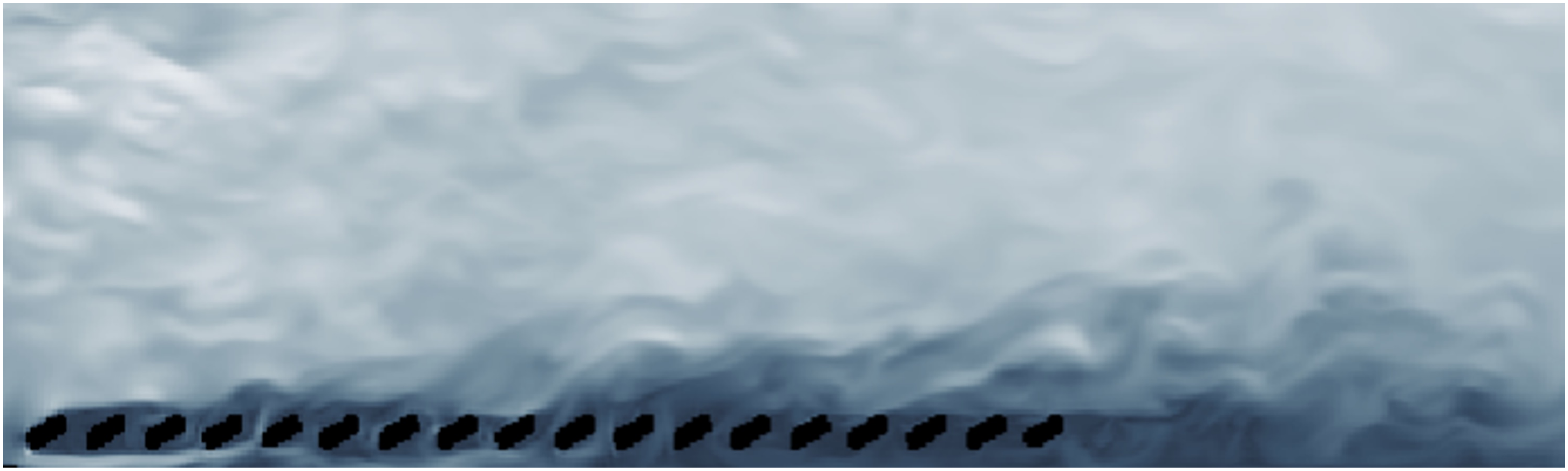

The influence of system-level design elements on convective cooling in PV solar farms

THE UNIVERSITY OF UTAH [1]

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PV Performance Modeling and Monitoring Workshop

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DE-EE0008168

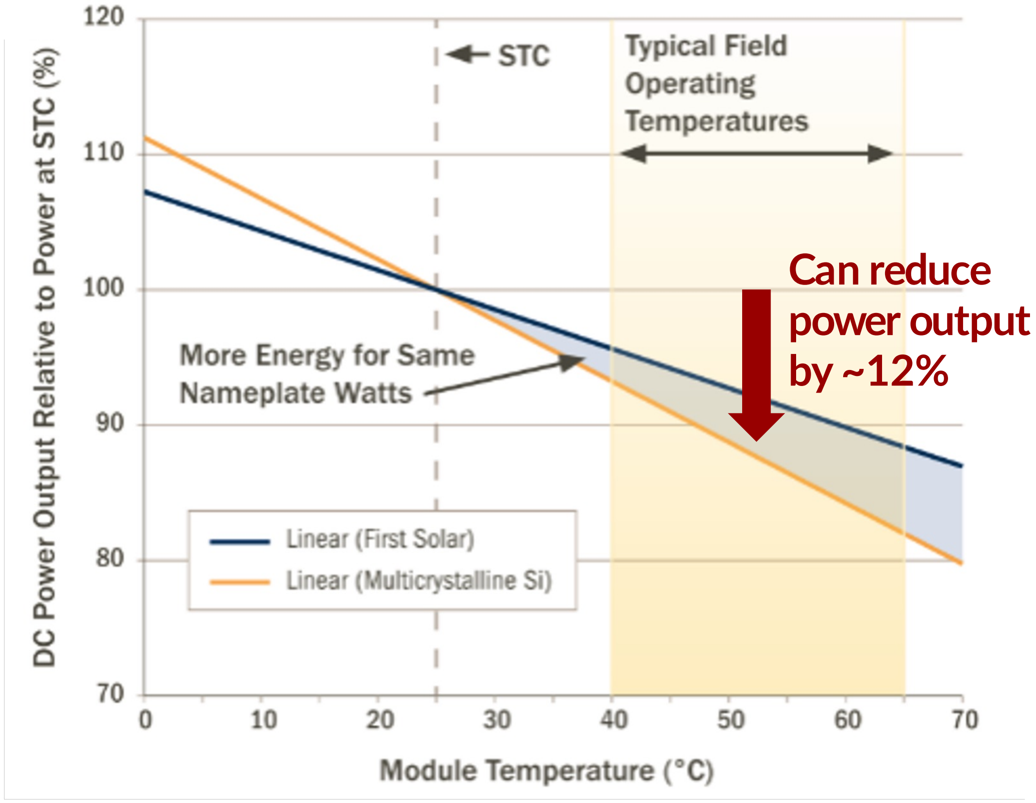
U.S. DEPARTMENT OF ENERGY

Portland State University [2]

NREL National Renewable Energy Laboratory [3]

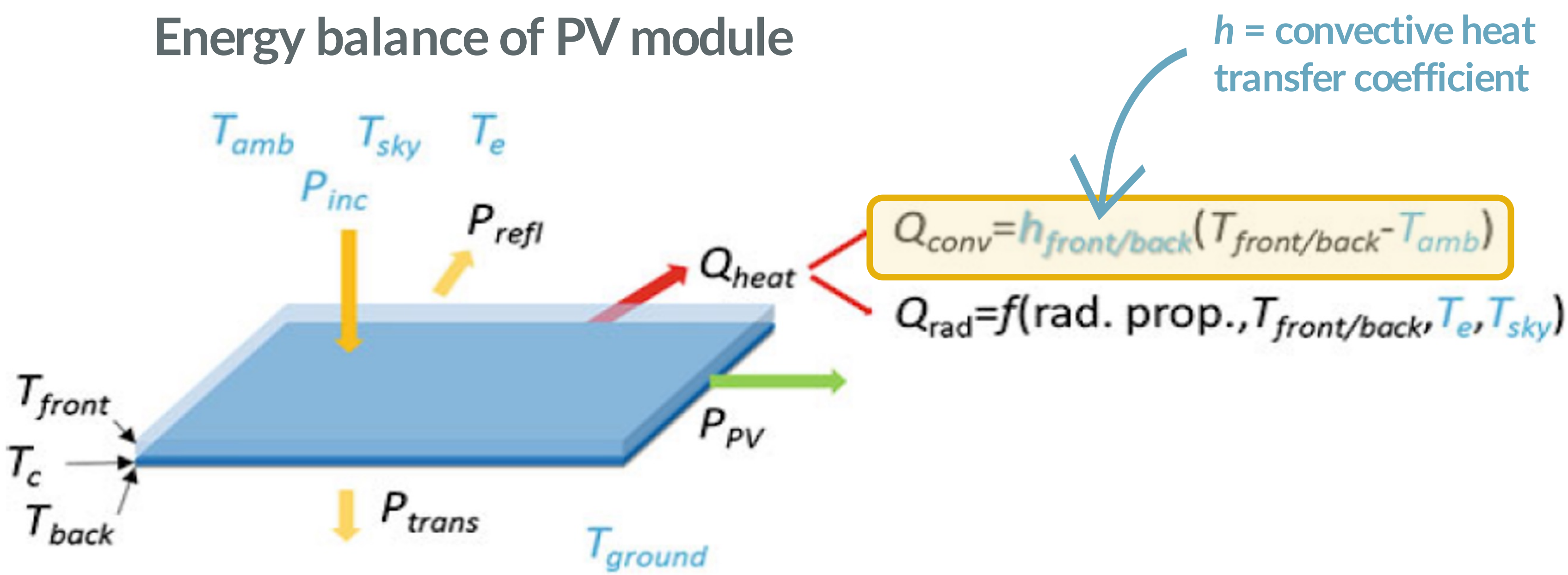
As PV module temperatures rise, efficiency drops and degradation accelerates

<u>STC</u>
1,000 W/m^2
AM 1.5
25^o C



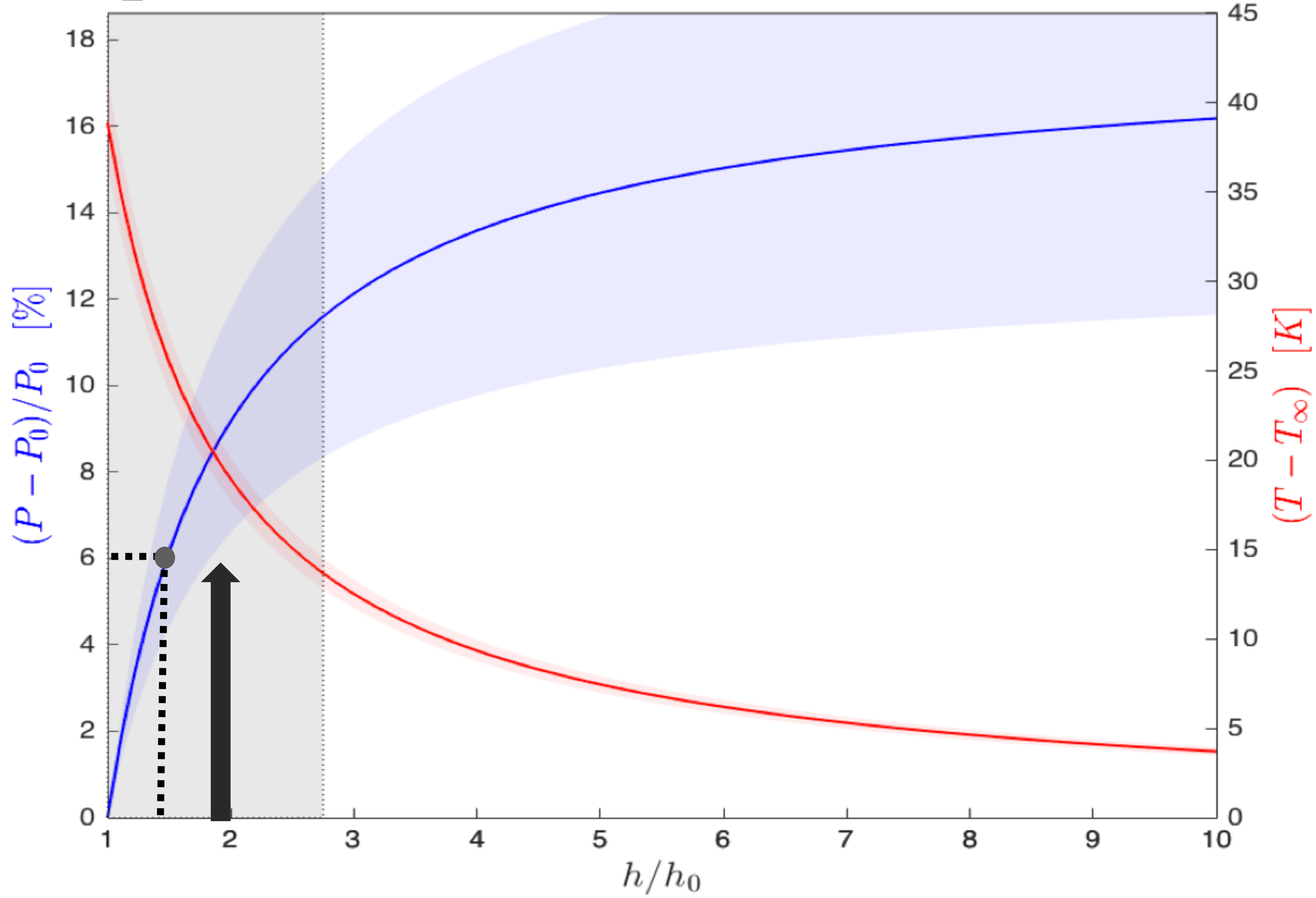
Dupré, O. (2016). Physics of the thermal behavior of photovoltaic devices
(edited for clarity)

Enhancing convective heat transfer can cool solar modules



Dupre, Vaillon, Thermal Behavior of Photovoltaic Devices, 2017

Increasing convective heat transfer can increase power output



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

Vaillon et al. 2018, Nature Scientific Reports

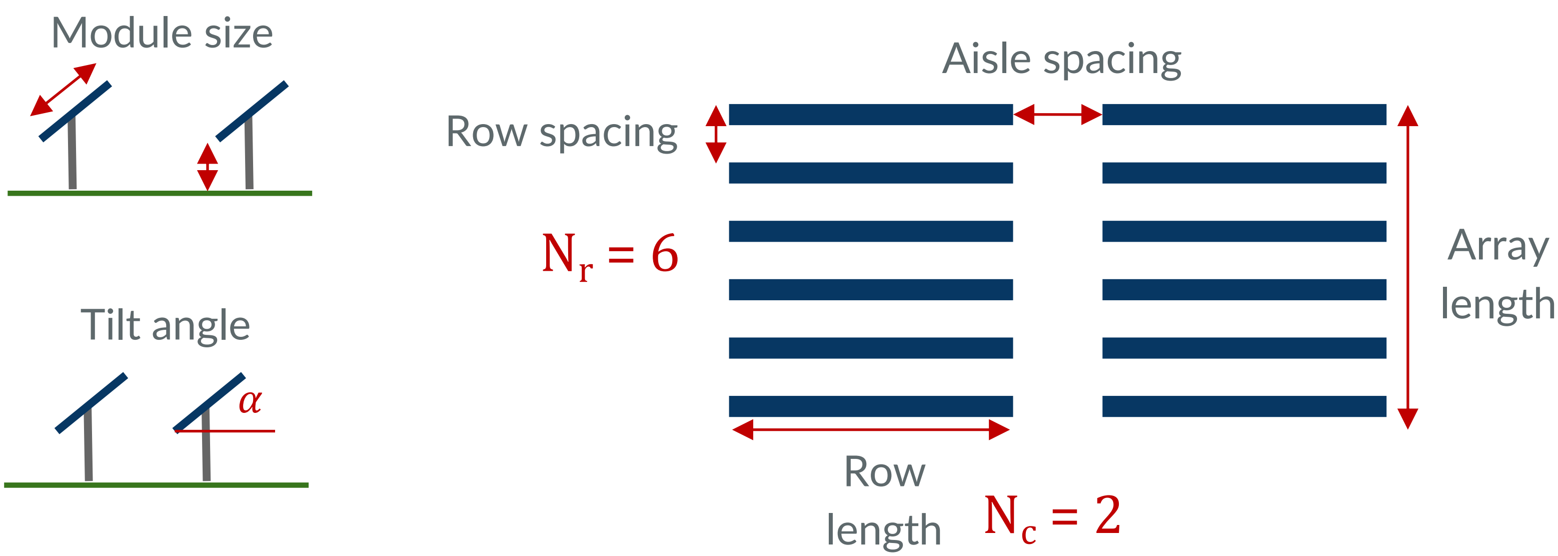
h = convective heat transfer coefficient

Convective heat transfer depends on several factors

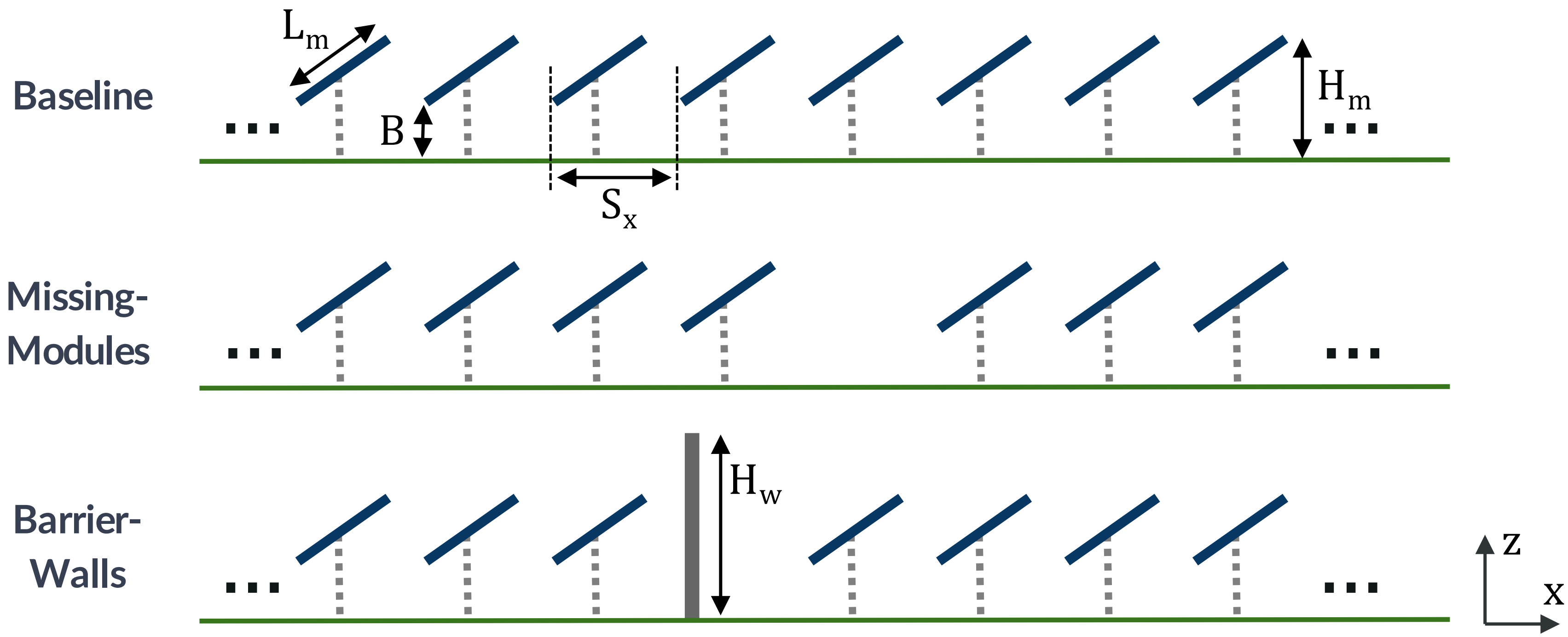
Environmental factors

Geometric variables

Research Question: Can the arrangement of a solar farm naturally enhance convective heat transfer (h)?



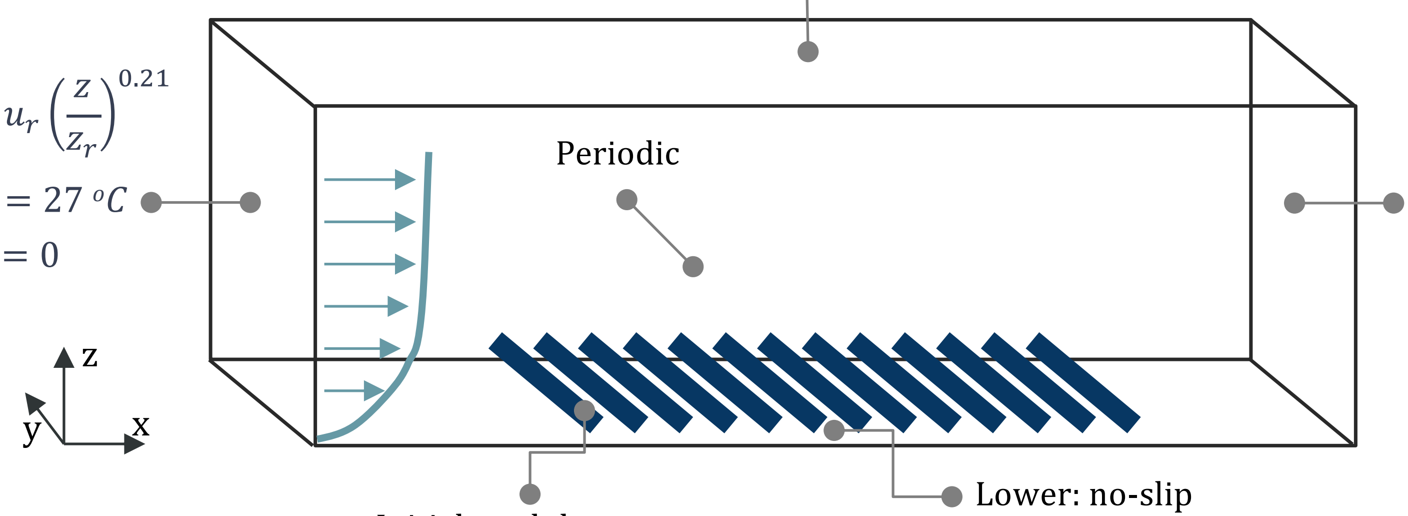
Three solar farm arrangements developed



Assembled module length: 3.3 m -- **Tilt angle**: 30 degrees -- **Number of rows**: 36

Uintah:MPMICE platform used for numerical simulations

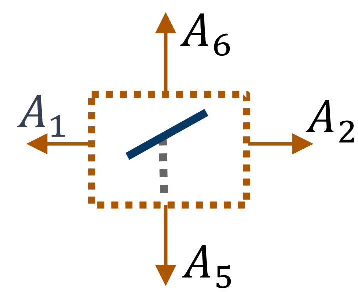
Boundary Conditions



Governing multi-material equations

1. Conservation of mass
2. Conservation of momentum: Filtered Navier-Stokes equations in rotational form
3. Conservation of energy: temperature transport equation

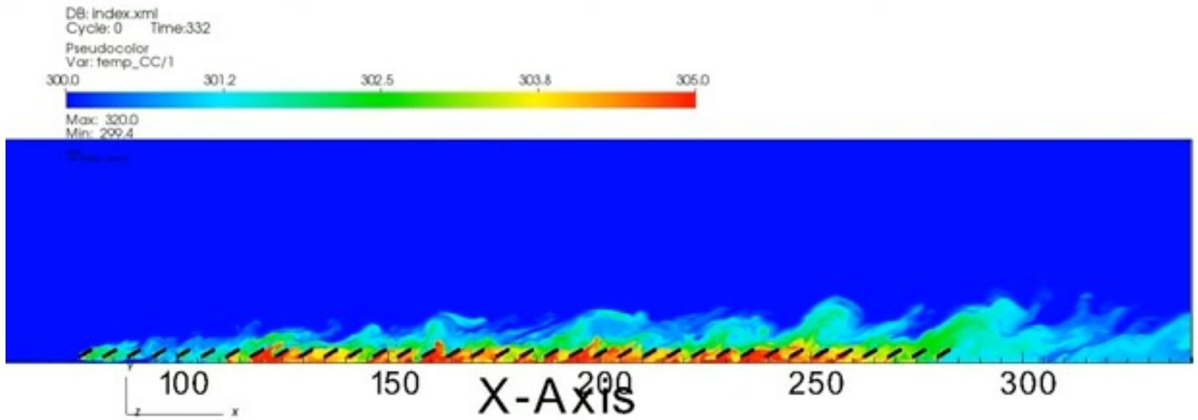
Sub-grid model: Smagorinsky turbulence model
Inflow Turbulence: Generated with inflow grid turbulence generator *(Hayati et al. 2017)*
Flow solver: MPMICE (Material Point Method, Implicit, Continuous fluid, Eulerian) method: cell-centered, finite-volume, multi-material *(Kashiwa & Rauenzahn, LANL 1994, Sulsky et al. 1994 & 1995, Guilkey et al. 2007)*



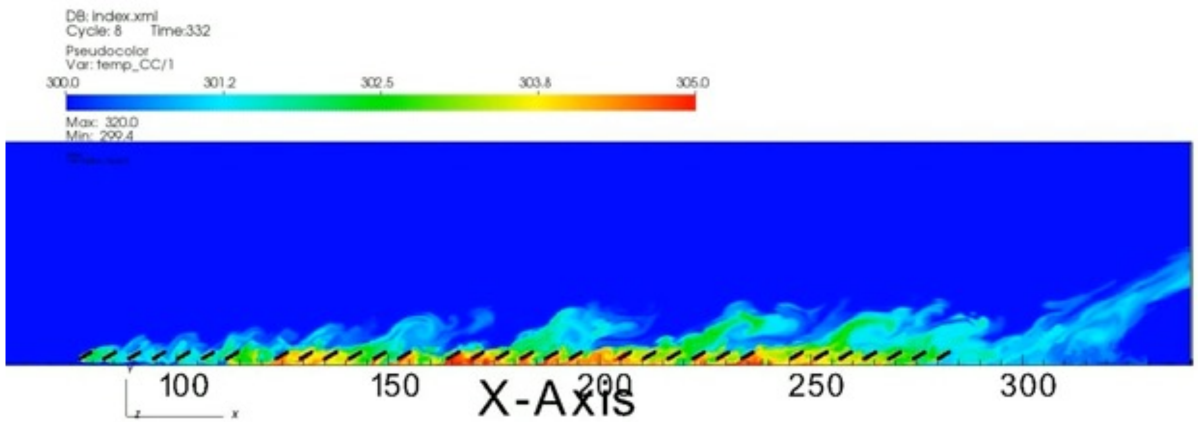
Newton's Law of Cooling

$$h = \frac{q_m}{T_m - T_\infty}$$

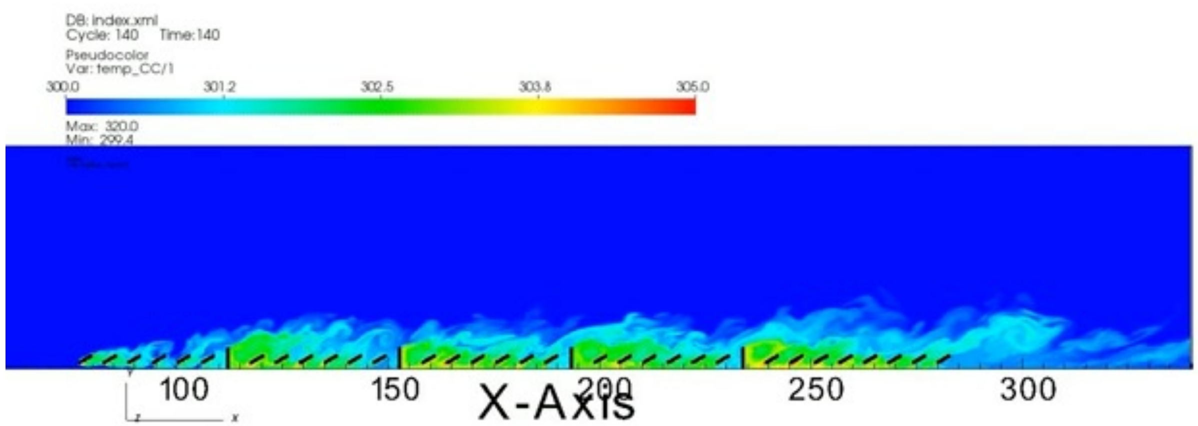
Baseline



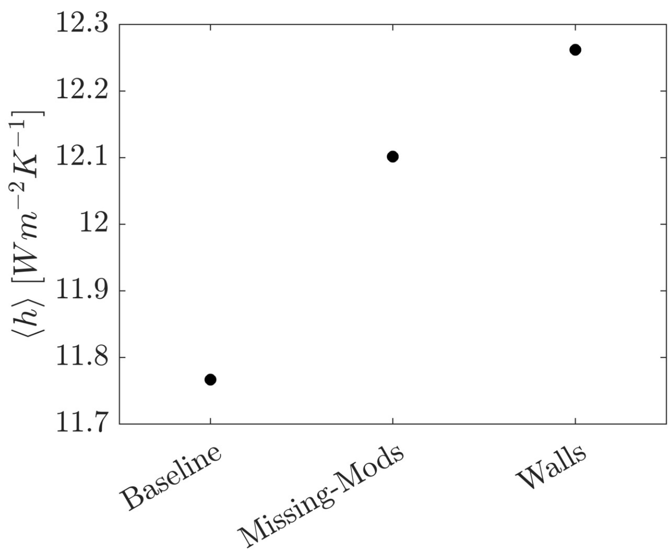
Missing-
Modules

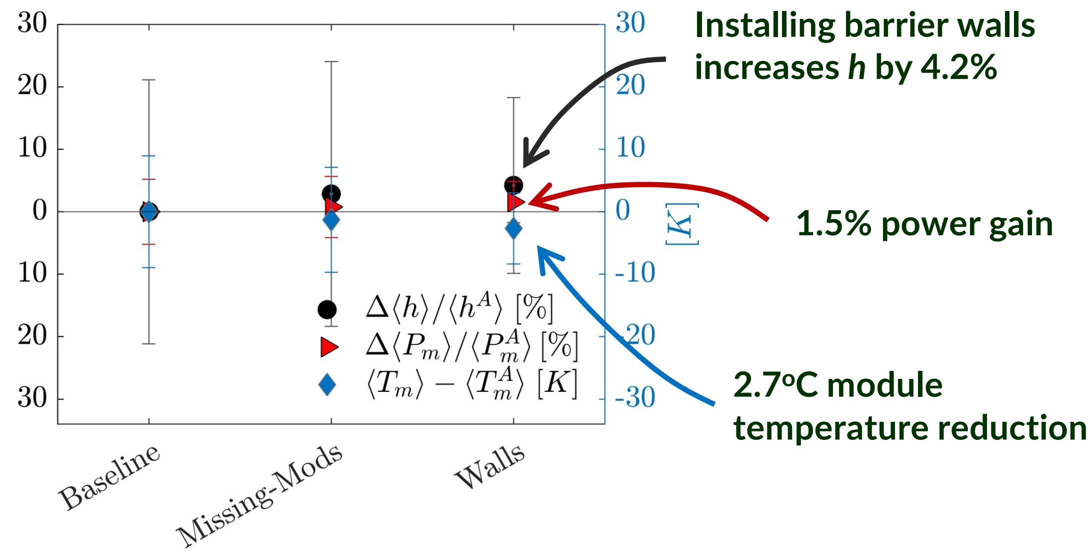


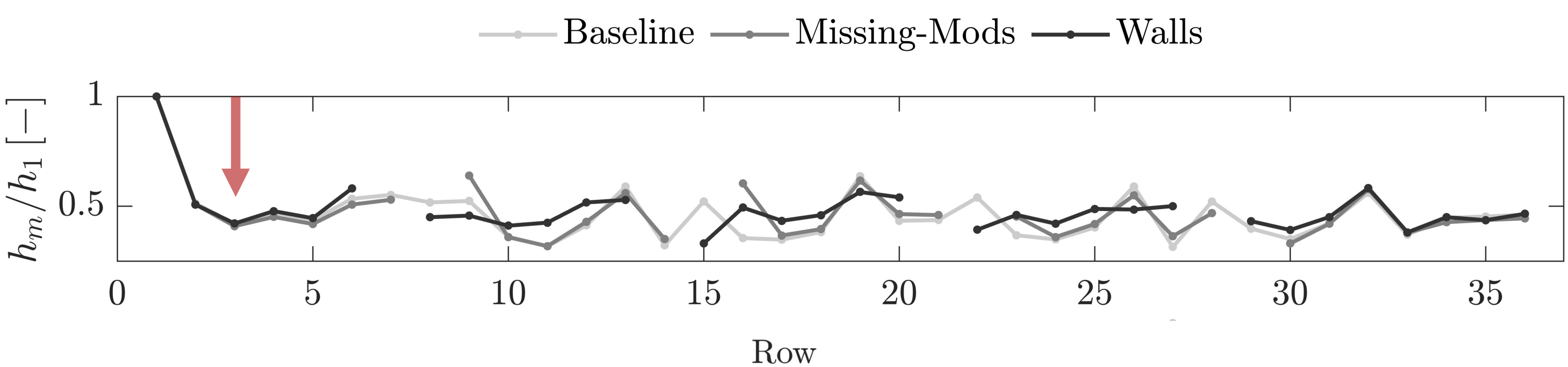
Barrier-
Walls



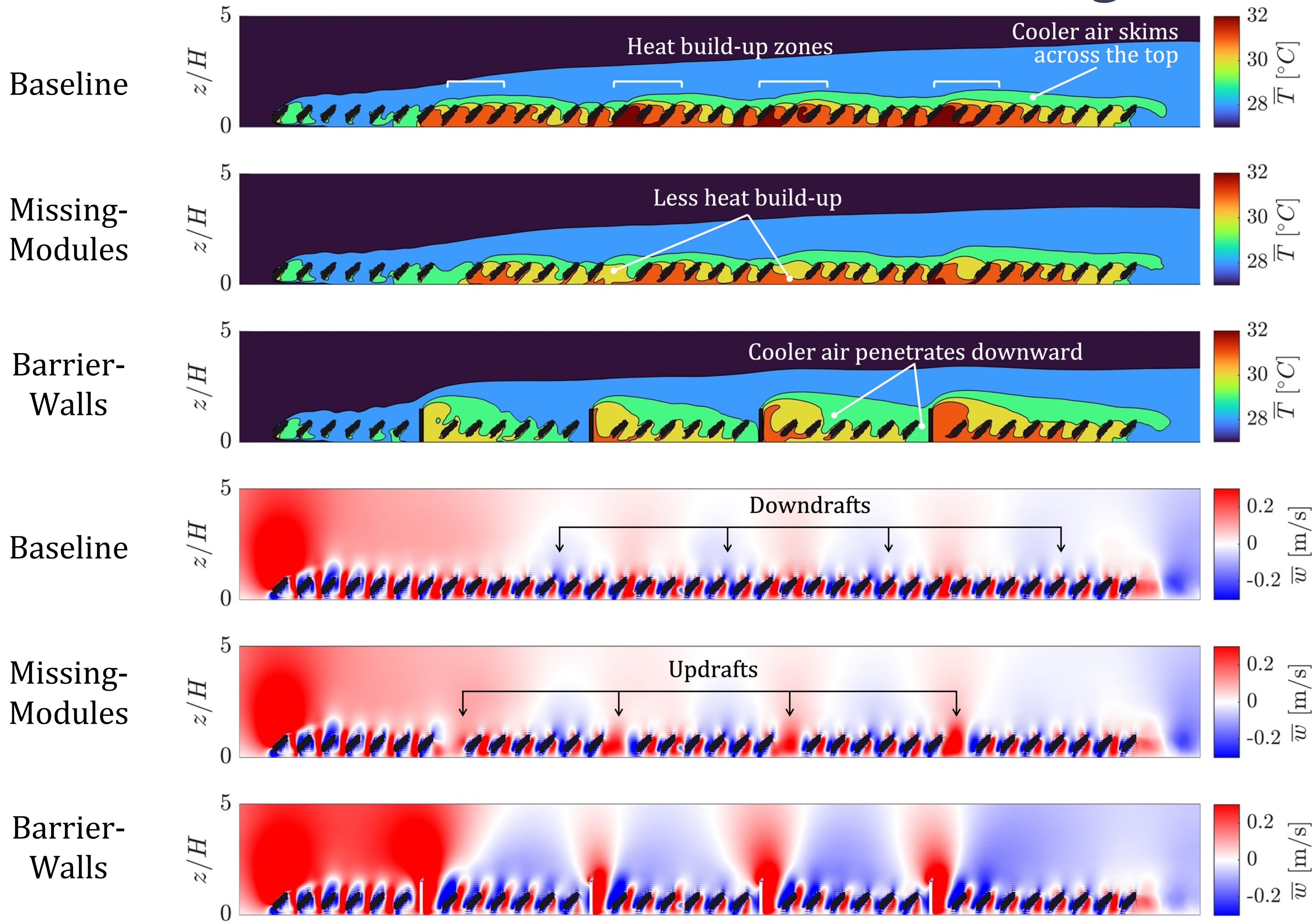
Barrier walls yield the greatest improvements







Thermal and flow behavior of each arrangement

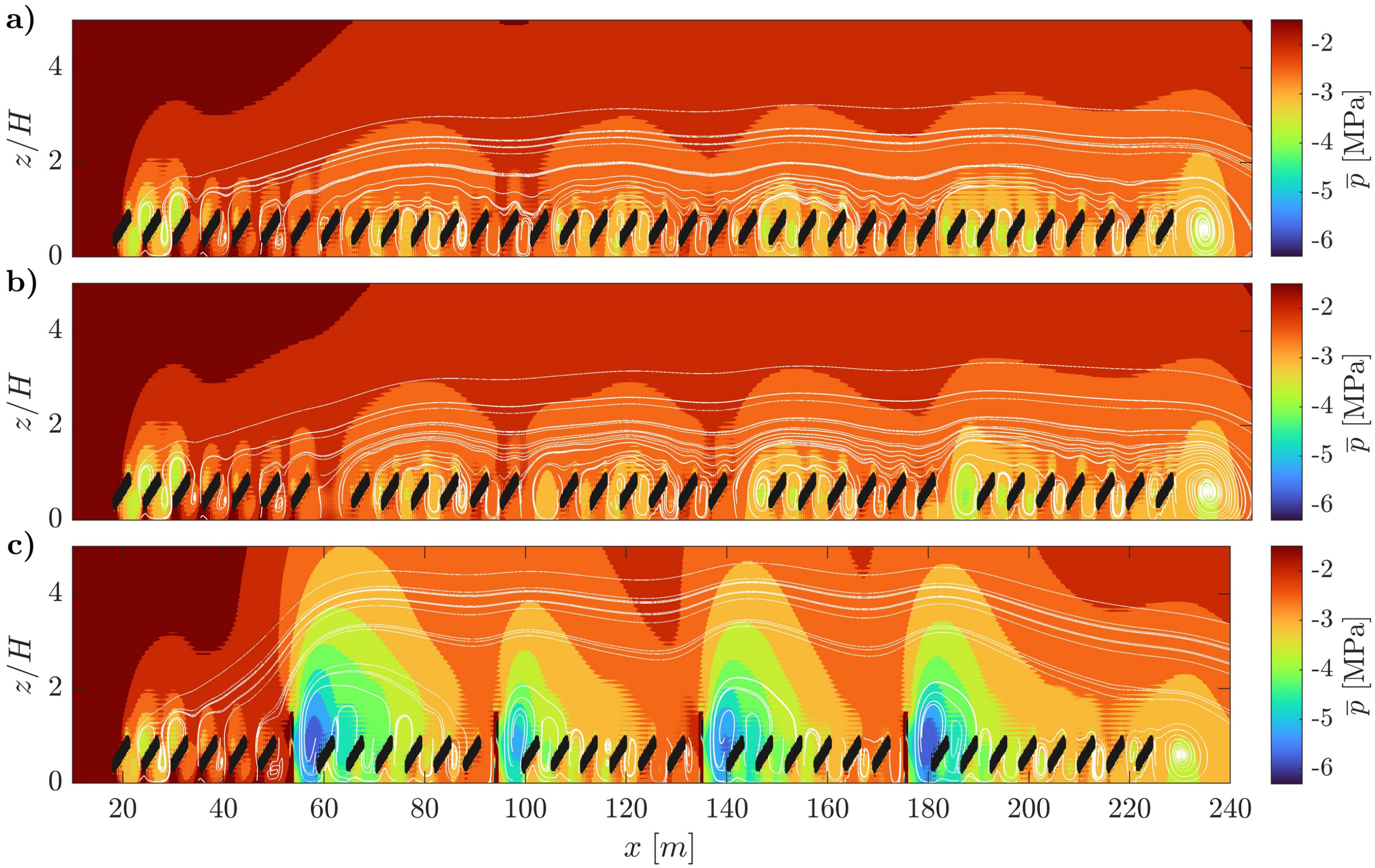


Pressure fields that induce flow behaviors

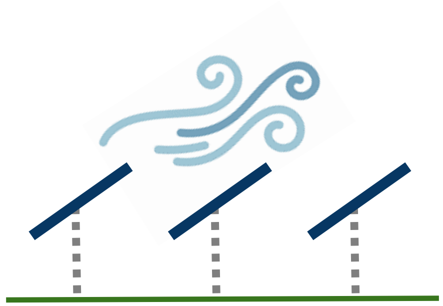
Baseline

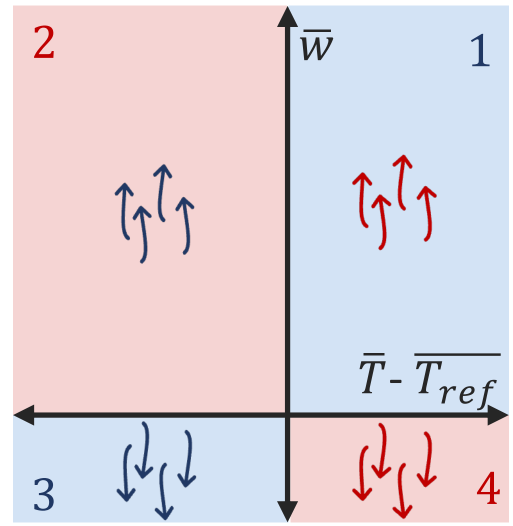
Missing-
Modules

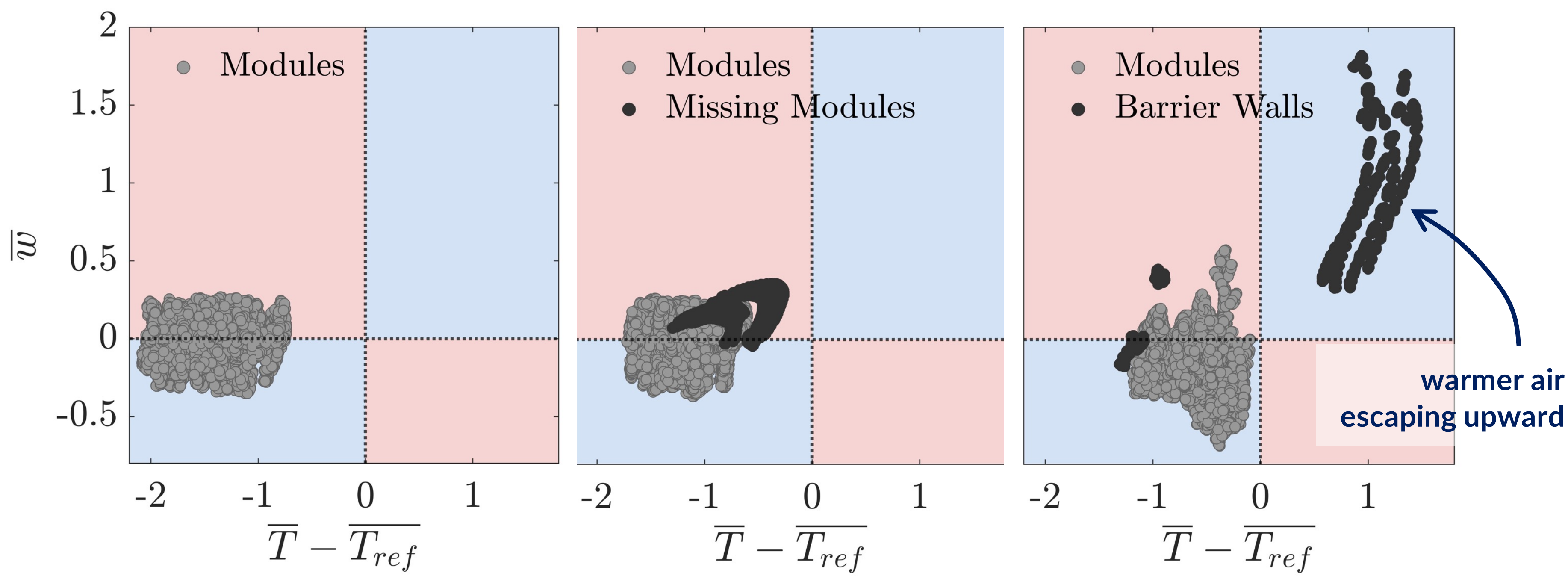
Barrier-
Walls



What flow behavior causes the enhanced cooling?

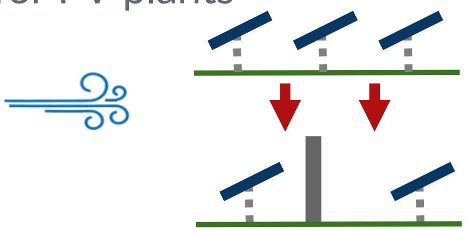




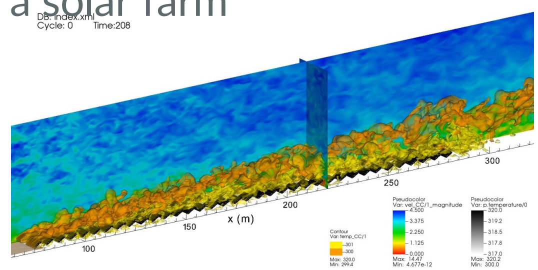


Contributions of this work

Low-cost cooling solution for PV plants



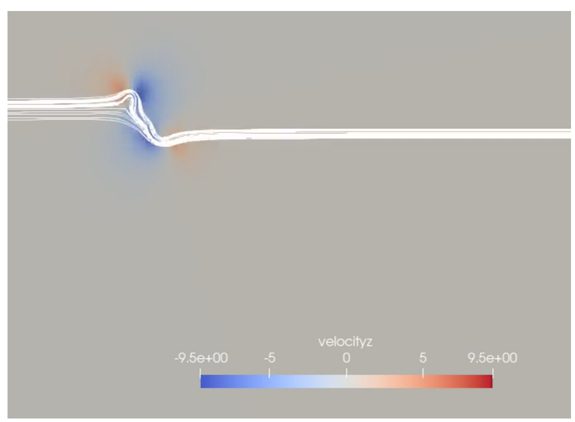
Spatial variations within a solar farm



Related work

Wind loading of heliostats in concentrated solar power plants

July 26, 2017 - Heliostats at the Ivanpah Solar Project, owned by NRG Energy, Bright Source Energy, Bechtel and Google. (Photo by Dennis Schroeder / NREL)



Flow past a heliostat. (Video by Eliot Quon and Shashank Yellapantula / NREL 2022)

Check out these posters to learn more about this project

6) Prilliman, Matthew. "Technoeconomic Analysis of changing PV System Layout and Convection Heat Transfer"
7) Davis, Jace. "Convective Cooling of Solar Photovoltaic Modules in Unperturbed Atmospheric Conditions"
8) Glick, Andrew. "Effects of module configuration on convective cooling for utility-scale solar PV plants"

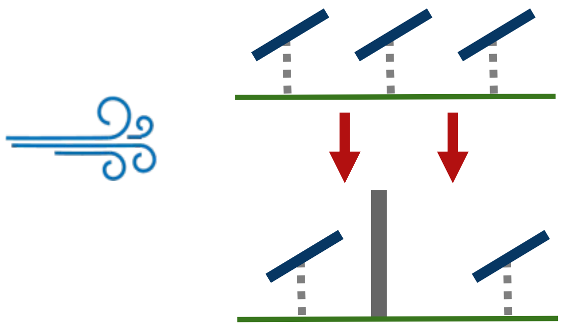
Thank you

Brooke Stanislawski
brooke.stanislawski@nrel.gov

Back-Up Slides

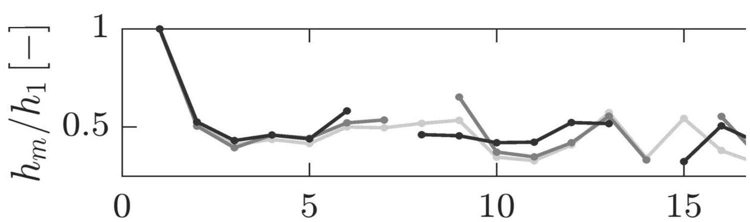
Contributions of this work

Low-cost cooling solution for PV plants



Manipulation of flow to induce cooling

Spatial variations within a solar farm



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Thank you

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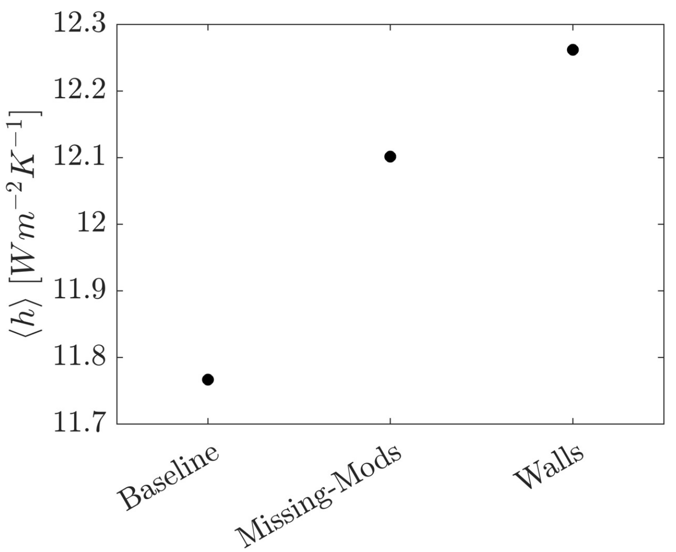
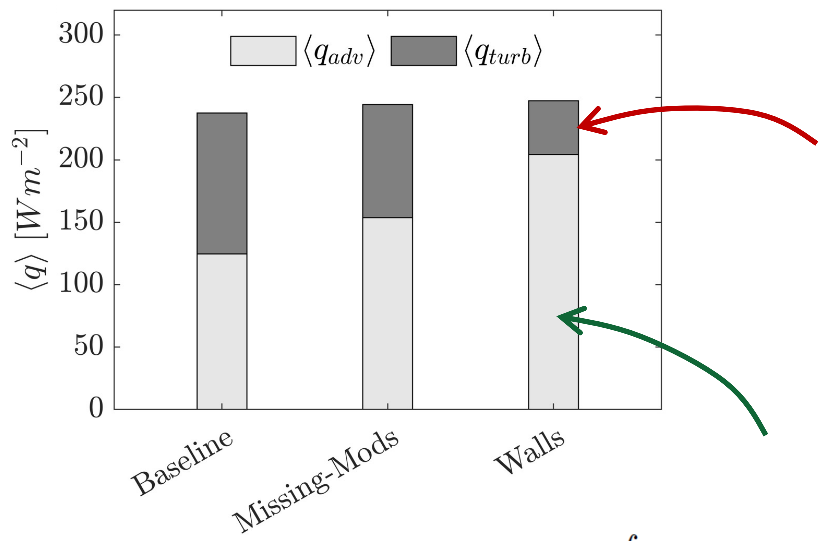
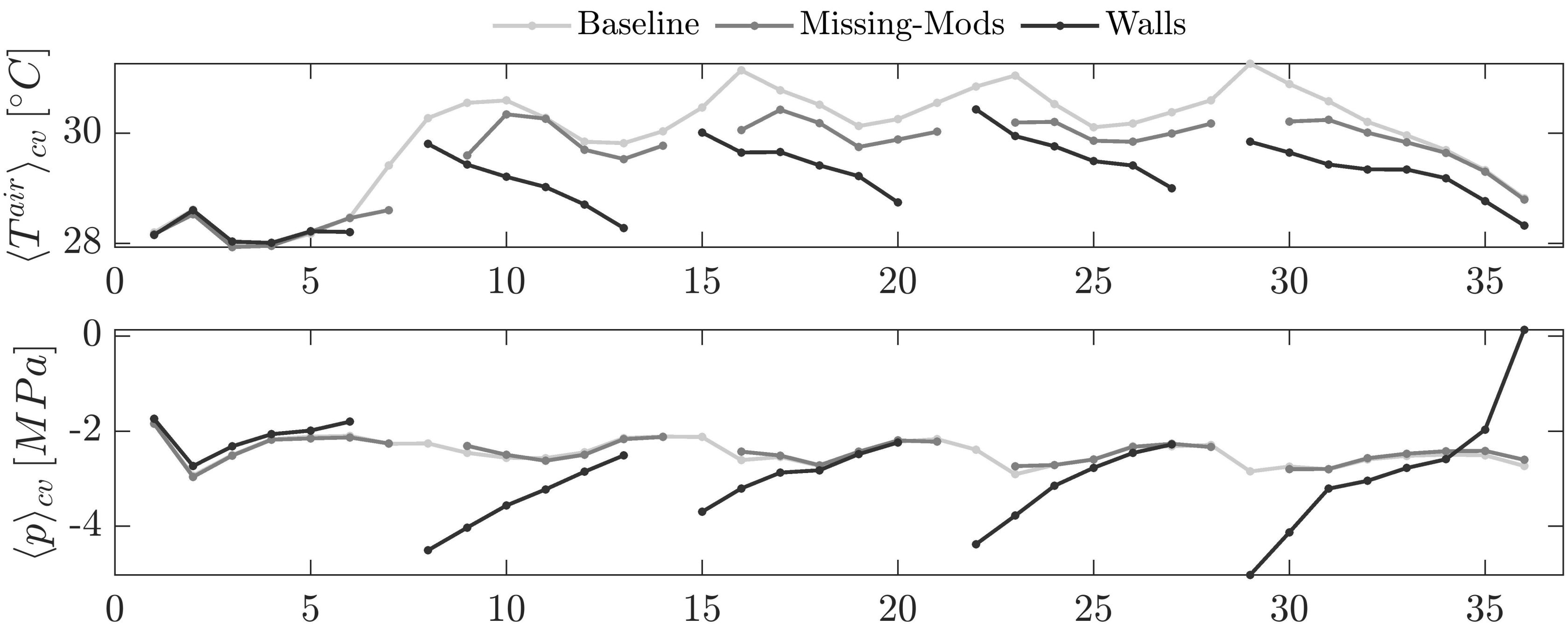
Barrier walls boost advective heat flux

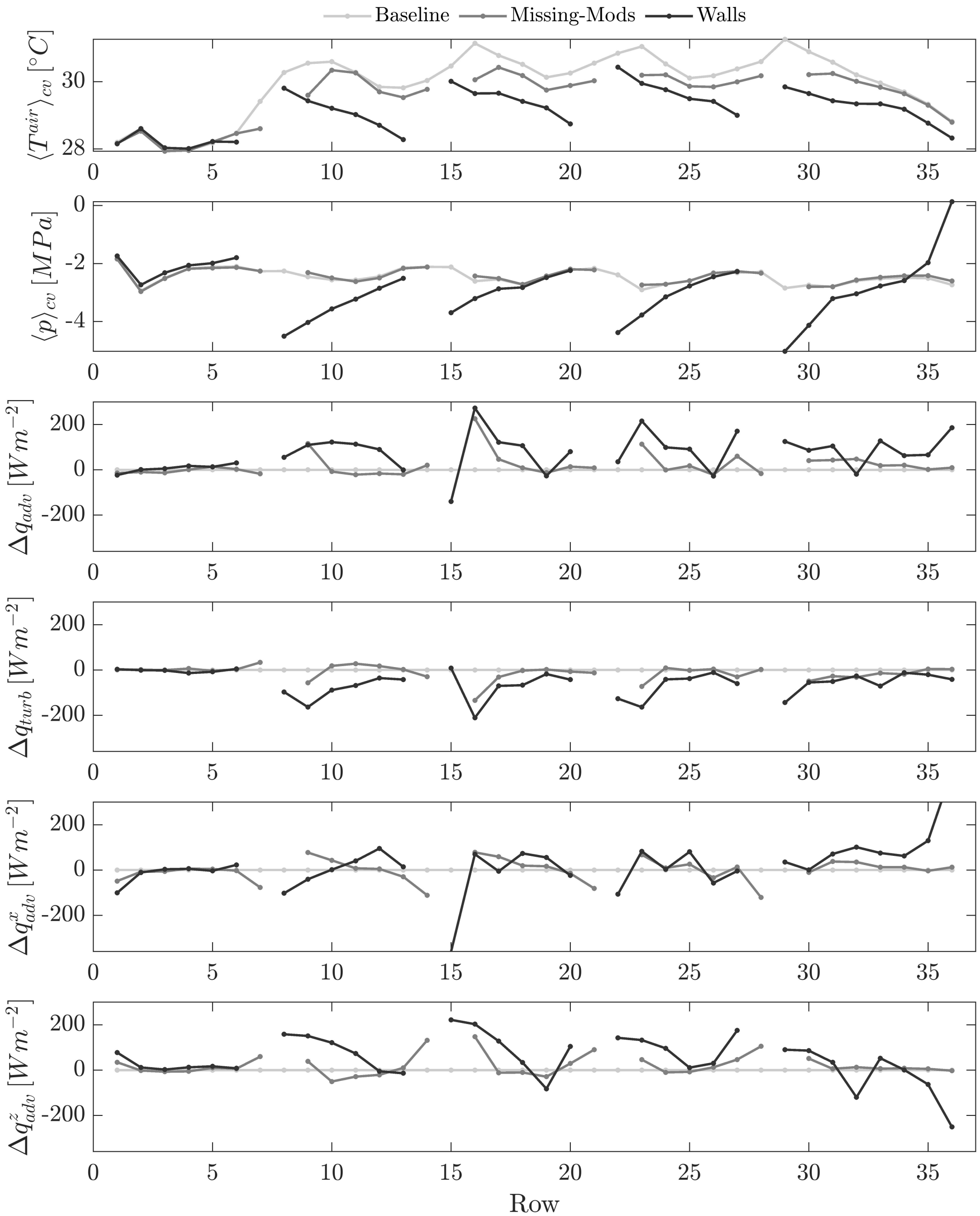




$$\underbrace{\int_{A_k} \left[\overline{\mathbf{u}}_{\perp} (\overline{T} - T_{ref}) \right] dA_k}_{q_{adv}}$$



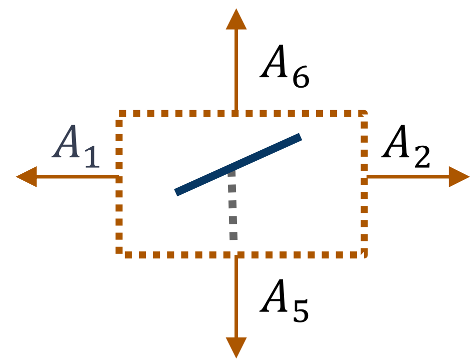
Baseline
Missing-Mods
Walls
$\langle T^{air} \rangle_{cv}$ [°C]
30
28
0
5
10
15
20
25
30
35
$\langle p \rangle_{cv}$ [MPa]
0
-2
-4
0
5
10
15
20
25
30
35


Baseline
Missing-Mods
Walls
$\langle T^{air}\rangle_{cv}$ [°C]
$\langle p\rangle_{cv}$ [MPa]
Δq_{adv} [Wm^{-2}]
Δq_{turb} [Wm^{-2}]
Δq^x_{adv} [Wm^{-2}]
Δq^z_{adv} [Wm^{-2}]
Row

LES results are analyzed to compute the convective heat transfer coefficient *h*

Newton's Law of Cooling

$$h = \frac{q_m}{T_m - T_\infty} \quad [\mathrm{W/m^2K}]$$



To solve for q_m, we start with the enthalpy equation

$$\rho C_p \frac{\partial \overline{T}}{\partial t} + \rho C_p \frac{\partial(\overline{u}_j \overline{T})}{\partial x_j} = -\rho C_p \frac{\partial\left(\overline{u_j' T'}\right)}{\partial x_j} + \overline{s} \quad [\mathrm{W\,m^{-3}}]$$

Integrating over the control volume

$$\underbrace{\rho C_p \int_{cv} \frac{\partial \overline{T}}{\partial t}\, dV}_{Q_{st}} + \underbrace{\rho C_p \int_{cv} \frac{\partial(\overline{u_j}\overline{T})}{\partial x_j}\, dV}_{Q_{adv}} + \underbrace{\rho C_p \int_{cv} \frac{\partial(\overline{u_j' T'})}{\partial x_j}\, dV}_{Q_{turb}} = \underbrace{\int_{cv} \overline{s}\, dV}_{Q_s\,[W]}, \quad [\mathrm{W}]$$

$$Q_s = Q_{cv} = Q_m$$

Neglecting storage and converting volume integrals to surface integrals

$$q_m = \rho C_p \left[\underbrace{\sum_{k=1}^{6} \int_{A_k} \left[\overline{\mathbf{u}}_\perp (\overline{T} - T_{ref})\right] dA_k}_{q_{adv}} + \underbrace{\sum_{k=1}^{6} \int_{A_k} (\overline{\mathbf{u}'_\perp T'})\, dA_k}_{q_{turb}} \right]. \quad [\mathrm{W\,m^{-2}}]$$

$$\text{where } T_{ref} = \langle T_{air} \rangle_{cv}$$

Morrison et al. 2020

MPMICE Equations

Conservation of mass

$$\frac{1}{V}\frac{\mathrm{D}_r M_r}{\mathrm{D}t} = \sum_{s=1}^{N} \Gamma_{rs}$$

Conservation of momentum

acceleration due to mean mixture stress

acceleration due to deviation of material stress from mean mixture stress

gravitational body force

$$\frac{1}{V}\frac{\mathrm{D}_r(M_r \mathbf{u}_r)}{\mathrm{D}t} = \theta_r \nabla \cdot \boldsymbol{\sigma} + \nabla \cdot \theta_r(\boldsymbol{\sigma}_r - \boldsymbol{\sigma}) + \rho_r \mathbf{g} + \sum_{s=1}^{N} \mathbf{f}_{rs} + \sum_{s=1}^{N} \mathbf{u}_{rs}^{+} \Gamma_{rs}$$

+turbulence

model for momentum exchange among materials

rate of mass conversion among materials

Conservation of energy

$$\frac{1}{V}\frac{\mathrm{D}_r(M_r e_r)}{\mathrm{D}t} = -\rho_r p \frac{\mathrm{D}_r v_r}{\mathrm{D}t} + \theta_r \boldsymbol{\tau}_r : \nabla \mathbf{u}_r - \nabla \cdot \mathbf{j}_r + \sum_{s=1}^{N} q_{rs} + \sum_{s=1}^{N} h_{rs}^{+} \Gamma_{rs}$$

model for heat energy exchange among materials

$$q_{12} = H_{12}\theta_1\theta_2(T_2 - T_1)$$

H_{12} is analagous to a convective heat transfer coefficient

closure relation for material stress

$$\boldsymbol{\sigma}_r = -p\mathbf{I} + \boldsymbol{\tau}_r$$