Deep learning photovoltaic temperature model

Comparison analysis between PV temperature digital twins of two PV measurement set-ups

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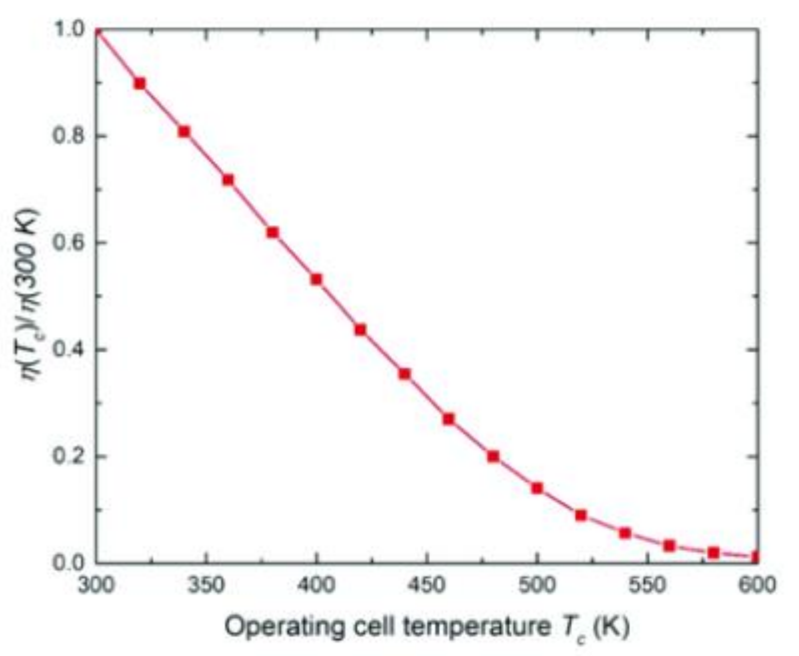
Background

$$P = \frac{G}{G_{STC}} * P_{STC} * (1 + \underbrace{\gamma * (T_{PV} - 25)} - \underbrace{L_{REST}})$$

Temperature losses

Rest losses
- Degradation
- Soiling
- Etc.

- Thermal losses reduces the yield and performance
- As the PV temperature goes up, solar cell conversion efficiency goes down



[1] 27.5 to 327.5°C

[1] Blandre, Etienne & Vaillon, Rodolphe & Drevillon, Jérémie. (2019). New insights into the thermal behavior and management of thermophotovoltaic systems. Optics Express. 27. 10.1364/OE.27.036340.

PV measurement set-ups

Ghent campus rooftop, KU Leuven, Belgium [1]

Tilt: 18°
Orientation:180° (due S)
Free back c-Si
Data period: 2021
Resolution: 1min (from 1 sec)
Sensors: T_{amb} (4-wire RTD), G_{POA} (CMP11), T_{CELL} (4-wire RTD), WS (ultrasonic anemometer)

NIST rooftop, Maryland, USA [2]

Tilt: 10°
Orientation:180° (due S)
Wind deflectors c-Si
Data period: 2017
Resolution: 1min (from 10 sec)
Sensors: T_{amb} (4-wire RTD), G_{POA} (CMP11), T_{BS} (4-wire RTD), WS (Vaisala WMT52 ultrasonic anemometer)

[1] Herteleer, B.: Outdoor thermal and electrical characterisation of photovoltaic modules and systems. PhD thesis (2016)

[2] Boyd, Matthew. (2015). High-Speed Monitoring of Multiple Grid-Connected Photovoltaic Array Configurations. 10.6028/NIST.TN.1896.

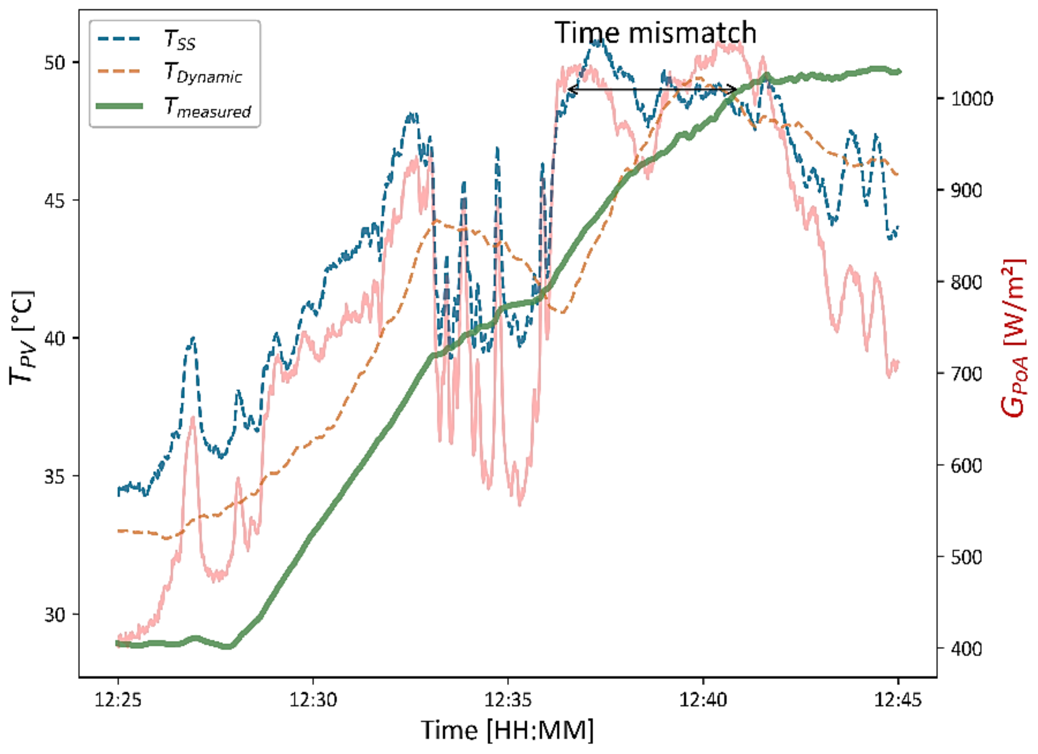
Accurate estimation of PV temperature

Statistical correlation between inputs (weather) and outputs (measured temperature)

The method selected is artificial neutral networks

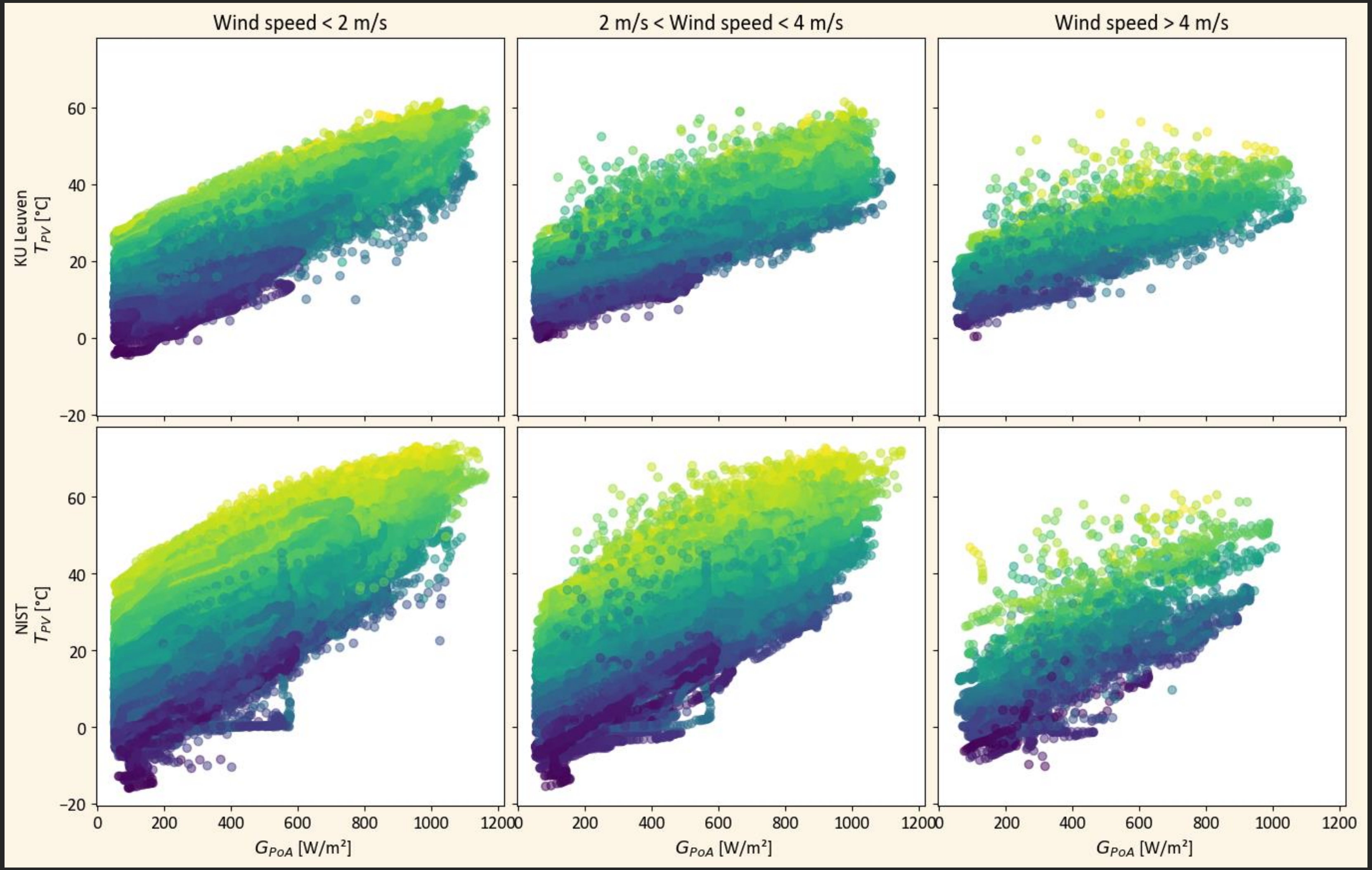
Digital object will be developed able to react as the physical based on the given inputs (digital twin)

Model development



- Steady state models neglect the thermal capacity of the PV
- Prior sequences should be considered
- The thermal time constant is approximated around 300s so the **prior 5 minutes will be included**

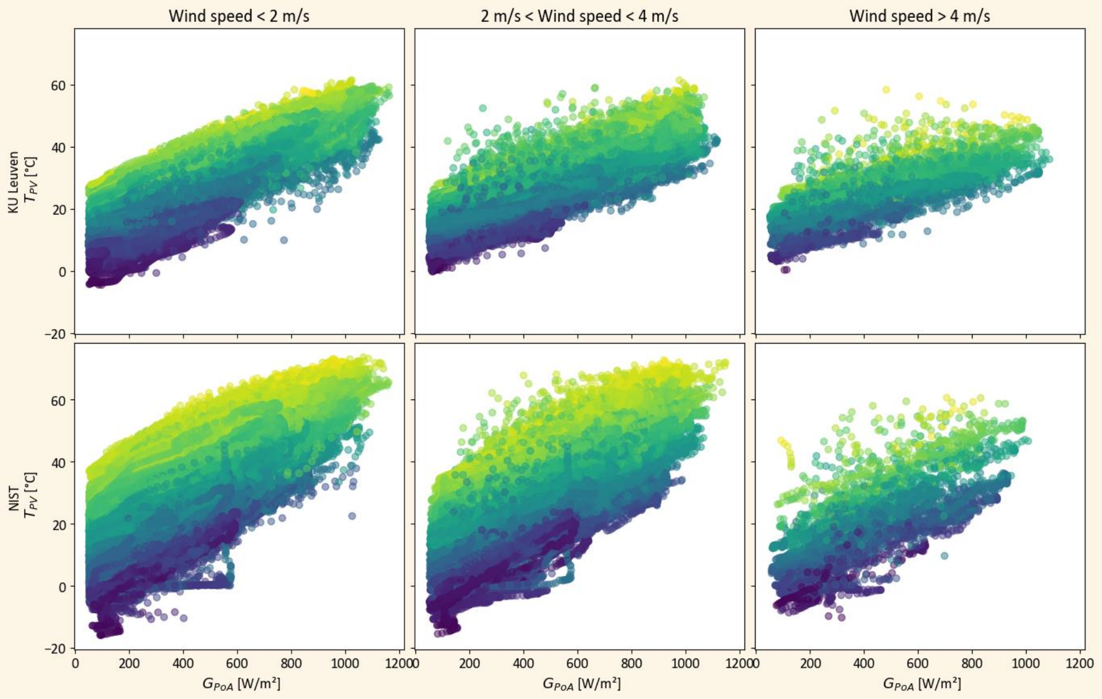
Model development



KUL appears more clear relationship with irradiance, ambient temperature and wind speed than NIST

Model development

All seasons



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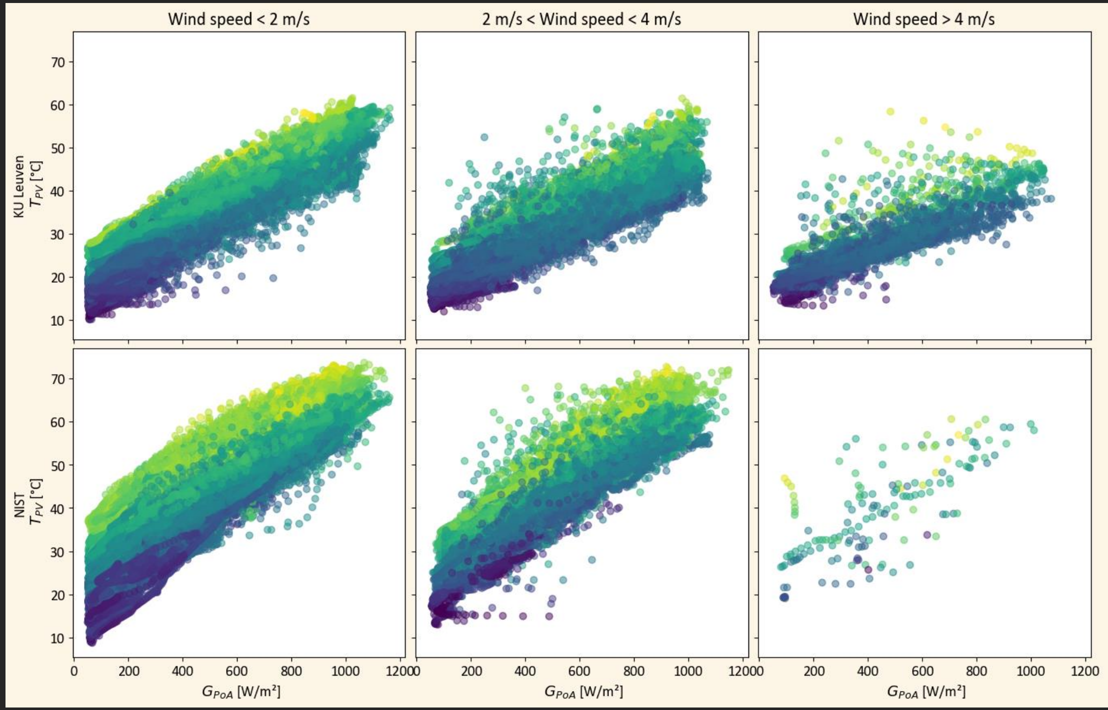
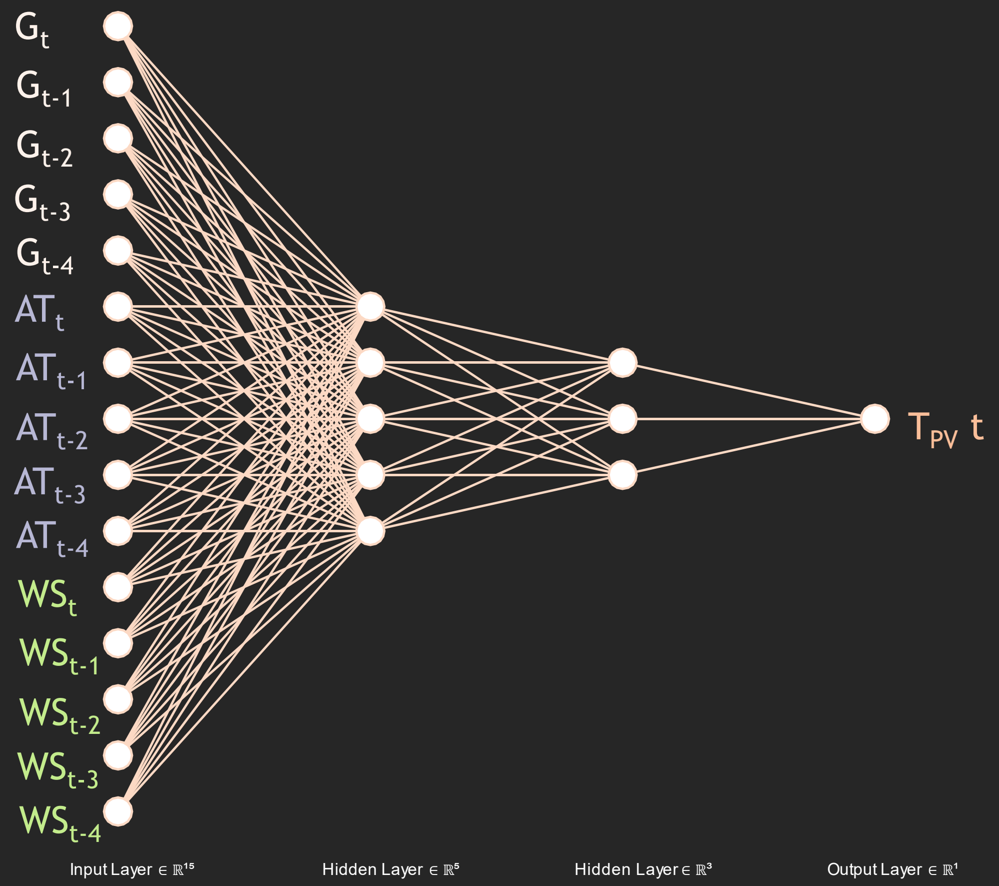
Summer



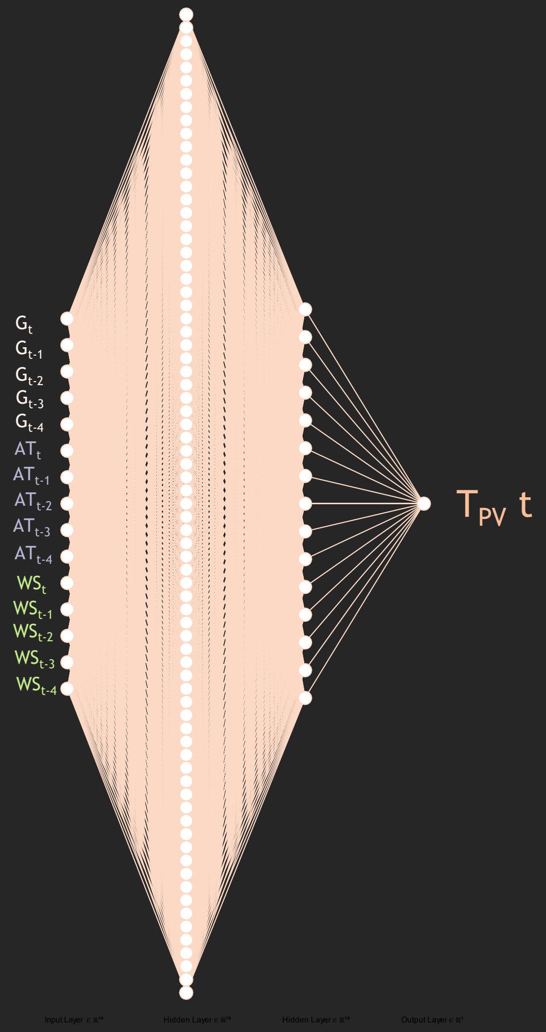
Both sites present a more clear trend

Model development

KUL

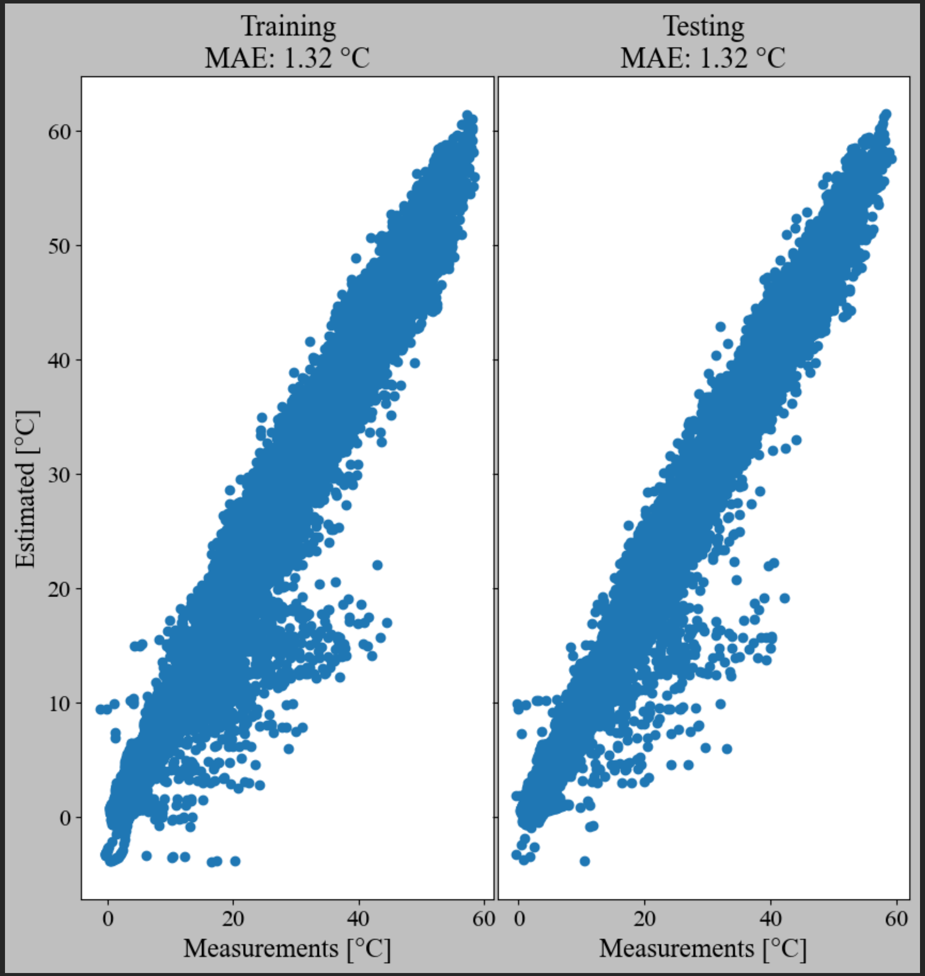


NIST

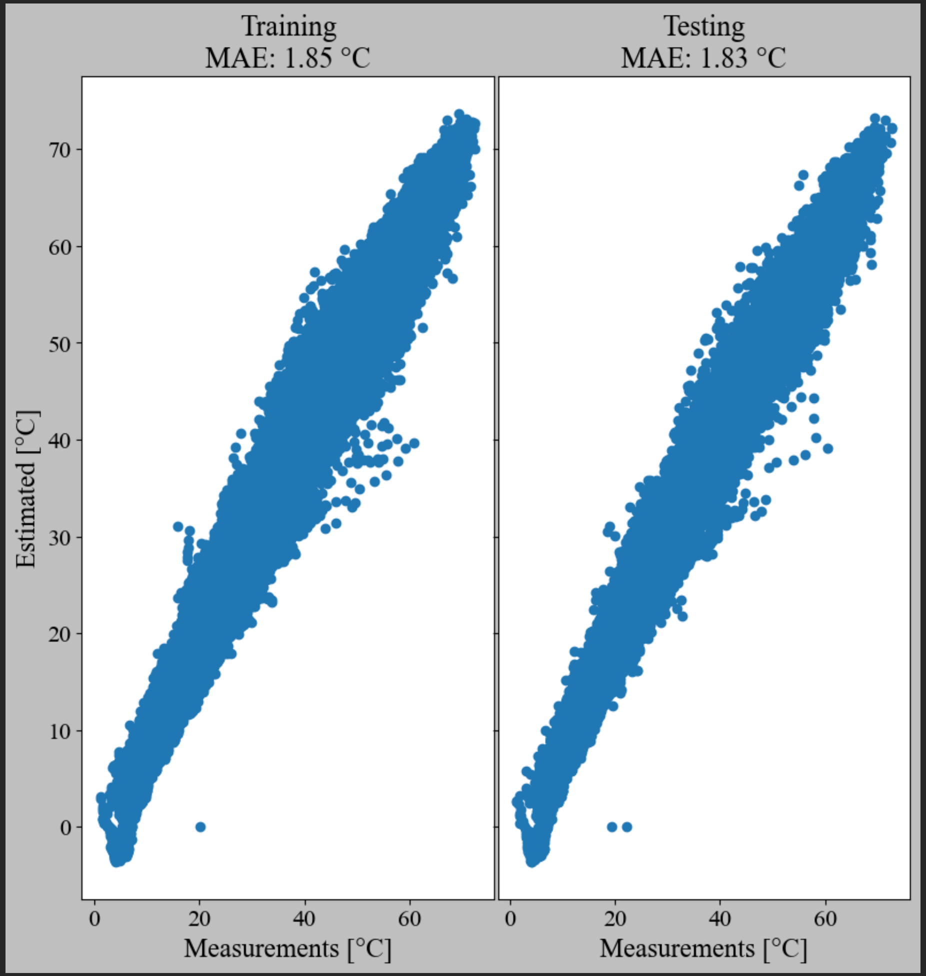


Model development

KUL



NIST



The models will be evaluated in comparison with other state-of-the-art PV models

Skoplaki [1]

$$T_{PV} = T_{amb} + \frac{0.32 * G_{PoA}}{\left(8.91 + 2 * (\frac{WS}{0.67}\right)}$$

Mattei [2]

$$T_{PV} = \frac{(20.9 + 3.32 * WS) * T_{amb} + G_{PoA} * 0.59}{(20.9 + 3.32 * WS) - 0.0005 * G_{PoA}}$$

Barry [3]

$$T_{PV}(t_{n-k}) = \frac{1}{C'} * \sum_{K=0}^{N} \exp\left(-k * \frac{\Delta T}{\tau}\right) * \left[T_{amb}(t_{n-k}) + \frac{G_{PoA}(t_{n-k})}{u_1 + u_2 * WS(t_{n-k})} + u_3 \Delta T_{s,a}(t_{n-k})\right]$$

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[1] E. Skoplaki, A. G. Boudouvis, and J. A. Palyvos, “A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting,” *Solar Energy Materials and Solar Cells*, vol. 92, no. 11, pp. 1393–1402, Nov. 2008, doi: 10.1016/j.solmat.2008.05.016.

[2] M. Mattei, G. Notton, C. Cristofari, M. Muselli, and P. Poggi, “Calculation of the polycrystalline PV module temperature using a simple method of energy balance,” *Renewable Energy*, vol. 31, no. 4, pp. 553–567, Apr. 2006, doi: 10.1016/j.renene.2005.03.010.

[3] J. Barry *et al.*, “Dynamic model of photovoltaic module temperature as a function of atmospheric conditions,” *Advances in Science and Research*, vol. 17, pp. 165–173, Jul. 2020, doi: 10.5194/asr-17-165-2020.

ALL SEASONS

BEST

WORST

	MAE		RMSE	
	KUL	NIST	KUL	NIST
NIST model	2.33	3.01	3.32	4.4
KUL model	1.22	3.67	1.61	4.69
Mattei	1.69	*4.08*	2.27	5.3
Skoplaki	1.74	4.05	2.36	5.29
Barry	1.73	3.09	2.45	4.05

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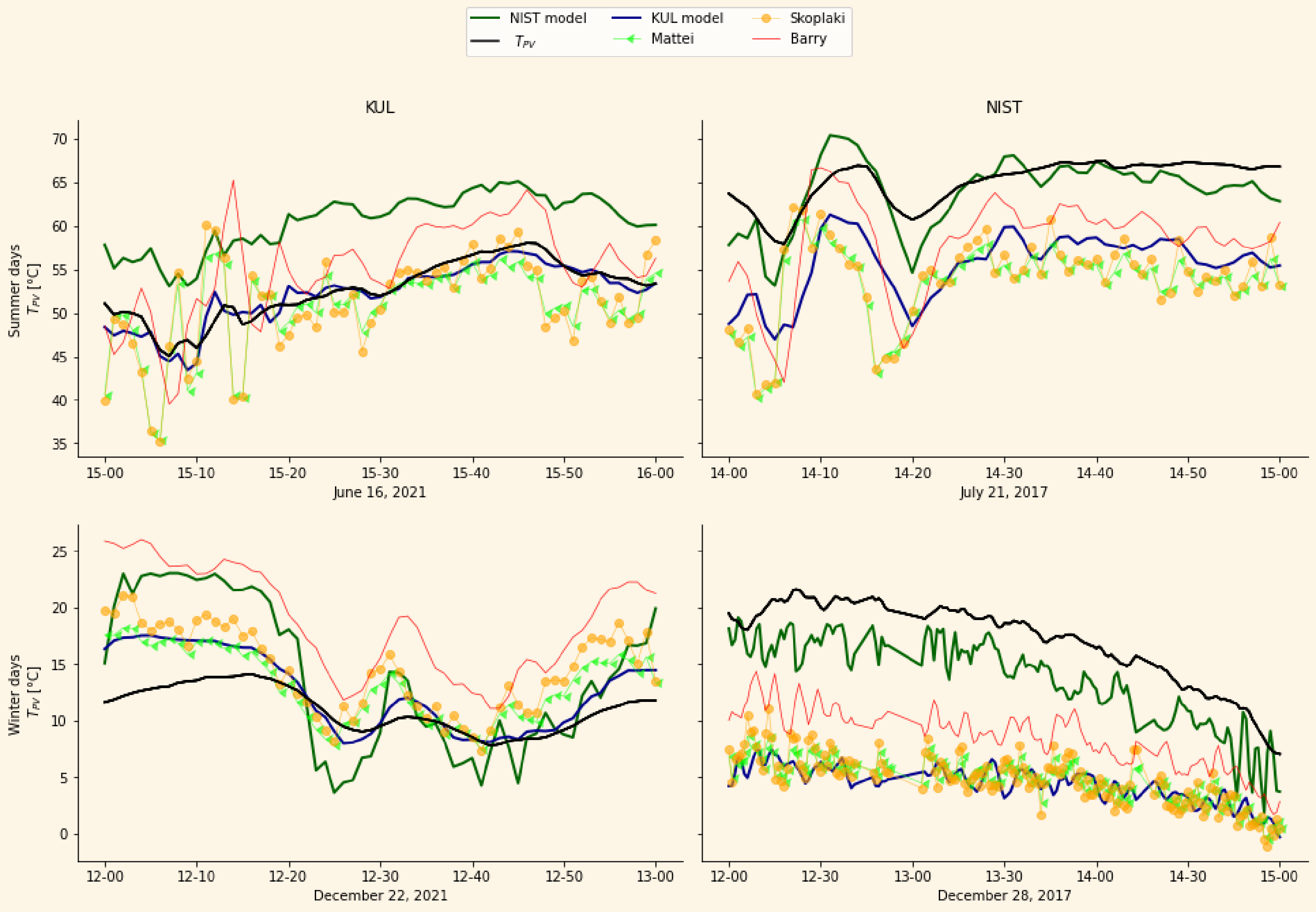
SUMMER

	MAE		RMSE	
	KUL	NIST	KUL	NIST
NIST model	*2.45*	1.83	*3.55*	2.36
KUL model	1.29	3.88	1.68	4.89
Mattei	1.86	*4.69*	2.48	*6.05*
Skoplaki	1.93	4.62	2.61	6.02
Barry	1.72	3.08	2.5	4.06

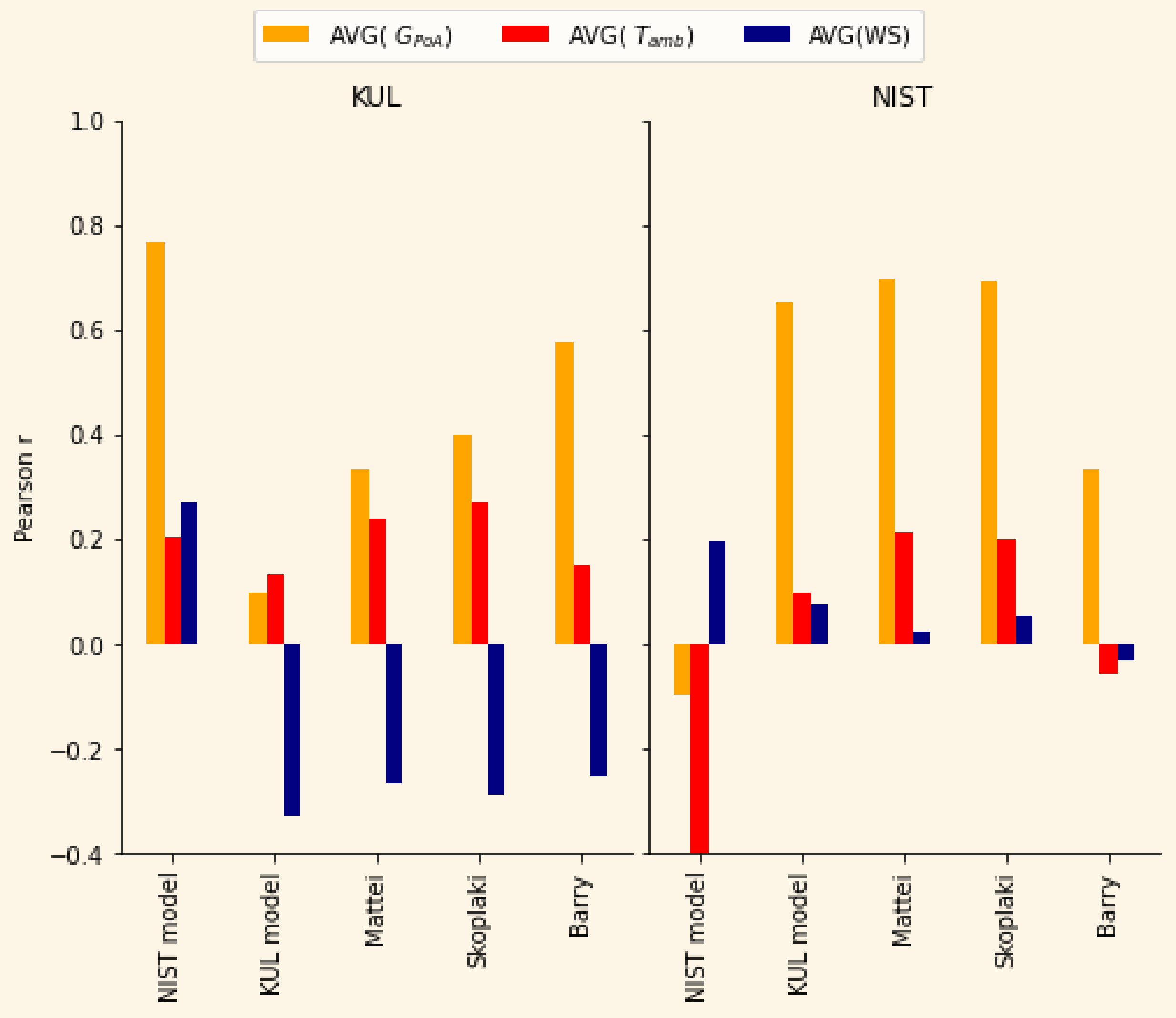
Steady state models perform weaker during summer
Dynamic model accuracy does not changes drastically
DL models perform better on their sites on summer while weaker on each others

The models will be evaluated in comparison with other state-of-the-art PV models

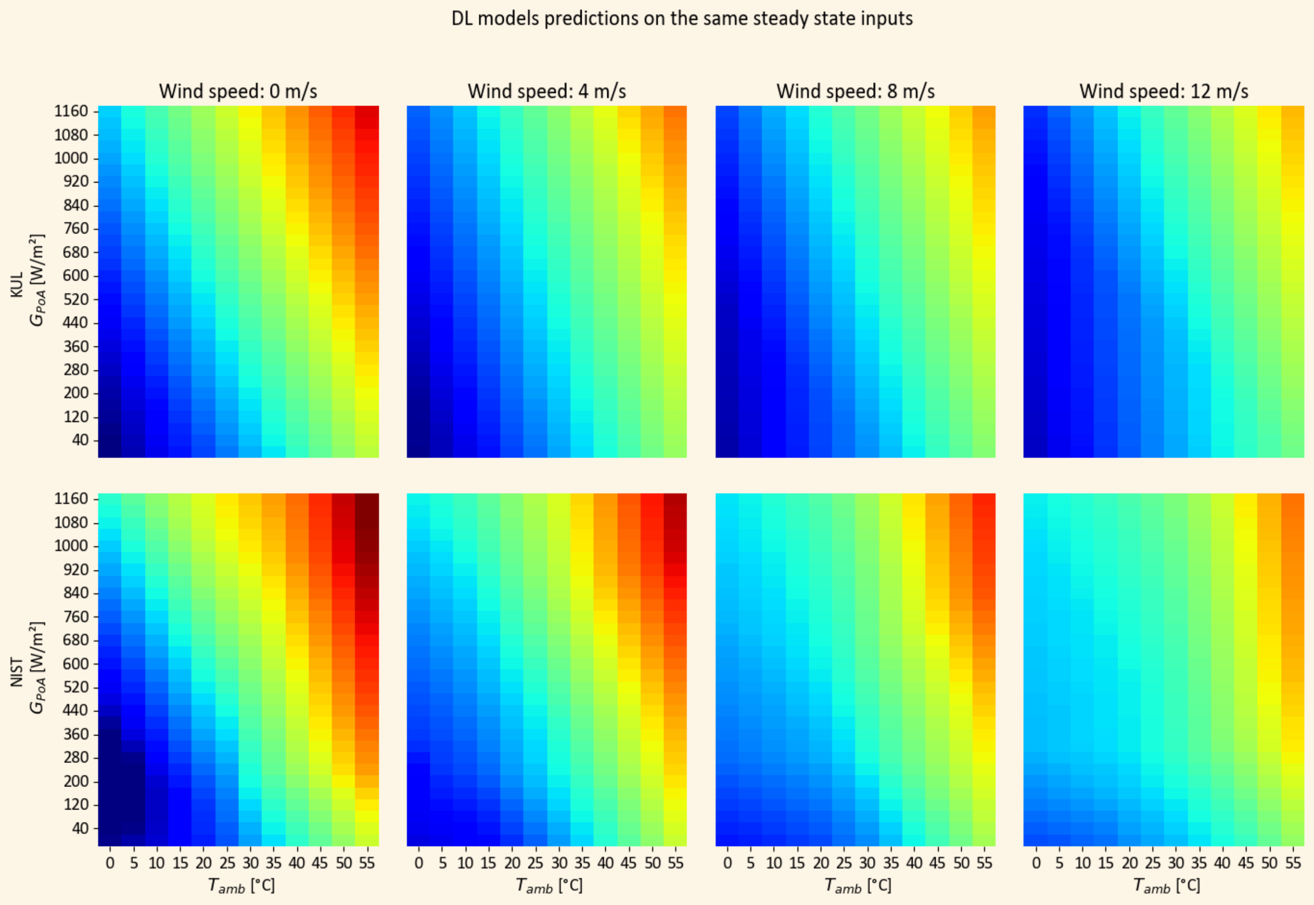


- DL models perform better on their site both in steady and transient conditions
- Barry model (dynamic), the steady state models regarding the response on transient conditions
- With proper calibration, all of the state-of-the-art models can improve their estimations

The models will be evaluated in comparison with other state-of-the-art PV models



- The convection is more intense during high irradiance
  - The primary determining factor for T_{pv} is the irradiance
  - Convection is proportional to over-temperature $H=H_L*A*(T_{PV}-T_{amb})$
  - Over temperature is proportional to the irradiance
- The accurate calculation is challenging because it should include
  - Installation characteristics
  - Surrounding objects
  - Wind direction and turbulence
- Therefore irradiance has the highest correlation with the error of each model
- NIST models applied on NIST site have the **lowest correlation with irradiance**
  - This could be arise from the lower tilt angle, and therefore less influence from the wind



- KUL model give cooler cell temperatures than NIST
- NIST PV warm up easier than KUL

Reasoning behind the different temperatures of the panels under the same inputs

- Installation characteristics
  - NIST have lower tilt (Possible explanation about the smaller correlation with the wind)
  - NIST module have a metal frame installed of the backsheet (can accumulate heat below)
- Sensor location
  - KUL sensors are attached against the sensors, while NIST on PVs backsheet
- Sensor uncertainty or offsets
- PV special characteristics
  - Hot spots, efficiency etc.

It would beneficial for the models to get calibrated for each different site

KU LEUVEN

GENT