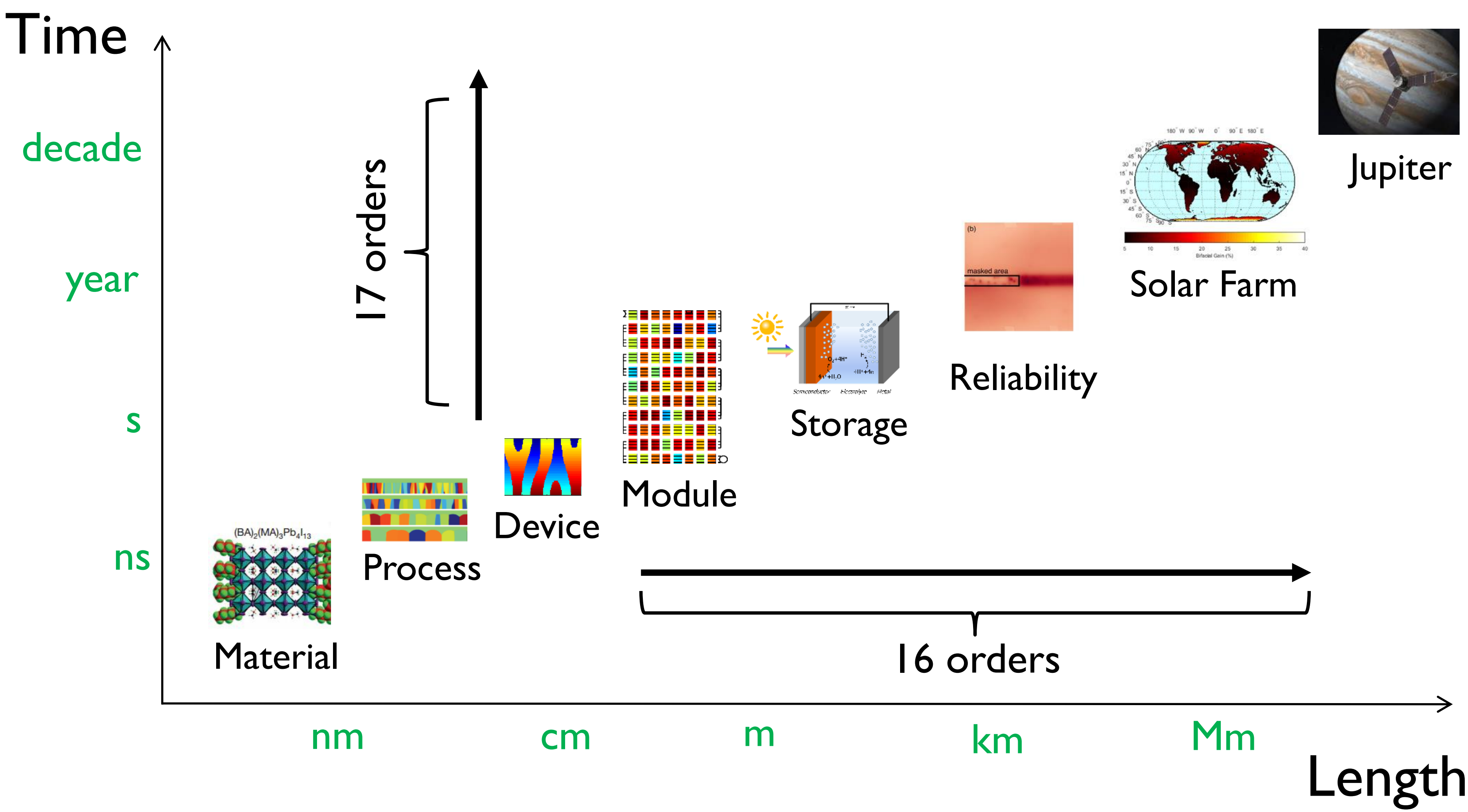
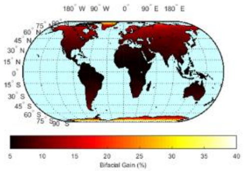
Physics and Performance Limits of Bifacial Solar Cells: A Global Perspective

M. A. Alam, X. Sun, R. Khan, C. Deline
(alam@purdue.edu)

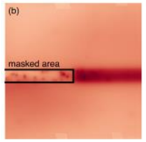
A magnificent multiscale problem: Atom-to-farm perspective



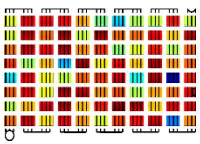
An atom-to-system approach for PV research.



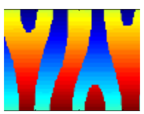
Solar Farm



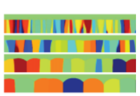
Reliability



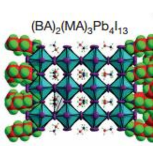
Module



Device



Process



Thermodynamic

Vertical Bifacial Solar Farms: Physics, Design, and Global Optimization

M. Ryyan Khan [b,1], Amir Hanna [a,1], Xingshu Sun [b,1], Muhammad A. Alam [b,1,*]

SCIENTIFIC REPORTS

OPEN Directing solar photons to sustainably meet food, energy, and

COLUMBIA UNIVERSITY

UPPSALA UNIVERSITET

First Solar.

MiaSolé

NSF

BAPVC

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Los Alamos NATIONAL LABORATORY EST. 1943

SERIIUS

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

IIT BOMBAY

Massachusetts Institute of Technology

APPLIED MATERIALS

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology

UNIVERSITY OF DELAWARE

Muhammad A. Alam[a)] and M. Ryyan Khan
School of Electrical and Computer Engineering, Purdue University, W

(Received 15 September 2012; accepted 15 June 2013)

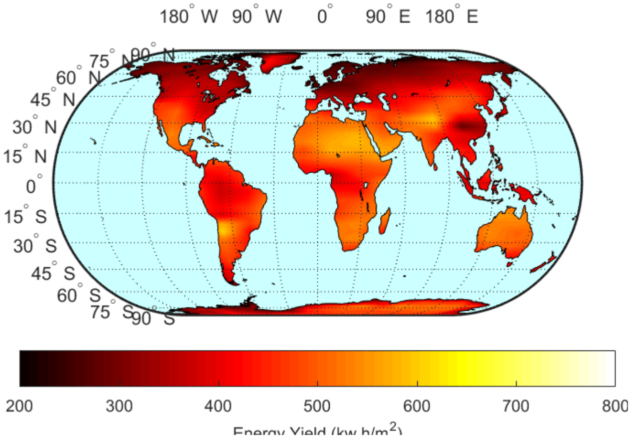
(Received 21 September 2015; accepted 6 November 2015; published online 1 December 2015)

Thermodynamic Efficiency Limits of Classical and Bifacial Multi-junction Tandem Solar Cells: An Analytical Approach

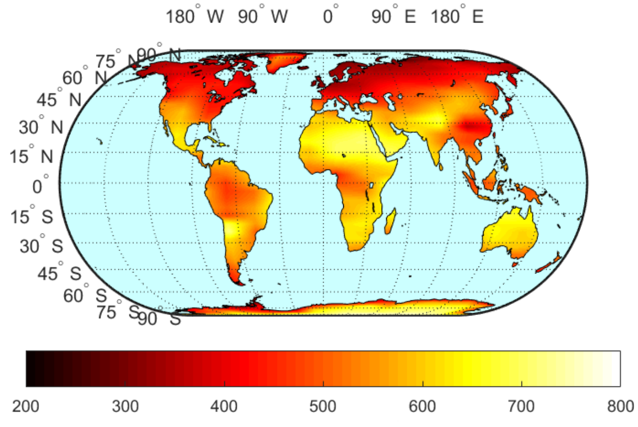
Muhammad A. Alam[a)] and M. Ryyan Khan
School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN-47907, USA

Like politics … PV is local

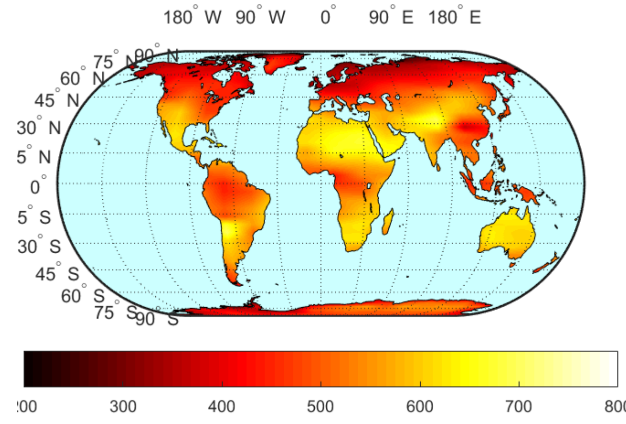
Mono-HIT

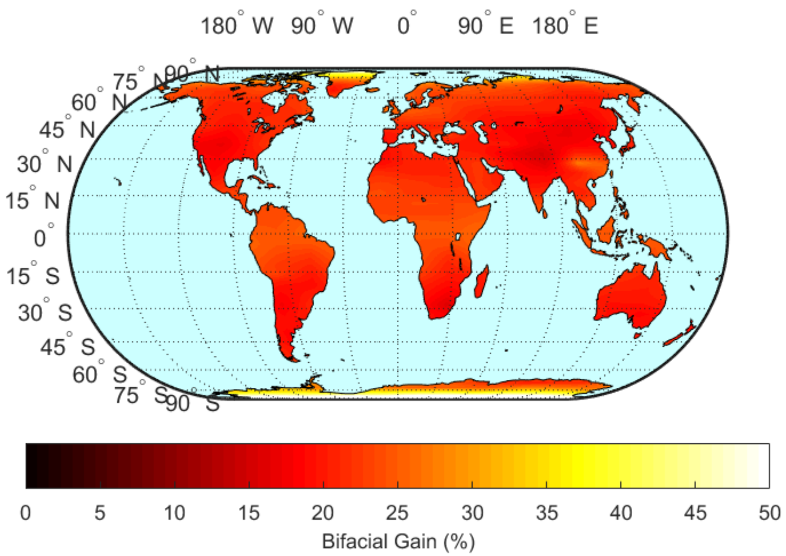


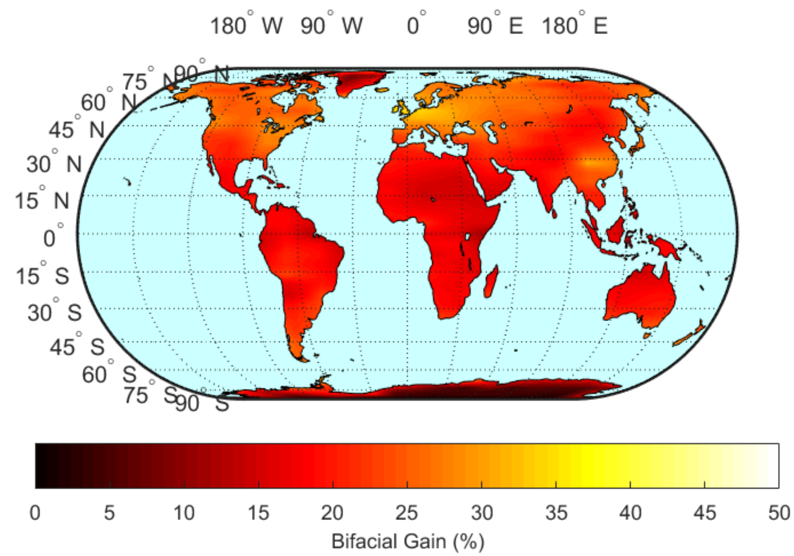
Bi-HIT



PVK-HIT





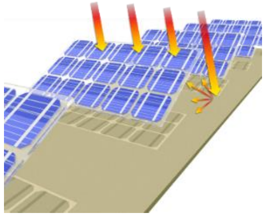


Outline

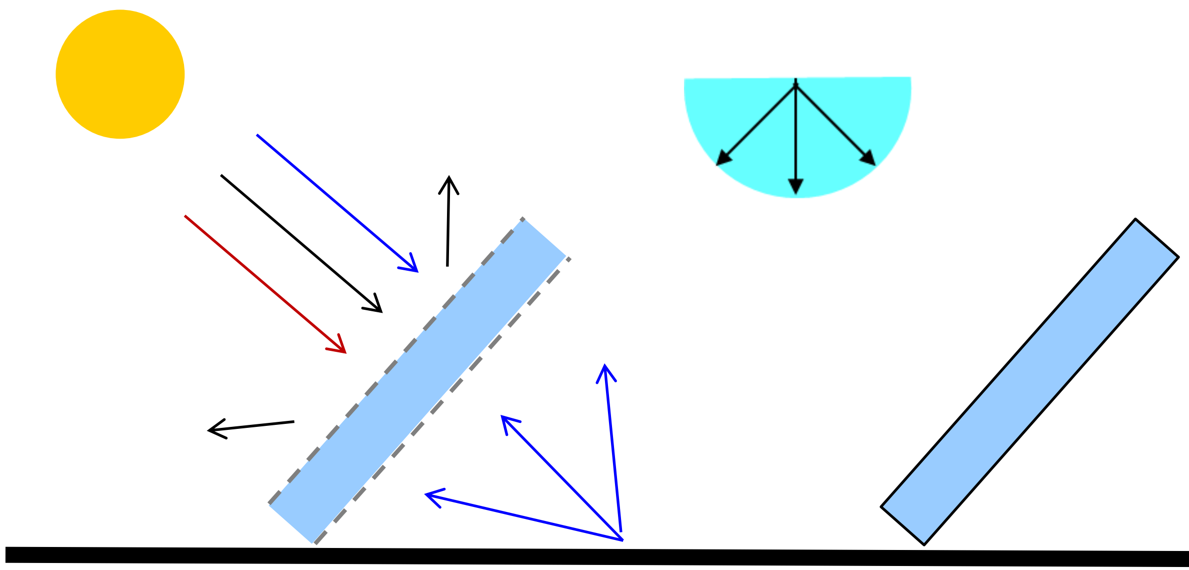
- Physics of bifacial solar cells
  - Solar Cell: A not-so-efficient technology
  - Efficiency of bifacial solar cells
  - Energy yield of actual solar farms

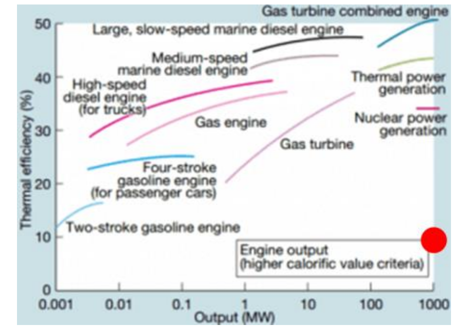
- Three types of bifacial solar farms
  - Standalone bifacial solar farms
  - Vertical and Ground Sculpted Solar Farms
  - LCOE and Optimally tiled Bifacial Solar Farms

- Opportunities
  - Simulator, Tandem, tracking solar cells



PV: An inefficient machine



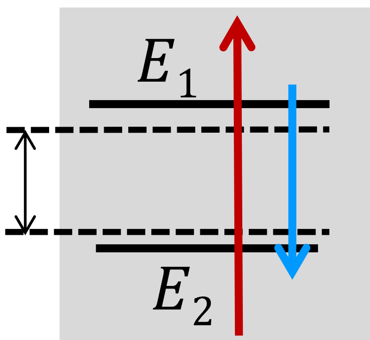


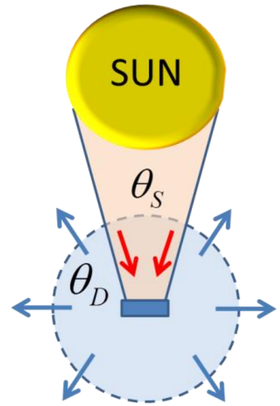
$$\eta = \eta_N \times \eta_{SQ} \times \eta_M \times \eta_A = \frac{2}{\pi} \times \frac{1}{3} \times \frac{5}{6} \times \frac{3}{4} \sim \frac{1}{7}$$

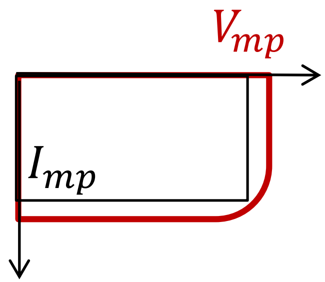
Tracking, multi-junction, bifacial

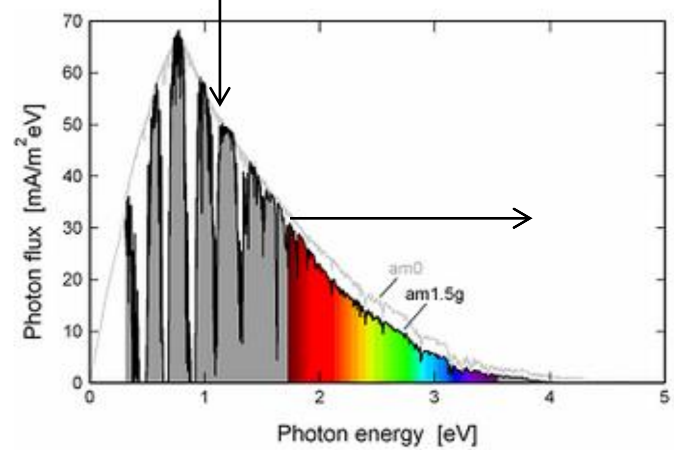
Sun and SQ Triangle…

$$I_{mp} = \frac{2q\theta_s\, k_B T_D}{c^2 h^3}\; E_g^2\, e^{-\frac{E_g}{k_B T_s}}$$

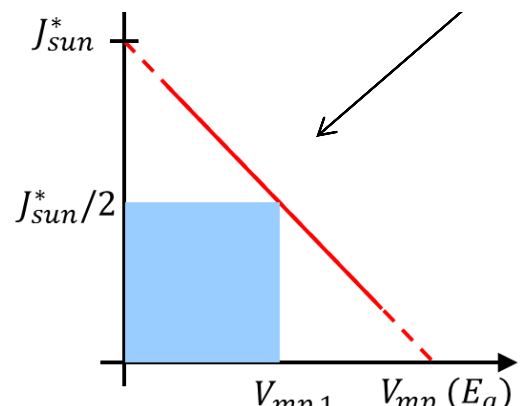








$$J_{mp} = 70\left(1 - 0.52\, V_{mp}\right)$$

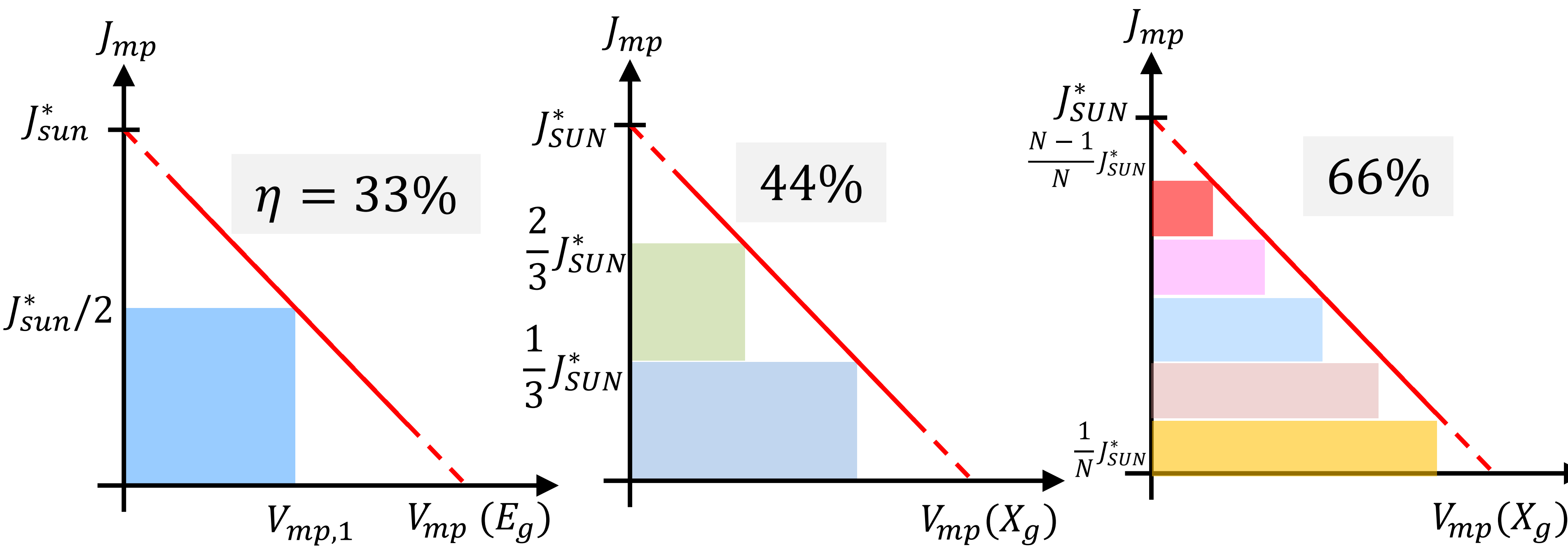


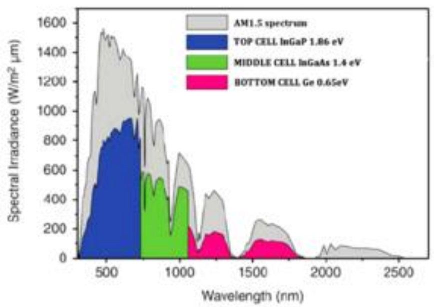
Khan & Alam, APL, 107, 223502, 2015, Also, see AJP, 2012

SQ Triangle and Tandem PV

$$J_{mp} = 70(1 - 0.52\, V_{mp})$$

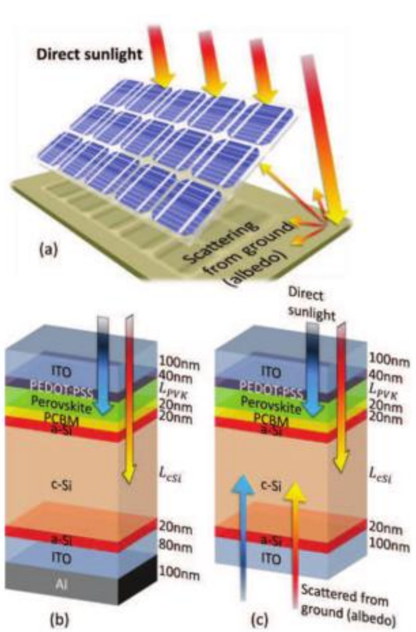
$$P_{out} = J_{mp} \times V_{mp}$$

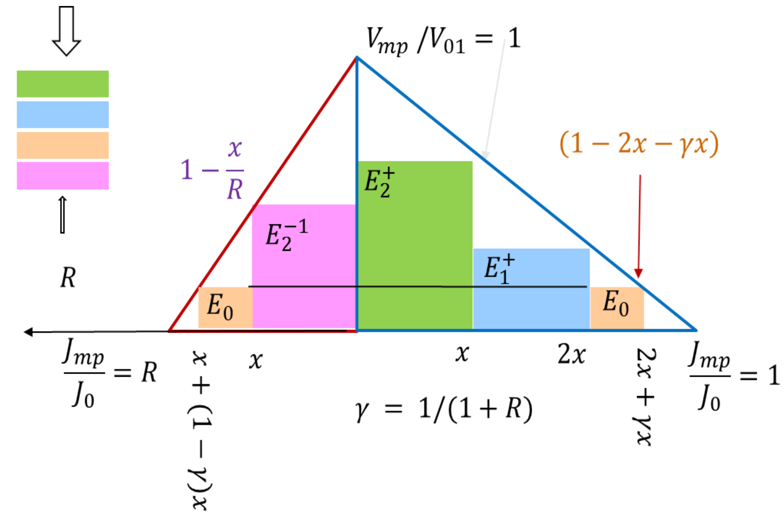




$$\eta_N = \eta_1 \times \frac{2N}{N+1}$$

SQ Limit of Bifacial Solar Cell

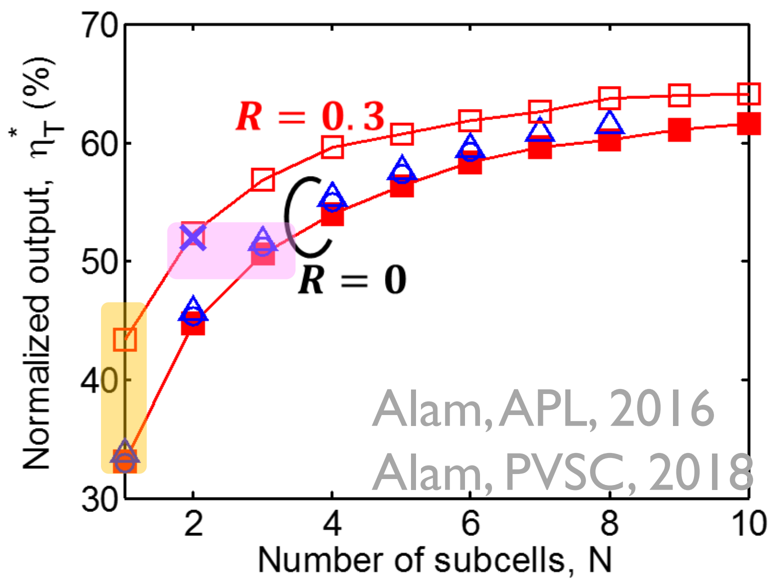




$$N_{crit} \leq 1 + R^{-1}$$

$$\frac{S_N}{S_1} = \frac{2(1+R)N^2}{N(N+1)(R+1) - 2R}$$

$$\frac{S_N}{S_1} = \frac{8R(1+R)N^2}{2R(2N^2+4N+1) - 9R^2 - 1}$$



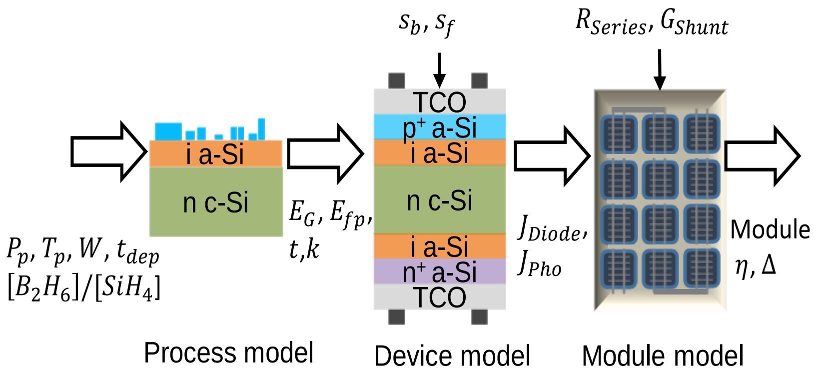
Outline

- Physics of bifacial solar cells
  - Solar Cell: A not-so-efficient technology
  - Efficiency of bifacial solar cells
  - Energy yield of actual solar farms

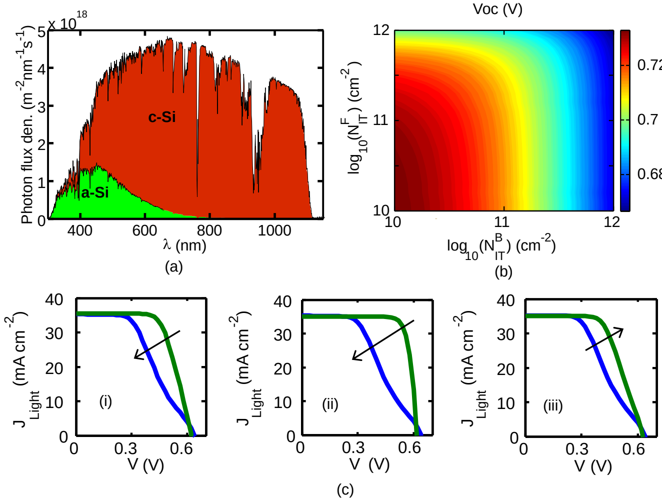
- Three types of bifacial solar farms
  - Illumination and electrical model of bifacial PV
  - Standalone bifacial solar farms
  - Vertical and Ground Scuplted Solar Farms
  - LCOE and Optimally tiled Bifacial Solar Farms

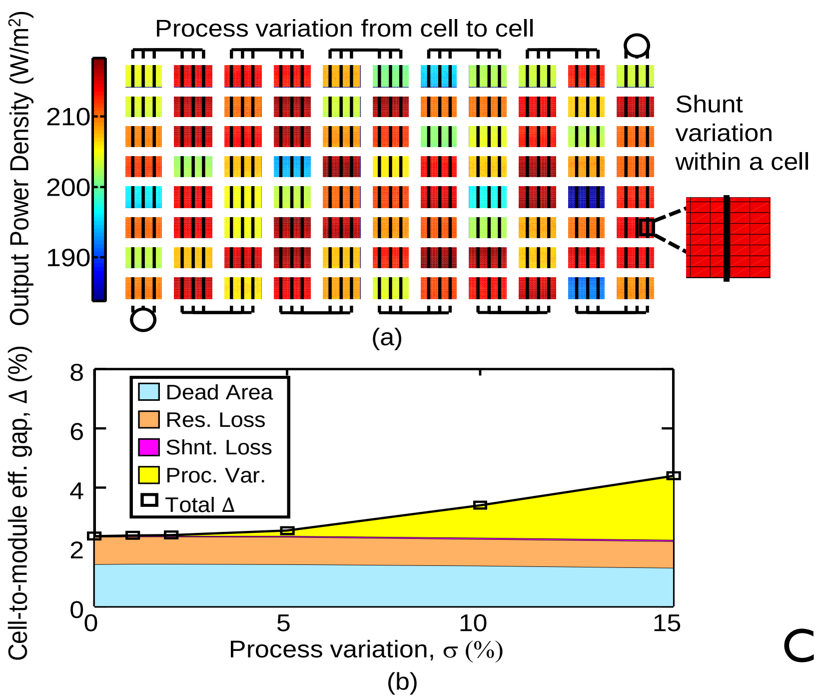
- Opportunities
  - Simulator, Tandem, tracking solar cells

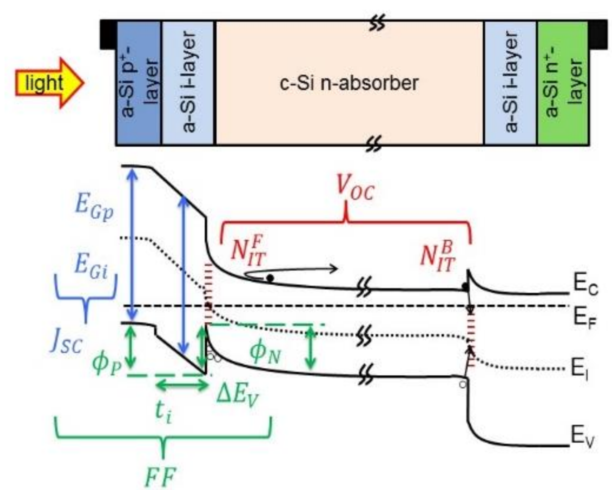
End-to-end modeling of Bifacial Si-Heterojunction Cell



(a)







Chavali, Stefaan De Wolf, M. A. Alam, PIP, 2018.

Sun and the solar cells …

Purdue University Meteorological Tool (PUMET):Available on nanoHUB

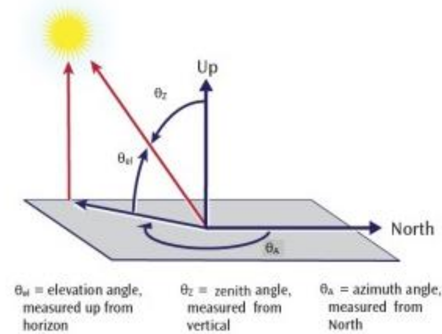
Irradiance Model

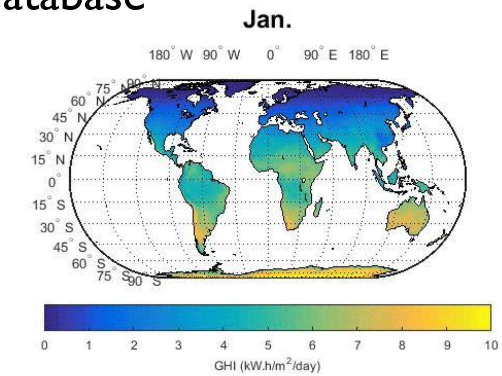
Light Collection

Electrical Output

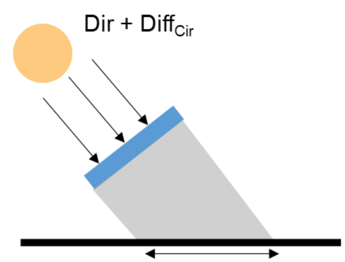
PUB in PVLiB, Cliff Hansen & J. Stein

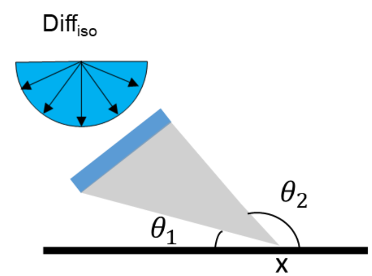
global meteorological database

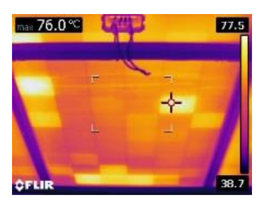




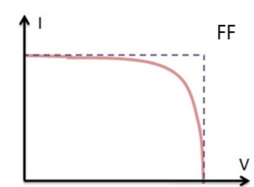
Optical view-factor based approach







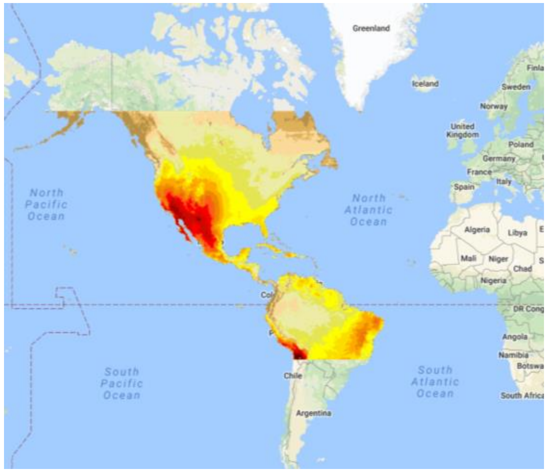
thermal



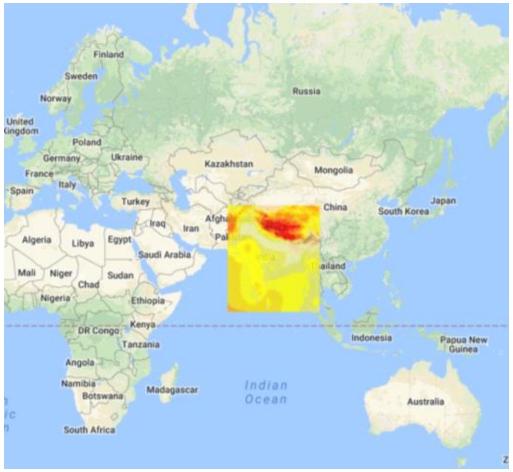
electrical

PUMET database

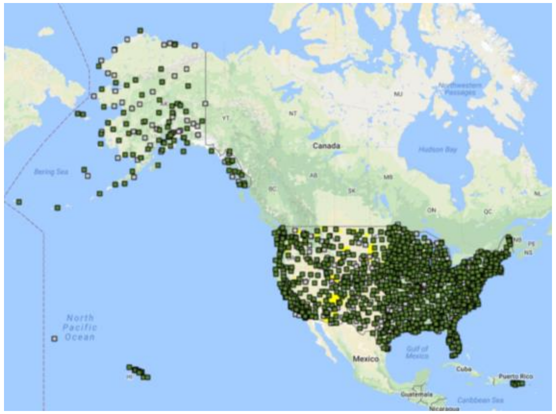
PSM (1998-2014)



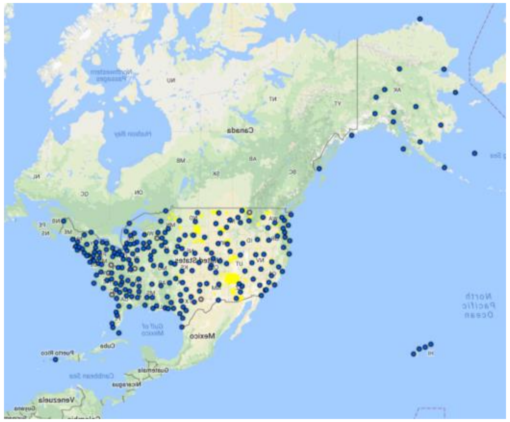
SUNY (2000-2014)



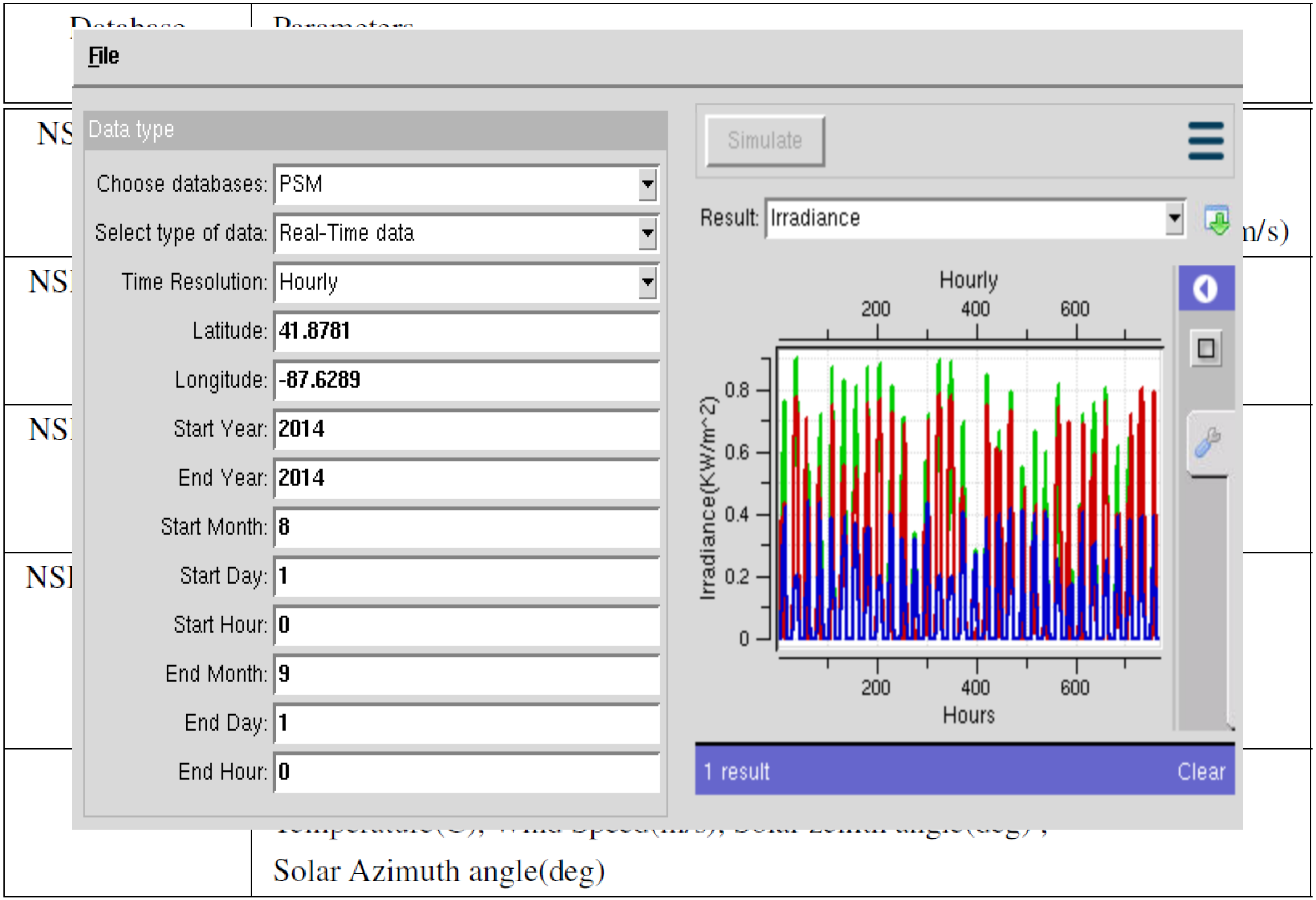
MTS2(1991-2005)



MTS1(1961-1990)



PUMET database



decompose irradiance

Diffuse

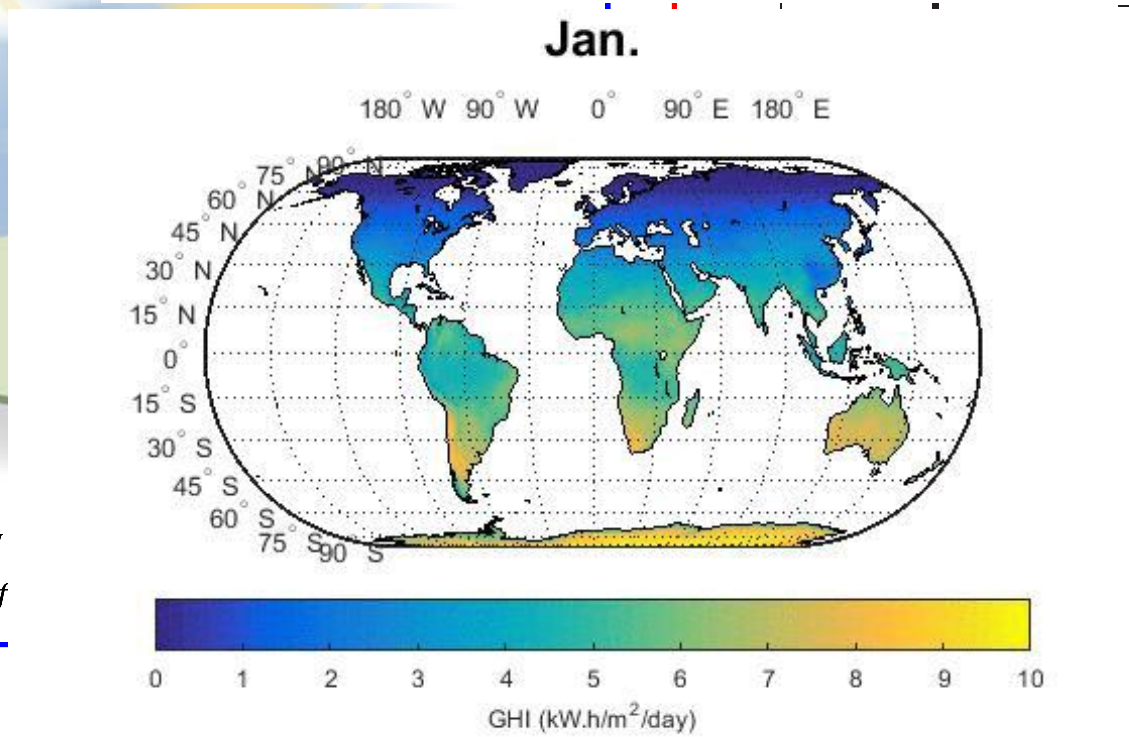
Diffuse

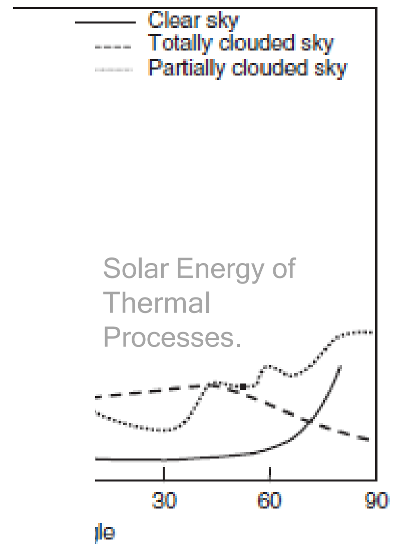
Circumsolar

Isotropic $I_{Diff(Iso)}$

Horizon Brightening $I_{Diff(Hor)}$

What is the sunlight intensity?





Gloabl(I_{GHI}

Diffuse(I_{Dif}

iffuse Light

Measure I_{GHI}

Orgill/Hollands model

I_{Dir} and I_{Diff}

Perez model

$I_{Diff(Cir)}$

$I_{Diff(Iso)}$

$I_{Diff(Hor)}$

X. Sun et al, Applied Energy, 2018

Stand-alone Bifacial PV

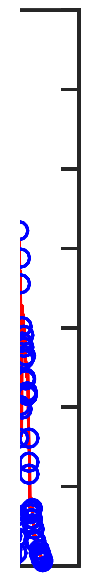
Light to electricity by opto-electro-thermal model

Table. 1 Modeling Framework Validation Against Literature

Location (Type)	Elevation / Module Height (m)	Albedo / Bifaciality	Tilt Angle / Facing	Reported Bifacial Gain (%)	Calculated Bifacial Gain (%)	Difference (%)
Cairo (Sim.) [11]	1 / 0.93	0.2 / 0.8	26° / South	11.0	11.1	-0.1
Cairo (Sim.) [11]	1 / 0.93	0.5 / 0.8	22° / South	24.8	25	-0.2
Oslo (Sim.) [11]	0.5 / 0.93	0.2 / 0.8	51° / South	10.4	13.6	-3.2
Oslo (Sim.) [11]	0.5 / 0.93	0.2 / 0.8	47° / South	16.4	22.8	-6.4
Hokkaido* (Exp.) [46]	0.5 / 1.66	0.2 / 0.95	35° / South	23.3	25.7	-2.4
Hokkaido* (Exp.) [46]	0.5 / 1.66	0.5 / 0.95	35° / South	8.6	13	-4.4
Albuquerque (Exp.) [16]	1.08 / 0.984	0.55 / 0.9	15° / South	32.5**	30.2	2.3
Albuquerque (Exp.) [16]	1.08 / 0.984	0.55 / 0.9	15° / West	39**	36.7	2.3
Albuquerque (Exp.) [16]	1.03 / 0.984	0.25 / 0.9	30° / South	19**	14.6	4.4
Albuquerque*** (Exp.) [16]	0.89 / 0.984	0.25 / 0. 9	90° / South	30.5**	32.2	-1.6
Golden (Exp.) ****	1.02 / 1.02	0.2 / 0.6	30° / South	8.3	8.6	-0.3

* Only data from May to August were used to eliminate snow effects.
** Average bifacial gain of multiple test modules was used.
*** The east-west-facing vertical modules measurement in [16] shows great discrepancy between two modules; therefor, it is not included here.
**** Bifacial measurement (12/2016 to 08/2017) performed by the National Renewable Energy Laboratory.

Th
Lal

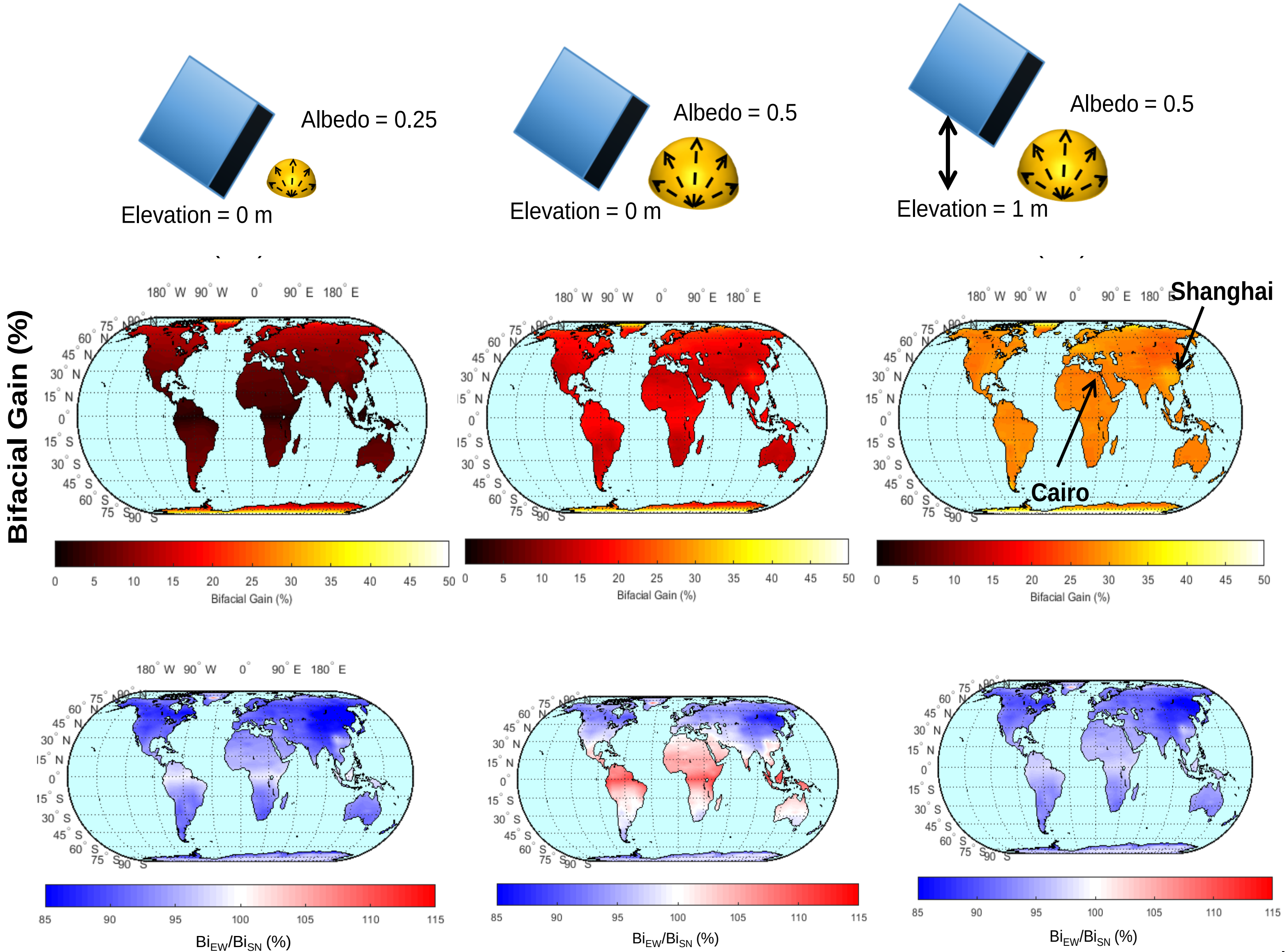


17

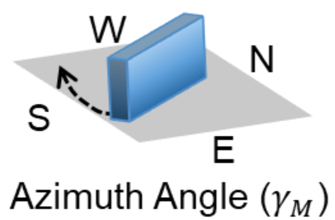
- N
  E
- C

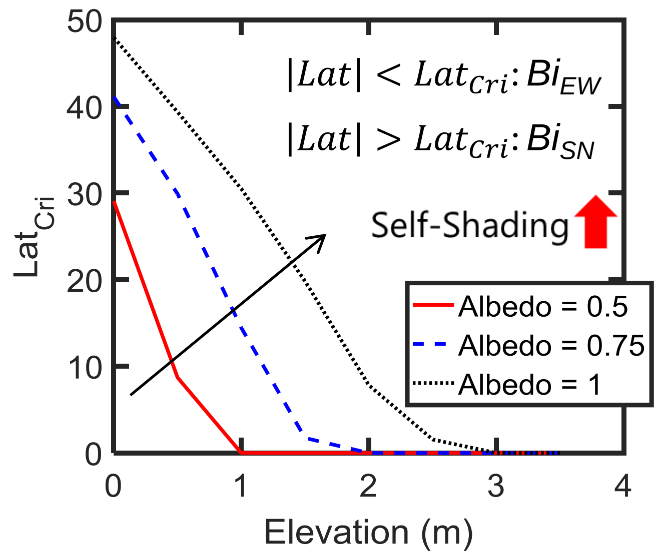
rica,

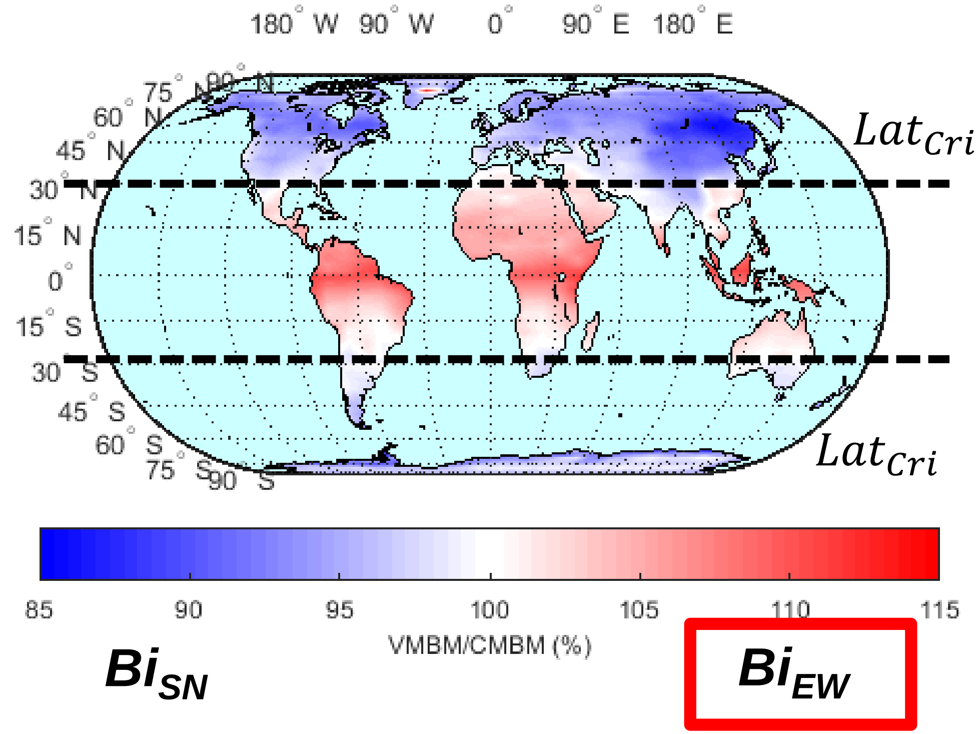
Bifacial Performance/Orientation



global optimization: orientation





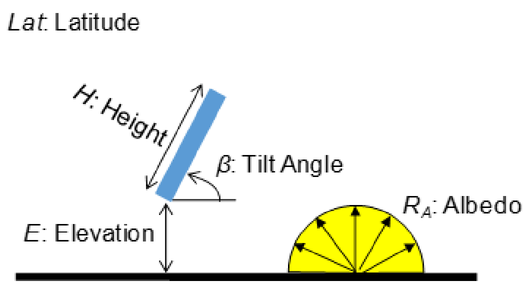


$$Lat_o = E/H \times (44R_A - 62) + 37R_A + 12$$

$$If\ Lat_o \le 0,\ \mathbf{Lat_{Cri}} = 0^o \text{ and}$$
$$If\ Lat_o > 0,\ \mathbf{Lat_{Cri}} = Lat_o$$

X. Sun et al, Applied Energy, 2018

Scaling theory of stand-alone Bifacial



X. Sun and M. Alam, Applied Energy, 2018

E_{95} in meter for a module height of *H*		
$E_o = H \times (-Lat \times (0.028 \times R_A + 0.009) + 3.3 \times R_A + 0.4)$	(A1)	E_{95} is the minimum elevation to achieve at least 95% of the self-shading absent maximum energy yield, i.e., further elevation only provides limited energy boost.
$If\ E_o \leq 0,\ E_{95} = 0$ and $If\ E_o > 0, E_{95} = E_o$	(A2)	
Lat_{Cri} of bifacial solar module for a given elevation (*E*), module height (*H*), and albedo (*R_A*)		
$Lat_o = E/H \times (44 \times R_A - 62) + 37 \times R_A + 12$	(A3)	Lat_{Cri} is the critical latitude below which Bi_{EW} produces more electricity than Bi_{SN} and vice versa.
$If\ Lat_o \leq 0,\ Lat_{Cri} = 0^o$ and $If\ Lat_o > 0,\ Lat_{Cri} = Lat_o$	(A4)	
Optimal Tilt Angle β_{Opt} for Bi_{SN} for a given latitude (*Lat*), elevation (*E*), module height (*H*), and albedo (R_A)		
$\beta_o = a \times Lat + b$	(A5)	β_{Opt} is the optimal tilt angle for Bi_{SN} for maximum electricity yield
$a = 0.86 - 0.57 \times R_A \times \exp(-E/H)$	(A6)	
$b = 4.5 + 62 \times R_A \times \exp(-E/H)$	(A7)	
$If\ \beta_o \geq 90^o,\ \beta_{Opt} = 90^o$ and $If\ \beta_o < 90^o,\ \beta_{Opt} = \beta_o$	(A8)	

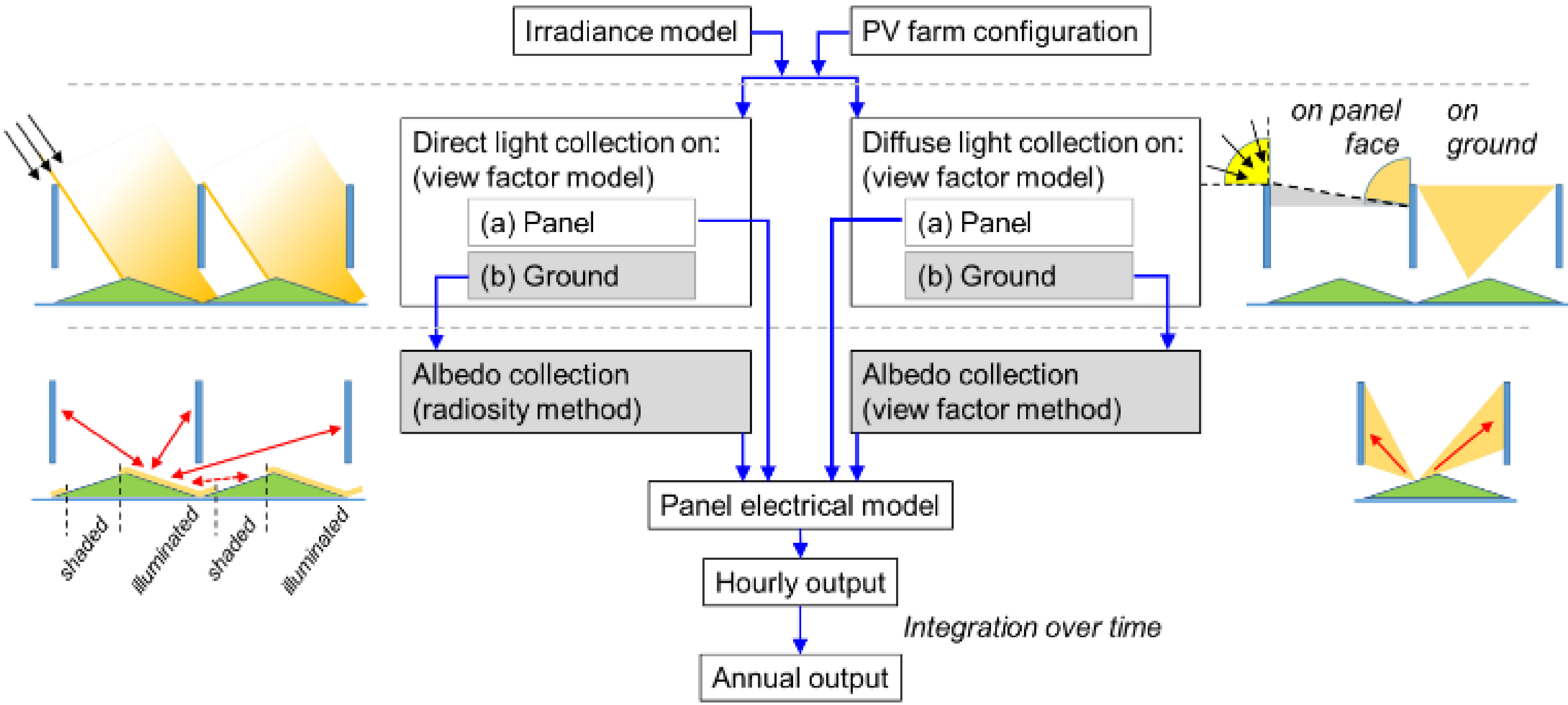
Outline

- Physics of bifacial solar cells
  - Solar Cell: A not-so-efficient technology
  - Efficiency of bifacial solar cells
  - Energy yield of actual solar farms

- Three types of bifacial solar farms
  - Illumination and electrical model of bifacial PV
  - Stand-alone bifacial solar farms
  - Vertical and Ground Scuplted Solar Farms
  - LCOE and Optimally tiled Bifacial Solar Farms

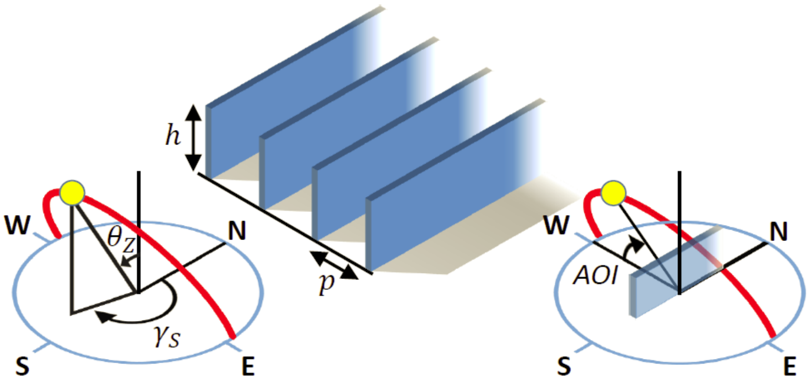
- Opportunities
  - Simulator, Tandem, tracking solar cells

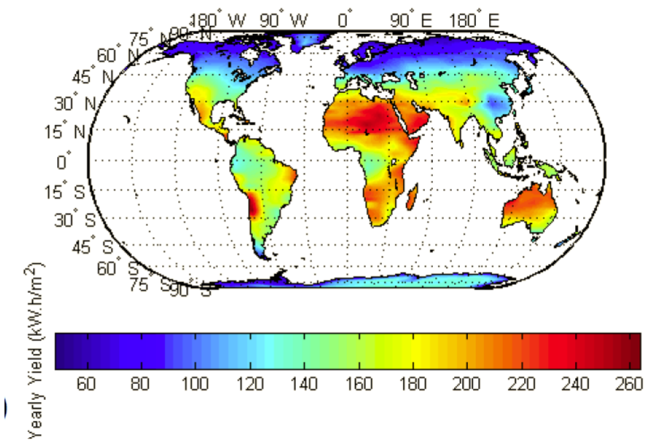
A bifacial solar farm requires complex opto-electro-thermal modeling

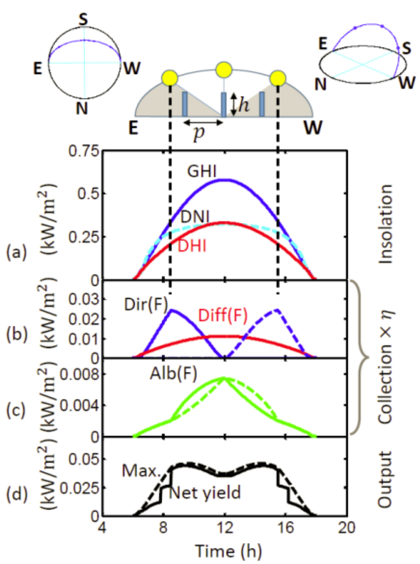


Vertical Solar Farm has advantages, but ....

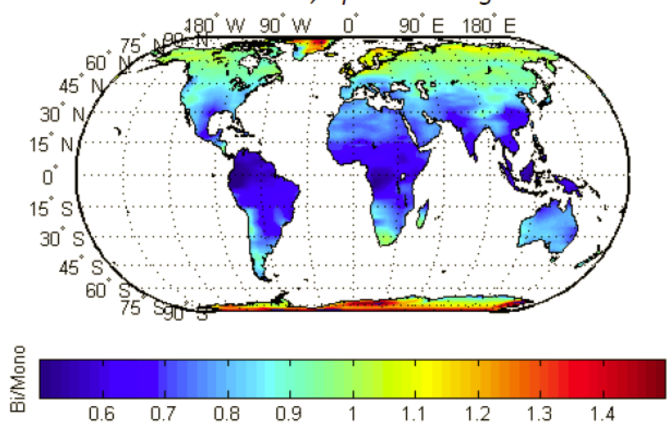
R. Khan and M. Alam, Applied Energy, 2017



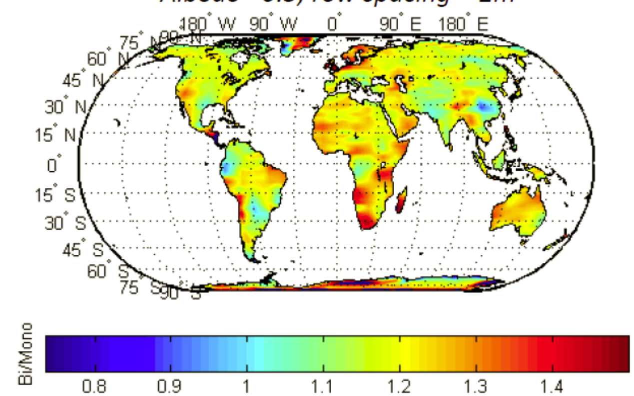




Albedo =0.5, optimal design



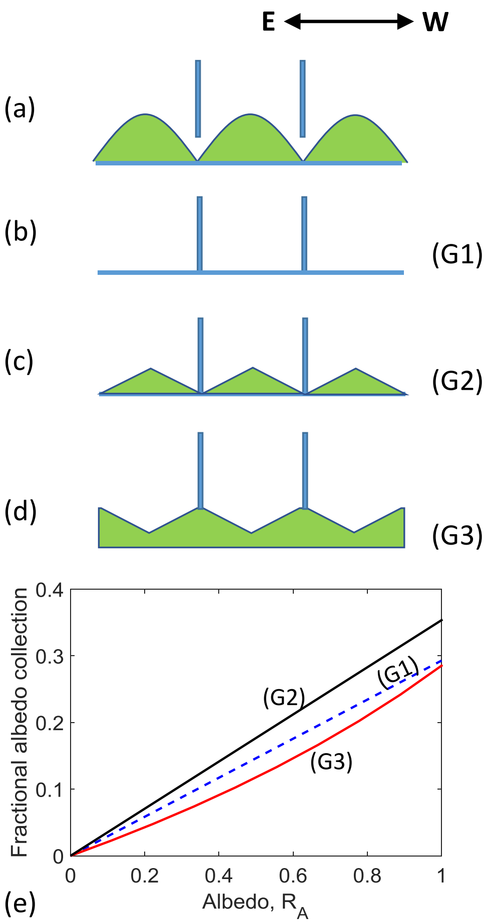
Albedo =0.5, row spacing = 2m

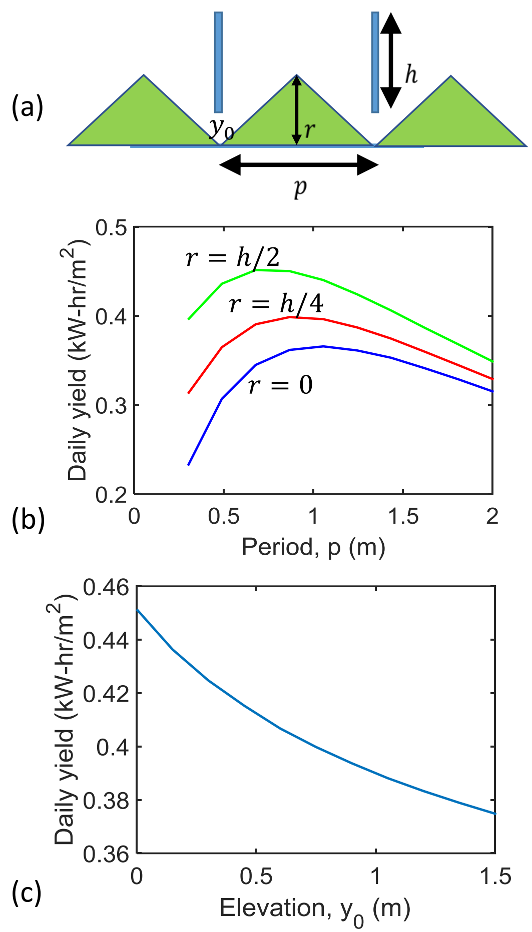


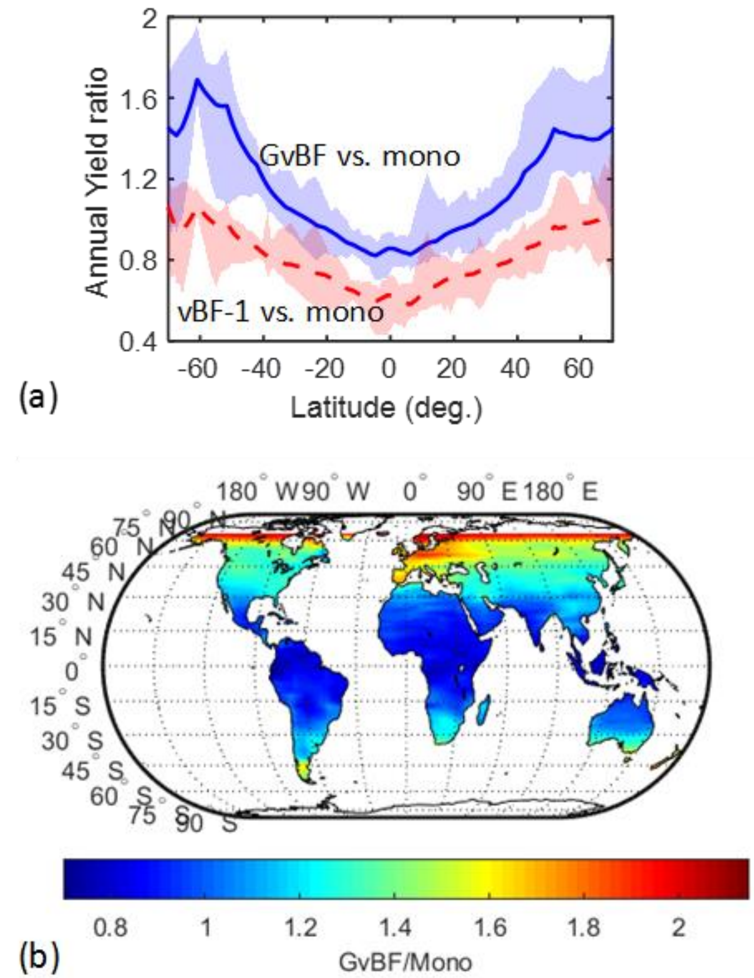
… even with high albedo, the gain is relatively small

Ground-sculpting offers significant improvement …

R. Khan and M. Alam, Applied Energy, 2018 (In review)

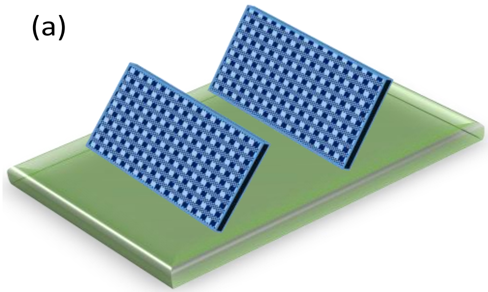




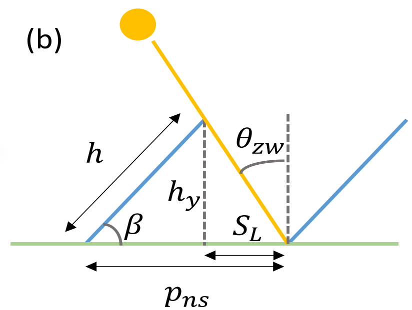


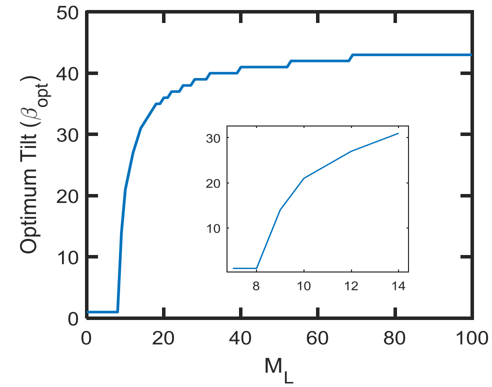
Optimally tilted and LCOE-optimized Farm

(a)

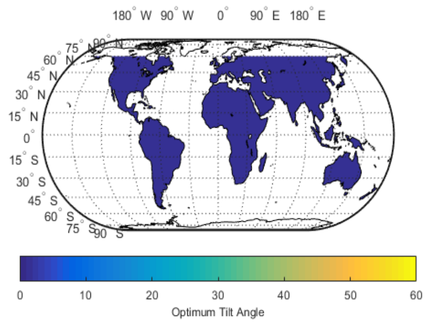


(b)

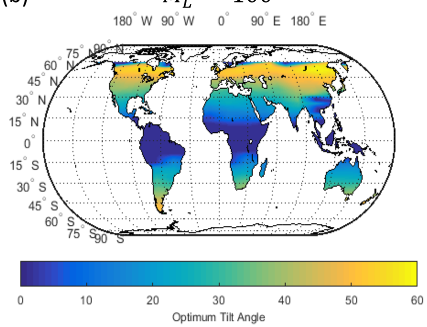




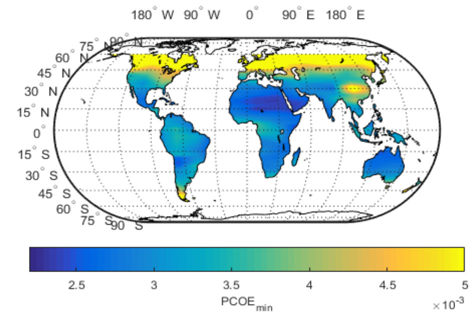
(a) $M_L = 0$



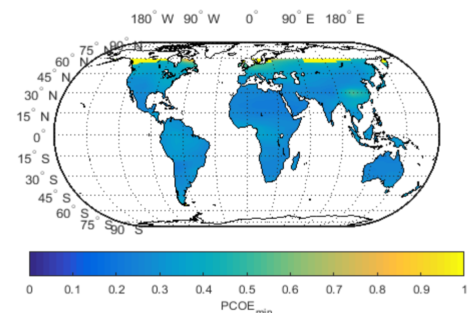
(b) $M_L = 100$



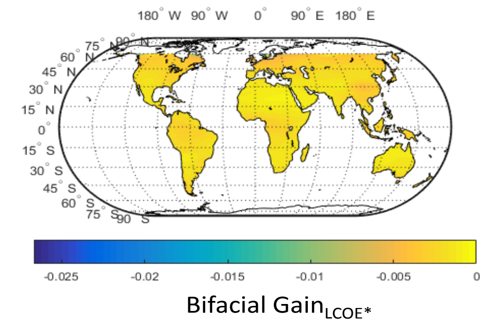
(a) $M_L = 0$



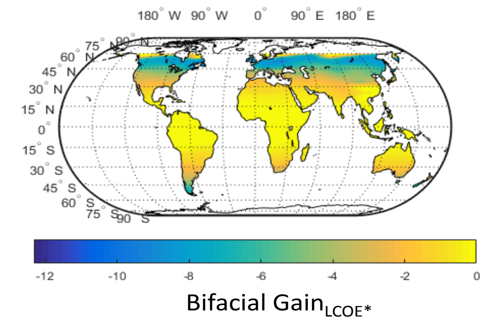
(b) $M_L = 100$



(a) $M_L = 0$



(b) $M_L = 100$



T. Patel and M. Alam, 2018 (Unpublished)

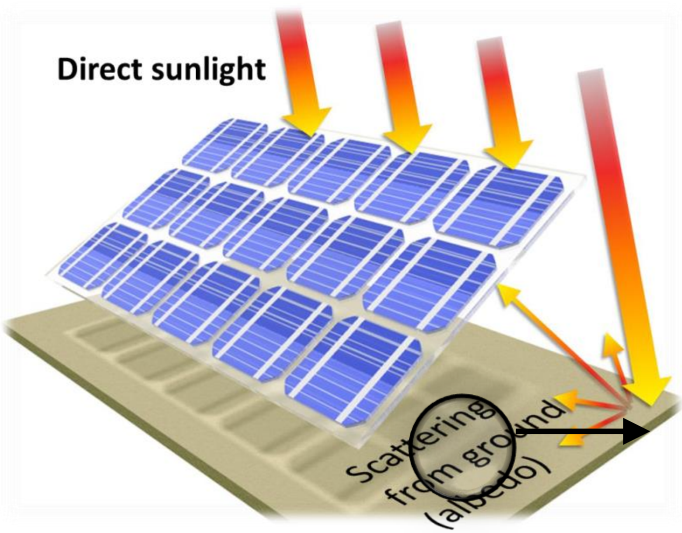
Outline

- Physics of bifacial solar cells
  - Solar Cell: A not-so-efficient technology
  - Efficiency of bifacial solar cells
  - Energy yield of actual solar farms

- Three types of bifacial solar farms
  - Standalone bifacial solar farms
  - Vertical and Ground Sculpted Solar Farms
  - LCOE and Optimally tiled Bifacial Solar Farms

- Opportunities
  - Simulator, Tandem, tracking solar cells

Bifacial tandem cell operation

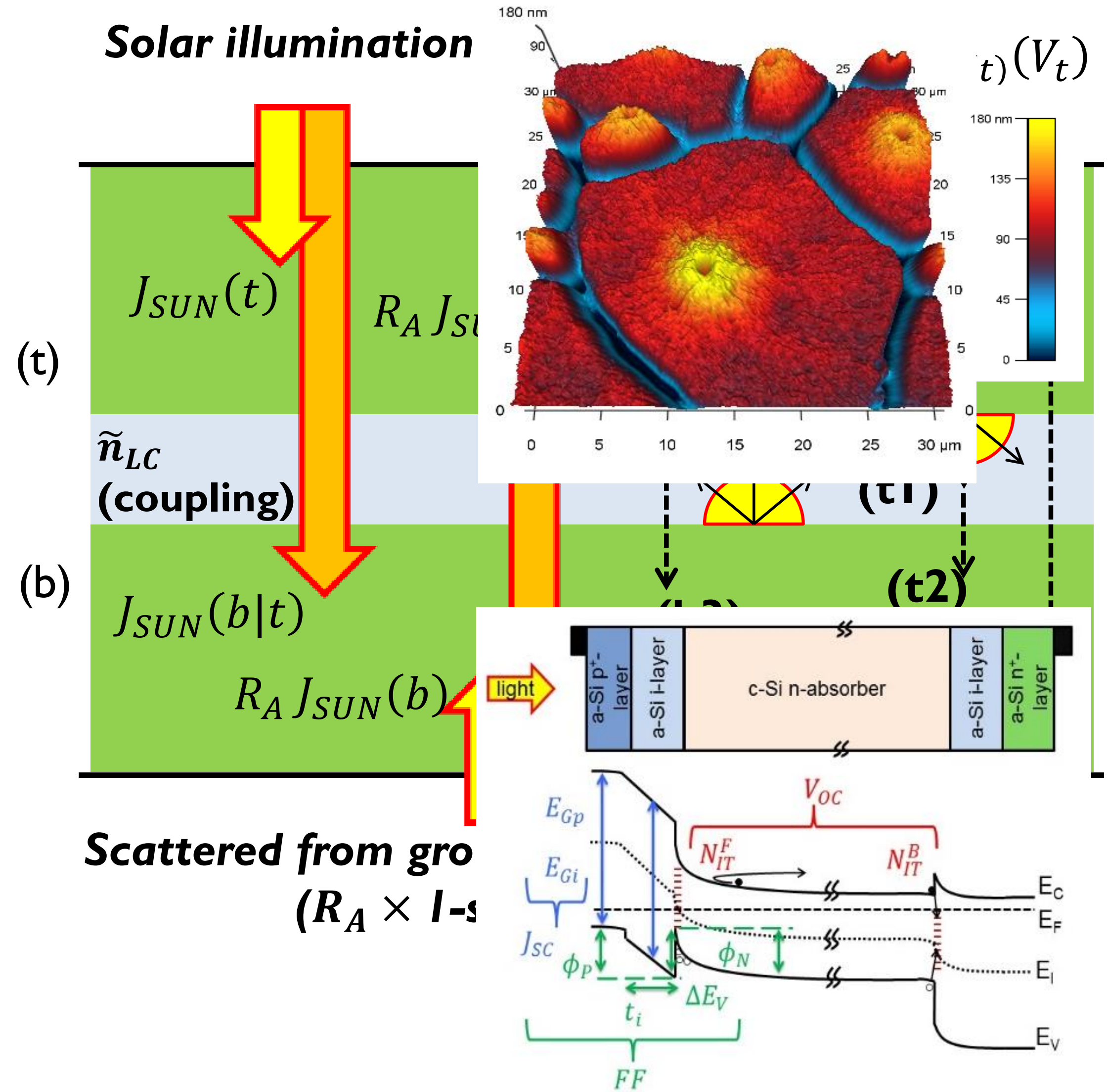


SOLAR CELLS

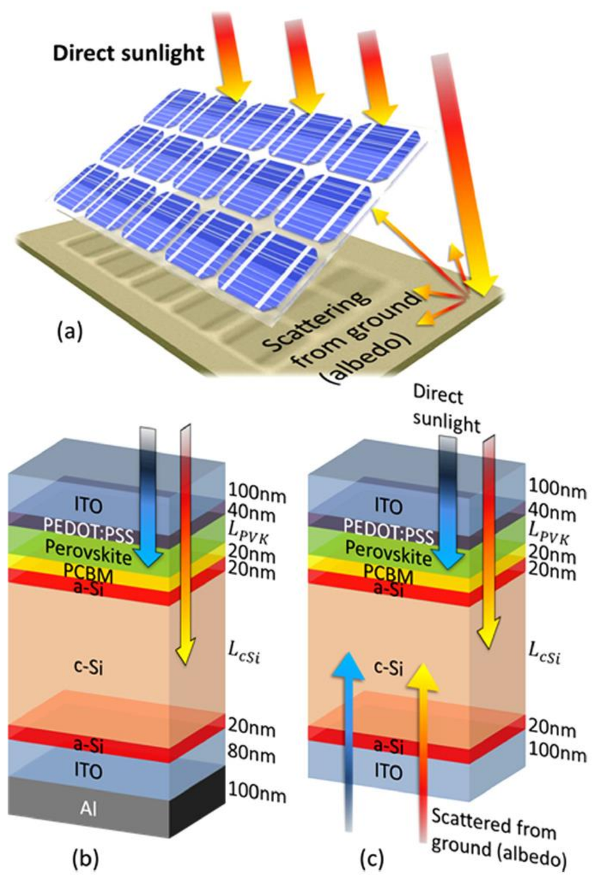
High-efficiency solution-processed perovskite solar cells with millimeter-scale grains

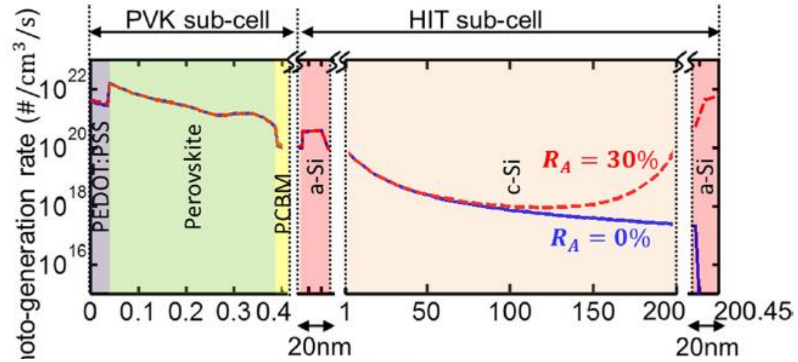
Wanyi Nie,[1*] Hsinhan Tsai,[2*] Reza Asadpour,[3†] Jean-Christophe Blancon,[2†] Amanda J. Neukirch,[4,5] Gautam Gupta,[1] Jared J. Crochet,[2] Manish Chhowalla,[6] Sergei Tretiak,[4] Muhammad A. Alam,[3] Hsing-Lin Wang,[2‡] Aditya D. Mohite[1‡]

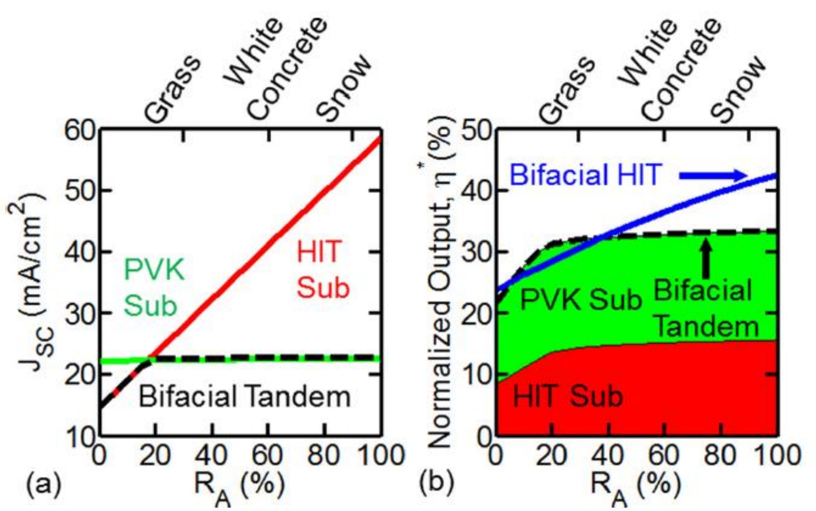
H. Chung, *Optics Express*, 2017.



33% Efficient HIT-Perovskite Cells!



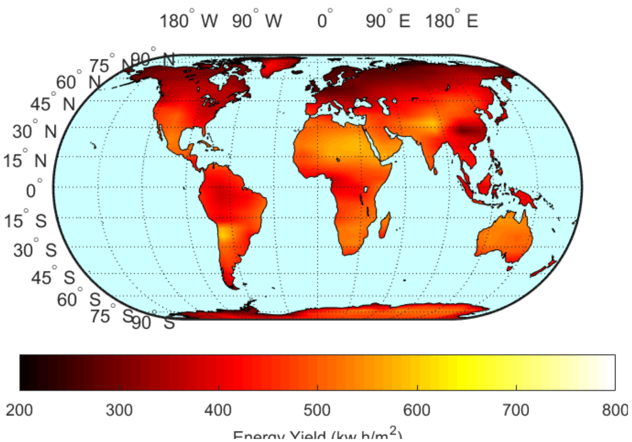




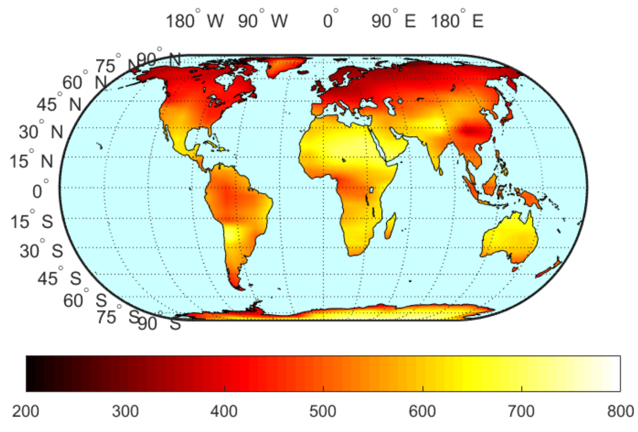
R. Asadpour*, R. V. K. Chavali*, M. R. Khan*, and M. A. Alam, APL, 106, p. 243902, Jun. 2015

Technology/location-specific BPV

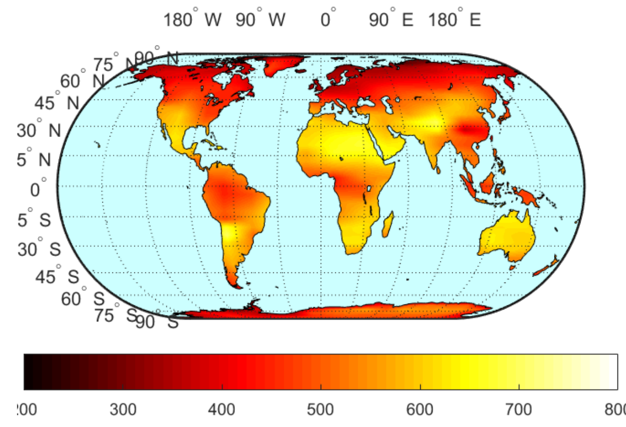
Mono-SHJ

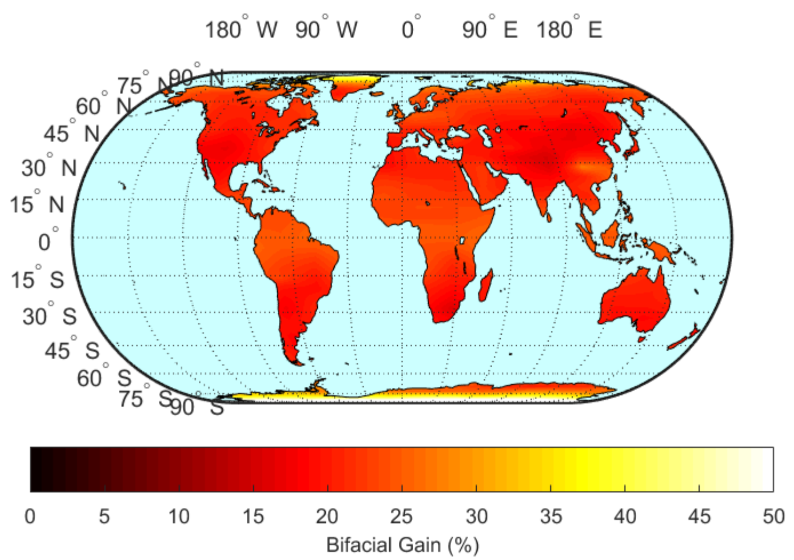


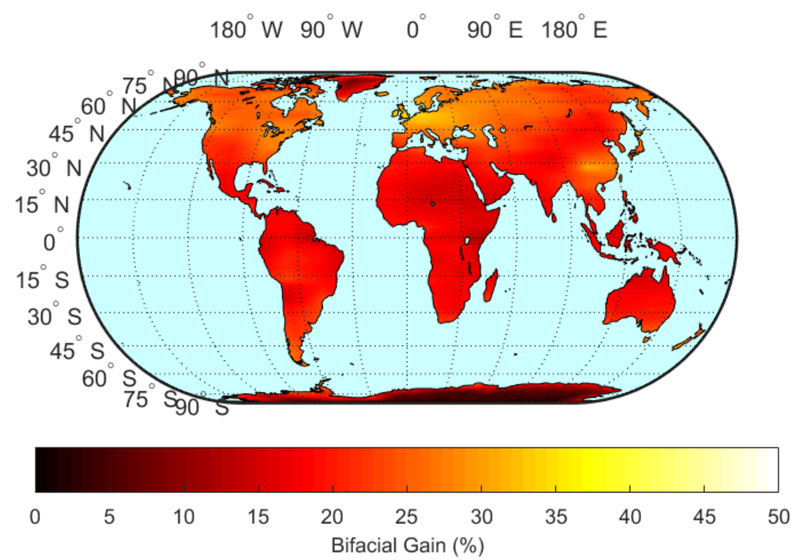
Bi-SHJ



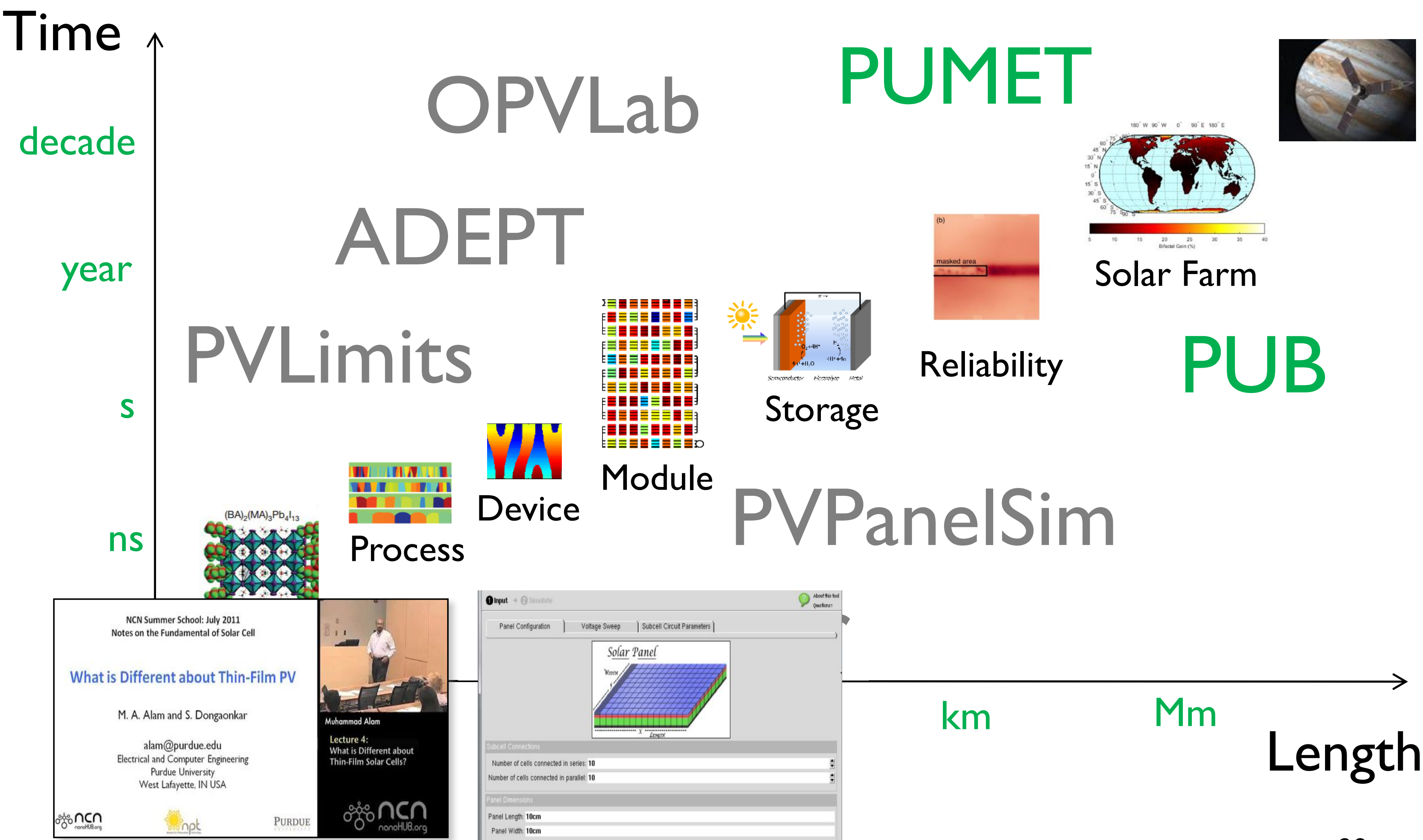
PVK-SHJ





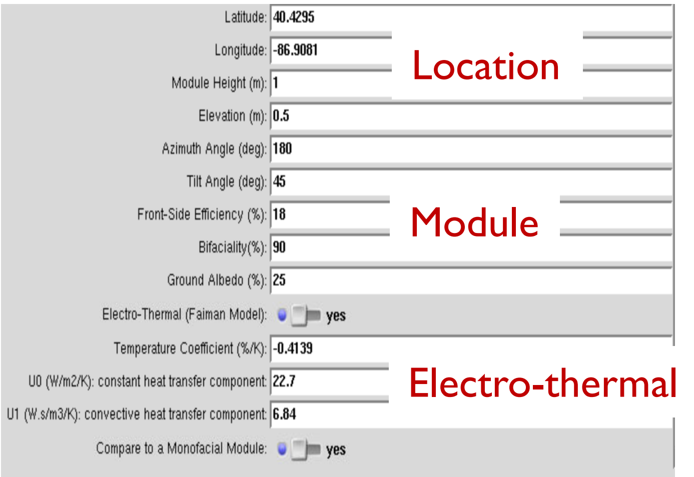


Conclusions: A magnificent Multiscale problem

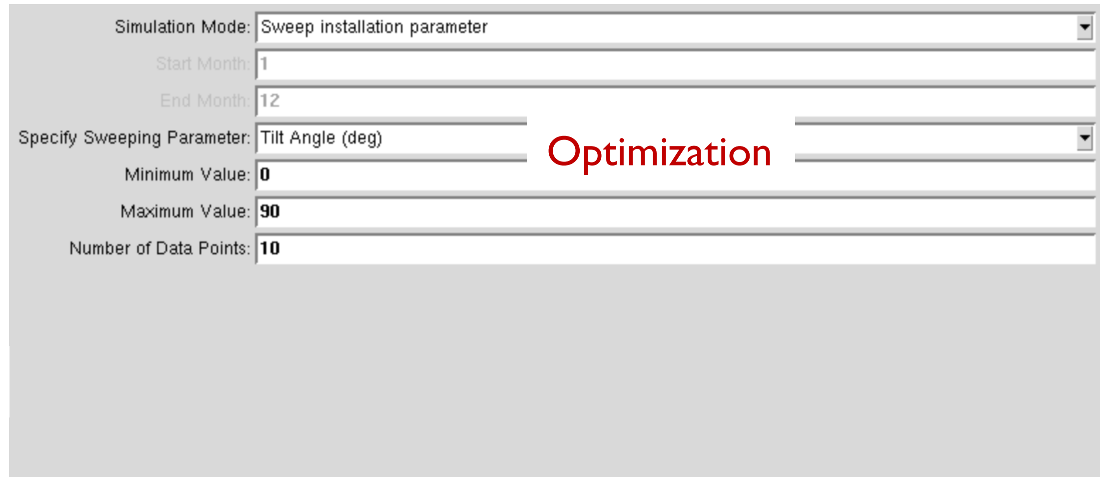


How to use PUB

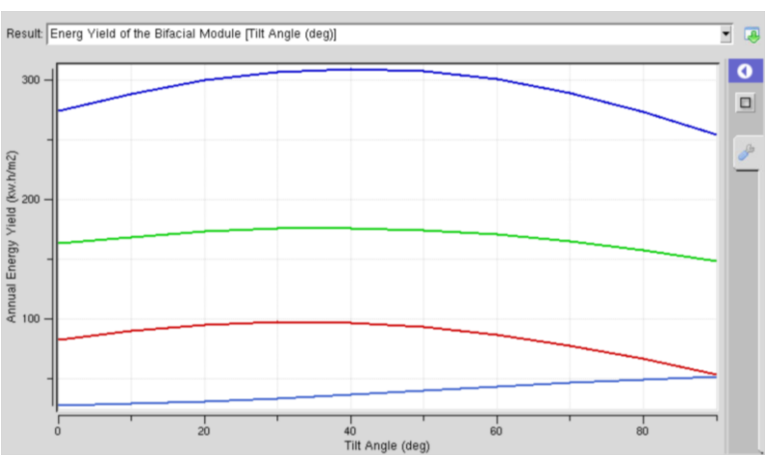
Specification



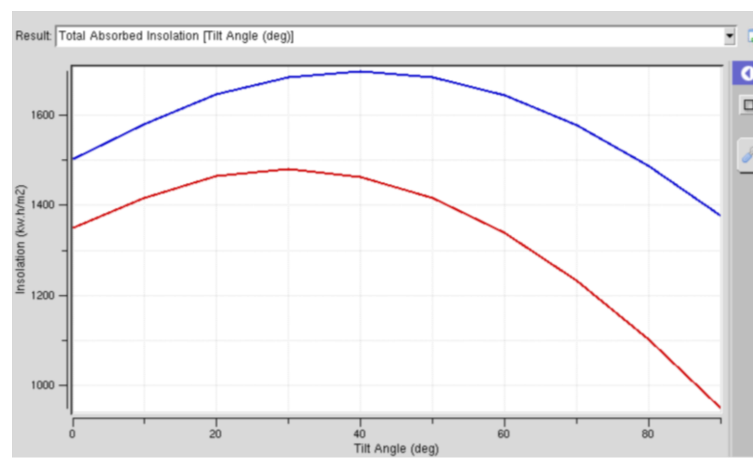
Simulation



Bifacial Energy Yield



Bifacial vs. monofacial energy yield



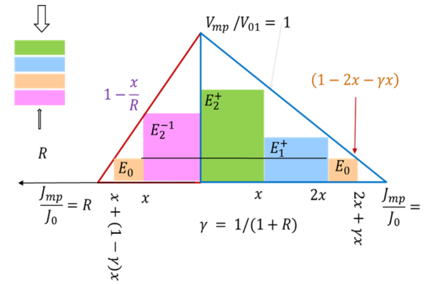
Conclusions: Geography specific solar

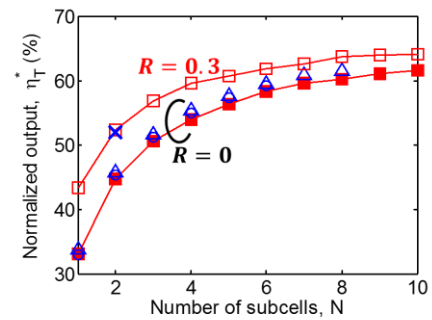
Solar cells are **fundamentally inefficient**. And end-to-end perspective provides opportunities for improvement at the cell, module, and farm levels.

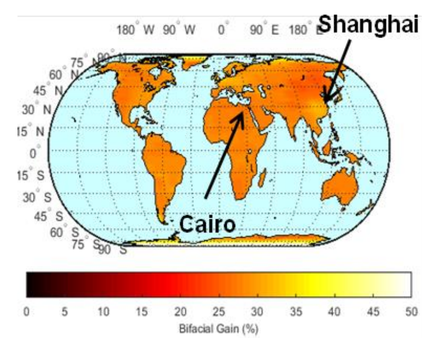
Thermodynamically, bifacial and bifacial tandems promise **dramatic gain.** .

Vertical bifacial farms may be a good choice for certain regions of world. The energy gain may not be significant, but reduction in **cleaning cost and water usage** could be make the system economically viable. For other regions tilt-optimized bifacial PV is profitable.

Reliability is fundamentally important – 5% increase in lifetime may be easier than 5% increase in efficiency.

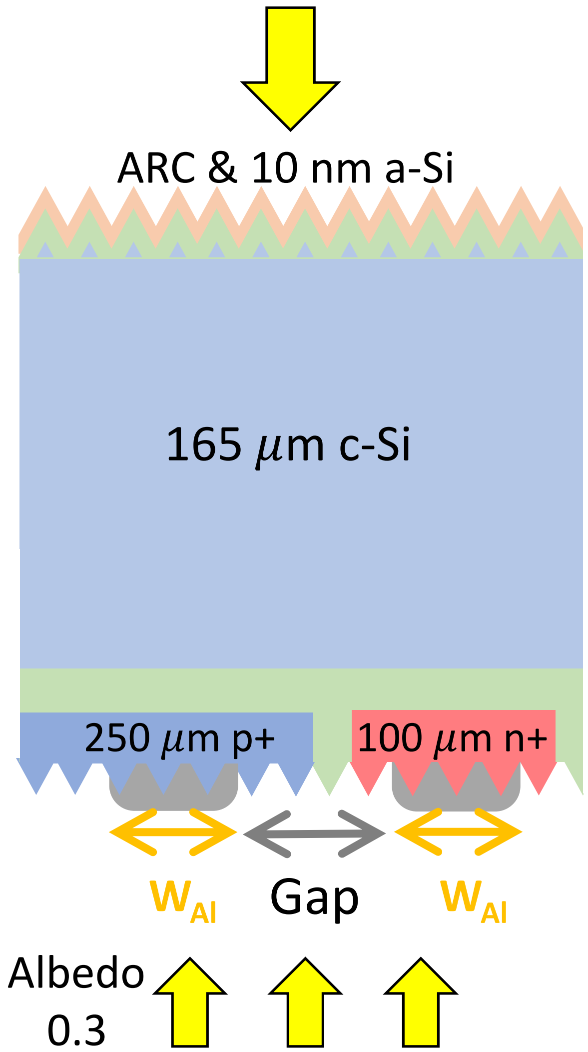


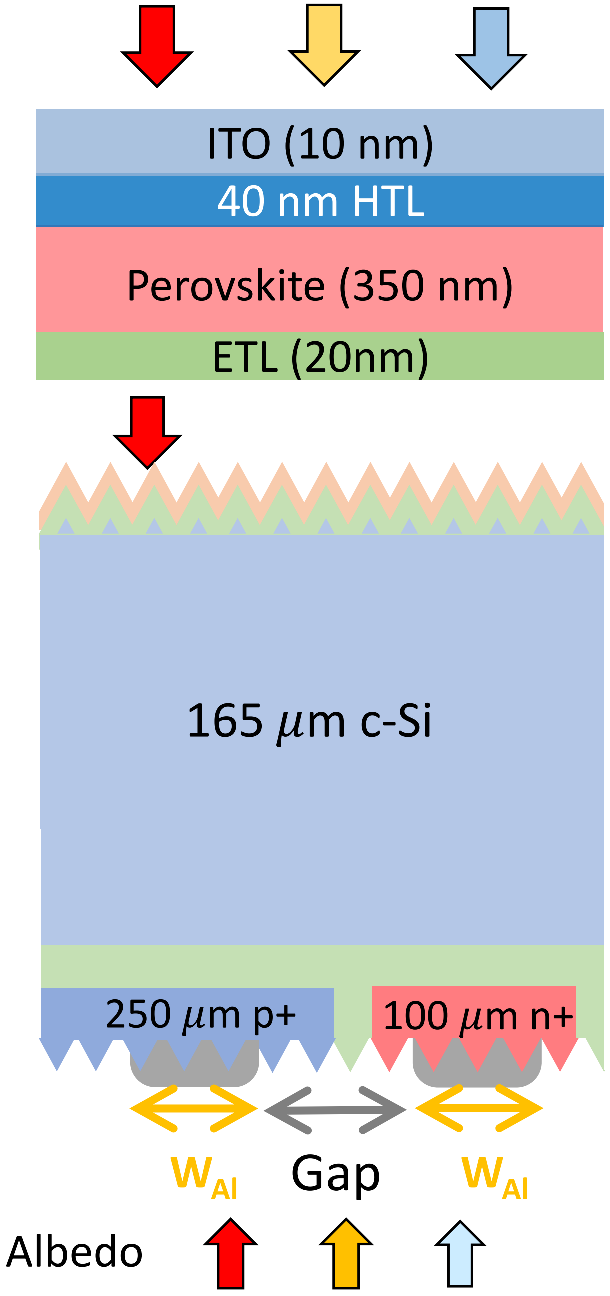


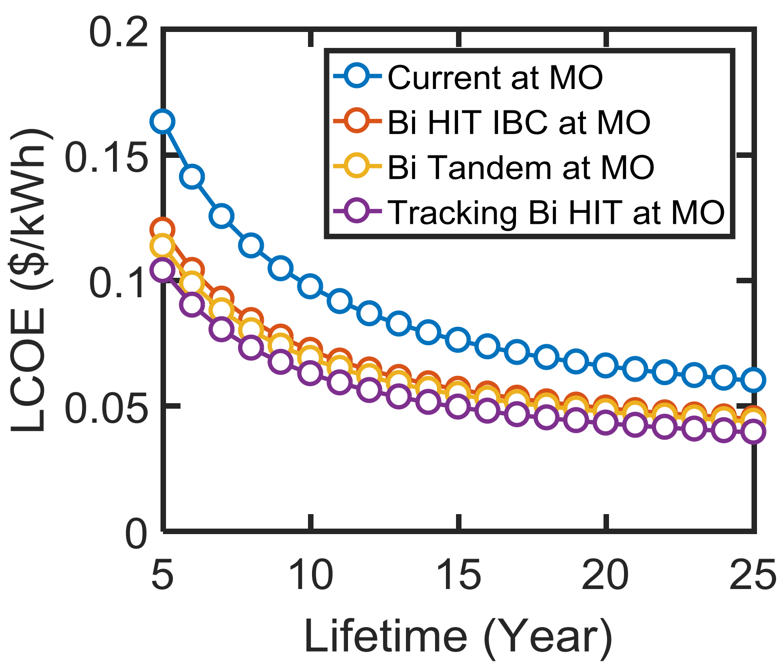


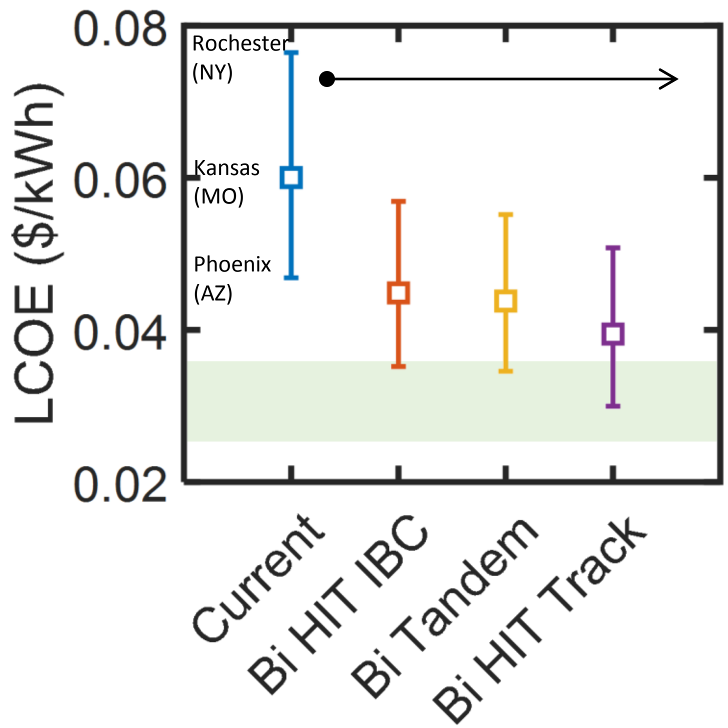
Questions/comments: alam@purdue.edu

Optimized design






0.2
0.15
0.1
0.05
0
LCOE ($/kWh)
5
10
15
20
25
Lifetime (Year)
Current at MO
Bi HIT IBC at MO
Bi Tandem at MO
Tracking Bi HIT at MO


0.08
0.06
0.04
0.02
LCOE ($/kWh)
Rochester
(NY)
Kansas
(MO)
Phoenix
(AZ)
Current
Bi HIT IBC
Bi Tandem
Bi HIT Track