Theory and Practice of Solar Cells: A Cell to System Perspective

PV Systems and Farm Design

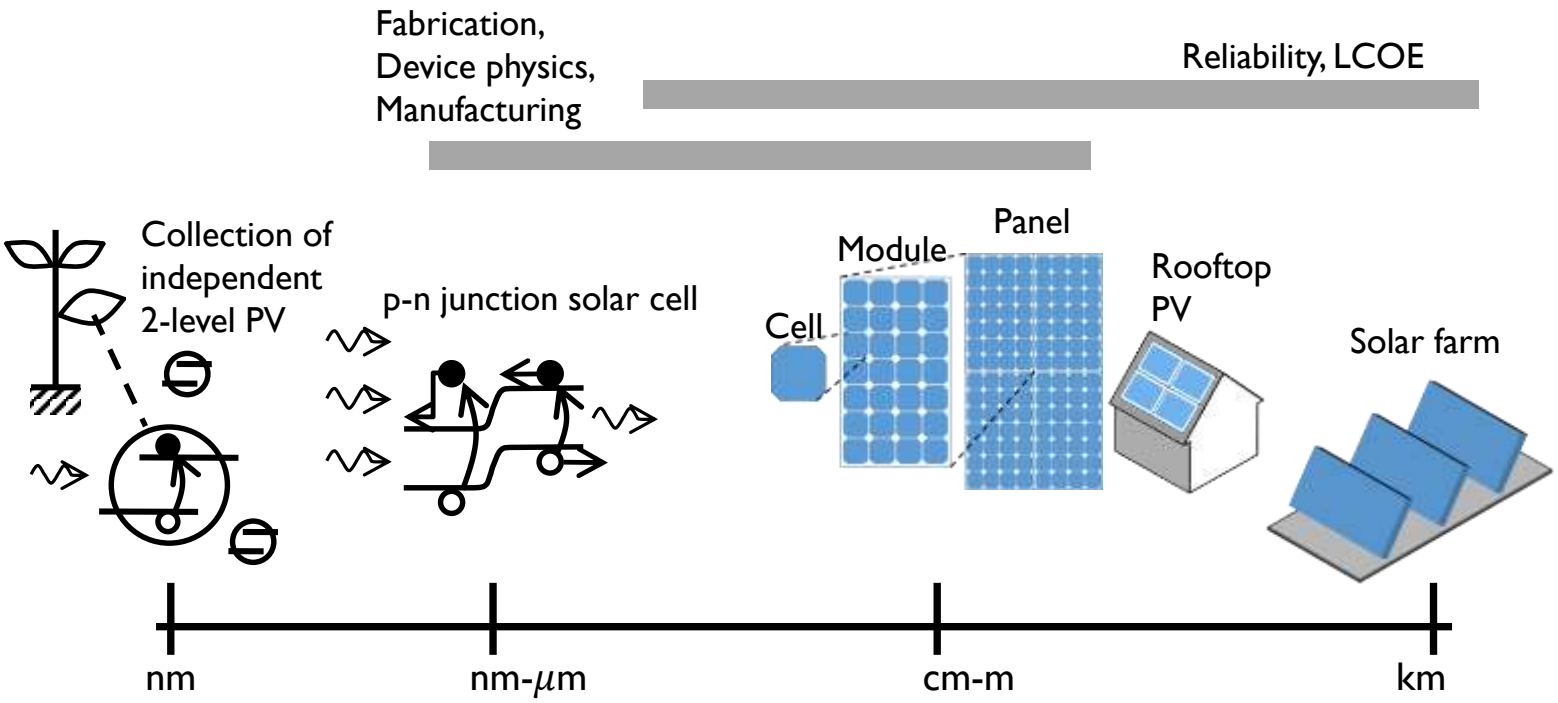
M. A. Alam

alam@purdue.edu
Electrical and Computer Engineering
Purdue University
West Lafayette, IN USA

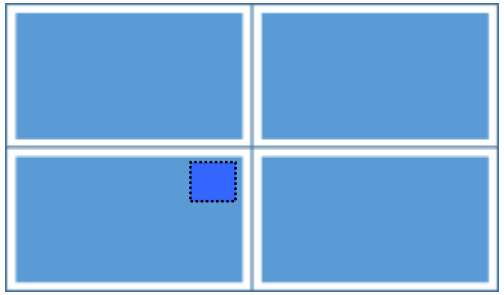
Outline

1) Configurations of PV systems
2) Principles of fixed tilt farm design
3) Calculation of yearly energy yield
4) Conclusions

Course outline: A multiscale problem

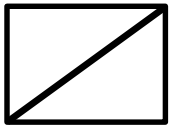


System Integration: Sysmbols

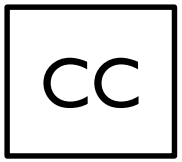


Cells, modules, panel

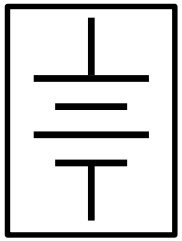
Inverter



Distribution panel



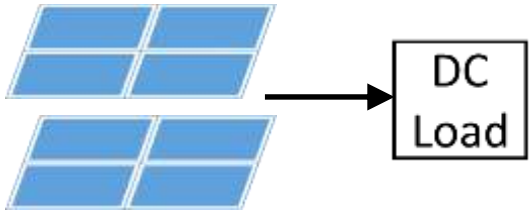
Charge controller

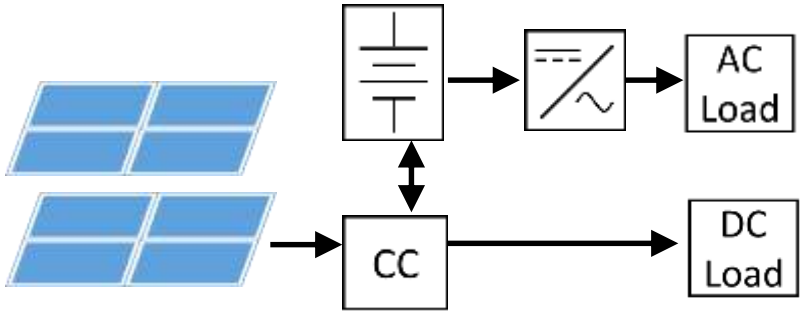


Battery/ storage

AC source/ grid

Stand-alone PV systems

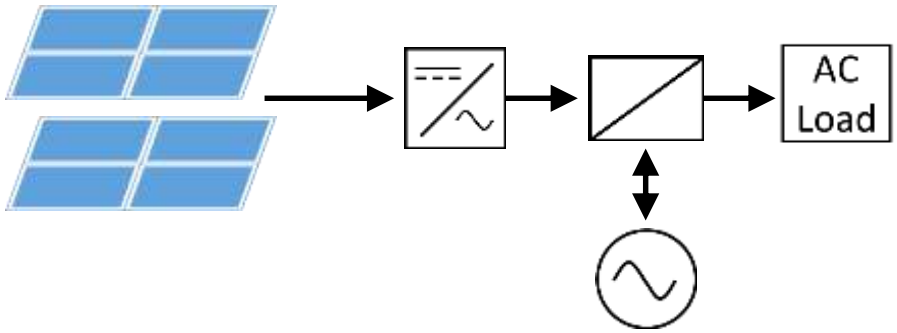




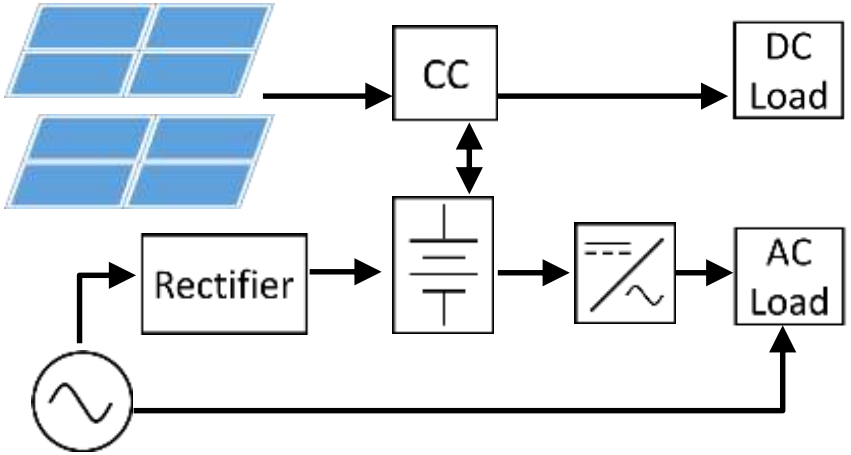
Simple
Low cost
Calculators
Irrigation

More expensive
Off-grid
Many home PV
Variety of electronics

Solar homes: Grid-connected PV

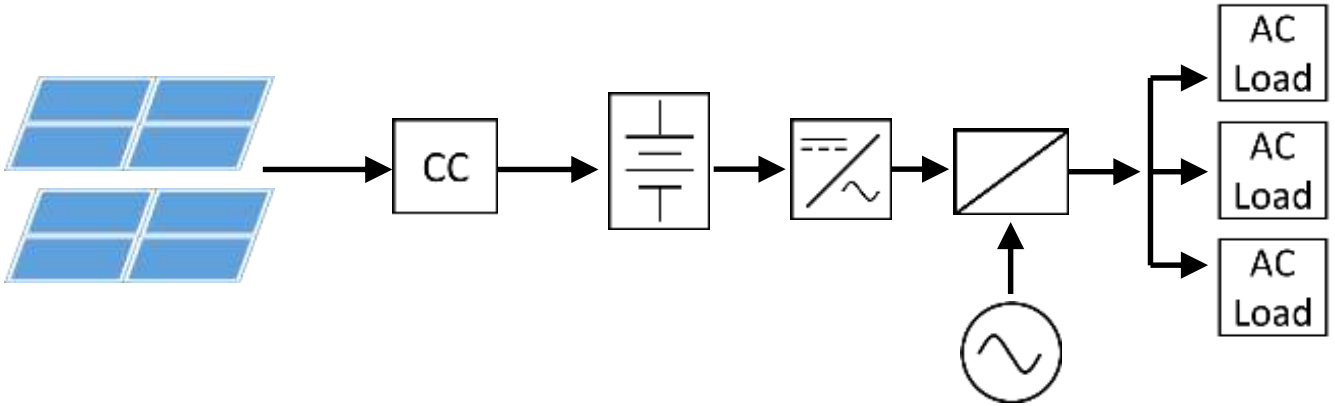


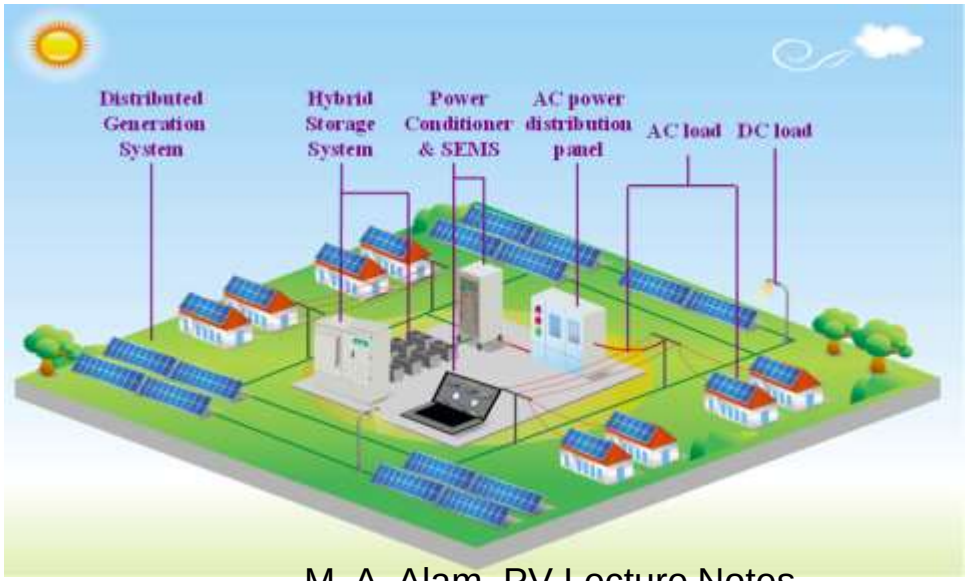
PV connected to Power-grid



Hybrid:
Multiple sources
Both AC/DC loads

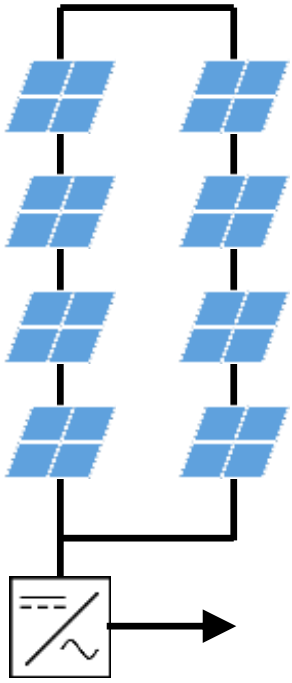
Community PV: Microgrid and Solar Farms



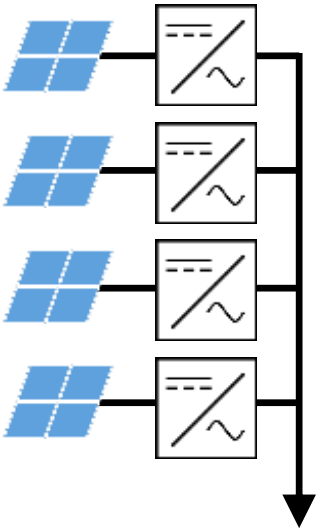


M. A. Alam, PV Lecture Notes

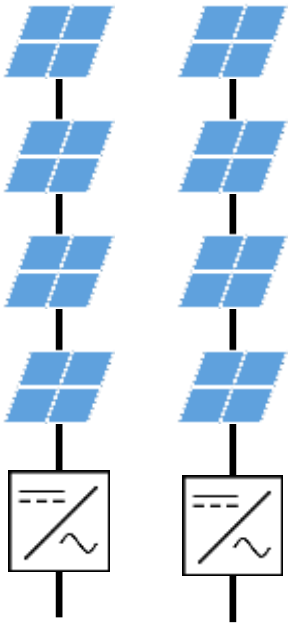
Aside: Inverter configurations



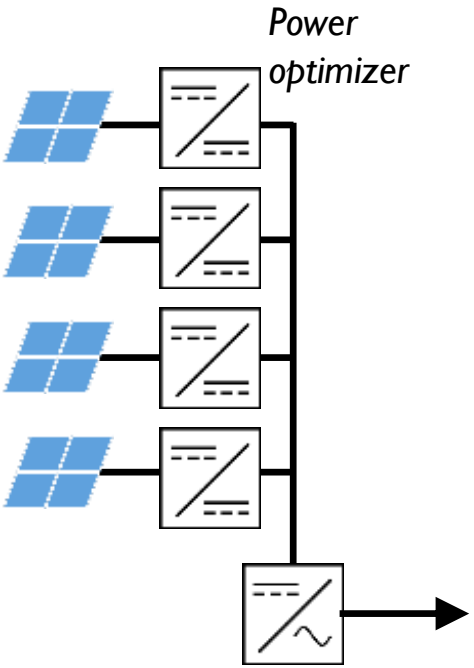
Central



Micro



String

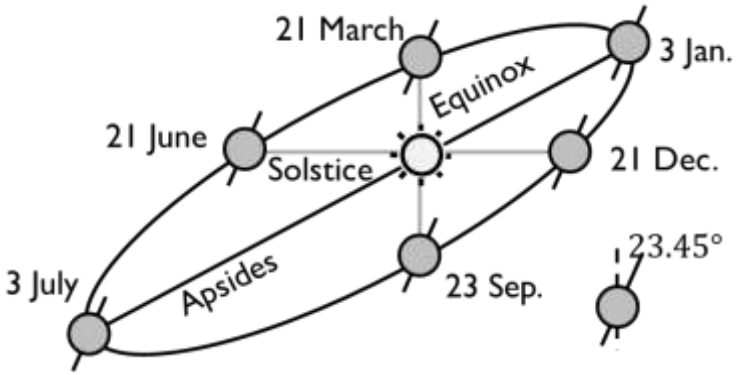


Micro with
Power-optimizer

Outline

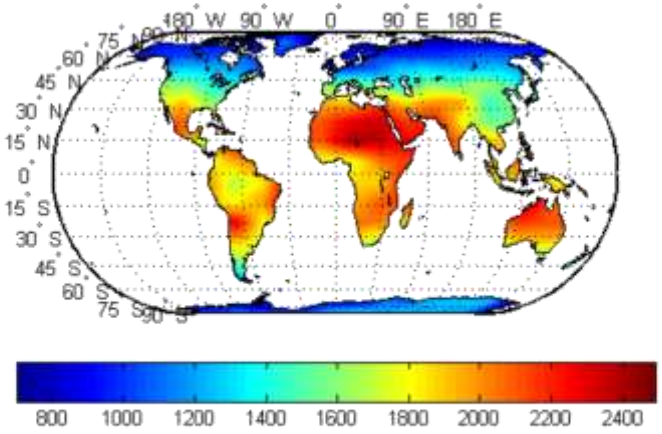
1) Configurations of PV systems
2) Principles of fixed tilt farm design
3) Calculation of yearly energy yield
4) Conclusions

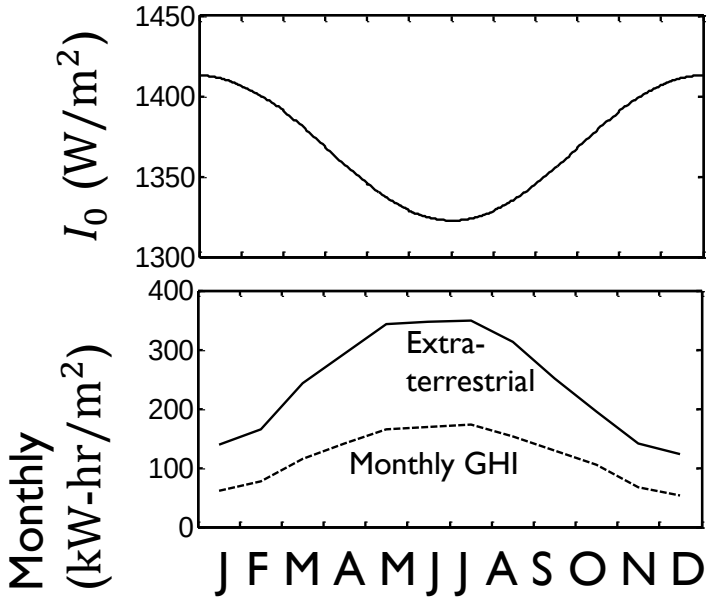
Sunlight varies with seasons



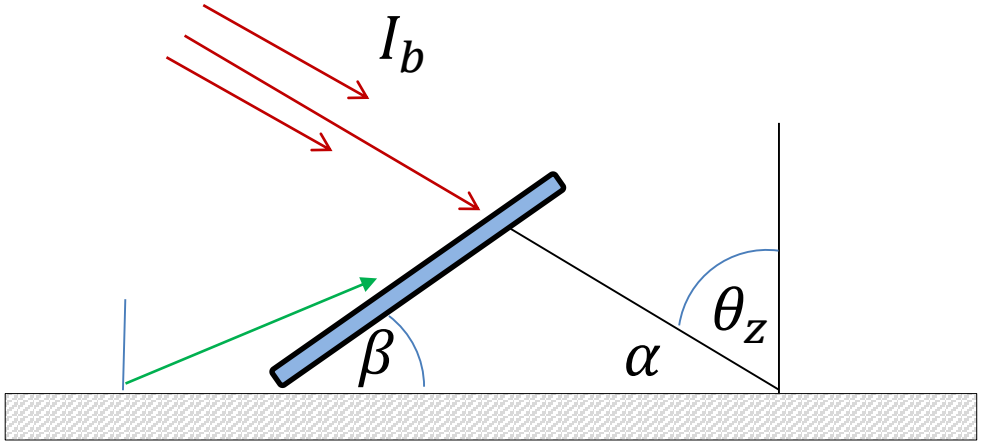
$$I_0(d_n) = I_0(1 + \Delta \cos 2\pi\, d_n\, /D)$$

$$\Delta = 2(R_{\max} - R_{\min})/d$$





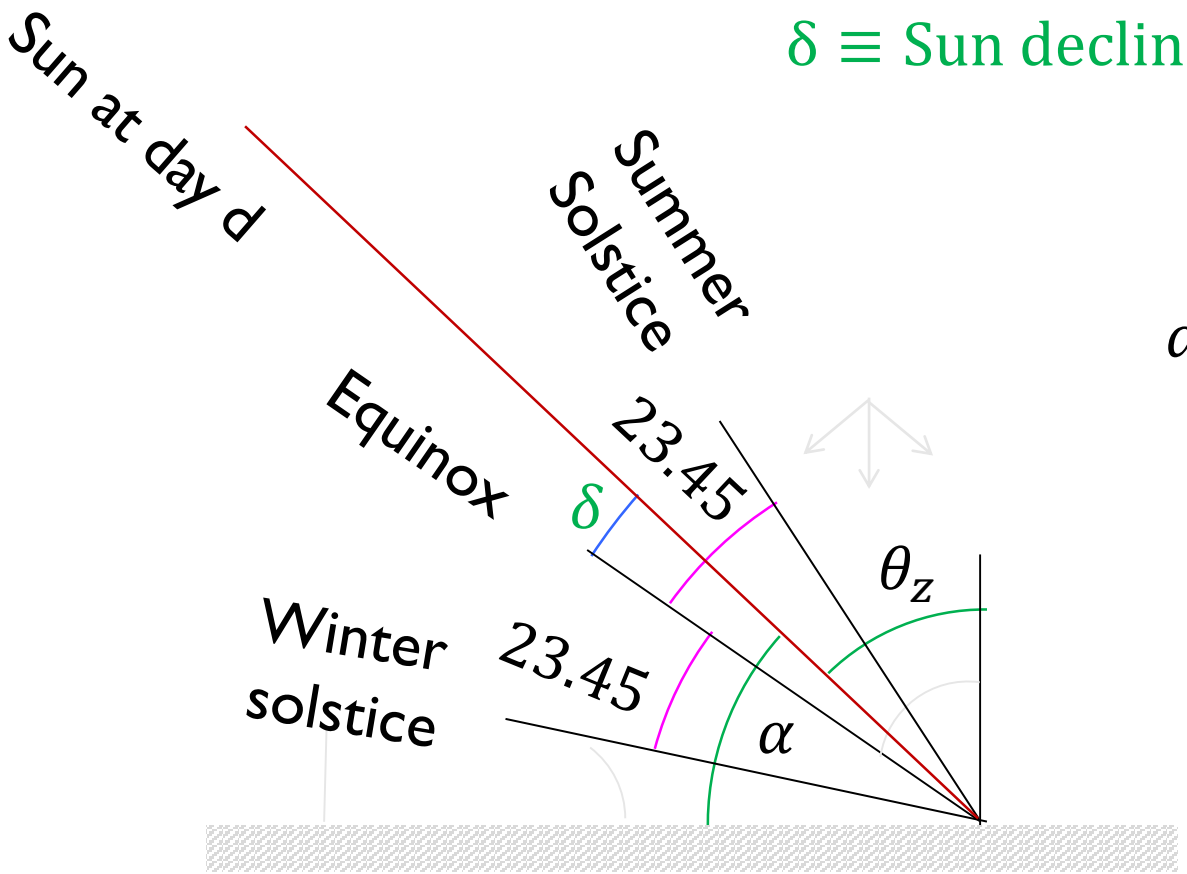
How to tilt a solar module (i.e. determine β)



$$I_{dir} = I_b \sin(\alpha + \beta) = I_b \cos(\theta_z - \beta)$$

θ_z varies throughout the year

$\delta \equiv$ Sun declination angle



$$\alpha(d) = 90 - L \pm \delta(d)$$

North

South

$$\theta_z(d) = L \mp \delta(d)$$

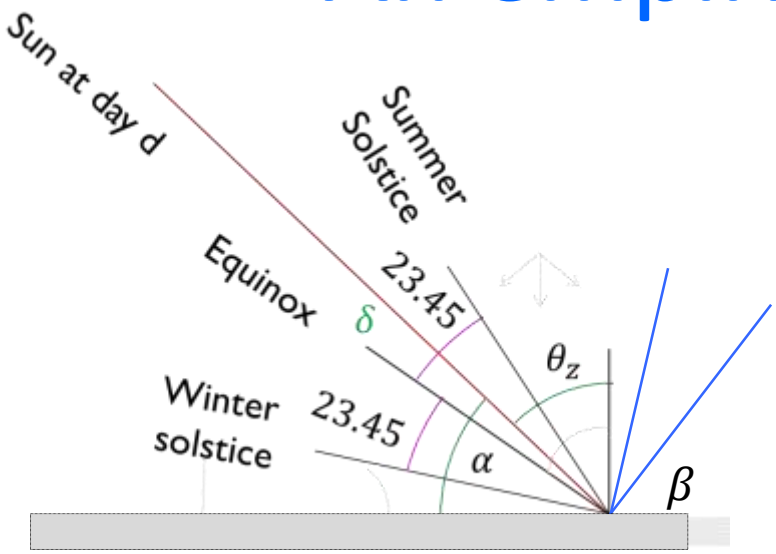
$$\theta_{z,w} = L + 23.45$$

$$\theta_{z,s} = L - 23.45$$

$$\delta = 23.45^0 \sin\left(\frac{2\pi(d-80)}{365}\right)$$

March 21st (Vernal Equinox)$\equiv$ 80 days

An empirical rule for tilt



$$\theta_z(d) = L \mp \delta(d)$$

$$\theta_{z,w} = L + 23.45$$

$$\theta_{z,s} = L - 23.45$$

Summer intensity is higher:

Optimize integral over daily intensity and solar angle for given β

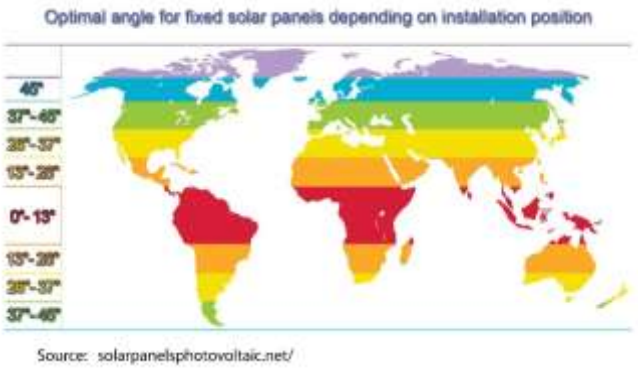
Two tilt, summer/winter:

$$\beta = L - 10$$

$$\beta = 0.69L + 3.7$$

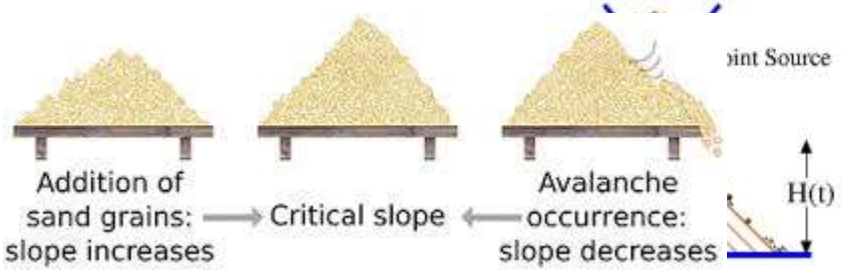
$$\beta_s = \theta_{z,s} \quad \beta_w = \theta_{z,w}$$

Example: How to tilt a module



	Lafayette	Madras	Shanghai
	$40.27N$	$13.5\ N$	$31.23\ N$
$\beta = L - 10$	30.27	3.50	21.23
$\beta = 0.69L + 3.6$	31.79	12.92	24.83
$\beta_s = \theta_{z,s}$	16.82	−9.95	7.78
$\beta_w = \theta_{z,w}$	63.72	36.95	54.68

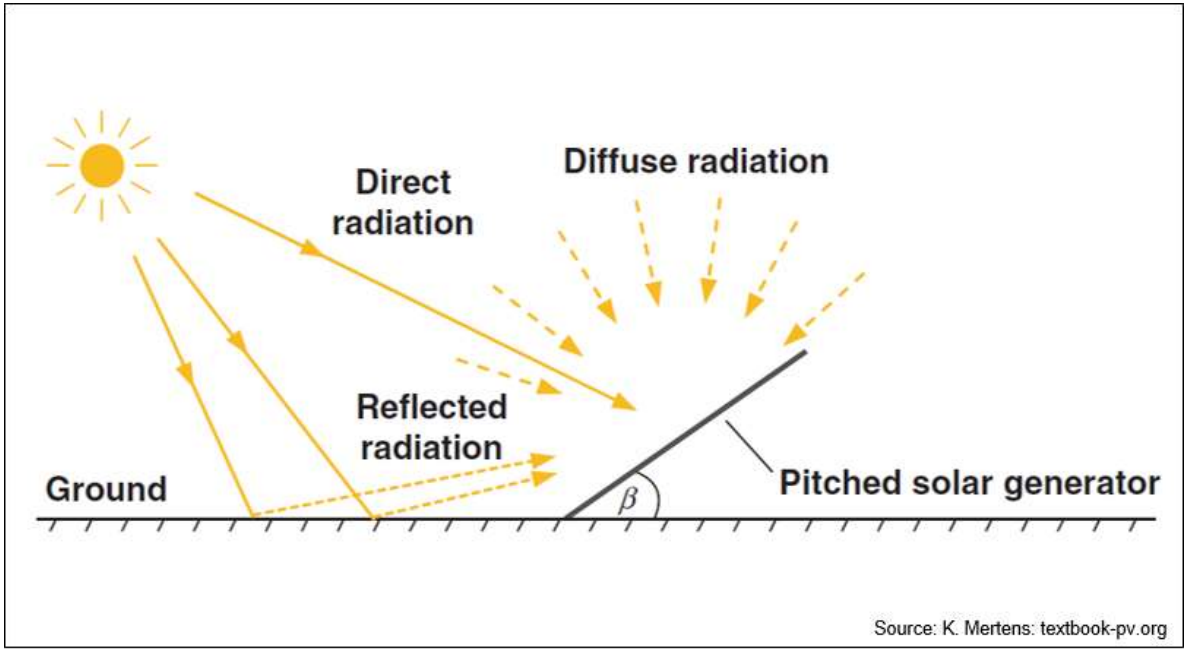
Aside: Cleaning considerations



Tilt angle, Electrical vs. mechanical, Air vs. water cleaning

M. A. Alam, PV Lecture Notes

Three components of irradiance



$$I_T = I_{dir} + I_{diff} + I_{alb}$$

$$k_T = I_{GHI}/I_0\cos(\theta_Z)$$

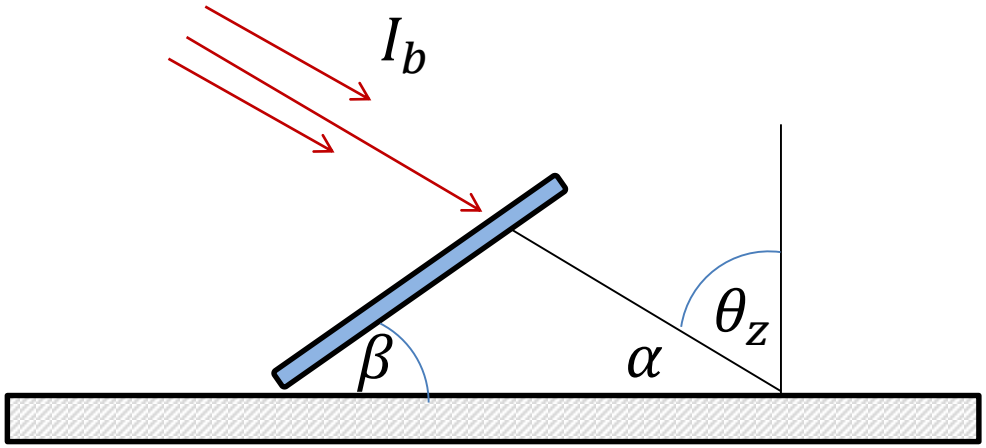
Orgill and Hollands correlation

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.249k_T & \text{for } 0 \le k_T \le 0.35 \\ 1.557 - 1.84k_T & \text{for } 0.35 < k_T < 0.75 \\ 0.177 & \text{for } k_T > 0.75 \end{cases}$$

Standalone yield: Direct light

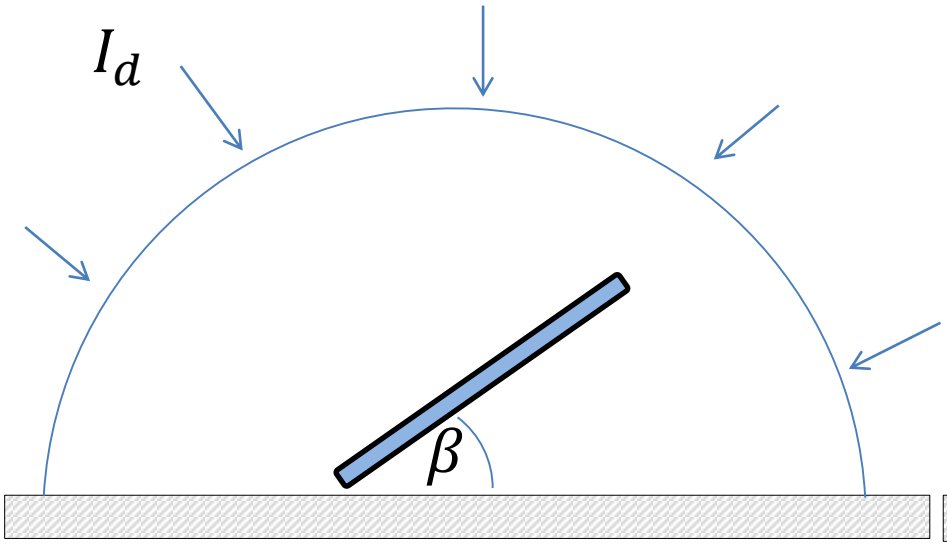
$$I_T = I_{dir} + I_{diff} + I_{alb}$$

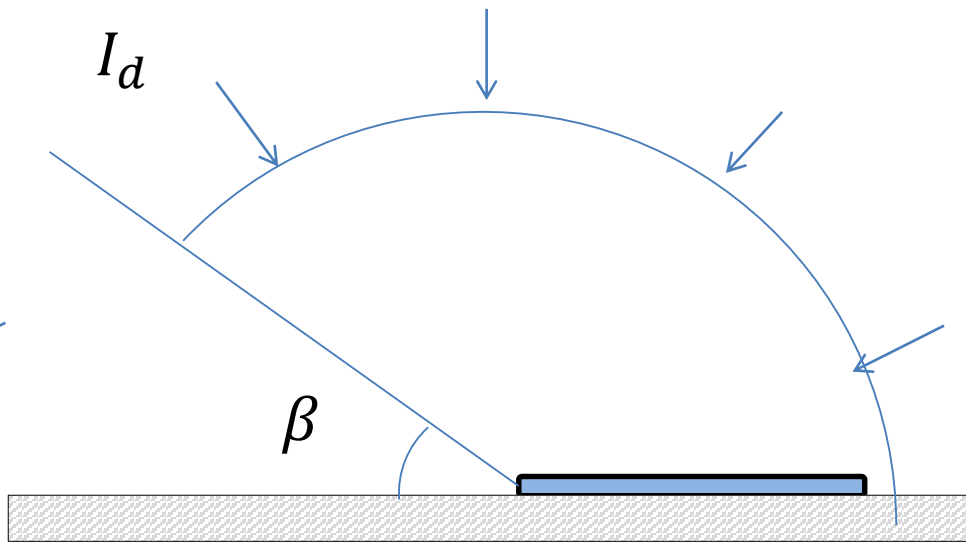
$$I_{dir} = I_b \sin(\alpha + \beta) = I_b \cos(\theta_z - \beta)$$



Stand-alone yield: diffuse component

$$I_T = I_{dir} + I_{diff} + I_{alb}$$



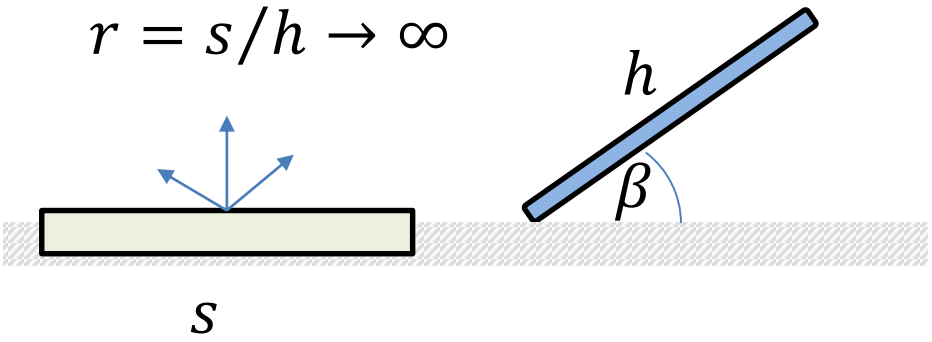


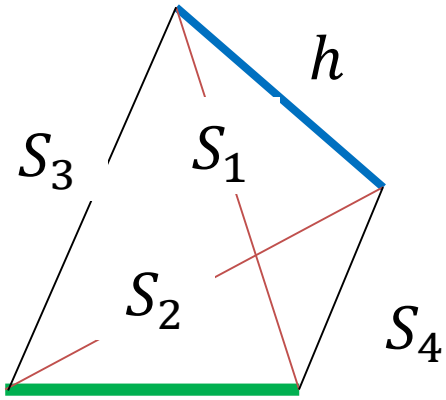
$$I_{diff} = \frac{I_d}{2}\int_{\beta}^{\pi} \sin\theta \, d\theta = \frac{I_d(1+\cos\beta)}{2}$$

Stand-alone yield: albedo

$$I_T = I_{dir} + I_{diff} + I_{alb}$$

$r = s/h \to \infty$





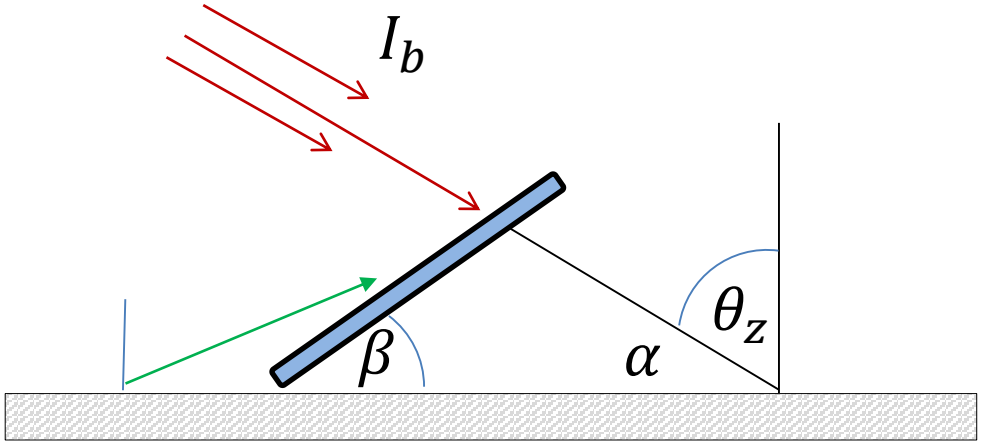
$$I_{alb} = I_{GHI}\, R_A\, VF$$

$$VF = \frac{(S_1 + S_2) - (S_3 + S_4)}{2h}$$

$$VF = \frac{(h + s) - (0 + \sqrt{s^2 + h^2 + 2sh\cos\beta})}{2h}$$

$$VF = \frac{1}{2}\left(1 + r - \sqrt{1 + r^2 + 2r\cos\beta}\right) \quad \to \ (1 - \cos\beta)/2$$

Stand-alone module: Energy yield



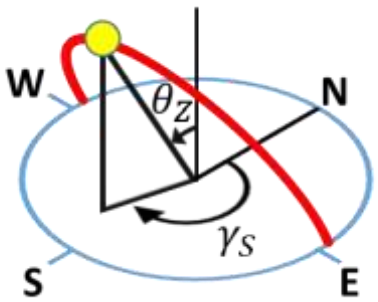
$$I_T = I_{dir} + I_{diff} + I_{alb}$$

$$I_{dir} = I_b \cos(\theta_z - \beta)$$

$$I_{diff} = \frac{I_d(1+\cos\beta)}{2}$$

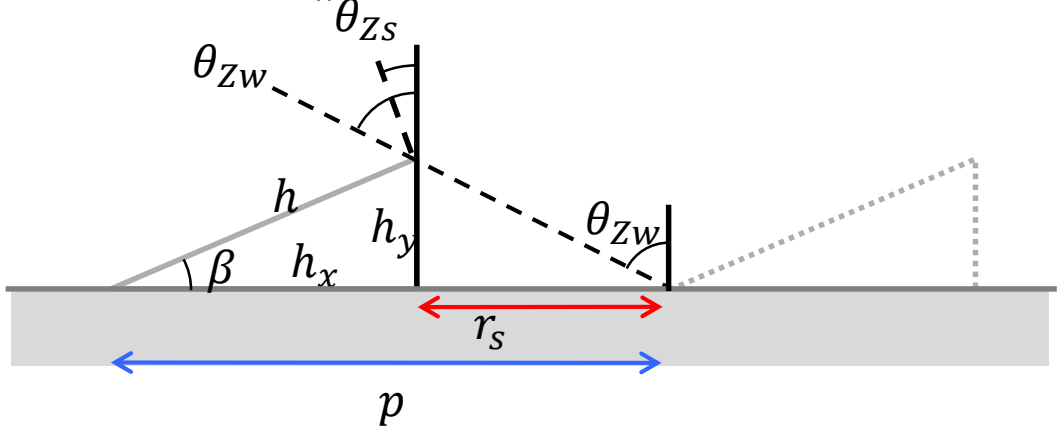
$$I_{alb} = I_{GHI}\, R_A(1-\cos\beta)/2$$

Row spacing in Lafayette, IN



Summer zenith: θ_{Zs}

Winter zenith: θ_{Zw}



$$\mathrm{SBR} \equiv r_s/h_y = \tan(90-\alpha) = \tan\left(\theta_{zw,p}\right)$$

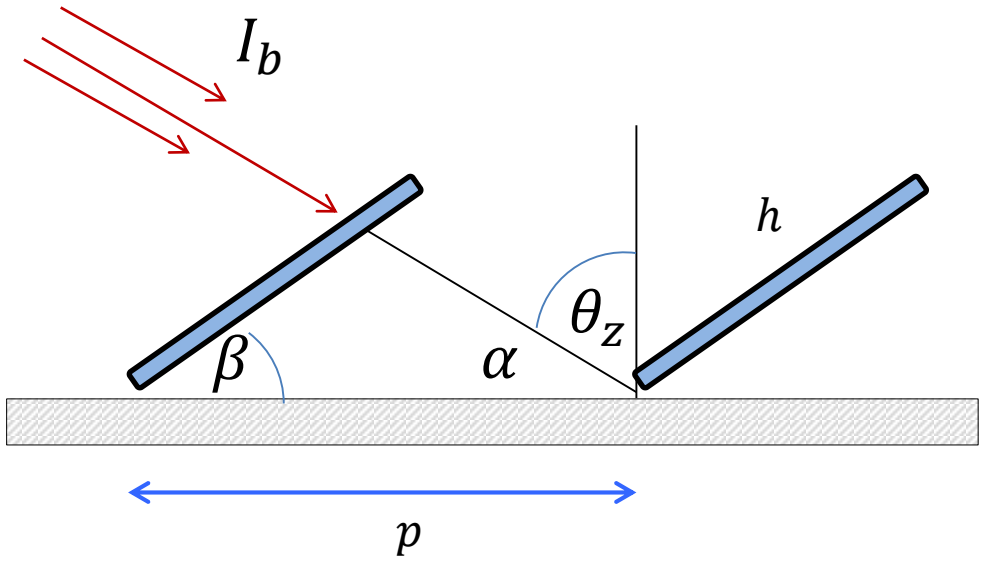
$$p/h = \cos(\beta) + \sin(\beta)\tan\theta_{zw,p}$$

$$\mathrm{SBR} \equiv r_s/h_y = \tan(90-18.14) = 3.05$$

Farm yield per unit area: direct beam

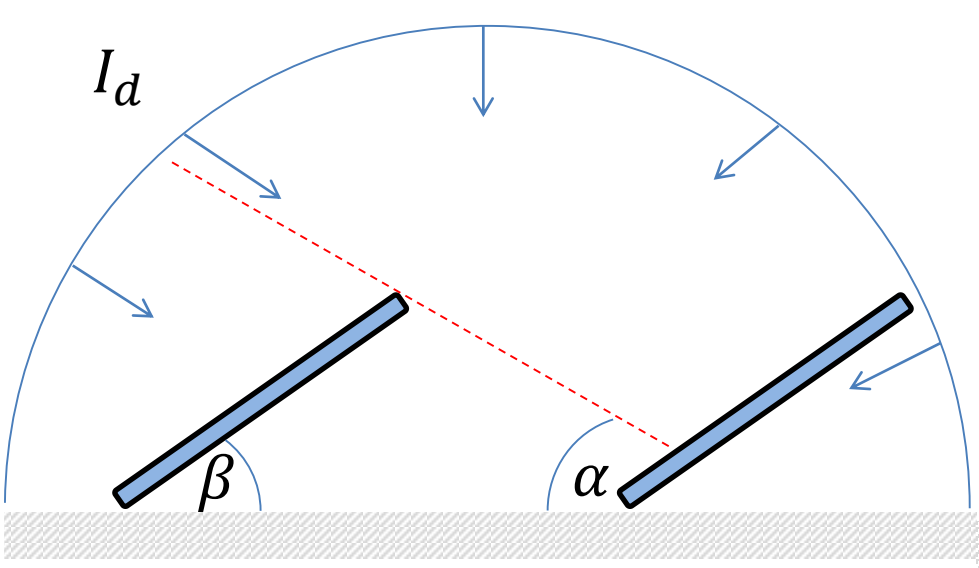
$$I_T = I_{dir} + I_{diff} + I_{alb}$$

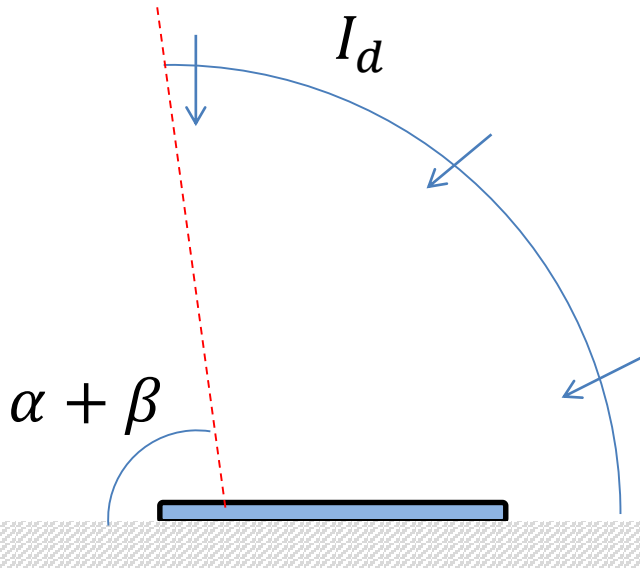
$$I_{dir} = I_b \sin(\alpha + \beta) h/p = I_b \cos(\theta_z - \beta) \times h/p$$



Farm yield: diffused energy collection

$$I_T = I_{dir} + I_{diff} + I_{alb}$$





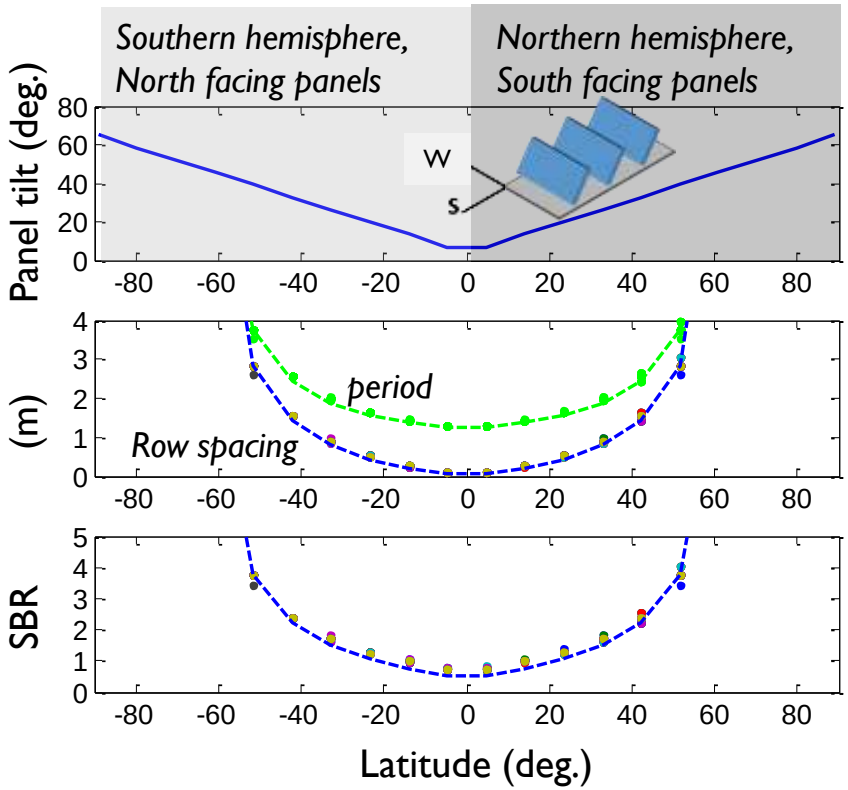
$$I_{diff}(\xi) = \frac{p}{h} \times \frac{I_d}{2} \int_{\beta+\alpha(\xi)}^{\pi} \sin\theta \, d\theta = \left(\frac{p}{h}\right) \times \frac{I_d(1+\cos(\alpha+\beta))}{2}$$

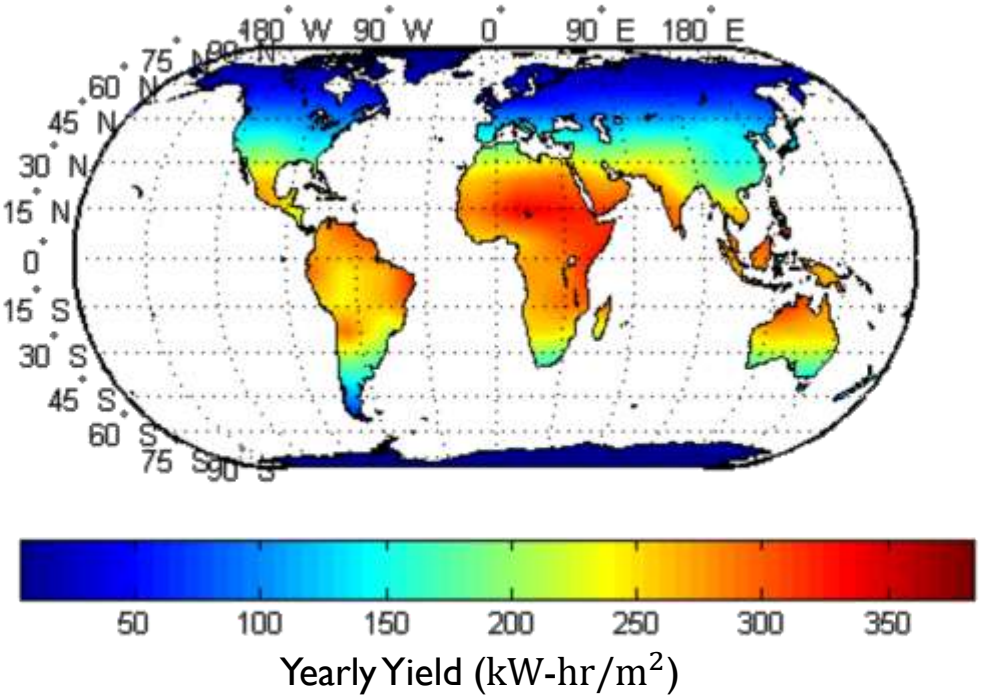
Outline

1) Configurations of PV systems
2) Principles of fixed tilt farm design
3) Calculation of yearly energy yield
4) Conclusions

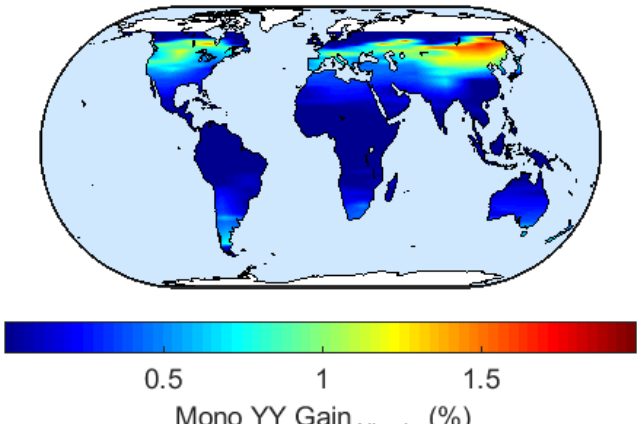
Variety of Solar Farms

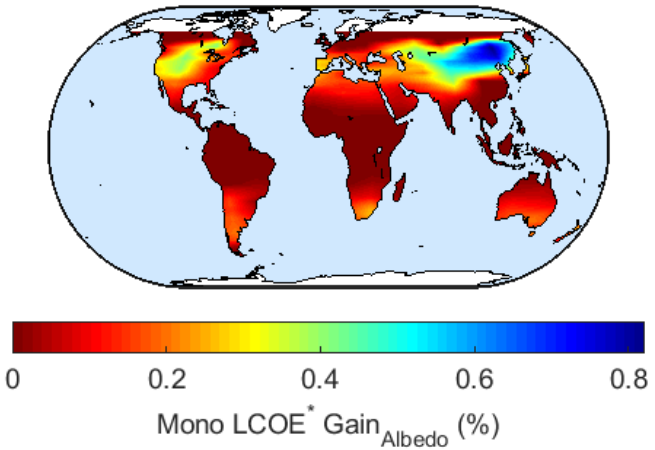
Monofacial solar farms

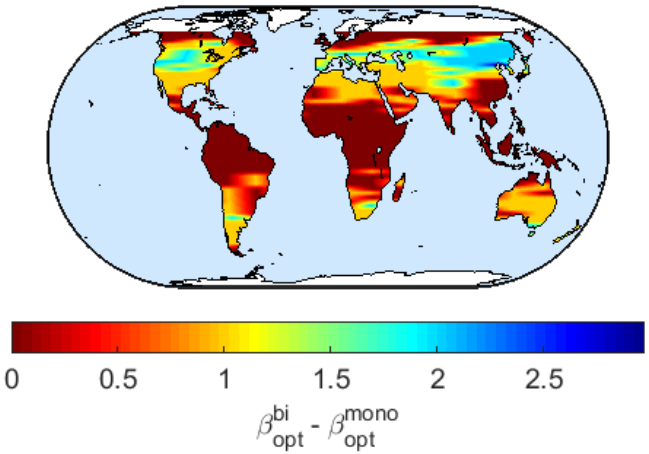




Albedo contribution to Monofacial Farms

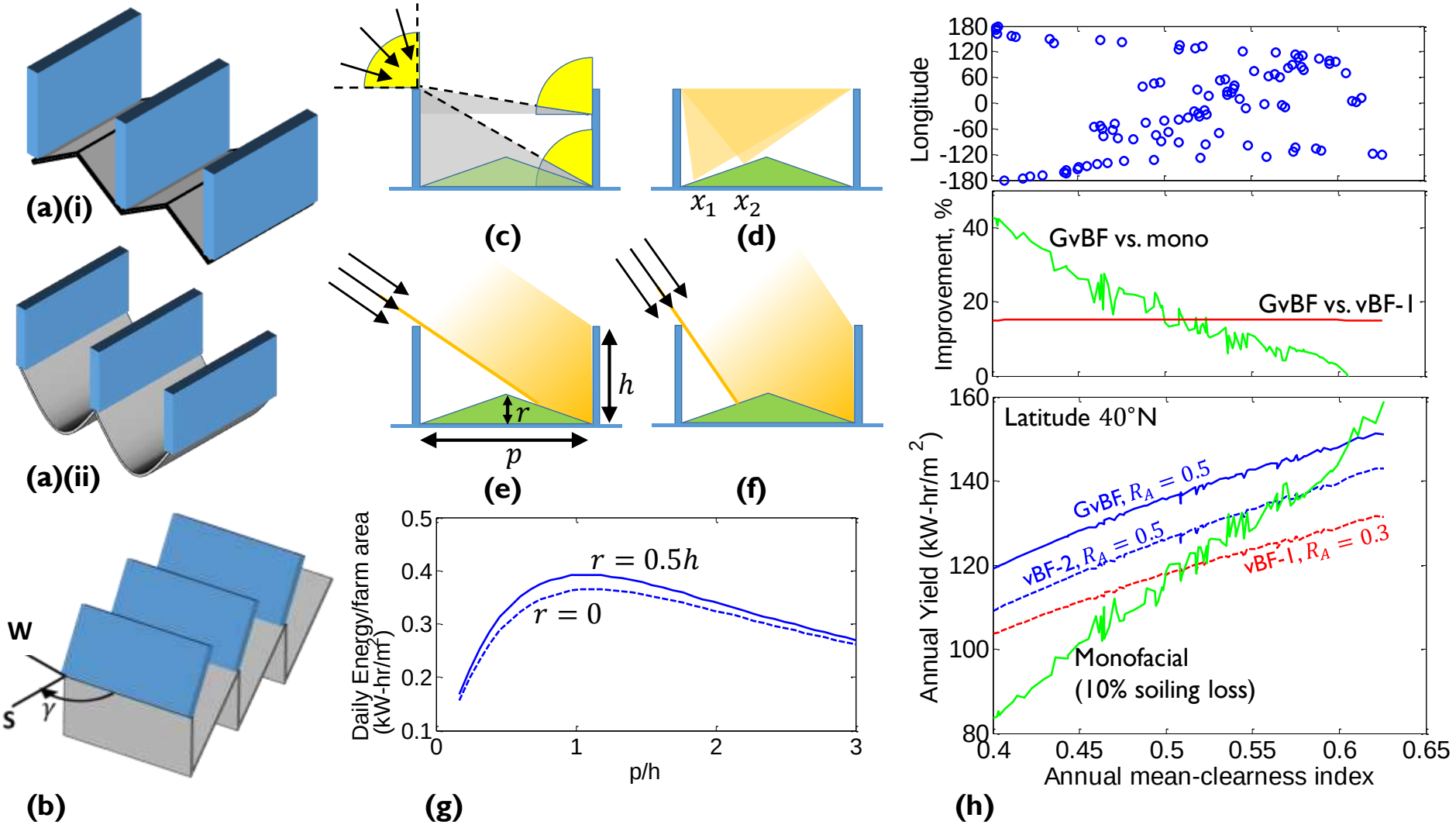






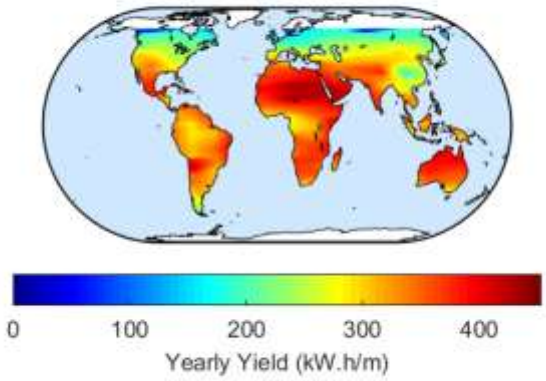
- $R_A = 0.2$
- 1-2 % gain in YY
- 1-2° increase in optimum tilt angle
- < 1% reduction in LCOE*

Ground-sculpted bifacial farms

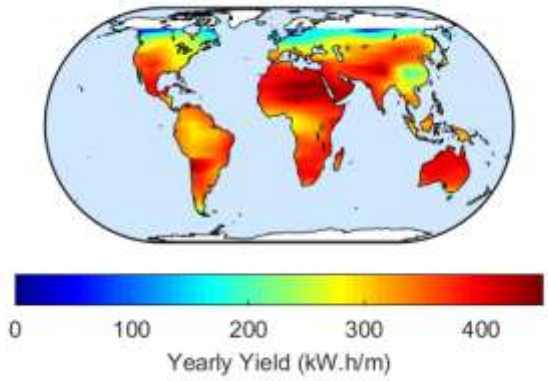


Land-cost inclusive optimization

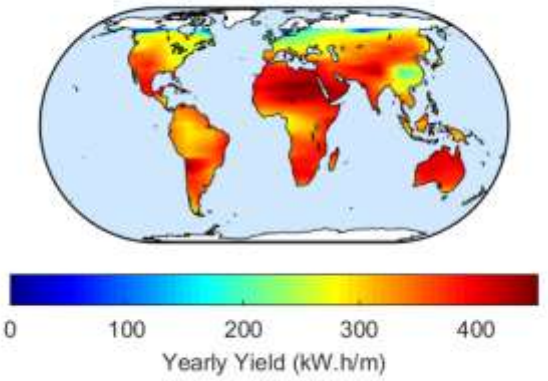
(a) $M_L = 0$



(b) $M_L = 15$



(c) $M_L = 100$



Conclusions

- PV design must be understood in a system context.
- Given the weather information, it is relatively easy to calculate the energy yield for stand-alone modules as well as solar farms.
- The increasing cost of land and wide-spread PV deployment are encouraging the PV industry to explore novel technologies (e.g. bifacial PV) and farm topologies (e.g. floating solar).
- An end-to-end cost-benefit analysis is essential to create a farm that is ideally suited to a location.

Self-study Quiz

- Which direction does 90 degrees Azimuth indicate?
- Names the light-components one must sum to calculate the energy yield.
- What is the cross-string method? Why do we need this technique?
- How does the albedo light collection by a module in a farm compare to that of an stand-alone module?
- What type of solar benefit the most from ground-sculpting?
- When should one use floating solar farms compared to normally tilted solar farms?