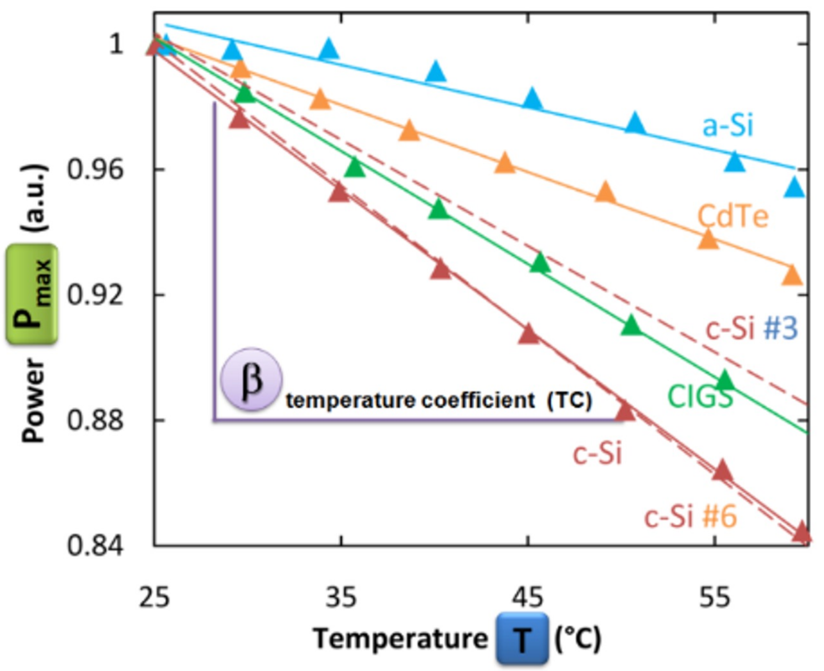
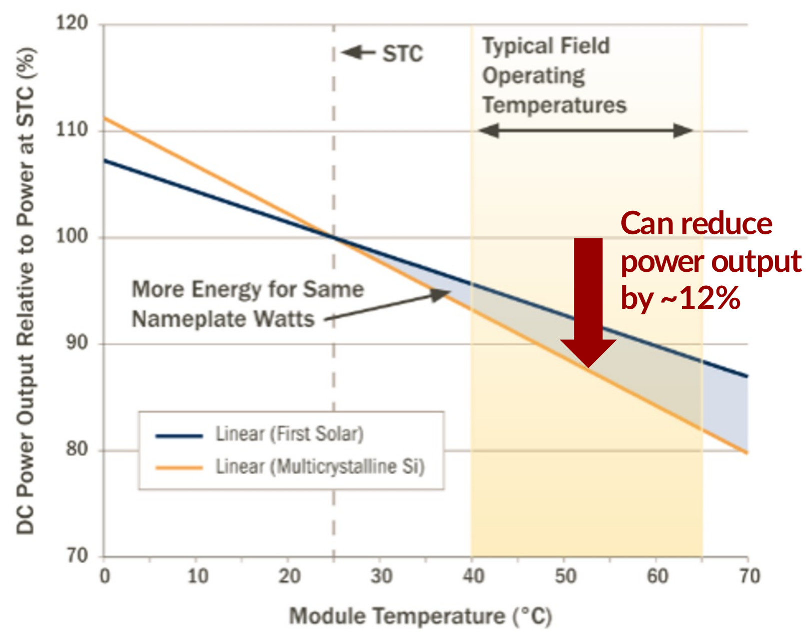
Improved Heat Transfer Correlation for Large Scale Solar PV Convection Modeling

Sarah E. Smith, Brooke J. Stanislawski, Byron Eng, Naseem Ali, Timothy Silverman, Marc Calaf and Raúl Bayoán Cal

DE-EE0008168

As module temperatures rise, efficiency drops and degradation accelerates





Dupré, O. (2016). Physics of the thermal behavior of photovoltaic devices

SCIENTIFIC REPORTS

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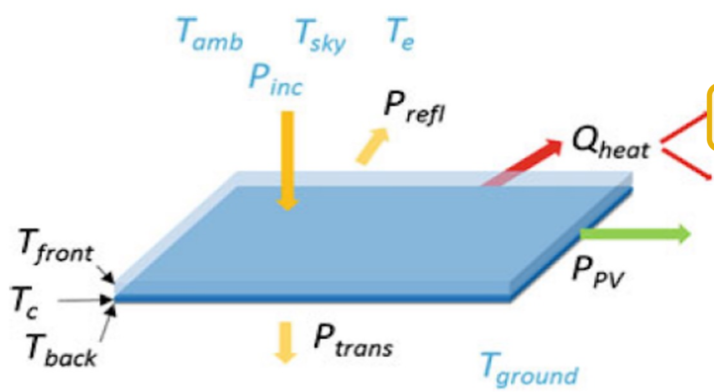
Pathways for mitigating thermal losses in solar photovoltaics

Rodolphe Vaillon[1,2,3], Olivier Dupré[4], Raúl Bayoán Cal[5] & Marc Calaf[2]

Energy balance of PV module

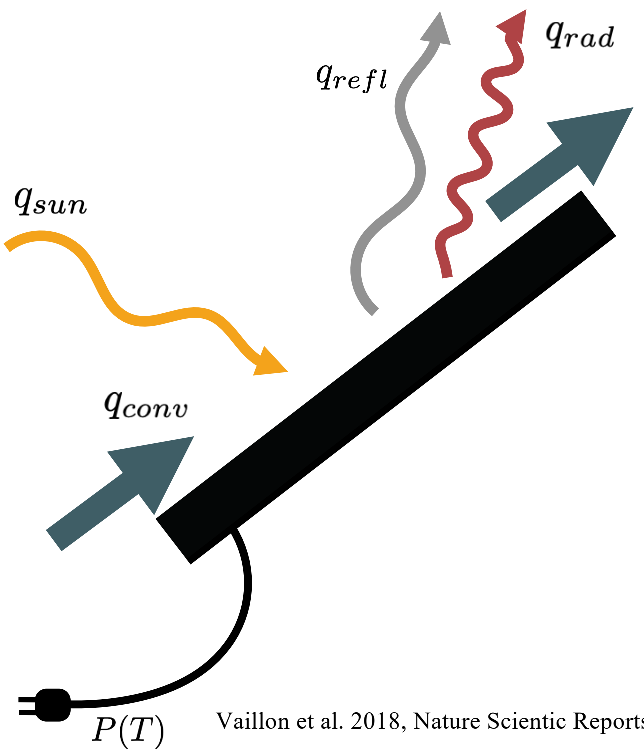


$Q_{conv}=h_{front/back}(T_{front/back}-T_{amb})$

$Q_{rad}=f(\text{rad. prop.}, T_{front/back}, T_e, T_{sky})$

h = convective heat transfer coefficient

Sources of thermal losses in solar PV



Vaillon et al. 2018, Nature Scientic Reports

$$q_{rad} + q_{conv} = q_{sun} - q_{refl} - P(T)$$

where:

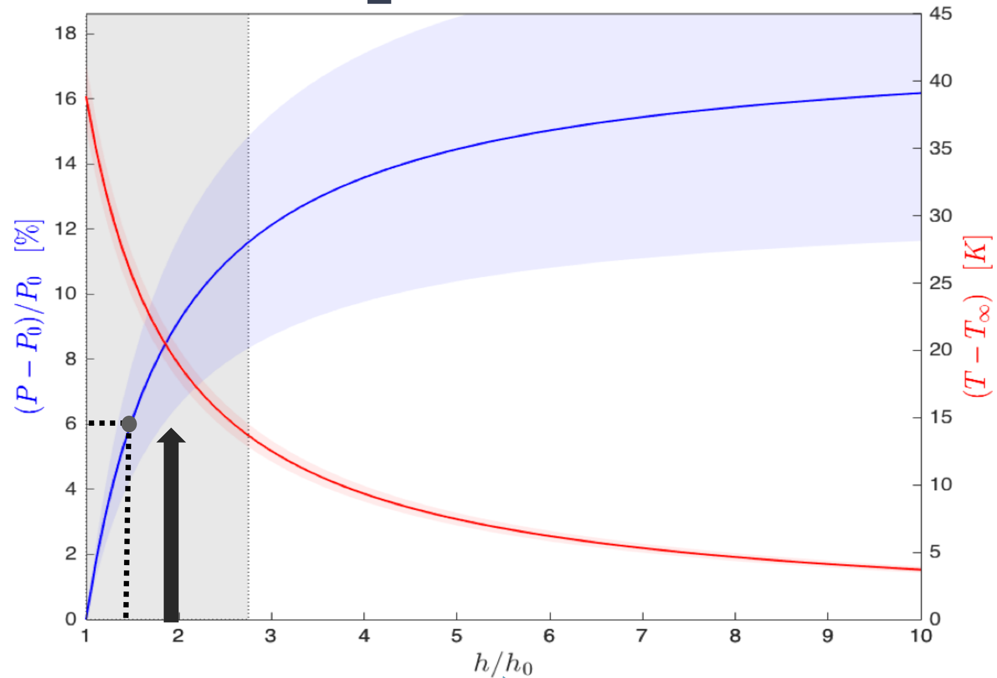
$$P(T) = P_{STC}\left[1 + \beta(T - T_{STC})\right]$$

$$q_{refl} = q_{refl}^{sub} + q_{refl}^{sup} \qquad q_{rad}(T)$$

$$q_{conv}(T) = h(T - T_{\infty})$$

$$T = \frac{hT_{\infty} + q_{Sun} - q_{refl} - q_{rad}(T) - P_{STC}(1 - \beta_P T_{STC})}{h + \beta_P P_{STC}}$$

Increasing convective heat transfer can increase power output



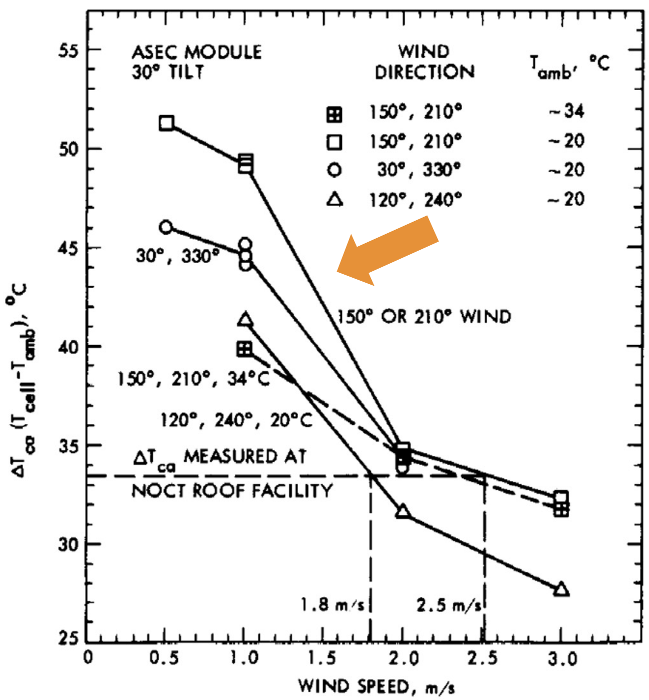
Solar PV has a strong non-linear relation with convective cooling!

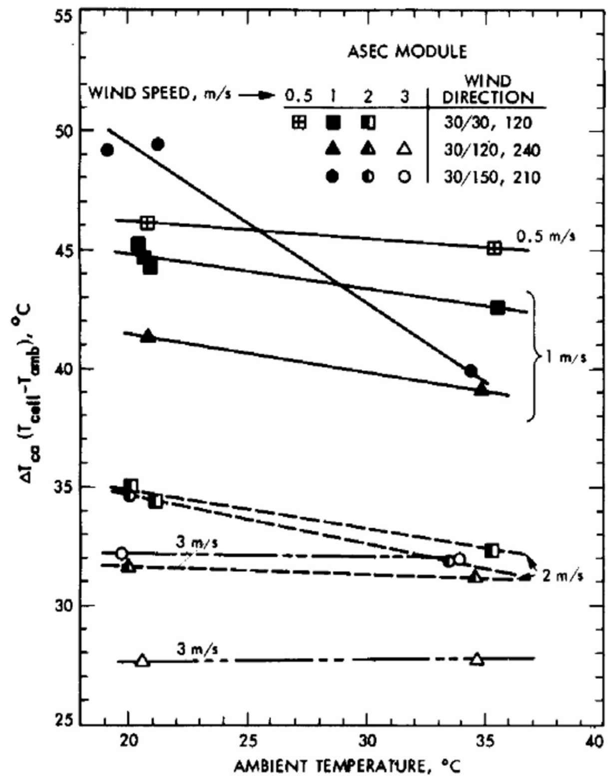
Increasing *h* by 50% can lead to an increase in power of 6%

h **= convective heat transfer coefficient**

Vaillon et al. 2018, Nature Scientific Reports

Module temperature strongly depends on local wind velocity





Griffith et al. 1981

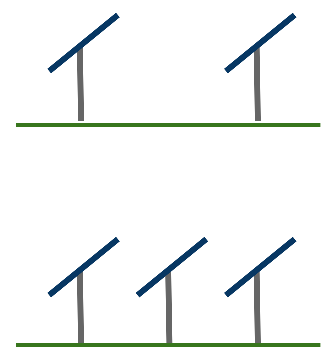
Existing relationships for *h* neglect important factors

Authors	Location of the velocity (V) measurement	Relationship
Sparrow and Tien [15]	Free stream	$(h/\rho C_p V)\ \mathrm{Pr}^{2/3} = 0.931\ \mathrm{Re}^{-1/2}$
Sparrow et al. [16]	Free stream	$(h/\rho C_p V)\ \mathrm{Pr}^{2/3} = 0.86\ \mathrm{Re}^{-1/2}$
Test et al. [42]	1 m above the plate	$h = 2.56\ \mathrm{V} + 8.55$
Kind et al. [43]	14 cm above the tunnel floor	$h/\rho V C_P = f[\mathrm{Re}]$ presented graphically
Shakerin [45]	Average near model	$(h/\rho C_p V)\ \mathrm{Pr}^{2/3} = 1.23\mathrm{Re}^{-1/2}$ $\alpha < 40$ deg $(h/\rho C_p V)\ \mathrm{Pr}^{2/3} = 0.90\mathrm{Re}^{-1/2}$ $\alpha \geq 40$ deg
Onur [46]	Not available	$\mathrm{Nu} = 0.568\ \mathrm{Re}^{0.524}$ Roof inclination 30 deg $\mathrm{Nu} = 1.067\ \mathrm{Re}^{0.466}$ Roof inclination 45 deg
Sharples and Charlesworth [47]	1.5 m above the ridge	$h = 2.2V + 11.9\ (0.5 < V < 6.7)$ or $h = 9.1V^{0.57}$

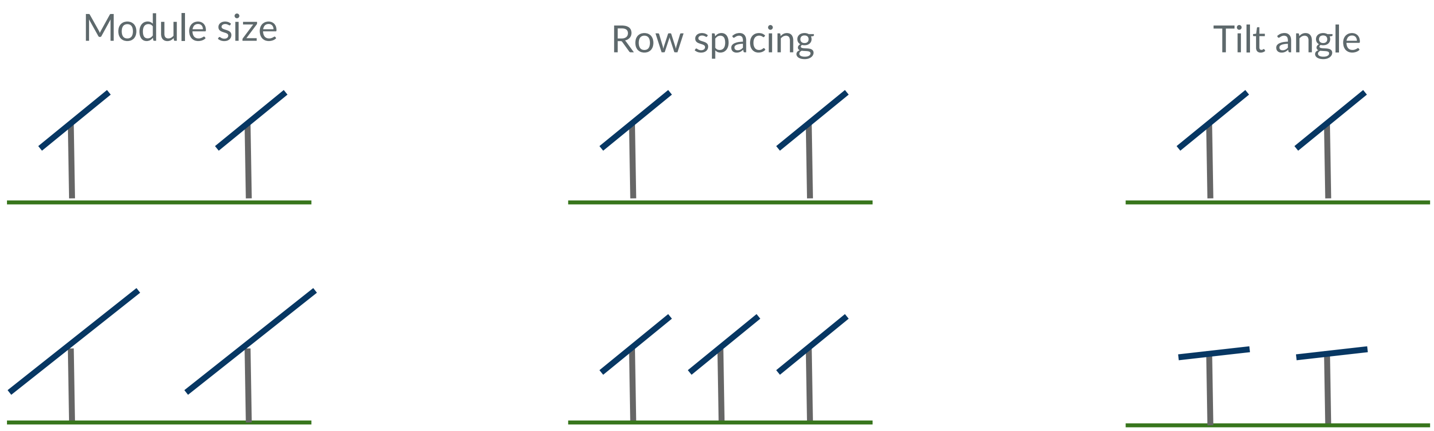
Karava et al. 2011

Environmental factors

Geometric variables



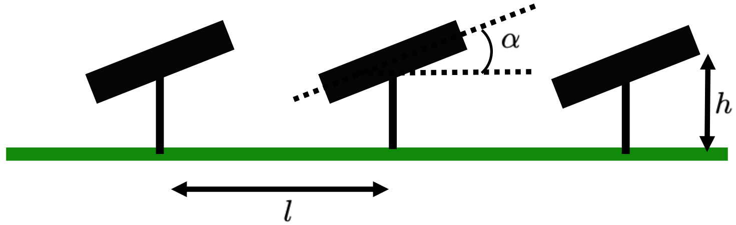
Hypothesis: The convective heat transfer coefficient *h* depends on solar farm arrangement



Research Question

Can one build a thermal model correlation taking into account solar farm arrangement strategies?

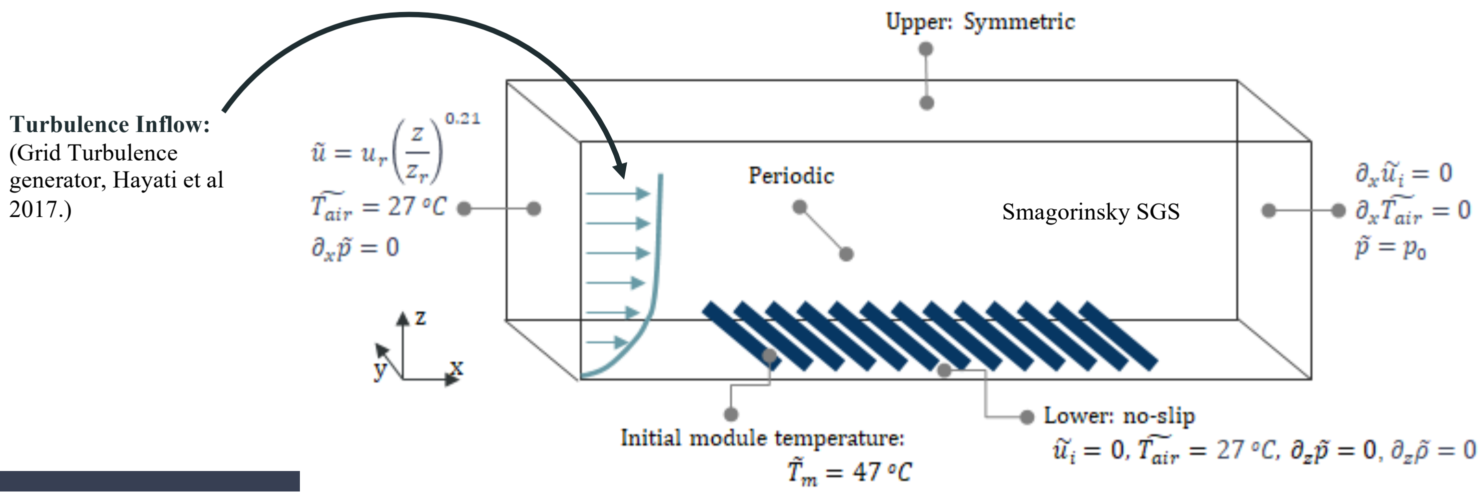
Can we modify the cooling capacity of solar farms through changes in module arrangements?



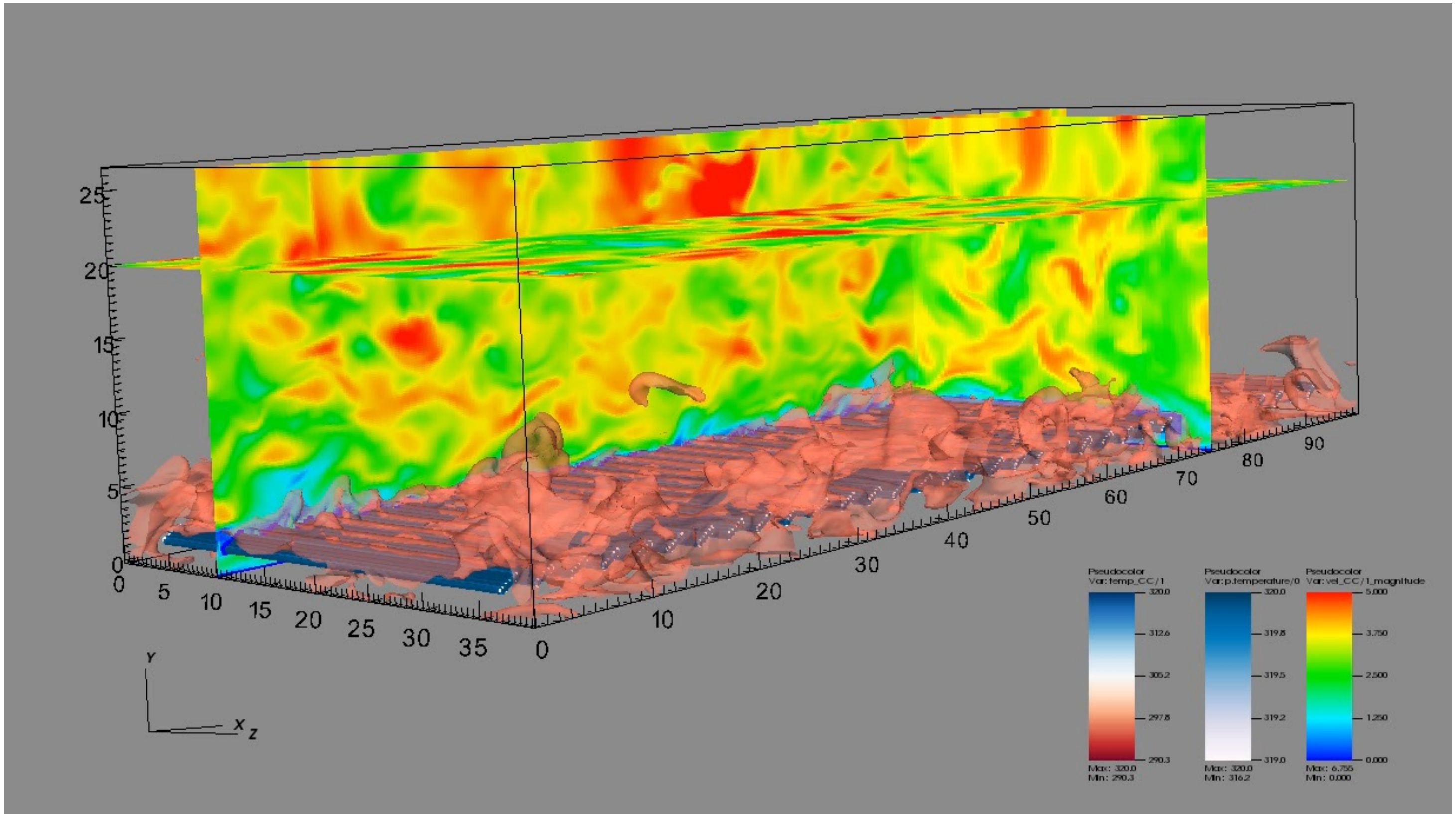
- Changes in row spacing
- Changes in module heights
- Changes in module tilt angles
- Combination of module heights …
- Changes in farm row configurations & addition of flow deflectors
- Addition of vortex generators

Use a combination of wind tunnel and field experiments & numerical simulations to explore the parameter space.

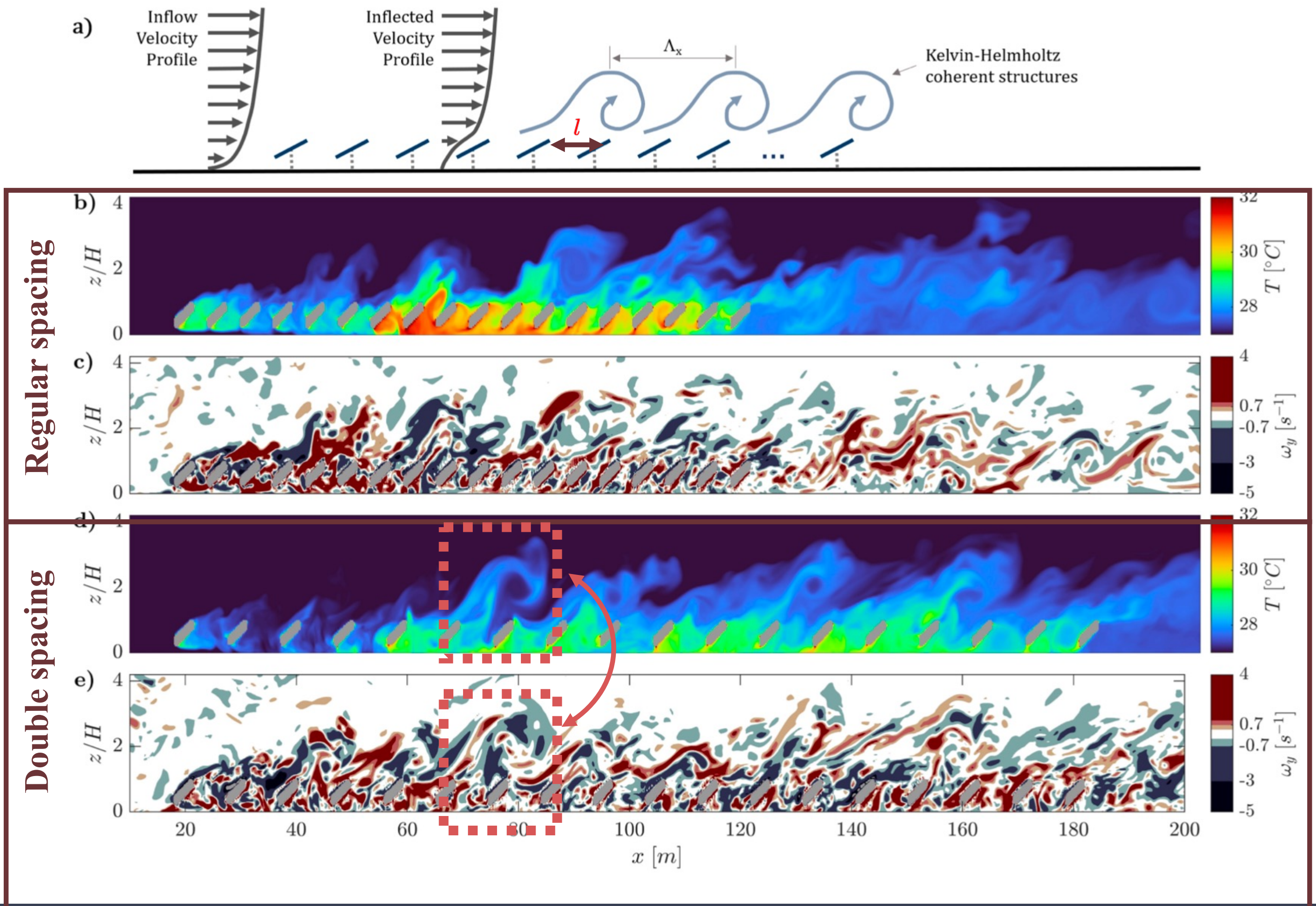
(a) **Large-Eddy Simulations** MPMICE (Material Point Method, Implicit, Continuous fluid, Eulerian) method: cell-centered, finite-volume, multi-material (Kashiwa & Rauenzahn, LANL 1994, Sulsky et al. 1994 & 1995, Guilkey et al. 2007)



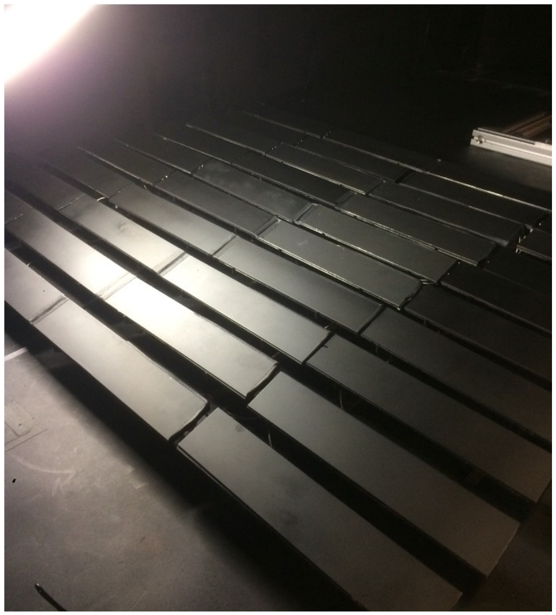
Instantaneous temperature fields

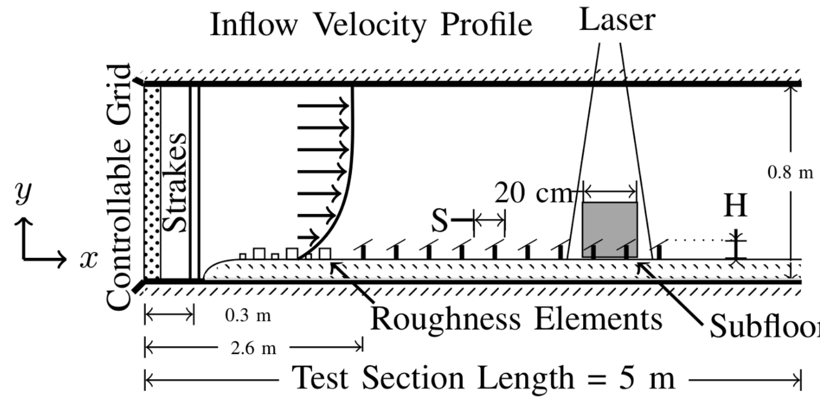


Analysis of the interaction between the flow field and the thermal field



(b) **Wind tunnel Measurements**



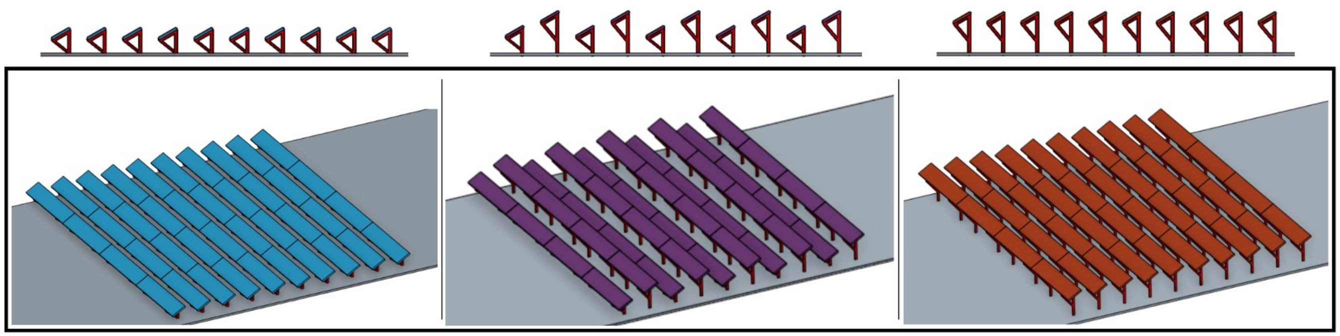


Angle variations:

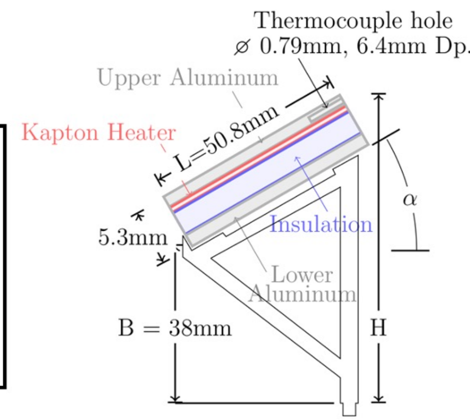
$\alpha = \{15^o, 30^o, 45^o, -30^o\}$

$U_\infty =$ 1 m/s; 3.9 m/s

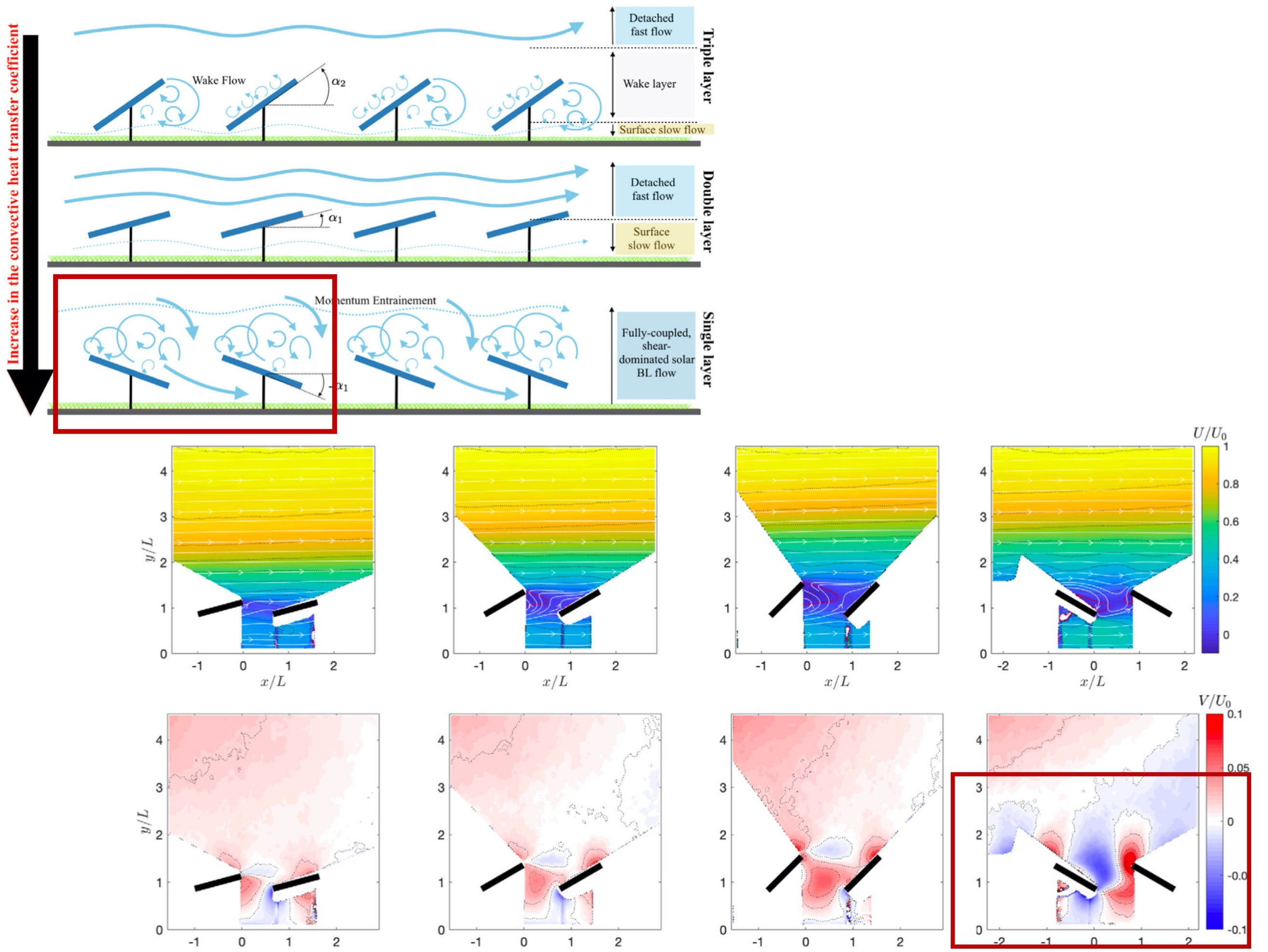
$TI = 11\%; 16\%; 18\%$



Nominal (NM) Staggered (SM) High (HM)



(b) **Wind tunnel Measurements**

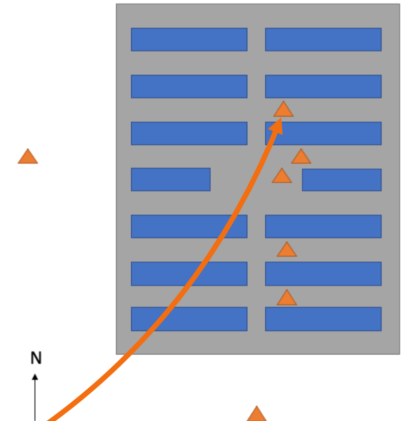


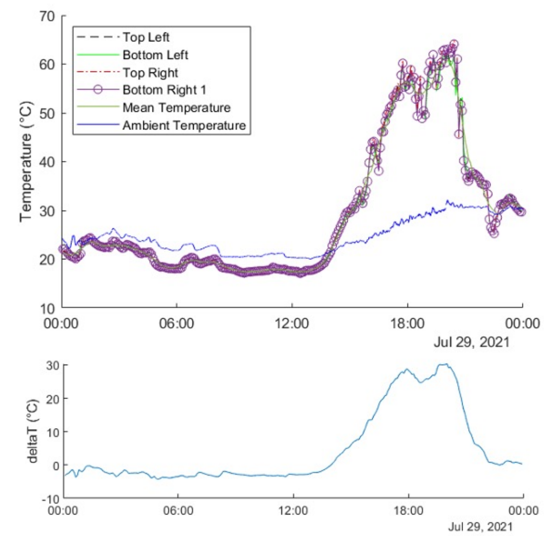
Glick et al. 2020, Solar Energy

(c) **Field Measurements**

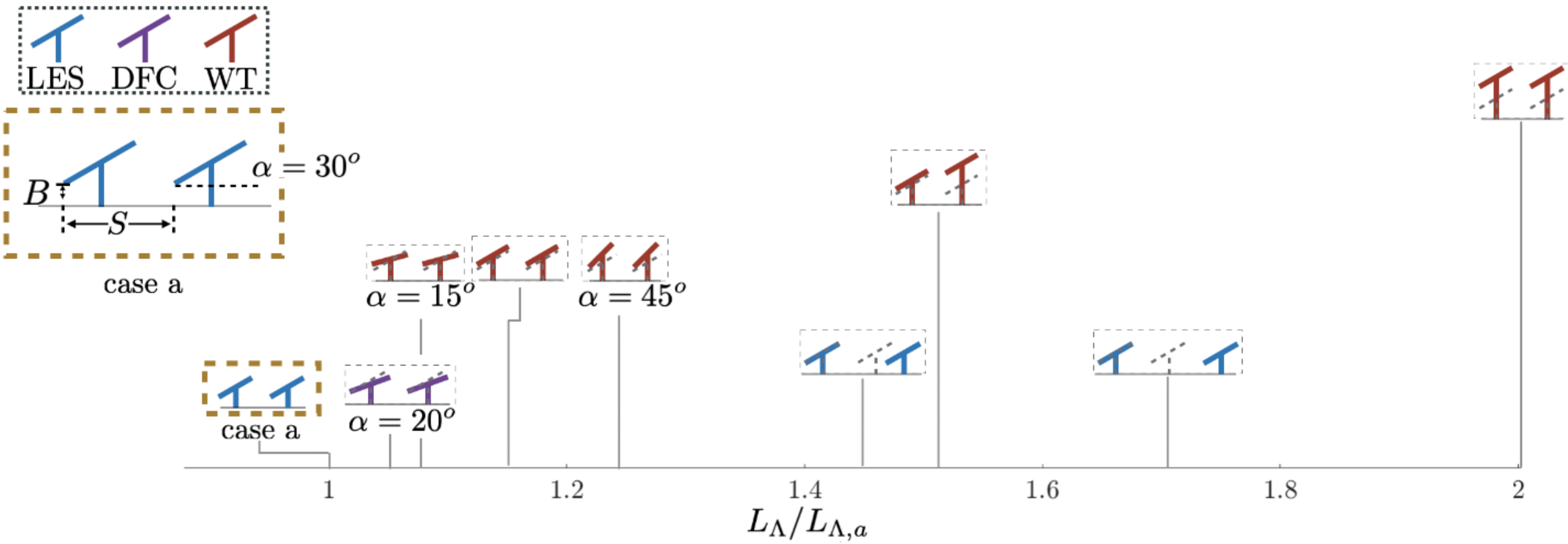
U.S. Army Dugway Proving Grounds Solar Farm

Array of turbulence measuring sensors & solar panel thermal characteristics



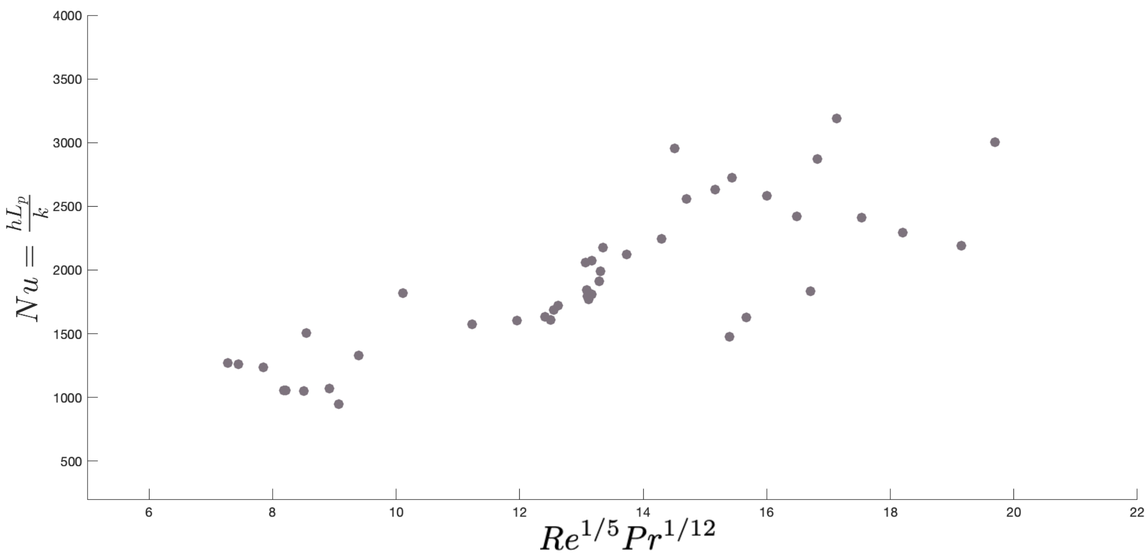


Summary of study cases:

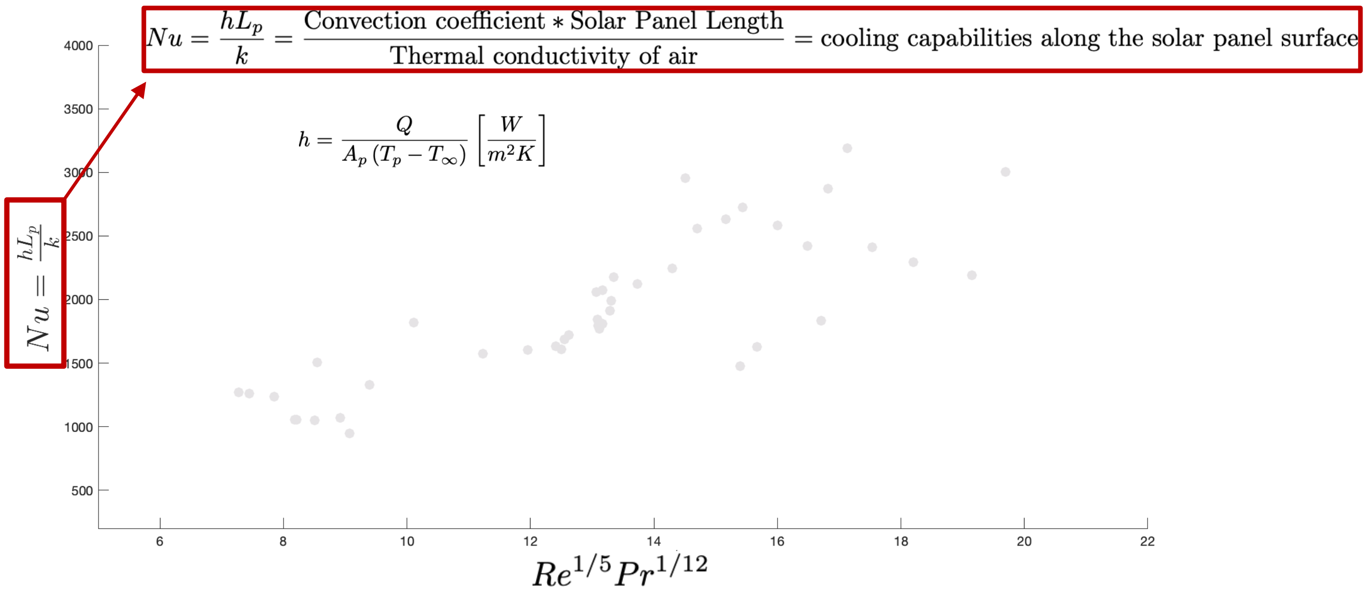


New Panel Convection Modelling: Geometry-dependent Model

Present goal: *Define convective cooling of* ***any solar farm*** *based on* ***multiple parameters***



New Panel Convection Modelling: Geometry-dependent Model



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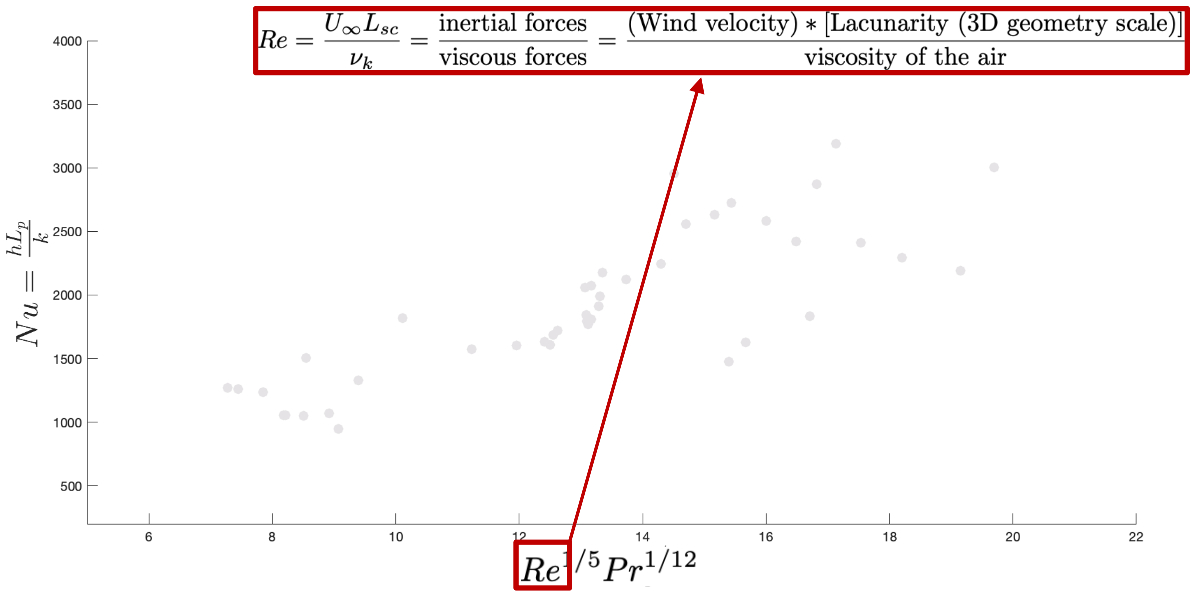
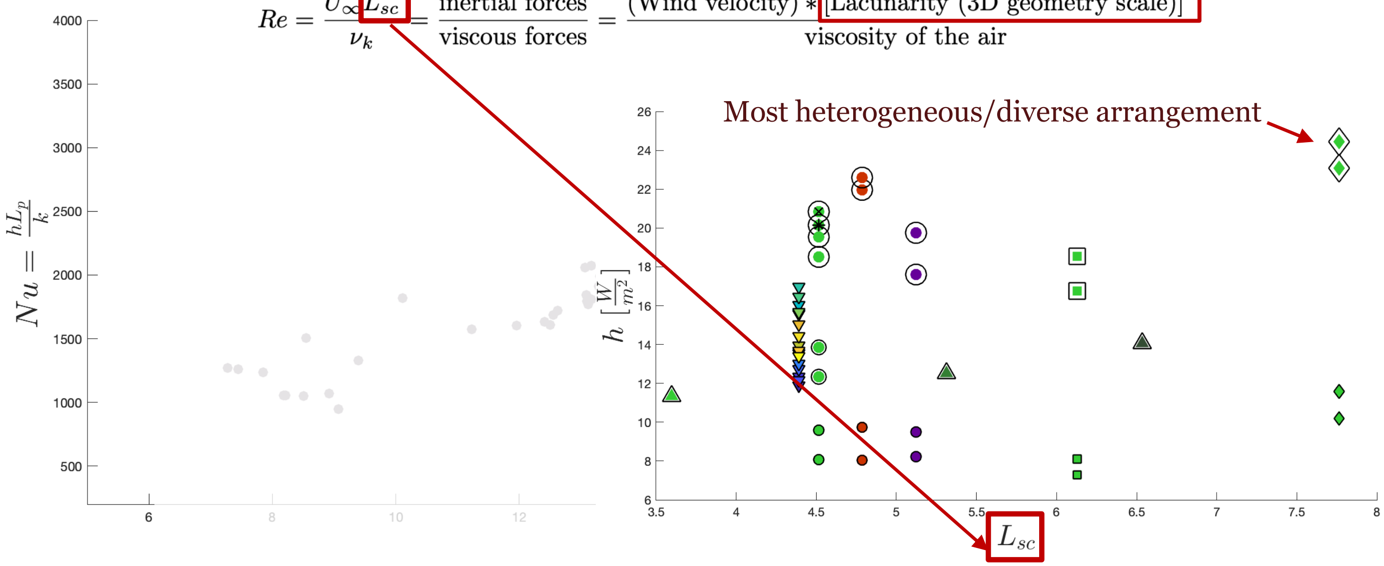


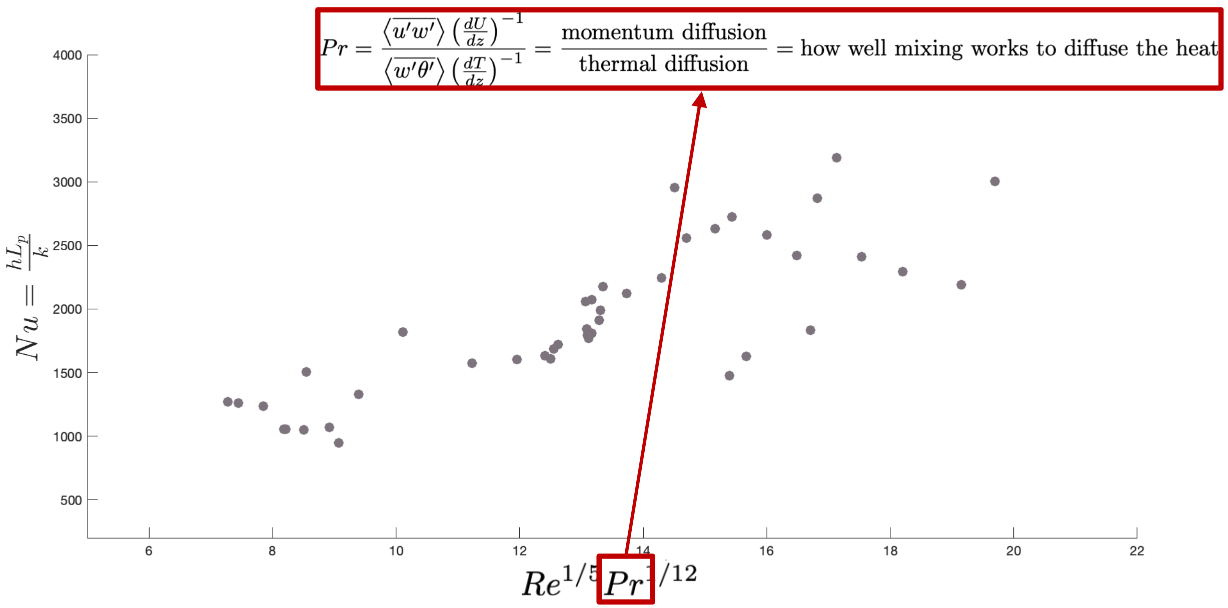
New Panel Convection Modelling: Geometry-dependent Model

$$Re = \frac{U_\infty L_{sc}}{\nu_k} = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{(\text{Wind velocity}) * [\text{Lacunarity (3D geometry scale)}]}{\text{viscosity of the air}}$$

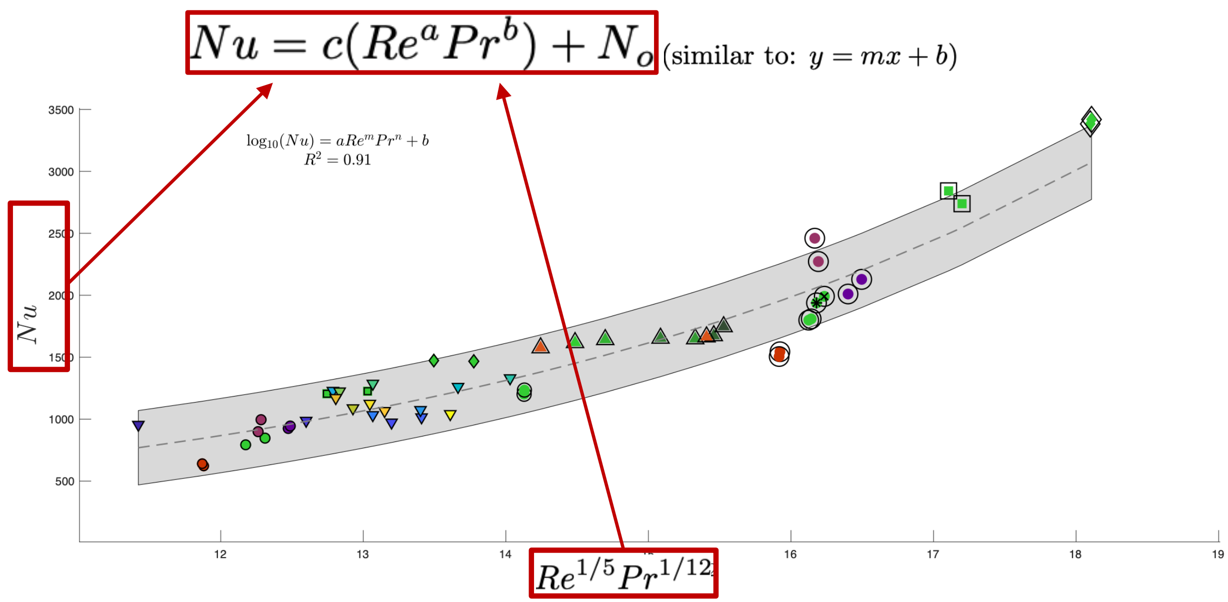


Representing 9 different variations in terms of 3D space

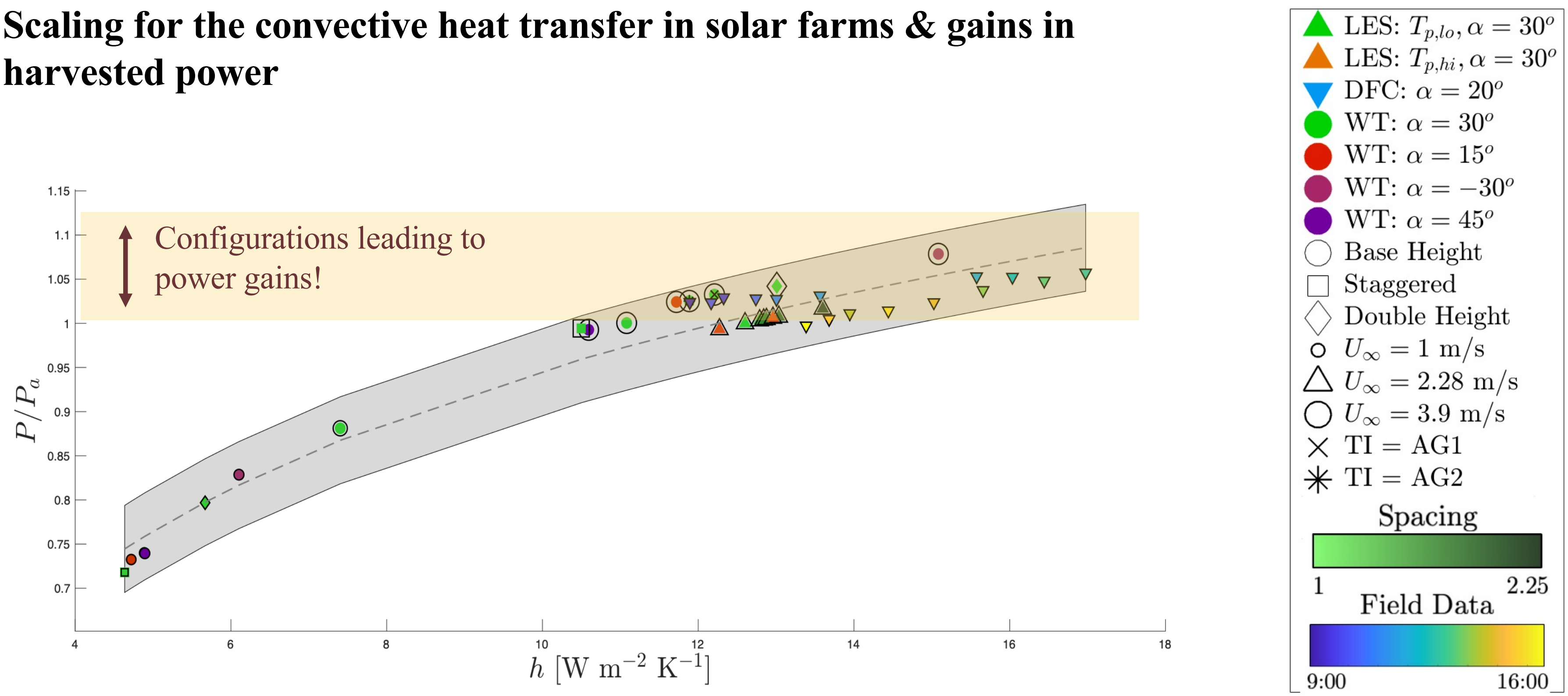
New Panel Convection Modelling: Geometry-dependent Model



New Panel Convection Modelling: Geometry-dependent Model



Scaling for the convective heat transfer in solar farms & gains in harvested power



Conclusions

- Simple changes in solar module arrangements in solar farms have the potential to lead to important gains in power efficiency.

- An improve model taking into account such variations.

- The same way that the wind energy industry realized that local meteorology and turbulence matter, the solar PV industry could take into consideration not only the effects of module arrangements, but also the local meteorology (i.e. beyond incident solar radiation) when installing solar farms.

- We just started scratching the surface of the potential improvements to be gained when considering fluid mechanics and turbulence…