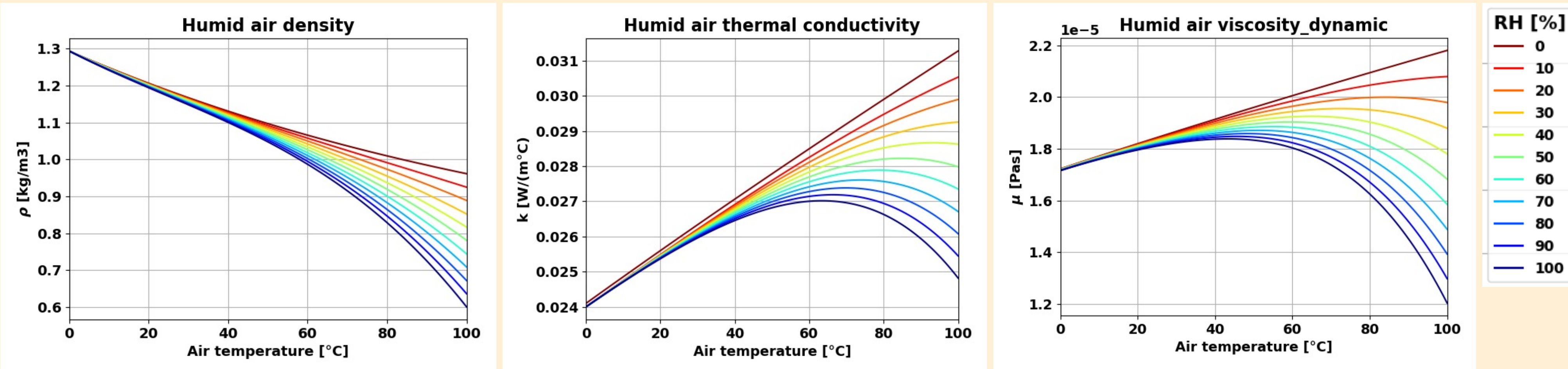
$P_{convect} = A * h * (T_{mod} - T_{air})\ [W]$ – (Frank P. Incropera, 2007)

$P_{rad} = F * A * \varepsilon * \sigma * \left(T_{mod}^4 - T_{sky}^4\right)\ [W]$ – (Driesse et al., 2022)

$A\ [m^2]$ – Panel surface => **separate for top and bottom site**



Material properties of humid air



(Tsilingiris, 2018)

- Floating panel does not “see” the water below mounting, but interacts with ambient air via air properties (specific heat, density, viscosity, temperature conductivity)
- Rate of convective heat transfer strongly depends on fluid properties
- Remarkable change in humid air properties starts at T ~40 °C
- Ambiguous shape of curves for elevated humidity
- Relative humidity close to water level: **RH > 80%**

h calculation

ISO 80000-11:2019(E)		
Characteristic number	**Simple description**	**Formula**
Reynolds number (Re)	$\frac{inertial\ force}{viscous\ force}$	$Re = \frac{\rho . v . L}{\mu}$
Prandtl number (Pr)	$\frac{momentum\ diffusivity}{thermal\ diffusivity}$	$Pr = \frac{c_p \mu}{k}$
Grashof number (Gr) (vertical surface)	$\frac{bouyancy\ force}{viscous\ force}$	$Gr = \frac{g . \beta . \rho^2 (T_{panel} - T_{air}) L^3}{\mu^2}$

(Frank P. Incropera, 2007; Hideaki Imura, 1972)

Semiempirical, non intuitive, complex, but still in use

$$h_{forced} = f(Pr, Re)$$

$f(Pr, Re)$ differs for:
- laminar/turbulent flow

$$h_{free} = f(Pr, Gr)$$

$f(Pr, Gr)$ differs for:
- laminar/turbulent air flow
- surface orientation top/bottom
- panel hotter/cooler than ambient air

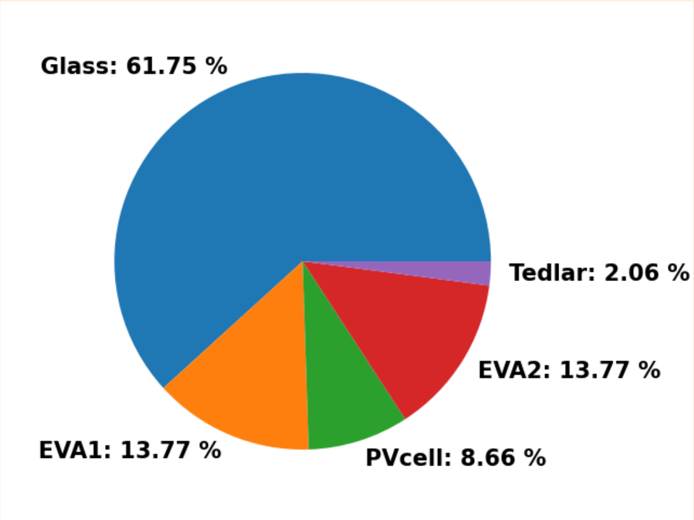
$$h = \sqrt[3]{h_{free}^3 + h_{forced}^3}$$

Model flow

- Model setting
- length, width
- Emissivity for top and bottom face
- Specific heat per area (IEC 61215-1:2021)

(Syafiqah et al., 2017)

- Temperature
- Wind speed
- Global tilt irradiance
- **Relative humidity**



1. Load environmental data for timestamp
2. Find humid air properties (μ, ρ, k, c_p)
3. Obtain convective heat transfer coefficient
4. Calculate input and output power terms
5. Solve differential heat balance equation $T_{panel}(t) \rightarrow T_{panel}(t+\Delta t)$
6. **Panel temperature in next timestamp** (loops back to step 1)

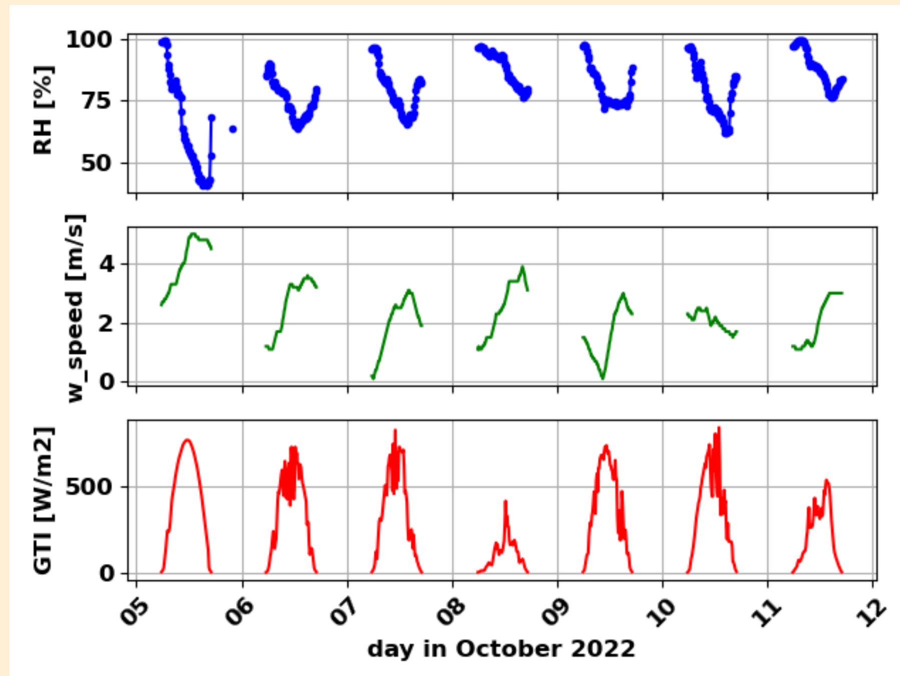
Model comparison with site-measured data

- Validation and tuning on ground measured data (Not allowed to present)
- First verification on floating PV measurements
  - Site (Western Europe)
  - Fixed tilt
  - Water dam
  - 5-min time resolution (only several days available)

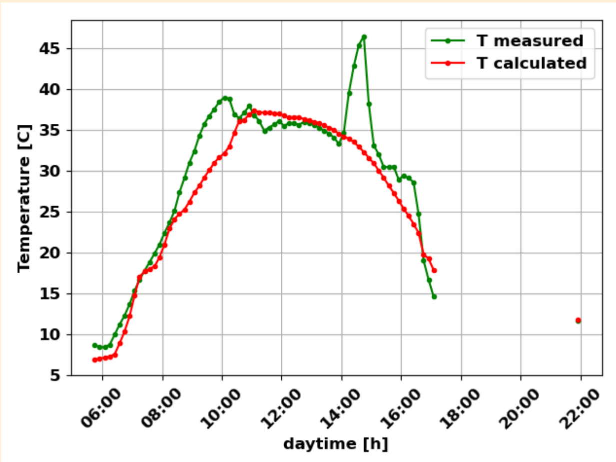
Inputs
- Temperature
- **Wind speed (ERA-5)** (Hersbach et al., 2020)
- Global tilt irradiance
- Relative humidity

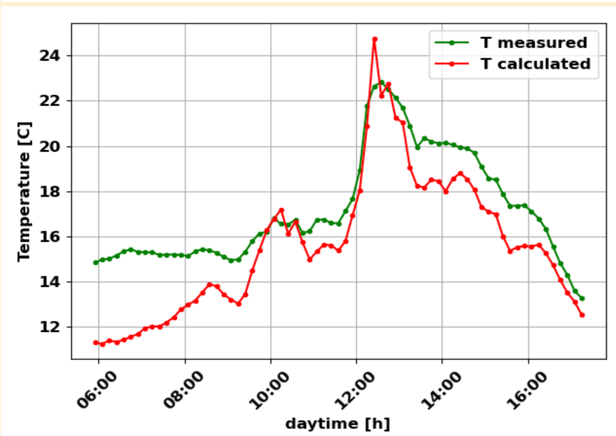
Model

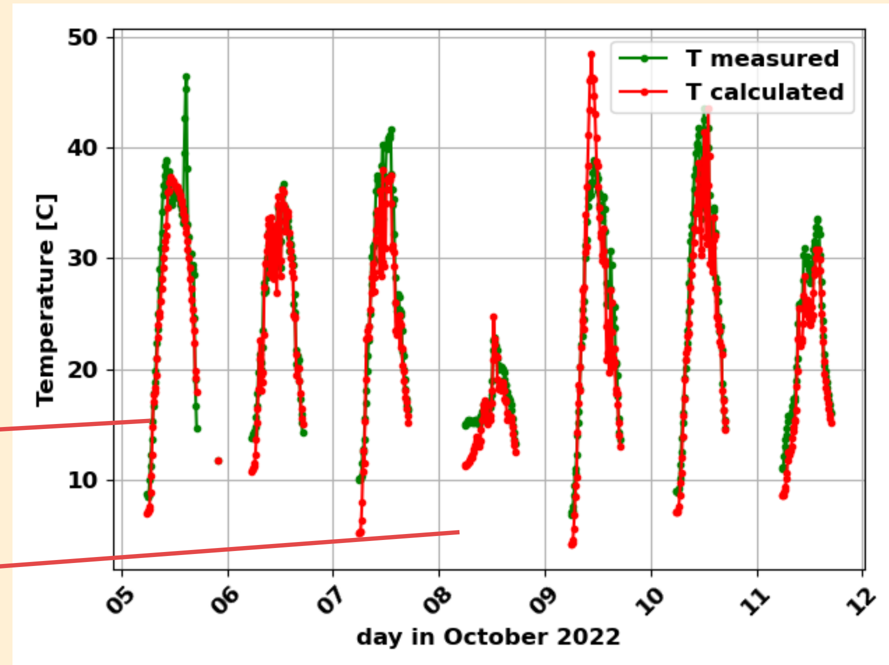
Selected environmental conditions



Model validation with site-measured data





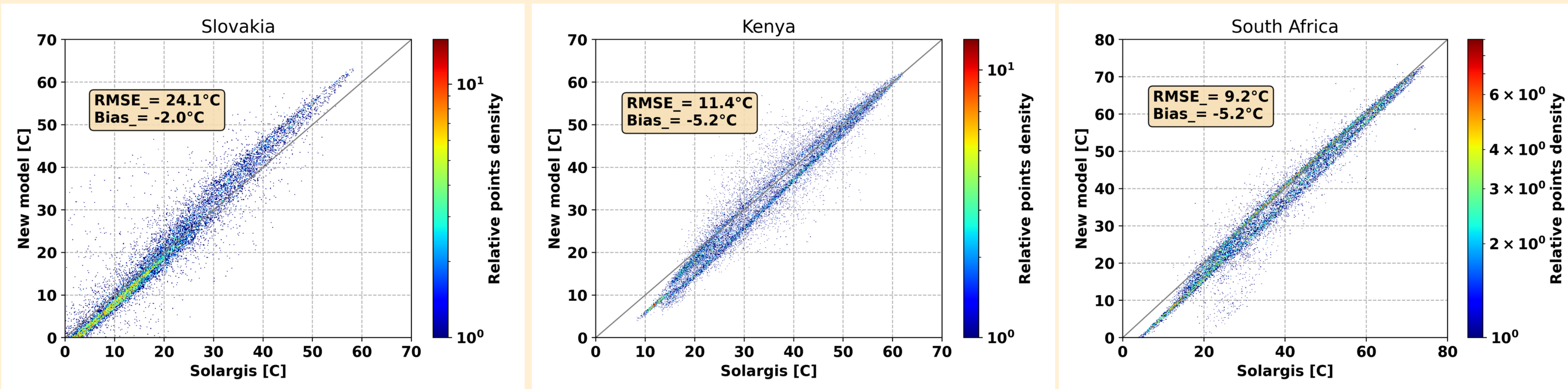


Comparison with Solargis temperature model

Country	Lat., Lon. [°]	Panel tilt [°]	Climate
Slovakia	49.258, 19.968	39	Continental, No dry season, Warm summer
Kenya	0.000, 37.210	4	Temperate, Dry and Warm summer
South Africa	-33.095, 19.038	29	Temperate, Dry and Warm summer

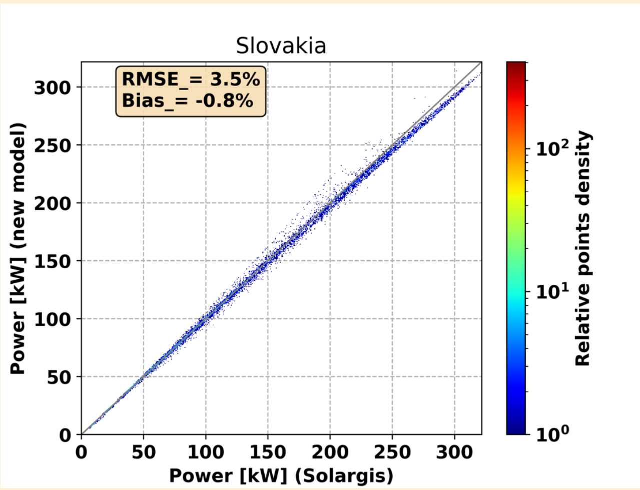
- Solargis time series 15-min resolution, year 2022
- Monofacial, ground mounted, fixed-tilt installation, OPTA calculated using Solargis tools
- Installed power = 300 kW
- Relative row spacing 2.5 m
- Modified NOCT temperature model is used as standard in Solargis calculation

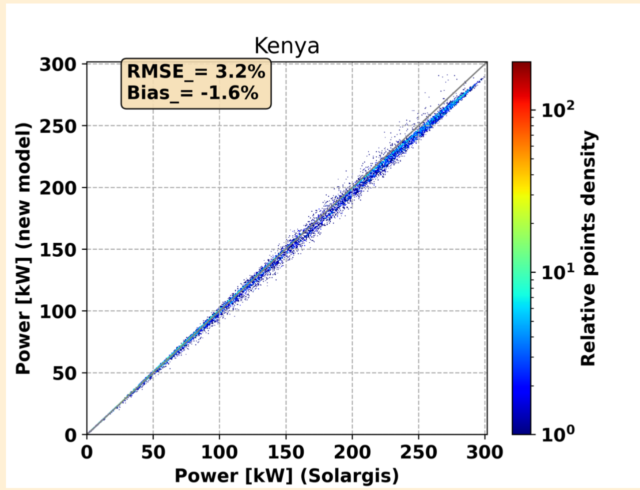
Comparison with Solargis temperature model

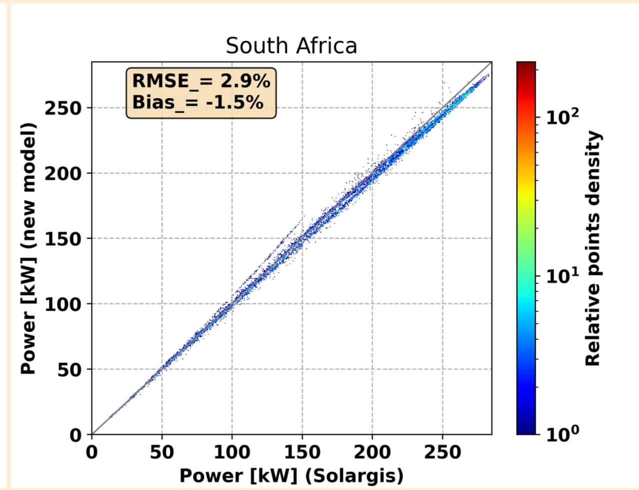


Country	RMSE [°C]	Bias [°C]
Slovakia	24.1	-2.0
Kenya	11.4	-5.2
South Africa	9.2	-5.2

Comparison with Solargis PV simulation







Country	RMSE [%]	Bias [%]
Slovakia	3.5	-0.8
Kenya	3.2	-1.6
South Africa	3.5	-0.8

Conclusions and further work

- New approach to the modeling of panel temperature was introduced
- The first but not the last step has been done
- Preliminary results with promising model accuracy

- Suggested solutions for open issues (radiation, model speed up,...)
- Besides site measurements, the FEM, FVM software is going to be involved as verification tool