Question 1

A particular module has NOCT 49 Degree C.

(a) What is cell temperature coefficient?

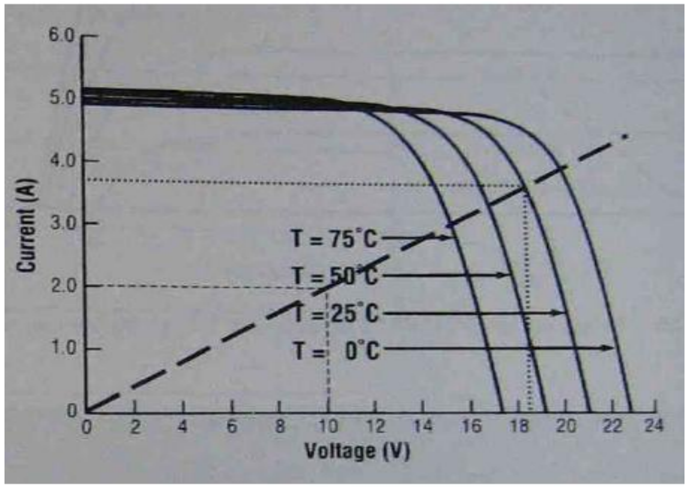
$$k = \frac{NOCT - 20}{800} = \frac{49 - 20}{800} = \frac{29}{800} = 0.03625°C / W - m^2$$

(b) What will be cell temperature if the ambient temperature is 35 Degree C & the irradiance is 65W/m^2

$$Tcell = T_a + \left(\frac{NOCT - 20}{800} \times 65 \right) = 35 + \left(\frac{49 - 20}{800} \times 65 \right) = 58.8°C$$

Question 2

What would be the output of the module in Figure 27 when connected to the 5.0Ω resistor, if the cell temperature was: 75 °C, 0 °C?



- Temperature 75°C: I_{op}= 3A , V_{op}=15V

$$Power = V_{op} \times I_{op} = 15 \times 3 = 45W$$

- Temperature 0°C: I_{op}= 4A , V_{op}=20V

$$Power = V_{op} \times I_{op} = 20 \times 4 = 80W$$

Question 3

What would be the output current, voltage and power for an SM 55 module connected to a 50 resistance for irradiances of 200W/m^2, 600W/m^2 and 1000W/m^2?

Module/Condition	Voltage	Current	Power
SM55 at 1000W/m2	14	3.35	44.8
SM55 at 600W/m2	14	2	4.2
SM55 at 200W/m2	14	0.65	4.2

Question 4

Find the output of a module operating at its maximum power point given the following data:

- **Typical maximum power at STC=77W**
- **NOCT = 49 °C**
- **Power output coefficient = -0.38%/°C (Note that this value is given a negative sign in most manufacturer's data, with its value as a percentage**
- **Ambient temperature = 35°C**
- **Irradiance = 865W/m^2.**

$$Tcell = T_a + \left(\frac{NOCT - 20}{800} \times G \right) = 35 + \left(\frac{49 - 20}{800} \times 865 \right) = 66.36°C$$

$$\begin{aligned} P_T &= P_{STC} \times \left(1 - \tau \left(T_{cell} - T_{STC}\right)\right) \times \frac{G}{G_{STC}} \\ &= 77 \times \left[1 - \frac{0.38}{100}\left(66.36 - 25\right)\right] \times \frac{865}{1000} \\ &= 56.1W \end{aligned}$$

Question 5

Calculate the daily energy output of a 100W poly-crystalline module operating under the following conditions: maximum power point tracking regulator; ambient day time temperature 25°C; irradiation 5.5kWh/m^2; dusty environment with annual maintenance only. The manufacturer, who tests modules to international standards, guarantees the minimum module power rating to be 95W, and NOCT is 49°C.

$$E_{\mathrm{module}} = P_{STC} \times \left[1 - \tau\left(T_{cell} - T_{ref}\right)\right] f_{man} \times f_{dirt} \times H_{daily}$$

P_{STC}=95W, f_{man}=1, f_{dirt}=95%=0.95, H_{daily}=5.5

$$T_{cell} = T_A + k\left(30 H_{daily} + 150\right)$$

$$k = \frac{NOCT - 20}{800} = \frac{49 - 20}{800} = \frac{29}{800} = 0.036$$

$$T_{cell} = 25 + 0.036 \times \left(30 \times 5.5 + 150\right) = 43°C$$

$$E_{\mathrm{module}} = P_{STC} \times \left[1 - \tau\left(T_{cell} - T_{ref}\right)\right] f_{man} \times f_{dirt} \times H_{daily}$$

$$= 95 \times \left[1 - \frac{0.05}{100}\left(43 - 35\right) \times 1 \times 0.95 \times 5.5\right]$$

$$= 435 W - hr$$

Question 6

a) **What is the average daily radiation (MJ/m^2) on a north facing collector tilted at the angle of latitude for Brisbane in May?**
Using the table 1, the average daily radiation on a north facing collector tilted at the angle of latitude for Brisbane in May is: 15.9MJ/m^2.

BRISBANE
Latitude: 27 degrees 25 minutes South Longitude: 153 degrees 05 minutes East
Elevation: 6 metres

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
5	3										7	8	2
6	38	18	6	2				1	10	34	75	61	21
7	184	155	116	48	24	15	18	39	152	224	248	222	120
8	368	354	348	314	261	240	235	325	398	421	437	413	343
9	536	538	504	525	435	438	424	526	617	575	576	554	522
10	686	662	631	653	610	587	577	690	772	703	697	688	663
11	785	763	735	711	669	667	654	767	841	784	745	781	742
12	832	808	776	733	670	665	669	797	866	783	774	811	765
13	825	808	794	699	601	632	624	752	823	738	725	779	733
14	754	714	731	616	506	549	539	652	732	640	614	688	645
15	618	587	563	472	387	414	418	504	552	487	460	525	499
16	419	415	379	284	209	224	288	315	351	311	309	341	317
17	223	221	178	65	22	17	29	50	91	129	147	183	113
18	58	50	22	4				2	6	10	26	44	19
19	8	4										6	1
20													
Daily	22.8	22.0	20.8	18.4	15.9	16.0	16.0	19.5	22.4	21.0	21.0	22.0	19.8

Extracted from the Australian Solar Radiation Data Handbook, Table 4.3 for Brisbane.

Table 1 Average total hourly irradiance (W/m^2) and daily total irradiation (MJ/m^2) on a *north facing plane tilted at latitude angle* for each month for Brisbane.
(Source: Lee et al)

b) What is the hourly irradiance at 9am, 12 noon and 3pm in August?

The hourly irradiance at 9am in August is: $526MJ/m^2$

The hourly irradiance at 12 noon in August is: $797MJ/m^2$

The hourly irradiance at 3pm in August is: $504MJ/m^2$

c) What do you notice about the irradiation levels before 8am and after 4pm in all months?

The irradiation levels in this period of time are the lowest values during the day. Between 8am and 4pm are the crucial hours for solar access as the majority of irradiation is received between these hours.

BRISBANE

Latitude 27 degrees 25 minutes South Longitude 153 degrees 05 minutes East

Elevation 8 metres

Plane Azimuth (Degrees)	Plane Inclination (degrees)									
	0	10	20	30	40	50	60	70	80	90
0	24.1	24.1	23.5	22.4	20.7	18.6	16.0	13.3	10.3	7.6
10	24.1	24.1	23.5	22.4	20.7	18.5	16.1	13.4	10.6	7.9
20	24.1	24.1	23.5	22.4	20.7	18.7	16.3	13.8	11.2	8.8
30	24.1	24.1	23.5	22.4	20.8	18.9	16.7	14.3	11.9	9.7
40	24.1	24.1	23.5	22.8	21.0	19.1	17.1	14.9	12.7	10.6
50	24.1	24.1	23.5	22.5	21.1	19.4	17.4	15.4	13.4	11.5
60	24.1	24.1	23.5	22.5	21.1	19.6	17.8	15.8	13.9	12.0
70	24.1	24.1	23.5	22.5	22.2	19.7	18.0	16.2	14.2	12.4
80	24.1	24.1	23.5	22.5	21.3	19.7	18.1	16.5	14.5	12.7
90	24.1	24.1	23.5	22.5	21.2	19.7	18.1	16.6	14.5	12.7
100	24.1	24.1	23.5	22.5	21.2	19.6	18.0	16.2	14.4	12.6
110	24.1	24.1	23.5	22.4	21.0	19.4	17.7	15.9	14.2	12.4
120	24.1	24.1	23.5	22.3	20.9	19.2	17.3	15.5	13.7	12.0
130	24.1	24.1	23.3	22.3	20.7	18.9	16.9	14.9	13.1	11.4
140	24.1	24.1	23.5	22.3	20.7	18.6	16.4	14.2	12.3	10.7
150	24.1	24.1	23.5	22.3	20.6	18.5	16.0	13.5	11.4	9.8
160	24.1	24.1	23.5	22.3	20.7	18.5	15.9	12.9	10.4	8.9
170	24.1	24.1	23.5	22.4	20.7	18.5	15.9	13.0	9.8	8.0
180	24.1	24.1	23.5	22.4	20.7	18.5	15.9	13.0	9.8	7.6
190	24.1	24.1	23.5	22.4	20.7	18.5	16.0	13.0	9.8	8.0
200	24.1	24.1	23.5	22.4	20.7	18.6	16.0	13.0	10.3	8.9
210	24.1	24.1	23.5	22.4	20.7	18.6	16.1	13.6	11.5	9.8
220	24.1	24.1	23.5	22.4	20.8	18.8	16.6	14.4	12.4	10.7
230	24.1	24.1	23.6	22.5	20.9	19.1	17.1	15.1	13.2	11.5
240	24.1	24.1	23.6	22.5	21.1	19.4	17.6	15.7	13.9	12.1
250	24.1	24.1	23.6	22.6	21.3	19.7	18.0	16.2	14.4	12.6
260	24.1	24.1	23.6	22.7	21.5	20.0	18.3	16.5	14.7	12.8
270	24.1	24.1	23.6	22.7	21.5	20.1	18.4	16.7	14.8	12.9
280	24.1	24.1	23.6	22.7	21.6	20.1	18.4	16.7	14.8	12.8
290	24.1	24.1	23.6	22.7	21.5	20.0	18.3	16.5	14.5	12.5
300	24.1	24.1	23.6	22.7	21.5	19.9	18.1	16.2	14.1	12.1
310	24.1	24.1	23.6	22.7	21.5	19.7	17.8	15.7	13.6	11.5
320	24.1	24.1	23.6	22.6	21.1	19.4	17.4	15.2	12.9	10.8
330	24.1	24.1	23.6	22.5	21.0	19.1	17.0	14.6	12.2	9.9
340	24.1	24.1	23.5	22.4	20.8	18.9	16.5	14.0	11.4	8.9
350	24.1	24.1	23.3	22.4	20.7	18.7	16.2	13.5	10.7	8.0

Extracted from the Australian Solar Radiation Data Handbook, Table 5.1 for Brisbane

Table 2 Average total daily irradiation (MJ/m^2) on an inclined plane during January for Brisbane (Source Lee et al)

BRISBANE

Latitude 27 degrees 25 minutes South Longitude 153 degrees 05 minutes East

Elevation 6 metres

Plane Azimuth (Degrees)	Plane Inclination (Degrees)									
	0	10	20	30	40	50	60	70	80	90
0	11.2	13.3	15.6	16.4	17.3	17.8	17.8	17.3	16.4	15.1
10	11.2	13.3	15.0	16.3	17.3	17.7	17.7	17.3	16.4	15.0
20	11.2	13.2	14.9	16.1	17.0	17.4	17.4	16.9	16.0	14.6
30	11.2	13.1	14.6	15.8	16.5	16.8	16.7	16.2	15.2	13.9
40	11.2	12.9	14.3	15.2	15.8	16.0	15.8	15.2	14.3	13.0
50	11.2	12.7	13.8	14.6	15.0	15.1	14.8	14.2	13.2	12.0
60	11.2	12.4	13.3	13.8	14.1	14.0	13.6	13.0	12.1	11.0
70	11.2	12.1	12.7	13.0	13.1	12.9	12.5	11.8	11.0	10.0
80	11.2	11.8	12.0	12.1	12.0	11.8	11.2	10.6	9.8	8.9
90	11.2	11.4	11.4	11.2	11.0	10.5	10.0	9.3	8.6	7.7
100	11.2	11.3	10.7	10.3	9.9	9.3	8.7	8.1	7.4	6.7
110	11.2	10.7	10.1	9.4	8.7	8.2	7.5	6.9	6.3	5.6
120	11.2	10.4	9.5	8.6	7.7	7.0	6.3	5.8	5.3	4.8
130	11.2	10.1	8.9	7.7	6.7	5.9	5.3	4.8	4.4	4.0
140	11.2	9.9	8.4	7.0	5.8	4.9	4.4	4.0	3.8	3.5
150	11.2	9.7	7.9	6.3	4.9	4.0	3.7	3.6	3.4	3.3
160	11.2	9.5	7.6	5.7	4.2	3.5	3.5	3.5	3.4	3.2
170	11.2	9.4	7.3	5.3	3.6	3.5	3.5	3.3	3.4	3.2
180	11.2	9.5	7.2	5.1	3.4	3.5	3.5	3.5	3.4	3.2
190	11.2	9.3	7.3	5.2	3.6	3.5	3.5	3.5	3.4	3.2
200	11.2	9.4	7.5	5.6	4.1	3.5	3.5	3.5	3.4	3.2
210	11.2	9.6	7.8	6.1	4.7	4.0	3.6	3.5	3.4	3.3
220	11.2	9.7	8.2	6.7	5.5	4.7	4.2	3.9	3.7	3.4
230	11.2	10.3	8.6	7.4	6.4	5.6	5.0	4.6	4.2	3.9
240	11.2	10.2	9.2	8.2	7.3	6.6	5.9	5.4	5.0	4.5
250	11.2	10.5	9.8	9.0	8.2	7.6	7.0	6.4	5.9	5.3
260	11.2	10.9	10.4	9.8	9.3	8.7	8.1	7.5	6.9	6.2
270	11.2	11.2	11.0	10.7	10.3	9.8	9.3	8.6	8.0	7.1
280	11.2	11.6	11.7	11.6	11.4	11.0	10.5	9.8	9.0	8.2
290	11.2	11.9	12.3	12.5	12.4	12.2	11.7	11.0	10.2	9.1
300	11.2	12.2	12.9	13.3	13.5	13.3	12.9	12.2	11.3	10.2
310	11.2	12.5	13.5	14.3	14.4	14.4	14.1	13.4	12.4	11.2
320	11.2	12.8	14.0	14.9	15.3	15.4	15.2	14.5	13.5	12.2
330	11.2	13.0	14.4	15.5	16.1	16.4	16.2	15.6	14.6	13.3
340	11.2	13.1	14.7	15.9	16.7	17.1	17.0	16.5	15.5	14.2
350	11.2	13.3	14.9	16.2	17.1	17.6	17.6	17.1	16.2	14.8

Extracted from the Australian Solar Radiation Data Handbook, Table 5.7 for Brisbane

Table 3 Average daily total irradiation (MJ/m²) on an inclined plane in Brisbane during July

Question 7

From the radiation tables for Brisbane, determine the average total daily irradiation received on a collector for the months of January and July if the collector has the following orientations:

a) Azimuth 45° degrees, tilt angle 20° degrees

<u>January:</u> Using Table 2, the average total daily irradiation for January is 23.5MJ/m^2.

<u>July:</u> Using Table 3

For azimuth 40° = 14.3MJ/m^2

For azimuth 50° =13.8MJ/m^2

By interpolation, the average total daily irradiation for July is calculated by

$$14.3-\left[\frac{45-40}{50-40}\times(14.3-13.8)\right]=14.05MJ/m^2$$

b) Azimuth 270° degrees, tilt angle 40° degrees

January: Using Table 2, the average total daily irradiation for January is 21.5MJ/m^2.

July: Using Table 3, the average total daily irradiation for July is 10.3MJ/m^2.

c) Azimuth 270° degrees, tilt angle 25° degrees

January: Using Table 2

For tilt 20° = 23.6MJ/m^2

For Tilt 30° = 22.7MJ/m^2

By interpolation, the average total daily irradiation for January is calculated by

$$23.6 - \left[\frac{25-20}{30-20} \times (23.6 - 22.7)\right] = 23.15 MJ/m^2$$

July: Using Table 3

For tilt 20° = 11.0MJ/m^2

For Tilt 30° = 10.7MJ/m^2

By interpolation, the average total daily irradiation for July is calculated by

$$11.0-\left[\frac{25-20}{30-20}\times(11.0-10.7)\right]=10.85MJ/m^2$$

3.2.4 Computer Software

Computer software such as RAD, SaPV Design (available on the disc accompanying this Resource Book) and other system design programs, will calculate the irradiation on an unshaded, tilted plane from the horizontal plane data. Input data consists of global irradiation on a horizontal plane for each month, tilt angle and possibly orientation of the collector.

A sample of the output data from RAD, which allows both tilt and orientation to be adjusted, is shown in Figure 4.

LOCATION: Melbourne LATITUDE:-37.7 TILT:45 ORIENTATION:15

month	H	H1	SR	SS	SR1	SS1
Jan	24.20	20.29	4.52	19.08	6.11	17.49
Feb	21.40	19.94	5.20	18.40	6.06	17.54
Mar	16.20	17.59	5.54	18.06	6.01	17.59
Apr	10.70	14.09	6.30	17.30	6.30	17.30
May	7.30	11.46	7.02	16.58	7.02	16.58
Jun	5.90	10.51	7.17	16.43	7.17	16.43
Jul	6.80	11.68	7.10	16.50	7.10	16.50
Aug	9.00	12.84	6.44	17.16	6.44	17.16
Sep	12.70	14.71	6.09	17.51	6.09	17.51
Oct	17.20	16.71	5.32	18.28	6.05	17.55
Nov	21.00	18.13	5.00	19.00	6.10	17.50
Dec	22.70	19.65	4.48	19.12	6.11	17.49
AV	14.67	15.63				

H : horizontal insolation
HI : inclined plane horizontal
SR : time of sunset over horizon
SS : time of sunrise over horizon
SRI : time of first sunrise on the plane
SS1 : time of first sunset on the plane

Figure 4 Results of irradiation in Melbourne on a tilted plane of 45°, orientated to 15°E from the program RAD.

TABLE B - AVERAGE IRRADIATION ON A NORTH FACING PLANE (South Hemisphere)

Solar Constant =
Latitude (-ve, south) = 1367 W/sq.m
Tilt Angle of Collector = -27.5 Degrees
Azimuth Angle = 0 Degrees
(NB. North taken as 180 degrees in Southern Hemisphere) 180 Degrees

Inputted radiation data on a horizontal plane

Month	Jan	Feb	Mar	Apr	May	Jun	Jul
H (MJ/sq.m)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
H (kWh/sq.m)	6.75	6.08	5.22	4.22	3.51	3.08	3.14
Reflectance	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Day of Hr	17.00	47.00	75.00	105.00	135.00	162.00	198.00
Declinat.	-20.90	-13.00	-2.40	9.40	18.80	23.10	21.25
Hour Angle Ws	101.47	98.90	91.25	85.08	79.79	77.17	78.35
	90.00	90.00	90.00	90.00	90.00	90.00	90.00
Sunset Hour W's	90.00	90.00	90.00	85.06	79.79	77.17	78.35
Ho	40.83	37.94	34.03	27.83	23.95	20.12	22.50
Kt	0.55	0.57	0.54	0.58	0.51	0.55	0.50
Hd/H	0.36	0.39	0.39	0.37	0.36	0.35	0.39
Rb	0.85	0.94	1.09	1.29	1.56	1.63	1.57
R	0.90	0.96	1.04	1.17	1.30	1.40	1.34
Ht (MJ/sq.m)	21.75	20.80	19.61	17.84	15.45	15.50	15.16
Ht (kWh/sq.m)	6.04	5.78	5.45	4.96	4.29	4.31	4.20

Resulting radiation data on a tilted plane

Figure 5 Spreadsheet calculations of irradiation data on an Equatorial Facing Plane tilted at the latitude angle of 27.5° (Source: SOLWATT software)

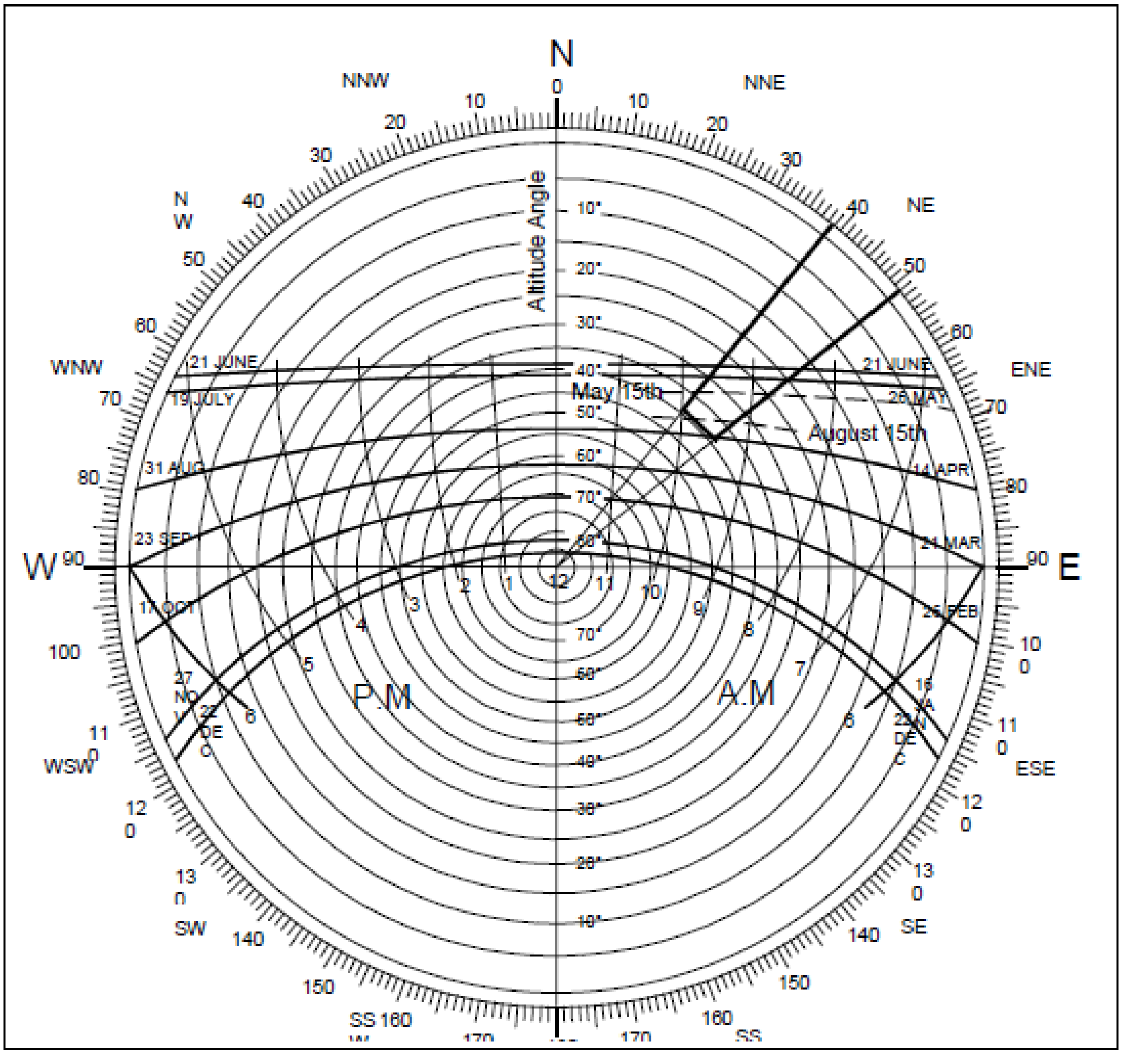


Figure A1.3.11 – Sun path diagram for Brisbane with shading from a tree shown

Question 8

Calculate the solar power arriving on 10 square meters of root area if the irradiance perpendicular to the roof is 1000W/m^2

$$P = G \times A = 1000 \times 10 = 10000W = 10kW$$

Question 9

Calculate the daily solar energy received by a standard hot water collector of dimensions 1m by 2m, in a location which receives 24MJ/m^2 day.

To determine the total solar energy received by an area over a period of time.

$$E = H \times A$$

$$E = a \times A \times t$$

E = Energy received by the collector area (J)
H = Irradiation (J/m^2)
a = Irradiance (W/m^2)
A = collector Area (m^2)
t = The period of time over which energy is received

$$E = H \times A = 24 \times 2 \times 1 = 48mJ$$

Question 10

Calculate the solar energy received by a standard hot water collector of dimensions 1m by 2m, over one hour at round noon, if the irradiance stays fairly constant at about 800W/m^2

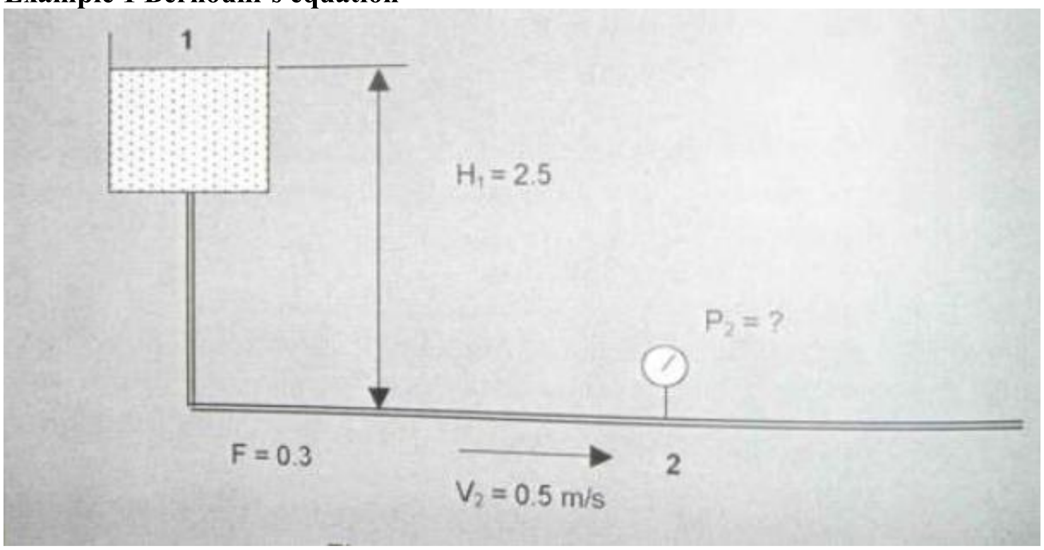
$$
\begin{aligned}
E &= a \times A \times t \\
&= 800 \times 1 \times 2 \times 3600 \\
&= 5760000J \\
&= 5.76mJ
\end{aligned}
$$

Question 11

Losses due to friction can be allowed for by adding a term

$$H_2 + \frac{V_2^2}{2g} + \frac{P_2}{\rho g} + F = H_1 + \frac{V_1^2}{2g} + \frac{P_1}{\rho g}$$

Example 1 Bernoulli's equation



$$H_1 + \frac{V_1^2}{2g} + \frac{P_1}{\rho g} = H_2 + \frac{V_2^2}{2g} + \frac{P_2}{\rho g} + F$$

$$2.5 + \frac{0^2}{2g} + \frac{0}{\rho g} = 0 + \frac{0.5^2}{2g} + \frac{P_2}{\rho g} + 0.3$$

$$2.5 = \frac{0.25}{2 \times 9.81} + \frac{P_2}{1 \times 9.81} + 0.3$$

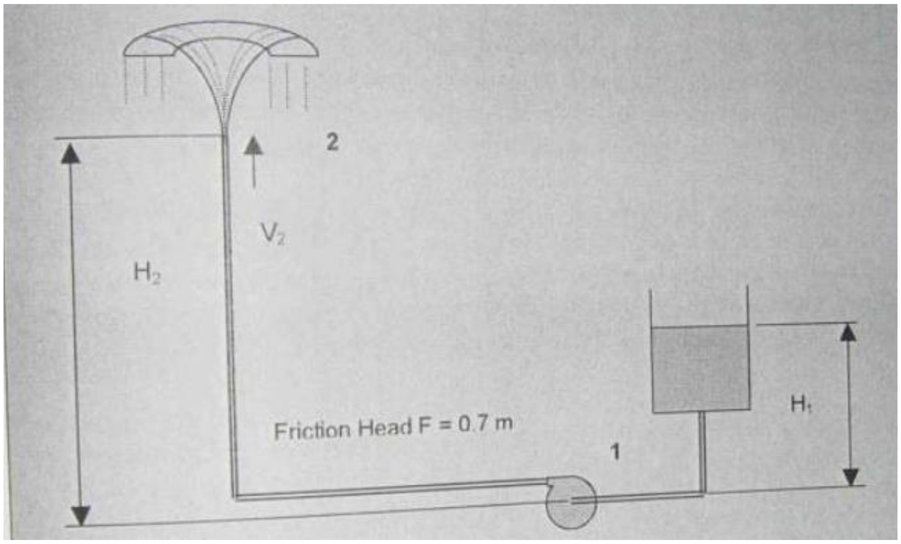
$$2.5 = 0.0127 + 0.3 + \frac{P_2}{9.81}$$

$$2.1873 = \frac{P_2}{9.81}$$

$$P_2 = 21.45 kPa$$

Question 12

Example 2 Pumping Head



Calculate Pumping Head P_1

$$H_1 + \frac{V_1^2}{2g} + \frac{P_1}{\rho g} = H_2 + \frac{V_2^2}{2g} + \frac{P_2}{\rho g} + F$$

$$0.5 + \frac{0^2}{2g} + \frac{P_1}{1 \times 9.81} = 3 + \frac{2^2}{2 \times 9.81} + \frac{0}{\rho g} + 0.7$$

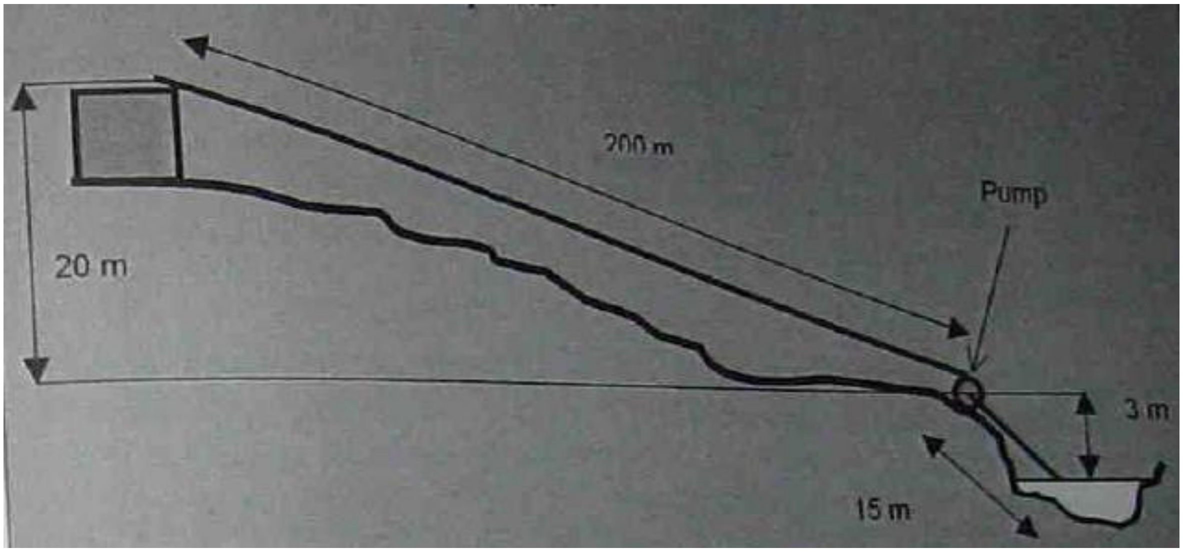
$$0.5 + \frac{P_1}{9.81} = 3 + \frac{4}{2 \times 9.81} + 0.7$$

$$\frac{P_1}{9.81} = 3 + \frac{4}{2 \times 9.81} + 0.7 - 0.5$$

$$P_2 = 9.81 \times 3.4 = 33.35 kPa$$

Question 13

Example 4 Total Head
The pump shown in Figure 5 below is lifting water from a dam at a rate of 3600L/hr to a storage tank 200m away. Select a suitable pipe size and determine the total head against which the pump must operate.



From friction loss table
Flow rate/m/s
Pipe diameter 50mm
Velocity =0,6m/s
Friction loss=1m/100
For (200+15)=215m, V_1=0.6m/s

$$flow = 3600L/hr = \frac{3600}{3600} L/s = 1L/s$$

$$\frac{\pi D^2}{4} \times V = Q(L/s)$$

$$\frac{\pi D^2}{4} \times V = 1$$

$$H_1 + \frac{V_1^2}{2g} + \frac{P_1}{\rho g} = H_2 + \frac{V_2^2}{2g} + \frac{P_2}{\rho g} = Total\ Head$$

$$\therefore Friction\, Loss = 2.2m$$

$$H_1 = 20m + 3m = 23m$$

$$\therefore Velocity\ Head = \frac{V_1^2}{2g} = \frac{0.6^2}{2 \times 9.81} = 0.02m$$

$$\therefore Total\ Head = 2.2 + 23 + 0.02 = 25.22m$$

Question 14

A solar module has NOCT of 49 C. What is cell temperature coefficient? What will be it's cell temperature if ambient temperature is 45 C and irradiance 75W/m^2.

$$T_{cell} = T_a + k \times G$$

T_{cell} = The cell temperature for the module (C)
T_a= The ambient air temperature (C)
K = cell temperature coefficient (C/W-m^2)
G = Irradiance (W/m^2)

$$k = \frac{T_{cell} - T_a}{G} = \frac{49 - 45}{75} = 0.053\ °C/W - m^2$$

Question 15

What are electrical, mechanical and thermal requirement of solar cell

(a) Electrical. Test for

- Isolation/ isolation rating
- I-V performance curve

(b) Mechanical. Tests are carried out to determine

- Resistance to impact
- Robustness of electrical terminals
- Rigidity of frame (twisting/bending)
- Wind loading (in excess of 200 km/hr)

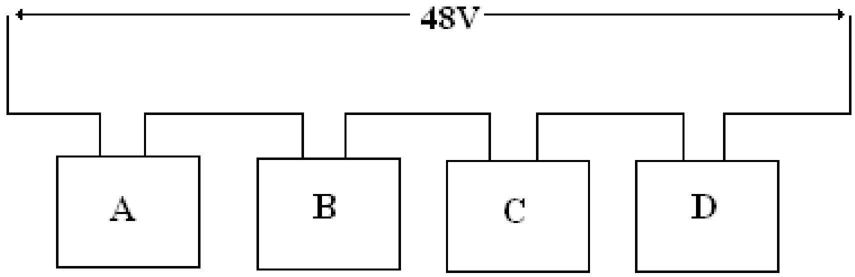
(c) Thermal. Test for

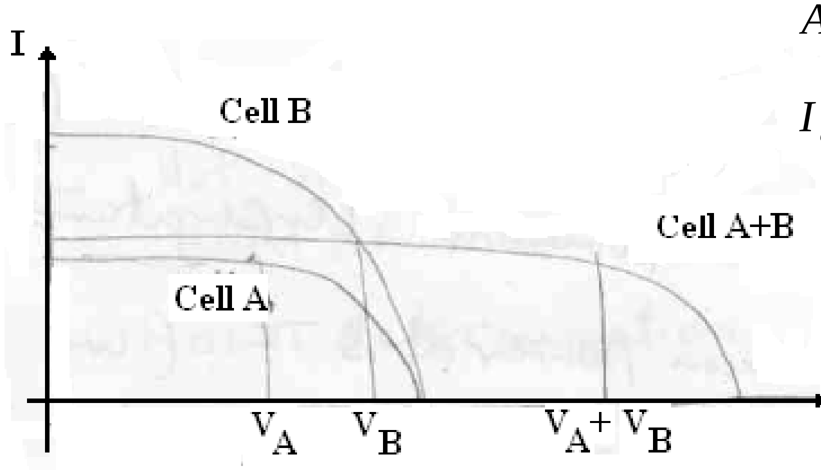
- Hot spot endurance test (to determine the effect of shading & cell overheating)
- NOCT determination

Question 16

Sketch the interconnection diagram of solar modules and explain the mismatch losses. How can it be avoided?

- **Interconnection of modules**





Average Operating Current

$$I_{co} = \frac{I_{ao} + I_{bo}}{2}$$

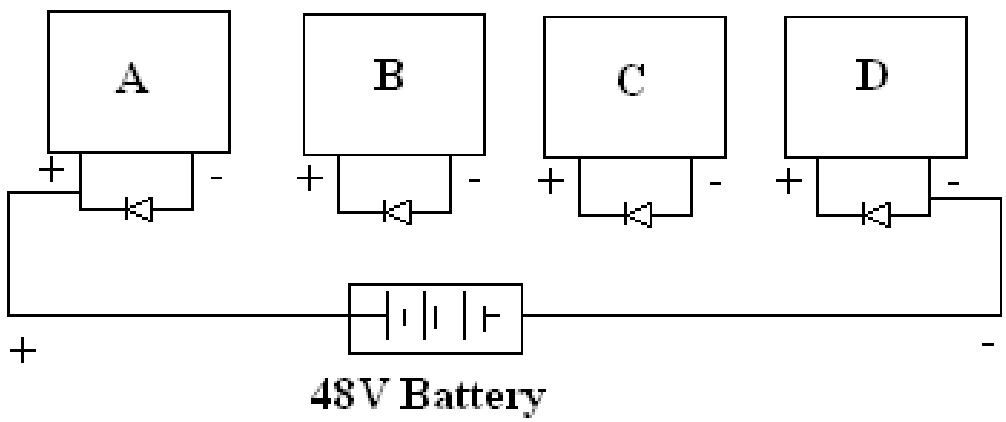
-
-
-
-
-
-
-
-
-

- **Mismatch Losses**

  The output of each series string of cells or modules is limited to the weakest one.

- **Shading & power dissipation**

  When part of a group of series connected modules is shaded, the unshaded cells in each of the modules will be trying to develop higher current than the shaded cells are able to develop. To avoid over loading, shunt connected diode is applied.



Question 17

Find the output power of a module operating maximum power point giving the followings that

- **typical maximum power at STC=87W**
- **NOCT -49°C**
- **Power output coefficient =-0.38%**
- **Ambient temperature =35°C**
- **Irradiance =865 w/m^2**

$$P_{STC} = 77W \quad \gamma = -0.38\%$$

$$T_A = 35°C \quad a = 865W/m^2$$

$$G_{STC} = 1000\,W/m^2 \quad T_{STC} = 25°C$$

$$P_T = 77 \times (1 - 0.38(T_{Cell} - 25)) \times \frac{865}{1000}$$

$$T_{Cell} = T_A + \frac{NOCT - 20}{800} \times G$$

$$= 35 + \frac{49 - 20}{800} \times 865$$

$$= 66.36$$

$$P_T = 77 \times (1 - 0.38(66.36 - 25)) \times \frac{865}{1000}$$

$$= 56.1W$$

Question 18

Calculate the daily energy output of a 100W poly crystalline module operating under the following conditions. Maximum power point tracking regulator MPPT, ambient temperature =25°C, Irradiation = 5.5kWH/m^2. The manufacturer who test the modules to international standard guarantees that the maximum module power rating to be 95W and NOCT=49°C and y=0.5%

$$E_{module} = P_{STC} \times \left[1 - \tau\left(T_{cell} - T_{ref}\right)\right] f_{man} \times f_{dirt} \times H_{daily}$$

P_{STC}=95W, f_{man}=1, f_{dirt}=95%=0.95, H_{daily}=5.5

$$T_{cell} = T_A + k\left(30 H_{daily} + 150\right)$$

$$k = \frac{NOCT - 20}{800} = \frac{49 - 20}{800} = \frac{29}{800} = 0.036$$

$$T_{cell} = 25 + 0.036 \times \left(30 \times 5.5 + 150\right) = 43°C$$

$$E_{module} = P_{STC} \times \left[1 - \tau\left(T_{cell} - T_{ref}\right)\right] f_{man} \times f_{dirt} \times H_{daily}$$

$$= 95 \times \left[1 - \frac{0.05}{100}\left(43 - 35\right) \times 1 \times 0.95 \times 5.5\right]$$

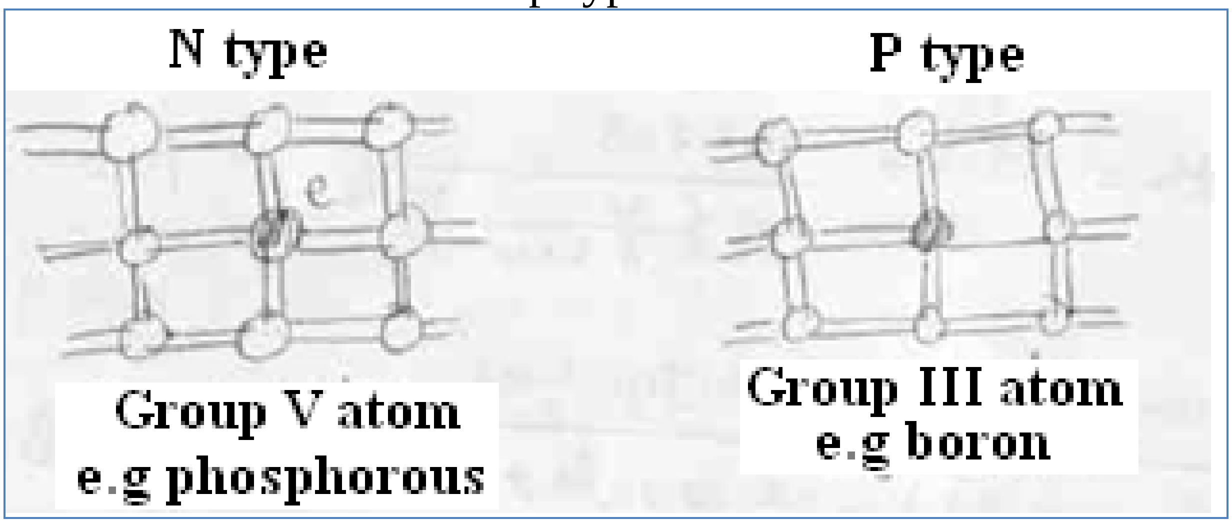
$$= 435W - hr$$

Question 19

Explain the followings

(i) Doping.

It is possible to shift the balance of electrons and holes in a silicon crystal lattice by doping it with other atoms. Atoms with one more valance electron than silicon an used to produce n type semiconductor material. Atom with one less valance electron result in p-type material.



(ii) Crystalline Silicon.

Ordered crystal structure

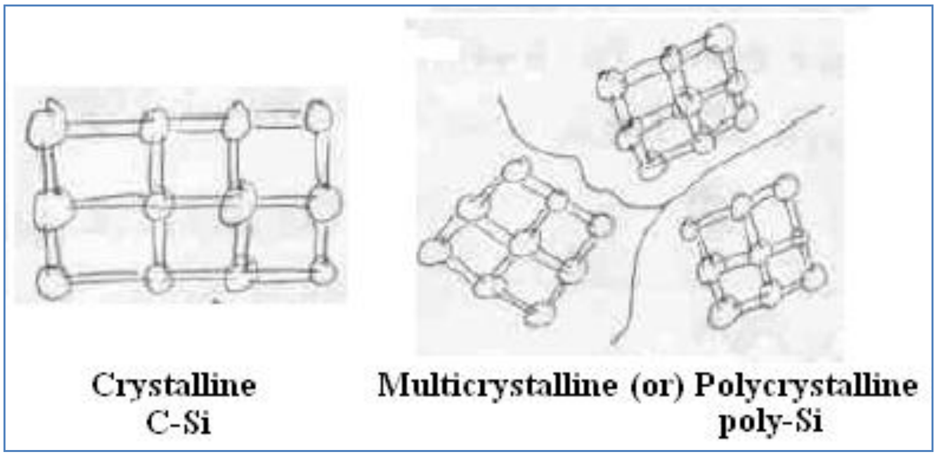
Each atom ideally lying in a pre-ordained position

Predictable and uniform behaviour

Most expensive type

Careful and slow manufacturing process required

(iii) Polycrystalline Silicon



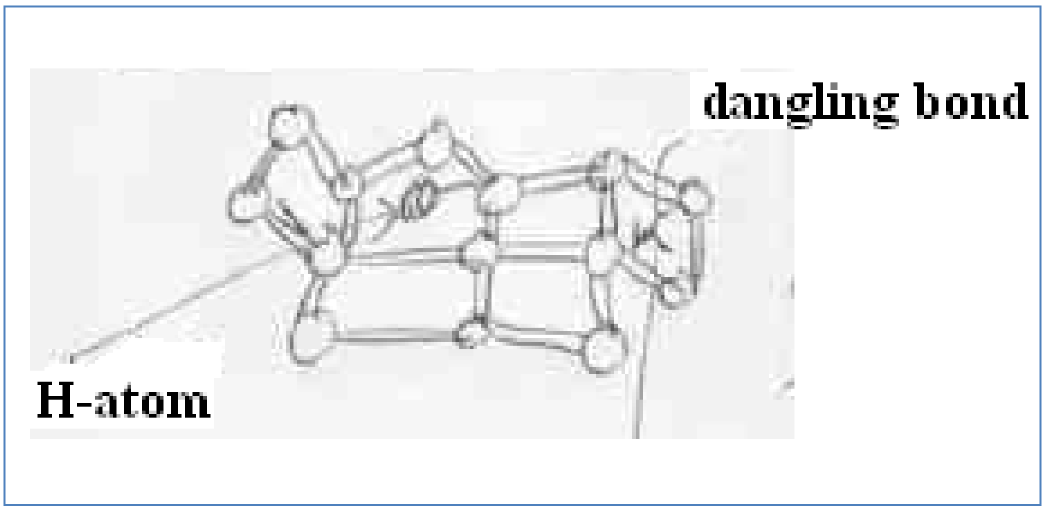
Regions of crystalline Si separated by grain boundaries where bonding is irregular

(iv) Amorphous

Like a liquid with less regular arrangement of atoms leading to internal dangling bonds.

Extra energy level with the forbidden gap

Making it impossible to dope the semiconductor when pure or to obtain reasonable carrier flow in a solar cell configuration.



Question 20

Express the equation for

(a) Dark characteristics

$$I_0 = A\left[\frac{qD_e n_1^1}{L_e N_A} + \frac{qD_h n_1^2}{L_h N_D}\right]$$

q = charge
L_h = difussion density
L_e = exposed length
A = crossectional area of diode
N_A = No. of acceptor electron
N_D = No. of donor electron

(b) Illuminated characteristics

$$I_L = qAG(L_e + W + L_h)$$

W= plate separation

A = crossectional area of diode

q = charge

G = Irradiance

Question 21

Explain the followings

(a) Solar irradiance

The rate at which solar energy strikes a surface. Intensity or the solar power (the power per unit area). On a clear day, around noon, the solar irradiance on a surface facing the sun will be about $1000W/m^2$ (or) $1kW/m^2$.

(b) Solar irradiation (Industry term – insolation)

The solar energy which strikes a surface over a period of time. In most places in Australia, for any month of the year the average daily irradiation on a horizontal surface will be between about $3kWh/m^2$ and $6kWh/m^2$.

(c) Black body

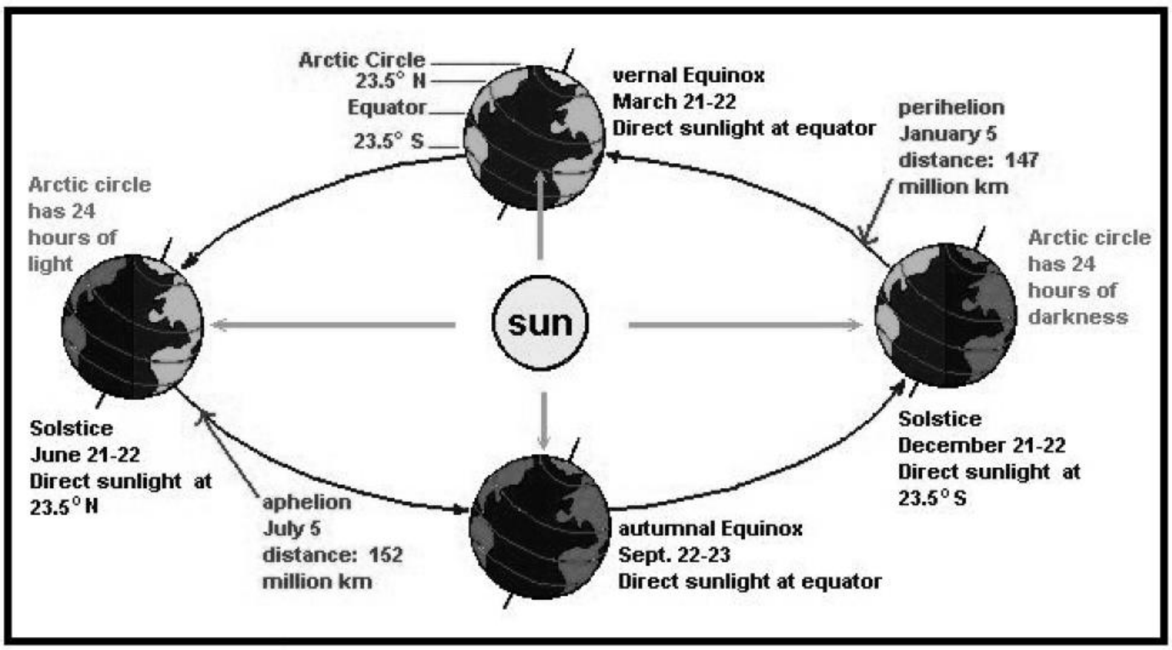
A black body is an ideal absorber, and emitter of radiation. As it is heated, it starts to glow, that is, to emit electromagnetic radiation.

Question 22

Sketch the solar geometry diagram for Australia

Australia

March 2/ Equinox
June 22 Winter
September 23 – Spring Equinox
December 21 – Summer Solstice



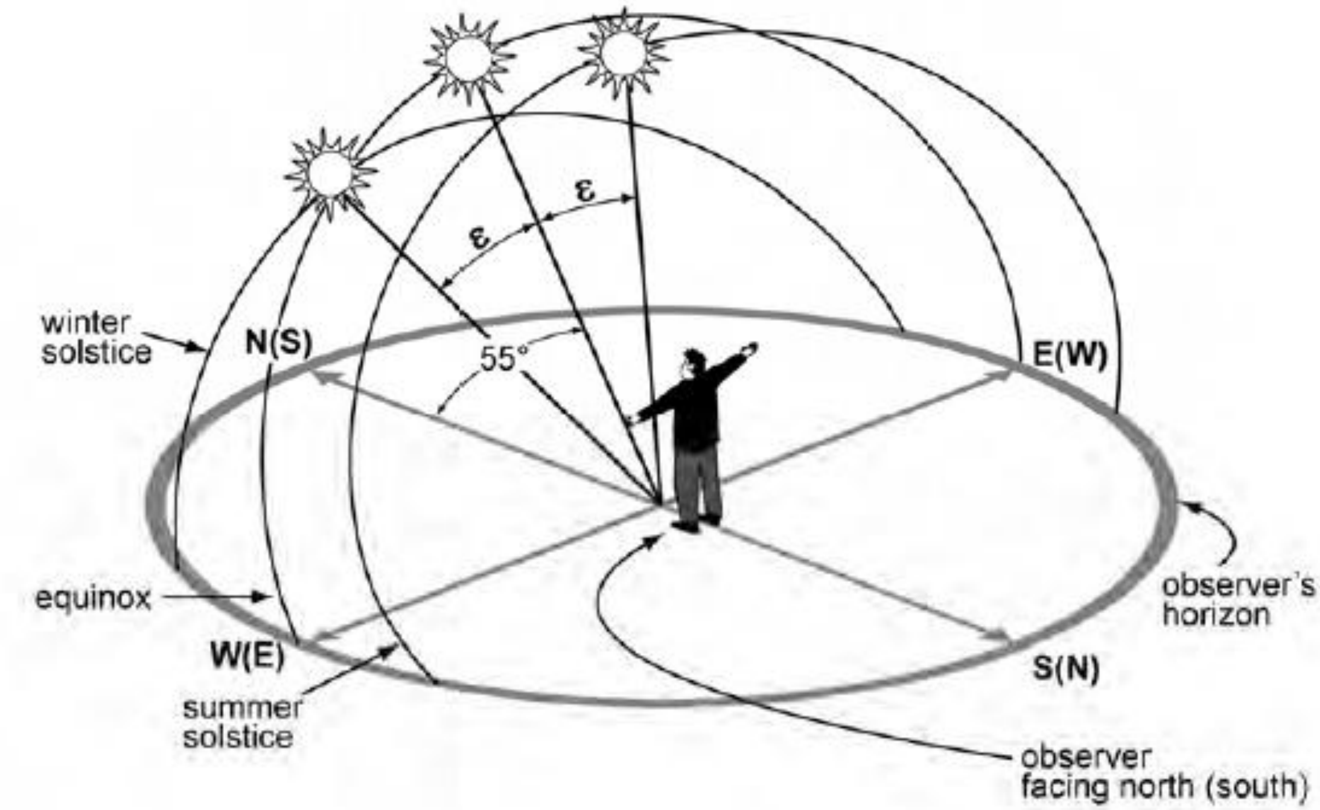


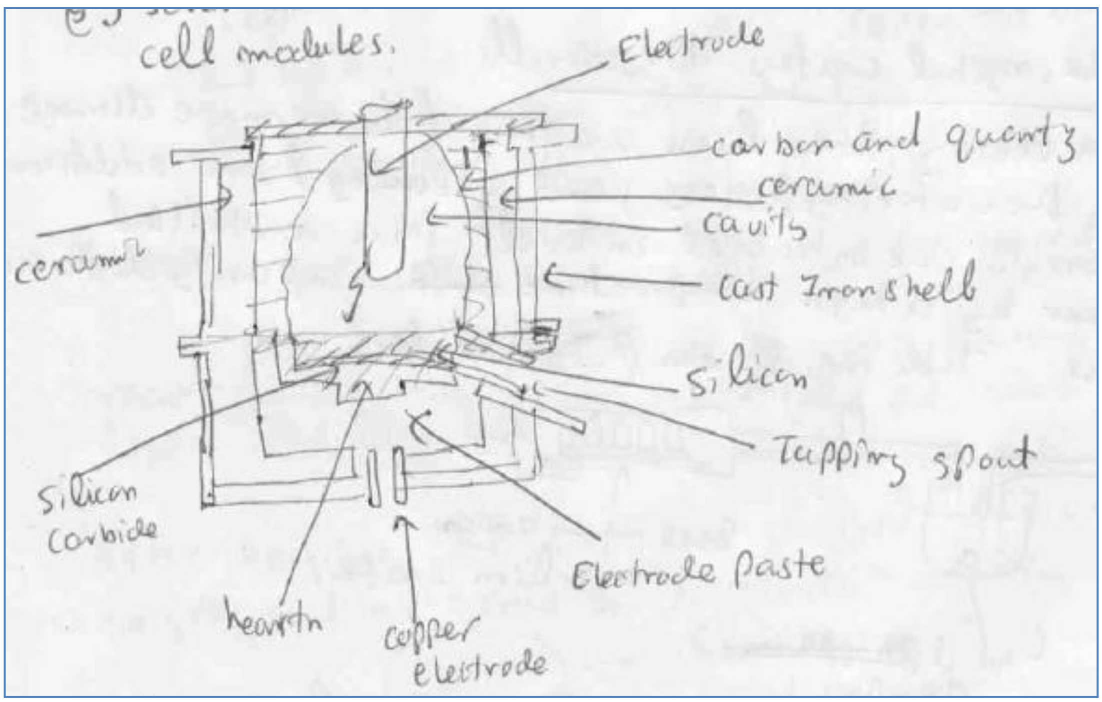
Figure 1.10. Apparent motion of the sun for an observer at 35°S (or N), where ε is the inclination of the earth's axis of rotation relative to its plane of revolution about the sun (= 23°27' = 23.45°).

Question 23

Describe the process to manufacture the solar cell

Standard Technology for making cells

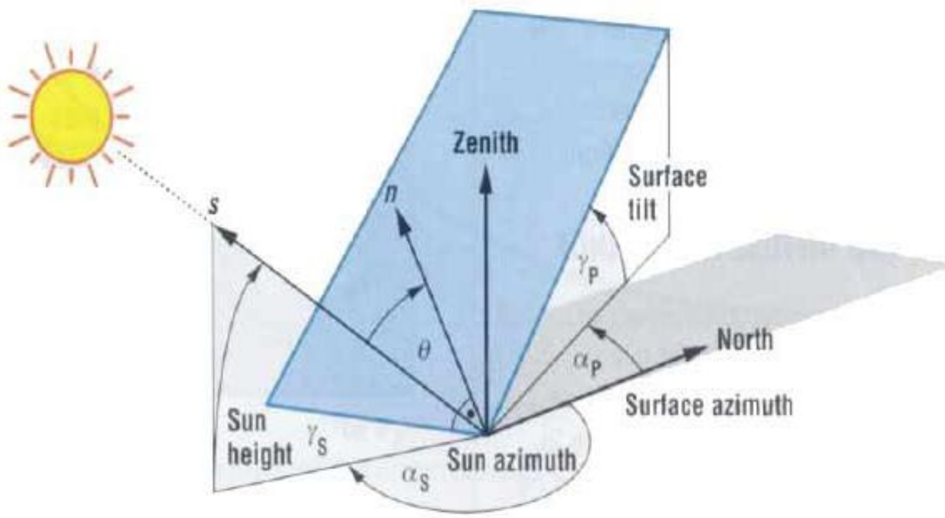
1) Reduction of sand to metallurgical grade silicon
2) Purification of metallurgical grade silicon to semiconductor grade silicon
3) Conversion of semiconductor grade silicon to single crystal silicon waters.
4) Processing of single crystal silicon waters in to solar cells.
5) Solar cell encapsulation into weather proof solar cell modules



Question 24

Locate the followings in the diagram

(a) Zenith (b) Angle of tilt plane (c) Incidence angle for tilted surface (d) Azimuth angle of sun (e) Orientation angle of tilted plane (f) Altitude angle of sun



$\beta = Tilt\ angle\ of\ solar\ plane$

$\gamma_Z = Azimuth\ angle\ of\ the\ sun$

$\gamma = Orientation\ angle\ of\ tilted\ plane$

$\theta_Z = Incidence\ angle\ for\ tilted\ surface$

$\alpha_r = Altitude\ angle\ for\ sun$

Question 25

What are the steps to be done in manual shading assessment?

Manual Shading Assessment using sun path diagram and hourly Irradiance

- Plotting the obstacles causing shading on to the sun path diagram to determine the likely day times and months of the year when the shading will occur.
- Then use the irradiation data table for hourly irradiance.
- The shaded amount of irradiation is estimated and deducted from the daily total irradiation.

Question 26

Calculate monthly daily average total irradiation on horizontal surface for January in Brisbane a=0.42, b=0.22 n=7.5 δ=20.9 ϕ= 27.5 n=17 (day number)

$$W = \cos^{-1}\left(-\tan\phi\tan\delta\right)$$

$$= \cos^{-1}(-\tan(-27.5)\tan(-20.9))$$

$$= 101.47$$

$$\bar{H}_a = \frac{24\times 3600\times G_{sc}}{\pi\times 10^6}\left[1+0.33\cos(\frac{360n}{365})\times\left(\cos\phi\cos\delta\sin\varpi\right)+\left(\frac{2\pi\varpi_s}{360}\right)\sin\phi\sin\delta\right]$$

$$= \frac{24\times 3600\times 1367}{\pi\times 100}\left[1+0.33\cos\left(\frac{360\times 17}{365}\right)\times\left(\cos(-27.5)\cos(-20.9)\sin(101.47)\right)+\left(\frac{2\pi\times 101.47}{360}\right)\sin(-27.5)\sin(-20.9)\right]$$

$$\bar{H}_a = 42.81 mJ/m^2$$

$$\bar{N} = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta)$$

$$= \frac{2}{15}\cos^{-1}(-\tan(-27.5)\tan(-20.9))$$

$$= 13.3$$

$$\frac{\bar{H}}{\bar{H}_a} = \left(a + b\frac{\bar{n}}{\bar{N}}\right)$$

$$\frac{\bar{H}}{42.81} = \left(0.42 + 0.22\times\frac{7.5}{13.3}\right)$$

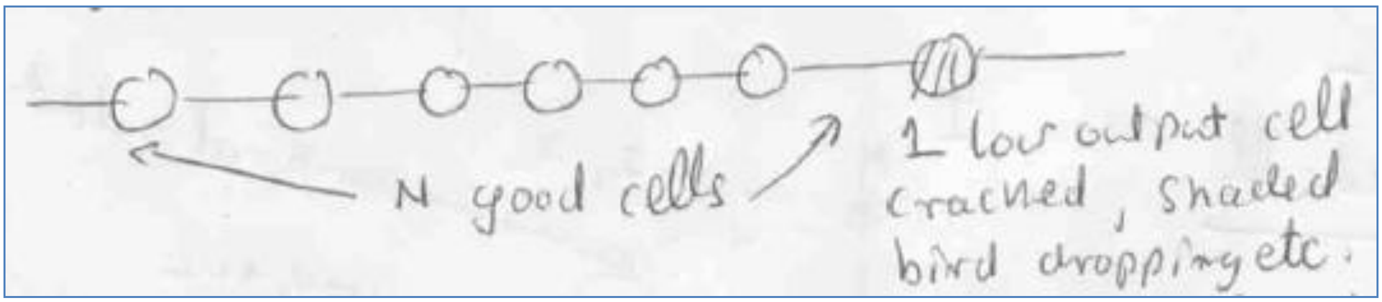
$$\bar{H} = 23.3 mJ/m^2$$

Question 27

Explain the followings

(a) Hot spot heating

Mismatched cell within a module can result in some cells generating and some dissipating power. In the worst case the whole output of good cells can be dissipated in the bad cell on short circuit.



Dissipation of power in poor cells leads in breakdown in localised regions of the cell p-n junction. Enormous power dissipation can occur in a small area leading to load overheating or hot spots which in turn leads to destructive effects such as cell or glass cracking or melting of solder

(b) Efficiency limit for black body cell

Blackbody solar cell in equilibrium emits photons. For photons of energy larger than band gap, the source of these photons is predominantly radiative recombination events in semiconductors. In thermal equilibrium these events will be balanced by an equal generation rate.
Silicon – minimum value of Io – max Voc=850mV

(c) Effect of temperature on solar cell

The short circuit current of solar cell is not strongly temperature dependant. The relation between short circuit current and open circuit voltage.

$$I_{SC} = I_0\left(e^{\frac{qV_{oc}}{KT}} - 1\right)$$

Ego=zero temperature bond gap of semiconductor making up cell

$$I_0 = AT^{\gamma} e^{-E_{go}/KT}$$

A=Independent of temperature
T=Temperature
γ=Temperature dependencies in determining Io

$$I_{SC} = AT^{\gamma} e^{-E_{go}/KT} \times e^{qV_{oc}/KT}$$

$$\frac{dV_{oc}}{dt} = \frac{V_{go} - V_{oc} + \gamma(KT/q)}{T}$$

For silicon V_{go}=1.2V, T=300K, V_{oc}=0.6V, =3, k/q=6.23x10^{-6}

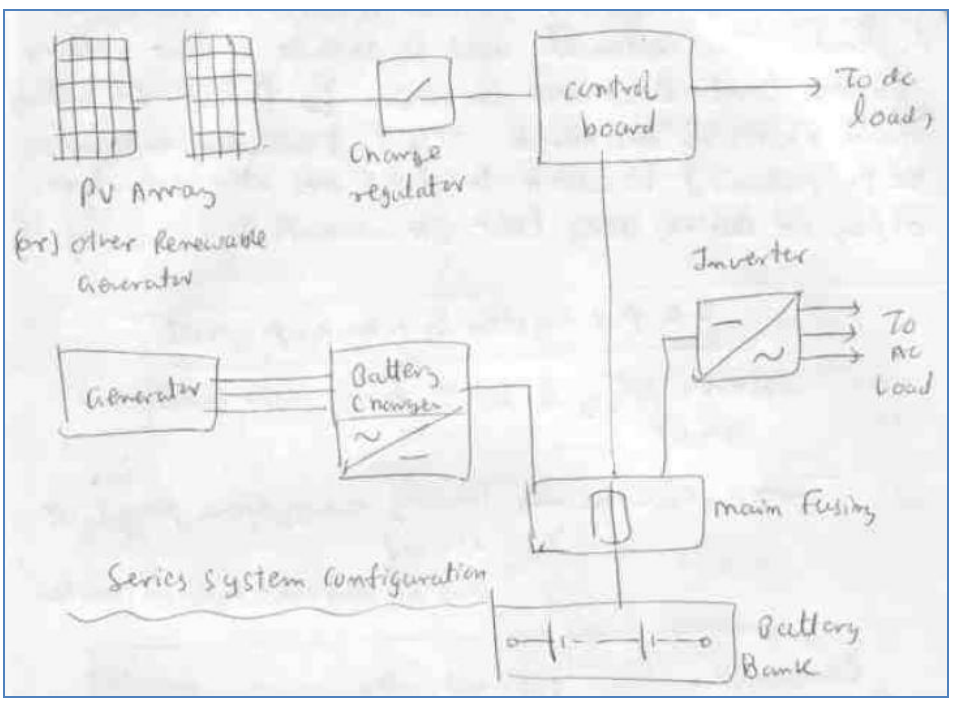
$$\frac{dV_{oc}}{dt} = \frac{1.2 - 0.6 + 3\left(300 \times 6.23 \times 10^{-6}\right)}{300} = \frac{1.2 - 0.6 + 0.078}{300} = 2.3mV/{}^{\circ}C$$

Question 28

Sketch the followings

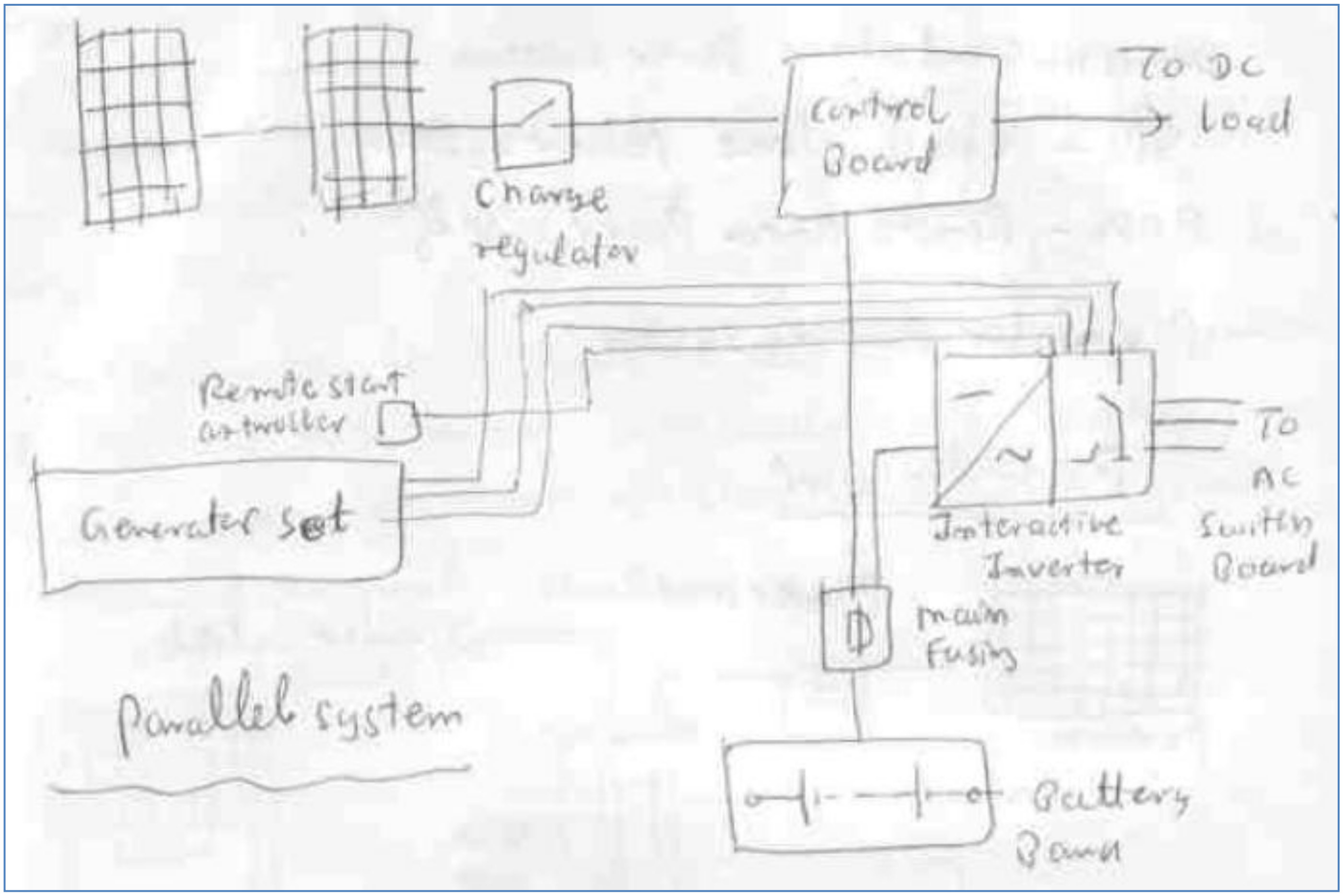
(a) Series system

- All of the supplementary energy input from the generator is fed into battery via battery charger.
- All of the supplementary energy provided by the generator passes through both the battery charger and the battery.
- For dc loads trough the inverter as well.
- The efficiency of use of gen set output is low.



(b) Parallel system

- Special inverter interactive/bidirectional inverter is used.
- Two type of inverter can charge the batteries as well as connected the generator supply to ac loads while the generator is running.



Question 29

Sketch the followings

(a) Grid connected PV system

An alternative to stand alone PV is to source supplementary energy from the electricity grid. This eliminates the need for energy storage since power can be drawn from the grid at times when the PV system cannot meet demand and excess power not immediately needed by the loud is supplied to the grid.

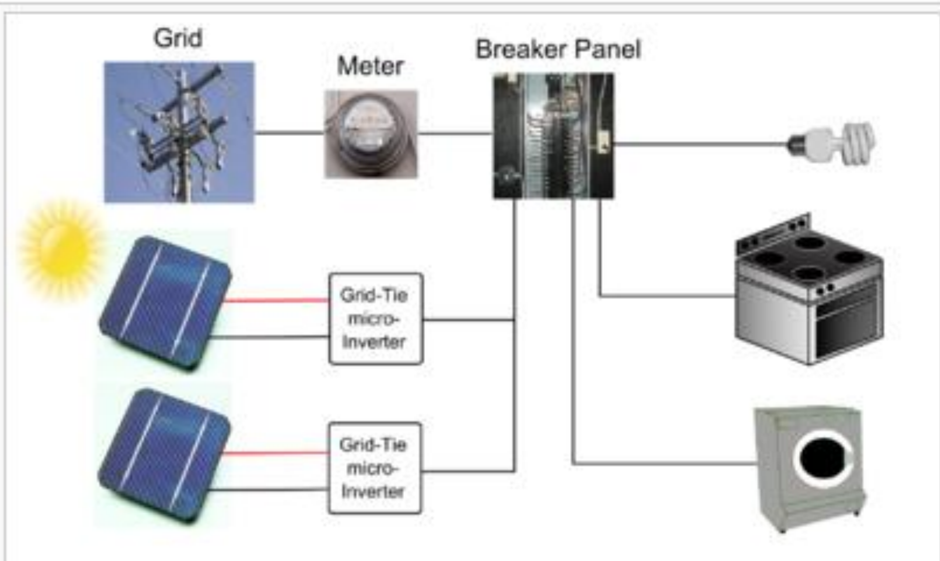
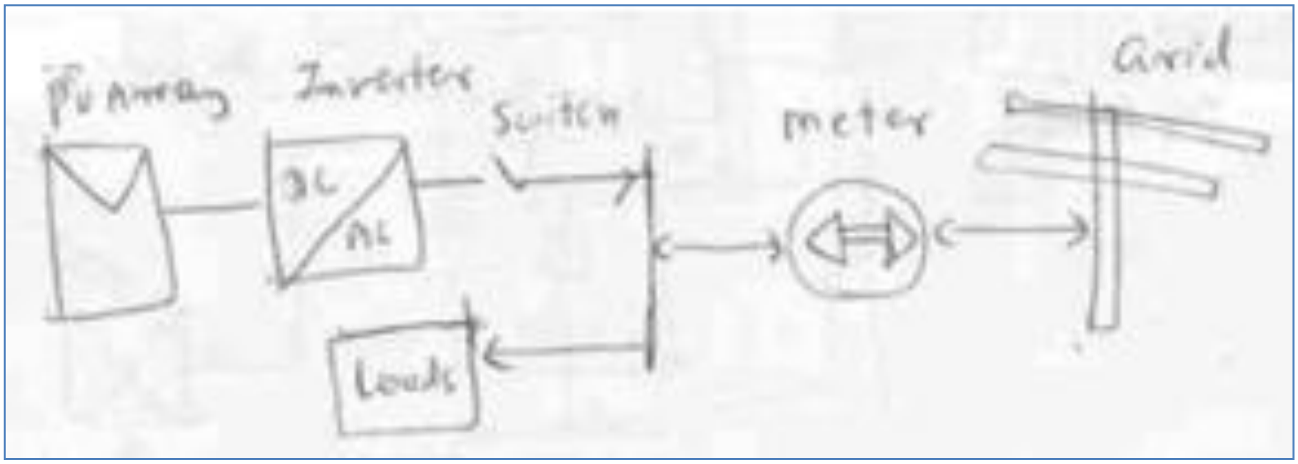
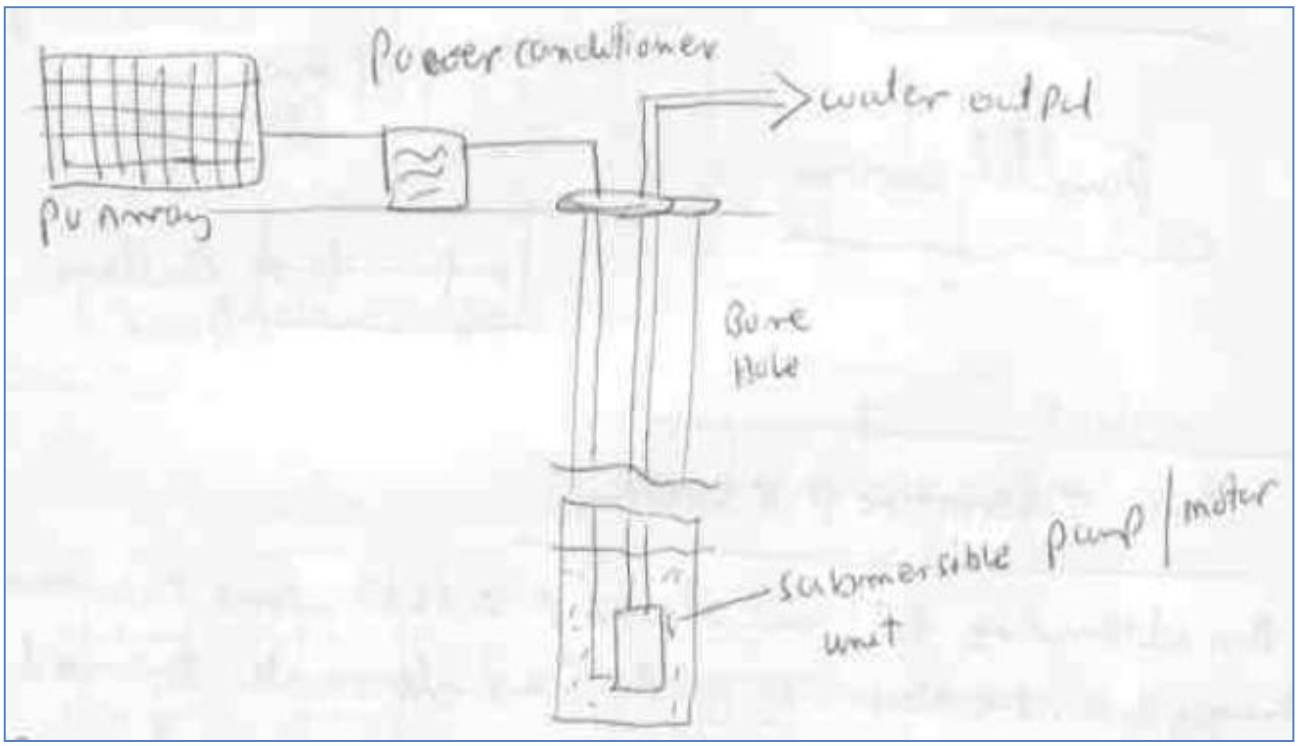


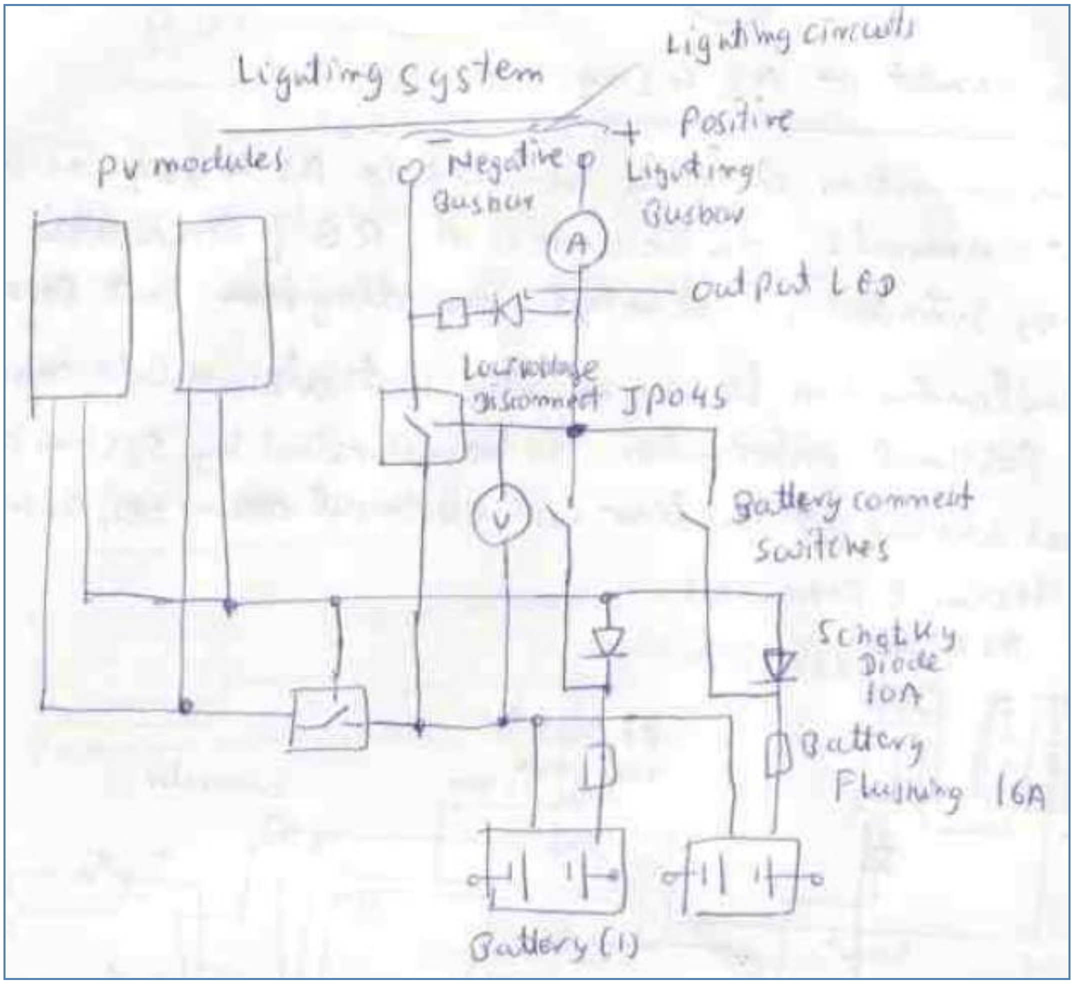
Diagram of a residential grid-connected PV system



PV water pumping system



(b) PV lighting system



Question 30

What are the steps to design the PV water pumping system?

- Determine the volume of water to be pumped each day and at what head
- Calculate the pump rate from the number of sun light hours.
- Select the pump type
- From the torque speed characteristic of the pump select a motor with a compatible torque-speed characteristics.
- Select appropriate solar panels

Direct Couple System

The direct coupled system is not suitable for the following situations

(a) When pumping heads are too large to be able to use a centrifugal pump with reasonable efficiency.
(b) When suitable dc motors are not available, such as with some large systems (>10HP) where little noise exists or when a submersible motor is

necessary and no brushless dc motors are available at a suitable price.

(c) When the pumping rate in bright sunshine exceeds the water source replenishment rates.

(d) When it is essential batteries to be used for energy storage (i.e. where availability of pumped water must be very high and tank storage) e.g. portable units.

(e) Locations characteristic by excessive cloudy weather making the poor part-loud efficiencies of directly coupled system unacceptable.

Consideration

- Volume of water to be pumped
- Pumping head and seasonal variations
- Water storage and consumer’s need
- Insolation data
- Select the pump to suit starting torque requirement
- Select a motor with a torque (speed characteristics compatible with that of the pump.

$$V_m = k\phi H + I_a R_a$$

m = motor, a= Armature, N=speed

ϕ = flux, k = motor constant, R_a = resistance of armature, I_n=motor current

Question 31

Why energy efficiency is important in solving the problem of Global warming?

Most of our energy comes from fossil fuels, and burning these fuels causes environmental problems, and in particular, the global warming problem. Global warming raises the sea level; brings drought in tropical regions near the equator; increases hurricanes, tornadoes, and floods; and causes the spread of diseases. Various measures to solve or mitigate the global warming problem have been proposed. Power electronics will play a very important role in clean energy generation, bulk storage of electricity, and efficient energy utilization, and eventually, it will be a key element in the energy policies of nations. It has been estimated that the widespread energy efficiency improvement by power electronics and other methods with the existing technologies can save 20% of the global energy demand, and another 20% can be saved by preventing waste, i.e., by various conservation methods.

Question 32

Present a typical Stand Alone Power System. The submission must include

(a) Construction diagram (b) Technical Data (c) Apparatus used

The design of stand-alone PV-based power system is determined by the location, climate, site characteristics and equipment used. Figure 6.2 shows a schematic of a typical PV-based stand-alone power system.

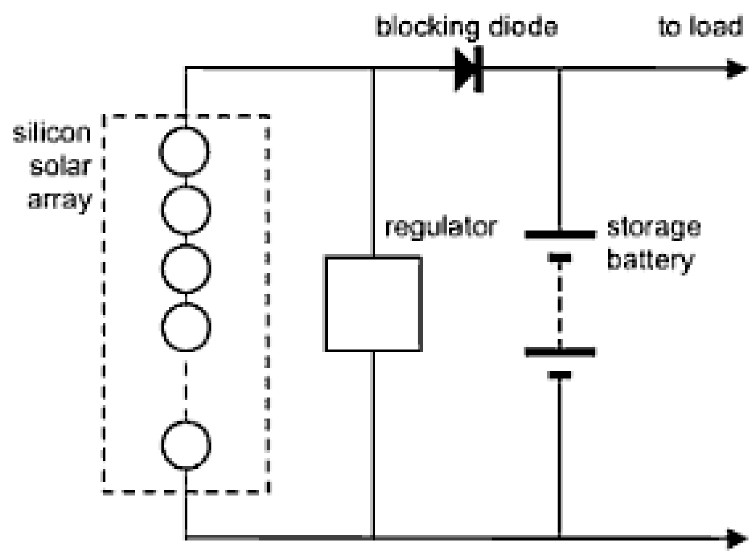


Figure 6.2. Simplified stand-alone PV power system (Mack, 1979, reprinted with permission of the Telecommunication Society of Australia).

Design Procedures

1. **Load determination** - To specify the load as accurately as possible, and hence achieve a system design that optimises components and costs, the following information is need:
   - Nominal system voltage
   - Range of voltages able to be tolerated by load
   - Average load per day
   - Load profile throughout the year

   For a microwave repeater station, for example, the voltage may be 24+/-5V, the average load 100W (current=4.17A), and the required storage 15 days.
2. **Select battery capacity** – For telecommunications loads, the design approach is quite conservative, allowing for 15 days of battery storage to give very high availabilities. For the example given above, this would be
   4.17A x 24h x 15 days = 1500Ah.

3. **First approximation of tilt angle** – This is based on site information and usually involves selecting a tilt angle 20° greater than the latitude. For example, for Melbourne, which is at latitude 37.8S, the first approximation for tilt angle is 37.8 + 20 = 57.8°

4. **Insolation** – From the available site insolation data, the actual insolation falling on the array at the selected tilt angle can be estimated. An example of typical insolation data throughout the year falling on a horizontal plane in Melbourne. Using this insolation data, sample calculations are provided for determining the actual corresponding amount of insolation that will fall on the photovoltaic array when tilted at an angle of 57.8°. An assumption made in these calculations is that the diffuse component of the insolation data is independent of tilt angle. This is a reasonable approximation, provided the tilt angle is not too great.
5. **First approximation of array size** – As a rule of thumb, the initial array size in peak amps (1kW/m2) is selected to be five times the average load current. This figure is large because:
   - The sun does not shine at night
   - There is reduced light intensity during mornings, afternoons and periods of cloudy weather.
   - The batteries have a limited charging efficiency

- There is some self-discharge of the batteries
- Dust often partly obscures light penetration

Using the initial array size and the modified insolation data from (4), the ampere-hours generated throughout the year can be calculated. In these calculations, allowance needs to be made for loss owing to dust coverage, assumed to be in the vicinity of 10% although this may be an overestimation for the impact of dust. An Arizona study (Hammond, 1997) found that for modules at normal incidence to the sun, soiling causes a maximum of 3% loss between periods of rain but that the loss increased with incidence angle, to 4.7% and 8% at 58. Bird droppings, however, can have a more serious impact.

The electricity generated can then be compared to the amount consumed by the load throughout the year. When calculating the load consumption, allowance needs to be made for self-discharge of the battery, usually set at about 3% of the battery charge per month.
Assuming the batteries are at a full state of charge in summer, the state of charge of the batteries throughout the year can be determined.

6. **Optimising array tilt angle** – Retaining the same array size, the above procedures can be repeated with small variations in the array tilt angle until the depth-of-discharge of the batteries is minimised. This represents the optimal tilt angle.

7. **Optimising array size-** Using the optimal tilt angle, the array size can be optimised, in conjunction with the depth-of-discharge of the batteries, by using successive approximations of array size in conjunction with the above procedures.
8. **Summarise the design.**

In a stand-alone system, solar modules are usually used to charge a battery. A typical 36 cell module, based on screen-printed or buried-contact silicon cell technology, has the cells series connected to suit of a 12V battery. Typical characteristics for each (screen printed) cell would be:

$$V_{oc} = 600mV(25°C)$$

$$I_{sc} = 3.0A$$

$$FF = 75\%$$

$$V_{n\psi} = 500mV(25°C)$$

$$I_{n\psi} = 2.7A$$

$$Area = 100cm^2$$

Therefore, 36 cells in series give:

$$V_{oc} = 21.6V(25°C)$$

$$I_{sc} = 3.0A$$

$$FF = 75\%$$

$$V_{n\psi} = 18V(25°C)$$

$$I_{n\psi} = 2.7A$$

Question 33

Estimate total electrical energy used in your home and calculate the size of solar panel to supply the electrical load. Also include the appropriate size of the battery. Use the following solar irradiation data a=0.42, b=0.22, n=7.5 δ=20.9 n= 17 (day number). You need to find latitude angle ϕ of Sydney

Sydney Latitude =-33.867

The daily average total irradiation on horizontal surface is calculated as follows

$$\begin{aligned}\varpi &= \cos^{-1}(-\tan\phi\tan\delta)\\ &= \cos^{-1}(-\tan(-33.86)\tan(-20.9))\\ &= -104.76\end{aligned}$$

$$\begin{aligned}H_a &= \frac{24\times 3600\times G_{SC}}{\pi\times 10^6}\left[1+0.33\cos\left(\frac{360\times n}{365}\right)\times\left[\cos\phi\cos\delta\sin\varpi_s + \frac{2\pi\varpi_s}{300}\sin\phi\sin\delta\right]\right]\\ &= \frac{24\times 3600\times 1367}{\pi\times 10^6}\left[1+0.33\cos\left(\frac{360\times 17}{365}\right)\times\left[\cos(-33.86)\cos(-20.9)\sin(104.76) + \frac{2\pi\times 104.76}{360}\sin(-33.86)\sin(-20.9)\right]\right]\\ &= 60.08 mJ/m^2\end{aligned}$$

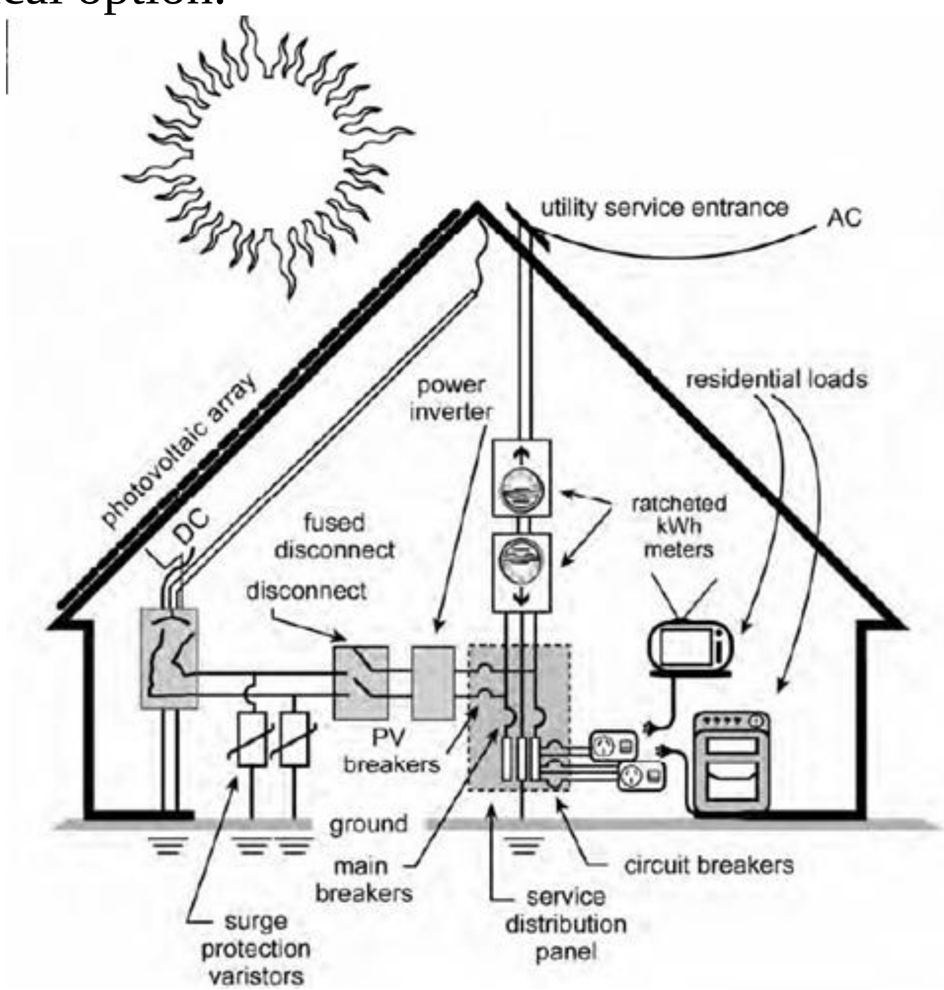
$$\begin{aligned}\bar{N} &= \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta)\\ &= \frac{2}{15}\cos^{-1}(-\tan(-33.86)\tan(-20.9))\\ &= 13.96\end{aligned}$$

$$\frac{\bar{H}}{\bar{H}_a} = \left\{ a + b \frac{\bar{n}}{\bar{N}} \right\}$$

$$\frac{\bar{H}}{60.08} = \left\{ 0.42 + 0.22 \times \frac{7.5}{13.96} \right\}$$

$$\bar{H} = 32.33 mJ / m^2$$

For household systems, modules can be mounted on array frames next to the house, in a position where no shading from buildings or trees would occur. However in many cases, rooftop mounted offers the best aspect and the safest and most economical option.



To make much impact on typical household electricity use, a photovoltaic system of about 2kWp or 20m^2 would be needed. A system rate at 3-4kWp would supply most household needs.
Example:

A house has the following electrical appliance usage:

- One 18 watt fluorescent lamp with electronic ballast used 4 hours per day
- One 60 watt fan used for 2 hours per day
- Size the PV panel
- One 75 watt refrigerator that runs 24 hours per day with compressor run 12 hours and off 12 hours.

The system will be powered by 12 Vdc, 110Wp PV module.

1. **Determine power consumption demands**

Total appliance use = (18W x 4 hours) + (60W x 2 hours) + (75W x 24 x 0.5 hours)

=1,092 Wh/day

Total PV panels energy needed = 1,092x1.3

=1,419.6 Wh/day

1.1 Total Wp of PV panel capacity needed = 1,419.6/3.4

= 413.9Wp

1.2 Number of PV panels needed =413.9/110

=3.76 modules

Actual requirement = 4 modules

So this system should be powered by at least 4 modules of 110 Wp PV module.

2. **Inverter sizing**

   Total Watt of all appliances = 18 + 60 +75 = 153 W

   For safety, the inverter should be considered 25-30% bigger size.

   The inverter size should be about 190 W or greater

3. **Battery sizing**

   Total appliances use = (18 W x 4 hours) + (60 W x 2 hours) + (75 W x 12 hours)

   Nominal battery voltage = 12V

   Days of autonomy = 3 days

$$Battery\ capacity = \frac{[(18W \times 4hours) + (60W \times 2hours) + (75W \times 12\,hours)] \times 3}{0.85 \times 0.6 \times 12}$$

$$Total\ \ Ampere - hours\ required\ 535.29\,Ah$$

So the battery should be rated 12V 600Ah for 3 day autonomy.

4. **Solar charge controller sizing**

   PV module specification

   Pm = 110Wp

   Vm = 16.7Vdc

   Im = 6.6A

   Voc = 20.7A

   Isc = 7.5A

Solar charge controller rating = (4 strings x 7.5A) x 1.3 = 39A
So the solar charge controller should be rated 40 A at 12 V or greater.