

Answers

4B14 Solar Electronic Power - 2006.

Q1
a)

Use the fact that reverse saturation is defined.

$$I_S = qA \left(\frac{D_e n_i^2}{L_e N_A} + \frac{D_h n_i^2}{L_h N_D} \right)$$

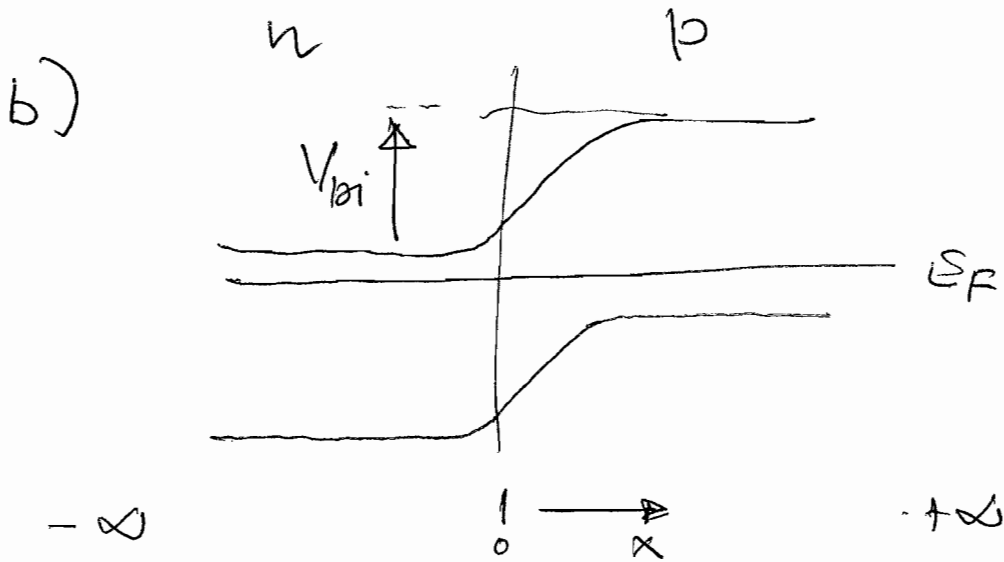
Since $L = \sqrt{Dt}$ $\therefore D = L^2/t$

$$\begin{aligned} \therefore I_S &= qA \left(\frac{L_e \cdot n_i^2}{\tau_e N_A} + \frac{L_h \cdot n_i^2}{\tau_h N_D} \right) \\ &= 1.602 \times 10^{-19} \times 10^{-2} \left(\frac{100 \times 10^{-6} \cdot 10^{32}}{2 \times 10^{-6} N_A} + \frac{0.5 \times 10^{-6} \cdot 10^{32}}{5 \times 10^{-9} \cdot 10^{24}} \right) \\ 10^{-4} &= 1.602 \times 10^{-11} \left[\frac{50}{N_A} + \frac{100}{10^{25}} \right] \end{aligned}$$

$$\frac{10^{-22}}{1.602} = \frac{50}{N_A} + 10^{-23}$$

$$\therefore N_A = \frac{50}{5.24 \times 10^{-23}} = 9.5 \times 10^{23} \approx \underline{\underline{10^{24} \text{ m}^{-3}}}$$

(2)



Under dark conditions with open circuit, no current can flow.

$$\therefore J_e = 0 \quad \text{and} \quad J_h = 0$$

Taking ~~J_e~~ electron current density J_e

$$J_e = -q n \mu_e E + q D_e \frac{dn}{dx} = 0$$

($-q$ for electrons; diff term $-\frac{D_e dn}{dx}$)

$$\therefore E = \frac{D_e}{\mu_e} \frac{1}{n} \frac{dn}{dx}$$

$$E = -\frac{dV}{dx} \quad \text{and} \quad \frac{D_e}{\mu_e} = \frac{kT}{q} \quad (\text{Einstein relationship})$$

$$\therefore \int_0^{V_{bi}} dV = -\frac{D_e}{\mu_e} \int_{n_0}^{n_0+d} \frac{dn}{n}$$

③

$$\begin{aligned} V_{bi} &= -\frac{De}{me} \ln \left[\frac{n^2}{N_D N_A} \right] = \frac{De}{me} \ln \left[\frac{N_D N_A}{n^2} \right] \\ &= 0.026 \ln \left[\frac{10^{25} \cdot 10^{24}}{10^{32}} \right] \\ &= \underline{\underline{1.02 \text{ V}}} \end{aligned}$$

$$\begin{aligned} c) \quad V_{oc} &= \frac{kT}{q} \ln \left(\frac{I_{sc}}{I_s} + 1 \right) \\ &= 0.026 \ln \left(\frac{3}{10^{-11}} + 1 \right) \\ &= \underline{\underline{0.69 \text{ V}}} \end{aligned}$$

Assumptions: ideality factor = 1 i.e. ideal
Temp remains at 300K
under solar light exposure.

$$\begin{aligned} d) \quad I_{sc} = I_{opt} &= q A g_{opt} (L_e + L_h) \\ 3 &= 1.602 \times 10^{-19} \times 10^2 g_{opt} (100.5 \times 10^{-6}) \\ g_{opt} &= \underline{\underline{186 \times 10^{25} \text{ m}^{-3}}} \end{aligned}$$

Assumptions - All carriers generated within a diffusion length contribute to current.
- No recombination.
- No change in L_e, L_h from 300K values.

e)

$$\eta = \frac{V_{oc} I_{sc} FF_0}{P_{in}}$$
$$= \frac{0.69 \times 3 \text{ FF}_0}{900 \times 10^2}$$

(4)

From the formula given in the data sheet
assuming 300K operation

$$FF_0 = 0.84 \quad (V_{oc} = 0.69 \text{ V})$$

$$\therefore \eta = \frac{0.69 \times 3 \times 0.84}{9} = 0.193$$
$$= \underline{\underline{19.3\%}}$$

But - this is very much a best figure.

- Temp will rise in the conversion process as ~~the~~ energy of photons above the band-gap energy is converted to heat. (solar peak 550nm Si b-g 1000nm). This in turn causes reduction in V_{oc} (rise in I_s) and a reduction in FF_0 - also further reduction due to rise in ~~temp~~ temp.

FF_0 has also got to be modified by taking into account the series ~~reduction~~ resistance of the cell.

Q2
a)

c-Si is an indirect band-gap semiconductor and hence optical absorption is weaker (a photon to electron-hole conversion requires the emission or absorption of a phonon to preserve momentum of the excited electron). In amorphous Si the ~~momentum~~ momentum conservation rules are relaxed due to the disorder introduced in the band structure by the lack of any long range ~~crystalline~~ ^{spatial} crystal-like order in the arrangement of the Si atoms. This makes a-Si a pseudo-direct band-gap material. It is therefore a much better optical absorber (photon to electron-hole converter). This allows the physical thickness of the a-Si layer to be much thinner than c-Si for the absorption of the same amount of light. This is despite the fact that a-Si has a larger band-gap ($\approx 1.8\text{ eV}$) compared to c-Si (1.12 eV).

(6)

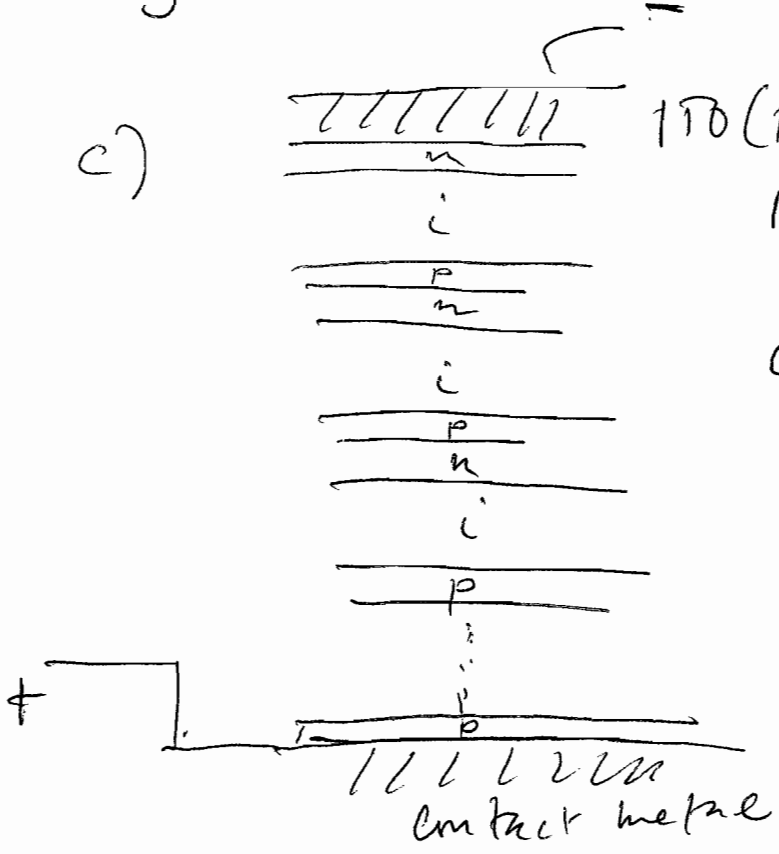
b) Photogenerated electron-hole pairs must be efficiently transferred to opposite electrodes ~~with~~ to generate the voltage and current required from a solar cell.

Electron and hole current ~~can~~ ~~to~~ have a drift component brought about by ~~the~~ an electric field acting on charge particles, and a diffusion component, brought about by concentration gradient of ~~the~~ charge particles. The electric field in a solar cell is due to the gradient of the built-in potential of the junction.

In c-Si ~~the~~ minority carriers (electrons on the p-side of the junction) ~~created~~ generated a long way from the junction can still 'diffuse' to it. Once close to the depletion layer at the junction interface, they experience the built-in electric field and 'drift' across ~~the~~ it to be collected on the n side of the junction (neg. terminal).

In a-Si: it the diffusion component is ~~almost~~ negligible. This is because of the high recombination rate due

to defects brought about disorder in the atomic structure. This leads to very short diffusion lengths. Therefore in a-Si:H the cell structure is made so that there is an extended depletion region within which photons are absorbed and electron-hole pairs generated. These generated carriers immediately experience a 'drift' field which acts to separate them. The extended depletion region is introduced by having ~~an i-l~~ a near intrinsic (undoped) a-Si:H layer sandwiched between the n and p layers.



c) TTC (transparent metal contact)
 number of series cells formed by sequential deposition of p-i-n layer. This allows the series connection of cell to obtain the required cell voltage
 - Because a-Si:H is a μ layer thin film

deposition process, it is possible to size ⁽⁸⁾ the area of the panel easily to achieve the required current rating.

d) a-Si:H panels are cheaper because the manufacturing process is large scale and lower temperature than that required for c-Si.

The energy consumed in the manufacturing process is directly reflected in the cost of the cell.

Therefore even though a-Si:H cells have lower efficiency ($\approx \times \frac{1}{2}$ of c-Si), they have $\frac{1}{2}$ the "energy pay back time" of a c-Si cell.

That is the time the solar cell has to operate to generate as energy as was consumed in its manufacture.

a-Si:H cells however, have a shorter operational lifetime ($\approx \times \frac{1}{2}$) than c-Si. Therefore the kWh/\$ available from both cells over their life time is about the same. One would use c-Si cells

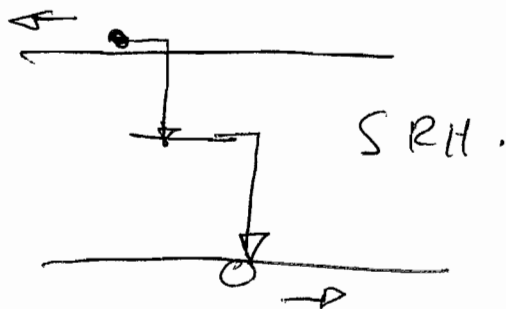
over a-Si:H cells when one wanted to maximise kWh/unit area and the operational life of the installation could extend to ≈ 20 years.

(9)

Q3

a)

Schokky-Read-Hall is an indirect mechanism mediated by states in the band-gap. An electron (hole) can first occupy a lower energy state in the band-gap. They can subsequently decay into the valence (conduction) band thereby effectively recombining with a hole (electron).

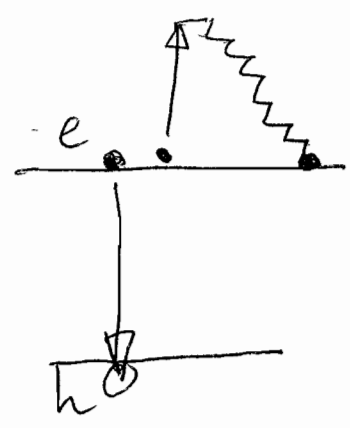


This occurs mainly in depletion regions where electrons and holes drift in opposite directions

$$R_{SRH} = \frac{n}{\tau_e} = \frac{p}{\tau_h} = \frac{n_p - n_i^2}{\tau_{ho}(n + n_i) + \tau_{eo}(p + p_i)}$$

where n_i and p_i are the concentration of electrons and holes in a depletion region due to excitement from traps states in the band-gap. Also in a depletion region, $n_i^2 = n_i p_i$

Auger recombination is a three body recombination process



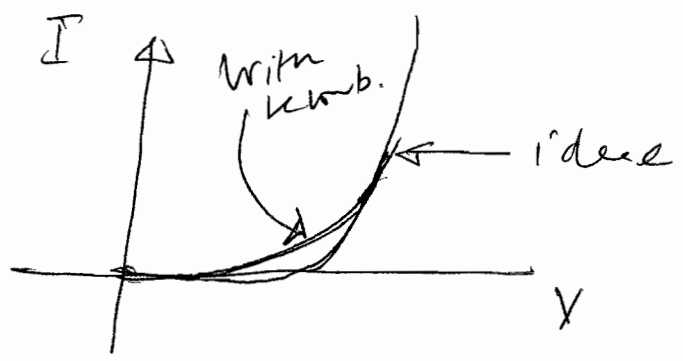
Electrons combine directly with holes. The energy liberated is absorbed by other electrons in the conduction band by being excited to a higher state. They then relax back to the bottom of the conduction band by emitting phonons (lattice vibrations) and generating heat.

$$R_{Aug} = \frac{n}{\tau_e} p \quad \text{where } \tau_e = G\tau_p + Dp^2$$

$$\text{or } \tau_h = G\tau_n + Dn^2$$

Therefore Auger processes only dominate in terms of minority carrier recombination when the ~~majority~~ majority carrier doping concentration is high (p^2, n^2 term). In C-Si when $N_D (N_A) > 10^{25} \text{ m}^{-3}$.

b) The ideality factor reflects the softer turn-on of a p-n junction diode due to the additional recombination current term - SRH in the depletion region.



$$I = I_S \left(\exp\left(\frac{q(V - V_{bi})}{kT}\right) - 1 \right)$$

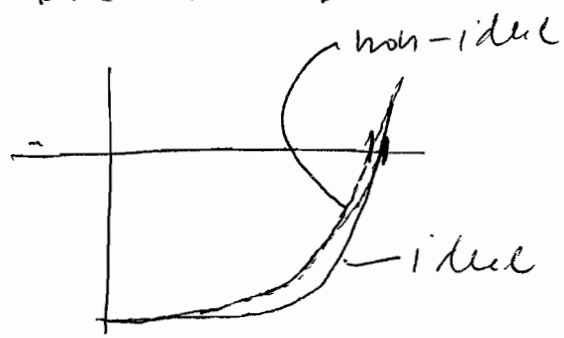
for an ideal diode

$$I = I_S^* \left(\exp\left(\frac{q(V - V_{bi})}{\eta kT}\right) - 1 \right)$$

for non-ideal diode $\eta > 1$ ideality factor

$$I_S^* > I_S \quad \eta > 1$$

In a solar cell



Reduction in V_{oc} and FF due to recombination - non-ideal.

c) Efficiency =
$$\frac{V_{oc} I_{sc} \cdot FF}{P_{in}}$$

$$V_{oc} = \frac{kT}{q} \cdot \eta \ln \left(\frac{I_{sc} + 1}{I_s} \right)$$

$$\approx 0.026 \times 1.1 \ln(10^8) = \overset{0.167}{0.53} V$$

$$I_{sc} = 2.5 A.$$

This is the short circuit current generated by the light coupled into the cell. This is (1-R) of the incident light; which could have been used for generating I_{sc}. Therefore the measured parameters are only on the basis of the actually absorbed light (excluding the reflected light). P_{in} on the other hand includes the absorbed and reflected light.

$$FF = 0.81 \quad (\text{From data sheet})$$

∴ power conversion efficiency (external)

$$= \overset{0.153}{15.3} \%$$

$$= \underline{\underline{10.8 \%}}$$

d) Optimise film to minimise reflectance at the peak of the solar spectrum - 600nm. (Assumption) (13)

$$\therefore \frac{\pi}{2} = \frac{2\pi \cdot 2.4 \cdot d}{600} = \frac{1600}{600}$$

$$d = \frac{600}{4 \times 2.4} = \underline{\underline{62.5 \text{ nm}}}$$

e) By applying the ATR coating the reflectance is:

$$R = \frac{(n_1 n_3 - n_2^2)^2}{(n_1 n_3 + n_2^2)^2} \quad (\text{from formula sheet})$$

$$= \left(\frac{\sqrt{11.9} - 2.4^2}{\sqrt{11.9} + 2.4^2} \right)^2 = 0.06$$

Prior to the application of the coating:

$$d=0 \quad \therefore$$

$$R = \frac{(n_1 - n_3)^2}{(n_1 + n_3)^2} = \frac{(1 - \sqrt{11.9})^2}{(1 + \sqrt{11.9})^2} = 0.3$$

∴ The absorption of photons at the solar ~~at~~ spectrum peak at 600 nm should go up by a factor ~~5~~

$$(1 - 0.3) / (1 - 0.06) = 1.38$$

To a first approximation it is possible to equate this to a proportional increase in I_{sc} .

∴ The new efficiency estimate would be

$$10.8 \times 1.38 = 0.184 \quad \text{or} \quad \underline{\underline{18.4\%}}$$

This is however an over estimate as only the peak of the spectrum ~~is~~ contributes to the I_{sc} increase of 1.38.

If we approximate the peak region to have 1/2 the available power within the spectrum, then the proportional increase should be halved.

$$\text{Then new efficiency} = \frac{12.9}{2} = \underline{\underline{6.45\%}}$$

Either answer acceptable - additional marks if 2nd estimate also given.

Q4.

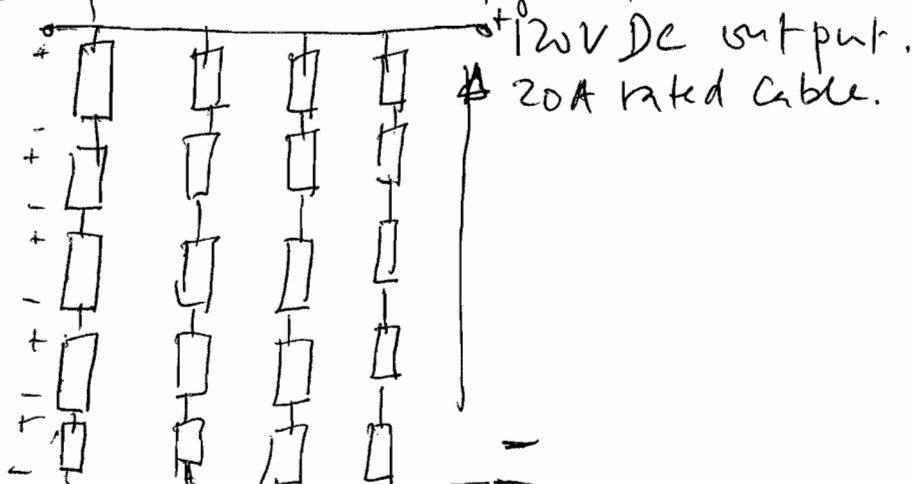
(75)

- a) A series and parallel combination. Better to have some series connection to raise voltage. Transmission of power from roof to the inverter at high voltage better to reduce I^2R losses in the cables.

But, series connection requires very well matched panels which have very similar I operating currents and voltages. Therefore, if some of the panels are shaded, for example, and the current drops, then power available from the whole installation is reduced. Power dissipation occurs in the shaded panel.

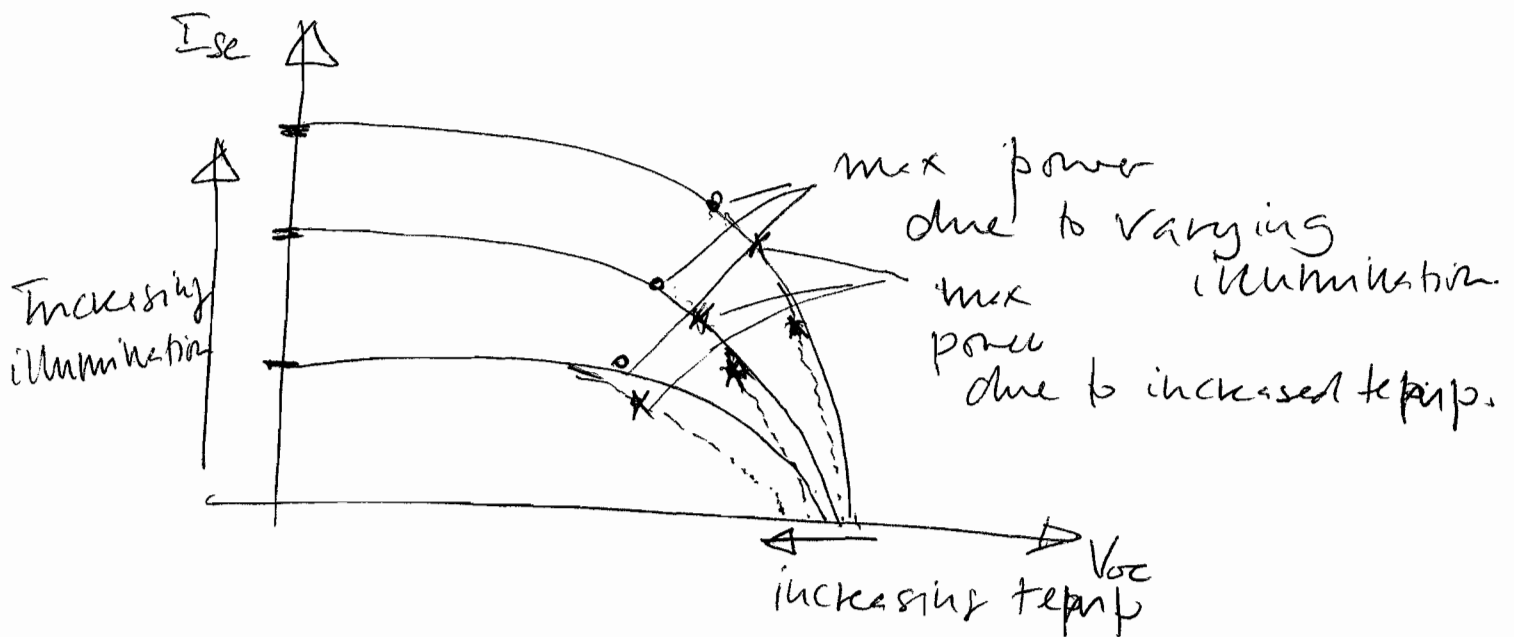
So, some series and parallel connection best. For a 2kW installation 20 panels

One possible configuration is:



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b) MPPT allows the solar panels to work at maximum power output by ~~constantly~~ load matching under conditions of varying illumination and temperature.



Two possible algorithms.

- 1) Dither. Change load current (impedance) and track power change. Example start at V_{oc} with $I=0$. Reduce ~~to~~ impedance ~~and~~ to increase I . Measure V and calculate $P (=VI)$. Continue until $P_{n+1} < P_n$. Then choose P_n as max power point. Once established dither around the point occurs at specified time intervals (typically 1-5 secs)

2) Mathematical section.

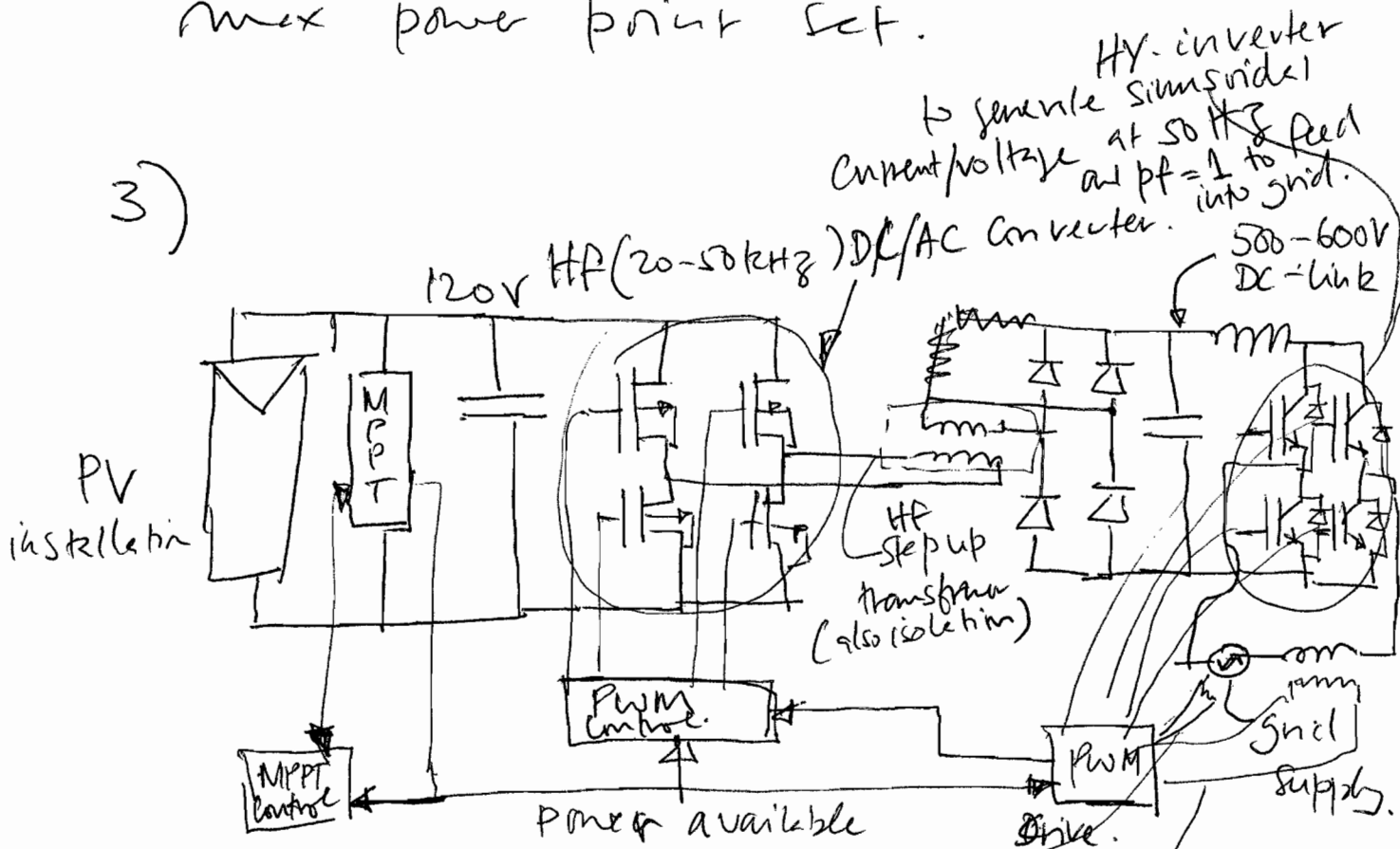
$$P = VI \quad \therefore \quad \frac{dP}{dI} = \frac{dV}{dI} \cdot I + V$$

At max power $\frac{dP}{dI} = 0$ as $\frac{dV}{dI} = -\frac{V}{I}$

I is changed and $V, \Delta V$ and ΔI monitored. When the $\frac{dV}{dI} = -\frac{V}{I}$

condition reached to a specified accuracy max power point set.

3)



MOSFETs better for LV HF inverter.
 IGBTs better for HV lower f. inverter.

Grid V measure. + phase measure
 output current measure

d) i)

Should cover

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- Possible to install in small and large units in a truly building integrated manner.
- All new building can have PV generators as part of building cladding/roofing.
- No green house gas emission
 - No energy storage required. Output directly to grid through efficient electronics
- Can generate enough power to smooth over load peaks in cities during the day.
- Net power consumption of a house can be made close to zero with solar installation.
 - ⇒ With new levys/credits on green house gas emission/mitigation, solar cells are not an expensive option compared to more traditional technologies.

ii) Should cover,

- Unreliability of electricity can lead to underdevelopment, lower ~~standard~~ quality of life and impaired health (due to lighting from oil lamps and inhalation of emissions). Particularly in developing countries.
- Standard electric power system cannot be expanded economically to isolated rural areas.
- 2bn people not connected to grid or present
- Solar a good option to provide a basic electric power capacity with battery storage. Can be supplemented by wind, mini-hydro, and biogas where appropriate.
- Cost can be cheaper than investment required to extend electric power system.
- Financing of consumer power independence not an established model for centralized electric power utilities. This is now changing through charging for generated power through metering in return for capital invested.

- Solar is a technology of widely ²⁰ adopted in rural areas can mitigate the increase in CO_2 which would normally occur with increase in electric power generation as economies grow!