Experimental Heat Transfer Characterization of Outdoor PV Modules

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Lyon 1

Thermal Challenges in PV

Why heat exchanges are important for PV plants ?

Predicting energy production is crucial for energy market

Need to balance electricity production on a daily basis ➔ Intraday or day-ahead trading

Precise forecasting of electricity production is a matter of competitiveness

➔ **Efficiency is temperature – dependent (cristalline silicon)**

Power temperature coefficient: $\frac{dP}{P} = \frac{d\eta}{\eta} \sim -\beta(T_{cell} - T_{STC})$

For cristaline silicon: $\beta \simeq -0.004\ K^{-1}$

$$T_{cell} = T_{STC} + 25°C \implies \frac{dP}{P} \simeq -10\%$$

➔ **PV module ageing** :

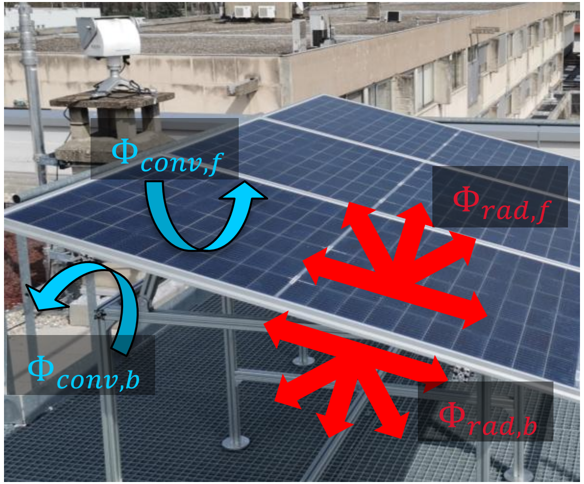
+1°C causes 3-5-years drop in modules lifetime(*)

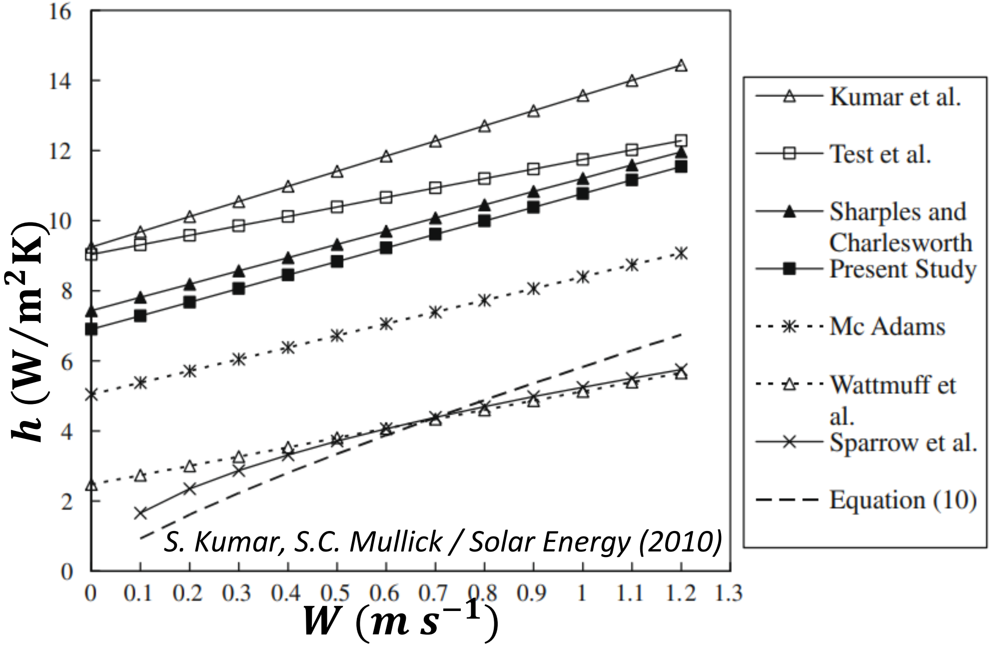
(*) *Xia, Z., Wohlgemuth, J. H. & Cunningham, D. W. IEEE Photovolt. Spec. Conf. (2009)*

Thermal Challenges in PV

Heat exchange on PV module

$$h_{global} = h_{conv} + h_{rad}$$





S. Kumar, S.C. Mullick / Solar Energy (2010)

Forced convection:

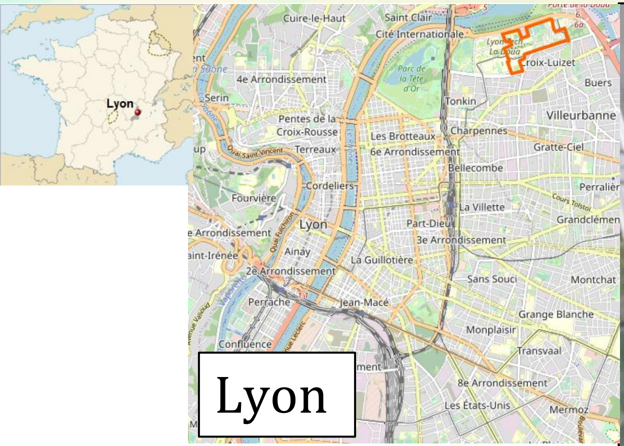
➔ $Nu = aRe^b \underset{Re \to Re_0}{\cong} Nu(Re_0) + abRe_0^{b-1}(Re - Re_0)$

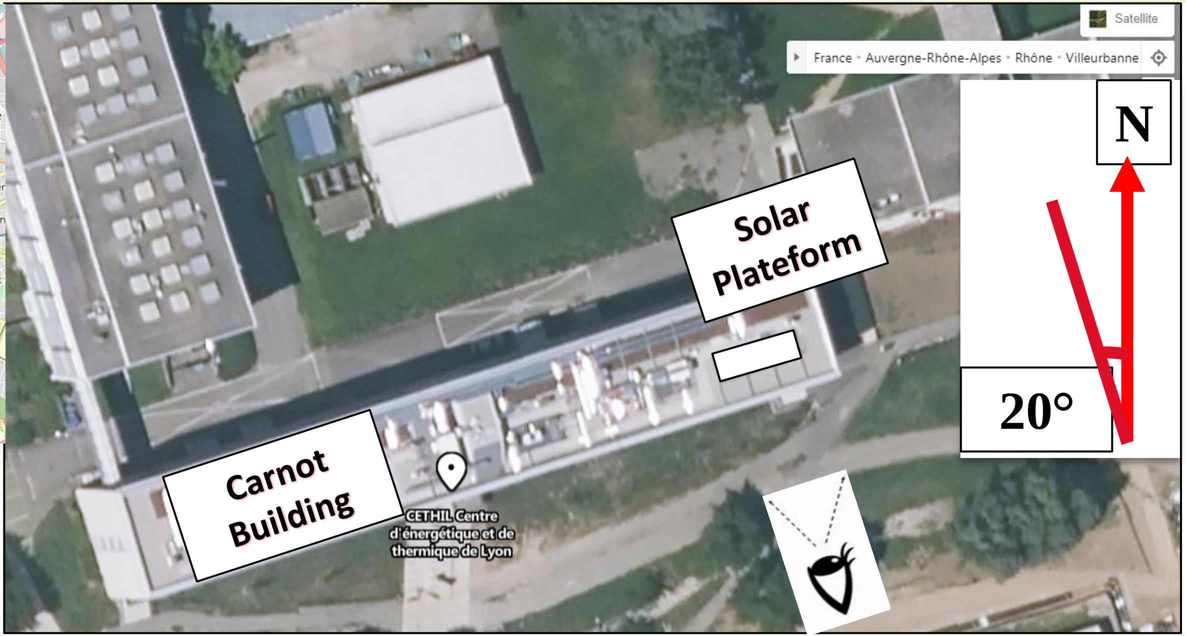
➔ $h = h_c + h_v W$

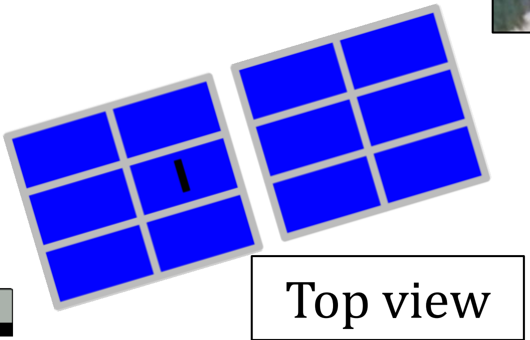
Convective heat transfer coefficient:

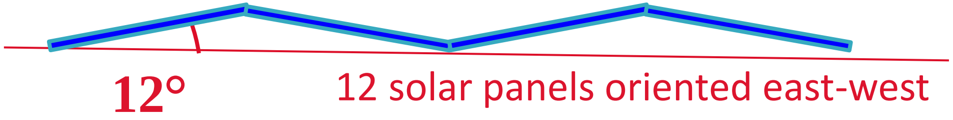
- **Measurement ?**
- **Modelling ?**

Solar Platform at CETHIL



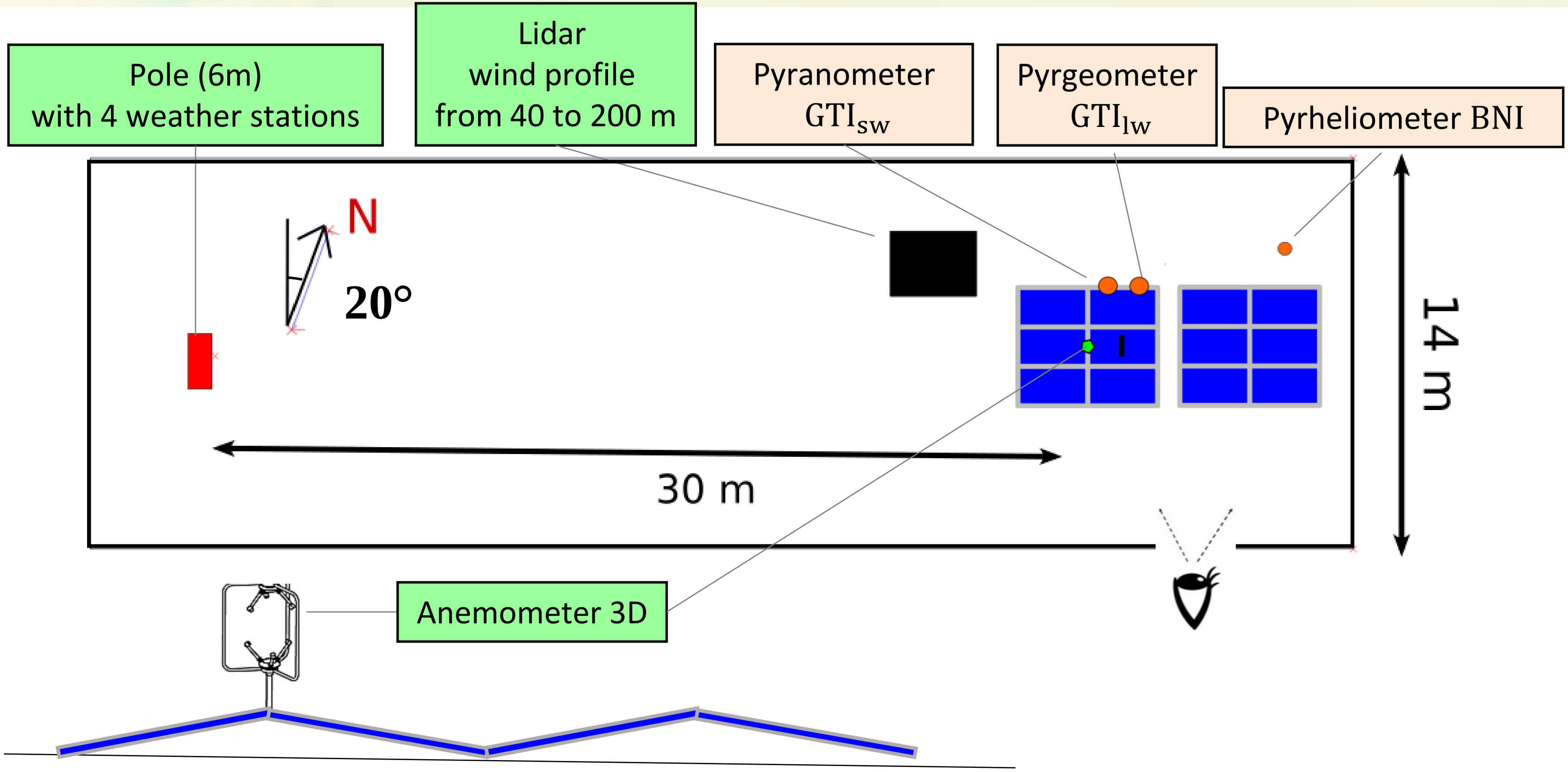






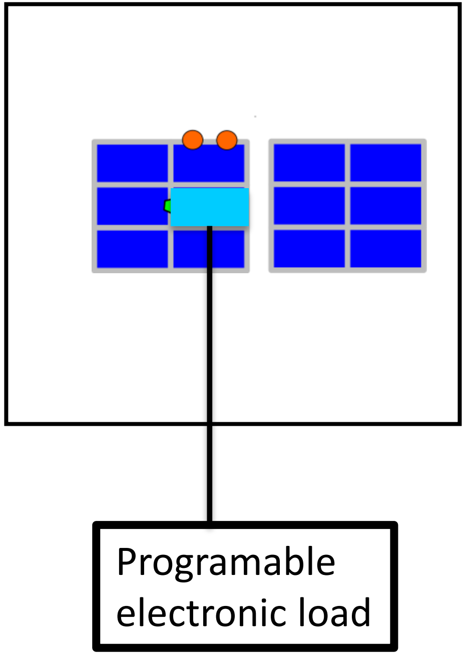
12 solar panels oriented east-west

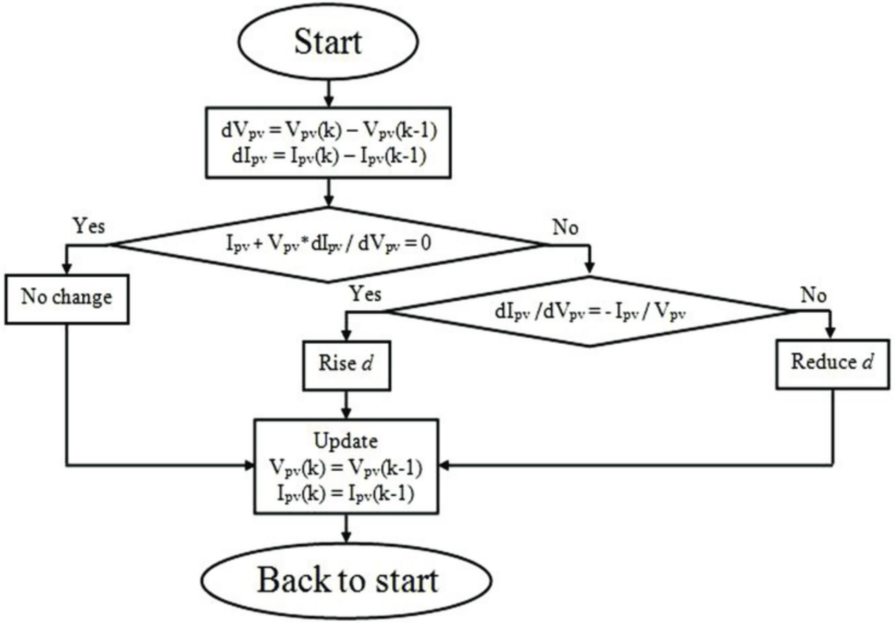
Solar Platform at CETHIL



Solar Platform at CETHIL

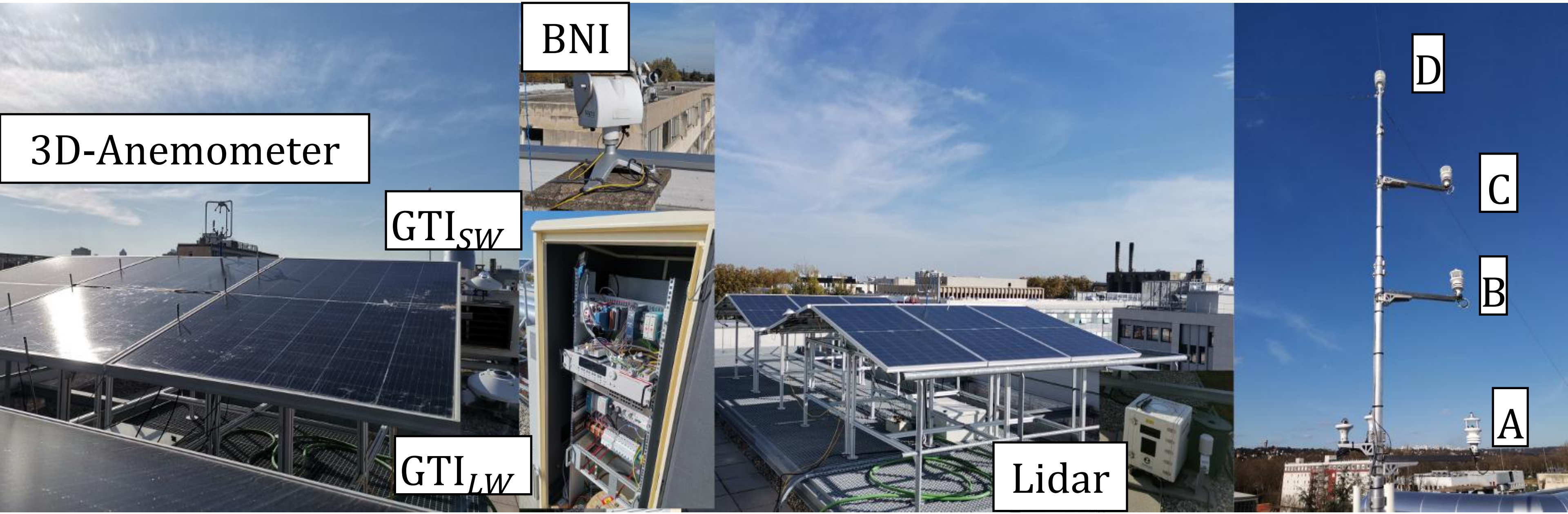
Electrical power: 1 panel at maximum power point





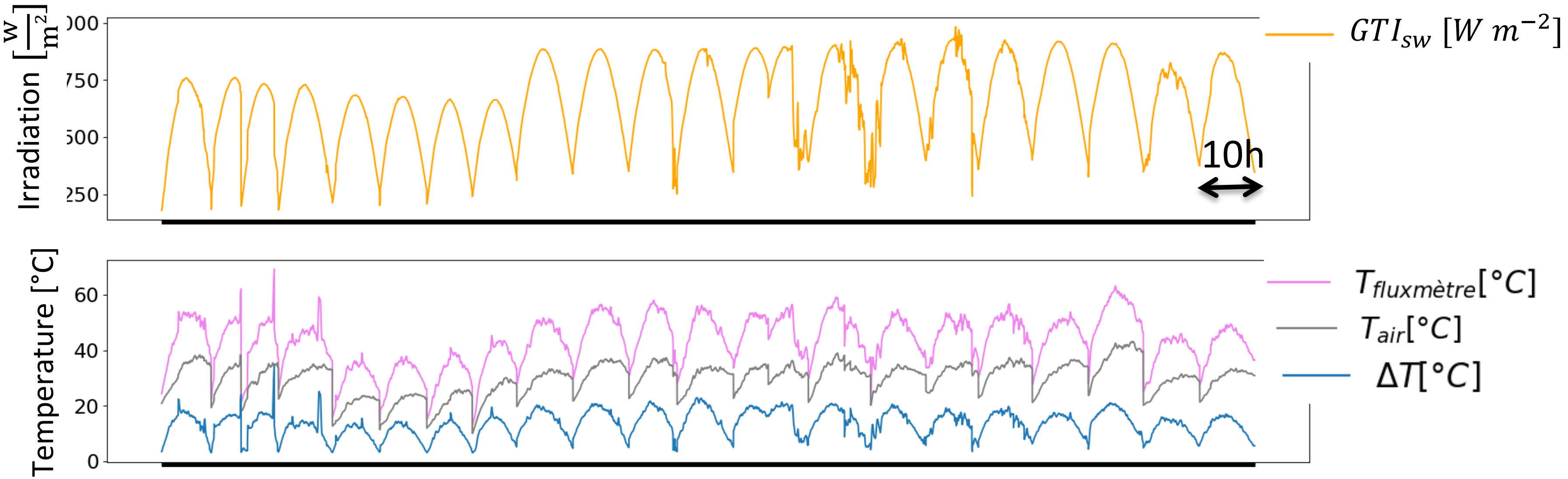
Incremental conductance algorithm

Solar Platform at CETHIL



Convective Heat Transfer - Dataset

Dataset: 10h/d x 22d = 220h ; 10min-rolling-average ; $f=1min^{-1}$

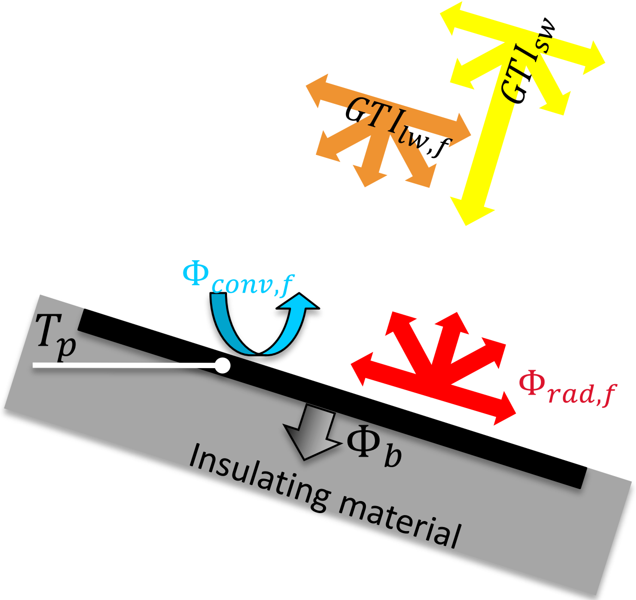


Convective Heat Transfer – Reference Measurement

Heat balance of an instrumented plate

$$m_p C_p \frac{dT_p}{dt} = \alpha_{sw} GTI_{sw} S_p - \varepsilon_{lw,f}(\sigma T_m^4 - GTI_{lw}) S_p - h_f (T_m - T_{air}) S_p - \Phi_b$$

$$h_f = \frac{1}{(T_m - T_{air}) S}\left[\alpha_{sw} GTI_{sw} S_p - \varepsilon_{lw,f}(\sigma T_m^4 - GTI_{lw}) S_p - \Phi_p - m_p C_p \frac{dT_p}{dt}\right]$$



Hypothesis

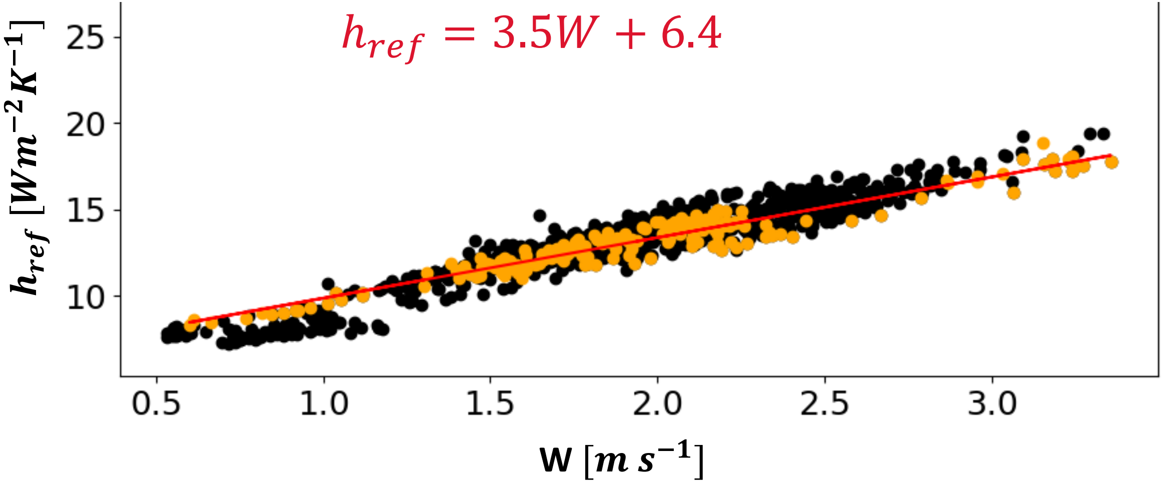
- View factor $F_{p \to sky} = 1$
- h_f independent on temperature

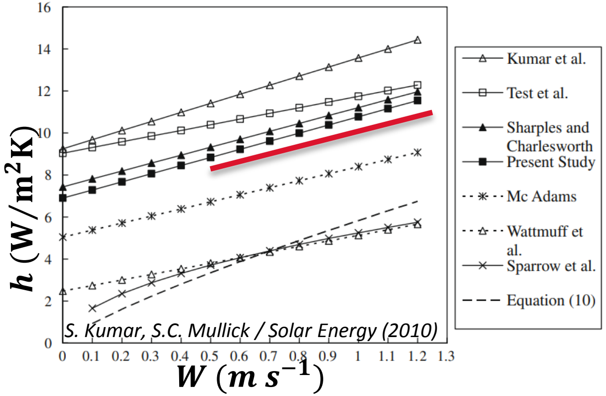
Measurements

- T_p, T_{air}: thermocouples
- $\alpha_{sw}, \varepsilon_{lw,f}$: spectrometer measurements
- GTI_{sw}: pyranometer
- GTI_{lw}: pyrgeometer or empirical law for T_{sky}
- Φ_p: heat flux meter or neglected
- $m_p C_p \frac{dT_p}{dt}$: may be neglected for thin film

Warning: plate can heat up to 90°C !!

Convective Heat Transfer – Reference Measurement



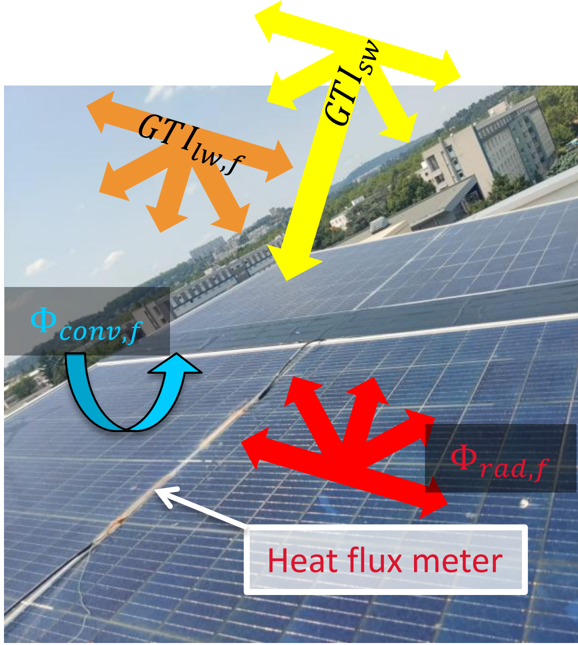


How to measure h_f on a PV panel in operation ?

Convective Heat Transfer – Direct Measurement

Heat flux sensor

- Custom-made sensor to avoir shading effect
- Sensitivity: $6\ \mu V\ /(Wm^{-2})$



$$\Phi_{meas} = \Phi_{conv} + \Phi_{net\_rad}$$

$$\Phi_{\text{net\_rad}} = [\cancel{\Phi_{emi}} - \Phi_{abs}]_{sw} + [\Phi_{emi} - \Phi_{abs}]_{lw}$$

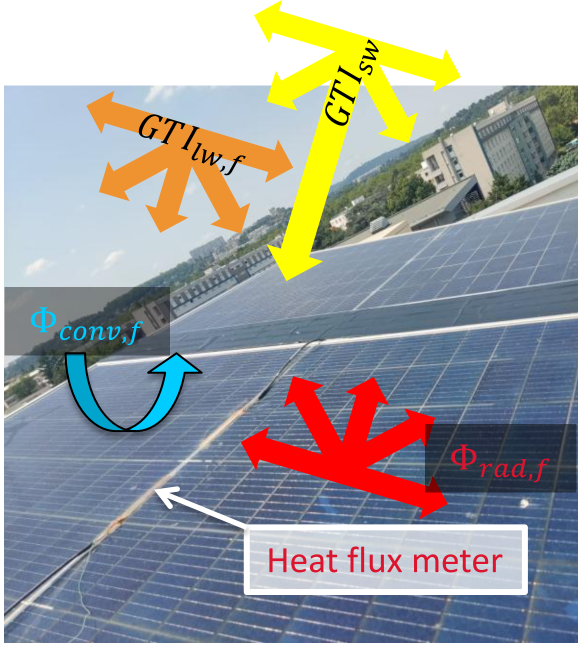
$$\Phi_{meas} = \underbrace{h_f(T_{fl} - T_{air})}_{conv} - \underbrace{\alpha_{fl,sw} GTI_{sw}}_{net\_rad_{sw}} + \underbrace{\alpha_{fl,lw}(\sigma T_{fl}^4 - GTI_{lw})}_{net\_rad_{lw}}$$

T_{fl}: temperature of the heat flux meter

$\alpha_{fl,sw}$; $\alpha_{fl,lw}$: absorptivity of the heat flux meter in the short and long wavelength ranges

Convective Heat Transfer – Direct Measurement

$$\Phi_{meas} = \underbrace{h_f\left(T_{fl} - T_{air}\right)}_{conv} - \underbrace{\alpha_{sw} GTI_{sw}}_{net\_rad_{sw}} + \underbrace{\alpha_{lw}\left(\sigma T_{fl}^4 - GTI_{lw}\right)}_{net\_rad_{lw}}$$



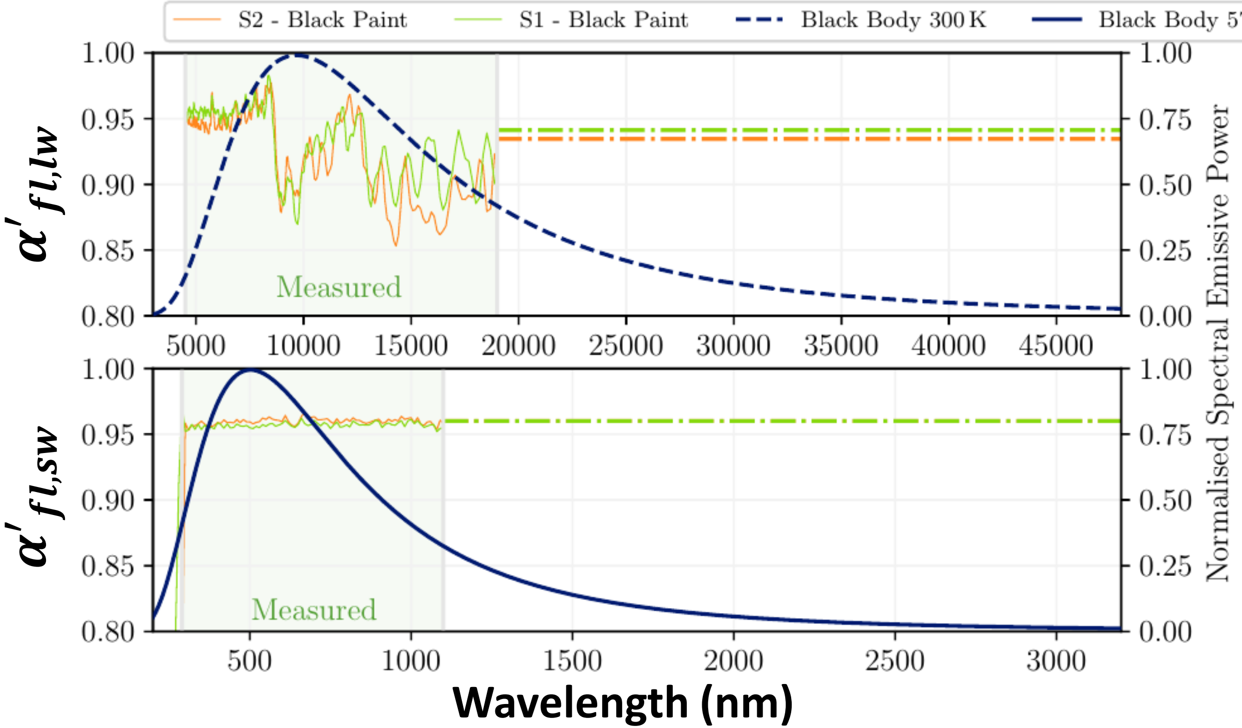
Measurements:

- Φ_{meas}
- T_{fl}, ; T_{air}
- $\alpha_{fl,sw}$; $\alpha_{fl,lw}$ (black coating)
- GTI_{sw} ; GTI_{lw} or T_{sky}

$\rightarrow$ $\boxed{h_f}$

Convective Heat Transfer – Direct Measurement

Absorptivity of black painted heat flux meter measured by spectrometer



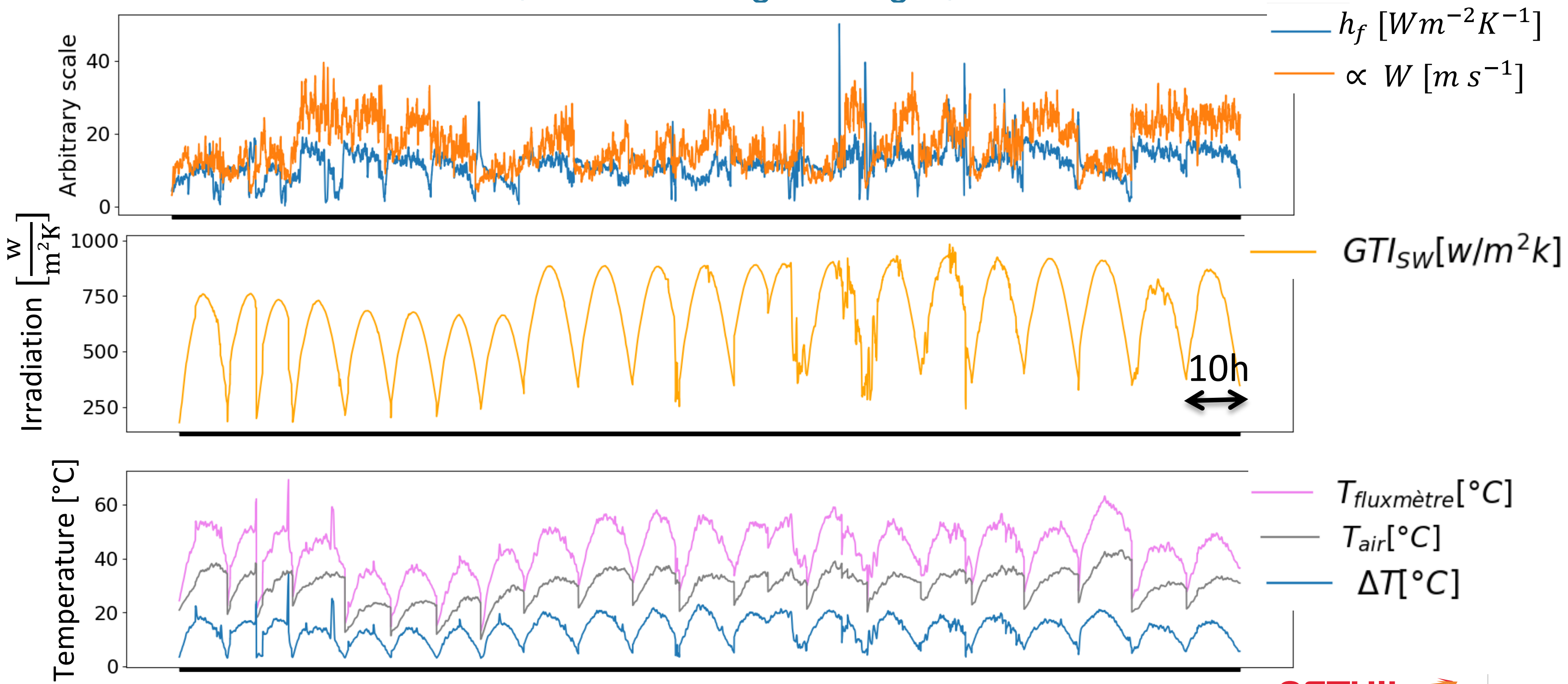
Black coating is assumed to be grey on the sw and lw bands

$$\alpha_{fl} = \frac{1}{\lambda_2 - \lambda_1}\int_{\lambda 1}^{\lambda 2} \alpha'_{fl}(\lambda)d\lambda$$

$$\boldsymbol{\alpha_{sw} = 0.9}$$
$$\boldsymbol{\alpha_{lw} = 0.95}$$

Convective Heat Transfer – Direct Measurement

Dataset: 10h/d x 22d = 220h ; 10min-rolling-average ; f=1min^{-1}



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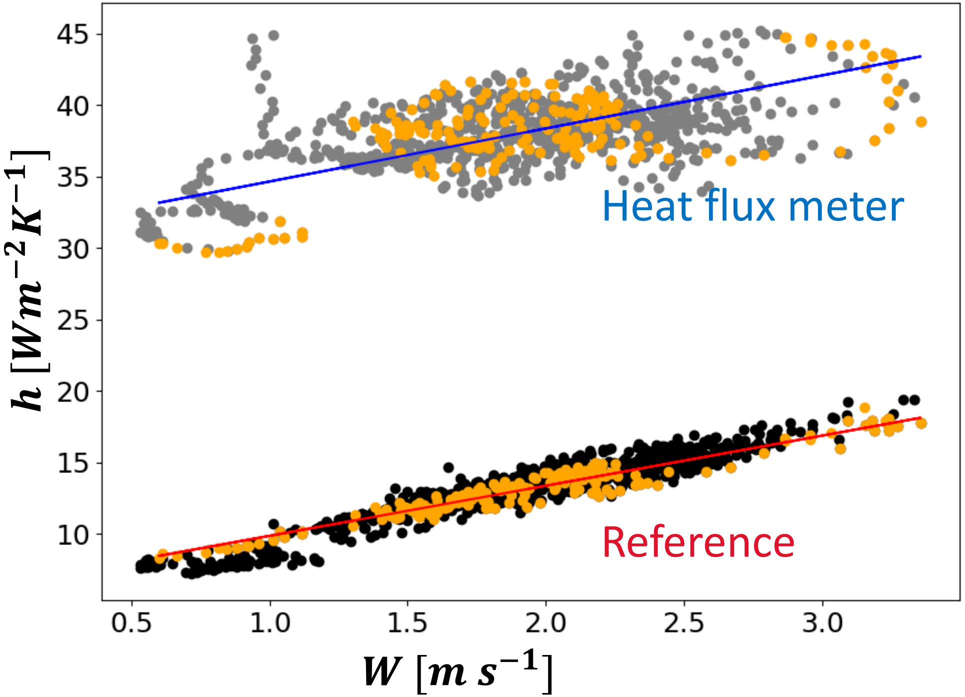
Convective Heat Transfer – Comparison with Reference



$h_f = 3.7W + 30.9$

?

$h_{ref} = 3.5W + 6.4$

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Convective Heat Transfer – Comparison with Reference

$$h_f\left(T_{fl} - T_{air}\right) = \Phi_{meas} + \alpha_{sw} GTI_{sw} - \alpha_{lw}\left(\sigma T_{fl}^4 - GTI_{lw}\right)$$

Visual inspection of the sensor 6 months after installation: sand soiling

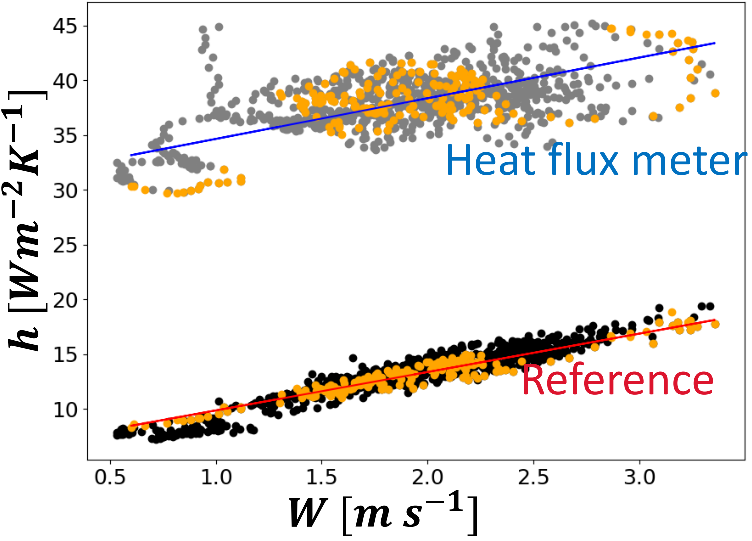
==> Hypothesis: uncertainty comes from a change in the absorptivity in the short wave range

$$\alpha_{sw\_true} = \alpha_{sw\_meas} + \delta\alpha_{sw}$$

$$\underbrace{h_f\left(\alpha_{sw\_true}\right)}_{corrected} = \underbrace{h_f\left(\alpha_{sw\_meas}\right)}_{measured} + \frac{\partial h_f}{\partial \alpha_{sw}} \delta\alpha_{sw} \qquad \text{with} \qquad \frac{\partial h_f}{\partial \alpha_{sw}} = \frac{GTI_{sw}}{T_{fl} - T_{air}}$$

$$\boxed{h_{f,corr} = h_{f,meas} + \frac{GTI_{sw}}{T_{fl} - T_{air}} \delta\alpha_{sw}}$$

Convective Heat Transfer – Comparison with Reference



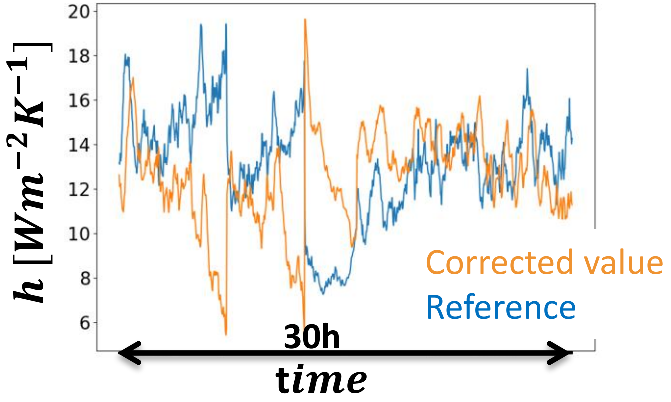
$h_f = 3.7W + 30.9$

$h_{ref} = 3.5W + 6.4$

Correction is consistent

$$h_{f,corr} = h_{f,meas} + \underbrace{\frac{GTI_{sw}}{T_{fl} - T_{air}}}_{\simeq U_{val}} \delta\alpha_{sw}$$

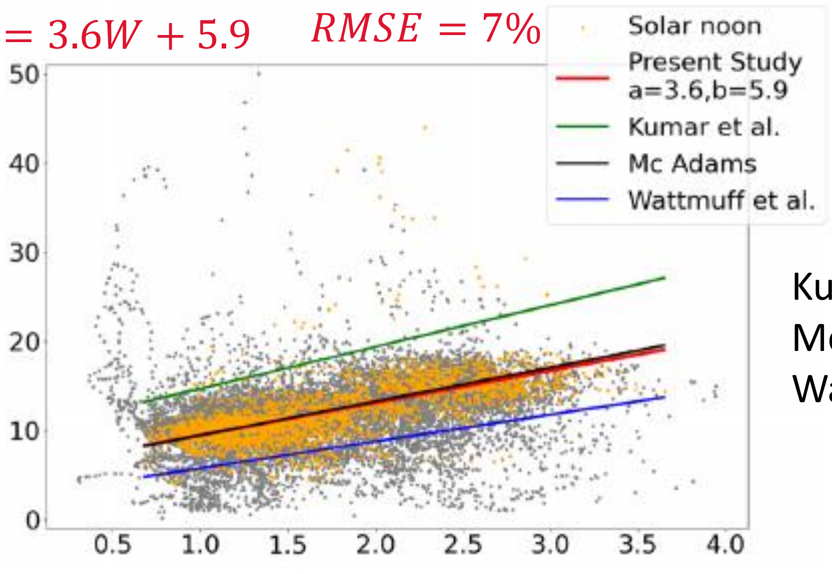
Best choice ➔ $\alpha_{sw,corr} = 0.45$



Convective Heat Transfer – Linear Regression at solar noon

$h_f = 3.6W + 5.9$ $RMSE = 7\%$

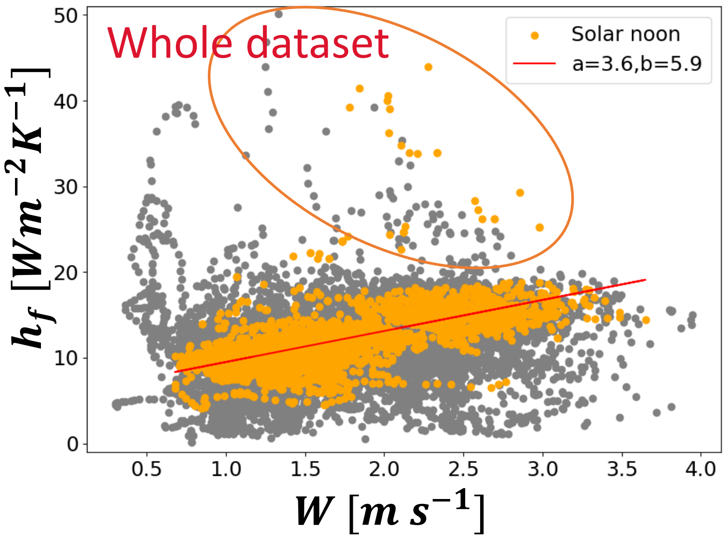
$h_f\ [Wm^{-2}K^{-1}]$

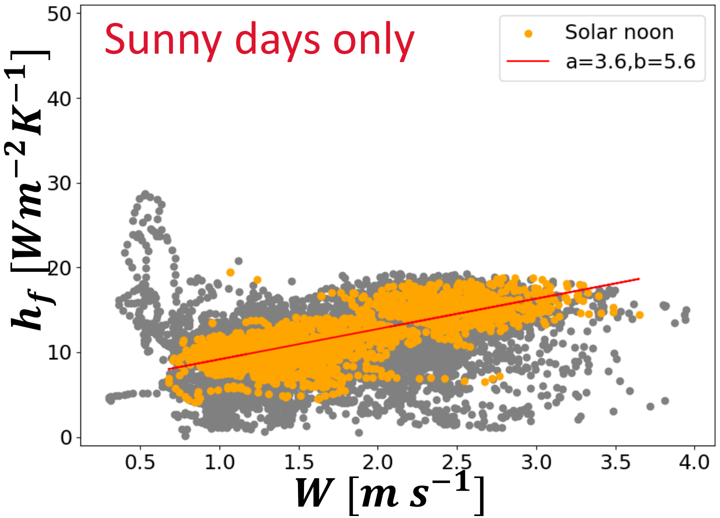


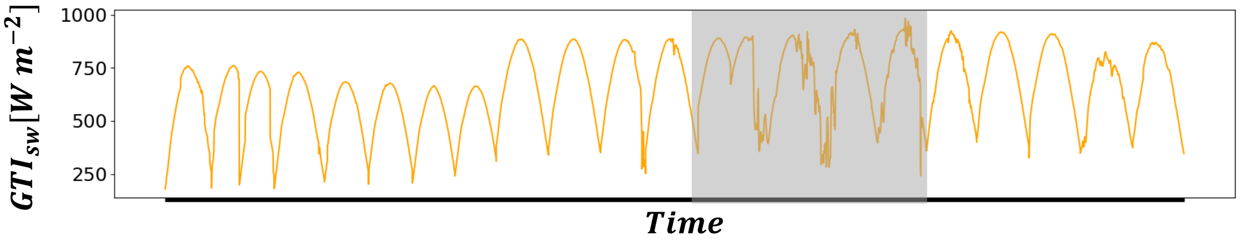
$W\ [m\ s^{-1}]$

Kumar et al. : indoor experiment
Mc Adams: Wind tunnel
Wattmuff et al. : Wind tunnel

Convective Heat Transfer – Outliers points

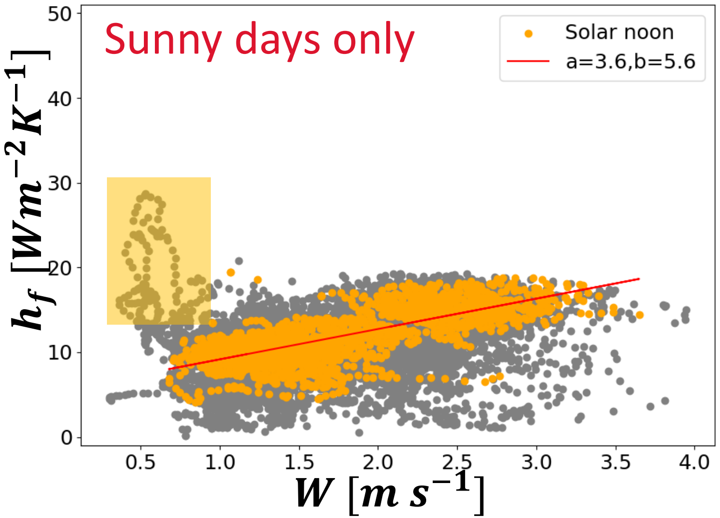


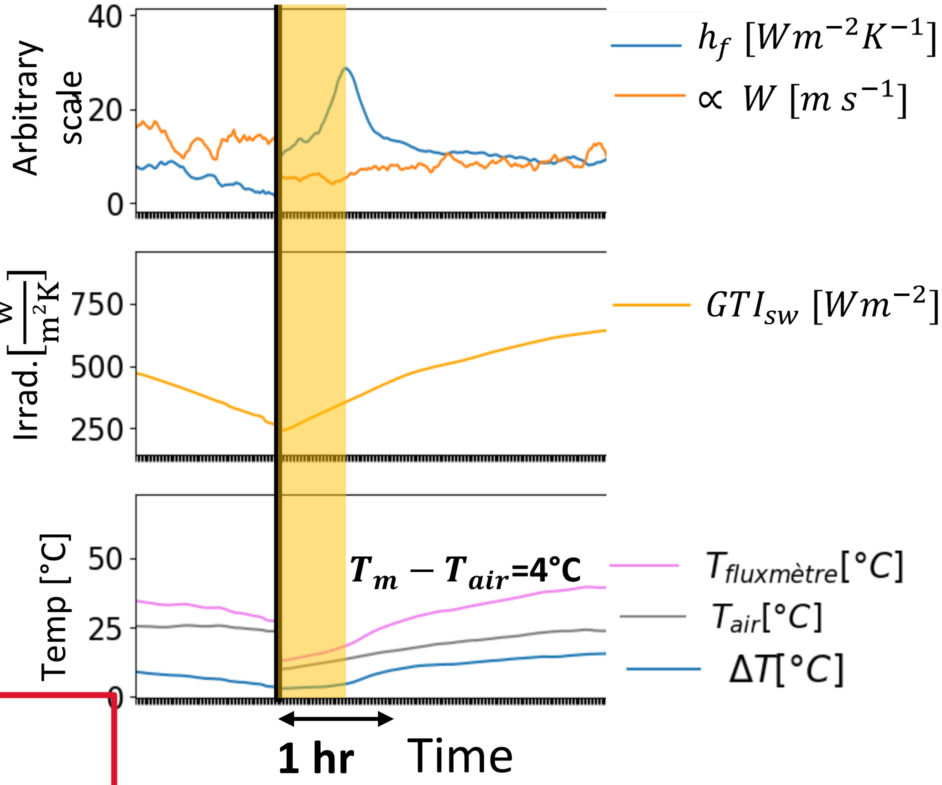




Most of outliers
occur during cloudy days

Convective Heat Transfer – Outliers points





Other outliers values due to inertia effect

➔ Φ_{meas} and $T_m - T_{air}$ are sometimes out of phase

Conclusions

Direct measurement of h_f

- Custom-made heat-flux meter
- The measurements are valid as long as the coating remains clean or if the measurements are taken immediately after installation
- Promising solution but improvements are needed especially in unsteady conditions (cloudy days) ➔ unsteady model for heat flux meter ?


Any questions ?