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

# Summary and Review

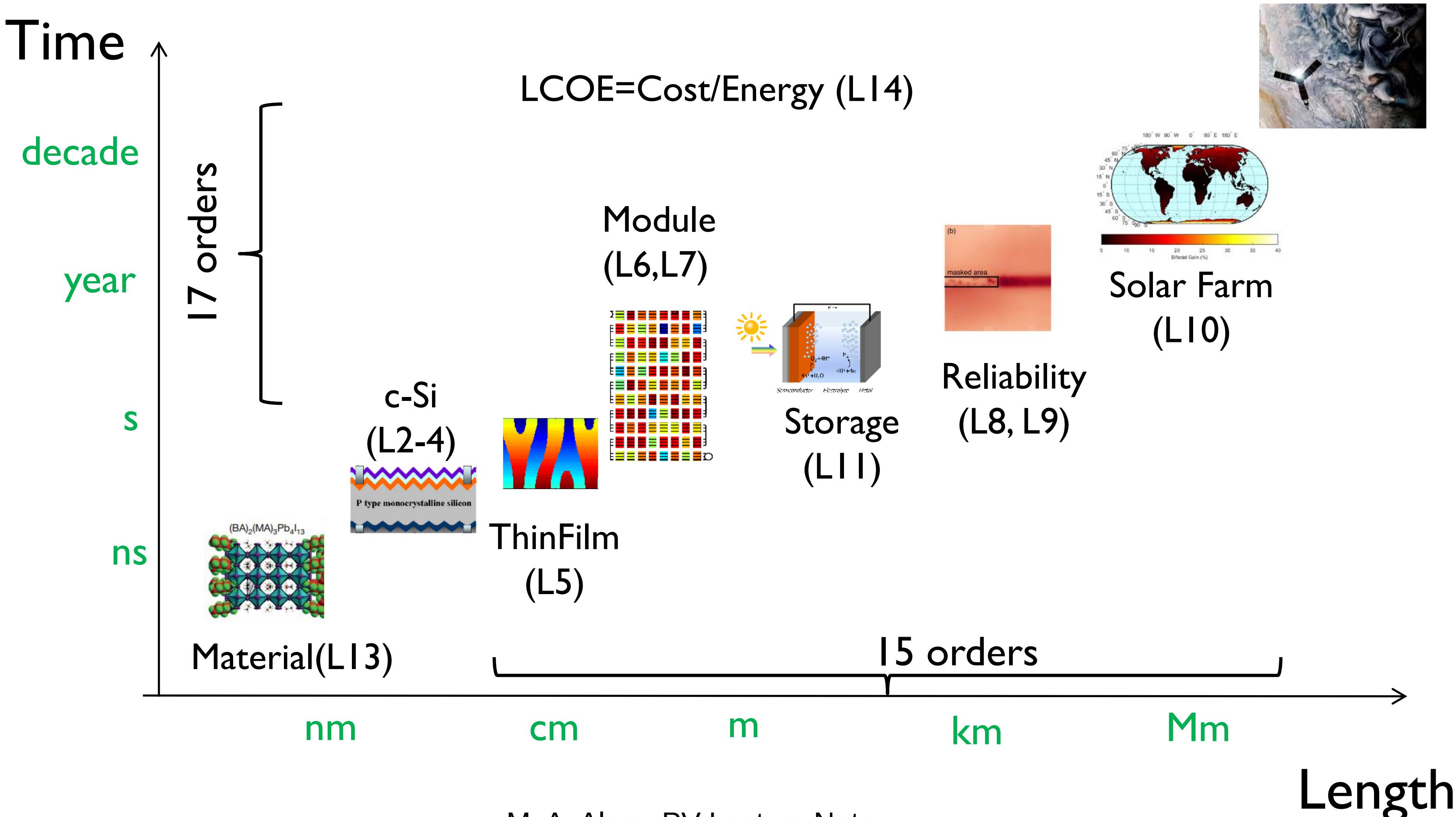
M. A. Alam and M. S. Lundstrom

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

# Summary of Lectures

- Overview: Sun, Earth, and Solar cells
- Physics of c-Si Solar Cells
- Design of c-Si Solar Cells
- Advanced Concepts in c-Si PV
- Physics of Thin-film solar cells
- Module-Stripes for Thin-film Solar Cells
- Module-Stripes for c-Si Solar Cells
- Reliability Physics: Shadow degradation, PID
- Reliability Physics: Corrosion, UV
- Design of Solar Farms
- Storage of Solar Energy
- Levelized cost of Electricity
- Thermodynamics of Solar Cells

# A magnificent multiscale problem: Atom-to-farm perspective



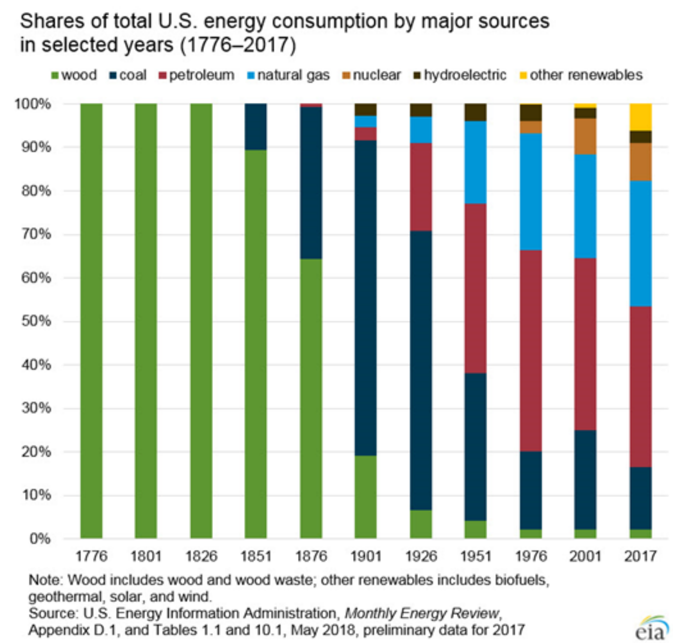

M. A. Alam, PV Lecture Notes

# Wait, Wait don't tell me …

What fraction of the total energy comes from PV sources

a) 10 b) 30 c) 50 d) 80

10

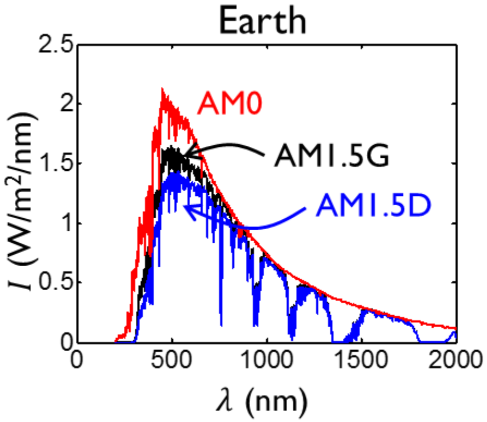


# Wait, Wait don't tell me …

What is the energy density in AM0 (in W/m2)

a) 2000 b) 1350 c) 800 d) 500

1350



# Wait, Wait don't tell me …

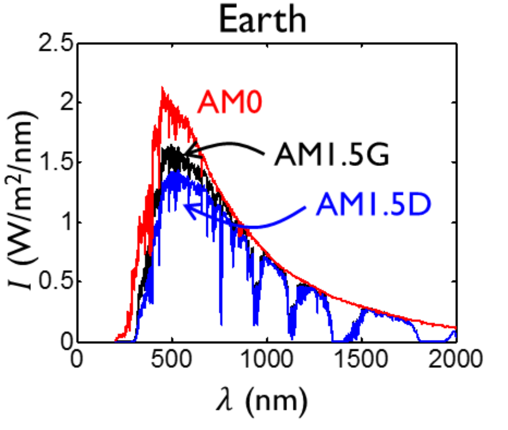
What is the temperature of the sun (in K)

a) 300    b) 1000    c) 3000    d) 6000

# Wait, Wait don't tell me …

What is the average photon energy in sunlight

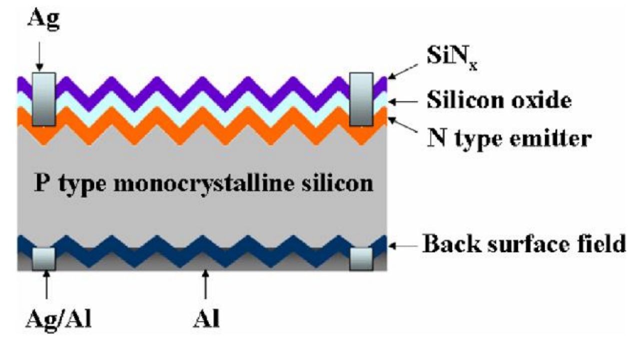
a) 0.25   b) 0.50   c) 1.10   d) 1.35



# Summary of Lectures

- Overview: Sun, Earth, and Solar cells
- Physics of c-Si Solar Cells
- Design of c-Si Solar Cells
- Advanced Concepts in c-Si PV
- Physics of Thin-film solar cells
- Module-Stripes for Thin-film Solar Cells
- Module-Stripes for c-Si Solar Cells
- Reliability Physics: Shadow degradation, PID
- Reliability Physics: Corrosion, UV
- Design of Solar Farms
- Storage of Solar Energy
- Levelized cost of Electricity
- Thermodynamics of Solar Cells

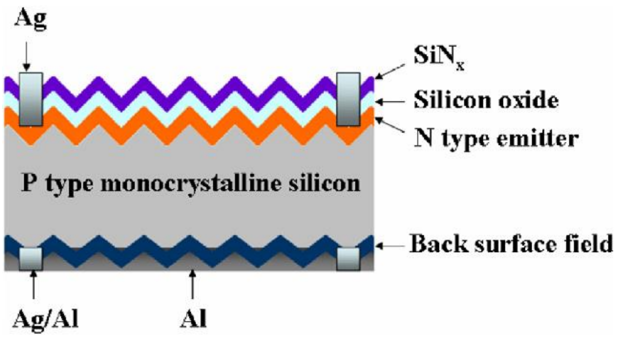
# Wait, Wait don't tell me …




A c-Si solar cell

(a) Obeys superposition principle
(b) Has the highest market share
(c) Has low absorption at longer wavelengths
(d) Typically comes in n+-p variety
(e) All of the above

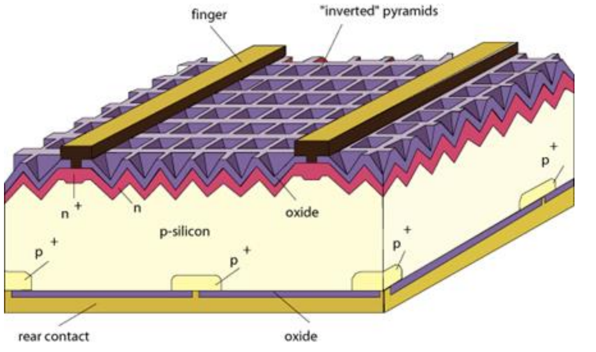
# Wait, Wait don't tell me …




What does SiN layer do

(a) Makes the cell look nicer
(b) Increases fill factor
(c) Reduces reflection loss
(d) None of the above

# Wait, Wait don't tell me …




A PERC cell involves

(a) A uniform back-surface field
(b) a-Si front and back-contact passivation
(c) Passivation by SiO2/SiN with selective opening for contact
(d) Ability to accept light from both surfaces

# Wait, Wait don't tell me …

A SiN in a c-Si solar cell is used to

(a) Increase light trapping
(b) Improve electron collection
(c) Improve light coupling into the cell and reduce reflection
(d) None of the above

# Summary of Lectures

- Overview: Sun, Earth, and Solar cells
- Physics of c-Si Solar Cells
- Design of c-Si Solar Cells
- Advanced Concepts in c-Si PV
- Physics of Thin-film solar cells
- Module-Stripes for Thin-film Solar Cells
- Module-Stripes for c-Si Solar Cells
- Reliability Physics: Shadow degradation, PID
- Reliability Physics: Corrosion, UV
- Design of Solar Farms
- Storage of Solar Energy
- Levelized cost of Electricity
- Thermodynamics of Solar Cells

# Wait, Wait don't tell me …

Typical thickness of thin-film solar cell (in micron)

a) 500 b) 300 c) 0.5 d) 0.01

# Wait, Wait don't tell me …

## Which type of super-position does c-Si satisfy

$(a)\ I(S_0, V) = I_{ph}(S_0, V) - I_{dark}(V, I)$

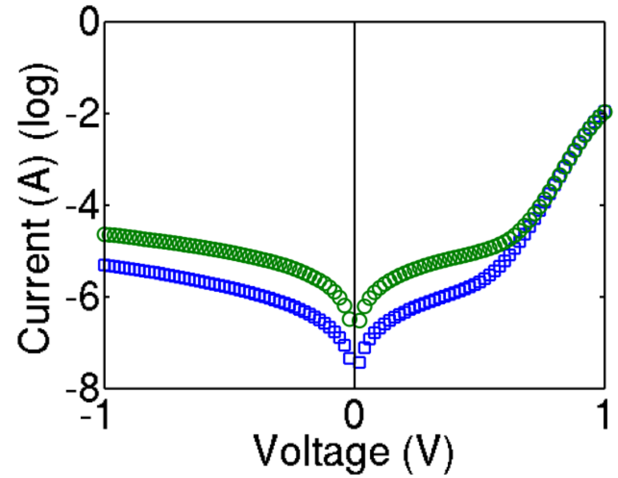
$(b)\ I(S_0, V) \simeq I_{ph}(S_0, V) - I_{dark}\left(V, I_{ph} = 0\right)$

$(c)\ I(S_0, V) \simeq I_{ph}(S_0, V = 0) - I_{dark}\left(V, J_{ph} = 0\right)$

# Wait, Wait don't tell me …

A shunt resistance is

(a) Voltage-symmetric
(b) Temperature insensitive
(c) Statistically distributed
(d) All of the above



# Wait, Wait don't tell me …

Gridding is used to

(a) Make the cell beautiful
(b) Reduce shunt resistance loss
(c) Decrease series-resistance loss
(d) Increase short-circuit current

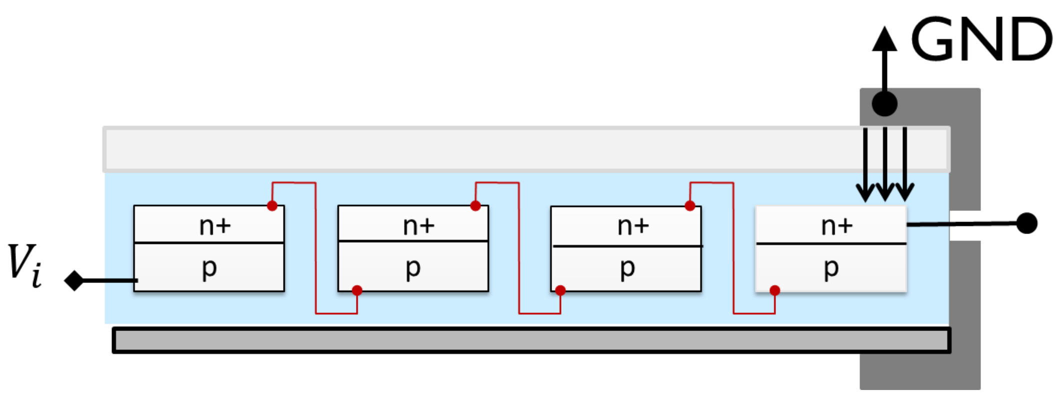
# Summary of Lectures

- Overview: Sun, Earth, and Solar cells
- Physics of c-Si Solar Cells
- Design of c-Si Solar Cells
- Advanced Concepts in c-Si PV
- Physics of Thin-film solar cells
- Module-Stripes for Thin-film Solar Cells
- Module-Stripes for c-Si Solar Cells
- Reliability Physics: Shadow degradation, PID
- Reliability Physics: Corrosion, UV
- Design of Solar Farms
- Storage of Solar Energy
- Levelized cost of Electricity
- Thermodynamics of Solar Cells

# Wait, Wait don't tell me …

PID occurs in only in

(a) Small rooftop system
(b) Thin-film solar cells
(c) Ungrounded solar farms
(d) Large farm with grounded frame
(e) p+-n c-Si solar cells

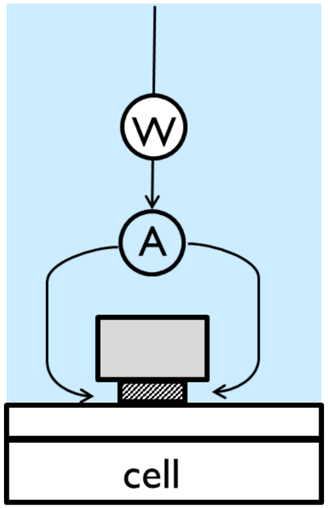


# Wait, Wait don't tell me …

## Dark corrosion

(a) Occurs night and day
(b) Involves acetic acid
(c) Does not depend on voltage
(d) All of the above

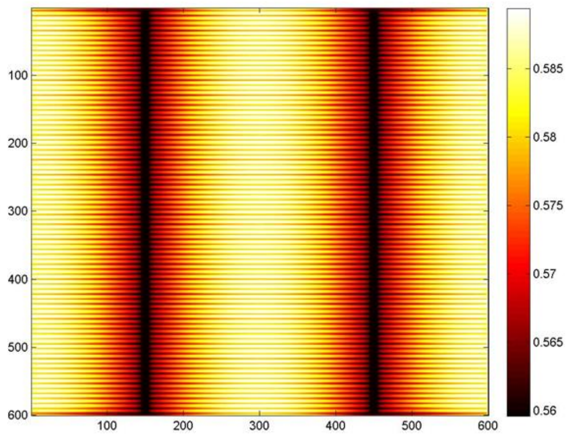
Dark



# Wait, Wait don't tell me …

In a pristine module, the busbar has

(a) The highest voltage
(b) The lowest voltage
(c) Depends on the busbar location
(d) Cannot be determined



# Wait, Wait don't tell me …

## TC test involves the following

(a) Moisture
(b) Light
(c) Voltage
(d) Temperature
(e) All of the above

TC: -40 to 85C(10min), 200-600 cycles (Delamination)

DH: 0 to 85%RH/65-85C, 1000hrs (Corrosion, Leak)

H-F: -40C to 85C @85RH, 10 cycles (Stress/corrosion)

UV: 0 to 25kWh/$m^2$, 4-5 cycles (Yellowing)

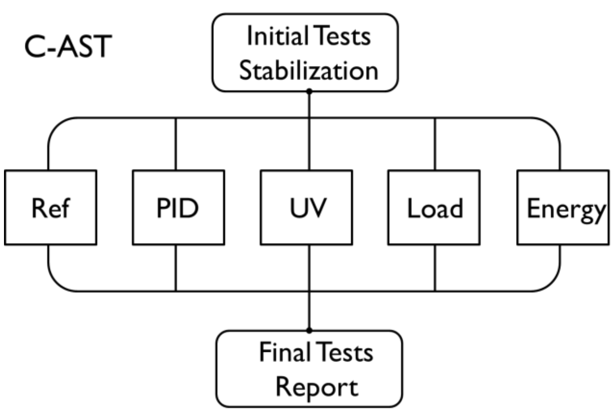
Load: 0 to 2.4/5.6 kPa, -40C, 2-5 cycles (Wind/Snow)

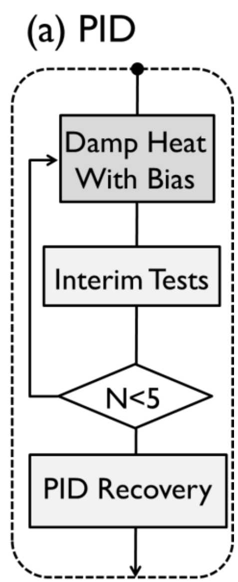
LID: 60 kWh/$m^2$, 1-10 cycles (EVA, Cells)

# Wait, Wait don’t tell me …

C-AST tries to achieve following goal

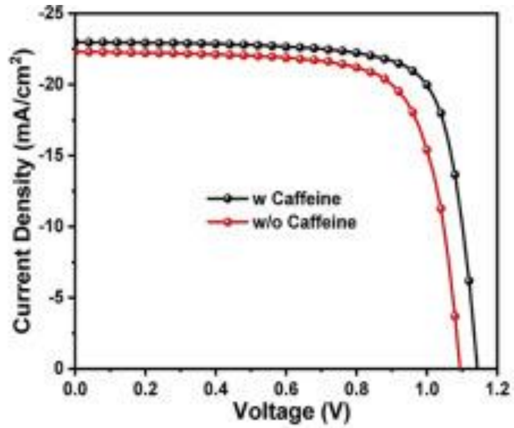
(a) Mimic environmental usage condition
(b) Create a new acronym to confuse people
(c) Calculate the time-dependent yield
(d) Accurately predict lifetime
(e) All of the above

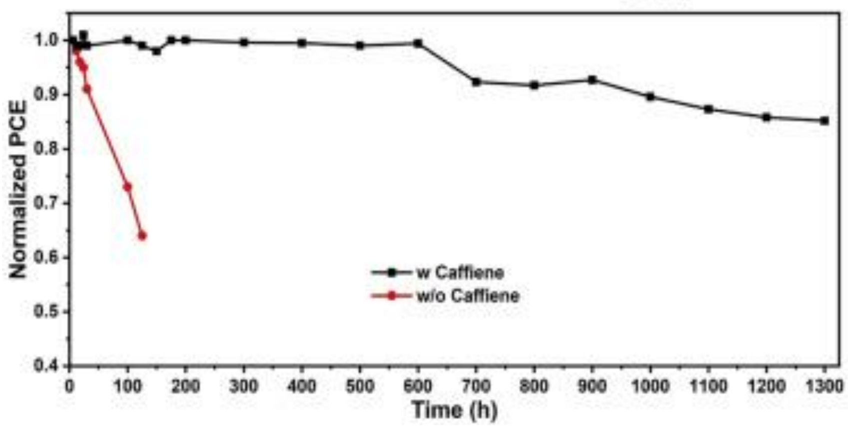


# Caffeine improves Perovskite PV efficiency and stability

https://doi.org/10.1016/j.joule.2019.04.005




https://www.cell.com/joule/fulltext/S2542-4351(19)30173-4#secsectitle0010

# Summary of Lectures

- Overview: Sun, Earth, and Solar cells
- Physics of c-Si Solar Cells
- Design of c-Si Solar Cells
- Advanced Concepts in c-Si PV
- Physics of Thin-film solar cells
- Module-Stripes for Thin-film Solar Cells
- Module-Stripes for c-Si Solar Cells
- Reliability Physics: Shadow degradation, PID
- Reliability Physics: Corrosion, UV
- Design of Solar Farms
- Storage of Solar Energy
- Levelized cost of Electricity
- Thermodynamics of Solar Cells

# Wait, Wait don't tell me …

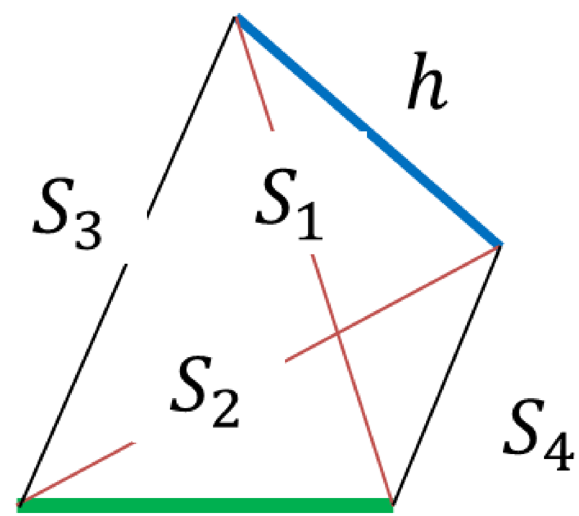
What is the Zenith angle on the shortest day of the year

(a) L
(b) L+23
(c) L-23
(d) L-10
(e) 0.7L + 3.6

# Wait, Wait don't tell me …

The cross-string method is used to calculate

(a) Direct light contribution
(b) Diffused light contribution
(c) Albedo light contribution
(d) Clearness index
(e) None of the above



# Wait, Wait don't tell me …

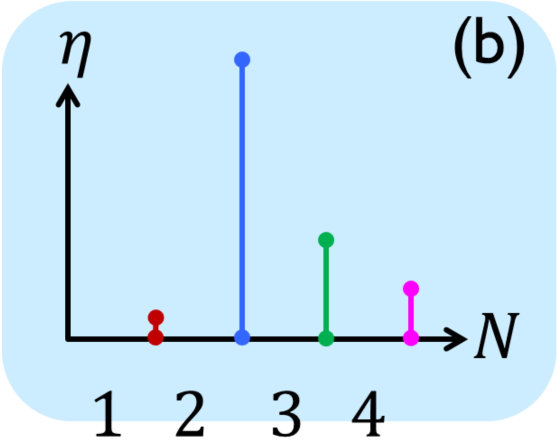
A flat solar farm is preferred when

(a) Module cost is high relative to land cost
(b) Module cost is low relative to land cost
(c) When diffused light component is high
(d) If diffused light component is low
(e) None of the above

# Wait, Wait don't tell me …

$H_2$ generation by solar cell is most efficienct when a single EC cell is coupled to the following number of PV cells

a) 1   b) 2   c) 4   d) 8



# Summary of Lectures

- Overview: Sun, Earth, and Solar cells
- Physics of c-Si Solar Cells
- Design of c-Si Solar Cells
- Advanced Concepts in c-Si PV
- Physics of Thin-film solar cells
- Module-Stripes for Thin-film Solar Cells
- Module-Stripes for c-Si Solar Cells
- Reliability Physics: Shadow degradation, PID
- Reliability Physics: Corrosion, UV
- Design of Solar Farms
- Storage of Solar Energy
- Levelized cost of Electricity
- Thermodynamics of Solar Cells

# Wait, Wait don't tell me …

LCOE accounts for the following factor that COE does not

a) Bank discount rate
b) Degradation rate
c) Energy yield
d) Cleaning cost

# Wait, Wait don't tell me …

What is the name of the law that expresses the decrease in manufacturing cost with manufacturing volume

a) Moore's law
b) Nernst law
c) Swanson law
d) None of the above

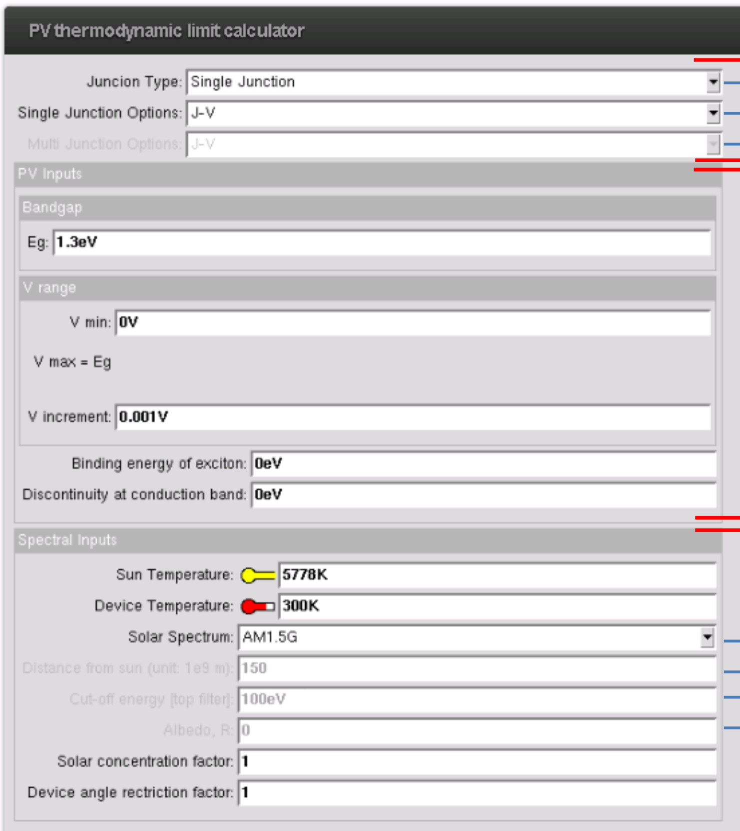
# Wait, Wait don't tell me …

You buy a 20% module and install it as a fixed tilt system. The effective efficiency is

a) 33%
b) 20% * (2/pi)
c) 20%
d) 20% * (pi/2)

# nanohub.org/resources/pvlimits

http://arxiv.org/abs/1606.01176




***Simulation setup***

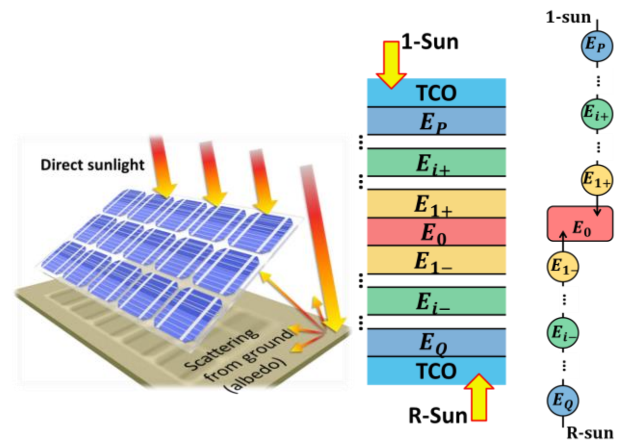
- Single (SJ) or multi-junction (MJ)
- SJ: J-V or Eg-sweep
- MJ: J-V or N-sweep

***Simulation specific input***

These set of inputs change based on the choice of simulation setup

***Spectral input***

- Input spectrum: AM1.5G or ideal Blackbody
- Distance from sun (for Blackbody input)
- Spectral low-pass filter (for MJ calculations)
- Reflectance of the ground (for MJ calc.)

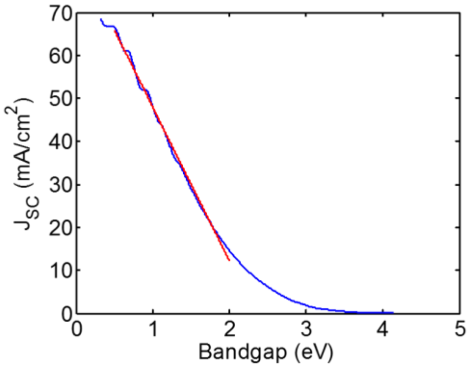



(a) (b) (c)

# Wait, Wait don't tell me …

Maximum Jsc (in mA/cm2) from AM1.5 spectrum is

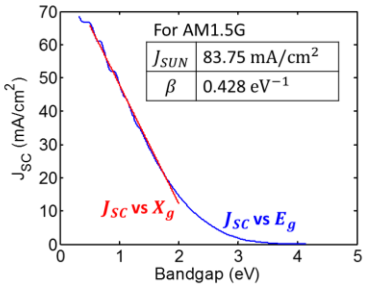
a) 7000 b) 700 c) 70 d) 7



# Wait, Wait don't tell me …

Maximum Jsc for Eg=1.7 eV perovskite under AM1.5 illumination is

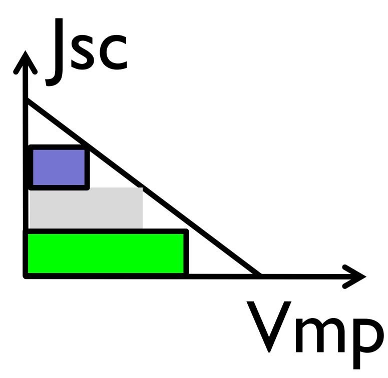
a) 100 b) 50 c) 20 d) 5



# Wait, Wait don't tell me …

For a 3-junction tandem, maximum Jsc in mA/cm2 is

a) 100 b) 70 c) 17 d) 4



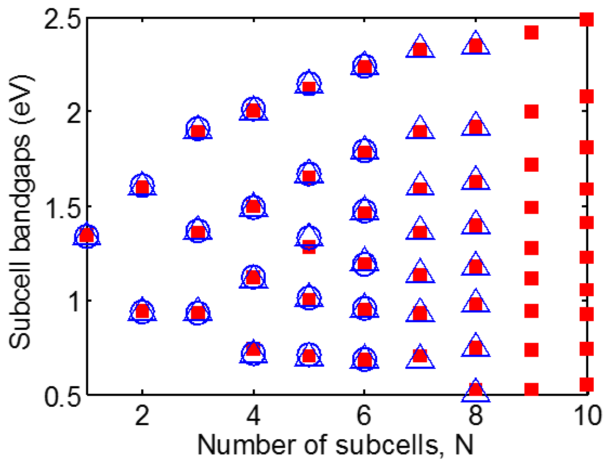
# Wait, Wait don't tell me …

If Eg=1eV, maximum $V_{mp}$ is

a) 1.0 b) 0.65 c) 0.45 d) 0.25

# Wait, Wait don't tell me …

In a N=3 tandem, E1=1.9eV, E3=0.97, what is E2?



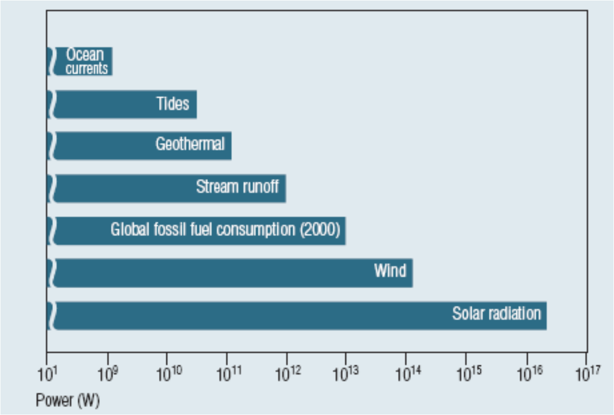

a) 2.5 b) 1.6 c) 1.3 d) 1.1

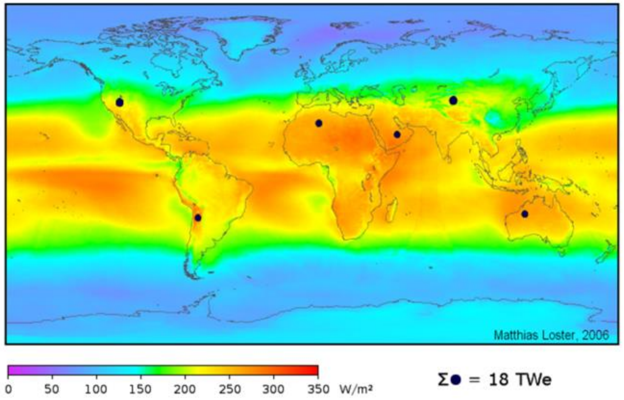
# Wait, Wait don't tell me …

In a N=3 tandem, What is Vmp?

a) 4 b) 3 c) 2 d) 1

# A world-wide grid for a global need




Demand

$W = 7.7 \times 10^9$
$P = 2.5 \times 10^3\ W$
$P_T \sim 2\ \ TW$

Smart heating, Smart transportation

Supply

$A = 510 \times 10^{12}\ m^2$
$P = 10^3\ W/m^2, \eta = 0.1$ (Technology)
$P_T \sim 0.5\ TW$ (if $A_R \sim 10^{-5}$ Indiana to USA)

Do we need a world-wide grid ?

# Conclusions

A fantastic multi-scale problem; a system-perspective is essential to have an impact and make a difference

A technology that of great significance for humanity

An technology that offers many opportunities for innovation

Reliability is fundamental; so is cost

# Wait, Wait don't tell me …

How hot a module can get, if the cells are 20%-efficient ? (h=10 W/m2/K)

a) 500C b) 100C c) 40C, d) 10C

# A Little Formula Sheet

**SJ cell**

$$J_{sc,SJ} = J_0\left(1 - \beta E_g\right) \quad (\text{AM1.5}, J_0 = 83.75, \beta = 0.428).$$

$$qV_{oc,SJ} = 0.95 \times E_g - 0.232$$

$$qV_{mp,SJ} = 0.95 \times E_g - 0.31$$

$$E_{g,SJ}^{opt} \cong 2.55\, kT_s$$

$$FF \sim (v_{oc}/v_{oc} + 4.7)$$

$$\eta_{T.SJ} = -26.45E_g^2 + 70.77E_g - 14.42 \quad (\text{AM1.5, empirical})$$

**Tandem**

$$J_{sc}(N) = \frac{2}{N+1} J_{sc}(\langle E_g \rangle)$$

$$qV_{mp}/N = \langle E_g \rangle \left(1 - \frac{T_D}{\langle E_g \rangle} \frac{E_{g,max}}{T_S}\right) - k_B\, T_D\, ln \frac{\theta_D}{\theta_S}$$

$$E_{g,\text{max}} = \frac{N-1}{\beta\, N} + \frac{\beta(1+R)E_0 - R}{\beta \times N}$$

**Module**

$$(T - T_a) = P/h = 1000(1 - \eta - R)/h$$