Chapter 1
Introduction to Solar Energy and Solar Photovoltaics

Solution to Exercises:

Q1. A solar cell is kept inclined at an angle of 30^0 equal to the latitude of the location. Assuming an insolation of 1000 W / m^2 incident perpendicular to the module, what will be the incident power if the module is kept horizontal?

Answer:

Insolation P_0 = 1000 W / m^2, P (θ) = $P_0 \cos\theta$ since $\theta = 30^0$,

P (θ) = 925 cos 30 = 801 W / m^2

Q2. Solar cells may provide a viable source of energy. Given the weekly average energy consumption in India is 30 x 10^9 kWh, average solar energy falling on India is 1800 W / m^2 with an average of 50 hours of sunlight per week, cell conversion efficiency is 15 %, each gram of Si in the finished cell requires 5 gm of polysilicon, and the cost of polysilicon is $40 / kg

a) Find how much polysilicon would be required to supply all the electricity requirements of India from 200 µm thick Si wafers.

b) How much land area would be required?

c) What will be the cost of the polysilicon?

Answer:

Amount of incident solar energy / week = 1800 x 50 = 90 kWh / m^2 per week

Module Efficiency = 15 % $\therefore$ E_{out} = 13.5 kWh / m^2 per week

Energy consumption / week = 30 x 10^9 kWh

$\therefore$ Cell Area required = 30 x 10^9 / 13.5 = 2.22 x 10^9 m^2

Assume land area = 2 x module area. $\therefore$ Land area = 4.44 x 10^9 m^2

= 4.44 x 10^3 km^2 $\approx$ 66.3 km x 66.3 km

Cell Volume = 200 µm x 2.22 x 10^9 m^3 = 4.44 x 10^5 m^3

Si density = 2.328. Weight of Si = 10.33 x 10^5 kg = 1.033 x 10^3 tonnes

Polysilicon amount = 5 x 1.033 x 10^3 tonnes = **5**.1 x 10^3 tonnes

Cost of Polysilicon = $ 40 x 10^3 x 5.1 x 10^3 = $ 2.4 x 10^8 = $ 240 million

= Rs 70 x 24 crores = Rs. 1689 crores

Q3. It is required to have a junction depth of 0.25 µm in a Si solar cell in which the p-type base layer has resistivity of 0.1 ohm.cm. Given μ_p = 400 cm^2 / V.s and μ_n = 1300 cm^2 / V.s, V_{bi} = 0.7 V,

Find the doping concentration of the front emitter layer and its resistivity.

Answer:

$\rho = 1/\sigma = 0.1\ \Omega$.cm. $\sigma = 10 = p\ e\ \mu_p$ = p. 1.6 x 10^{-19} x 400 $(\Omega.cm)^{-1}$

$\therefore$ p = N_A = 1.56 x 10^{17} / cm^3

W = 0.25 x 10^{-4} cm = $[(2\ \varepsilon_s / q) \{(N_A + N_D) / N_A N_D\} V_{bi}]^{1/2}$

Substituting N_D = 1.68 x 10^{17} /cm^3 and $\sigma = n\ e\ \mu_n$

σ = 1.68 x 10^{17} x 1.6 x 10^{-19} x 1500 = 40.3 $\therefore \rho = 1/\sigma$ = 0.0248 Ω.cm

Q4. A Si solar cell has an area of 5 cm^2. Under AM 1 illumination it develops V_{OC} = 0.7 V. Under these conditions V_m / V_{OC} = 0.85 and the fill-factor is 0.75. If J_S = 10^{-15} A / cm^2 , estimate the value of a) I_{sc} and b) cell efficiency η.

Answer:

AM 1 = 925 W / m^2 ; A = 5 cm^2 P_{in} = 0.4625 W

V_{oc}= 0.7 V, V_m = 0.85 x 0.7 = 0.595 V , FF = 0.75

V_{oc}= kT / q [ln (I_L / I_S) + 1] or 0.7 = 0.026 ln x $\therefore$ ln x = 26.9

I_L / I_S = 5.8×10^{12} $J_S = 10^{-15}$ A / cm^2 $\therefore$ I_S = 5×10^{-15} A / cm^2

I_L = = I_{SC} = $5 \times 10^{-14} \times 5.8 \times 10^{12}$ = 29. 10^{-3} A = 29 mA.

η = FF V_{oc} I_{sc} / P_{in} = $0.75 \times 0.7 \times 29 \times 10^{-3} \times 100 / 92.5 \times 10^{-3}$ = 16.45 %

Q5. A Si p-n solar cell with an area of 2 cm^2 has the following characteristics: $N_A = 1.7 \times 10^{17}$ cm^{-3} and N_D = 5×10^{19} cm^{-3}, τ_n = 10 μs, τ_p = 0.5 μs, D_n = 9.3 cm^2 / V.s and D_p = 2.5 cm^2 / V.s and I_L = 95 mA. a) Calculate and plot the I-V characteristics b) Calculate the open circuit voltage V_{OC} and c) find the maximum power output of the cell.

Answer:

a) Plot I-V characteristic

b) Using Eq (1.29), $I_S = 4.75 \times 10^{-15}$ A. V_{OC} = 0.736 V

c) 52.2 mW

Q6. i) CdTe has a refractive index n = 2.98.

i)What will be the reflection coefficient R at a CdTe - air interface ?

ii) Find the refractive index of an AR coating which will minimize R.

iii) SiO_2 has n = 1.46 and Si_3N_4 has n = 2.05 What should be composition of the optimum AR coating for CdTe ?

Answer:

n_{AR} = $(n_{sc} . n_{air})^{1/2}$ $(2.38 \times 1)^{1/2}$ = 1.72

For SiO_2 n = 1.46 and for Si_3N_4 n = 2.05.

Assuming linear variation of n with composition for n = 1.72

$\therefore$ Composition is $SiO_{0..44}N_{0.56}$

Q7. The effects of series resistance R_S and shunt resistance R_{SH} on power output P_{MP} and can be represented in simplified form by the equations:

$P'_{MP} = P_{MP}$ [1 – (I_{SC} / V_{OC}) R_S] and $P''_{MP} = P_{MP}$ [1 – (V_{OC} / I_{SC}) / R_{SH}]

where P'_{MP} and P''_{MP} are the values of Max Power Output with R_S = 0 and $R_{SH} = \infty$ respectively. Given I_{SC} = 35 mA and V_{OC} = 0.65 V,

Find the loss of power for a) R_S = 2 Ω and b) R_{SH} = 1000 Ω

Answer:

$P'_{MP} = P_{MP}$ [1 – (I_{SC} / V_{OC}) R_S] and $P''_{MP} = P_{MP}$ [1 – (V_{OC} / I_{SC}) / R_{SH}]

(I_{SC} / V_{OC}) R_S = (35×10^{-3} / 0.65) x 2 = 107 .7 x 10^{-3} = 0.107

$\therefore$ P'_{MP} / P_{MP} = 0.893

(V_{OC} / I_{SC}) / R_{SH} = 0.0186×10^3 / 1000 = 0.0186

$\therefore$ P''_{MP} / P_{MP} = 1 - 0.0186 = 0.9814

Q8. A Au- GaAs Schottky barrier solar cell has ϕ_B = 0.8 V. Find I_s at 300 K & 500K

Given A = 74.4 A/ cm^2 / K^2. If I_L = 25 mA at 300 K find V_{OC}**

Answer:

For a Schottky barrier I_s = A** T^2 exp (- q ϕ_B / kT)

V_{oc} = kT / q [ln (I_L / I_S) + 1]

Substituting, at 300 K $I_s = 2.87 \times 10^{-7}$ A ; at 500 K I_s = 8.17×10^{-7} A

At 300 K V_{oc}= 0.32 V

Q9. Draw the band diagram of a n - CdS / p – CdTe heterojunction. Assuming the doping concentrations are 2×10^{17} / cm^3 and 5×10^{17} / cm^3 respectively what are width of the depletion layers on each side and the built-in voltage V_{bi} ?

Answer:

Draw the band diagram of a n - CdS / p – CdTe heterojunction. Assuming the doping concentrations are 2×10^{17} / cm^3 and 5×10^{17} / cm^3 respectively what are width of the depletion layers on each side and the built-in voltage V_{bi} ?

a) Draw band diagram of n - CdS / p CdTe heterojunction

Electron affinities $\chi_2 - \chi_1 = 4.87 – 4.28 = 0.59$ eV = ΔE_C

$\Delta E_V = \Delta E_G - \Delta E_C = (2.42 – 1.56) – 0.59$ eV $= 0.86 – 0.59 = 0.27$ eV

b) $N_{D1} = 2 \times 10^{17}$ / cm^3 ; $N_{A2} = 5 \times 10^{17}$ / cm^3

ε_1 (CdS) = 5.4 ; ε_2 (CdTe) = 10.2 $\varepsilon_0 = 8.8 \times 10^{-12}$ F / m

From Poisson's equation,

conditions electric displacement at interface $\varepsilon_1 N_{D1} = \varepsilon_2 N_{A2}$

Charge equality on either side of junction

For n- p heterojunction $N_{D1} w_1 = N_{A2} w_2$ where w = depletion width

$w_1 = [2 N_{A2} \varepsilon_1 \varepsilon_2 (V_{bi} – V) / q N_{D1}(\varepsilon_1 N_{D1} + \varepsilon_2 N_A)]^{1./2}$

$w_2 = [2 N_{D1} \varepsilon_1 \varepsilon_2 (V_{bi} – V) / q N_{A2} (\varepsilon_1 N_{D1} + \varepsilon_2 N_A)]^{1./2}$

Assuming applied bias V = 0 and V_{bi} = 1 V

Substituting w_1 = 1.5 µm and w_2 = 0. 6 µm

viz. lightly doped side has wider depletion width

Chapter 2
Crystalline Silicon cells

Solution to Exercises:

Q1. Why is TCS preferred to the other chlorosilanes in the Siemens process ?

Answer:

TCS is a liquid with a reasonably low vapour pressure and can be cracked at a lower temperature than $SiCl_4$. Other silanes are in the gaseous state.

Q2. Why is the seed crystal in a Czochralski growth process usually necked down to a small diameter (3 m)?

Answer:

Necking of seed crystal is done to reduce the dislocation content in the grown crystal.

Q3. Iron, a common impurity in quartz crucibles, is present in a concentration of 2 x 10^{18} / cm^3. assuming that 300 cm^3 of the crucible is dissolved in a 6500 gm melt, all at the beginning of the growth cycle, find the Iron concentration in the at the seed and tang end (when 90 % of the melt is solidified). Given $C_S = k\, C_M\, (1 - W / W_M)^{k-1}$ and distribution coefficient k of Fe in Si = 8 x 10^{-6}

Answer

In 300 cm^3 crucible Fe content = 300 x 2 x 10^{18} / cm^3 = 6 x 10^{20}

Conc in 6500 gm melt = 6 x 10^{20} / 6500 = 9 x 10^{16} / gm

At start of growth cycle W = 0, $C_S = k\, C_M\, (1 - W / W_M)^{k-1} = 8.10^{-6} \times 9.\,10^{16} \times 1^{k-1}$

$C_S = 7.2 \times 10^{11}$ / cm^3

At tang end $W/ W_M = 0.9$, $C_S = 7.2 \times 10^{12}$ / cm^3

Q4. Why is Indium not used as a p-type dopant in Si (see Fig 2.14) ? Is there any possible application of In-doped Si ?

Answer

In is not used as a p-type dopant as it creates an acceptor level 0.16 eV above the valence band. This is much larger than kT (0.026 eV at 300 K) and hence a very small percentage of the In atoms are ionized and give rise to holes. In also has a relatively low solid solubility in Si (3.2 x 10^{19}/cm^3) and low distribution coefficient k because of its atomic size and hence large concentration cannot be introduced.

In - doped in Si can be used as a IR detector at λ = 1.2 / 0.16 eV = 7.5 µm

Q5. Can the spectral response of a solar cell be improved by introducing an impurity level in the mid-gap ? Discuss the possible advantages and disadvantages .

Answer

An impurity level in the Si band gap can give rise to optical absorption in the IR region, depending on its energy level, thus enhancing long wavelength response i.e larger I_{sc} in principle. However such a level will also act as a recombination centre thus increasing I_S which will reduce V_{OC}. Despite many such proposals this has not been successfully implemented.

Q6. Find the effective lifetime τ_{eff} in Si if the bulk lifetime is 10 µsec and the surface recombination velocity of one active surface is 1000 cm / s. Assume d = 300 µm.

Answer

$1/ \tau_{eff} = 1/ \tau_B + 1 / \tau_S$. $\tau_S = 2d / s = 2 \times 300 \times 10^{-4} / 1000 = 6 \times 10^{-5}$ s

$\tau_B = 10 \times 10^{-6}$ s $= 10^{-5}$ s $\quad \therefore \tau_{eff} = [(6 \times 1) / (6 + 1)] \times 10^{-5}$ s = 8.57 µs

Q7. For a grain-boundary barrier height of 0.4 eV, find the percentage of carriers that can surmount the barrier at T= 300 K.

Answer

% age = kT / 0.4 eV = 0.026 / 0.4 = 65 %

Q8. From Fig. 2.28 estimate electron density in an Ag nanoparticle with a plasma resonance at 497 nm. Assume m = 9.1×10^{-31} kg and $\varepsilon_0 = 8.85 \times 10^{-12}$ F / m.

Answer

For surface plasma

$\omega_p^2 = 4\pi Ne^2 / m\varepsilon_0$; $\omega_{sp} = \omega_p / \sqrt{3}$,

m = 9.1×10^{-31} kg and $\varepsilon_0 = 8.85 \times 10^{-12}$ F / m.

λ_{sp} = 497 nm. $\lambda.\nu = c$, $\nu = c / \lambda_{sp}$, $\omega_{sp} = 2 \pi c / \sqrt{3} \lambda_{sp}$

$= 2 \pi \times 3 \times 10^8 / \sqrt{3} \times 4.97 \times 10^{-7}$

$\therefore$ N = $\omega_{sp}^2 m \varepsilon_0 / \sqrt{3}\, 4 \pi e^2 = 2.07 \times 10^{20}$ / cm^3

Q9. What is the critical angle θ in Silicon if n = 3.45 ? Hence find the maximum path length if the absorber thickness is 7 µm.

Answer

Critical angle $\theta = \sin^{-1} n_1/ n_2$ $= \sin^{-1} 0.2898 = 17^0$

Maximum path length = $7 \times 10^{-4} / \cos 17^0 = 7 \times 10^{-4} / 0.96$ = 7.3 µm

Q10. Compare the advantages of CdTe solar cells over mc- Si solar cells if the operating temperature is 50^0 C ?

Assume the efficiencies at 25^0 C are 15% and 12% respectively ; prices are \$1.00 / W and \$0.80 /W respectively and the installed capacity is required to be 1 MWp.

Answer

Temp dependence of η of m Si = - 0.45% ; η = 15% at 25^0 C

Temp dependence of η of CdTe = -0.31% ; η = 12 % at 25^0 C

At 50^0 C η (m Si) = 15 – (25 x 0.45 x 15 /100) = 15 – 1.6875 = 13. 3125 %

At 50^0 C η (CdTe) = 12 – (25 x 0.31 x 12 / 100) = 12 – 0.93 = 11. 07 %

For 1 MWp m-Si requires 10^6 / 13.875; Cost = \$ 10^6 / 13.3125 x 1 = \$ 7.51 x 10^5

For 1 MWp CdTe requires 10^6 /11.225, Cost = \$ 10^6 / 11.07) x 0.80 = \$ 7.21 x 10^5

Thus the CdTe will be slightly more cost-effective at 50^0 C

Chapter-3
Thin film solar cells

Solution to Exercises:

Q1. Using solar insolation data from Ch 1. find the photon concentration in cm^2 / sec that can be absorbed by a-Si: H film with $E_{opt} \approx 1.7$ eV

Answer:

For a-Si: H $E_g = 1.7$ eV, cut-off $\lambda_c = 1.2 / 1.7 = 0.705$ µm
a-Si: H can produce a maximum of 420 W / m^2 (without reflection losses) compared with a AM1 input of 925 W / m^2. Since AM 1 corresponds to 5.2×10^{17} photons / cm^2, a-Si: H can absorb 420 x 5.2 / 925 = 2.36×10^{17} photons / cm^2.

Q2. c-Si cells have J_{sc} = 35 mA / cm^2 compared with J_{sc} = 18 mA / cm^2 for typical a-Si cells. Explain possible reasons for the difference.

Answer:

a-Si:H $E_{opt} \approx 1.7$ eV gas has higher band gap than c-Si with $E_g = 1.14$ eV and hence absorbs less photons. It has a quasi-direct gap and hence much lower absorption depth ~ 1 – 5 µm. However the main reasons are much the lower electron and hole mobilities and hence diffusion lengths $L_n \approx 1$ µm and $L_p \approx 0.1$ µm compared with 10 – 100 µm with c-Si.

Q3. What are the effects of alloying a-Si:H with C or Ge ?

Answer:

Addition of C increases the optical gap but reduces the carrier mobility due to increasing disorder. Addition of Ge decreases the optical gap thus increasing the no of solar photons that can be absorbed but also increases disorder. Thus only ~ 10% C or Ge are added to a-Si: H as and when required. Thus a-Si C - H is used a front window layer and a-$Si_{0.18}Ge_{0.82}$ – H as the base layer in Tandem solar cells to yield efficiencies as high as 13%.

Q4. a-$Si_{0.18}Ge_{0.82}$ has an optical gap $E_{opt} \approx 1.3$ eV and for a-Si:H $E_{opt} \approx 1.7$ eV. Assuming a linear variation with composition, what is the estimated optical gap of a-Ge: H ?

Answer:

a-$Si_{0.18}Ge_{0.82}$ has $E_{opt} \approx 1.3$ eV and for a-Si:H $E_{opt} \approx 1.7$ eV.
x = 0.82 lowers E_g by 0.4 eV $\therefore$ x = 1 will reduce E_g by 0.4 x 1.0 / 0.82 = 0.49 eV.
Thus a-Ge should have $E_g = 1.21$ eV

Q5. Boron doping increase the conductivity of a-Si: H from 10^{-9} Ω-cm to 10^{-2} Ω-cm. Find the concentration of B in substitutional sites if µ = 10^{-1} cm^2 / V.s. If the doping efficiency is 3 % , how much B_2H_6 is required for the doping ?

Answer:

$\sigma = n\, e.\mu$. $\therefore n = \sigma / e\,\mu = 10^{-9} / 1.6 \times 10^{-19} \times 10^{-1} = 6.25 \times 10^{10}$ / cm^3
On B doping, assuming µ remains same, $\sigma = 10^{-2}$ $\therefore$ n = 6.25×10^{17} / cm^3
Doping efficiency is 3% $\therefore$ B atoms introduced = $6.25 \times 10^{17} / 0.03 = 2.08 \times 10^{19}$ / cm^3
B_2 has atomic mass = 30 and mass of B_2 = 24.
$\therefore$ B_2H_6 to be introduced = 30/ 24 x 2.08×10^{19} / cm^3 = 2.6×10^{19} / cm^3
Actually B_2H_6 is highly diluted with H_2 as the carrier gas.
B_2H_6 has atomic mass = 30 x 1.55×10^{-24} gm = 4.65×10^{-23} gm
Mass of 2 B atoms (atomic mass =12) = 3.72×10^{-23} gm. Mass of 2.6×10^{19} B_2H_6 = 1.73×10^{-3} gm
Density of B_2H_6 = 1.2 gm / litre $\therefore$ Vol. of B_2H_6 = 1.73×10^{-3} / 1.2 = 1.44 cm^3

Q6. a- Si films are widely used in flat panel displays. Explain why and in what type of devices ?
Answer:
a-Si thin film transistors (TFT) are widely used as switches in matrix form to address flat panel LCD displays as:
(i) these can gave fast switching speeds of < 1 μsec
(ii) very low off currents < 1 nA
(iii) can use Si_3N_4 as gate insulator
(iv) can be deposited by r.f glow discharge at 350^0 C on conducting glass substrates

Q7. During deposition of CIS films anti-site doping may cause problems. What will be the nature of In_{Cu} and Cu_{In} defects, their effects on conductivity if any. Which are more likely ?
Answer:
In_{Cu} will act as donor and Cu_{In} as acceptor. These defects lead to compensation, increase scattering and reduce carrier mobility. From ionic size considerations Cu_{In} will be more probable.

Q8. Why are heterojunction CdS / CdTe cells preferred to p-CdTe / n-CdTe homojunction cells ?
Answer:
CdS with E_g = 2.2 eV as a window layer and does not absorb any of the solar radiation that can be absorbed by the p- CdTe base layer with E_g = 1.54 eV. n-CdTe layer has holes as minority carriers which have lower diffusion. Thus p-CdTe with electrons as minority carriers provides most of the J_{SC}

Q9. Fig. 3.18 c) shows incident photon-to-electron transfer efficiency (IPCE) vs. wavelength of MAPI and MAPBr. Compare the currents that can be collected from the 2 films assuming no other losses.
Answer:
Comparing the areas under the curves for MAPI and MAPBr.
Area of MAPI = 40 x 800 ≈ 32000 units ; Area for MAPBr ≈ 60 x 575 = 34500 units
From Fig. 3.21a) MAPI cells have J_{sc} = 20.29 mA/cm^2;
Thus for MAPBr cells J_{sc} = 20.29 x 345 / 320 = 21.875 mA/cm^2

Q10. If the exciton binding energy of MAPI is 15 meV, what fraction will dissociate at 300 K ?
Answer:
Fraction dissociating = exp - (15 / 26) = exp (- 0.576) = 56 %

Q11. The J-V curve of perovskite solar cells shows hysteresis. What could be the reason for this ?
a) ferroelectricity caused by dipoles of the MA molecules
b) ionic conductivity and ion migration
c) unbalanced charge collection rate at the interfaces
Answer:
Meloni, Moehl and Gratzel (Nature Comm. 7, 2016, Article number 10334) have recently examined the possible causes of the hysteresis in both MAPI and MAPBr. Their conclusion was this was not due to ferroelectricity which could have arisen due to the rotation of MA^+ ions as found both theoretically and experimentally. On the other hand experiments showed that hysteresis was due to ionic migration of the halide ions.
They studied the J-V curves at different temperatures between + 20^0 C to – 20^0 C and also at different scanning ates. It was thus found that the hysteresis effects were enhanced at temperatures. The activation energy thus found was 0.337 eV for MAPI and 0.275 eV for MAPBr in consonance with the larger ionic size of the I^- ion. The hysteresis effect also disappeared at high scanning rates as the ionic movement could not follow the electric field. Unbalanced charge collection rate at the interfaces was also ruled out.

Chapter-4

III-V compound, Concentrator & PEC cells

Solution to Exercises:

Q1. Solar radiation has peak intensity at 550 nm. From Fig 4.2 find the penetration depth of this radiation in a) GaAs b) CdTe

Answer:

At λ = 550 nm, α (GaAs) $\approx 10^5$ cm^{-1} $\therefore$ d = 0.1 µm.

α (CdTe) $\approx 8 \times 10^4$ cm^{-1} $\therefore$ d = 0.125 µm.

Q2. A GaAs n – on - p junction cell has the following properties: $N_D = 6 \times 10^{17}$ / cm^3, $N_A = 6 \times 10^{18}$ cm^3. $N_c = 4.7 \times 10^{17}$/ cm^3, $N_v = 7 \times 10^{18}$ / cm^3. ε_s = 11.9. Find a) width of the depletion layer b) depletion capacitance at V = 0 and built-in voltage V_{bi}.

Answer:

Depletion width w = [$(2\varepsilon_s/ q) \{(N_A + N_D) / N_A N_D\} V_{bi}$]

Given $N_D = 6 \times 10^{17}$ / cm^3, $N_A = 6 \times 10^{18}$ cm^3, ε_s = 11.9 for V_{bi} = 1 V

Substituting w = 0.54 µm

C = ε_s / w = 1.87 µF /cm^2

Electric field at junction $E_m = q N_D x_n / \varepsilon_s = q N_A x_p / \varepsilon_s$ where $w = x_n + x_p$

x_n = [$(2\varepsilon_s/ q / N_D) V_{bi}$] = 0.47 µm

Thus $E_m = 4.3 \times 10^4$ V /cm and V_{bi} = (1/2) E_mw = 1.16 eV.

Q3. For the above cell if the junction depth is 0.1 µm and diffusion lengths L_n = 3 µm and L_p = 1 µm. Find the photo-induced currents in the n , p and depletion regions at AM 1 insolation. (See Ch 1 for details). Assume R = 0 using AR coatings

Answer:

G(x) = $\alpha\ \phi_0$ (1-R) exp {- $\alpha(\lambda)$ .x}

J_{TOT} = q ϕ_0 (1-R) [1 / (α -1/L_p)].[exp {- d / L_p}. exp{- αd}] + [1 / (α + 1/ L_n)]. exp (- αd)

+ exp (- αd). [1- exp (- αW)] where d = x_j = junction depth and w = depletion width

Assume R = 0. RHS 1st and 2nd terms are negligible. $\alpha = 10^5$ cm^{-1}

J_{TOT} = q ϕ_0 exp (- αd). [1- exp (- αW)] = 1.6 x 2.10^{17} exp (- 10^5. 10^{-5}) [1 – exp (- 10^5. 0.54 x 10^{-4}]

= 1.6 x 2.10^{17} exp (- 1) = 11.84 mA

Q4. What is the advantage of MOVPE over other methods of thin film formation such as sputtering, physical vapour deposition ? Why are organo-metallics used as sources for the cations Ga, In etc ?

Answer:

MOVPE gives epitaxial single crystal layers as opposed to multicrystalline layers by sputtering and PVD.

Ga and In organo-metallic sources decompose at low temperatures allowing growth at low substrate temperatures. This reduces interdiffusion and permits growth of sharp interfaces.

Q5. In a Si concentrator cell working at C = 10, V_{oc} = 0.65 V and J_{sc} = 300 mA at T = 60^0 C. Find J_s

Answer:

$V_{OC} = (kT / q)$ [ln $(J_{SC} / J_s) + 1$] ; At 60^0 C T= 333 K , kT = 0.02886. ∴ 0.65 = 0.02886 [ln (0.3 / J_S) + 1]
22.52 = ln (0.3 / J_S) + 1; ln (0.3 / J_S) = 21.52 ; 0.3 / J_S = 2.218×10^9 ∴ $J_S = 1.35 \times 10^{-10}$ A.

Q6. A multi-junction solar cell has the structure $Ga_{1-y} In_y As$ / GaAs with band gaps 1.0 eV / 1.41 eV respectively. Find
a) the value of `y' $Ga_{1-y} In_y As$ that will give a band gap of 1.0 eV and
b) the maximum thickness of this $Ga_{1-y} In_y As$ layer on GaAs
Answer:
a) From diagram for E_g = 1.0 eV in composition $Ga_{1-y} In_y As$ y = 0.275
b) a (GaAs) = 5.6533 Å, a (InAs) = 6.0584 Å. For $Ga_{0.725} In_{0.275} As$ a = 5.7647
Δa = 0.1114 Å ∴ Critical thickness t_c = 50 <u>b</u> / m = 50 ; <u>b</u> = 1/ 2 <110> ; m = 0.1114 / 5.6533 = 1.97 %
t_c = 50 x 0.705 x 5.6533 / 1.114 = 170.3 Å

Q7. The cell efficiency is assumed to decrease with increasing temperature T according to η = a (1 − bT) (eqn. 4.10) with constants a = 0.425 and b = 0.00176. Up to what temperature can this equation be valid ?
Answer:
η = a (1 − bT) with a = 0.425 and b = 0.00176. Condition bT = 1 i.e. T = 1/ b = 568 K = 295^0 C

Q8. The plane that circumnavigated the globe Solar Impulse 2 had 17,248 photovoltaic cells rated at 66 kW peak. The area of each cell was 156. 25 cm^2. Find the output per cell and the cell efficiency.
Answer:
Each cell output = 66 kW / 17,248 = 3.82 W. Area = 156. 25 cm^2. ∴ P = 3820 / 156.25 = 24.45 mW / cm^2
Assuming P_{in} = 100 mW / cm^2 in space, η = 24.45 %

Q9. The solar spectrum extends till 2.6 µm. What semiconductor can be used as an absorbing layer for this wavelength and what composition can be grown on a) Ge and b) $Ga_{1-y} In_y As$?
Answer:
For λ = 2.6 µm, E = 1.2 / 2.6 = 0.46 eV.
a) Ge has lattice parameter a = 5.6461 Å on which can be grown as a strained layer PbS a = 5.9362 Å with E_g = 0.41 eV as absorber
b) E_g (InP) = 1.34 eV, a = 5.8686 Å; E_g (InAs) = 0.36 eV a = 6.0584 Å
Assuming linear variation, E_g ($InAs_xP_{1-x}$) for x = 0.9 will give E_g = 0.46 eV. a ($InAs_xP_{1-x}$) = 6.0394 Å which can be grown epitaxially on InAs
Alternatively to provide high α, InAs can be used as an absorber

Q10. Is it possible to use a semiconductor as a photo-cathode in a PEC cell for solar hydrogen generation ? Draw the diagram of such a PEC cell using semiconductors as photo-anode and photo-cathode, specifying the properties of both the semiconductors
Answer:
The valence band of photo-anode is lower than the O_2/ H_2O potential 5.7 eV below the vacuum level and E_g > 1.8 eV.
Candidates are: CdSe, CdS, ZnO, SnO_2, WO_3, TiO_2 and SiC. Of these only TiO_2 has proved to be stable.
Cathode can use activated Carbon

Q11. Assuming 1.8 V is required for hydrogen generation, what is the composition of a $In_{1-x}Ga_xN$ photo-anode cell that will generate the required V_{oc} ?
Answer:
E_g (GaN) = 3.4 eV ; E_g InN = 0.7 eV Assuming linear variation, for E_g (1.8 eV), x = 1.0 ΔE_g = 2.7 eV
Δy = 1.1 / 1.7 = 0.40 x = 1 - y = 0.6 Composition : $In_{0.4}Ga_{0.6}N$

Chapter-5
Organic and Polymer solar cells

Solution to Exercises:

Q1. Explain from the molecular structure why a) pentacene has high electron mobility and b) polyacetylene is an excellent conductor.
Answer:
See Text.

Q2. In organic semiconductors why does carrier mobility $\mu \propto T$ and $\mu \propto E^{1/2}$ where E = electric field ?
Answer:
See Text.

Q3. Why do excitons in organic semiconductors have much larger binding energies than those in inorganic semiconductors ?
Answer:
See Text.

Q4. Explain the difference between donor and acceptors in inorganic and organic semiconductors.
Answer:
See Text.

Q5. The short circuit current I_{sc} in a OPV cell is 10 mA . Assuming $\mu = 10^{-2}$ cm^2 / V.s, E = 10^2 V / cm what should be the carrier density ?
Answer:
I_{sc} = 10 ma, $\mu = 10^{-2}$ cm^2 / V.s, E = 10^2 V / cm
$n = I_{sc} / e \mu E = 10^{-2} / 1.6 \times 10^{-19} \times 10^{-2} \times 10^2 = 10^{17} / 1.6 = 6.6 \times 10^{16} / cm^3$

Q6. Indium Tin Oxide (ITO) has a work function ϕ = 4.5 eV. ITO is used as the top electrode with Ca (ϕ = 3.0 eV) as the bottom electrode in a single layer PV cell (Fig. 5.9). The thickness of the organic layer = 100 nm with $\mu = 10^{-4}$ cm^2 / V.s. What must be the minimum lifetime τ ?
Answer:
Voltage difference = 4.5 – 3.0 V = 1.5 V. Field E = 1.5 / 100 nm = 1.5×10^5 V / cm
From 5.7.1 (c) $\tau = d / \mu E$ = 100 nm / $10^{-4} \times 1.5 \times 10^5 = 10^{-5} / 15 = 6.6 \times 10^{-7}$ s

Q7. Fig 5.19 gives the condition for highest efficiency of 11 % in an OPV cells. Draw the heterojunction band diagram for this condition showing the HOMO and LUMO levels of Donor and Acceptor layers. What will be the expected V_{OC} ?
Answer:
V_{oc} linearly dependent on energy difference E_{DA} between highest occupied HOMO level of the donor and lowest unoccupied LUMO level of the acceptor
Lumo level of Donor = - 4.0 eV , Bandgap of donor = – 1.5 eV
Homo level of Donor = - 2.5 eV.
Lumo level of Acceptor = - 4.3 eV $\quad \therefore V_{OC}$ = 1.8 V

Q8. Compare the properties of bulk heterojunction cells with planar heterojunction cells. What are their advantages and disadvantages?

Answer:

See Text.

Q9. Si NCs have E_g = 1.2 eV. The exciton-production quantum yield was found to be 2.6 excitons per absorbed photon at $3.4E_g$ (4.08 eV). Considering the AM 1 solar spectrum (Fig. 1. 3) and assuming the quantum yield decreases linearly from 2.6 at 4.08 eV to 1.0 at 1.2 eV, estimate how many additional electron-hole pairs may be created ?

Answer:

At 4.08 eV, Exc QY = 2.6

Upto 1.2 eV, Exc. QY = 1.0 n_{ph} = 2.5 x 10^{17} / cm^2. s

n_{mex} = 0 / cm^2. s

$\therefore$ Upto 2.0 eV, Exc. QY = (1.6/ 2.8) x 0.8 = 0.46; n_{ph} = 1.1 x 10^{17} / cm^2. s

Δn_{mex} = 0.50 x 10^{17} / cm^2. s

Upto 3.0 eV, Exc. QY = (1.6/ 2.8) x 1.8 = 1.03 ; n_{ph} = 0.2 x 10^{17} / cm^2. s

Δn_{mex} = 0.2 x 10^{17} / cm^2. s

Upto 4.08 eV, Exc. QY = (1.6 / 2.8) x 2.8 = 1.6 n_{ph} = 0

Δn_{mex} = 0

$\sum \Delta n$ = 0.7 x 10^{17} / cm^2. s *+ 1.2 – 2.0 eV photons*

Increase = 0.7 / 2.5 = 28 %

Note : Total no of photons under AM 1 = 5.2 x 10^{17} / cm^2. S

$\therefore$ No of photons E < 1.2 eV = 5.2 – (2.5 + 1.1 + 0.2) = 1.4 x 10^{17} / cm^2. s

Chapter-6

Manufacture of c-Si and III-V Based High Efficiency Solar PV Cells

Solution to Exercises:

Q1. Explain the difference between "substrate" and "superstrate". Why some solar cells are to be made on superstrate instead of substrate?

Answer:

By convention the "substrate" is the base where additional layers are formed. In general substrate forms the bottom most layer of a composite structure. However, sometimes due to operational reasons, the base layer has to be put on top instead of bottom. Such base layer is called "superstrate". For some solar cells structure glass, which is transparent, is used as a base layer. The transparent glass has to face the sun and becomes the top layer and hence the "superstrate".

Q2. What is the basic difference between "Bulk" device and "Thin Film" device?

Answer:

In a "Bulk" device, the device structure is made using the substrate itself. For example to form a silicon p-n junction device, some part of the top portion of a p type bulk silicon can be doped n type. On the other hand, thin film device is formed by depositing thin layers on a substrate. For example, a-Si p-i-n device is formed on a glass substrate by depositing thin n, i and p layers. Glass only act as a substrate for support and does not form the active part of the device as such.

Q3. Looking at Fig 6.6, is it possible to tell which defects, surface or bulk , is dominant for deciding the effective life time? Explain the reason stating the origin of such defects.

Answer:

Two distinct decay rates can be seen. One is faster and defined by surface lifetime (τ_S) **.** The other one has slower decay rate and defined by bulk lifetime (τ_B). The faster decay rate signifies that the photo generated carriers are being captured at a faster rates by defects. As this is mainly due to surface recombination, the defect density at the surface is higher than the bulk. The effective lifetime (τ_{eff}), which is defined by the following equation, is dominated by τ_S as it is much lower than τ_B.

$$1/\tau_{eff} = 1/\tau_S + 1/\tau_B$$

The origin of the defects are due to dangling bonds resulting in surface states. The density of the surface states are determined by the crystal orientation and passivation techniques. The bulk defects on the other hands primarily depends on the purity of the materials and grain size in case the material is polycrystalline. Therefore although in a very pure material bulk defects are low, the surface defects may be significantly high. More details can be found in Chapter 2.

Q4. A multi c-Si cell fabricated using process flow, as shown in Fig 6.4, has conversion efficiency of 17%. The measurement after ARC step has shown that about 2.0% light is being reflected from the surface. Same measurements done on starting wafer and texturization show a reflection loss 40% and 20% respectively. What would have been the conversion efficiency in case:

- **(a) Texturization and ARC steps are skipped.**
- **(b) ARC step is skipped.**
- **(c) Texturization is skipped. Assume a reflection loss of 4% after ARC if texturization is not done.**

Answer:

The bare silicon wafer has 40% reflection loss, i.e 60% light enters silicon. After texturization, the reflection loss come down to 20%, i.e. 80% light is now entered silicon. ARC reduces the reflection loss further to 2%, i.e. 98% light enters silicon. The efficiency with 98% light entering silicon is 17%. In case the entire 100% light would have been entering silicon, the efficiency would have been increased by another 2%. The efficiency with 100% light entering silicon would have been: [17 (1+2/100)]% = 17.34%

(a) In case texturization and ARC steps are skipped the reflection loss is equal to the reflection loss due to bare silicon, i.e. 40% amounting to 60% light entering silicon. The efficiency is then 60% of 17.34, i.e. 10.404%.

(b) If ARC step is skipped, the reflection loss is 20% amounting to 80% light entering silicon. The efficiency is then 80% of 17.34 i.e. 13.872%.

(c) If texturization is skipped but ARC is done, the reflection loss is 4% amounting to 96% light entering silicon. The efficiency is then 96% of 17.34 i.e. 16.65%.

Q5. Light Trapping/Optical Confinement (see Fig 6.9) is generally applicable for c-Si solar cell technology. This is not so important for III-V high efficiency solar cell technology. Also a thin film layer of the order of 10µm thickness is good enough for III-V high efficiency solar cells. However much larger thickness is required for c-Si solar cell technology. Explain the reason.

Answer:

Silicon is an Indirect band gap material. The absorption depth is much higher for such materials. Therefore to absorb the complete incoming irradiance, higher thickness is required. Direct band gap materials such as III-V compound semiconductors have much smaller absorption depth and therefore even much thinner materials are sufficient to absorb the complete irradiance. Dealing on further, the absorption characteristics of light travelling through a material is given by:

$$I = I_0\, e^{-\alpha x}$$

Where I is the intensity of light at a depth x, I_0 is the intensity at x = 0, i.e. at the surface and α is the absorption co-efficient. α is very high for direct band gap semiconductor, e.g. III-V compound, and very small for indirect band gap semiconductor, e.g. silicon.

It may be noted that only the irradiance part having photons with energy more than the band gap ($h\nu > E_g$) of the material will be absorbed. Rest of the photons having lower energy ($h\nu < E_g$) are not being absorbed by the material and the above equation is not applicable.

Q6. A mono c-Si 2 bus bars cells having 70 numbers of 110µm wide fingers has a conversion efficiency of 19%. The bus bar width is 2.2mm. Determine conversion efficiency in case:

- **(a) Number of fingers are changed to 75 keeping the width same.**
- **(b) Number of fingers changed to 80 keeping the width same.**
- **(c) Number of fingers are 70 but the bus bars are 3 in number. The bus bar width is 1.8mm.**
- **(d) Numbers of fingers are 70, but the width is 100µm. The bus bars are 3 in number with width of 1.8mm.**

Answer:

19% efficiency is achieved with 2BB having width of 2.2mm each, 70 numbers of 110µm width fingers. We will assume 156mm x 156mm pseudo square cells. It is important to find out how much light is getting lost due to the metal (bus bars and fingers) coverage. This can be done by calculating the percentage of metal coverage over the entire surface area of the cell.

The total surface area of the cell is 15.6cm x 15.6cm = 243.36cm^2.

The fingers and bus bars run perpendicular to each other (see Fig 6.1 & Fig 6.3). The bus bar runs the entire length of the cell. The area occupied by one bus bars of width 2.2mm is 0.22cm x 15.6cm = 3.432cm^2. The area occupied by two bus bars is 3.432cm^2 x 2 = 6.864cm^2.

The fingers also runs across the entire length, except the portion occupied by the bus bars. The effective length of each (110µm = 110 x 10^{-4}cm = 0.011cm) wide fingers is therefore [156mm - (2 x 2.2)mm] = 151.6mm = 15.16cm for bus bar width of 2.2mm. The total area occupied by 70 fingers is [(0.011cm x 15.16cm) x 70] = 11.673cm^2.

The total area occupied by the bus bars and the fingers is then: 6.864cm^2 + 11.673cm^2 = 18.537cm^2.

As the total surface area of cell is 243.36cm^2, the metal coverage is (18.537cm^2/243.36cm^2) x 100% = 7.617%.

7.617% light is obstructed by metal and remaining 92.383% entering silicon giving 19% efficiency. In case 100% light is entering silicon, i.e. with zero metal coverage, the efficiency would have been 7.617% more, i.e. 19 (1+7.617/100)% = 20.45%.

(a) If the number of fingers are increased to 75, the coverage due to fingers is [(0.011cm x 15.16cm) x 75] = 12.507cm^2. The total coverage due to fingers and bus bars is (12.507cm^2 + 6.864cm^2) = 19.371cm^2. The metal coverage compared to entire cell surface area is (19.371cm^2/243.36cm^2) x 100% = 7.96%. It means 92.04% light is entering silicon. If entire light entering silicon gives 20.45% efficiency, 92.04% light entering silicon will give 20.45 x(92.04/100)% = 18.82% efficiency.

(b) If the number of fingers are increased to 80, the coverage due to fingers is [(0.011cm x 15.16cm) x 80] = 13.34cm^2. The total coverage due to fingers and bus bars is (13.34cm^2 + 6.864cm^2) = 20.204cm^2. The metal coverage compared to entire cell surface area is (20.204cm^2/243.36cm^2) x 100% = 8.3%. It means 91.7% light is entering silicon. If entire light entering silicon gives 20.45% efficiency, 91.7% light entering silicon will give 20.45 x(91.7/100)% = 18.75% efficiency.

(c) Number of fingers are 70, the coverage due to fingers is 11.673cm^2. The coverage due to 3 bus bars of 1.8mm each is (0.18cm x 15.6cm) x 3 = 8.424cm^2. The total coverage due to fingers and bus bars is (11.673cm^2 + 8.424cm^2) = 20.097cm^2. The metal coverage compared to entire cell surface area is (20.079cm^2/243.36cm^2) x 100% = 8.26%. It means 91.74% light is entering silicon. If entire light entering silicon gives 20.45% efficiency, 91.74% light entering silicon will give 20.45 x(91.74/100)% = 18.76% efficiency.

(d) Number of fingers are 70 but have width of 100µm. The coverage due to fingers is [(0.010cm x 15.16cm) x 70] = 10.612cm^2. The coverage due to 3 bus bars of 1.8mm each is 8.424cm^2. The total coverage due to fingers and bus bars is (10.612cm^2 + 8.424cm^2) = 19.036cm^2. The metal coverage compared to entire cell surface area is (19.036cm^2/243.36cm^2) x 100% = 7.82%. It means 92.18% light is entering silicon. If entire light entering silicon gives 20.45% efficiency, 92.18% light entering silicon will give 20.45 x(92.18/100)% = 18.85% efficiency.

Q7. A c-Si solar cell have 110µm metal fingers with a specific resistivity of 1.5µΩ-cm. The height of the fingers is 15µm. Calculate effective resistances offered by fingers between bus bars for finger specification details as given in Example 1(a) - 1(d). Assume the distance between bus bars are 52mm for 2 bus bars and 39mm for 3 bus bars. For 3 bus bar case , take any two bus bars for calculation.

Answer:

The sheet resistivity of each finger can be determined as

$$R_{Sh}\,(\Omega\text{-Sq}) = \rho\,(\Omega\text{-cm})/(\text{Thickness of the finger}) = 1.5\mu\Omega\text{-cm}/15\mu\text{m} = 0.001\Omega$$

For 110µm wide fingers and 2 bus bars: The length between bus bars for 2 bus bars cell is 52mm and the width of the finger is 110µm. The resistance offered by the finger between bus bars is then

$$R_{Finger} = (R_{Sh})_{Finger} \times (L/W) = 0.001(\Omega) \times (5.2\text{cm}/0.011\text{cm}) = 0.47\Omega$$

There are 75 fingers connected and all are appearing in parallel. The effective resistance of the fingers between bus bars in this case is then 0.47Ω/75 = 6.2mΩ.

For 100µm wide fingers and 2 bus bars: The length is still 52mm but the width of individual finger is 100µm. The resistance offered by the finger between bus bars is then

$$R_{Finger} = (R_{Sh})_{Finger} \times (L/W) = 0.001(\Omega) \times (5.2cm/0.010cm) = 0.52\Omega$$

For 75 fingers, the effective resistance is 0.52Ω/75 = 6.9mΩ.

For 110µm wide fingers and 3 bus bars: The length between bus bars for 2 bus bars cell is 39mm and the width of the finger is 110µm. The resistance offered by the finger between bus bars is then

$$R_{Finger} = (R_{Sh})_{Finger} \times (L/W) = 0.001(\Omega) \times (3.9cm/0.011cm) = 0.35\Omega$$

There are 75 fingers connected and all are appearing in parallel. The effective resistance of the fingers between bus bars in this case is then 0.35Ω/75 = 4.67mΩ.

For 100µm wide fingers and 2 bus bars: The length is still 39mm and the width is 100µm. The resistance offered by the finger between bus bars is then

$$R_{Finger} = (R_{Sh})_{Finger} \times (L/W) = 0.001(\Omega) \times (3.9cm/0.010cm) = 0.39\Omega$$

For 75 fingers, the effective resistance is 0.39Ω/75 = 5.2mΩ.

Q8. The power distribution of a batch of cells is shown in Fig 6.25. These are to be segregated in bins in terms of wattages of the cells. Each bin will contain a wattage spread (a) ±1% (b) ±0.05%. Starting from the peak wattage of 4.333W_P, find out the number of bins required for this distribution (Fig 6.25) between wattage values from 4.197W_P to 4.45W_P.

Answer:

(a) The wattage for the peak bin , where the number of cells peak, is 4.333W_P and the corresponding bin is (4.333-1% of 4.333)W_P to (4.333+1% of 4.333)W_P. The peak bin (Bin_{Peak}) is therefore is from 4.323W_P - 4.337W_P. The other bins are either side of this peak bin. After some rounding off of 4th decimal place and rearranging the bin details are given below. The peak bin is highlighted.

Bin 1	4.193W_P - 4.202W_P	Bin12	4.282W_P - 4.290W_P	Bin23	4.377W_P - 4.386W_P
Bin2	4.202W_P - 4.210W_P	Bin13	4.290W_P - 4.299W_P	Bin24	4.386W_P - 4.394W_P
Bin3	4.210W_P - 4.218W_P	Bin14	4.299W_P - 4.307W_P	Bin25	4.394W_P - 4.402W_P
Bin 4	4.218W_P - 4.226W_P	Bin 15	4.307W_P - 4.315W_P	Bin26	4.402W_P - 4.410W_P
Bin5	4.226W_P - 4.234W_P	Bin16	4.315W_P - 4.323W_P	Bin27	4.410W_P - 4.418W_P
Bin6	4.234W_P - 4.242W_P	**Bin17**	**4.323W_P - 4.337W_P**	Bin28	4.418W_P - 4.427W_P
Bin7	4.242W_P - 4.250W_P	Bin18	4.337W_P - 4.345W_P	Bin29	4.427W_P - 4.435W_P
Bin8	4.250W_P - 4.258W_P	Bin19	4.345W_P - 4.353W_P	Bin30	4.435W_P - 4.443W_P
Bin 9	4.258W_P - 4.266W_P	Bin 20	4.353W_P - 4.361W_P	Bin31	4.443W_P - 4.451W_P
Bin10	4.266W_P - 4.274W_P	Bin21	4.361W_P - 4.369W_P		
Bin11	4.274W_P - 4.282W_P	Bin22	4.369W_P - 4.377W_P		

(b) The peak wattage is 4.333W_P and the corresponding bin is (4.333 - 0.5% of 4.333)W_P to 4.333 + 0.5% of 4.333)W_P. Following the similar procedure as above, the bin details are as follows:

Bin 1	4.195W_P - 4.199W_P	Bin 21	4.279W_P - 4.284W_P	Bin 41	4.365W_P - 4.369W_P
Bin2	4.199W_P - 4.203W_P	Bin22	4.284W_P - 4.288W_P	Bin42	4.369W_P - 4.374W_P
Bin3	4.203W_P - 4.207W_P	Bin23	4.288W_P - 4.292W_P	Bin43	4.374W_P - 4.378W_P
Bin 4	4.207W_P - 4.211W_P	Bin 24	4.292W_P - 4.296W_P	Bin 44	4.378W_P - 4.383W_P
Bin5	4.211W_P - 4.216W_P	Bin25	4.296W_P - 4.301W_P	Bin45	4.383W_P - 4.387W_P
Bin6	4.216W_P - 4.220W_P	Bin26	4.301W_P - 4.305W_P	Bin46	4.387W_P - 4.391W_P
Bin7	4.220W_P - 4.224W_P	Bin27	4.305W_P - 4.309W_P	Bin47	4.391W_P - 4.396W_P
Bin8	4.224W_P - 4.228W_P	Bin28	4.309W_P - 4.314W_P	Bin48	4.396W_P - 4.400W_P
Bin 9	4.228W_P - 4.232W_P	Bin 29	4.314W_P - 4.318W_P	Bin 49	4.400W_P - 4.405W_P
Bin10	4.232W_P - 4.237W_P	Bin30	4.318W_P - 4.323W_P	Bin50	4.405W_P - 4.409W_P
Bin11	4.237W_P - 4.241W_P	Bin31	4.323W_P - 4.327W_P	Bin51	4.409W_P - 4.413W_P
Bin 12	4.241W_P - 4.245W_P	Bin 32	4.327W_P - 4.331W_P	Bin 52	4.413W_P - 4.418W_P
Bin13	4.245W_P - 4.250W_P	**Bin33**	**4.331W_P - 4.335W_P**	Bin53	4.418W_P - 4.422W_P
Bin14	4.250W_P - 4.254W_P	Bin34	4.335W_P - 4.339W_P	Bin54	4.422W_P - 4.427W_P
Bin15	4.254W_P - 4.258W_P	Bin35	4.339W_P - 4.343W_P	Bin55	4.427W_P - 4.431W_P
Bin16	4.258W_P - 4.262W_P	Bin36	4.343W_P - 4.348W_P	Bin56	4.431W_P - 4.436W_P
Bin17	4.262W_P - 4.266W_P	Bin37	4.348W_P - 4.352W_P	Bin57	4.436W_P - 4.440W_P
Bin18	4.266W_P - 4.271W_P	Bin38	4.352W_P - 4.356W_P	Bin58	4.440W_P - 4.444W_P
Bin19	4.271W_P - 4.275W_P	Bin39	4.356W_P - 4.361W_P	Bin59	4.444W_P - 4.449W_P
Bin20	4.275W_P - 4.279W_P	Bin40	4.361W_P - 4.365W_P	Bin60	4.449W_P - 4.453W_P

Q9. Prior to the electrical measurements of the cells described in Exercise 8, optical characterization are done and cells are segregated as "A" , "B" and "C" categories. Then the cells are furthers segregated as per category described in Exercise 8. What will be the total number of "Bins" in case (a) no further segregation as per power is done for "C" category (b) power segregation is also done for "C" category.

Answer:

(a) Initially C category cells are segregated in one bin and no further testing (electrical) is done on these. Rest of the cells are tested and binned as per the table derived at Exercise 8. Each wattage bin will now split into two bins one for A and other for B category cells. The total wattage bins then now will be double as shown in the table (Exercise 8). Therefore there will be 62 bins denoting optical (A and B) and electrical test for ±1% spread and 120 bins for ±0.5% spread. In addition there is one bin for C category cells. Therefore the total number of bins for ±1% spread is 63 and for ±0.5% is 121.

(b) If C category cells are also tested for electrical, each bin in the tables (Exercise 8) will now split in 3 and the total number of bins for ±1% spread is 93 and for ±0.5% is 180.

Q10. A 3 bus bars mono c-Si cell, made using base line technology (Fig 6.4), has 76 fingers with width of 110µm and height of 15µm. The efficiency of this cell is found out to be 18.5%. In case this is made using double printing technology with dimensions as per Fig 6.26(b), what would be its efficiency.

Answer:

The DP technology will reduce the metal coverage. This will reflect in efficiency improvement. The comparative metal coverage can be calculated similar to Exercise # 6.

The total surface area of the cell is 15.6cm x 15.6cm = 243.36cm^2.

The area occupied by the bus bars is 0.18cm x 15.6cm x 3 = 8.424cm^2. Please note that bus bar width of 1.8mm is assumed.

For conventional (without DP) process:

The effective length of the finger is [156 mm - (3 x 1.8)mm] = 150.6mm. The total area occupied by 76 fingers is [(0.011cm x 15.06cm) x 76] = 12.59cm^2.
The total area covered by bus bars and fingers in conventional process is 8.424cm^2 + 12.59cm^2 = 21.014cm^2. The metal coverage is (21.014cm^2/243.36cm^2) x 100% = 8.6%.

For DP the effective width of fingers determining the metal coverage is now 70µm. All other parameters remain same. The coverage due to finger is [0.007cm x 15.06cm) x 76] = 8.012cm^2. The total area covered by bus bars and fingers in conventional process is 8.424cm^2 + 8.012cm^2 = 16.436cm^2. The metal coverage is (16.436cm^2/243.36cm^2) x 100% = 6.75%.

Metal coverage of 8.6% gives an efficiency of 18.5%. In this case 91.4% light reached silicon. In case 100% light reaches silicon, the efficiency would have been [(18.5/91.4) x 100]% = 20.24%. For DP the coverage is 6.75% i.e. 93.25% light reaches silicon. The efficiency is then [(93.25/100) x 20.24] % = 18.87%.

The electrical resistance of fingers created by DP also changes as compared to conventional process. The calculation is not as straightforward as metal step coverage. There are several other electrical resistances are to be considered for such calculation. The details are discussed in Chapter 7. It can be found that the contribution of electrical resistance change on efficiency due to DP is not significant. However it is important to ensure the electrical resistance offered by metal fingers is not significantly reduced due to DP process. The resistance offered by the fingers can be estimated using the method discussed in Exercise # 7.

Assuming a specific resistivity of 1.5µΩ-cm:

For conventional process:
The sheet resistivity of each finger is 1.5µΩ-cm/15µm = 0.001Ω. Resistance offered by each finger: R_{Finger} = $(R_{Sh})_{Finger}$ x (L/W) = 0.001(Ω) x (15.06cm/0.011cm) = 1.37Ω.

For DP process:
There are two parallel resistances one having 70µm width and 10µm thickness and the other having 50µm and 20µm thickness. The sheet resistivity of these two resistances are (1.5µΩ-cm/10µm) = 0.0015Ω and (1.5µΩ-cm/20µm) = 0.00075Ω. The resistance offered by line one is 0.0015(Ω) x (15.06cm/0.007cm) = 3.23Ω and the resistance offered by second line is 0.00075(Ω) x (15.06cm/0.005cm) = 2.26Ω. the effective resistance R_{eff} = (3.23 x 2.26)/(3.23 + 2.26)µ = 1.32Ω.

It is clear that the DP technology aims to reduce the step coverage without increasing the overall electrical resistance of the fingers.

Q11. A mono c-Si solar cell is made using MWT technology has 70 fingers and efficiency of 19.0%. This cell is made using conventional metallization process. Calculate the efficiency in case the cells are made using double printing metallization process. Use the metal line dimensions as shown in Fig 6.26.
Answer:
MWT process does not have bus bars. The length of the fingers will then be 15.6cm. As per Fig 6.26, the finger width is 120µm. The metal coverage due to 70 numbers of fingers is then [(0.012cm x 15.6cm) x 70] = 13.104cm^2. The total surface area of the cell is 15.6cm x 15.6cm = 243.36cm^2. The total area covered by metal is (13.104cm^2/243.36cm^2) x 100% = 5.38%.

For DP the effective width of fingers determining the metal coverage is now 70µm. All other parameters remain same. The coverage due to finger is [0.007cm x 15.6cm) x 70] = 7.644cm^2. The metal coverage is (7.644cm^2/243.36cm^2) x 100% = 3.14%.

Metal coverage of 5.38% gives an efficiency of 19.0%. In this case 91% light reached silicon. In case 100% light reaches silicon, the efficiency would have been [(19/91) x 100]% = 20.88%. For DP the coverage is 3.14% i.e. 96.86% light reaches silicon. The efficiency is then [(96.86/100) x 20.88] % = 20.22%.

The effect of electrical resistance change on efficiency is negligible (see Exercise # 10).

Q12. In case the same cell as described in Exercise 10 is made with EWT, what would have been its efficiency. Neglect other factors such as increase of electrical resistance in EWT cells as compared to that of MWT cells.

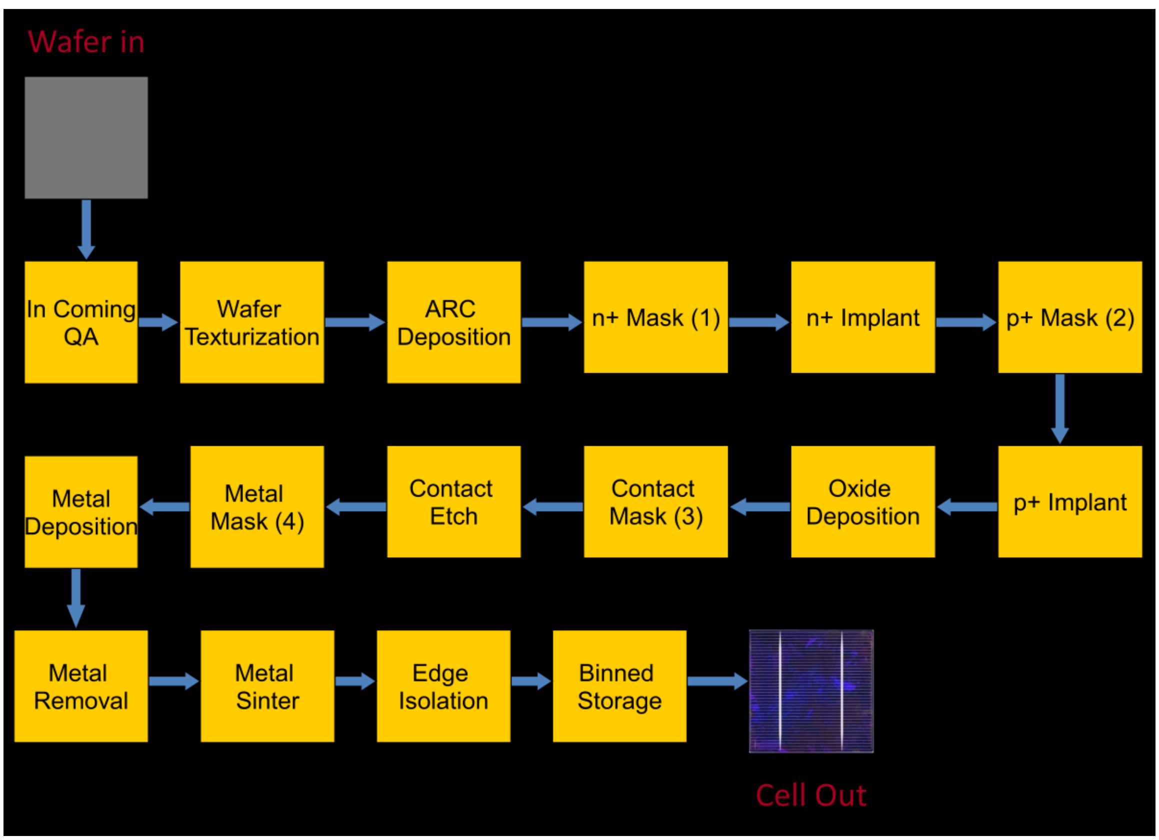
Answer:

As both fingers and bus bars are not present on the front side, almost 100% light reaches silicon. The efficiency in this case would be 20.24% as calculated in solution to Exercise #10.

Q13. IBC cell fabrications require typically 4 masking/photolithography steps. Define the masks, masking sequence and the process flow for IBC formation.

Answer:

In the IBC cell process the emitters (n^+), p^+ regions and corresponding metal connections are formed at the back. The required masks in sequential order, are (1) for creating n^+ regions on the back which has to be separated from p^+ regions (2) for creating separate p^+ regions (3) for creating contact holes to take electrical connection with metal (4) for defining the metal lines separately for n^+ and p^+. Lift- off process (see Fig 6.40) is used to define metal lines. A representative process flow is given below:



Q14. Several masks and photolithography steps have been mentioned for MJ high efficiency solar cells. List the masks and define its masking sequence.

Answer:

Typically there are three masks as described below:

S No	Mask Number	Mask Name	Purpose
1	Mask 1	Mesa Formation	For formation of By-pass diode. See Fig 6.39.
2	Mask 2	Cap Layer Formation	Selective Etching of GaAs for cap layer. See Fig 6.38.
3	Mask 3	Metal Mask	Defining the metal connection by lift-off lithography. See Fig 6.40.

Q15. Compare the process flow of the MJ high efficiency cell with or without the monolithic diode. Clearly bring out the extra process steps, including masking steps, required to integrate the monolithic diode.

Answer:

By-pass diode formation require mesa formation using one mask (see Fig 6.39). This mask along with mesa etch process are not required in case monolithic by-pass diode is not formed along with the cell.

Q16. A MJ high efficiency solar cell has been fabricated on a 100mm Ge substrate without the monolithic diode. The measured conversion efficiency is 30%. In case the monolithic diode has also been integrated, what would be the efficiency of the cell. Assume the monolithic diode occupies 7mm^2 area.

Answer:

100mm wafer signifies that the diameter (D) is 100mm. The area of the entire surface is $\pi\ (D/2)^2$ = 7850mm^2. The area occupied by the diode (7mm^2), which is about 0.089% of the total area. In case of no by-pass diode 100% area (7850mm^2) is available for light collection. The corresponding efficiency is 30%. In case the bypass diode is used the efficiency would be (1-0.089/100) x 30% = 29.97%.

Q17. Is it possible to use "lift off" photolithography technique (see Fig 6.40) for Mesa formation (see Fig 6.39)? Explain with reasons.

Answer:

It is not possible to use lift-off photolithography techniques for mesa formation. Lift-off photolithography can be used to define layers which can be deposited on top of photoresist without compromising the properties of the deposited layer and also the photoresist. In case of mesa etching, the thin film MOVPE layers are to be removed. These high purity single crystal thin film layers cannot be deposited on photoresist without compromising the properties of these thin film layers. This is the primary reason. For some other materials, lift-off photolithography may not be possible due to use of higher deposition temperature. The photoresist may decompose at high temperature to lose its properties and/or resulting contamination.

Chapter-7
Manufacture of Solar PV Modules

Solution to Exercises:

Q1. A customer wants glass-on-glass c-Si modules without a frame for a special application. Is it possible to manufacture such modules? If yes, describe the lay-up sequence and what are the negatives the customer needs to be aware of?
Answer:
Yes it is possible. Similar to thin film module, the Tedlar backsheet is replaced with glass. The layup layers starting from the front glass are: Front glass-EVA-Cell string-EVA-Back Glass. The lamination process parameter have to be adjusted. The back side glass hardness specification may be relaxed to certain extent. The negative are:

i) Since such modules do not have frames, it is not possible to easily fix these to the structures during installation. Conventional modules have holes in the frame and therefore can easily be fixed to the structures using the matching holes by nut-bolts during installation. Glass-on-glass modules without frame are installed using glue which is more complex and have less strength.

ii) The weight of the module is more as glass is heavier than the backsheet.

iii) Tempered glass used for solar module can break into many pieces due to impact on the edges. The edges are protected by frames for conventional module. Frame less module has to be handled carefully to avoid the glass damage.

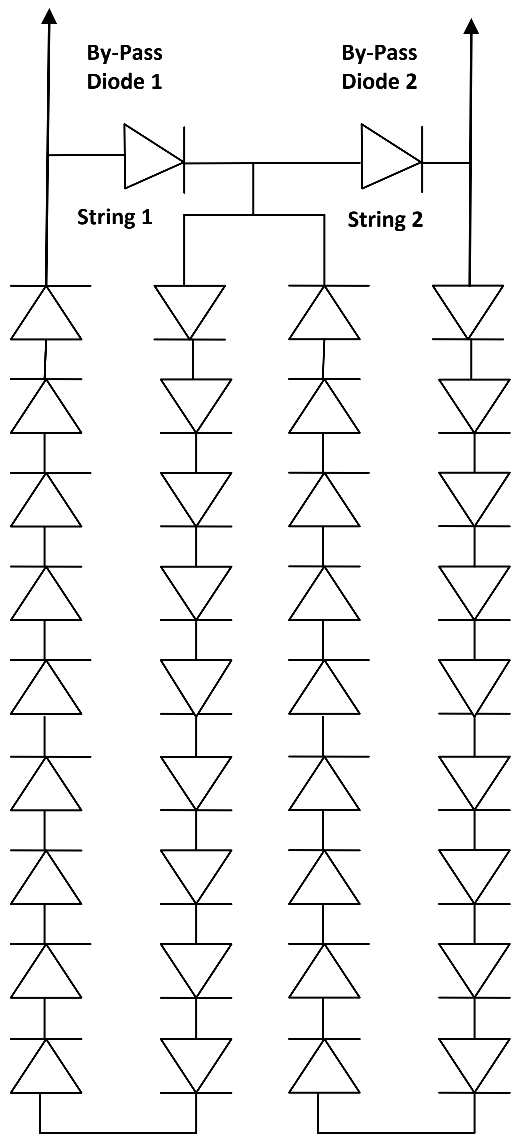
Q2. A customer wants conventional c-Si modules without frame for a special application. Compare the manufacturing steps with the conventional one. What would be approximate saving on bill of material (BOM)?
Answer:
Yes this is possible. The framing steps are not required; rest of the steps are identical to the conventional process. The disadvantages listed in answers to Exercise # 1 (i) and (iii) are applicable here also. The weight is a bit less as compared to conventional module due to absence of frame.

As can be seen in Table 7.16, the cost of metal frame is about \$10 per module (60 cells). This will reduce the BOM cost of about \$0.041/W_P. Rest of the BOM will same. The throughput and factory cost will marginally improve.

Q3. What would be the best possible string configuration of a 36 cells module? How many by-pass diodes are required for the suggested configuration? Draw the diode representation of the complete cell string. Determine the approximate size of the module if a 60 cells module, made using the same manufacturing process, has a size of 1.6m x 0.9m (area:1.52m^2). Assume the size of the cell is 156mm x 156mm and the gap between cells is 3mm.
Answer:
The popular 60 cells module use 10 x 6 configuration as shown in Fig 7.2 and Fig 7.23. The by-pass diode rating is compatible to voltage generated by 10 series connected cells. The best configuration for 36 cells is 9 x 4 as shown in below Figure. Same diode can be used. A 3-way junction box with two diodes is required for such module.

As compared to 60 cells, the length side will have one less [cell (156mm) + gap (3mm)]. The length of the 36 cells module is then 1.6m - 0.156m x 1 - 0.003m x 1 = 1.441m. Similarly the width direction there are two less (cells + gaps). The width of 36 cells module is then 0.9m - 0.156m x 2 - 0.003m x 2 = 0.582m.

The size of the 36 cells module is then 1.441m x 0.582m and the area is ≈ 0.84m^2.



Q4. A 156mm x 156mm c-Si solar cell has two bus bars with width of 2.2mm each. The total area covered by fingers is about 1200mm^2. The short circuit current (I_{SC}) of this cell at STC is 8.5A. Calculate the short circuit current after T&S for tabbing ribbon width of 1.8mm, 2.0mm, 2.2mm, 2.4mm, 2.6mm, 2.8mm and 3.0mm.

Answer:

Short circuit current is proportional to the effective cell area at a particular intensity. Area covered by ribbons and bus bars do not allow any light to pass. The effective area (A_e) is therefore less than the cell area. The pre T&S effective area for two bus bar cells can be calculated as:

A_e (Pre T&S for two bus bar cell) = (Total cell area) – (Area covered by ribbons + Area covered by bus bars). Total cell area is 156mm x 156mm = 24336mm^2. Area covered by Ribbons = 1200mm^2. Area covered by bus bars = 2.2mm x 156mm x 2 = 686.4mm^2.

A_e (Pre T&S for two bus bars cell) = 24336mm^2 – (1200mm^2 + 686.4mm^2) = 22449.6mm^2

There will be further loss of effective area after T&S in case the tabbing ribbon width is more than bus bar width. It is obvious that if the tabbing ribbon width is the same or less than that of bus bar, the effective area after T&S does not change. Therefore the change of active area (ΔA_e) after T&S for stabbing ribbon width of 1.8mm, 2.0mm and 2.2mm are zero. For ribbon width larger than that of bus bar, the area covered by the stabbing ribbon is to be considered instead of the area covered by bus bars. Post T&S the effective area in this case is:

A_e (Post T&S for two bus bar cell) = (Total cell area) – (Area covered by ribbons + Area covered by stabbing ribbons).

For stabbing ribbon width of 2.4mm:
A_e (Post T&S for two bus bars cell) = 24336mm^2 – (1200mm^2 + 748.8mm^2) ≈ 22387mm^2.

Change of active area for 2.4 mm is:
ΔA_e = A_e (Pre T&S for two bus bars cell) - A_e (Post T&S for two bus bars cell) = = 22449mm^2 – 22387mm^2 = 62mm^2. This is about 0.27%. The expected change of short circuit current (ΔI_{SC}) is therefore 0.27% for this ribbon size.

ΔA_e (or ΔI_{SC}**)** for ribbon widths of 2.6mm, 2.8mm and 3.0mm can be calculated similarly. The values are given in the below table.

	Width in mm (2 Bus Bars Cell)						
	1.8	2.0	2.2	2.4	2.6	2.8	3.0
ΔI_{SC} (%)	0	0	0	0.27	0.51	0.77	1.0

Q5. Repeat exercise 4 for a 3bus bar cells with bus bar width of 1.5mm each and tabbing ribbon width of 1.3mm, 1.5mm, 1.7mm, 2.1mm and 2.3mm.
Answer:

For 3 bus bars cells, the pre T&S effective area is:

A_e (Pre T&S for three bus bars cell) = (Total cell area) – (Area covered by ribbons + Area covered by bus bars). Total cell area is 156mm x 156mm = 24336mm^2. Area Covered by Ribbons = 1200mm^2. Area covered by bus bars = 1.5mm x 156mm x 3 = 702mm^2.

A_e (Pre T&S for two bus bars cell) = 24336mm^2 – (1200mm^2 + 702mm^2) = 22434mm^2.

In this case also, if the tabbing ribbon width is same or less than that of bus bar, the effective area after T&S does not change. Therefore the change of active area (ΔA_e) after T&S for stabbing ribbon width of 1.3mm and 1.5mm are zero. The corresponding values for stabbing ribbon width of 1.7mm are:

A_e (Post T&S for three bus bars cell) = 24336mm^2 – (1200mm^2 +795.6mm^2) ≈ 22340mm^2.

Change of active area for 1.7 mm is: ΔA_e = 22540mm^2 – 22340mm^2 = 200mm^2**.** This is about 0.82%. The expected change of short circuit current (ΔI_{SC}) is therefore 0.82% for this ribbon size.

ΔA_e (or ΔI_{SC}) for ribbon widths of 2.1mm and 2,3mm and 2.5mm can be calculated similarly; values given in the below table.

	Width in mm (3 Bus Bar Cell)				
	1.3	1.5	1.7	2.1	2.3
ΔI_{SC} (%)	0	0	0.82	1.6	1.97

Wider stabbing ribbon reduces the series resistance resulting in smaller I^2R loss. On the other hand it decreases the power through reduction of I_{SC} due to increased shading. An optimum value can be obtained using the model and calculations described here. In practice, using a ribbon width equal to that of bus bar is safe. However marginally higher value can give better power output.

Q6. Repeat exercise 4 with tabbing ribbon width of 2.2mm and area covered by fingers are 800mm^2, 1000mm^2 and 1400mm^2.

Answer:

Short circuit current is proportional to the effective cell area at a particular intensity. Area covered by ribbons and bus bars do not allow any light to pass. In this case the tabbing ribbon width is the same that of bus bar. Therefore there will be no change of current after the T&S.

Q7. Repeat exercise 5 with tabbing ribbon width of 1.5mm and area covered by fingers are 800mm^2, 1000mm^2 and 1400mm^2.

Answer:

Short circuit current is proportional to the effective cell area at a particular intensity. Area covered by ribbons and bus bars do not allow any light to pass. In this case the tabbing ribbon width is the same that of bus bar. Therefore there will be no change of current after the T&S.

Q8. c-Si cells with 4.5W$_P$ each have been used to make a 60 cells modules. T&S loss and lamination gains are 4% and 2.5% respectively. Junction box results in a 2W$_P$ reduction of power. Determine the total W$_P$ of the module with or without ARC coating on glass. The ARC coating improves the power (W$_P$) by 1.5%.

Answer:

The total wattage for incoming 60 cells are 4.5W$_P$ x 60 = 270W$_P$. Due to T&S wattage loss is 4%, the wattage will reduced to (1 - 0.04) x 270W$_P$ = 259.2W$_P$. During lamination, there will be a gain of 2.5% and the wattage of the module after lamination is (1 + 0.025) x 259.2W$_P$ ≈ 264.38W$_P$.

There will be an additional gain of 1.5% if ARC glass is used. The total gain during lamination is then 2.5% + 1.5%) = 4%. The wattage of the module after lamination with ARC glass is then (1 + 0.04) x 259.2W$_P$ ≈269.57W$_P$.

The junction box add another 2W$_P$ wattage loss. Therefore:
the module wattage without ARC glass is:

$$264.38W_P - 2W_P = 262.38W_P$$

and the wattage of the laminated module with ARC glass is:

$$269.57W_P - 2W_P = 267.57W_P.$$

Q9. Repeat exercise 8 for a 72 cells module.

Answer:

The total wattage for incoming 72 cells are $4.5W_P$ x 72 = $324W_P$. Due to T&S wattage loss is 4%, the wattage will reduced to (1 - 0.04) x $324W_P$ = $311.04W_P$. During lamination, there will be a gain of 2% and the wattage of the module after lamination is (1 + 0.025) x $311.04W_P \approx 318.8W_P$.

There will be an additional gain of 1.5% if ARC glass is used. The total gain during lamination is then 2.5% + 1.5%) = 4%. The wattage of the module after lamination with ARC glass is then (1 + 0.04) x $311.04W_P$ $\approx 323.48W_P$.

The junction box add another $2W_P$ wattage loss. Therefore:

the module wattage without ARC glass is:

$$318.8W_P - 2W_P = 316.8W_P$$

and the wattage of the laminated module with ARC glass is:

$$323.48W_P - 2W_P = 321.48W_P.$$

Q10. Repeat the exercise 8 for a 96 cells module with junction box associated drop of $3W_P$.

Answer:

The total wattage for incoming 96 cells are $4.5W_P$ x 96 = $432W_P$. Due to T&S wattage loss is 4%, the wattage will reduced to (1 - 0.04) x $432W_P$ = $414.72W_P$. During lamination, there will be a gain of 2% and the wattage of the module after lamination is (1 + 0.025) x $414.72W_P \approx 425.1W_P$.

There will be an additional gain of 1.5% if ARC glass is used. The total gain during lamination is then 2.5% + 1.5%) = 4%. The wattage of the module after lamination with ARC glass is then (1 + 0.04) x $414.72W_P$ $\approx 431.3W_P$.

The junction box add another $3W_P$ wattage loss. Therefore:

the module wattage without ARC glass is:

$$425.1W_P - 3W_P = 422.1W_P$$

and the wattage of the laminated module with ARC glass is:

$$431.3W_P - 3W_P = 429.3W_P.$$

Q11. 60 identical cells are used to make a SPV module. V_{OC} , I_{SC} and fill factor (FF) of each cell are 0.6V, 8A and 0.7 respectively at STC. The series resistance (R_S) and shunt resistance of each cell are 0.002Ω and 15Ω respectively. Find the I-V characteristics of the module if one cell is completely shaded and no by-pass diode is used. Compare the maximum power output (P_{max}) of the module at STC with no cell shaded and one cell shaded. Also determine P_{max} at STC of the shaded module in case 3 by-pass diodes (One diode per 20 cells) are used.

Answer:

The I-V curve of the module with no shaded cell having the parameters given has been depicted in Fig 7.27. The voltage drops for a particular current when one cell is shaded. The module output voltage (V_L) at 8A with one cell shaded can be determined using Eq 7.15.

$$V_L = (60\text{-}1) \times 0.6 - 8\ (0.002 + 15) = -84\ V$$

This is dramatic number as the drop is more than the voltage of the module with no cell shaded. It is also clear that contribution of R_S is insignificant and can be neglected. More insight can be obtained by determining the I-V curve by calculating ΔV as per Eq 7.15.

$$\Delta V \approx 0.6 + 8 \times 15 = 120.6V$$

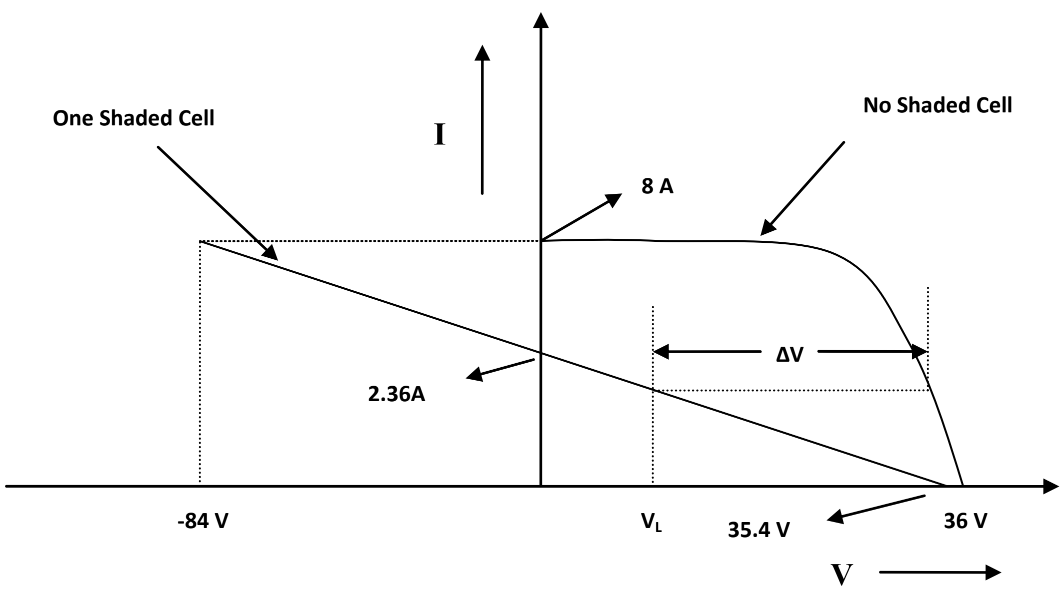
This implies that at I_{SC}, the shaded module has voltage of about -84. The un-shaded module at I_{SC} has a voltage of + 36 V. The negative V_L has no significance as current cannot be extracted from load. V_L will be positive at some current value. It is therefore important to find out the transition point at which the voltage becomes positive. This can be done by determining current value for $V_L = 0$ or $\Delta V = 36$ V. Using Eq 7.14 and putting $V_L = 0$, the corresponding current can be calculated as:

$$I\ (\text{at } V_L=0) \approx \frac{(n-1)V}{Rsh} = 2.36\ A$$

The open circuit voltage can be calculated by putting I = 0 in Eq 7.14:

$$V_L\ (\text{at } I = 0) \approx (n\text{-}1)\ V = 35.4\ V$$

The I-V characteristics of the shaded module can now be drawn with the above values (V_L at $I = I_{SC}$, V_L at $I = 0$ and I at $V_L = 0$). The characteristic is shown below in the below Figure. The characteristic of the normal module having no shaded cell is also shown along with ΔV in this Figure.



The power dissipation in the shaded cell at STC illumination (1000 W m^{-2}) and temperature (25^{0}C) can be calculated as:

$$\text{Power dissipation in the shaded cell} \approx I_{SC}^2\ R_{Sh} = 8^2 \times 15 = 960\ W$$

This is very large and therefore apart from losing significant amount of power the shading effect can damage the shaded cell by creating a hot spot. The by-pass diode apart from improving the power output prevents the hot spot formation as the current is by-passed through the external diode. These external diodes have to be chosen in such a way that they can carry large currents without damaging themselves.

The maximum power produced by the shaded module (without by-pass diode) can be determined by finding MPP point and multiplying V_L and I at that point. MPP point can be determined by a spread sheet by finding power at different V_L. Also since the I-V characteristic is a straight line, the MPP voltage (V_m) lies at midpoint between $V_L = 0$ and $V_L = V_{OC}$ (35.4V in this case), which is about 17.7V. Similarly MPP current (I_m) will lie at midpoint between I at $V_L = 0$ (2.36A in this case) and $V_L = V_{OC}$ (I = 0A), which is 1.18A . The maximum power (P_{max}) at STC is therefore:

$$P_{max} \text{ (One cell shaded, no by-pass diode)} = 17.7 \times 1.18 \approx 20.9\ W_P$$

The maximum power at STC of un-shaded module is:

$$P_{max} \text{ (No cell shaded)} = V_{OC} \times I_{SC} \times FF = 36 \times 8 \times 0.7 \approx 202\ W_P$$

In case by-pass diode is used (Fig 7.23), one of the strings (20 cells) containing the shaded cell is by-passed. The other two strings produce full power with:

$$V_{OC} = (n\text{-}20)\ V = 40 \times 0.6 = 24\ V$$

The maximum power produced by the module is then:

$$P_{max} \text{ (One cell shaded, one by-pass per 20 cells)} = 24\ (V_{OC}) \times 8\ (I_{SC}) \times 0.7\ (FF) \approx 134\ W_P.$$

This is an approximation as there is some voltage drop across the by-pass diode as it conducts. The voltage drop (V_{DD}) is about 0.6V for a conventional p-n junction diode. More advanced diodes, e.g. Schottky diodes, have voltage drop as low as 0.2 V. This voltage drop across the by-pass diode effectively reduces the V_{OC} to (V_{OC} - V_{DD}). The revised value of maximum power of the module with one shaded cell and having a by-pass diode is:

$$P_{max} \text{ (One cell shaded, one by-pass per 20 cells)} = (24 - 0.6) \times 8 \times 0.7 \approx 131\ W_P \text{ with conventional by-pass diode}$$

$$P_{max} \text{ (One cell shaded, one by-pass per 20 cells)} = (24 - 0.2) \times 8 \times 0.7 \approx 133\ W_P \text{ with advanced by-pass diode}$$

Q12. Repeat exercise 11 in case two cells are shaded. (a) Both the cells belong to the same string (20 cells) (b) Shaded cells belong to two different strings.
Answer:

(a) The I-V curve of the module with no shaded cell having the parameters given has been depicted in Fig 7.27. Due to shading of two cells, effectively the series and shunt resistances will now be double as compared to that of only one shaded cell. The module output voltage (V_L) at 8A with two cells shaded can be determined using Eq 7.15.

$$V_L = (60-2) \times 0.6 - 8\ (0.004 + 30) = -205.2\ V$$

ΔV as per Eq 7.15.

$$\Delta V \approx 1.2 + 8 \times 30 = 241.2V$$

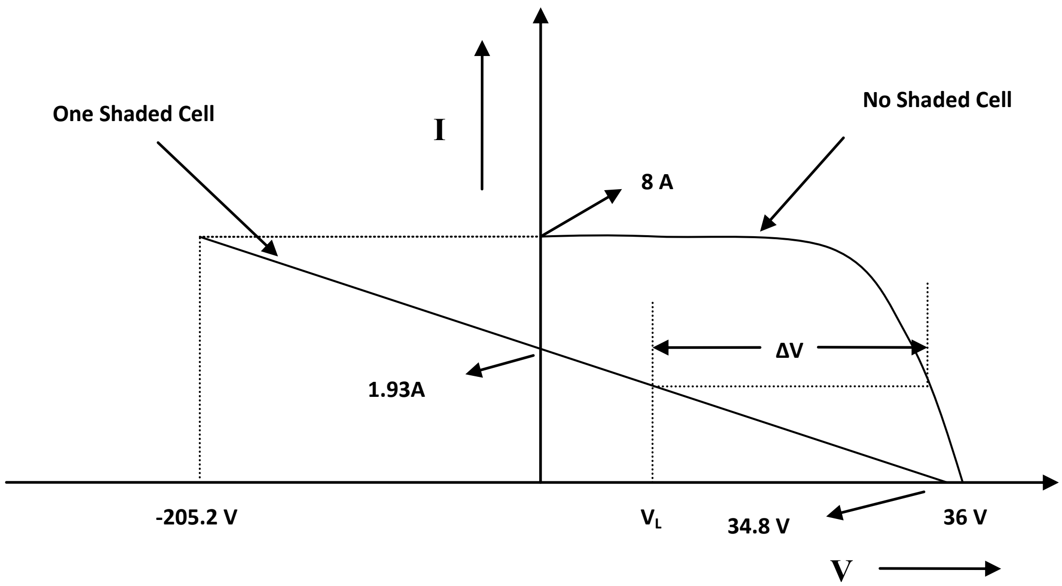
The current value at $V_L = 0$ or $\Delta V = 36$ V can be calculated as:

$$I \text{ (at } V_L\text{=0)} \approx \frac{(n-2)V}{Rsh} = 1.93 \text{ A}$$

The open circuit voltage can be calculated by putting I = 0 in Eq 7.14:

$$V_L \text{ (at I =0)} \approx \text{(n-2) V} = 34.8 \text{ V}$$

The I-V characteristics of the shaded module can now be drawn with the above values (V_L at I = I_{SC} , V_L at I = 0 and I at V_L = 0). The characteristic is shown below in the below Figure. The characteristic of the normal module having no shaded cell is also shown along with ΔV in this Figure.



The power dissipation in the shaded cell at STC illumination (1000 W m^{-2}) and temperature (25^0C) can be calculated as:

$$\text{Power dissipation in the shaded cell} \approx I_{SC}^2 \, R_{Sh} = 8^2 \text{x } 30 = 1920 \text{ W}$$

The MPP voltage (V_m) is about 17.4V. MPP current (I_m) is 0.965A . The maximum power (P_{max}) at STC is therefore:

$$P_{max} \text{ (One cell shaded, no by-pass diode)} = 17.4 \text{ x } 0.965 \approx 16.8 \text{ } W_P$$

The maximum power at STC of un-shaded module is:

$$P_{max} \text{ (No cell shaded)} = V_{OC} \text{ x } I_{SC} \text{ x FF} = 36 \text{ x } 8 \text{ x } 0.7 \approx 202 \text{ } W_P$$

In case by-pass diode is used (Fig 7.23), one of the strings (20 cells) containing the shaded cell is by-passed. The other two strings produce full power with:

$$V_{OC} = \text{(n-20) V} = 40 \text{ x } 0.6 = 24 \text{ V}$$

The maximum power produced by the module is then:

$$P_{max} \text{ (two cell shaded in a single string)} = 24 \text{ } (V_{OC}) \text{ x } 8 \text{ } (I_{SC}) \text{ x } 0.7 \text{ (FF)} \approx 134 \text{ } W_P.$$

Taking into the effect of By-pass diode drop:

$$P_{max} = (24 - 0.6) \times 8 \times 0.7 \approx 131\ W_P \text{ with conventional by-pass diode}$$

$$P_{max} = (24 - 0.2) \times 8 \times 0.7 \approx 133\ W_P \text{ with advanced by-pass diode}$$

(b) In case the two shaded cells are distributed along two different strings, the analysis without the by-pass diode will be identical. However with the by-pass diode, the power with come only from the one un-effected string:

$$P_{max} \text{ (two cells shaded in two different strings)} = 12\ (V_{OC}) \times 8\ (I_{SC}) \times 0.7\ (FF) \approx 67.2\ W_P.$$

By-pass diode drop is not considered.

Q13. 60 identical cells are used to make a SPV module. V_{OC}, I_{SC} and fill factor (FF) of each cell are 0.6V, 8A and 0.7 respectively at STC. The shunt resistance of each cell is 15Ω. One of the cells is 50% shaded. Determine the I-V characteristics of this module. Mention what happens if 3 by-pass diodes (4-way junction box) are used. Consider two types of by-pass diodes with typical voltage drop of 0.7V and 0.3V respectively. Neglect the effect of series resistance (R_S) in the calculations.

Answer:

The shaded cell has short circuit current and open circuit voltage of 4A and 0.6V respectively, which are 50% of the values applicable for un-shaded cell. At current (I) less than 4A, the characteristic is similar to a normal module having no un-shaded with open circuit voltage:

$$V_{OC} = (n-1) \times 0.6 + 1 \times 0.6 = 36.0V.$$

As current (I) becomes greater than 4A, Eq 7.18 and Eq 7.19 are applicable. The voltage drop (V_L) and difference (ΔV) at a particular current can be calculated using these two equations. V_L at I = 8A (I_{SC} of normal module) is:

$$V_L = (60-1) \times 0.6 - (8-4) \times 15 = -24.6V$$

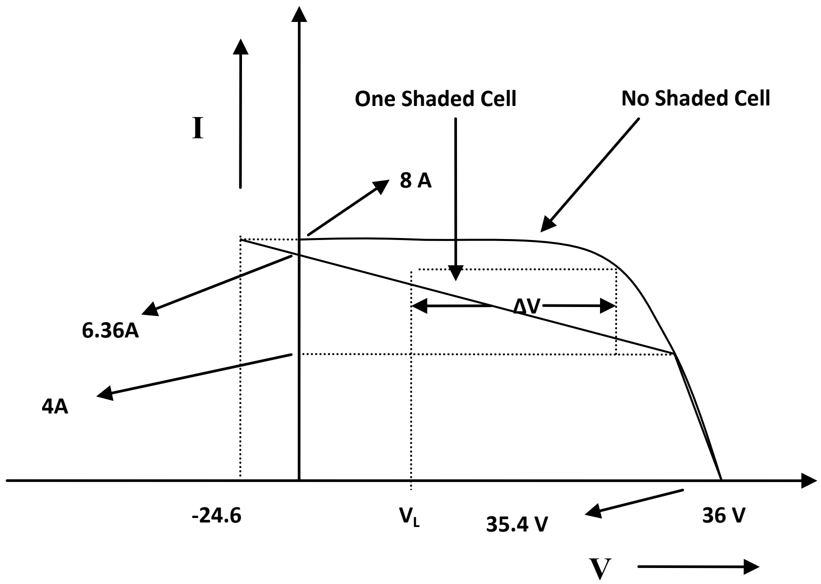
Current at $V_L = 0$, gives the point where the I-V characteristic cuts the Y-axis. This point can be determined by putting $V_L = 0$ in Eq 7.18.

$$0 = (60-1) \times 0.6 - (I - 8/2) \times 15; \quad I = 6.36A$$

ΔV at any current and more than 4A can be determined from Eq 7.19.

$$\Delta V = 0.6 + (I - 4) \times 15$$

Using these values calculated above, the I-V characteristics of the module with one 50% shaded cell can be drawn as shown in the below Fig.



A normal module I-V characteristic is also shown for comparison and to show ΔV. A spread sheet can be used to determine the set of values for I, V and P (power). This can be used to determine P_{max}. Plots of I-V and P-V can also be drawn as per scale using the spread sheet.

Now let us see what happens when a by-pass diode is used. As long as the current (I) is less than 4A ($I_{SC}/2$), by-pass diodes are reverse biased and do not play any role. As the current exceeds 4A, the diode connected across the applicable string gets forward biased and starts conducting, reducing the current through the shaded cell. In equilibrium, 4A flows through the shaded cell, in fact through the entire affected string and rest of the current (I-4) A, flows through the by-pass diode. At STC under short circuit condition, 4A flows through the affected string and remaining 4A through the by-pass diode resulting in a total short circuit current of 8A (I_{SC}) at the output. As 19 of the 20 cells in the affected string have V_{OC} of 0.6V each and the one with 50% shading also has V_{OC} of 0.6 V, the total open circuit voltage of the affected string of 20 cells is:

$$(20 - 1) \times 0.6 + 0.6 = 12.0 \text{ V}$$

The effective short circuit current is 4A. Considering a FF of 0.7, the maximum power produced by this string is:

$$P_{max} \text{ of string 1} \approx 12.0 \times 4 \times 0.7 \approx 34 \text{ W}_P$$

At STC, remaining 40 cells in the other two strings have V_{OC} and I_{SC} of 0.6V and 8A each respectively. Considering the diode drop, the total maximum power produced by these strings is:

$$[(40 \times V_{OC} - \text{Diode voltage drop})] \times 8 \times 0.7$$

P_{max} of string 2 & 3 combined ≈ 130.5 W_P with normal by-pass diode having 0.7V drop

P_{max} of string 2 & 3 combined ≈ 132.7 W_P with Schottky by-pass diode having 0.3V drop

The total maximum power produced by the module is then:

P_{max} of the module ≈ 34 + 130.5 = 164.5 W_P with normal by-pass diode having 0.7 V drop

P_{max} of the module ≈ 34 + 132.7 = 166.7 W_P with Schottky by-pass diode having 0.3 V drop

For the normal module P_{max} at STC is:

$$V_{OC} \times I_{SC} \times FF = 60 \times 0.6 \times 0.7 \approx 202\ W_P.$$

Q14. Repeat exercise 13 with (a) 40% shading (b) 60% shading.

Answer:

(a) The shaded cell has short circuit current and open circuit voltage of (1-0.4) x 8A = 4.8A and 0.6V respectively, which are 60% of the values applicable for un-shaded cell. At current (I) less than 4.8A, the characteristic is similar to a normal module having no un-shaded with open circuit voltage:

$$V_{OC} = (n-1) \times 0.6 + 1 \times 0.6 = 36.0V.$$

As current (I) becomes greater than 4.8A, Eq 7.18 and Eq 7.19 are applicable. The voltage drop (V_L) and difference (ΔV) at a particular current can be calculated using these two equations. V_L at I = 8A (I_{SC} of normal module) is:

$$V_L = (60-1) \times 0.6 - (8-4.8) \times 15 = -12.6V$$

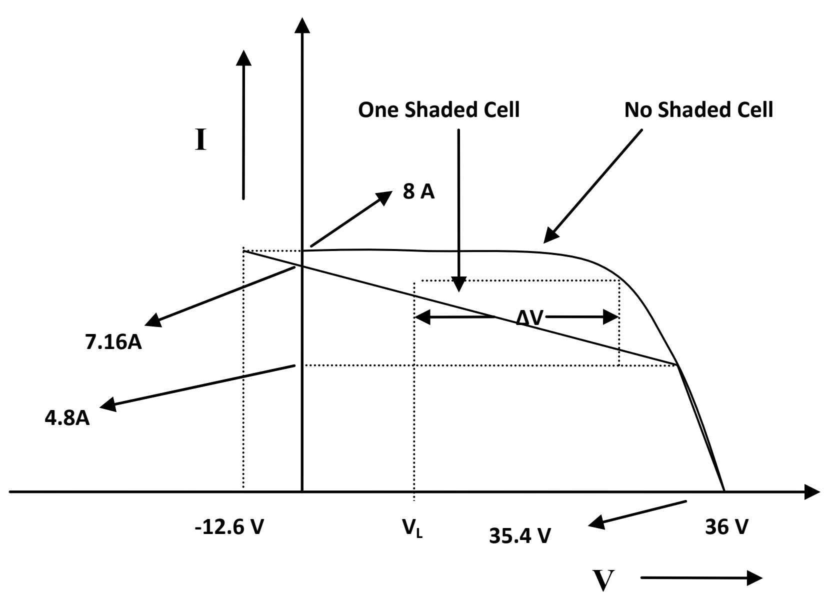
Current at V_L = 0, gives the point where the I-V characteristic cuts the Y-axis. This point can be determined by putting V_L = 0 in Eq 7.18.

$$0 = (60-1) \times 0.6 - (I - 4.8) \times 15; \quad I = 7.16A$$

ΔV at any current and more than 4A can be determined from Eq 7.19.

$$\Delta V = 0.6 + (I - 4.8) \times 15$$

Using these values calculated above, the I-V characteristics of the module with one 40% shaded cell can be drawn as shown in the below Fig.



A normal module I-V characteristic is also shown for comparison and to show ΔV. A spread sheet can be used to determine the set of values for I, V and P (power). This can be used to determine P_{max}. Plots of I-V and P-V can also be drawn as per scale using the spread sheet.

Now let us see what happens when a by-pass diode is used. As long as the current (I) is less than 4.8A , by-pass diodes are reverse biased and do not play any role. As the current exceeds 4.8A, the diode connected across the applicable string gets forward biased and starts conducting, reducing the current through the shaded cell. In equilibrium, 4.8A flows through the shaded cell, in fact through the entire affected string and rest of the current (I-4.8) A, flows through the by-pass diode. At STC under short circuit condition, 4.8A flows through the affected string and remaining 3.2A through the by-pass diode resulting in a total short circuit current of 8A (I_{SC}) at the output. As 19 of the 20 cells in the affected string have V_{OC} of 0.6V each and the one with 40% shading also has V_{OC} of 0.6 V, the total open circuit voltage of the affected string of 20 cells is:

$$(20 - 1) \times 0.6 + 0.6 = 12.0 \text{ V}$$

The effective short circuit current is 4.8A. Considering a FF of 0.7, the maximum power produced by this string is:

$$P_{max} \text{ of string 1} \approx 12.0 \times 4.8 \times 0.7 \approx 40.3 \text{ W}_P$$

At STC, remaining 40 cells in the other two strings have V_{OC} and I_{SC} of 0.6V and 8A each respectively. Considering the diode drop, the total maximum power produced by these strings is:

$$[(40 \times V_{OC} – \text{Diode voltage drop})] \times 8 \times 0.7$$

$$P_{max} \text{ of string 2 \& 3 combined} \approx 130.5 \text{ W}_P \text{ with normal by-pass diode having 0.7V drop}$$

$$P_{max} \text{ of string 2 \& 3 combined} \approx 132.7 \text{ W}_P \text{ with Schottky by-pass diode having 0.3V drop}$$

The total maximum power produced by the module is then:

$$P_{max} \text{ of the module} \approx 40.3 + 130.5 = 170.8 \text{ W}_P \text{ with normal by-pass diode having 0.7 V drop}$$

$$P_{max} \text{ of the module} \approx 40.3 + 132.7 = 173 \text{ W}_P \text{ with Schottky by-pass diode having 0.3 V drop}$$

For the normal module P_{max} at STC is:

$$V_{OC} \times I_{SC} \times FF = 60 \times 0.6 \times 0.7 \approx 202 \text{ W}_P.$$

(b) The shaded cell has short circuit current and open circuit voltage of (1-0.6) x 8A = 3.2A and 0.6V respectively, which are 40% of the values applicable for un-shaded cell. At current (I) less than 3.2A, the characteristic is similar to a normal module having no un-shaded with open circuit voltage:

$$V_{OC} = (n-1) \times 0.6 + 1 \times 0.6 = 36.0\text{V}.$$

As current (I) becomes greater than 3.2A, Eq 7.18 and Eq 7.19 are applicable. The voltage drop (V_L) and difference (ΔV) at a particular current can be calculated using these two equations. V_L at I = 8A (I_{SC} of normal module) is:

$$V_L = (60-1) \times 0.6 – (8-3.2) \times 15 = -36.6\text{V}$$

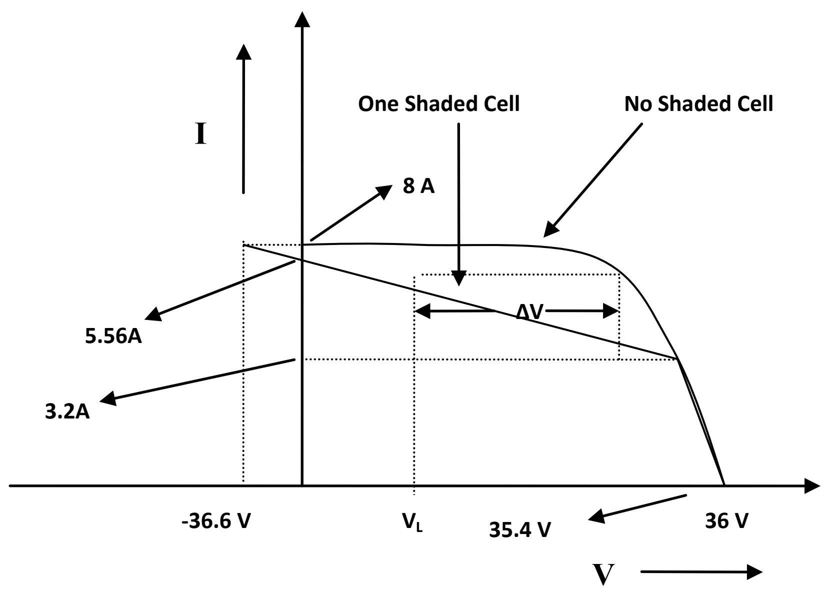
Current at $V_L = 0$, gives the point where the I-V characteristic cuts the Y-axis. This point can be determined by putting $V_L = 0$ in Eq 7.18.

$$0 = (60-1) \times 0.6 - (I - 3.2) \times 15; \quad I = 5.56A$$

ΔV at any current and more than 4A can be determined from Eq 7.19.

$$\Delta V = 0.6 + (I - 3.2) \times 15$$

Using these values calculated above, the I-V characteristics of the module with one 60% shaded cell can be drawn as shown in the below Fig.



A normal module I-V characteristic is also shown for comparison and to show ΔV. A spread sheet can be used to determine the set of values for I, V and P (power). This can be used to determine P_{max}. Plots of I-V and P-V can also be drawn as per scale using the spread sheet.

Now let us see what happens when a by-pass diode is used. As long as the current (I) is less than 3.2A , by-pass diodes are reverse biased and do not play any role. As the current exceeds 3.2A, the diode connected across the applicable string gets forward biased and starts conducting, reducing the current through the shaded cell. In equilibrium, 3.2A flows through the shaded cell, in fact through the entire affected string and rest of the current (I-3.2) A, flows through the by-pass diode. At STC under short circuit condition, 3.2A flows through the affected string and remaining 4.8A through the by-pass diode resulting in a total short circuit current of 8A (I_{SC}) at the output. As 19 of the 20 cells in the affected string have V_{OC} of 0.6V each and the one with 60% shading also has V_{OC} of 0.6 V, the total open circuit voltage of the affected string of 20 cells is:

$$(20 - 1) \times 0.6 + 0.6 = 12.0 \text{ V}$$

The effective short circuit current is 4.8A. Considering a FF of 0.7, the maximum power produced by this string is:

$$P_{max} \text{ of string 1} \approx 12.0 \times 3.2 \times 0.7 \approx 26.9\ W_P$$

At STC, remaining 40 cells in the other two strings have V_{OC} and I_{SC} of 0.6V and 8A each respectively. Considering the diode drop, the total maximum power produced by these strings is:

$$[(40 \times V_{OC} - \text{Diode voltage drop})] \times 8 \times 0.7$$

$$P_{max} \text{ of string 2 \& 3 combined} \approx 130.5\ W_P \text{ with normal by-pass diode having 0.7V drop}$$

$$P_{max} \text{ of string 2 \& 3 combined} \approx 132.7\ W_P \text{ with Schottky by-pass diode having 0.3V drop}$$

The total maximum power produced by the module is then:

$$P_{max} \text{ of the module} \approx 26.9 + 130.5 = 157.4\ W_P \text{ with normal by-pass diode having 0.7 V drop}$$

$$P_{max} \text{ of the module} \approx 26.9 + 132.7 = 159.6\ W_P \text{ with Schottky by-pass diode having 0.3 V drop}$$

For the normal module P_{max} at STC is:

$$V_{OC} \times I_{SC} \times FF = 60 \times 0.6 \times 0.7 \approx 202\ W_P.$$

Q15. Repeat exercise 13 with two cells shaded (a) 40% shading and cells belong to same string (b) 60% shading and cells belong to same string (c) 40% shading and cells belong to two different strings (d) 60% shading and cells belong to two different strings.

Answer:

(a) Both the shaded cell has short circuit current and open circuit voltage of (1-0.4) x 8A = 4.8A and 0.6V respectively, which are 60% of the values applicable for un-shaded cell. At current (I) less than 4.8A, the characteristic is similar to a normal module having no un-shaded with open circuit voltage:

$$V_{OC} = (n-2) \times 0.6 + 2 \times 0.6 = 36.0V.$$

As current (I) becomes greater than 4.8A, Eq 7.18 and Eq 7.19 are applicable. The voltage drop (V_L) and difference (ΔV) at a particular current can be calculated using these two equations. V_L at I = 8A (I_{SC} of normal module) is:

$$V_L = (60-2) \times 0.6 - (8-4.8) \times (2\times15) = -61.2V$$

Note that the shunt resistance is now double as two cells are shaded.

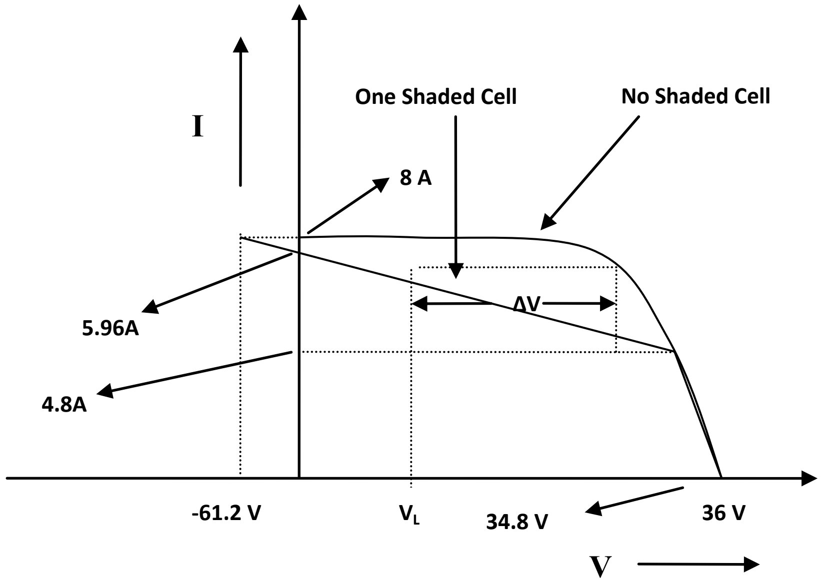
Current at $V_L = 0$, gives the point where the I-V characteristic cuts the Y-axis. This point can be determined by putting $V_L = 0$ in Eq 7.18.

$$0 = (60-2) \times 0.6 - (I - 4.8) \times 30; \quad I = 5.96A$$

ΔV at any current and more than 4A can be determined from Eq 7.19.

$$\Delta V = 0.6 + (I - 4.8) \times 30$$

Using these values calculated above, the I-V characteristics of the module with one 40% shaded cell can be drawn as shown in the below Fig.



A normal module I-V characteristic is also shown for comparison and to show ΔV. A spread sheet can be used to determine the set of values for I, V and P (power). This can be used to determine P_{max}. Plots of I-V and P-V can also be drawn as per scale using the spread sheet.

Now let us see what happens when a by-pass diode is used. As long as the current (I) is less than 4.8A , by-pass diodes are reverse biased and do not play any role. As the current exceeds 4.8A, the diode connected across the applicable string gets forward biased and starts conducting, reducing the current through the shaded cell. In equilibrium, 4.8A flows through the shaded cell, in fact through the entire affected string and rest of the current (I-4.8) A, flows through the by-pass diode. At STC under short circuit condition, 4.8A flows through the affected string and remaining 3.2A through the by-pass diode resulting in a total short circuit current of 8A (I_{SC}) at the output. As 18 of the 20 cells in the affected string have V_{OC} of 0.6V each and the one with 40% shading also has V_{OC} of 0.6 V, the total open circuit voltage of the affected string of 20 cells is:

$$(20 - 2) \times 0.6 + 0.6 \times 2 = 12.0 \text{ V}$$

The effective short circuit current is 4.8A. Considering a FF of 0.7, the maximum power produced by this string is:

$$P_{max} \text{ of string 1} \approx 12.0 \times 4.8 \times 0.7 \approx 40.3 \text{ W}_P$$

At STC, remaining 40 cells in the other two strings have V_{OC} and I_{SC} of 0.6V and 8A each respectively. Considering the diode drop, the total maximum power produced by these strings is:

$$[(40 \times V_{OC} - \text{Diode voltage drop})] \times 8 \times 0.7$$

P_{max} of string 2 & 3 combined ≈ 130.5 W_P with normal by-pass diode having 0.7V drop

P_{max} of string 2 & 3 combined ≈ 132.7 W_P with Schottky by-pass diode having 0.3V drop

The total maximum power produced by the module is then:

P_{max} of the module ≈ 40.3 + 130.5 = 170.8 W_P with normal by-pass diode having 0.7 V drop

P_{max} of the module ≈ 40.3 + 132.7 = 173 W_P with Schottky by-pass diode having 0.3 V drop

For the normal module P_{max} at STC is:

$$V_{OC} \times I_{SC} \times FF = 60 \times 0.6 \times 0.7 \approx 202\ W_P.$$

(b) Both the shaded cell has short circuit current and open circuit voltage of (1-0.6) x 8A = 3.2A and 0.6V respectively, which are 40% of the values applicable for un-shaded cell. At current (I) less than 3.2A, the characteristic is similar to a normal module having no un-shaded with open circuit voltage:

$$V_{OC} = (n-2) \times 0.6 + 2 \times 0.6 = 36.0V.$$

As current (I) becomes greater than 3.2A, Eq 7.18 and Eq 7.19 are applicable. The voltage drop (V_L) and difference (ΔV) at a particular current can be calculated using these two equations. V_L at I = 8A (I_{SC} of normal module) is:

$$V_L = (60-2) \times 0.6 - (8-3.2) \times (2 \times 15) = -109.2V$$

Note that the shunt resistance is now double as two cells are shaded.

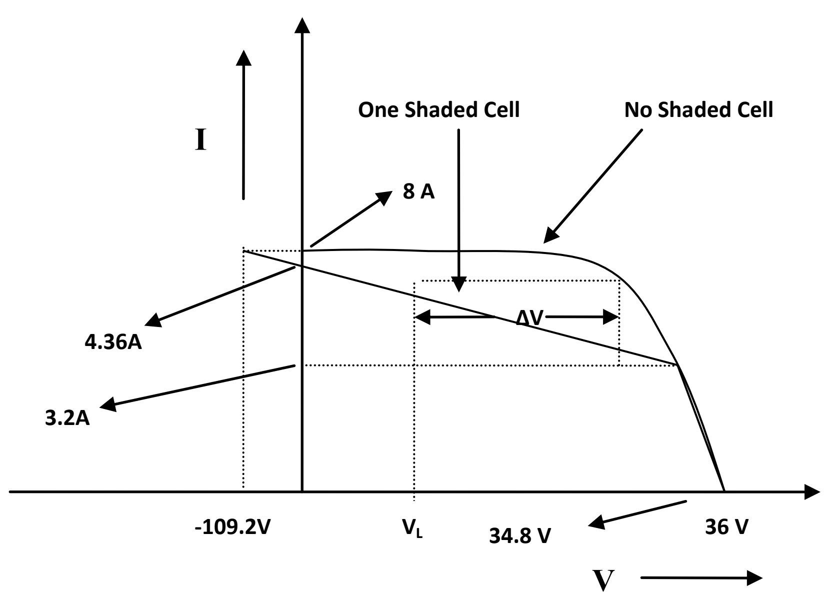
Current at $V_L = 0$, gives the point where the I-V characteristic cuts the Y-axis. This point can be determined by putting $V_L = 0$ in Eq 7.18.

$$0 = (60-2) \times 0.6 - (I - 3.2) \times 30; \quad I = 4.36A$$

ΔV at any current and more than 4A can be determined from Eq 7.19.

$$\Delta V = 0.6 + (I - 3.2) \times 30$$

Using these values calculated above, the I-V characteristics of the module with one 60% shaded cell can be drawn as shown in the below Fig.



A normal module I-V characteristic is also shown for comparison and to show ΔV. A spread sheet can be used to determine the set of values for I, V and P (power). This can be used to determine P_{max}. Plots of I-V and P-V can also be drawn as per scale using the spread sheet.

Now let us see what happens when a by-pass diode is used. As long as the current (I) is less than 3.2A , by-pass diodes are reverse biased and do not play any role. As the current exceeds 3.2A, the diode connected across the applicable string gets forward biased and starts conducting, reducing the current through the shaded cell. In equilibrium, 3.2A flows through the shaded cell, in fact through the entire affected string and rest of the current (I-3.2) A, flows through the by-pass diode. At STC under short circuit condition, 3.2A flows through the affected string and remaining 4.8A through the by-pass diode resulting in a total short circuit current of 8A (I_{SC}) at the output. As 18 of the 20 cells in the affected string have V_{OC} of 0.6V each and the one with 60% shading also has V_{OC} of 0.6 V, the total open circuit voltage of the affected string of 20 cells is:

$$(20 - 2) \times 0.6 + 0.6 \times 2 = 12.0 \text{ V}$$

The effective short circuit current is 3.2A. Considering a FF of 0.7, the maximum power produced by this string is:

$$P_{max} \text{ of string 1} \approx 12.0 \times 3.2 \times 0.7 \approx 26.9 \text{ W}_P$$

At STC, remaining 40 cells in the other two strings have V_{OC} and I_{SC} of 0.6V and 8A each respectively. Considering the diode drop, the total maximum power produced by these strings is:

$$[(40 \times V_{OC} - \text{Diode voltage drop})] \times 8 \times 0.7$$

P_{max} of string 2 & 3 combined ≈ 130.5 W_P with normal by-pass diode having 0.7V drop

P_{max} of string 2 & 3 combined ≈ 132.7 W_P with Schottky by-pass diode having 0.3V drop

The total maximum power produced by the module is then:

P_{max} of the module ≈ 26.9 + 130.5 = 157.4 W_P with normal by-pass diode having 0.7 V drop

P_{max} of the module ≈ 26.9 + 132.7 = 159.6 W_P with Schottky by-pass diode having 0.3 V drop

For the normal module P_{max} at STC is:

$$V_{OC} \times I_{SC} \times FF = 60 \times 0.6 \times 0.7 \approx 202 \text{ W}_P.$$

(c) The I-V characteristics analysis is identical to 15(a). However, the total P_{max} is now different as two strings are affected. Each effected string produces

$$(20 - 1) \times 0.6 + 0.6 \times 1 = 12.0 \text{ V}$$

The effective short circuit current is 4.8A. Considering a FF of 0.7, the maximum power produced by each of these strings are:

$$P_{max} \approx 12.0 \times 4.8 \times 0.7 \approx 40.3 \text{ W}_P$$

At STC, remaining 20 cells in the remaining un-effected string have V_{OC} and I_{SC} of 0.6V and 8A each respectively. Considering the diode drop, the total maximum power produced by these strings is:

$$[(20 \times V_{OC} - \text{Diode voltage drop})] \times 8 \times 0.7$$

P_{max} of un-effected string is ≈ 63.3W_P with normal by-pass diode having 0.7V drop

P_{max} of un-effected string ≈ 65.5 W_P with Schottky by-pass diode having 0.3V drop

The total maximum power produced by the module is then:

P_{max} of the module ≈ 40.3 x 2+ 63.3 = 143.9 W_P with normal by-pass diode having 0.7 V drop

P_{max} of the module ≈ 40.3 x 2 + 65.5 = 146.1 W_P with Schottky by-pass diode having 0.3 V drop

For the normal module P_{max} at STC is:

$$V_{OC} \times I_{SC} \times FF = 60 \times 0.6 \times 0.7 \approx 202\ W_P.$$

(d) In this case also the total P_{max} will be less than that obtained for 15(b).

Each effected string produces

$$(20 - 1) \times 0.6 + 0.6 \times 1 = 12.0\ V$$

The effective short circuit current is 3.2A. Considering a FF of 0.7, the maximum power produced by each of these strings are:

$$P_{max} \approx 12.0 \times 3.2 \times 0.7 \approx 26.9 W_P$$

At STC, remaining 20 cells in the remaining un-effected string have V_{OC} and I_{SC} of 0.6V and 8A each respectively. Considering the diode drop, the total maximum power produced by these strings is:

$$[(20 \times V_{OC} - \text{Diode voltage drop})] \times 8 \times 0.7$$

P_{max} of un-effected string is ≈ 63.3W_P with normal by-pass diode having 0.7V drop

P_{max} of un-effected string ≈ 65.5 W_P with Schottky by-pass diode having 0.3V drop

The total maximum power produced by the module is then:

P_{max} of the module ≈ 26.9 x 2+ 63.3 = 117.1W_P with normal by-pass diode having 0.7 V drop

P_{max} of the module ≈ 26.9 x 2 + 65.5 = 119.3W_P with Schottky by-pass diode having 0.3 V drop

For the normal module P_{max} at STC is:

$$V_{OC} \times I_{SC} \times FF = 60 \times 0.6 \times 0.7 \approx 202\ W_P.$$

Q16. Repeat exercise 15(c) and 15(d) in case one of the by-pass diodes of the affected string is not functioning (open circuit).

Answer:

It depends on which one out the three diodes are bad and which string the bad cells belong. Let us define the left most, middle and extreme right strings as string 1, string 2 and string 3 respectively. Also the left most, middle and right by-pass diodes as bypass diode 1, bypass diode 2 and bypass diode 3 respectively.

Case 1: Shaded cells belong to string 2 and string 3 and bypass diode 1 is bad. This will not alter the analysis done in 15 (c) and 15(d). String 1 will produce full power as 8A current produced flows partially through the series connected string 2 and 3 and remaining through diodes.

Case 2: Shaded cells belong to string 2 and string 3 and the bypass diode 2 is bad. This will eventually reduce the power for all three strings as only the current equivalent to shaded cell(s) can flow through the entire cell string circuit.

Any other combination can similarly be analyzed.

Q17. What happens if the layer sequence for a tandem a-Si junctions is reversed; i.e. instead of a-Si:C (top), a-Si (middle) and a-Si:Ge (bottom) the layer sequence becomes a-Si:Ge (top), a-Si (middle) and a-Si:C (bottom)?

Answer:

In case the lower band gap material (a-Si:Ge) cell is at the top, the entire light is absorbed by that layer itself. The bottom layers do not absorb any light and therefore produce no currents. As all the three cells are connected in series, the net current is zero and such arrangement of tandem cell does not produce any power.

Q18. Why is it important to have all the junctions of the tandem solar cells producing the same short circuit current (I_{SC})?

Answer:

As all the cells in the tandem structure are connected in series, it is important to have near equal current for all the cells. Otherwise the effective current is decided by the lowest current producing cell and even if other cells produces more current, these are not fully utilized.

Q19. By-pass diodes are not used in thin film modules. What is the reason? :

Answer:

The thin film module is made of several cells which are mostly connected in parallel. The currents add up and therefore the partial or complete shading of a cell only effect current of the effected cells and not the entire structure (cells). In any case the by-pass diode concept is not applicable for parallel connected cells.

Q20. What is the utility of the CdS layer in CIGS solar cells? What happens in case this layer is not present?

Answer:

The CdS is high band gap material and transparent for most of the light spectrum. This layer act as a transparent window and the light is absorbed mostly in the underlying CIGS layer (see Fig 7.27), which is away from the surface. As surface has defects, known as surface states, due to dangling bonds photogenerated carriers near surface get lost due to recombination with these defects. Using CdS window layer, the carrier generation at the surface is avoided.

Q21. 100MW$_P$ and 200MW$_P$ plants have been installed in 18 months with a total expenditure of \$10 million and \$18million respectively. The plants start producing SPV modules immediately after that and start earning in 24 months. Calculate overall expenditure (principal & interest) for both the plants at t = 24months for the following scenario:

- **Equity to loan ratio is 50:50 available in 4 equal instalments at t=0, t=6 months and t=12months and t=18 months.**
- **Equity to loan ratio is 40:60 available in 4 equal instalments at t=0, t=6 months and t=12months and t=18 months.**
- **Equity to loan ratio is 20:80 available in 4 equal instalments at t=0, t=6 months and t=12months and t=18 months.**

Also indicate approximate payback period if the earnings are about \$5million and \$11million per annum for 100MW$_P$ and 200MW$_P$ plants respectively. Assume interest rate for equity and loan are 8% per annum and 10% per annum respectively.

Answer:
The $100MW_P$ plant example is same as Example -5. The readers are requested to do this exercise first without looking at Example-5 and then verify the answers.

For $200MW_P$ plant the total expenditure calculations are given in the below Table. The approximate payback period is close to 2 years for all cases.

	Equity			Interest on Equity			Loan			Interest on Loan		
	50	40	20	50	40	20	50	60	80	50	40	20
Equity/Loan & Interest at t=0 (in million $)	2.25	1.8	0.9	-	-	-	2.25	2.7	3.6	-	-	-
Equity/Loan & Interest at t=6 months (in million $)	2.25	1.8	0.9	0.09	0.072	0.036	2.25	2.7	3.6	0.1125	0.135	0.18
Equity/Loan & Interest at t=12 months (in million $)	2.25	1.8	0.9	0.27	0.216	0.108	2.25	2.7	3.6	0.3375	0.405	0.54
Equity/Loan & Interest at t=18 months (in million $)	2.25	1.8	0.9	0.54	0.432	0.216	2.25	2.7	3.6	0.675	0.81	1.08
Equity/Loan & Interest at t=2 Years (in million $)	-	-	-	0.9	0.72	0.36	-	-	-	1.125	1.35	1.8
Total Expenditure after t=2 years (in million $)	9.0	7.2	3.6	1.8	1.44	0.72	9.0	10.8	14.4	2.25	2.7	3.6
Overall Expenditure after t=2 years (in million $)	Equity: Loan- 50:50			22.05								
	Equity: Loan- 40:60			22.14								
	Equity: Loan- 20:80			22.32								

Q22. Repeat the exercise 21 for a 500MW$_P$ plant taking 24 months installation time and total expenditure of \$45 million spanning over 4 equal instalments.

Answer:

For 500MW$_P$ plant the total expenditure calculations are given in the below Table.

	Equity			Interest on Equity			Loan			Interest on Loan		
	50	40	20	50	40	20	50	60	80	50	40	20
Equity/Loan & Interest at t=0 (in million \$)	5.625	4.5	2.25	-	-	-	5.625	6.75	9.0	-	-	-
Equity/Loan & Interest at t=6 months (in million \$)	5.625	4.5	2.25	0.225	0.18	0.09	5.625	6.75	9.0	0.281	0.337	0.45
Equity/Loan & Interest at t=12 months (in million \$)	5.625	4.5	2.25	0.675	0.54	0.27	5.625	6.75	9.0	0.844	1.012	1.35
Equity/Loan & Interest at t=18 months (in million \$)	5.625	4.5	2.25	1.35	1.08	0.54	5.625	6.75	9.0	1.687	2.025	2.7
Equity/Loan & Interest at t=2 Years (in million \$)	-	-	-	2.25	1.8	0.9	-	-	-	2.812	3.375	4.5
Total Expenditure after t=2 years (in million \$)	22.5	18	9	4.5	3.6	1.8	22.5	27	36	5.624	6.749	9.0
Overall Expenditure after t=2 years (in million \$)	Equity: Loan- 50:50			55.124								
	Equity: Loan- 40:60			55.349								
	Equity: Loan- 20:80			55.8								

Q23. Calculate the depreciation cost for above (exercise 21 and 22) 200MW$_P$ and 500MW$_P$ plants. The factory costs for 100MW$_P$, 200MW$_P$ and 500MW$_P$ are \$0.05/W$_P$, \$0.045/W$_P$ and \$0.375/W$_P$ respectively. Determine the manufacturing cost for 19% efficiency cells costing \$0.26/W$_P$ if the CTM conversion loss is 2%. Take the other BOM cost from Table 7.12.

Answer:

The 200MW$_P$ plants costing \$18 million. 7 years depreciation amount to about (\$18 million/7)/(200MW$_P$) ≈ \$0.013 per W$_P$. This is (\$18 million/5)/(200MW$_P$) ≈ \$0.018 per W$_P$ for 5 years depreciation based accounting.

The 500MW$_P$ plants costing \$45 million. 7 years depreciation amount to about (\$45 million/7)/(500MW$_P$) ≈ \$0.0129 per W$_P$. This is (\$45 million/5)/(500MW$_P$) ≈ \$0.018 per W$_P$ for 5 years depreciation based accounting.

For 100MW$_P$ and factory cost of \$0.05/W$_P$:
The total cost of manufacturing is (Depreciation cost + BOM cost + Factory cost).

Depreciation cost, assuming 7 years based accounting, of a 100MW$_P$ plant costing \$10 million (see Exercise 21) is (\$10 million/7)/(100MW$_P$) ≈ \$0.0143 per W$_P$.

The 19% efficiency cells has wattage of 4.62W$_P$ at STC (see Example 6). 60 cells module produces (1-0.02) x 4.62 x 60W$_P$ ≈ 271.7W$_P$ assuming 2% overall CTM loss. Cost of the 60 cells is \$0.26 x 4.62 x 60 ≈ \$70.1 or \$70.1/271.7W$_P$ ≈ \$0.258 per W$_P$ as appears on the final module.

The cost of other BOM (except cells) as per Table 7.12 id \$39.85 or \$39.85/271.7W$_P$ ≈ \$0.15 per W$_P$.

The total BOM cost including cell is \$0.408 per W$_P$.

The total cost of manufacturing = Depreciation cost + BOM cost + Factory cost = \$0.0143 + \$0.408 + \$0.05 ≈ \$0.4723 per W$_P$.

For 200MW$_P$ and factory cost of \$0.045/W$_P$:
The BOM cost including cell cost remains same.

Depreciation cost, assuming 7 years based accounting, of a 200MW$_P$ plant costing \$18 million (see Exercise 21) is (\$18 million/7)/(200MW$_P$) ≈ \$0.0129 per W$_P$.

The total cost of manufacturing = Depreciation cost + BOM cost + Factory cost = \$0.0129 + \$0.408 + \$0.045≈ \$0.4659 per W$_P$.

For 500MW$_P$ and factory cost of \$0.0375/W$_P$:

The BOM cost including cell cost remains same.

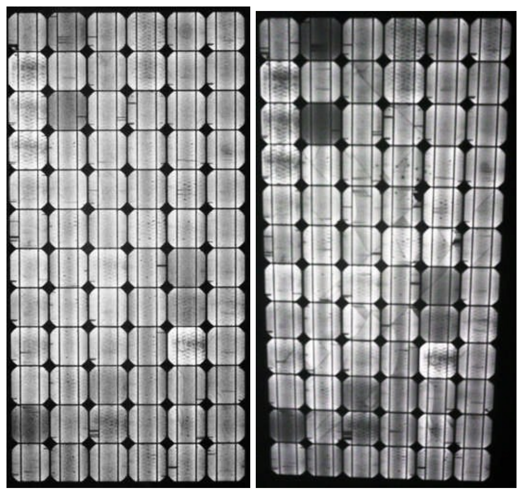
Depreciation cost, assuming 7 years based accounting, of a 500MW$_P$ plant costing \$45 million (see Exercise 22) is (\$45 million/7)/(500MW$_P$) ≈ \$0.0129 per W$_P$.

The total cost of manufacturing = Depreciation cost + BOM cost + Factory cost = \$0.0129 + \$0.408 + \$0.0375≈ \$0.4584 per W$_P$.

Chapter-8
Characterization, Testing and Reliability of Solar PV Module

Solution to Exercises:

Q1. Pre-lamination (Fig a) and post- lamination (Fig b) EL pictures of the same module are shown below. Identify first the defects in pre-lamination EL picture and then additional defects arising due to lamination and post- lamination processes. Try to identify possible causes of both pre- and post-lamination defects.



(a) **(b)**

Answer:
The pre-lamination picture of the module (Fig a) shows an acceptable module with the following observations:

i) Some of the cells looks a bit dark as compared to other cells. This happens mainly due to cells having lower I_{SC} as compared to other cells show somewhat less bright. This is not a major issue unless the less bright cells are completely dark. The overall brightness of all the cells can be increased by adjusting the EL set up.

ii) There are burnt fingers happened during Tabbing & Stringing (T&S) operation. These are generally acceptable. These can be eliminated by adjusting T&S set up parameters.

iii) Some black patches are seen in particularly few cells; these are probably due to I_{SC} variation in the cells itself.

iv) No micro-cracks are seen.

The post lamination picture (Fig b) shows major micro-cracks appearing due to improper lamination process. Such modules are finally rejected. Overall brightness has decreased as compared to Fig a. This is mainly due to EL set up and nothing to do with additional defects.

Q2. The configurations of three different EL cameras, all using the same CCD camera, are given below. The image processing software may vary.

- **(a) The camera is kept 10ft above the module and the whole image is taken using a single shot.**

(b) The camera is kept 5ft above the module and the whole image is constructed by first taking two images of two halves of the module and then applies stitching.

(c) The camera is kept 2.5ft above and the whole image is constructed from four images and then stitching.

Discuss advantages and disadvantages. Also mention specific situations for using each of these three EL configurations.

Answer:
When the camera height is lowered, the resolution increases but the process time increases as more number of EL snaps have to be taken per modules. The stitching of snaps, which is done by the software, also require additional time. More resolutions therefore come at a cost of throughput (number of module tested per a specified time). Typically a low resolution picture (as per configuration a), is taken during 100% EL testing. Higher resolution pictures are required for failure analysis or during development.

Q3. As discussed in section 2.2, a CCD camera sensitive to the radiative emission corresponding to the band gap of the semiconductor materials used for making a Solar cell. Calculate the corresponding wavelengths for Si, a-Si:H, a-Si:Ge, a-Si:C, GaAs and CdTe having band gaps of 1.12eV, 1.7eV, 1.4eV, 1.9eV, 1.43eV and 1.49eV respectively. Assume Plank constant (h) = 6.626 x 10^{-34} Joule sec, speed of light (c) = 3 x 10^{8} ms^{-1} and electron charge (q) = 1.6 x 10^{-19}Coulomb.

Answer:
The following equation can be used:

$$\lambda = (hc)/E_g$$

where λ and E_g are the wavelength and band gap respectively. For example for silicon having band gap of 1.12eV, the cut-off wavelength can be calculated as:

$$\lambda_{Si} = [6.626 \times 10^{-34} \text{ (J.sec)} \times 3 \times 10^{8} \text{ (m sec}^{-1})]/[1.12 \text{ (eV)} \times 1.6 \times 10^{-19} \text{ (J. eV}^{-1})] = 1.11 \times 10^{-6} \text{ m} = 1.11 \text{ µm}.$$

The values of the corresponding wavelengths of the materials calculated similarly are given blow:

Material	Si	a-Si:H	a-Si:G	a-Si:C	GaAs	CdTe
Bang Gap (eV)	1.12	1.7	1.4	1.9	1.43	1.49
Cut-off Wavelength (µm)	1.11	0.73	0.89	0.66	0.87	0.83

Q4. A SPV module manufacturing line produces on an average 1500 modules, 60 cells and 250W_P each, per day. Initially it was decided not to have pre-lamination EL provision. The EL set up available for 100% finished module EL inspection reported on an average 0.5% failure. Further analysis suggested that on an average two cells per failed module show EL failure. The failures were traced back to mainly the pre-lamination (Tabbing and Stringing) operation. Realizing that just for two cells the entire module BOM including remaining 58 good cells were being rejected, 100% pre-lamination EL inspection provision was made. Two EL systems costing about $45000 each were installed. This showed a similar failure rate (0.5% of the module and 2 cells per module) at the pre-lamination stage. It is possible to replace the two defective cells with good ones. The finished module EL test now shows 0.02% failure. Using the BOM cost from Table 7.12, calculate the total financial saving per year due to installation of pre-lamination EL. Also calculate the payback period. Make reasonable assumptions, (e.g. zero CTM loss, except two 2 cells per module other BOM loss is not significant for cells replacements, etc.).

Answer:
Rejection rate of 0.5% for 1500 module per day production is 7.5 modules a day. The total BOM cost of 7.5 finished modules (see Table 7.12) is : 7.5 x 250 (W_P) x 0.39 ($/$W_P$) = $731.25.

In case the pre-lamination EL is installed, the finished module rejection is 0.02% i.e. 0.3 module per day. The cost of 0.3 finished module is 0.3 x 250 (W_P) x 0.39 ($\$/W_P$) = \$29.25. In addition there are 0.5% rejection at pre-lamination EL amounting to 7.5 module. 2 cells per module, i.e. a total of 15 cells are replaced. The cost of each cell is about \$0.96 (see Table 7.12). The cost of replacement of cell replacement is therefore \$0.96 x 15 = \$14.4.

The total BOM cost due to rejection in case pre-lamination EL is installed is \$29.25 + \$14.4 = \$43.65.

The total saving per day due to installation of pre-lamination EL is \$731.25 - \$43.65 = \$687.6.

The cost of installation of pre-lamination EL (2 numbers) is \$90000. The payback period is:

(\$90000/\$687) days ≈ 131 Days ≈ 4.4 Months.

Q5. Repeat Exercise 5 for (a) 0.5% of the modules and average 1 cell per module failing during pre-lamination EL testing (b) 1% of the module and average 2 cells failing during pre-lamination EL testing.

Answer:
(a) Rejection rate of 0.5% for 1500 module per day production is 7.5 modules a day. The total BOM cost of 7.5 finished modules (see Table 7.12) is : 7.5 x 250 (W_P) x 0.39 ($\$/W_P$) = \$731.25.

In case the pre-lamination EL is installed the finished module rejection is 0.02% i.e. 0.3 module per day. The cost of 0.3 finished module is 0.3 x 250 (W_P) x 0.39 ($\$/W_P$) = \$29.25. In addition there are 0.5% rejection at pre-lamination EL amounting to 7.5 module. 1 cell per module, i.e. a total of 7.5 cells are replaced. The cost of each cell is about \$0.96 (see Table 7.12). The cost of replacement of cell replacement is therefore \$0.96 x 7.5 = \$7.2.

The total BOM cost due to rejection in case pre-lamination EL is installed is \$29.25 + \$7.2 = \$36.45.

The total saving per day due to installation of pre-lamination EL is \$731.25 - \$36.45 = \$694.8.

The cost of installation of pre-lamination EL (2 numbers) is \$90000. The payback period is:

(\$90000/\$694.8) days ≈ 129 Days ≈ 4.3 Months.

(b) Rejection rate of 1% for 1500 module per day production is 15 modules a day. The total BOM cost of 15 finished modules (see Table 7.12) is : 15 x 250 (W_P) x 0.39 ($\$/W_P$) = \$1462.5.

In case the pre-lamination EL is installed the finished module rejection is 0.02% i.e. 0.3 module per day. The cost of 0.3 finished module is 0.3 x 250 (W_P) x 0.39 ($\$/W_P$) = \$29.25. In addition there are 0.5% rejection at pre-lamination EL amounting to 7.5 module. 2 cells per module, i.e. a total of 15 cells are replaced. The cost of each cell is about \$0.96 (see Table 7.12). The cost of replacement of cell replacement is therefore \$0.96 x 15 = \$14.4.

The total BOM cost due to rejection in case pre-lamination EL is installed is \$29.25 + \$14.4 = \$43.65.

The total saving per day due to installation of pre-lamination EL is \$1462.5 - \$43.65 = \$1418.85.

The cost of installation of pre-lamination EL (2 numbers) is \$90000. The payback period is:

(\$90000/\$1418.85) days = 63 Days ≈ 2.1 Months.

Q6. The measured resistance values of different materials used to configure a module are given below. Assume that after lamination EVA1 and EVA2 reduced it resistance value by half. Calculate the equivalent resistance application to dry and wet insulation tests. Make reasonable assumptions whenever required and use Figs 8.11-8.14.

S.No	Name of the material	Resistance
1	Toughened glass	3 TΩ
2	EVA-1	3 TΩ
3	Cell string	0.6Ω
4	EVA-2	3 TΩ
5	Back sheet	1.68 TΩ
6	Foam tape	1.03TΩ
7	Al Frame	164 mΩ

Answer:
Eqs 8.4 - 8.6 (Example 1) can used to equivalent resistance.

R_{eq} (Dry Insulation) = $(R_1 + R_2 + R_3 + R_4)(R_6 + R_7 + R_8 + R_9)/(R_1 + R_2 + R_3 + R_4 + R_6 + R_7 + R_8 + R_9)$

R_{eq} (Wet Insulation 1) = $(R_1 + R_2 + R_3 + R_4)(R_6 + R_7 + R_8 + R_9 + R_{WFS})/(R_1 + R_2 + R_3 + R_4 + R_6 + R_7 + R_8 + R_9 + R_{WFS})$

R_{eq} (Wet Insulation 2) = $(R_{WBS} + R_1 + R_2 + R_3 + R_4)(R_6 + R_7 + R_8 + R_9 + R_{WFS})/(R_{WBS} + R_1 + R_2 + R_3 + R_4 + R_6 + R_7 + R_8 + R_9 + R_{WFS})$

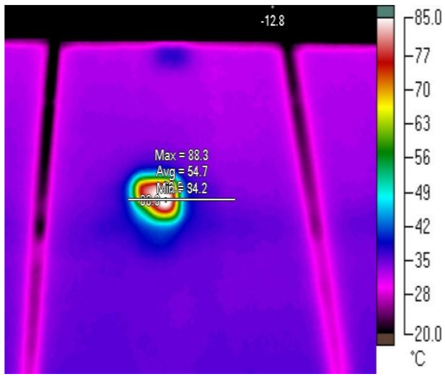
$R_1 = R_9 = 164m\Omega$: The resistances offered by Al frame.
$R_2 = R_8 = 1.03T\Omega$: The resistances offered by Foam Tape.
$R_3 = 1.68T\Omega$: The resistance offered by Back Sheet.
$R_4 = R_6 = (1/2)\ 3T\Omega = 1.5T\Omega$: The resistances offered by EVA. The value is half of the starting material after lamination.
$R_7 = 3T\Omega$: The resistances offered by Toughened Glass.

The resistances offered by Al frame and water are low as compared to other materials and can be neglected. The dry insulation resistance can therefore be calculated as:

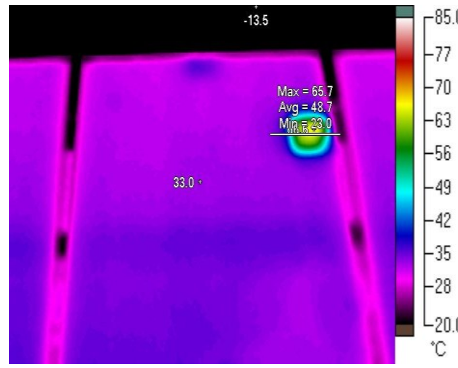
R_{eq} (Dry Insulation) = $(1.03T\Omega + 1.68T\Omega + 1.5T\Omega)(1.5T\Omega + 3T\Omega + 1.03T\Omega)/(1.03T\Omega + 1.68T\Omega + 1.5T\Omega + 1.5T\Omega + 3T\Omega + 1.03T\Omega) = 2.39T\Omega$.

In case there is no water intrusion inside the module, the resistance measured for wet insulation test will also be roughly same as the water resistance is much smaller than the resistances of the glass and polymers such as back sheet and EVA.

Q7. IR images of two modules with hot spots are shown below in Figures (a) and (b). Generate information similar to Fig 8.19 and Table 8.6.



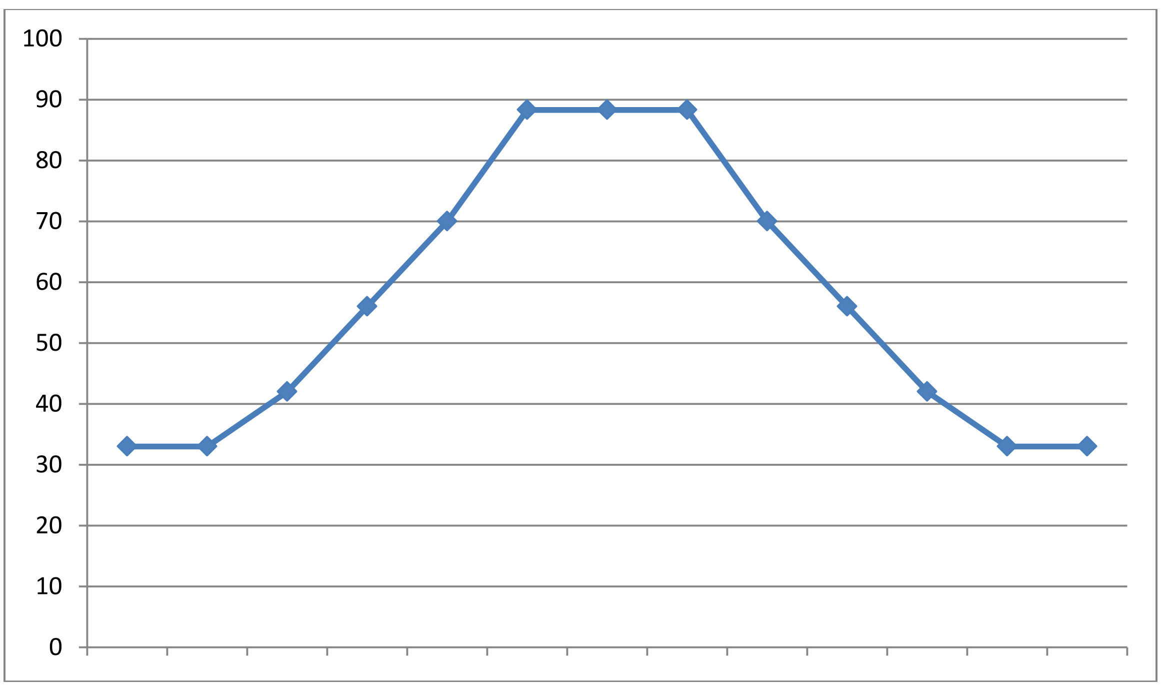
(a)



(b)

Answer:

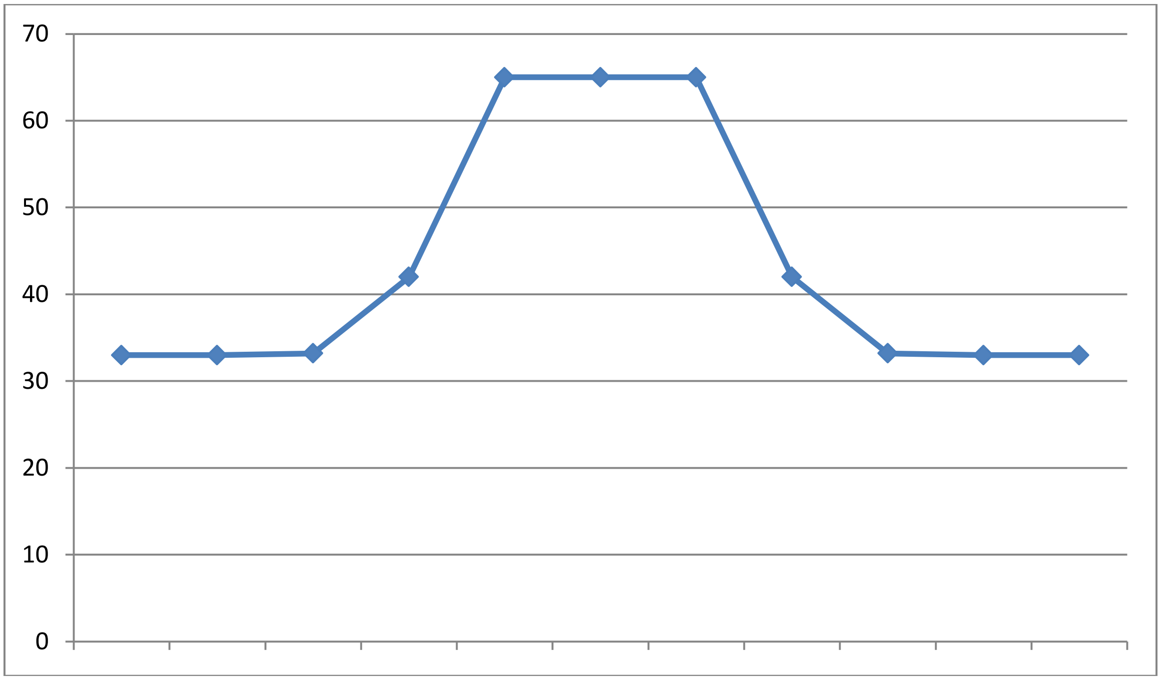
(a) Temperature profile across the hot spot can be drawn as:



Same in Tabular Form:

S. No	Description		Temperature (^{0}C)
1	Background (Ambient)		12.8
2	Normal Module		33
3	Hot Spot -I	Minimum	34.2
		Average	54.7
		Maximum	88.3

(b) Temperature profile across the hot spot can be drawn as:



Same in Tabular Form:

S. No	Description		Temperature (^{0}C)
1	Background (Ambient)		13.5
2	Normal Module		33
3	Hot Spot -I	Minimum	33
		Average	48.7
		Maximum	65.7

Q8. A 300W$_P$ c-Si module is being tested with a class A tester (solar simulator). The thermocouple for measuring the module temperature during test is malfunctioning and recording an incorrect temperature of 0^{0}C. The actual module temperature is 25^{0}C. Find out the STC power measured by the tester in this condition. Assume the temperature co-efficient for power (γ) = -0.4% per ^{0}C.

Answer:
The power of the 300W$_P$ module at 0^{0}C is 300 (W$_P$) [1 + (-0.4/100) per ^{0}C x (0-25)^{0}C] = 330W$_P$. The power measured by the tester is then 330W$_P$ although the actual power of the module is 300W$_P$

Q9. A c-Si module with unknown W$_P$ is being tested with a class A tester. The thermocouple for measuring the module temperature during test is malfunctioning and recording an incorrect temperature of 50^{0}C. The actual temperature is 25^{0}C. The measured power is 225W$_P$. Find out what is the actual STC power of this module. Assume the temperature co-efficient for power (γ) = -0.4% per ^{0}C.

Answer:
The measured power is 225W$_P$ assuming the module temperature as 50^{0}C. The tester first measure the power and the temperature. The power value is then extrapolated by calculating the power at 25^{0}C (STC)

taking the temperature co-efficient for power into account. If the power measured assuming temperature at 50^0C is X (W_p), the extrapolated power at 25^0C will be X (W_P) [1 + (-0.4/100) per ^0C x (50-25) ^0C] = 0.9 X W_P. This is the measured power by the tester which is 225W_P. The actual power of the module at STC is therefore 225W_P/0.9 = 250W_P.

Q10. NOCT values of three different c-Si module manufacturers are 40^0C, 45^0C and 50^0C respectively. At STC each have 250W_P power output. Compare the cell temperatures and output power of these modules at (ambient) temperatures of 0^0C and 45^0C and irradiance level of 1000 Wm^{-2}. Assume the temperature co-efficient for power (γ) = -0.4% per ^0C.

Answer:
NOCT is defined as the temperature of the cell in a module when the irradiance level and temperature are 800Wm^{-2} and 20^0C respectively (see Example 3). Cell temperature can be calculated as per the ambient temperature (T_{amb}) and irradiance level ($P_{irradiance}$):

$$T_{cell} = T_{amb} + [(NOCT - 20^0C)/800] \times (P_{irradiance})$$

The cell temperature at ambient temperature of 0^0C having NOCT of 40^0C is:

$$T_{cell} = 0^0C + [(40^0C - 20^0C)/800Wm^{-2}] \times (1000Wm^{-2}) = 25^0C$$

The cell temperature at ambient temperature of 45^0C having NOCT of 40^0C is:

$$T_{cell} = 45^0C + [(40^0C - 20^0C)/800Wm^{-2}] \times (1000Wm^{-2}) = 70^0C$$

The cell temperature at ambient temperature of 0^0C having NOCT of 45^0C is:

$$T_{cell} = 0^0C + [(45^0C - 20^0C)/800Wm^{-2}] \times (1000Wm^{-2}) = 31.25^0C$$

The cell temperature at ambient temperature of 45^0C having NOCT of 45^0C is:

$$T_{cell} = 45^0C + [(45^0C - 20^0C)/800Wm^{-2}] \times (1000Wm^{-2}) = 76.25^0C$$

The cell temperature at ambient temperature of 0^0C having NOCT of 50^0C is:

$$T_{cell} = 0^0C + [(50^0C - 20^0C)/800Wm^{-2}] \times (1000Wm^{-2}) = 37.5^0C$$

The cell temperature at ambient temperature of 45^0C having NOCT of 40^0C is:

$$T_{cell} = 45^0C + [(50^0C - 20^0C)/800Wm^{-2}] \times (1000Wm^{-2}) = 82.5^0C$$

Q11. A 250W_P module is being tested using a constant source solar simulator. Due to continuous exposure during testing, the module is heated up to 10^0C more than the ambient, which is maintained at 25^0C. What will the power tester measure if (a) no temperature correction is employed (b) temperature correction is employed but the inaccuracy of temperature co-efficient can be as high as ± 30%. Assume the temperature co-efficient for power (γ) = -0.4% per ^0C.

Answer:
(a) If the temperature is measured correctly the module will measure 250W_P. If the module is heated up to 10^0C more than the ambient the module temperature is 35^0C. If no temperature correction is employed the measured power of the module will be:

$$250\ (W_P)\ [1 + (-0.4/100) \text{ per } ^0C \times (35-25)^0C] = 240W_P$$

(b) Inaccuracy of the temperature coefficient is ± 30%. The power temperature co-efficient can vary from -0.4% per ^{0}C (1- 30/100) to -0.4% per ^{0}C (1+ 30/100) i.e. -0.28% per ^{0}C to -0.52% per ^{0}C. If the power temperature co-efficient value is accurate (-0.4% per ^{0}C) the actual power measured at 35^{0}C by the tester, prior to extrapolation to 25^{0}C (STC), is 240W_P.

The extrapolated value at STC with -30% inaccuracy of power temperature co-efficient is therefore:

$$240\ (W_P)\ [1 + (-0.28/100) \text{ per } {}^0C \times (25\text{-}35)^0C] = 246.72W_P$$

The extrapolated value at STC with +30% inaccuracy of power temperature co-efficient is :

$$240\ (W_P)\ [1 + (-0.52/100) \text{ per } {}^0C \times (25\text{-}35)^0C] = 252.48W_P$$

Q12. 250 numbers of a particular device manufactured using identical materials and processes are to be qualified as MIL- STD- 883 for AQL level of 0.65, 1, 1.5 and 2.5 respectively. Define test strategy and pass/fail criteria. Assume two devices have infant mortality problem.

Answer:
All the devices undergo a screening test for 7 days. Twenty devices failed during this test due to infant mortality problem. The lot size for qualification test is (250 - 2) = 248. As per Table 8.9:

A total of 32 numbers have to go for qualification test for about 42 days for AQL level 0.65. If the total number of devices failed during this test is more than 1, the entire lot is rejected. Otherwise the lot is considered `pass' and all 32 devices which have undergone qualification testing must be rejected. Total number of good devices is therefore = (total lot size - number of devices failed during screening - number of devices used for qualification test) = (250 - 2 - 32) = 216 devices.

For AQL level 1 and 1.5 same analysis is valid (see Table 8.9).

For AQL level 2.5, only difference is that the lot is rejected if more than 2 devices failed during qualification test. Rest of the analysis is the same.

Q13. Assuming the devices in Exercise 12 are solar modules. How many environmental chambers are required if (a) screening test (7 days) and full reliability test (42 days) are to be done (b) screening test is skipped but full reliability test is done. Calculate these for three chamber sizes: Big (can accommodate 10 modules at a time) and medium (5 modules at a time) and small (1 module at a time).

Answer:
(a) All 250 devices need screening test for 7 days:
This test can be finished in 7 days if 25 big or 50 medium or 250 small chambers are used. If only one big chamber is used than 175 days are required to complete the screening test. Similarly for one medium chamber requires 350 days and one small chamber requires 1750 days to complete the screening test.

Qualification test required 32 devices to be tested for about 42 days. This is in addition to screening test. In case a single chamber is used this can be completed (42 x 4) = 168 days for big, (42 x 7) = 294 days for medium and (42 x 32) = 1344 days to complete the qualification test. The test time reduced in case of more number of chambers are used. For example if 4 big chambers are used, the qualification test can be completed in 42 days.

Even if 4 big chambers, which can accommodate 40 module at a time, are used and both screening and qualification tests the total time required would be:

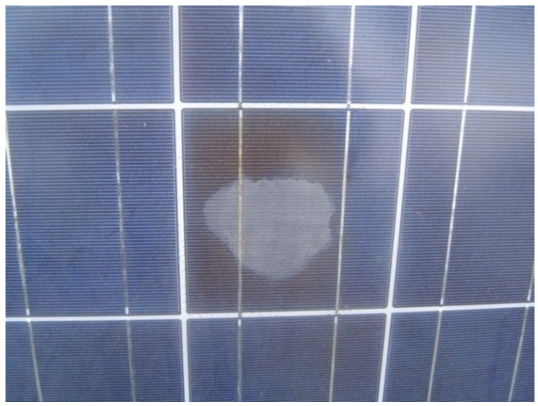
(250/40) x 7 ≈ 44 days for screening and 42 days for qualification; a total of 86 days.

In case only one big chamber, which can accommodate 10 modules at a time, are used for both screening and qualification tests the total time required would be:

(250/10) x 7 = 175 days for screening and (42 x 4) = 168 days for qualification; a total of 343 days.

(b) In case the screening test is skipped and 4 big chambers are used the test can be completed in 42 days time. Other scenarios can be determined.

Q14. Visual picture of a cell in a module operating in a field is shown below. The module cleared final (finished module) inspection during manufacturing indicating one of the modes of reliability failure discussed in the text. What could be the failure type and for what reason(s)?



Answer:
This is the front (glass) side of the module. This looks to be due to the damaged occurred due to hot spot. The heat generated due to severe hot spot caused de-lamination on the front side (Cell-EVA interface).

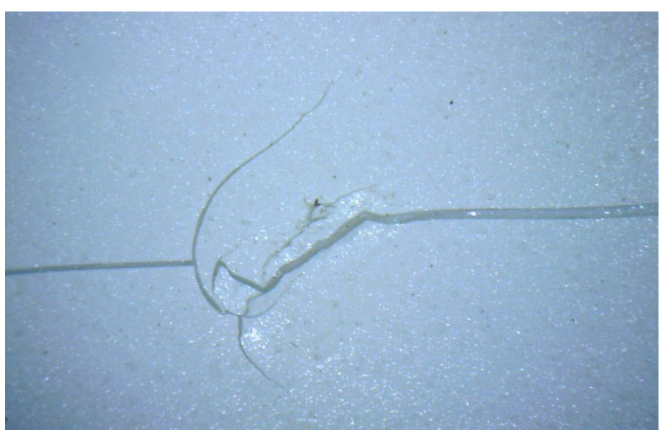
Q15. The visual picture of portion of a module is shown below which was taken after the HF10 test. What could be the type of failure and possible reason(s)?

Answer:
This is a picture of the back side of the module. This is due to delimitation of EVA-Backsheet interface. this probably happens due to poor quality of EVA or improper lamination process.

Q16. The visual picture of a module after DH1000 is shown below. Identify the defects and propose possible reasons.

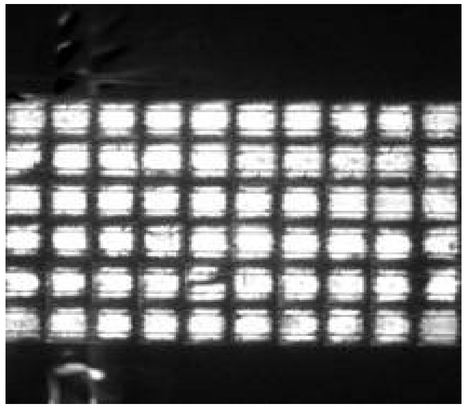
Answer:
This is a typical case of bubble formation at the backside and can happen due to several reasons. Improper lamination process during which the EVA is not properly cured. The gases present in the EVA generally gets neutralized during lamination process. However incomplete curing of the EVA can emit gases afterward in presence of moisture and heat. This, trying to escape, creates bubble below the back sheet. Another reason can be bad metal paste used in cell manufacturing. The metal paste have binders (see chapter 6) and can react with organic compounds present in the EVA in present of water. This can generate volatile gases and result backside bubble.

Q17. The picture below is of a part of the rear of the module after DH2200. A crack is visible. What could be cause of this failure?



Answer:
This is typical cases of "Wear and Tear" happens due to end of life pertaining to particularly the back sheet.

Q18. The picture of the part of front side of the same module after DH2200. Identify the problem, reason and implication on the power output of the module.



Answer:
This happens due to long DH exposure. The metal fingers of the cells gradually gets corroded and losses effectiveness. This mainly happens due prolonged exposure to the moisture during DH. The front side is protected by glass and moisture cannot penetrate. The moisture enters through the back sheet. The edges of the cells are therefore exposed to the moisture and first to get effected. Gradually, it encroaches the cells from all four directions. The resistance of the metal fingers increases and the power decreases. The loss of power will increase gradually and ultimately the cells will produce negligible power when the entire front metal grid area of the cells loses its functionality.

Q19. The following table gives some important parameters applicable for hail test using ice balls. Calculate the momentum, kinetic energy and impact pressure as they hit the glass surface.

Ball type	Diameter (in mm)	Mass (in grams)	Velocity
Ice ball	25	7.53	23 m/sec
Iron ball	38	225	4.43 m/Sec
Ice ball	75	203	39.5 m/sec

Answer:
The momentum [mass (m) x velocity (v)] and the kinetic energy (½ x mv^2). For calculating the impact pressure [P = force(F)/area(A)]; force = m x acceleration (a), the value of acceleration is required. We will assume that the final velocity mentioned in the above table is achieved in 3 seconds. The required parameters are calculated and given in the below table:

Dia (mm)	Area (m^2)	m (gm)	v (m/sec)	a m/sec^2	force (Newton)	Momentum (kg-m/sec)	Kinetic Energy (Joules)	Impact Pressure (Newton/m^2
25	4.9×10^{-4}	7.53	23	7.6	0.057	0.173	1.99	116.3
38	11.3×10^{-4}	225	4.43	1.48	0.333	0.997	2.21	294.7
75	44.16×10^{-4}	203	39.5	13.17	2.67	8.018	158.36	604.6

Q20. The electrical test results of a module before and after PID test are given below. Calculate the degradation of electrical parameters including fill factor. What is the common reason for such degradation and what establishes that?

Status	V_{OC} (V)	I_{SC}(A)	P_m(W_P)	V_m(V)	I_m(A)
Before Test	37.6	8.7	245	30.2	8.1
After Test	33.3	8.64	128	22.1	5.8

Answer:
The I_{Sc} and V_{OC} have not degraded much as compared to I_m and V_m. This clearly indicated a Fill Factor (FF) related issue. The FFs of pre and post LID test are:

FF before LID Test : (30.2 x 8.1)/(37.6 x 8.7) = 0.75

FF after LID Test : (22.1 x5.8)/(33.3 x 8.64) = 0.44

The large decrease of FF can be attributed to either (or both) series or shunt resistance increase. Reduction of V_{OC} is more than that of I_{SC}. This indicated that the FF reduction might have caused due to increase of shunt resistance. This can be ascertained by doing further analysis such as EL.

Chapter-9
Overview of Solar PV System Technology and Design

Solution to Exercises:

Q1. Find out the values of solar constant applicable to other planets in our solar system. Use the parameters mentioned in the below table.

S. No.	Planet	Distance from Sun (km)	Other Parameters
1	**Mercury**	**5.8×10^7**	**Surface Temperature of Sun : 5800K** **Emissivity : 1** **Radius of Sun: 7×10^8m** **Stefan Boltzmann Constant: 5.67×10^{-8} W m^{-2} K^{-4}**
2	**Venus**	**1.08×10^8**	
3	**Mars**	**2.28×10^8**	
4	**Jupiter**	**7.78×10^8**	
5	**Saturn**	**1.4×10^9**	
6	**Uranus**	**2.87×10^9**	
7	**Neptune**	**4.5×10^9**	
8	**Pluto**	**5.95×10^9**	

Answer:
As given in Eq 9.1, the total power emitted by the sun is 3.9×10^{26} W. The solar power per unit area at the surface of any planet is given by Eq 9.3 and Eq 9.4. The solar constants as calculated from Eq 9.1, 9.2 and 9.3 are given in the below table:

S. No.	Planet	Distance from Sun (km)	Solar Constant (W m^{-2})
1	Mercury	5.8×10^7	9230
2	Venus	1.08×10^8	2662
3	Mars	2.28×10^8	597
4	Jupiter	7.78×10^8	51
5	Saturn	1.4×10^9	1.6
6	Uranus	2.87×10^9	0.38
7	Neptune	4.5×10^9	0.15
8	Pluto	5.95×10^9	0.088

Q2. On a clear sunny day, the intensity recorded at a location on Earth's surface has been found to be 1000 W m^{-2} when the sun is at 45° in reference to horizon. Calculate the approximate intensity values for this location on this particular day when the sun is at 15, 30°, 60°, 75°, 90°, 105°, 130°, 145°, 160°.

Answer:
The intensity at any angle can be calculated from Eq (9.1) as given below:

$$I = I_O \cos\theta$$

I_0 is the intensity when $\theta = 0^0$ with respect to the normal to the collector plane. The intensity at $\theta = 45^0$ is given as 1000 W m^{-2}. Using the above equation the I_0 can be calculated as (1000 W m^{-2})/Cos$(90-45)^0$ ≈

1414 W m^{-2}. The intensity I at any angle can now be calculated using the I_0. The calculated values are given in the below table.

Angle (^{0})	Angle from Normal (^{0})	Intensity (W m^{-2})
15	75	366
30	60	707
60	30	1224
75	15	1366
90	0	1414
105	15	1366
130	40	942
145	55	811
160	70	483

There is an abnormality as the Intensity on Earth is more than the solar constant (1370 W m^{-2}), which is not possible. It indicates that the irradiance value at 45^0 cannot be 1000 W m^{-2}.

Q3. (a) A fixed SPV installation in northern hemisphere has south facing modules such that at 12noon on March 21 and Sept 21 (equinox), the sun is at zenith, i.e. sun rays are perpendicular to the module face. Compare the instantaneous power at 12 noon for these equinoxes and on June 21 (summer solstice) and Dec 21 (winter solstice) for c-Si, CdTe, a-Si and CIGS technologies. Between summer and winter solstices, the sun angle in north-south plane changes to 47^o (-23.5^o to $+23.5^o$) passing through zero during equinox. Assume, the ambient temperature is -15^oC less during winter solstice and $+15^oC$ more during summer solstice respectively as compared to that of equinox days. Also assume that the module temperature is 20^0C more than ambient. Use temperature co-efficient values from Table 9.2.
(b) Repeat the comparative study as above when the fixed installation is optimized to give maximum output during summer solstice, i.e. at noon on June 21, the sun rays are perpendicular to module face.
(c) Repeat the comparative study as above when the fixed installation is optimized to give maximum output during winter solstice, i.e. at noon on Dec 21, the sun rays are perpendicular to module face.

Answer:
(a) The effective irradiance is reduced by Cos 23.5^0 during summer and winter solstice as compared to that of equinox. Considering the irradiance variation only; If the power delivered during equinox time is $P_{equinox}$ (W_P), the power delivered during summer and winter solstice are ($P_{equinox}$ x Cos 23.5^0) W_P = 0.917 $P_{equinox}$. It is assumed that the change of irradiance is directly proportional to the change of I_{SC} and the effect of change of irradinace is on V_{OC} and Fill factor is negligible. The temperature effect is also need to considered.

The module heating effect is assumed to be same during all conditions; equinox, summer solstice and winter solstice. The cell temperature during summer solstice is $+15^0C$ more than that of equinox. The power of the module therefore during the summer solstice is:

$$P_{summer} \text{ for c-Si} = 0.917\ P_{equinox}\ [1 + (15) \times (-0.4/100)]\ W_P \approx 0.86\ P_{equinox}$$

$$P_{summer} \text{ for CdTe} = 0.917\ P_{equinox}\ [1 + (15^0C) \times (-0.25/100)]\ W_P \approx 0.88\ P_{equinox}$$

$$P_{summer} \text{ for a-Si} = 0.917\ P_{equinox}\ [1 + (15^0C) \times (-0.2/100))]\ W_P \approx 0.89\ P_{equinox}$$

The cell temperature during winter solstice is (-15^0C) more than that of equinox . The power of the module during the summer solstice is:

$$P_{winter} \text{ for c-Si} = 0.917\ P_{equinox}\ [1 + (-15^0C) \times (-0.4/100)]\ W_P \approx 0.97\ P_{equinox}$$

$$P_{winter} \text{ for CdTe} = 0.917\ P_{equinox}\ [1 + (-15^0C) \times (-0.25/100)]\ W_P \approx 0.95\ P_{equinox}$$

$$P_{winter} \text{ for a-Si} = 0.917\ P_{equinox}\ [1 + (-15^0C) \times (-0.2/100)]\ W_P \approx 0.94\ P_{equinox}$$

(b) In this case output is optimized for summer solstice in terms of irradiance. The effective irradiance is reduced by Cos 23.5^0 during equinox and Cos 47^0 in winter solstice as compared to that of summer solstice. Considering the irradiance variation only; If the power delivered during summer solstice times is P'_{summer} (W_P), the power delivered during equinox is

$$P'_{equinox} = (P'_{suumer} \times \text{Cos } 23.5^0)\ W_P \approx 0.917\ P'_{summer}$$

and during winter solstice is

$$P'_{winter} = (P'_{suumer} \times \text{Cos } 47^0)\ W_P \approx 0.682\ P'_{summer}$$

Now let us consider the temperature effect. The temperature at the time of equinox and winter solstice are 15^0C and 30^0C less respectively as compared to summer solstice. Cell temperature during equinox is therefore (-15^0C) during equinox. The power of the module therefore during the equinox time is:

$$P'_{equinox} \text{ for c-Si} = 0.917\ P'_{summer}\ [1 + (-15^0C) \times (-0.4/100)]\ W_P \approx 0.97\ P'_{summer}$$

$$P'_{equinox} \text{ for CdTe} = 0.917\ P'_{summer}\ [1 + (-15^0C) \times (-0.25/100)]\ W_P \approx 0.95\ P'_{summer}$$

$$P'_{equinox} \text{ for a-Si} = 0.917\ P'_{summer}\ [1 + (35^0C - 25^0C) \times (-0.2/100)]\ W_P \approx 0.94\ P'_{summer}$$

The cell temperature during winter solstice is (-30^0C). The power of the module therefore during the winter solstice is:

$$P'_{winter} \text{ for c-Si} = 0.682\ P'_{summer}\ [1 + (-30^0C) \times (-0.4/100)]\ W_P \approx 0.76\ P'_{summer}$$

$$P'_{winter} \text{ for CdTe} = 0.0682\ P'_{summer}\ [1 + (-30^0C) \times (-0.25/100)]\ W_P \approx 0.73\ P'_{summer}$$

$$P'_{winter} \text{ for a-Si} = 0.682\ P'_{summer}\ [1 + (-30^0C) \times (-0.2/100)]\ W_P \approx 0.72\ P'_{summer}$$

(c) In this case output is optimized for winter solstice in terms of irradiance. The effective irradiance is reduced by Cos 23.5^0 during equinox and Cos 47^0 in summer solstice as compared to that of winter solstice. Considering the irradiance variation only; If the power delivered during winter solstice is P''_{winter} (W_P), the power delivered during equinox is

$$P''_{equinox} = (P''_{winter} \times \text{Cos } 23.5^0)\ W_P \approx 0.917\ P''_{winter}$$

and during summer solstice is

$$P''_{summer} = (P''_{winter} \times \text{Cos } 47^0)\ W_P \approx 0.682\ P''_{winter}$$

Now let us consider the temperature effect. The temperature at the time of equinox and summer solstice are 15^0C and 30^0C more respectively as compared to summer solstice. Cell temperature during equinox is therefore (15^0C) during equinox. The power of the module therefore during the equinox time is:

$$P''_{equinox} \text{ for c-Si} = 0.917\ P''_{winter}\ [1 + (15^0C) \times (-0.4/100)]\ W_P \approx 0.86\ P''_{winter}$$

$$P''_{equinox} \text{ for CdTe} = 0.917\ P''_{winter}\ [1 + (-15^0C) \times (-0.25/100)]\ W_P \approx 0.88\ P''_{winter}$$

$$P''_{equinox} \text{ for a-Si} = 0.917\ P''_{winter}\ [1 + (35^0C - 25^0C) \times (-0.2/100)]\ W_P \approx 0.89\ P''_{winter}$$

The cell temperature during winter solstice is (30^0C). The power of the module therefore during the winter solstice is:

$$P''_{summer} \text{ for c-Si} = 0.682\ P''_{winter}\ [1 + (30^0C) \times (-0.4/100)]\ W_P \approx 0.60\ P''_{winter}$$

$$P''_{summer} \text{ for CdTe} = 0.682\ P''_{winter}\ [1 + (30^0C) \times (-0.25/100)]\ W_P \approx 0.63\ P''_{winter}$$

$$P''_{summer} \text{ for a-Si} = 0.682\ P''_{winter}\ [1 + (30^0C) \times (-0.2/100)]\ W_P \approx 0.64\ P''_{winter}$$

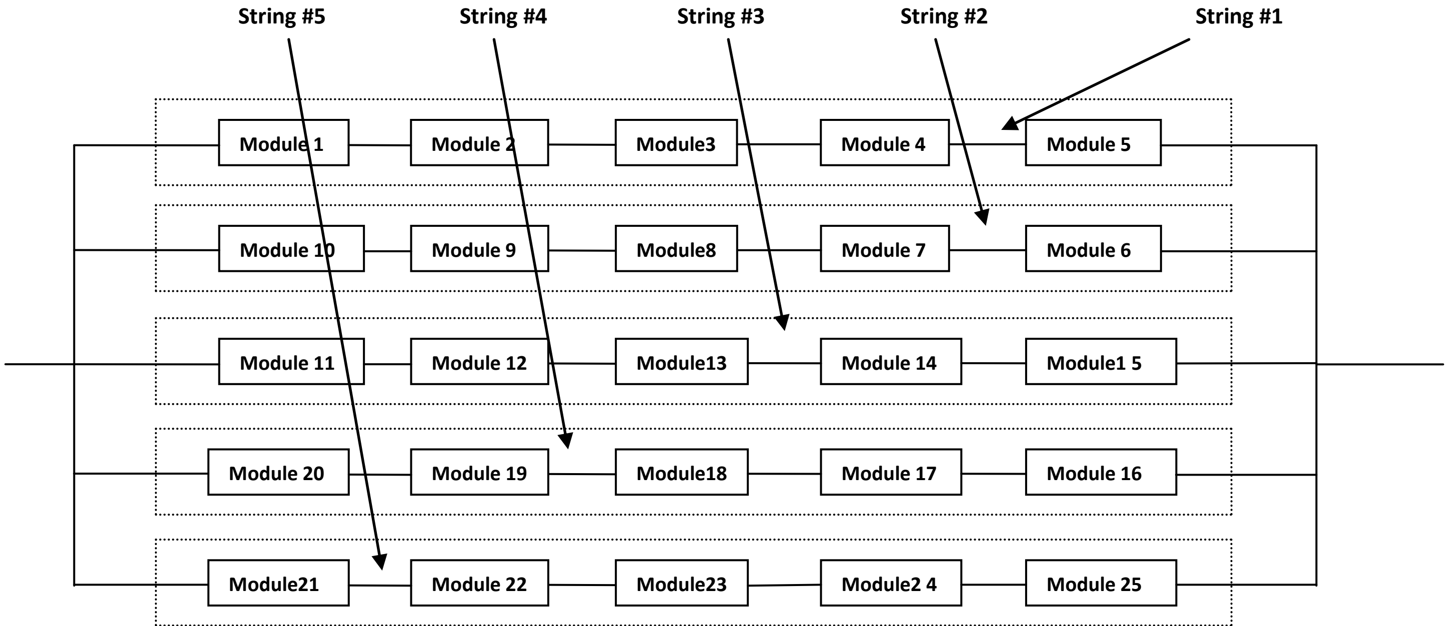
Q4. (a) A fixed SPV system with 25 numbers of $100W_P$ a-Si modules have been installed at a location having average 5 numbers of peak sun hours per day, i.e. average 5kWh per day. Calculate the DC power output obtained by this system annually. Assume average ambient temperature is 35^oC and the module temperature is 20^oC more than ambient. Use temperature co-efficient values of Table 9.2.
(b)Repeat this for 25 numbers of $100W_P$ CdTe modules.
(c)Repeat this for 17 numbers of $100W_P$ CIGS modules.

Answer:
(a) The total annual peak sun hours = 5 (no of peak sun hours/day) x 365 Days/year = 1825 Hrs per year
At STC temperature (25^oC) each module produces 100W.
Module temperature is: Ambient temperature + 20^oC = 35^oC + 20^oC = 55^oC, which is 30^oC higher than STC value. Temperature co-efficient of power (see Table-2) = -0.2% per ^oC.
The power reduction due to temperature effect is therefore = 0.2% per ^oC x 30^oC = 6%
100W module will produce 100W – (0.06x100)W = 94W
25 numbers of $100W_P$ module will now be equivalent to $94W_P$ x 25 = $2.35kW_P$
Total power produced = 2.35kW x 1825Hrs ≈ 4289 kWh (Units).

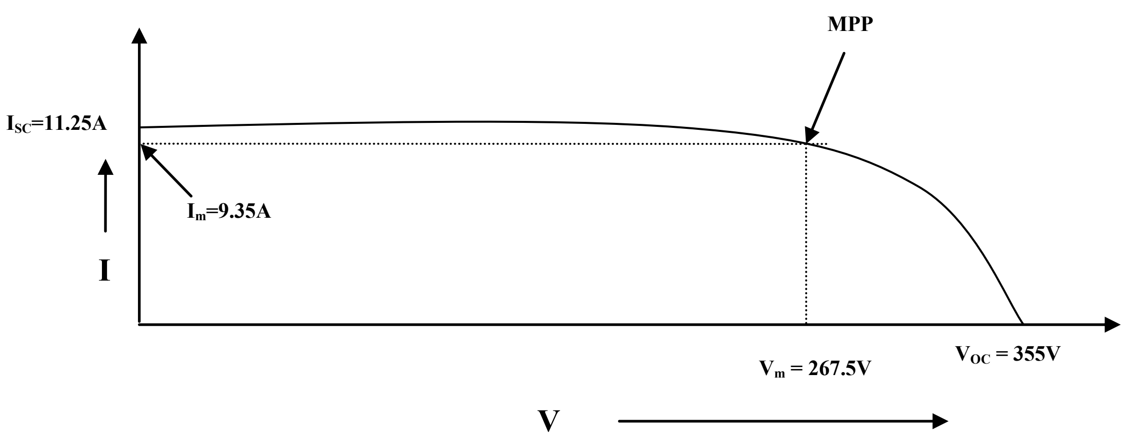
(b) The total annual peak sun hours = 5 (no of peak sun hours/day) x 365 Days/year = 1825 Hrs per year
At STC temperature (25^oC) each module produces 100W.
Module temperature is: Ambient temperature + 20^oC = 35^oC + 20^oC = 55^oC, which is 30^oC higher than STC value. Temperature co-efficient of power (see Table-2) = -0.25% per ^oC.
The power reduction due to temperature effect is therefore = 0.25% per ^oC x 30^oC = 7.5%
100W module will produce 100W – (0.075x100)W = 92.5W
25 numbers of $100W_P$ module will now be equivalent to $92.5W_P$ x 25 ≈ $2.31kW_P$
Total power produced = 2.31kW x 1825Hrs ≈ 4220 kWh (Units).

(c) The total annual peak sun hours = 5 (no of peak sun hours/day) x 365 Days/year = 1825 Hrs per year
At STC temperature (25^oC) each module produces 100W.
Module temperature is: Ambient temperature + 20^oC = 35^oC + 20^oC = 55^oC, which is 30^oC higher than STC value. Temperature co-efficient of power (see Table-2) = -0.45% per ^oC.
The power reduction due to temperature effect is therefore = 0.45% per ^oC x 30^oC = 13.5%
100W module will produce 100W – (0.135x100)W = 86.5W
17 numbers of $100W_P$ module will now be equivalent to $86.5W_P$ x 13 ≈ $1.47kW_P$
Total power produced = 1.47kW x 1825Hrs ≈ 2684 kWh (Units).

Q5. A 2.5 kW_P SPV system with 25 numbers of $100W_P$ a-Si module has been configures as shown in below figure. All modules have identical I-V characteristics (V_{OC} = 71V, I_{SC} = 2.25A, V_m = 53.5V, I_m = 1.87A). Calculate the string voltage and current applicable to STC. Also draw resultant I-V characteristics.

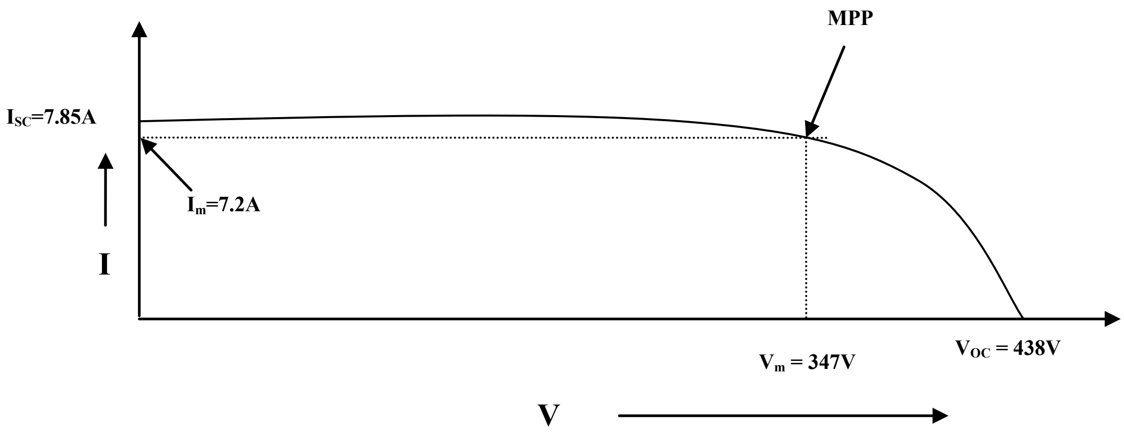


Answer:
The V_{OC} and I_{SC} of each string is 71V x 5 = 355V and 2.25A respectively. The array has 5 such strings. The V_{OC} and I_{SC} of the array are therefore 355V and (2.25A x5) = 11.25A. Similarly the array V_m = 53.5V x 5 = 267.5V and the array I_m = 1.87A x 5 = 9.35A. The I-V Characteristics of the array is shown in the figure below:



Q6. Repeat Exercise 5 with 25 numbers of 100W$_P$ CdTe modules. Here also assume all modules have identical I-V characteristics (V_{OC} = 87.6V, I_{SC} = 1.57A, V_m = 69.4V, I_m = 1.44A).

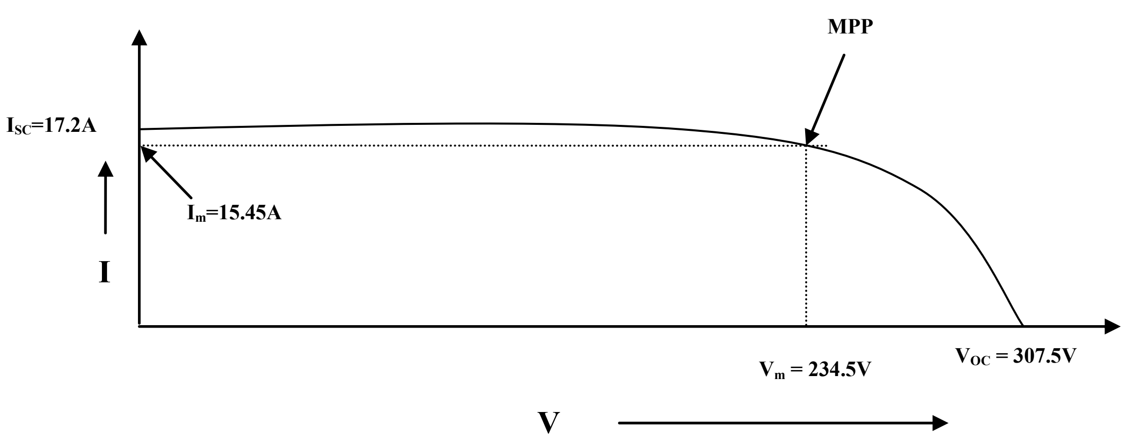
Answer:
The V_{OC} and I_{SC} of each string is 87.6V x 5 = 438V and 1.57A respectively. The array has 5 such strings. The V_{OC} and I_{SC} of the array are therefore 438V and (1.57A x5) = 7.85A. Similarly the array V_m = 69.4V x 5 = 347V and the array I_m = 1.44A x 5 = 7.2A. The I-V Characteristics of the array is shown in the figure below:



Q7. Repeat Exercise 5 with 25 numbers of 145W$_P$ CIGS modules having identical I-V characteristics (V_{OC} = 61.5V, I_{SC} = 3.44A, V_m = 46.9V, I_m = 3.09A).

Answer:

The V_{OC} and I_{SC} of each string is 61.5V x 5 = 307.5V and 3.44A respectively. The array has 5 such strings. The V_{OC} and I_{SC} of the array are therefore 307.5V and (3.44A x5) = 17.2A. Similarly the array V_m = 46.9V x 5 = 234.5V and the array I_m = 3.09A x 5 = 15.45A. The I-V Characteristics of the array is shown in the figure below:



Q8. A fixed 100KW$_P$ SPV system has to be installed. c-Si modules with P_m=250W$_P$, V_{OC} = 37V, I_{SC} = 9.6A, V_m = 30V, I_m = 8.33A are available. A 100KVA inverter having the following specifications has been used for this system:

Maximum Voltage = 1000V, MPP tracking voltage range = 350V to 700V DC. Annual temperature variation range of the location = 0^{o}C to 45^{o}C. Describe the string design procedure for this system and determine the best configuration.

Answer:

This can be worked out as described in Example-5.

Consideration 1:

The highest voltage of the module is decided by the lowest temperature. During early morning, the irradiance is very low and the module temperature is close to the ambient temperature, whose minimum is 0^{o}C. Also during very low radiation condition the module current is close to zero and module voltage is close to V_{OC}. As the temperature is less than 25^{o}C, V_{OC} is higher than the specified value at STC. This will determine the worst case voltage of the string and has to be less than the maximum operating voltage of the inverter.

The V_{OC} in the early morning at 0^oC ambient temperature = 37V x [1+{(0-25)^oC x (-0.36/100) per ^oC}] = 40.33V; temperature co-efficient of V_{OC} is -0.36%/^oC (see Table 9.2).
The maximum number of modules connected in series can therefore must be < (maximum voltage of the inverter/40.33) = 1000V/40.33 = 24.79. Therefore maximum possible modules can be connected from this standpoint is 24.

Consideration 2:
During operation of the module the module operates at MPP and V_m is applicable. Also the modules get heated up and the module temperature is more than the ambient. It is assumed, as before, that the module temperature is 20^oC more than the ambient. The string voltage has to be within the MPP tracking voltage. Maximum voltage will occur at minimum (0^oC) ambient temperature and minimum at highest ambient (45^oC) temperature. The corresponding module temperatures are (0^oC + 20^oC) = 20^oC and (45^oC + 20^oC) =65^oC respectively.

Maximum V_{mp} = 30V x [1+{(20-25)^oC x (-0.36/100) per ^oC}] = 30.54V.
Maximum MPPT voltage = 700V
Maximum number of modules in a string = 700V/30.54V = 22.9 ≈22

Minimum V_{mp} = 30V x [1+{(65-25)^oC x (-0.36/100) per ^oC}] = 25.68V.
Minimum MPPT voltage = 350V
Minimum number of modules in a string = 350V/25.68V = 13.63 ≈14

Considering all the factors the string must have minimum of 14 modules and maximum of 22 modules. Below Table captures possible combinations and the best option is highlighted.

Possible String Design Options for a 100kW$_P$ SPV System

S. No.	No of Modules in Series (String)	No of Strings in parallel	Total no of Modules	Power per Module (W_P)	Total Installed Power (kW_P)
1	14	28	392	250	98
2	14	29	406	250	101.5
3	15	26	390	250	97.5
4	15	27	405	250	101.25
5	**16**	**25**	**400**	**250**	**100**
6	17	23	391	250	97.5
7	17	24	408	250	102
8	18	22	396	250	99
9	18	23	414	250	103.5
10	19	21	399	250	99.75
11	19	22	418	250	104.5
12	**20**	**20**	**400**	**250**	**100**
13	21	19	399	250	99.75
14	21	20	420	250	105
15	22	18	396	250	99
16	22	19	418	250	104.5
17	23	17	391	250	97.75
18	23	18	414	250	103.5
19	24	16	384	250	96
20	24	17	408	250	102

S. No. 5 and 12 are the ideal solutions.

Q9. A fixed 30KW$_P$ SPV system has to be installed. a-Si modules with P_m=100W$_P$, V_{OC} = 71V, I_{SC} = 2.25A, V_m = 53.5V, I_m = 1.87A are available. A 30KVA inverter having the following specifications has been used for this system:
Maximum Voltage = 800V, MPP tracking voltage range = 350V to 700V DC. Annual temperature variation range of the location = 0^{o}C to 45^{o}C. Describe the string design procedure for this system and determine the best configuration.
Answer:
This can be worked out as described in Example-5 and previous exercise (#9).

Consideration 1:
The highest voltage of the module is decided by the lowest temperature. During early morning, the irradiance is very low and the module temperature is close to the ambient temperature, whose minimum is 0^{o}C. Also during very low radiation condition the module current is close to zero and module voltage is close to V_{OC}. As the temperature is less than 25^{o}C, V_{OC} is higher than the specified value at STC. This will determine the worst case voltage of the string and has to be less than the maximum operating voltage of the inverter.

The V_{OC} in the early morning at 0^{o}C ambient temperature = 71V x [1+{(0-25)^{o}C x (-0.3/100) per ^{o}C}] = 76.325V; temperature co-efficient of V_{OC} is -0.3%/^{o}C (see Table 9.2).
The maximum number of modules connected in series can therefore must be < (maximum voltage of the inverter/76.325) = 800V/76.325 = 10.48. Therefore maximum possible modules can be connected from this standpoint is 10.

Consideration 2:
During operation of the module the module operates at MPP and V_m is applicable. Also the modules get heated up and the module temperature is more than the ambient. It is assumed, as before, that the module temperature is 20^{o}C more than the ambient. The string voltage has to be within the MPP tracking voltage. Maximum voltage will occur at minimum (0^{o}C) ambient temperature and minimum at highest ambient (45^{o}C) temperature. The corresponding module temperatures are (0^{o}C + 20^{o}C) = 20^{o}C and (45^{o}C + 20^{o}C) =65^{o}C respectively.

Maximum V_{mp} = 53.5V x [1+{(20-25)^{o}C x (-0.3/100) per ^{o}C}] = 54.3V.
Maximum MPPT voltage = 700V
Maximum number of modules in a string = 700V/54.3V = 22.9 ≈22

Minimum V_{mp} = 53.5V x [1+{(65-25)^{o}C x (-0.3/100) per ^{o}C}] = 47.08V.
Minimum MPPT voltage = 350V
Minimum number of modules in a string = 350V/47.08V = 7.43 ≈ 8

Considering all the factors the string must have minimum of 8 modules and maximum of 10 modules.
Below Table captures possible combinations and the best option is highlighted.

Possible String Design Options for a 30kW$_P$ SPV System

S. No.	No of Modules in Series (String)	No of Strings in parallel	Total no of Modules	Power per Module (W$_P$)	Total Installed Power (kW$_P$)
1	8	37	296	100	29.6
2	8	38	304	100	30.4
3	9	33	297	100	29.7
4	9	34	306	100	30.6
5	**10**	**30**	**300**	**100**	**30**

S. No. 5 is the ideal solutions.

Q10. A fixed 30KW$_P$ SPV system has to be installed. CdTe modules with P_m=100W$_P$, V_{OC} = 87.6V, I_{SC} = 1.57A, V_m = 69.4V, I_m = 1.44A are available. A 30KVA inverter having the following specifications has been used for this system:
Maximum Voltage = 800V, MPP tracking voltage range = 350V to 700V DC. Annual temperature variation range of the location = 0^{o}C to 45^{o}C. Describe the string design procedure for this system and determine the best configuration.
Answer:
This can be worked out as described in Example-5 and previous two exercises (#8 & 9).

Consideration 1:
The highest voltage of the module is decided by the lowest temperature. During early morning, the irradiance is very low and the module temperature is close to the ambient temperature, whose minimum is 0^{o}C. Also during very low radiation condition the module current is close to zero and module voltage is close to V_{OC}. As the temperature is less than 25^{o}C, V_{OC} is higher than the specified value at STC. This will determine the worst case voltage of the string and has to be less than the maximum operating voltage of the inverter.

The V_{OC} in the early morning at 0^{o}C ambient temperature = 87.6V x [1+{(0-25)^{o}C x (-0.25/100) per ^{o}C}] = 93.075V; temperature co-efficient of V_{OC} is -0.25%/^{o}C (see Table 9.2).
The maximum number of modules connected in series can therefore must be < (maximum voltage of the inverter/93.075) = 800V/40.33 = 8.59. Therefore maximum possible modules can be connected from this standpoint is 8.

Consideration 2:
During operation of the module the module operates at MPP and V_m is applicable. Also the modules get heated up and the module temperature is more than the ambient. It is assumed, as before, that the module temperature is 20^{o}C more than the ambient. The string voltage has to be within the MPP tracking voltage. Maximum voltage will occur at minimum (0^{o}C) ambient temperature and minimum at highest ambient (45^{o}C) temperature. The corresponding module temperatures are (0^{o}C + 20^{o}C) = 20^{o}C and (45^{o}C + 20^{o}C) =65^{o}C respectively.

Maximum V_{mp} = 69.4V x [1+{(20-25)^{o}C x (-0.25/100) per ^{o}C}] ≈ 70.27V.
Maximum MPPT voltage = 700V
Maximum number of modules in a string = 700V/70.27V = 9.96 ≈9

Minimum V_{mp} = 69.4V x [1+{(65-25)^{o}C x (-0.25/100) per ^{o}C}] = 62.46V.
Minimum MPPT voltage = 350V
Minimum number of modules in a string = 350V/62.46V = 5.6 ≈ 6

Considering all the factors the string must have minimum of 6 modules and maximum of 8 modules.
Below Table captures possible combinations and the best option is highlighted.

Possible String Design Options for a 30kW$_P$ SPV System

S. No.	No of Modules in Series (String)	No of Strings in parallel	Total no of Modules	Power per Module (W$_P$)	Total Installed Power (kW$_P$)
1	**6**	**50**	**300**	**100**	**30**
2	7	42	294	100	29.4
3	7	43	301	100	30.1
4	8	37	296	100	29.6
5	8	38	304	100	30.4

S. No. 1 is the ideal solutions.

Q11. A fixed 30KW$_P$ SPV system has to be installed. CIGS modules with P_m = 145W$_P$, V_{OC} = 61.5V, I_{SC} = 3.44A, V_m = 46.9V, I_m = 3.09A) are available. A 30KVA inverter having the following specifications has been used for this system:

Maximum Voltage = 800V, MPP tracking voltage range = 350V to 700V DC. Annual temperature variation range of the location = 0°C to 45°C. Describe the string design procedure for this system and determine the best configuration.

Answer:

This can be worked out as described in Example-5 and previous two exercises (#8, 9 & 10).

Consideration 1:

The highest voltage of the module is decided by the lowest temperature. During early morning, the irradiance is very low and the module temperature is close to the ambient temperature, whose minimum is 0°C. Also during very low radiation condition the module current is close to zero and module voltage is close to V_{OC}. As the temperature is less than 25°C, V_{OC} is higher than the specified value at STC. This will determine the worst case voltage of the string and has to be less than the maximum operating voltage of the inverter.

The V_{OC} in the early morning at 0°C ambient temperature = 61.5V x [1+{(0-25)°C x (-0.36/100) per °C}] = 67.035V; temperature co-efficient of V_{OC} is -0.36%/°C (see Table 9.2).

The maximum number of modules connected in series can therefore must be < (maximum voltage of the inverter/67.035) = 800V/67.035 = 11.93. Therefore maximum possible modules can be connected from this standpoint is 11.

Consideration 2:

During operation of the module the module operates at MPP and V_m is applicable. Also the modules get heated up and the module temperature is more than the ambient. It is assumed, as before, that the module temperature is 20°C more than the ambient. The string voltage has to be within the MPP tracking voltage. Maximum voltage will occur at minimum (0°C) ambient temperature and minimum at highest ambient (45°C) temperature. The corresponding module temperatures are (0°C + 20°C) = 20°C and (45°C + 20°C) =65°C respectively.

Maximum V_{mp} = 46.9V x [1+{(20-25)°C x (-0.36/100) per °C}] ≈ 47.74V.
Maximum MPPT voltage = 700V
Maximum number of modules in a string = 700V/47.74V = 14.66 ≈ 14

Minimum V_{mp} = 46.9V x [1+{(65-25)°C x (-0.36/100) per °C}] ≈ 40.15V.
Minimum MPPT voltage = 350V
Minimum number of modules in a string = 350V/40.15V ≈ 8.72 ≈ 9

Considering all the factors the string must have minimum of 9 modules and maximum of 11 modules.
Below Table captures possible combinations and the best option is highlighted.

Possible String Design Options for a 30kW$_P$ SPV System

S. No.	No of Modules in Series (String)	No of Strings in parallel	Total no of Modules	Power per Module (W$_P$)	Total Installed Power (kW$_P$)
1	9	33	297	100	29.7
2	9	34	306	100	30.6
3	**10**	**30**	**300**	**100**	**30**
4	11	27	297	100	29.7
5	11	28	308	100	30.8

S. No. 3 is the ideal solutions.

Q12. A load profile and use pattern has been summarized in below Table. Design an appropriate grid interactive battery backup system including the sizing of the battery. Assume inverter operating voltage is 415 V. Draw the final configuration with the help of a Single Line Diagram (SLD). In case night loads are not to be supported by the SPV, what will be the system sizing and configuration then?

S. No.	**Load**	**Wattage Rating**	**Quantity**	**Operation Hrs -Day**	**Operation Hrs -Night**
1	**Light**	**40**	**100**	**5**	**5**
2	**Fan**	**80**	**50**	**5**	**5**
3	**AC**	**2000**	**10**	**5**	**5**
4	**Laptop**	**150**	**20**	**5**	**5**
5	**TV**	**100**	**4**	**5**	**5**
6	**Fridge**	**300**	**5**	**6**	**4**

Answer:
The requirement can be estimated as

Energy Requirement based on the given load profile

S. No.	Load	Wattage Rating	Quantity	Total Wattage	Operation Hrs -Day	Operation Hrs -Night	kWhr (day)	kWHr (Night)	Total (kWHr)
1	Light	40	100	4000	5	5	20	20	40
2	Fan	80	50	4000	5	5	20	20	40
3	AC	2000	10	20000	5	5	100	100	200
4	Laptop	150	20	3000	5	5	15	15	30
5	TV	150	100	15000	5	5	75	75	150
6	Fridge	300	5	1500	6	4	9	6	15
						Total	239 Units	236 Units	475 Units

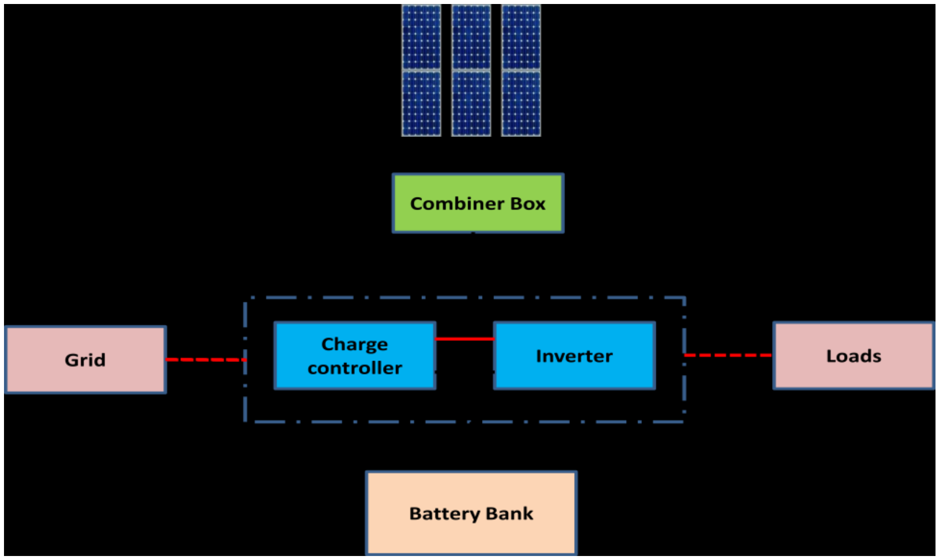
Assuming the parameters of Example 2 with a peak sun hour of 5, the required size of the SPV installation is (475/5) = 95kW$_P$. It may be noted that temperature effects on the module power output have not been included in this calculation. The addition power required to compensate the loss due to temperature can be calculated knowing the average temperature of the location of installation and technology used (power temperature co-efficient). Apart from temperature, there are other loss mechanism due to inverter efficiency, soiling, mismatch, battery charging discharging efficiency, wiring resistance, etc. and are not considered here.

This system requires a battery for storage. There are requirement of 236kWh (units) for night time load per day. This much energy is to be stored in the battery. Some margin has to be given to compensate the efficiency. If the efficiency is assumed to be 80% then the energy storage requirement increases to (236/0.8)kWh = 295kWh. Approximate battery backup time required is 5 hrs.

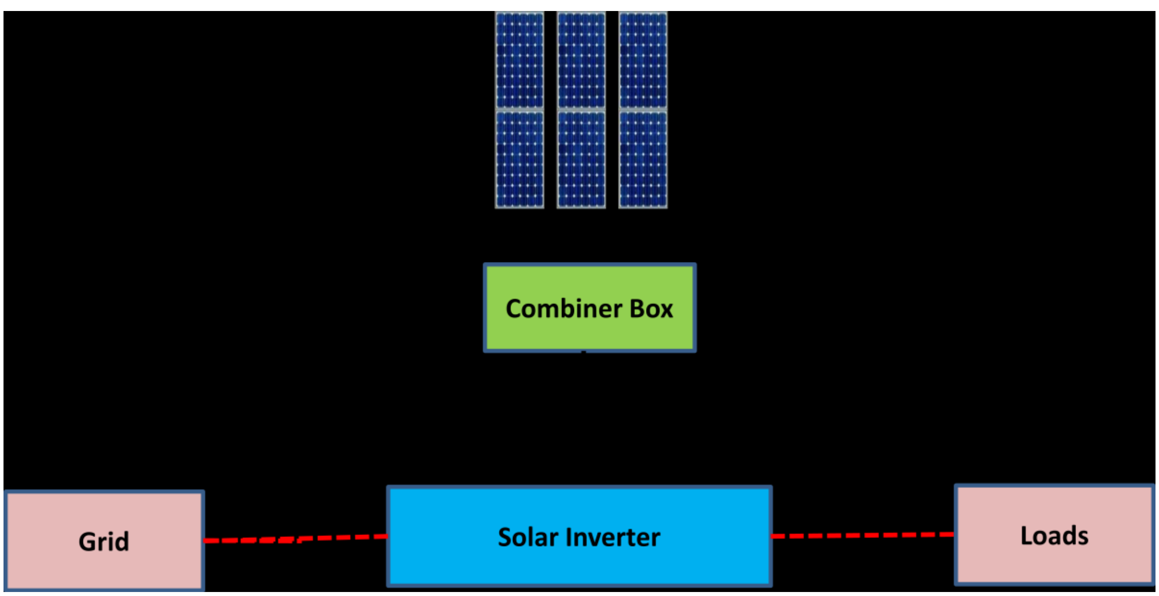
A 500VA inverter/PCU with 415V is required to support this system. The capacity of the battery can be estimated as (295kWh/415V) ≈ 710Ah battery. The battery capacity has to be enhanced to extend the life. The criteria have been not to allow full discharging at any time; the depth of discharge (DOD) of about 80% is an accepted figure. An overall margin of 20% is generally provided for temperature de-rating and aging.

The capacity requirement considering 80% DOD = 710 Ah/0.8 = 887.5Ah
The capacity requirement considering 20% margin = 887.5Ah x 1.2 = 1065Ah

In case the night load is not to be supported by SPV, no battery is required. The system has to support only day time load which is 239kWh. The SPV installation requirement is then (239kWh/5) = 47.8kW$_P$. Again the temperature effect is not consider here.



Configuration with battery back-up .



Configuration without battery back-up .

Q13. A c-Si module operating at STC and having P_m = 250 W_P, V_{OC} = 37V, I_{SC} = 9.6A, V_m = 30V, I_m = 8.33A and Fill Factor = 70%. Calculate P_m at 800 W m^{-2}, 500 W m^{-2} and 200 W m^{-2} intensity levels. Neglect temperature effect and assume the change of V_{OC} due to intensity variation is negligible. Also assume that I_{SC} is directly proportional to intensity with proportionality constant of 1.

Answer:
Assuming V_{OC} and fill factor do not change with the change of intensity level; the power will change linearly with intensity due to changes of I_{SC}. Therefore the power at different intensity levels can be estimated as:

P_m at 800 W m^{-2} = (P_m at 1000 W m^{-2}) x (800/1000) = 250 W_P x (800/1000) = 200 W_P

P_m at 500 W m^{-2} = (P_m at 1000 W m^{-2}) x (500/1000) = 250 W_P x (500/1000) = 125 W_P

P_m at 200 W m^{-2} = (P_m at 1000 W m^{-2}) x (200/1000) = 250 W_P x (200/1000) = 50 W_P

Q14. For the Exercise 13, Compute power (P_m) at -20°C, 0°C, 20°C and 40°C ambient temperatures. Assume module temperature is 20°C more than ambient and use temperature co-efficient values from Table 9.2.

Answer:
The module temperatures at -20^{0}C ambient temperatures is (-20 + 20)^{0}C = 0^{0}C. The power of the module at 1000 W m^{-2} is 250 W_P [1 + (0 - 25)^{0}C x (-0.4/100) %/^{0}C] = 275 W_P

P_m at 800 W m^{-2} and at -20^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 275 W_P x (800/1000) = 220 W_P

P_m at 500 W m^{-2} and at -20^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 275 W_P x (500/1000) = 137.5 W_P

P_m at 200 W m^{-2} and at -20^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 275 W_P x (200/1000) = 55 W_P

The module temperatures at 0^{0}C ambient temperatures is (0 + 20)^{0}C = 20^{0}C. The power of the module at 1000 W m^{-2} is 250 W_P [1 + (20 - 25)^{0}C x (-0.4/100) %/^{0}C] = 255 W_P

P_m at 800 W m^{-2} and at 0^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 255 W_P x (800/1000) = 204 W_P

P_m at 500 W m^{-2} and at 0^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 255 W_P x (500/1000) = 127.5 W_P

P_m at 200 W m^{-2} and at 0^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 255 W_P x (200/1000) = 51 W_P

The module temperatures at 20^{0}C ambient temperatures is (20 + 20)^{0}C = 40^{0}C. The power of the module at 1000 W m^{-2} is 250 W_P [1 + (40 - 25)^{0}C x (-0.4/100) %/^{0}C] = 235 W_P

P_m at 800 W m^{-2} and at 20^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 235 W_P x (800/1000) = 188 W_P

P_m at 500 W m^{-2} and at 20^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 235 W_P x (500/1000) = 117.5 W_P

P_m at 200 W m^{-2} and at 20^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 235 W_P x (200/1000) = 47 W_P

The module temperatures at 40^0C ambient temperatures is $(40 + 20)^0C = 60^0C$. The power of the module at 1000 W m^{-2} is 250 W_P [1 + $(60 - 25)^0C$ x (-0.4/100) %/^0C] = 215 W_P

P_m at 800 W m^{-2} and at 40^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 215 W_P x (800/1000) = 172 W_P

P_m at 500 W m^{-2} and at 40^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 215 W_P x (500/1000) = 107.5 W_P

P_m at 200 W m^{-2} and at 40^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 215 W_P x (200/1000) = 43 W_P

Q15. A a-Si module operating at STC and having P_m=100W_P, V_{OC} = 71V, I_{SC} = 2.25A, V_m = 53.5V, I_m = 1.87A and Fill Factor = 61.5%. Calculate P_m at 800 W m^{-2}, 500 W m^{-2} and 200 W m^{-2} intensity levels. Neglect temperature effect and assume the change of V_{OC} due to intensity variation is negligible. Also assume that I_{SC} is directly proportional to intensity with proportionality constant of 1.

Answer:
Assuming V_{OC} and fill factor do not change with the change of intensity level; the power will change linearly with intensity due to changes of I_{SC}. Therefore the power at different intensity levels can be estimated as:

P_m at 800 W m^{-2} = (P_m at 1000 W m^{-2}) x (800/1000) = 100 W_P x (800/1000) = 80 W_P

P_m at 500 W m^{-2} = (P_m at 1000 W m^{-2}) x (500/1000) = 100 W_P x (500/1000) = 50 W_P

P_m at 200 W m^{-2} = (P_m at 1000 W m^{-2}) x (200/1000) = 100 W_P x (200/1000) = 20 W_P

Q16. For the Exercise 15, Compute power (P_m) at -20°C, 0°C, 20°C and 40°C ambient temperatures. Assume module temperature is 20°C more than ambient and use temperature co-efficient values from Table 9.2.

Answer:
The module temperatures at -20^0C ambient temperatures is $(-20 + 20)^0C = 0^0C$. The power of the module at 1000 W m^{-2} is 100 W_P [1 + $(0 - 25)^0C$ x (-0.2/100) %/^0C] = 105 W_P

P_m at 800 W m^{-2} and at -20^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 105 W_P x (800/1000) = 84 W_P

P_m at 500 W m^{-2} and at -20^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 105 W_P x (500/1000) = 52.5 W_P

P_m at 200 W m^{-2} and at -20^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 105 W_P x (200/1000) = 21 W_P

The module temperatures at 0^0C ambient temperatures is $(0 + 20)^0C = 20^0C$. The power of the module at 1000 W m^{-2} is 100 W_P [1 + $(20 - 25)^0C$ x (-0.2/100) %/^0C] = 101 W_P

P_m at 800 W m^{-2} and at 0^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 101 W_P x (800/1000) = 80.8 W_P

P_m at 500 W m^{-2} and at 0^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 101 W_P x (500/1000) = 50.5 W_P

P_m at 200 W m^{-2} and at 0^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 101 W_P x (200/1000) = 20.2 W_P

The module temperatures at 20^0C ambient temperatures is $(20 + 20)^0C = 40^0C$. The power of the module at 1000 W m^{-2} is 250 W_P [1 + (40 - 25)^{0}C x (-0.2/100) %/^{0}C] = 97 W_P

P_m at 800 W m^{-2} and at 20^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 97 W_P x (800/1000) = 77.6 W_P

P_m at 500 W m^{-2} and at 20^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 97 W_P x (500/1000) = 48.5 W_P

P_m at 200 W m^{-2} and at 20^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 97 W_P x (200/1000) = 19.4 W_P

The module temperatures at 40^0C ambient temperatures is $(40 + 20)^0C = 60^0C$. The power of the module at 1000 W m^{-2} is 250 W_P [1 + (60 - 25)^{0}C x (-0.2/100) %/^{0}C] = 93 W_P

P_m at 800 W m^{-2} and at 40^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 93 W_P x (800/1000) = 74.4 W_P

P_m at 500 W m^{-2} and at 40^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 93 W_P x (500/1000) = 46.5 W_P

P_m at 200 W m^{-2} and at 40^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 93 W_P x (200/1000) = 18.6 W_P

Q17. A CdTe module operating at STC and having P_m=100W_P, V_{OC} = 87.6V, I_{SC} = 1.57A, V_m = 69.4V, I_m = 1.44A and Fill Factor = 72%. Calculate P_m at 800 W m^{-2}, 500 W m^{-2} and 200 W m^{-2} intensity levels. Neglect temperature effect and assume the change of V_{OC} due to intensity variation is negligible. Also assume that I_{SC} is directly proportional to intensity with proportionality constant of 1.

Answer:
Assuming V_{OC} and fill factor do not change with the change of intensity level; the power will change linearly with intensity due to changes of I_{SC}. Therefore the power at different intensity levels can be estimated as:

P_m at 800 W m^{-2} = (P_m at 1000 W m^{-2}) x (800/1000) = 100 W_P x (800/1000) = 80 W_P

P_m at 500 W m^{-2} = (P_m at 1000 W m^{-2}) x (500/1000) = 100 W_P x (500/1000) = 50 W_P

P_m at 200 W m^{-2} = (P_m at 1000 W m^{-2}) x (200/1000) = 100 W_P x (200/1000) = 20 W_P

Q18. For the Exercise 17, Compute power (P_m) at -20^{o}C, 0^{o}C, 20^{o}C and 40^{o}C ambient temperatures. Assume module temperature is 20^{o}C more than ambient and use temperature co-efficient values from Table 9.2.

Answer:
The module temperatures at -20^0C ambient temperatures is $(-20 + 20)^0C = 0^0C$. The power of the module at 1000 W m^{-2} is 100 W_P [1 + (0 - 25)^{0}C x (-0.25/100) %/^{0}C] = 106.25 W_P

P_m at 800 W m^{-2} and at -20^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 106.25 W_P x (800/1000) = 85 W_P

P_m at 500 W m^{-2} and at -20^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 106.25 W_P x (500/1000) = 53.125 W_P

P_m at 200 W m^{-2} and at -20^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 106.25 W_P x (200/1000) = 21.25 W_P

The module temperatures at 0^0C ambient temperatures is $(0 + 20)^0$C = 20^0C. The power of the module at 1000 W m^{-2} is 100 W_P [1 + (20 - 25)^{0}C x (-0.25/100) %/^{0}C] = 101.25 W_P

P_m at 800 W m^{-2} and at 0^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 101.25 W_P x (800/1000) = 81 W_P

P_m at 500 W m^{-2} and at 0^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 101.25 W_P x (500/1000) = 50.625 W_P

P_m at 200 W m^{-2} and at 0^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 101.25 W_P x (200/1000) = 20.25 W_P

The module temperatures at 20^0C ambient temperatures is $(20 + 20)^0$C = 40^0C. The power of the module at 1000 W m^{-2} is 100 W_P [1 + (40 - 25)^{0}C x (-0.25/100) %/^{0}C] = 96.25 W_P

P_m at 800 W m^{-2} and at 20^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 96.25 W_P x (800/1000) = 77 W_P

P_m at 500 W m^{-2} and at 20^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 96.25 W_P x (500/1000) = 48.125 W_P

P_m at 200 W m^{-2} and at 20^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 96.25 W_P x (200/1000) = 19.25 W_P

The module temperatures at 40^0C ambient temperatures is $(40 + 20)^0$C = 60^0C. The power of the module at 1000 W m^{-2} is 100 W_P [1 + (60 - 25)^{0}C x (-0.25/100) %/^{0}C] = 91.25 W_P

P_m at 800 W m^{-2} and at 40^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 91.25 W_P x (800/1000) = 73 W_P

P_m at 500 W m^{-2} and at 40^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 91.25 W_P x (500/1000) = 45.625 W_P

P_m at 200 W m^{-2} and at 400^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 91.25 W_P x (200/1000) = 18.25 W_P

Q19. A CIGS module operating at STC and having P_m=145W_P, V_{OC} = 61.5V, I_{SC} = 3.44A, V_m = 46.9V, I_m = 3.09A and Fill Factor = 68.5%. Calculate P_m at 800 W m^{-2}, 500 W m^{-2} and 200 W m^{-2} intensity levels. Neglect temperature effect and assume the change of V_{OC} due to intensity variation is negligible. Also assume that I_{SC} is directly proportional to intensity with proportionality constant of 1.

Answer:
Assuming V_{OC} and fill factor do not change with the change of intensity level; the power will change linearly with intensity due to changes of I_{SC}. Therefore the power at different intensity levels can be estimated as:

P_m at 800 W m^{-2} = (P_m at 1000 W m^{-2}) x (800/1000) = 145 W_P x (800/1000) = 116 W_P

P_m at 500 W m^{-2} = (P_m at 1000 W m^{-2}) x (500/1000) = 145 W_P x (500/1000) = 72.5W_P

P_m at 200 W m^{-2} = (P_m at 1000 W m^{-2}) x (200/1000) = 145 W_P x (200/1000) = 29W_P

Q20. For the Exercise 19, Compute power (P_m) at -20^{o}C, 0^{o}C, 20^{o}C and 40^{o}C ambient temperatures. Assume module temperature is 20^{o}C more than ambient and use temperature co-efficient values from Table 9.2.

Answer:

The module temperatures at -20^{0}C ambient temperatures is (-20 + 20)^{0}C = 0^{0}C. The power of the module at 1000 W m^{-2} is 145 W_P [1 + (0 - 25)^{0}C x (-0.45/100) %/^{0}C] = 161.3 W_P

P_m at 800 W m^{-2} and at -20^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 161.3 W_P x (800/1000) = 129 W_P

P_m at 500 W m^{-2} and at -20^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 161.3 W_P x (500/1000) = 80.66 W_P

P_m at 200 W m^{-2} and at -20^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 161.3 W_P x (200/1000) = 32.26 W_P

The module temperatures at 0^{0}C ambient temperatures is (0 + 20)^{0}C = 20^{0}C. The power of the module at 1000 W m^{-2} is 145 W_P [1 + (20 - 25)^{0}C x (-0.45/100) %/^{0}C] = 148.26 W_P

P_m at 800 W m^{-2} and at 0^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 148.26W_P x (800/1000) = 118.61 W_P

P_m at 500 W m^{-2} and at 0^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 148.26 W_P x (500/1000) = 74.13 W_P

P_m at 200 W m^{-2} and at 0^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 148.26 W_P x (200/1000) = 29.65 W_P

The module temperatures at 20^{0}C ambient temperatures is (20 + 20)^{0}C = 40^{0}C. The power of the module at 1000 W m^{-2} is 145 W_P [1 + (40 - 25)^{0}C x (-0.45/100) %/^{0}C] = 135.21 W_P

P_m at 800 W m^{-2} and at 20^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 135.21 W_P x (800/1000) = 108.17 W_P

P_m at 500 W m^{-2} and at 20^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 135.21 W_P x (500/1000) = 67.6 W_P

P_m at 200 W m^{-2} and at 20^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 135.21 W_P x (200/1000) = 27.04 W_P

The module temperatures at 40^{0}C ambient temperatures is (40 + 20)^{0}C = 60^{0}C. The power of the module at 1000 W m^{-2} is 145 W_P [1 + (60 - 25)^{0}C x (-0.45/100) %/^{0}C] = 122.16 W_P

P_m at 800 W m^{-2} and at 40^0 ambient temperature = (P_m at 1000 W m^{-2}) x (800/1000) = 122.16 W_P x (800/1000) = 97.73 W_P

P_m at 500 W m^{-2} and at 400^0 = (P_m at 1000 W m^{-2}) x (500/1000) = 122.16 W_P x (500/1000) = 61.08 W_P

P_m at 200 W m^{-2} and at 400^0 = (P_m at 1000 W m^{-2}) x (200/1000) = 122.16 W_P x (200/1000) = 24.43 W_P

Q21. Tabulate and plot the findings of Exercises 13-20 to highlight the power generation (normalized value) at different temperature and intensity levels for c-Si, a-Si, CdTe and CIGS technologies.

Answer:

Intensity (W m^{-2})	Temperature (^{0}C)	Normalized Power (W_P)*			
		c-Si	a-Si	CdTe	CIGS
1000	STC	100	100	100	100
	-20	110	105	106.25	111.24
	0	102	101	101.25	102.25
	20	94	97	96.25	93.25
	40	86	93	91.25	84.25
800	-20	88	84	85	88.97
	0	81.6	80.8	81	81.8
	20	75.2	77.6	77	74.6
	40	68.8	74.4	73	84.25
500	-20	54.8	52.5	53.125	55.63
	0	51	50.5	50.625	51.12
	20	47	48.5	48.125	46.62
	40	43	46.5	45.625	42.12
200	-20	22	21	21.25	22.25
	0	20.4	20.2	20.25	20.45
	20	18.8	19.4	19.25	18.65
	40	17.2	18.6	18.25	16.85

* Normalized to 100W_P at STC

Q22. A fixed 500kW_P SPV installation cost is \$ 0.65 Million. The annual maintenance cost is 5% of the installation cost and no capital subsidy is available. Assuming the location has an average of 5 peak sun hours, calculate the payback period and effective cost of unit for 25 years life for the following cases:

(a) The alternative power generation is entirely from DG set. Assume the effective cost of DG power is \$ 0.3.

(b) The alternative power generation is entirely grid supply. Assume the effective grid power cost is \$0.13.

(c) The alternative power generation is 50% DG and 50% grid.

Neglect temperature effect.

Answer:

The energy generated can be calculated as (see Example 1 and 500kW x 5 (Hrs/day) x 356 days = 912500kWh

(a)

Cost and payback period as compared to DG set

S. No.	Parameters	Without Subsidy
1	Installation Cost	$ 0.65 Million
2	Capital Subsidy	NA
3	Effective System Cost	$ 0.65 Million
4	Annual Maintenance cost	$ 0.0325 Million
5	Cost after 1st Year	$ 0.6825 Million
6	Cost after 2nd Year	$ 0.715 Million
7	Cost after 3rd Year	$ 0.75 Million
8	System life	25 Years
9	Unit (kWh) generated per year	912500 kWh
10	Cost per unit of DG set power	$0.3
11	Cost savings (earning) per year	$ 0.274 Million
12	Payback Period (year)	≈3
13	Total maintenance cost for 25 years	$0.8125 Million
14	Total cost for 25 years	$1.46 Million
15	Total Units (kWh) generated in 25 years	22.8 Million
16	Effective cost per unit for 25 years life	≈$0.064

(b)

Cost and payback period as compared to Grid

S. No.	Parameters	Without Subsidy
1	Installation Cost	$ 0.65 Million
2	Capital Subsidy	NA
3	Effective System Cost	$ 0.65 Million
4	Annual Maintenance cost	$ 0.0325 Million
5	Cost after 1st Year	$ 0.6825 Million
6	Cost after 2nd Year	$ 0.715 Million
7	Cost after 3rd Year	$ 0.75 Million
8	Cost after 4th Year	$ 0.78 Million
9	Cost after 5th Year	$ 0.8125 Million
10	Cost after 6th Year	$ 0.845 Million
11	Cost after 7th Year	$ 0.8775 Million
12	Cost after 8th Year	$ 0.91 Million
13	Cost after 9th Year	$ 0.9425 Million
14	System life	25 Years
15	Unit (kWh) generated per year	912500 kWh
16	Cost per unit of Grid power	$0.13
17	Cost savings (earning) per year	$ 0.119 Million
18	Payback Period (year)	≈7.5
19	Total maintenance cost for 25 years	$0.8125 Million
20	Total cost for 25 years	$1.46 Million
21	Total Units (kWh) generated in 25 years	22.8 Million
22	Effective cost per unit for 25 years life	≈$0.064

(c)

Cost and payback period as compared to 50% DG and 50% Grid

S. No.	Parameters	Without Subsidy
1	Installation Cost	$ 0.65 Million
2	Capital Subsidy	NA
3	Effective System Cost	$ 0.65 Million
4	Annual Maintenance cost	$ 0.0325 Million
5	Cost after 1st Year	$ 0.6825 Million
6	Cost after 2nd Year	$ 0.715 Million
7	Cost after 3rd Year	$ 0.75 Million
	Cost after 4th Year	$ 0.78 Million
	Cost after 5th Year	$ 0.8125 Million
	Cost after 6th Year	$ 0.845 Million
	Cost after 7th Year	$ 0.8775 Million
	Cost after 8th Year	$ 0.91 Million
	Cost after 9th Year	$ 0.9425 Million
8	System life	25 Years
9	Unit (kWh) generated per year	912500 kWh
10	Cost per unit of Grid power	$0.13
10	Cost per unit of DG power	$0.3
	Cost savings (earning) per year due to Grid (456250kWh)	$ 0.059 Million
11	Cost savings (earning) per year due to DG (456250kWh)	$ 0.137 Million
	Total Cost savings (earning) per year (912500kWh)	$ 0.196 Million
12	Payback Period (year)	≈4
13	Total maintenance cost for 25 years	$0.8125 Million
14	Total cost for 25 years	$1.46 Million
15	Total Units (kWh) generated in 25 years	22.8 Million
16	Effective cost per unit for 25 years life	≈$0.064

Q23. Repeat the Exercise 22 for tracking system. Assume the installation cost is $ 0.75 Million and the average peak sun hours is 6. Rest of the parameters and assumptions are same as given in Exercise 22.

Answer:

The energy generated can be calculated as (see Example 1 and 500kW x 6 (Hrs/day) x 356 days = 1095000kWh

(a)

Cost and payback period as compared to DG set

S. No.	Parameters	Without Subsidy
1	Installation Cost	$ 0.75 Million
2	Capital Subsidy	NA
3	Effective System Cost	$ 0.75 Million
4	Annual Maintenance cost	$ 0.0375 Million
5	Cost after 1st Year	$ 0.7875 Million
6	Cost after 2nd Year	$ 0.825 Million
7	Cost after 3rd Year	$ 0.8625 Million
8	System life	25 Years
9	Unit (kWh) generated per year	1095000 kWh
10	Cost per unit of DG set power	$0.3
11	Cost savings (earning) per year	$ 0.3285 Million
12	Payback Period (year)	≈2.5
13	Total maintenance cost for 25 years	$0.9375 Million
14	Total cost for 25 years	$1.6875 Million
15	Total Units (kWh) generated in 25 years	27.375 Million
16	Effective cost per unit for 25 years life	≈$0.0616

(b)

Cost and payback period as compared to Grid

S. No.	Parameters	Without Subsidy
1	Installation Cost	$ 0.75 Million
2	Capital Subsidy	NA
3	Effective System Cost	$ 0.75 Million
4	Annual Maintenance cost	$ 0.0375 Million
5	Cost after 1st Year	$ 0.7875 Million
6	Cost after 2nd Year	$ 0.825 Million
7	Cost after 3rd Year	$ 0.8625 Million
8	Cost after 4th Year	$ 0.9 Million
9	Cost after 5th Year	$ 0.9375 Million
10	Cost after 6th Year	$ 0.975 Million
11	Cost after 7th Year	$ 1.0125 Million
12	Cost after 8th Year	$ 1.05 Million
13	Cost after 9th Year	$ 1.0875 Million
14	System life	25 Years
15	Unit (kWh) generated per year	1095000 kWh
16	Cost per unit of Grid power	$0.13
17	Cost savings (earning) per year	$ 0.14235Million
18	Payback Period (year)	≈7
19	Total maintenance cost for 25 years	$0.9375 Million
20	Total cost for 25 years	$1.6875 Million
21	Total Units (kWh) generated in 25 years	27.375Million
22	Effective cost per unit for 25 years life	≈$0.0616

(c)

Cost and payback period as compared to 50% DG and 50% Grid

S. No.	Parameters	Without Subsidy
1	Installation Cost	\$ 0.75 Million
2	Capital Subsidy	NA
3	Effective System Cost	\$ 0.75 Million
4	Annual Maintenance cost	\$ 0.0375 Million
5	Cost after 1st Year	\$ 0.7875 Million
6	Cost after 2nd Year	\$ 0.825 Million
7	Cost after 3rd Year	\$ 0.8625 Million
	Cost after 4th Year	\$ 0.9 Million
	Cost after 5th Year	\$ 0.9375 Million
	Cost after 6th Year	\$ 0.975 Million
	Cost after 7th Year	\$ 1.0125 Million
	Cost after 8th Year	\$ 1.05 Million
	Cost after 9th Year	\$ 1.0875 Million
8	System life	25 Years
9	Unit (kWh) generated per year	1095000 kWh
10	Cost per unit of Grid power	\$0.13
10	Cost per unit of DG power	\$0.3
	Cost savings (earning) per year due to Grid (547500kWh)	\$ 0.071 Million
11	Cost savings (earning) per year due to DG (547500kWh)	\$ 0.164 Million
	Total Cost savings (earning) per year (912500kWh)	\$ 0.23525 Million
12	Payback Period (year)	≈3.75
13	Total maintenance cost for 25 years	\$0.9375 Million
14	Total cost for 25 years	\$1.6875 Million
15	Total Units (kWh) generated in 25 years	27.375Million
16	Effective cost per unit for 25 years life	≈\$0.0616

Q24. Repeat Exercises 22 and 23 assuming 30% subsidy on capital cost.

Answer:
The energy generated for a fixed system (Exercise 22) is 912500kWh

(a)

Cost and payback period as compared to DG set

S. No.	Parameters	With Subsidy
1	Installation Cost	\$ 0.65 Million
2	Capital Subsidy	\$ 0.195 Million
3	Effective System Cost	\$ 0.455 Million
4	Annual Maintenance cost	\$ 0.0325 Million
5	Cost after 1st Year	\$ 0.4875 Million
6	Cost after 2nd Year	\$ 0.52 Million
7	Cost after 3rd Year	\$ 0.5525 Million
8	System life	25 Years
9	Unit (kWh) generated per year	912500 kWh
10	Cost per unit of DG set power	\$0.3
11	Cost savings (earning) per year	\$ 0.274 Million
12	Payback Period (year)	≈2
13	Total maintenance cost for 25 years	\$0.8125 Million
14	Total cost for 25 years	\$1.2675 Million
15	Total Units (kWh) generated in 25 years	22.8 Million
16	Effective cost per unit for 25 years life	≈\$0.056

(b)

Cost and payback period as compared to Grid

S. No.	Parameters	With Subsidy
1	Installation Cost	\$ 0.65 Million
2	Capital Subsidy	\$ 0.195 Million
3	Effective System Cost	\$ 0.455 Million
4	Annual Maintenance cost	\$ 0.0325 Million
5	Cost after 1st Year	\$ 0.4875 Million
6	Cost after 2nd Year	\$ 0.52 Million
7	Cost after 3rd Year	\$ 0.5525 Million
8	Cost after 4th Year	\$ 0.585 Million
9	Cost after 5th Year	\$ 0.6175 Million
10	Cost after 6th Year	\$ 0.65 Million
11	Cost after 7th Year	\$ 0.6825 Million
12	Cost after 8th Year	\$ 0.715 Million
13	Cost after 9th Year	\$ 0.6475 Million
14	System life	25 Years
15	Unit (kWh) generated per year	912500 kWh
16	Cost per unit of Grid power	\$0.13
17	Cost savings (earning) per year	\$ 0.119 Million
18	Payback Period (year)	≈5.5
19	Total maintenance cost for 25 years	\$0.8125 Million
20	Total cost for 25 years	\$1.2575 Million
21	Total Units (kWh) generated in 25 years	22.8 Million
22	Effective cost per unit for 25 years life	≈\$0.055

(c)

Cost and payback period as compared to 50% DG and 50% Grid

S. No.	Parameters	With Subsidy
1	Installation Cost	$ 0.65 Million
2	Capital Subsidy	$ 0.195 Million
3	Effective System Cost	$ 0.455 Million
4	Annual Maintenance cost	$ 0.0325 Million
5	Cost after 1st Year	$ 0.4875 Million
6	Cost after 2nd Year	$ 0.52 Million
7	Cost after 3rd Year	$ 0.5525 Million
	Cost after 4th Year	$ 0.585 Million
	Cost after 5th Year	$ 0.6175 Million
	Cost after 6th Year	$ 0.65 Million
	Cost after 7th Year	$ 0.6825 Million
	Cost after 8th Year	$ 0.715 Million
	Cost after 9th Year	$ 0.6475 Million
8	System life	25 Years
9	Unit (kWh) generated per year	912500 kWh
10	Cost per unit of Grid power	$0.13
10	Cost per unit of DG power	$0.3
	Cost savings (earning) per year due to Grid (456250kWh)	$ 0.059 Million
11	Cost savings (earning) per year due to DG (456250kWh)	$ 0.137 Million
	Total Cost savings (earning) per year (912500kWh)	$ 0.196 Million
12	Payback Period (year)	≈2.5
13	Total maintenance cost for 25 years	$0.8125 Million
14	Total cost for 25 years	$1.2575 Million
15	Total Units (kWh) generated in 25 years	22.8 Million
16	Effective cost per unit for 25 years life	≈$0.055

The energy generated for tracking system (Exercise 23) is 1095000kWh

(a)

Cost and payback period as compared to DG set

S. No.	Parameters	With Subsidy
1	Installation Cost	$ 0.75 Million
2	Capital Subsidy	$0.225 Million
3	Effective System Cost	$ 0.525 Million
4	Annual Maintenance cost	$ 0.0375 Million
5	Cost after 1st Year	$ 0.5635 Million
6	Cost after 2nd Year	$ 0.6 Million
7	Cost after 3rd Year	$ 0.6375 Million
8	System life	25 Years
9	Unit (kWh) generated per year	1095000 kWh
10	Cost per unit of DG set power	$0.3
11	Cost savings (earning) per year	$ 0.3285 Million
12	Payback Period (year)	≈1.75
13	Total maintenance cost for 25 years	$0.9375 Million
14	Total cost for 25 years	$1.4625 Million
15	Total Units (kWh) generated in 25 years	27.375 Million
16	Effective cost per unit for 25 years life	≈$0.053

(b)

Cost and payback period as compared to Grid

S. No.	Parameters	With Subsidy
1	Installation Cost	\$ 0.75 Million
2	Capital Subsidy	\$0.225 Million
3	Effective System Cost	\$ 0.525 Million
4	Annual Maintenance cost	\$ 0.0375 Million
5	Cost after 1st Year	\$ 0.5635 Million
6	Cost after 2nd Year	\$ 0.6 Million
7	Cost after 3rd Year	\$ 0.6375 Million
8	Cost after 4th Year	\$ 0.675 Million
9	Cost after 5th Year	\$ 0.7125 Million
10	Cost after 6th Year	\$ 0.75 Million
11	Cost after 7th Year	\$ 0.7875 Million
12	Cost after 8th Year	\$ 0.825 Million
13	Cost after 9th Year	\$ 0.8625 Million
14	System life	25 Years
15	Unit (kWh) generated per year	1095000 kWh
16	Cost per unit of Grid power	\$0.13
17	Cost savings (earning) per year	\$ 0.14235Million
18	Payback Period (year)	≈5
19	Total maintenance cost for 25 years	\$0.9375 Million
20	Total cost for 25 years	\$1.4625 Million
21	Total Units (kWh) generated in 25 years	27.375 Million
22	Effective cost per unit for 25 years life	≈\$0.053

(c)

Cost and payback period as compared to 50% DG and 50% Grid

S. No.	Parameters	With Subsidy
1	Installation Cost	$ 0.75 Million
2	Capital Subsidy	$0.225 Million
3	Effective System Cost	$ 0.525 Million
4	Annual Maintenance cost	$ 0.0375 Million
5	Cost after 1st Year	$ 0.5635 Million
6	Cost after 2nd Year	$ 0.6 Million
7	Cost after 3rd Year	$ 0.6375 Million
	Cost after 4th Year	$ 0.675 Million
	Cost after 5th Year	$ 0.7125 Million
	Cost after 6th Year	$ 0.75 Million
	Cost after 7th Year	$ 0.7875 Million
	Cost after 8th Year	$ 0.825 Million
	Cost after 9th Year	$ 0.8625 Million
8	System life	25 Years
9	Unit (kWh) generated per year	1095000 kWh
10	Cost per unit of Grid power	$0.13
10	Cost per unit of DG power	$0.3
	Cost savings (earning) per year due to Grid (547500kWh)	$ 0.071 Million
11	Cost savings (earning) per year due to DG (547500kWh)	$ 0.164 Million
	Total Cost savings (earning) per year (912500kWh)	$ 0.23525 Million
12	Payback Period (year)	≈2.75
13	Total maintenance cost for 25 years	$0.9375 Million
14	Total cost for 25 years	$1.4625 Million
15	Total Units (kWh) generated in 25 years	27.375 Million
16	Effective cost per unit for 25 years life	≈$0.053

Chapter-10
Design and Implementation of Off-Grid and On-Grid SPV Systems

Solution to Exercises:

Q1. A small SPV system with storage has two modules connected in series. This is connected to a 48V battery through a charge controller and DC-DC converter along with a MPPT controller. The STC rated values of the individual modules are V_{OC} = 36V, V_m = 30V, I_{SC} = 9A and I_m = 8A. Assume the modules have identical I-V characteristics. The temperature co-efficient of voltage and current are -0.36% and +0.04 respectively. Assume converter efficiency is 95%. Determine the duty cycle of the MPPT and the charging current of the battery for the following operating conditions:

(a) Modules are operating at STC.

(b) The irradiance is 1000Wm^{-2} and the ambient temperature is 40^{0}C, 20^{0}C or 0^{0}C. Assume the module temperature is 20^{0}C more than the ambient.

(c) The module is at 25^{0}C and the irradiance receiving by the modules are 1100Wm^{-2}, 800Wm^{-2} or 600Wm^{-2}. Assume a linear relation between I_{SC} and irradiance, change of V_{OC} with irradiance is negligible and temperature co-efficient of Fill Factor is zero.

(d) The module temperature is 50^{0}C and the irradiance is 500Wm^{-2}. Consider assumptions listed in (c) above are valid.

Answer:
The Maximum Power Point (MPP) voltage and current of the SPV system are $(V_m)_{String}$ = 30V x 2 = 60V and (I_m) = 8A.

(a) Eq 10.7 can be used to determine the duty cycle (D) taking $V_{in} = (V_m)_{Total}$ = 60V and V_{out} = Input voltage of the battery (V_{Bat}) = 48V.

$$48V/60V = D/(1-D)$$

$$D \approx 0.44$$

The total power pumped from the solar modules is equal to the power received by the capacitor/load. Therefore if I_{Bat} is the charging current of the inverter, the following relation is valid:

$$V_m \times I_m = V_{Bat} \times I_{Bat}$$

$$I_{Bat} = (V_m \times I_m)/V_{Bat} = (60V \times 8A)/48V \approx 10A$$

The efficiency of the converter is 95%. The input power of the battery is therefore reduced by 5% as compared to what is being delivered by the modules. The input voltage of the battery is decided by the duty cycle and maintained at 48V. The battery current is therefore reduced by 5%, i.e 0.95 x 10A = 9.5A.

(b) Cell temperature is (ambient temperature + 20^{0}C).

(i) At ambient temperature of 40^{0}C the cell temperature is = (40^{0}C + 20^{0}C) = 60^{0}C. This is 35^{0}C higher than the STC temperature of 25^{0}C. Given the voltage temperature co-efficient is -0.36% per ^{0}C, the total MPP voltage (V_m) at 60^{0}C cell temperature = 60V [1-(0.36/100) per ^{0}C x 35^{0}C] ≈ 52.44V

Using Eq 10.7, the duty cycle in this case can be calculated as

$$48V/52.44V = D/(1-D)$$

$$D \approx 0.48$$

The charging current can be calculated as in (a):

$$V_m \text{ x } I_m = V_{Bat} \text{ x } I_{Bat}$$

$$I_{Bat} = (V_m \text{ x } I_m)/V_{Bat} = (52.44V \text{ x } 8A)/48V \approx 8.74A$$

This reduces to 0.95 x 8.74A ≈ 8.3A considering the converter efficiency.

(ii) At ambient temperature of 20^0C the cell temperature is = $(20^0C + 20^0C) = 40^0C$. This is 15^0C higher than the STC temperature of 25^0C. Given the voltage temperature co-efficient is -0.36% per ^0C, the total MPP voltage (V_m) at 60^0C cell temperature = 60V [1-(0.36/100) per ^0C x 15^0C] ≈ 56.76V

Using Eq 10.7, the duty cycle in this case can be calculated as

$$48V/56.76V = D/(1-D)$$

$$D \approx 45.8$$

The charging current can be calculated as in (a):

$$V_m \text{ x } I_m = V_{Bat} \text{ x } I_{Bat}$$

$$I_{Bat} = (V_m \text{ x } I_m)/V_{Bat} = (56.76V \text{ x } 8A)/48V \approx 9.46A$$

This reduces to 0.95 x 9.46A ≈ 9A considering the converter efficiency.

(iii) At ambient temperature of 0^0C the cell temperature is = $(0^0C + 20^0C) = 20^0C$. This is 5^0C lower than the STC temperature of 25^0C. Given the voltage temperature co-efficient is -0.36% per ^0C, the total MPP voltage (V_m) at 60^0C cell temperature = 60V [1-(0.36/100) per ^0C x (-5^0C)] ≈ 61.08V

Using Eq 10.7, the duty cycle in this case can be calculated as

$$48V/61.08V = D/(1-D)$$

$$D \approx 44$$

The charging current can be calculated as in (a):

$$V_m \text{ x } I_m = V_{Bat} \text{ x } I_{Bat}$$

$$I_{Bat} = (V_m \text{ x } I_m)/V_{Bat} = (61.08V \text{ x } 8A)/48V \approx 10.18A$$

This reduces to 0.95 x 9.46A ≈ 9.7A considering the converter efficiency.

(c) Cell temperature is at STC but Irradiance is different than STC. Changes in V_m is assumed to be negligible with change in irradiance level. The duty cycle therefore is assumed to be not affected by the change of irradiance. Only the charging current will be different at different irradiance levels.

(i) At 1100 Wm^{-2}, the current at MPP is (1100/1000) x 8A = 8.8A. The charging current of the battery is therefore:

$$V_m \times I_m = V_{Bat} \times I_{Bat}$$

$$I_{Bat} = (V_m \times I_m)/V_{Bat} = (60V \times 8.8A)/48V \approx 11A$$

This reduces to 0.95 x 11A ≈ 10.45A considering the converter efficiency.

(ii) At 800 Wm^{-2}, the current at MPP is (800/1000) x 8A = 6.4A. The charging current of the battery is therefore:

$$V_m \times I_m = V_{Bat} \times I_{Bat}$$

$$I_{Bat} = (V_m \times I_m)/V_{Bat} = (60V \times 6.4A)/48V \approx 8A$$

This reduces to 0.95 x 8A ≈ 7.6A considering the converter efficiency.

(iii) At 600 Wm^{-2}, the current at MPP is (600/1000) x 8A = 4.8A. The charging current of the battery is therefore:

$$V_m \times I_m = V_{Bat} \times I_{Bat}$$

$$I_{Bat} = (V_m \times I_m)/V_{Bat} = (60V \times 4.8A)/48V \approx 6A$$

This reduces to 0.95 x 6A ≈ 5.7A considering the converter efficiency.

(d) At ambient temperature of 50^0C the cell temperature is = (50^0C + 20^0C) = 70^0C. This is 45^0C higher than the STC temperature of 25^0C. Given the voltage temperature co-efficient is -0.36% per ^{0}C, the total MPP voltage (V_m) at 60^0C cell temperature = 60V [1-(0.36/100) per ^{0}C x 45^0C] ≈ 50.28V

Using Eq 10.7, the duty cycle in this case can be calculated as

$$48V/50.28V = D/(1-D)$$

$$D \approx 0.49$$

At 500 Wm^{-2}, the current at MPP is (500/1000) x 8A = 4A. The charging current can be calculated as in (a):

$$V_m \times I_m = V_{Bat} \times I_{Bat}$$

$$I_{Bat} = (V_m \times I_m)/V_{Bat} = (50.28V \times 4A)/48V \approx 4.19A$$

This reduces to 0.95 x 4.19A ≈ 4A considering the converter efficiency.

Q2. A SPV system consisting of 100 modules having 250W_P each has been installed in a location having peak sun hours of 4Hrs. The array is configured as 10 strings of 10 modules each. A single MPPT is used. There is a shading problem, occurring about 50% of the time, and the P-V characteristics during that

period is similar to that shown in Fig 10.6. MPP1 and MPP2 for each module on an average then occurring at 20kW and 15kW respectively at peak sun (1000Wm^{-2}) and at actual ambient condition. During the period when there is no shading a single MPP with power of 23kW at peak sun and at actual ambient condition is produced. Determine the energy generated per year (a) if the MPPT is latched permanently at MPP2 during shading period (b) MPPT is correctly latched on to MMP1 during the shading period and (c) if the shading problem is altogether eliminated.

Answer:

(a) The modules produces 15kW$_P$ if it latches on to MPP1, which happens during 50% of the time. Rest of the period of the year it produces 23kW$_P$. The average peak sun hour is 4 Hrs per day. The energy generated per year is therefore (0.5 x 15 + 0.5 x 23) (kW) x 4 (Hrs/day) x 365 (days) = 27740kWh.

(b) The modules produces 20kW$_P$ if it latches on to MPP2, which happens during 50% of the time. Rest of the period of the year it produces 23kW$_P$. The average peak sun hour is 4 Hrs per day. The energy generated per year is therefore (0.5 x 20 + 0.5 x 23) (kW) x 4 (Hrs/day) x 365 (days) = 31390kWh.

(c) The modules produces 23kW$_P$ in no shading condition. The average peak sun hour is 4 Hrs per day. The energy generated per year is therefore 23 (kW) x 4 (Hrs/day) x 365 (days) = 33580kWh.

Q3. The shading problem described in Exercise 2 is found to occur due to partial shading of only 5 modules in a particular string. Determine the power output in case (a) 2 inverters; 1 MPPT per 5 Strings, (b) 5 inverters; 1MPPT per string is used and (c) Micro inverters; 1MPPT per module, are used.

Answer:

(a) There are two inverters. Each inverter is controlling 5 strings. The inverter (inverter 1) which does not have any shaded modules connected to it produces (0.5 x 23kW$_P$) = 11.5kW$_P$. The other inverter (inverter 1) having the shaded module connected to it produces (0.5 x 15kW$_P$) = 7.5kW$_P$ if it is latched on to MPP1 and (0.5 x 20kW$_P$) = 10kW$_P$ if it is latched on to MPP2.
(i) In case MPP1 is applicable; the inverter1 generates 11.5(kW) x 4 (Hrs/day) x 365 (days) = 16790kWh. The inverter 2 produces (0.5 x 7.5 + 0.5 x 11.5) (kW) x 4 (Hrs/day) x 365 (days) = 13870kWh. The total energy produced = 16790 + 13870 = 30660kWh.
(ii) In case MPP2 is applicable; the inverter1 generates 11.5(kW) x 4 (Hrs/day) x 365 (days) = 16790kWh. The inverter 2 produces (0.5 x 10 + 0.5 x 11.5) (kW) x 4 (Hrs/day) x 365 (days) = 15695kWh. The total energy produced = 16790 + 13870 = 32485kWh.
(iii) In case of no shading energy generated per year is 23 (kW) x 4 (Hrs/day) x 365 (days) = 33580kWh.

(b) There are five inverters. Each inverter is controlling 2 strings. The four inverters (inverter 1-4) which does not have any shaded modules connected to it produces (0.8 x 23kW$_P$) = 18.4kW$_P$. The other inverter (inverter 5) having the shaded module connected to it produces (0.2 x 15kW$_P$) = 3kW$_P$ if it is latched on to MPP1 and (0.2 x 20kW$_P$) = 4kW$_P$ if it is latched on to MPP2. During no shading condition inverter 5 produces 0.2 x 23kW$_P$ = 4.6kW$_P$
(i) In case MPP1 is applicable; the inverter1-4 generates 18.4(kW) x 4 (Hrs/day) x 365 (days) = 26864kWh. The inverter 5 produces (0.5 x 3 + 0.5 x4.6) (kW) x 4 (Hrs/day) x 365 (days) = 5548kWh. The total energy produced = 26864 + 5548 = 32412kWh.
(ii) In case MPP2 is applicable; the inverter1-4 generates 26864kWh. The inverter 5 produces (0.5 x 4 + 0.5 x4.6) (kW) x 4 (Hrs/day) x 365 (days) = 6278kWh. The total energy produced = 26864 + 6278 = 33142kWh.
(iii) In case of no shading energy generated per year is 23 (kW) x 4 (Hrs/day) x 365 (days) = 33580kWh

(c) In case of micro-inverter, only 5 modules will be affected. There will now be only one MPP, which is higher i.e. at 0.2kW$_P$ for each micro-inverter connected to only one module each. The 5 modules will produce (5 x 0.2) = 1kW$_P$ during shading condition. If there is no shading these 5 modules produces

$(5/100) \times 23kW_P = 1.15kW_P$. Rest of the 95 modules will produce full power i.e $(95/100) \times 23kW_P = 21.85kW_P$. The total energy produced per year will then be [(0.5 x 1 + 0.5 x 1.15) + 21.85] (kW) x 4 (Hrs) x 365 (days) = 33470.5kWh.

Q4. Calculate CEC efficiency of the inverter described in Example 2. Compare Peak, Euro and CEC efficiencies of this inverter.

Answer:
The rated capacity of the inverter is 5kW = 5000W.The corresponding efficiency, i.e. when the inverter is operating at 100% rated capacity, $\eta_{100\%} = 98.5\%$ (Table 10.1).

The euro efficiency is calculated in Example 2 as about 90%.

The CEC efficiency definition is as follows (see Eq 10.11):

$$\eta_{CEC} = 0.04\ \eta_{10\%} + 0.05\ \eta_{20\%} + 0.12\ \eta_{30\%} + 0.21\ \eta_{50\%} + 0.53\ \eta_{75\%} + 0.05\ \eta_{100\%}$$

Using Table 10.1, the CEC efficiency can be calculated:

$$\eta_{CEC} = 0.04 \times 82\% + 0.05 \times 84\% + 0.12 \times 86\% + 0.21 \times 90\% + 0.53 \times 95\% + 0.05 \times 98.5\% \approx 92\%.$$

The efficiencies are reproduced in the below Table:

S.No.	Classification	Efficiency (%)
1	Peak	98.5
2	Euro	90%
3	CEC	92

Q5. Use the efficiency chart of a 5kW inverter as given in Table 10.1 of Example 2. Assume the utilization behaviours of this inverter for a particular installation is as per the below Table:

Utilization %	Utilization in W
10	250
20	500
30	1000
20	1500
10	2500
10	5000

Determine the actual efficiency applicable to this installation and compare this with Peak, Euro and CEC efficiencies.

Answer:
The corresponding efficiency relation can be written as

$$\eta_{Actual} = 0.1\ \eta_{5\%} + 0.2\ \eta_{10\%} + 0.3\ \eta_{20\%} + 0.2\ \eta_{30\%} + 0.1\ \eta_{50\%} + 0.1\ \eta_{100\%}$$

Using Table 10.1:

$$\eta_{Actual} = 0.1 \times 81\% + 0.2 \times 82 + 0.3 \times 84\% + 0.2 \times 86\% + 0.1 \times 90\% + 0.1 \times 98.5\% = 85.75\%$$

Q6. The system described in Exercise 1(a) also has a battery. The SPV system charges the battery during day time and this stored energy is used in the night to support some household loads. Find out the average energy stored in the battery per day assuming average peak sun hour of 5Hrs. How many hours per night the battery can support a fixed DC load of 500W or a fixed AC load of 500W with a allowed MDOD of 50%, 80% or 100%? Assume the charging and discharging efficiencies of the battery are 85% and 90% respectively. Also assume that the charge controller and solar inverter efficiencies are 96% and 98% respectively.

Answer:
There are two modules. At STC each producing power (W_P) = (V_m x I_m) = (30 x 8) W_P = 240W_P. The total power produced by these two modules at STC = 480W_P. The energy generation per day is:

$$480 \text{ W} \times 5 \text{ Hrs} = 2400 \text{ Wh}$$

Considering the charge controller efficiency (0.96) and battery charging efficiency (0.85), the energy stored per day is:

$$2400 \text{ (Wh)} \times 0.96 \times 0.85 \approx 1958 \text{ Wh.}$$

(a) For DC load, this power can be supplied directly. Battery discharging efficiency (0.9) is to be considered. Also MDOD criteria has to be considered. The energy available to the load for 100% MDOD is:

$$1958 \text{ (Wh)} \times 0.9 \approx 1762 \text{ Wh}$$

(i) For 50% MDOD, the energy available to the load per night is 1762 (Wh) x 0.5 = 881Wh. This can support a load of 500W for about 1 Hr 46 Mins.

(ii) For 80% MDOD, the energy available to the load per night is 1762 (Wh) x 0.8 ≈ 1410 Wh. This can support a load of 500W for about 2 Hr 49 Mins.

(iii) For 100% MDOD, the energy available to the load per night is 1762 Wh. This can support a load of 500W for about 3 Hr 31 Mins.

(b) For AC load, this power can be supplied through inverter. Inverter efficiency (0.98) and battery discharging efficiency (0.9) are to be considered. Also MDOD criteria has to be considered. The energy available to the load for 100% MDOD is:

$$1958 \text{ (Wh)} \times 0.98 \times 0.9 \approx 1727 \text{ Wh}$$

(i) For 50% MDOD, the energy available to the load per night is 1727 (Wh) x 0.5 = 863.5 Wh. This can support a load of 500W for about 1 Hr 44 Mins.

(ii) For 80% MDOD, the energy available to the load per night is 1727 (Wh) x 0.8 = 1381.6 Wh. This can support a load of 500W for about 2 Hr 46 Mins.

(iii) For 100% MDOD, the energy available to the load per night is 1727 Wh. This can support a load of 500W for about 3 Hr 27 Mins.

Q7. Determine allowed number of cycles of the battery with 50% and 80% MDOD for the configuration and assumptions described in Exercise 6. Use the characteristic shown in Fig 10.13.

Answer:
The 100% MDOD can never be used. As per Fig 10.13, the battery will have a cycle life of about 400 Cycles for 80% MDOD and about 500 Cycles for 50% MDOD.

Q8. Two 200Ah, 0.5C batteries are connected in parallel. A household loads require an average current of 15A per hour. Calculate how many hours the battery will continue to provide the required current to the load if allowed MDOD is 50% or 80% assuming a nominal battery temperature. Using Fig 10.15, determine the revised values for the above in case battery temperatures are -40^{0}C,-10^{0}C, +10^{0}C, +40^{0}C.

Answer:
As two 200Ah batteries are connected in parallel, the total capacity is 400Ah. The rated capacity of the battery at nominal temperature (25^{0}C) is

0.5C = C/20 = 400Ah/20h = 20A per hour.

(a) In this case the battery is delivering 15A per hour and the battery is fully discharged in (400/15) = 26.7Hrs. This is equivalent to C/26.7. Fig 10.15 does not have comparative C/26.7 parameters. It can be calculated indirectly. The capacity of C/20 battery increases to about (115/100) = 1.15 times if it is operating as C/48. Extrapolating this to C/26.7 assuming a linear relation the capacity is about 1.03times i.e. (400 x 1.03) = 412Ah.

(i) for 50% MDOD, 0.5 x 412Ah = 206Ah is available for the load. If the load is taking 15A per hour, the battery can supply current for (206/15) = 13 Hrs 44 Mins.

(ii) for 80% MDOD, 0.8 x 412Ah = 329.6Ah is available for the load. If the load is taking 15A per hour, the battery can supply current for (329.6/15) = 21 Hrs 58 Mins.

(b) Looking at Fig 10.16, the capacity utilization at -40^{0}C is about 35% of the rated value at nominal temperature. The capacity at -40^{0}C is then about (0.35 x 412) = 144.2Ah. Similarly the capacity at -10^{0}C is (0.75 x 412) = 309Ah, at +10^{0}C is (0.9 x 412) = 370.8Ah and at +40^{0}C is (1.05 x 412) = 432.6Ah.

For 50% MDOD:
(i) At -40^{0}C; 0.5 x 144.2Ah = 72.1Ah is available for the load. If the load is taking 15A per hour, the battery can supply current for (72.1/15) = 4 Hrs 48 Mins.

(ii) At -10^{0}C; 0.5 x 309Ah = 154.5Ah is available for the load. If the load is taking 15A per hour, the battery can supply current for (154.5/15) = 10 Hrs 18 Mins.

(iii) At +10^{0}C; 0.5 x 370.8Ah = 185.4Ah is available for the load. If the load is taking 15A per hour, the battery can supply current for (185.4/15) = 12 Hrs 22 Mins.

(iv) At +40^{0}C; 0.5 x 432.6Ah = 216.3Ah is available for the load. If the load is taking 15A per hour, the battery can supply current for (216.3/15) = 14 Hrs 25 Mins.

For 80% MDOD:
(i) At -40^{0}C; 0.8 x 144.2Ah = 115.36Ah is available for the load. If the load is taking 15A per hour, the battery can supply current for (115.36/15) = 7 Hrs 41 Mins.

(ii) At -10^{0}C; 0.8 x 309Ah = 247.2Ah is available for the load. If the load is taking 15A per hour, the battery can supply current for (247.2/15) = 16 Hrs 29 Mins.

(iii) At +10^{0}C; 0.8 x 370.8Ah = 296.64Ah is available for the load. If the load is taking 15A per hour, the battery can supply current for (296.64/15) = 19 Hrs 47 Mins.

(iv) At +40^{0}C; 0.8 x 432.6Ah = 346.08Ah is available for the load. If the load is taking 15A per hour, the battery can supply current for (346.08/15) = 23 Hrs 4 Mins.

Q9. Determine the battery specification and SPV installation capacity required to support a 500W DC load for 6 Hrs per night with no autonomy and 3 Days autonomy. Assume the DC loads required 12V and the energy efficiency of the battery is 80%. The charge controller efficiency is 95% and the MDOD allowed are 80%.

Answer:
The total energy required per night is 500W x 6 Hrs = 3000Wh. In case 3 days autonomy is required, the total energy required will be (3000Wh x 3) = 9000Wh. Considering the battery efficiency (80%), the charge controller efficiency (95%) and MDOD (80%) the energy to be stored in battery is:

$$3000Wh/(0.8 \times 0.95 \times 0.8) \approx 4934Wh \text{ for zero autonomy}$$

$$9000Wh/(0.8 \times 0.95 \times 0.8) \approx 14802Wh \text{ for 3 days autonomy}$$

For a 12V battery; capacity (Ah) required is (4934Wh/12V) ≈411Ah for zero autonomy and 1233Ah for 3 days autonomy will be required.

The SPV installation must be able to generated the required power to be stored in the battery. Assuming a peak sun hour of 5 hrs per day, the installed capacity can be calculated as:

$$4934Wh/5h \approx 987W_P \approx 1kW_P \text{ for zero autonomy}$$

$$14802Wh/5h \approx 2960W_P \approx 3kW_P \text{ for 3 days autonomy}$$

Q10. Determine the cost of the total SPV system (excluding load) of all the options mentioned in Exercise 6. Assume the combined cost of SPV module and BOS (excluding battery) is $\$1.0/W_P$ and the battery cost is $0.12/Wh.

Answer:
The total W_P of the SPV system is 2 x (V_m x I_m) = 480W_P. A load has to be assumed and to be normalized for different MDOD to estimate the battery requirement and cost. In case it is normalized with 100% MDOD then the following battery capacity can be estimated:

For DC Load:

Required capacity with 100% MDOD is about 1762Wh
Required capacity with 80% MDOD is about 2202Wh
Required capacity with 50% MDOD is about 3524Wh

For AC Load:

Required capacity with 100% MDOD is about 1727Wh
Required capacity with 80% MDOD is about 2159Wh
Required capacity with 50% MDOD is about 3454Wh

S.No	W_P of SPV System	SPV System Cost ($)	Storage Requirement	Storage Capacity (Wh)	Storage Cost ($)	Total Cost ($)
1	480	480	DC: MDOD 100%	1762	211.44	691.44
2			DC: MDOD 80%	2202	264.24	744.24
3			DC: MDOD 50%	3524	422.88	691.44
			AC: MDOD 100%	1727	207.24	615.24
			AC: MDOD 80%	2159	259.08	739.08
			AC: MDOD 50%	3454	414.48	894.48

Q11. The energy efficiency of a Pb-Acid battery is about 80%. The battery charging and discharging voltages are 14V and 12V respectively. Determine the “Voltage Efficiency” and “Coulomb Efficiency” of this battery.

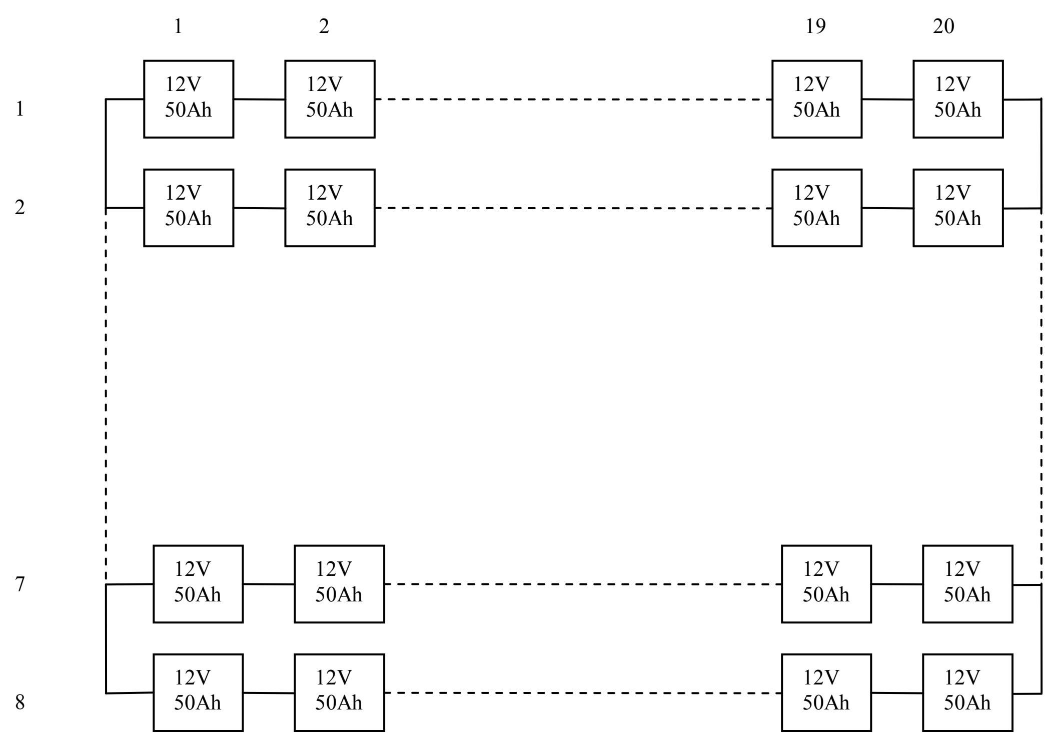
Answer:
The energy efficiency is defined as (see Eq 10.17)

$$\eta_{energy} = (\text{Voltage efficiency}) \times (\text{Coulomb efficiency})$$

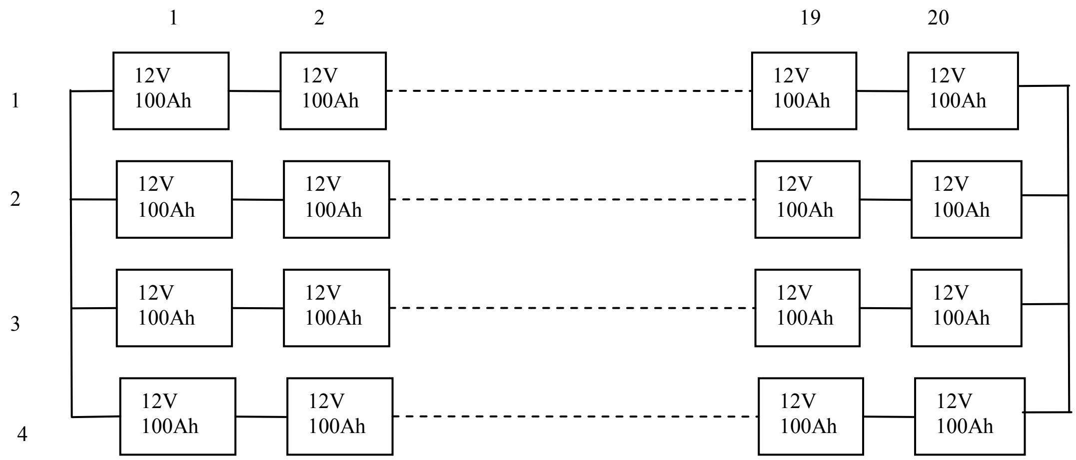
Voltage efficiency is defined as the ratio of discharging and charging voltage i.e. (12V/14V) ≈ 0.86 (86%). The energy Coulomb efficiency can be calculated as (Energy efficiency/Voltage efficiency) = (0.8/0.86) ≈ 0.93 (93%).

Q12. In Fig 10.17 and Fig 10.18, a 240V, 400Ah requirement was met by using several 48V, 100Ah or 48V, 200Ah batteries. Re-configure the same requirement by using 12V, 50Ah and 12V, 100Ah batteries. State the comparative features of these two systems.

Answer:
A (20 x 8) matrix configuration can be used to realize 240V, 400Ah using 12V, 50Ah batteries as shown below:



A (20 x 4) matrix configuration can be used to realize 240V, 400Ah using 12V, 100Ah batteries as shown below:



Configuration with (20 x 8) 12V, 50Ah is preferable. In case if any one of the batteries becomes faulty, the current capacity is 7/8th of the original capacity, i.e. 350Ah, is still available to the load. On the other hand, the configuration shown with (20 x 4) 12V, 100Ah provides 3/4th of the current capacity, i.e. 300Ah if one battery is defective.

Q13. An event management farm, mostly operated at day time, has installed a 20kW$_P$ SPV system with net metering provision. The location has average peak sun hour of 5Hrs. The firm uses electricity during the event booking which happen typically 5 days in a week. During these periods, 50% electricity consumption is fulfilled by the SPV generation. Other 50% is taken from the grid supply. Rest of the 2 days in a week, no electricity is consumed and the entire SPV generation is pumped to the grid. The grid electricity cost $0.12 per kWh at that location for the applicable category. Determine the electricity bill for a quarterly billing cycle (about 13 weeks) by this customer and compare this with (a) if SPV system is not installed and (b) if SPV system is installed but without net metering provision. Neglect the effect of temperature on the power generation.

Answer:
The energy generation per day is (20kW x 5h) = 100kWh. The consumption/export pattern during the week:

For 5 days in a week: 100kWh from SPV and 100kW from grid per day which is (100kWh x 5days) = 500kWh from SPV and (100kWh x 5days) = 500kWh from grid supply. This (500 + 500)kWh = 1000kWh is the total energy requirement per week.

For 2 days in a week: (100kWh x 2 days) = 200kWh is exported to the grid.

(a) If SPV system is not installed then the total requirement of energy is met from the grid supply which cost (1000kWh x $0.12/kWh) = $120 per week. The electricity bill for 13 week billing cycle is $120 x 13 = $1560.

(b) In case SPV system with export provision is used then for 5 days of the week the electricity consumption from the grid is 500kWh which cost (500kWh x $0.12/kWh) = $60. During the 2 days in a week 200kWh is exported to the grid. The earning is (200kWh x $0.12/kWh) = $24 per week. The net electricity consumption from the grid is (\$60 - \$24) = \$36per week and (\$36/week x 13weeks) = \$468 per billing cycle of 13 weeks.

Q14. For the SPV system described in Exercise 13, If the average ambient temperature during the day for a 13 weeks billing cycle is (a) 25^{0}C and (b) 35^{0}C, calculate the electricity bill. Assume module temperature is 20^{0}C more than the ambient temperature.

Answer;
(a) The energy generation per day is (20kW x 5h) = 100kWh at STC. The cell temperature is (25^{0}C + 20^{0}C) = 45^{0}C. Assuming power temperature co-efficient as -0.4%/^{0}C, the power generated at 45^{0}C cell temperature is 100kWh[1 + (-0.4%/^{0}C) x (45^{0}C - 20^{0}C)] = 90kWh. It is assumed that the farm required 200kWh power per day for the 5 days of the week. The net billing is calculated as follows:

For 5 days in a week: 90kWh from SPV and 110kW from grid per day which is (90kWh x 5days) = 450kWh from SPV and (110kWh x 5days) = 550kWh from grid supply.

For 2 days in a week: (90kWh x 2 days) = 180kWh is exported to the grid.

(i) If SPV system is not installed then the total requirement of energy is met from the grid supply which cost (1000kWh x \$0.12/kWh) = \$120 per week. The electricity bill for 13 week billing cycle is \$120 x 13 = \$1560.

(ii) In case SPV system with export provision is used then for 5 days of the week the electricity consumption from the grid is 550kWh which cost (550kWh x \$0.12/kWh) = \$66. During the 2 days in a week 180kWh is exported to the grid. The earning is (180kWh x \$0.12/kWh) = \$21.6 per week. The net electricity consumption from the grid is (\$66 - \$21.6) = \$44.4per week and (\$44.4/week x 13weeks) ≈ \$577 per billing cycle of 13 weeks.

(b) The cell temperature is (35^{0}C + 20^{0}C) = 55^{0}C. Assuming power temperature co-efficient as -0.4%/^{0}C, the power generated at 45^{0}C cell temperature is 100kWh[1 + (-0.4%/^{0}C) x (55^{0}C - 20^{0}C)] = 86kWh. It is assumed that the farm required 200kWh power per day for the 5 days of the week. The net billing is calculated as follows:

For 5 days in a week: 86kWh from SPV and 114kW from grid per day which is (86kWh x 5days) = 430kWh from SPV and (114kWh x 5days) = 570kWh from grid supply.

For 2 days in a week: (86kWh x 2 days) = 172kWh is exported to the grid.

(i) If SPV system is not installed then the total requirement of energy is met from the grid supply which cost (1000kWh x \$0.12/kWh) = \$120 per week. The electricity bill for 13 week billing cycle is \$120 x 13 = \$1560.

(ii) In case SPV system with export provision is used then for 5 days of the week the electricity consumption from the grid is 570kWh which cost (570kWh x \$0.12/kWh) = \$68.4. During the 2 days in a week 172kWh is exported to the grid. The earning is (172kWh x \$0.12/kWh) = \$20.64 per week. The net electricity consumption from the grid is (\$68.4 - \$20.64) = \$47.76per week and (\$47.76/week x 13weeks) ≈ \$621 per billing cycle of 13 weeks.

Q15. Due to lack of knowledge, the SPV system described in Exercise 8 is installed using a uni-directional conventional meter, which calculates power using I^2R principle, instead of a bi-directional meter. Determine electricity bill for a 13 weeks billing cycle for such scenario.

Answer:
In this case the energy which is exported to the grid will be metered and included in the bill. This will not affect the billing for the 5 days of the week when the entire SPV generation is consumed and nothing is exported. However during 2 days of the week when the energy is exported (200kWh per week: see Exercise 13), this will actually be added to the bill. The net bill per week will then be (500kWh from grid for 5 days + 200kWh for 2 days of SPV generation) = 700kWh per week. The bill per week is (700kWh x \$0.12/kWh) = \$84 per week and (\$84/week x 13 weeks) = \$1092 per billing cycle of 13 weeks.

Q16. In general, Performance Ratio (PR) decreases in summer months as compared to that of winter months (see Fig 10.24 and Fig 10.25). Explain the reason by assuming a temperature chart applicable to a location of your choice.

Answer:
PR is calculated by normalizing the irradiance with the power output. Therefore, ideal PR of the two plants having identical installation capacity have same energy output in case the temperature effect is neglected. However, the temperature effect on the power output cannot be neglected. As the power output decreases with the increasing temperature, the PR value of a particular SPV plant decrease with the increase of temperature. As the temperature in the summer months are higher the PR in those months are lower.

Q17. A fixed 100MW$_P$ SPV plant has been installed with an initial cost of \$1.0/W$_P$. The interest rate, which is applicable from the time the plant is commission, is 10%. The maintenance cost is \$10K/MW$_P$ per year and this is applicable after one year from the plant is commissioned. This plant is producing 1.5Million kWh per year per MW$_P$ and it is fetching a uniform \$0.15/kWh. Determine the LCOE if the degradation rate is 0.6%, 0.8% or 1.0% and the plant life is 10years, 15years, 20years, 25yrars or 30years.

Answer:
(a) 0.6% degradation per year:

(i) Plant Life 10 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 10 years + Interest cost

= \$100M + (\$10K per MW$_P$ per year x 100MW$_P$ x 10year) + \$132 M = \$100M + \$10M + \$132M = \$242M

Assuming uniform 0.6% degradation rate, the total energy output for 10 years = 14.6Million Unit per MW$_P$. (see Eq 10.22), which is 1460 Million units for 100MW$_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$242M/1460Million kWh) ≈ \$0.17 per kWh

(ii) Plant Life 15 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 15 years + Interest cost

= \$100M + (\$10K x 100M x 15) + \$160.5 M = \$100M + \$15M + \$160.5M = \$275.5M

Assuming uniform 0.6% degradation rate, the total energy output for 15 years = 21.58Miillion Unit per MW$_P$. (see Eq 10.22), which is 2158 Million units for 100MW$_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$275.5M/2158Million kWh) ≈ \$0.13 per kWh

(iii) Plant Life 20 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 20 years + Interest cost

= \$100M + (\$10K x 100M x 20) + \$194 M = \$100M + \$20M + \$194M = \$314M

Assuming uniform 0.6% degradation rate, the total energy output for 20 years = 28.35Miillion Unit per MW_P. (see Eq 10.22), which is 2835 Million units for 100MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$314M/2835Million kWh) ≈ \$0.11 per kWh

(iv) Plant Life 25 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 25 years + Interest cost

= \$100M + (\$10K x 100M x 25) + \$194 M = \$100M + \$25M + \$227.5M = \$352.5M

Assuming uniform 0.6% degradation rate, the total energy output for 25 years = 34.92Miillion Unit per MW_P. (see Eq 10.22), which is 3492 Million units for 100MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$352.5M/3492Million kWh) ≈ \$0.1 per kWh

(v) Plant Life 30 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 30 years + Interest cost

= \$100M + (\$10K X 100M x 30) + \$194 M = \$100M + \$30M + \$264M = \$394M

Assuming uniform 0.6% degradation rate, the total energy output for 30 years = 42.55Miillion Unit per MW_P. (see Eq 10.22), which is 4255 Million units for 100MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$394M/4255Million kWh) ≈ \$0.09 per kWh

(b) 0.8% degradation per year:

(i) Plant Life 10 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 10 years + Interest cost

= \$100M + (\$10K x 100M x 10) + \$132 M = \$100M + \$10M + \$132M = \$242M

Assuming uniform 0.8% degradation rate, the total energy output for 10 years = 14.47Miillion Unit per MW_P. (see Eq 10.22), which is 1447 Million units for $100MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$242M/1447Million kWh) ≈ \$0.17 per kWh

(ii) Plant Life 15 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 15 years + Interest cost

= \$100M + (\$10K X 100M x 15) + \$160.5 M = \$100M + \$15M + \$160.5M = \$275.5M

Assuming uniform 0.8% degradation rate, the total energy output for 15 years = 21.28Miillion Unit per MW_P. (see Eq 10.22), which is 2128 Million units for $100MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$275.5M/2128Million kWh) ≈ \$0.13 per kWh

(iii) Plant Life 20 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 20 years + Interest cost

= \$100M + (\$10K X 100M x 20) + \$194 M = \$100M + \$20M + \$194M = \$314M

Assuming uniform 0.8% degradation rate, the total energy output for 20 years = 27.83Miillion Unit per MW_P. (see Eq 10.22), which is 2783 Million units for $100MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$314M/2783Million kWh) ≈ \$0.11 per kWh

(iv) Plant Life 25 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 25 years + Interest cost

= \$100M + (\$10K X 100M x 25) + \$194 M = \$100M + \$25M + \$227.5M = \$352.5M

Assuming uniform 0.8% degradation rate, the total energy output for 25 years = 34.11Miillion Unit per MW_P. (see Eq 10.22), which is 3411 Million units for $100MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$352.5M/3411Million kWh) ≈ \$0.1 per kWh

(v) Plant Life 30 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 30 years + Interest cost

= \$100M + (\$10K X 100M x 30) + \$194 M = \$100M + \$30M + \$264M = \$394M

Assuming uniform 0.8% degradation rate, the total energy output for 30 years = 40.15Miillion Unit per MW_P. (see Eq 10.22), which is 4015 Million units for 100MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= ($394M/4015Million kWh) ≈ $0.98 per kWh

(c) 1% degradation per year:

(i) Plant Life 10 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 10 years + Interest cost

= $100M + ($10K X 100M x 10) + $132 M = $100M + $10M + $132M = $242M

Assuming uniform 1% degradation rate, the total energy output for 10 years = 14.34Miillion Unit per MW_P. (see Eq 10.22), which is 1434 Million units for 100MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= ($242M/1434Million kWh) ≈ $0.17 per kWh

(ii) Plant Life 15 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 15 years + Interest cost

= $100M + ($10K x 100M x 15) + $160.5 M = $100M + $15M + $160.5M = $275.5M

Assuming uniform 1% degradation rate, the total energy output for 15 years = 20.99Miillion Unit per MW_P. (see Eq 10.22), which is 2099 Million units for 100MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= ($275.5M/2099Million kWh) ≈ $0.13 per kWh

(iii) Plant Life 20 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 20 years + Interest cost

= $100M + ($10K x 100M x 20) + $194 M = $100M + $20M + $194M = $314M

Assuming uniform 1% degradation rate, the total energy output for 20 years = 27.31Miillion Unit per MW_P. (see Eq 10.22), which is 2731 Million units for 100MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= ($314M/2731Million kWh) ≈ $0.11 per kWh

(iv) Plant Life 25 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 25 years + Interest cost

= \$100M + (\$10K x 100M x 25) + \$194 M = \$100M + \$25M + \$227.5M = \$352.5M

Assuming uniform 1% degradation rate, the total energy output for 25 years = 33.33Miillion Unit per MW_P. (see Eq 10.22), which is 3333 Million units for $100MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$352.5M/3333Million kWh) ≈ \$0.105 per kWh

(v) Plant Life 30 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 30 years + Interest cost

= \$100M + (\$10K x 100M x 30) + \$264 M = \$100M + \$30M + \$264M = \$394M

Assuming uniform 1% degradation rate, the total energy output for 30 years = 39.04Miillion Unit per MW_P. (see Eq 10.22), which is 1434 Million units for $100MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$394M/3904Million kWh) ≈ \$0.10 per kWh

Q18. The fixed SPV $100MW_P$ system of Exercise 17 is replaced with tracking based system at the same location. The initial cost is increased to \$1.3/W_P. The maintenance cost also increased due to additional maintenance cost of motor (including controller) and other moving parts. This cost is now \$15K/MW_P. The energy output is also increased to 1.8Million kWh per year. Determine LCOE for various degradation rate and plant lifetime as given in Exercise 17.

Answer:
(a) 0.6% degradation per year:

(i) Plant Life 10 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 10 years + Interest cost

= \$130M + (\$15K per MW_P per year x $130MW_P$ x 10year) + \$172 M = \$100M + \$19.5M + \$172M = \$291.5M

Assuming uniform 0.6% degradation rate, the total energy output for 10 years = 17.52Miillion Unit per MW_P. (see Eq 10.22), which is 2279 Million units for $130MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$291.5M/2279Million kWh) ≈ \$0.13 per kWh

(ii) Plant Life 15 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 15 years + Interest cost

= \$130M + (\$15K x 100M x 15) + \$210 M = \$130M + \$22.5M + \$210M = \$362.5M

Assuming uniform 0.6% degradation rate, the total energy output for 15 years = 25.89Miillion Unit per MW_P. (see Eq 10.22), which is 3366 Million units for $130MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= ($362.5M/3366Million kWh) ≈ $0.11 per kWh

(iii) Plant Life 20 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 20 years + Interest cost

= $130M + ($15K x 100M x 20) + $280 M = $130M + $30M + $250M = $410M

Assuming uniform 0.6% degradation rate, the total energy output for 20 years = 34.02Miillion Unit per MW_P. (see Eq 10.22), which is 4423 Million units for $130MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= ($410M/4423Million kWh) ≈ $0.093 per kWh

(iv) Plant Life 25 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 25 years + Interest cost

= $130M + ($15K x 100M x 25) + $194 M = $130M + $37.5M + $295M = $462.5M

Assuming uniform 0.6% degradation rate, the total energy output for 25 years = 41.94Miillion Unit per MW_P. (see Eq 10.22), which is 5452 Million units for $130MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= ($462.5M/5452Million kWh) ≈ $0.085 per kWh

(v) Plant Life 30 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 30 years + Interest cost

= $130M + ($15K X 100M x 30) + $342 M = $130M + $45M + $342M = $517M

Assuming uniform 0.6% degradation rate, the total energy output for 30 years = 49.55Miillion Unit per MW_P. (see Eq 10.22), which is 6442 Million units for $130MW_P$ plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= ($517M/6442Million kWh) ≈ $0.08 per kWh

(b) 0.8% degradation per year:

(i) Plant Life 10 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 10 years + Interest cost

$$= \$130M + (\$15K \times 100M \times 10) + \$172\ M = \$130M + \$15M + \$172M = \$317M$$

Assuming uniform 0.8% degradation rate, the total energy output for 10 years = 17.36Miillion Unit per MW_P. (see Eq 10.22), which is 2257 Million units for 130MW_P plant.

$$LCEO = (\text{Total Cost over lifetime})/(\text{Total Energy Produced over Lifetime})$$

$$= (\$317M/2257\text{Million kWh}) \approx \$0.14 \text{ per kWh}$$

(ii) Plant Life 15 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 15 years + Interest cost

$$= \$130M + (\$15K \times 100M \times 15) + \$210\ M = \$100M + \$22.5M + \$210M = \$332.5M$$

Assuming uniform 0.8% degradation rate, the total energy output for 15 years = 25.54Miillion Unit per MW_P. (see Eq 10.22), which is 3320 Million units for 130MW_P plant.

$$LCEO = (\text{Total Cost over lifetime})/(\text{Total Energy Produced over Lifetime})$$

$$= (\$332.5M/3320\text{Million kWh}) \approx \$0.1 \text{ per kWh}$$

(iii) Plant Life 20 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 20 years + Interest cost

$$= \$130M + (\$15K \times 100M \times 20) + \$236\ M = \$130M + \$30M + \$236M = \$396M$$

Assuming uniform 0.8% degradation rate, the total energy output for 20 years = 33.39Miillion Unit per MW_P. (see Eq 10.22), which is 4341 Million units for 130MW_P plant.

$$LCEO = (\text{Total Cost over lifetime})/(\text{Total Energy Produced over Lifetime})$$

$$= (\$396M/4341\text{Million kWh}) \approx \$0.091 \text{ per kWh}$$

(iv) Plant Life 25 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 25 years + Interest cost

$$= \$130M + (\$15K \times 100M \times 25) + \$295\ M = \$130M + \$37.5M + \$295M = \$462.5M$$

Assuming uniform 0.8% degradation rate, the total energy output for 25 years = 40.93Miillion Unit per MW_P. (see Eq 10.22), which is 5321 Million units for 130MW_P plant.

$$LCEO = (\text{Total Cost over lifetime})/(\text{Total Energy Produced over Lifetime})$$

$$= (\$462.5M/5321\text{Million kWh}) \approx \$0.087 \text{ per kWh}$$

(v) Plant Life 30 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 30 years + Interest cost

= \$130M + (\$15K X 100M x 30) + \$342 M = \$130M + \$45M + \$342M = \$517M

Assuming uniform 0.8% degradation rate, the total energy output for 30 years = 48.18Miillion Unit per MW_P. (see Eq 10.22), which is 6263 Million units for 130MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$517M/6263Million kWh) ≈ \$0.082 per kWh

(c) 1% degradation per year:

(i) Plant Life 10 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 10 years + Interest cost

= \$130M + (\$15K X 100M x 10) + \$172 M = \$130M + \$15M + \$172M = \$317M

Assuming uniform 1% degradation rate, the total energy output for 10 years = 17.21Miillion Unit per MW_P. (see Eq 10.22), which is 2237 Million units for 130MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$317M/2237Million kWh) ≈ \$0.14 per kWh

(ii) Plant Life 15 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 15 years + Interest cost

= \$130M + (\$15K X 100M x 15) + \$210 M = \$100M + \$22.5M + \$210M = \$332.5M

Assuming uniform 1% degradation rate, the total energy output for 15 years = 25.19Miillion Unit per MW_P. (see Eq 10.22), which is 3275Million units for 130MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$332.5M/3275Million kWh) ≈ \$0.10 per kWh

(iii) Plant Life 20 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 20 years + Interest cost

= \$130M + (\$15K X 100M x 20) + \$236 M = \$130M + \$30M + \$236M = \$396M

Assuming uniform 1% degradation rate, the total energy output for 20 years = 32.78Miillion Unit per MW_P. (see Eq 10.22), which is 4261 Million units for 130MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$396M/4261Million kWh) ≈ \$0.093 per kWh

(iv) Plant Life 25 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 25 years + Interest cost

= \$130M + (\$15K X 100M x 25) + \$295 M = \$130M + \$37.5M + \$295M = \$462.5M

Assuming uniform 1% degradation rate, the total energy output for 25 years = 39.99Miillion Unit per MW_P. (see Eq 10.22), which is 5199 Million units for 130MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$462.5M/5199Million kWh) ≈ \$0.089 per kWh

(v) Plant Life 30 Years:

The "Total Cost over Lifetime" = Initial Cost + Plant maintenance cost per year x 30 years + Interest cost

= \$130M + (\$15K X 100M x 30) + \$342 M = \$130M + \$45M + \$342M = \$517M

Assuming uniform 1% degradation rate, the total energy output for 30 years = 46.85Miillion Unit per MW_P. (see Eq 10.22), which is 6091 Million units for 130MW_P plant.

LCEO = (Total Cost over lifetime)/(Total Energy Produced over Lifetime)

= (\$517M/6091Million kWh) ≈ \$0.085 per kWh

Q19. Comment on the PR of the two plants mentioned in Exercise 17 and Exercise 18. Are these supposed to be identical or different?

Answer:
If these two plants are located in nearby locations and the yearly temperature behavior is same, they have identical PR.

Q20. A SPV plant has "Peak Sun Hours" of 4Hrs, 4.5Hrs or 5Hrs. Calculate Capacity Utilization Factor (CUF) if the average module temperature is +10^{0}C, +25^{0}C, 35^{0}C, 50^{0}C. Neglect other factors such as inverter downtime, grid outage, solar field downtime, etc.

Answer:

The CUF can be calculated as per Eq 10.20 which is reproduced below:

CUF = Energy Obtained (kWh) per year/[(365 x 24) x (Installed Capacity of the Plant in kW_P)] x 100%

The energy generation (kWh) for a particular installation, say X kW_P. The energy generation per year can be calculated as X (kW_P) x Peak sun hours per day x 365. This is applicable for modules opetaion at STC temperature, i.e. 25^{0}C.

(a)

(i) If the peak sun hour is 4hr:

CUF = X (kW_P) x 4hr per day x 365days per year/[(365days x 24hr) x X (kW_P)] x 100%

$= (4/24) \times 100\% \approx 16.7\%$.

(ii) If the peak sun hour is 4.5hr:

$$CUF = X\ (kW_P) \times 4.5hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$= (4.5/24) \times 100\% \approx 18.75\%.$$

(iii) If the peak sun hour is 5hr:

$$CUF = X\ (kW_P) \times 5hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$= (5/24) \times 100\% \approx 20.8\%.$$

(b) The CUF at $+10^0C$:

The power generation will change as the temperature deviates from STC temperature of 25^0C. Assuming a power temperature coefficient of $-0.4\%/^0C$ the power at $+10^0C$ module temperature can be calculated as:

$$X\ (kW_P)_{+10} = X\ (kW_P)\ [1 + (10^0C - 25^0C) \times (-0.4/100)] = 1.06\ X\ (kW_P).$$

(i) If the peak sun hour is 4hr:

$$CUF = 1.06\ X\ (kW_P) \times 4hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$\approx 17.7\%.$$

(ii) If the peak sun hour is 4.5hr:

$$CUF = 1.06\ X\ (kW_P) \times 4.5hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$\approx 19.9\%.$$

(iii) If the peak sun hour is 5hr:

$$CUF = 1.06\ X\ (kW_P) \times 5hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$= (5/24) \times 100\%) \approx 22\%.$$

(c) The CUF at $+35^0C$:

The power generation will change as the temperature deviates from STC temperature of 25^0C. Assuming a power temperature coefficient of $-0.4\%/^0C$ the power at $+10^0C$ module temperature can be calculated as:

$$X\ (kW_P)_{+10} = X\ (kW_P)\ [1 + (35^0C - 25^0C) \times (-0.4/100)] = 0.94\ X\ (kW_P).$$

(i) If the peak sun hour is 4hr:

$$CUF = 0.94\ X\ (kW_P) \times 4hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$\approx 15.7\%.$$

(ii) If the peak sun hour is 4.5hr:

$$CUF = 0.94\ X\ (kW_P) \times 4.5hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$\approx 17.6\%.$$

(iii) If the peak sun hour is 5hr:

$$CUF = 1.06\ X\ (kW_P) \times 5hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$= (5/24) \times 100\%) \approx 19.5\%.$$

(d) The CUF at $+50^0C$:

The power generation will change as the temperature deviates from STC temperature of 25^0C. Assuming a power temperature coefficient of $-0.4\%/^0C$ the power at $+10^0C$ module temperature can be calculated as:

$$X\ (kW_P)_{+10} = X\ (kW_P)\ [1 + (50^0C - 25^0C) \times (-0.4/100)] = 0.9\ X\ (kW_P).$$

(i) If the peak sun hour is 4hr:

$$CUF = 0.9\ X\ (kW_P) \times 4hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$\approx 15.03\%.$$

(ii) If the peak sun hour is 4.5hr:

$$CUF = 1.06\ X\ (kW_P) \times 4.5hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$\approx 16.9\%.$$

(iii) If the peak sun hour is 5hr:

$$CUF = 1.06\ X\ (kW_P) \times 5hr\ per\ day \times 365days\ per\ year/[(365days \times 24hr) \times X\ (kW_P)] \times 100\%$$

$$= (5/24) \times 100\%) \approx 18.8\%.$$

Q21. Two SPV plants installed at two different locations have identical PRs. Explain with reason if:

(a) The CUFs of these two plants are necessarily identical.

(b) The LCOEs of these plants are necessarily identical.

Answer:
(a) Identical PR of two plants indicate that energy output normalized with respect to irradiance is same. It does not mean both plants giving identical energy output. CUF of these two plants are not necessarily identical.

(b) The input cost of the installation for both the plants may be assumed to be same as the installed capacity is same. But the energy output may differ. Therefore the LCOEs of these two plants may not be identical.

Q22. Two SPV plants installed at two different locations have identical CUFs. Explain with reason if:

(a) The PRs of these two plants are necessarily identical.

(b) The LCOEs of these plants are necessarily identical.

Answer:
(a) Identical CUF means both the plants are producing identical energy output. The PR will also be identical. Installed capacity is assumed to be same for both the plants.

(b) Identical CUF means both the plants are producing identical energy output. The LCOE will also be identical. Installed capacity is assumed to be same for both the plants.

Q23. Two SPV plants installed at two different locations have identical LCOEs. Explain with reason if:

(a)The PRs of these two plants are necessarily identical.
(b)The CUFs of these plants are necessarily identical.

Answer:
If the installed capacity and financial calculation methods are same, both PR and CUF will be identical.