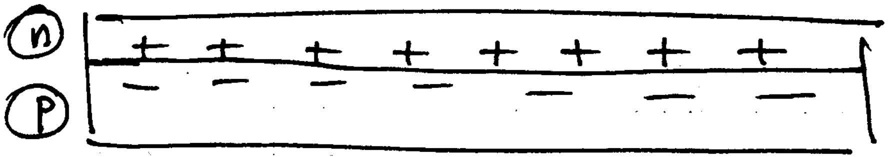
Lecture 12

Solar Cell in the dark, i.e. n-p junction in the dark



There is no net current in the cell.

There is a balance of two currents

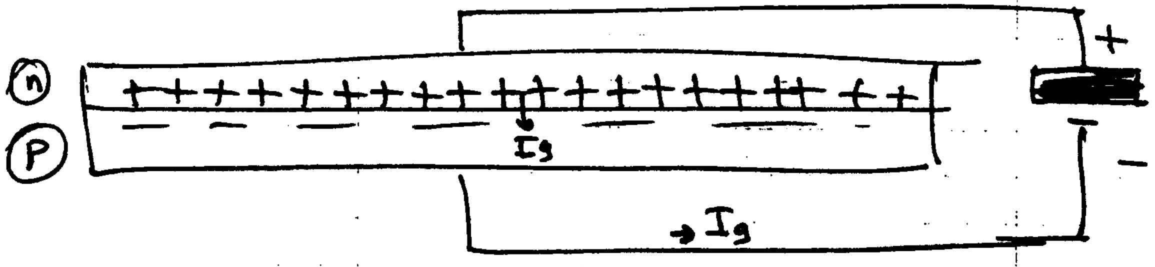
$\underset{+}{\uparrow} I_r$

Recombination Current. Net flow of majority carrier, i.e. flow of wandering holes from P to n, seeking an electron, and flow of wandering electrons from n to P, seeking a positive charge.

$\overset{+}{\downarrow} I_g$

Generation Current. Net flow of minority carriers from generation of electrons and holes. Created from vibrations - from heat.

Suppose we apply an external voltage to make the n-side more positive, the p-side more negative



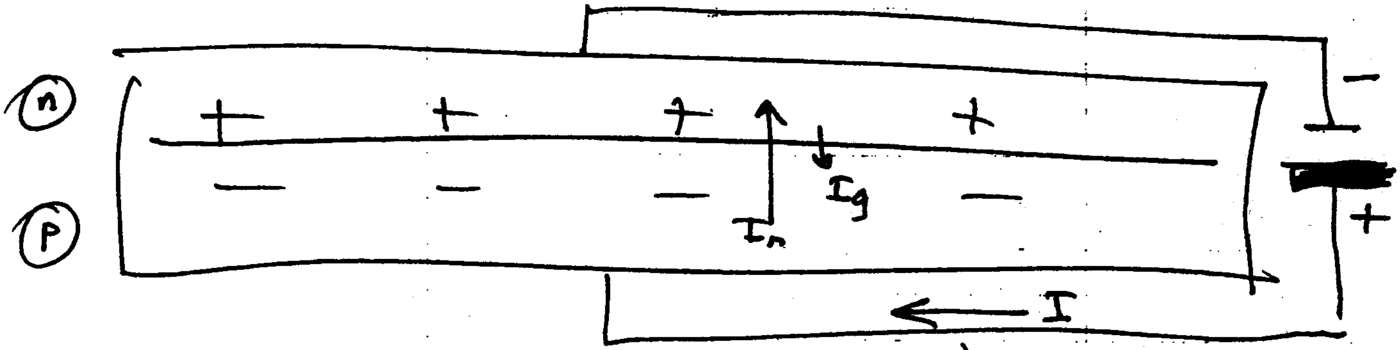
We have made net upward diffusion of ⊕ more difficult -- has to fight increased voltage

Reverse bias

$I_r \to 0$

I_g remains -- small downward current

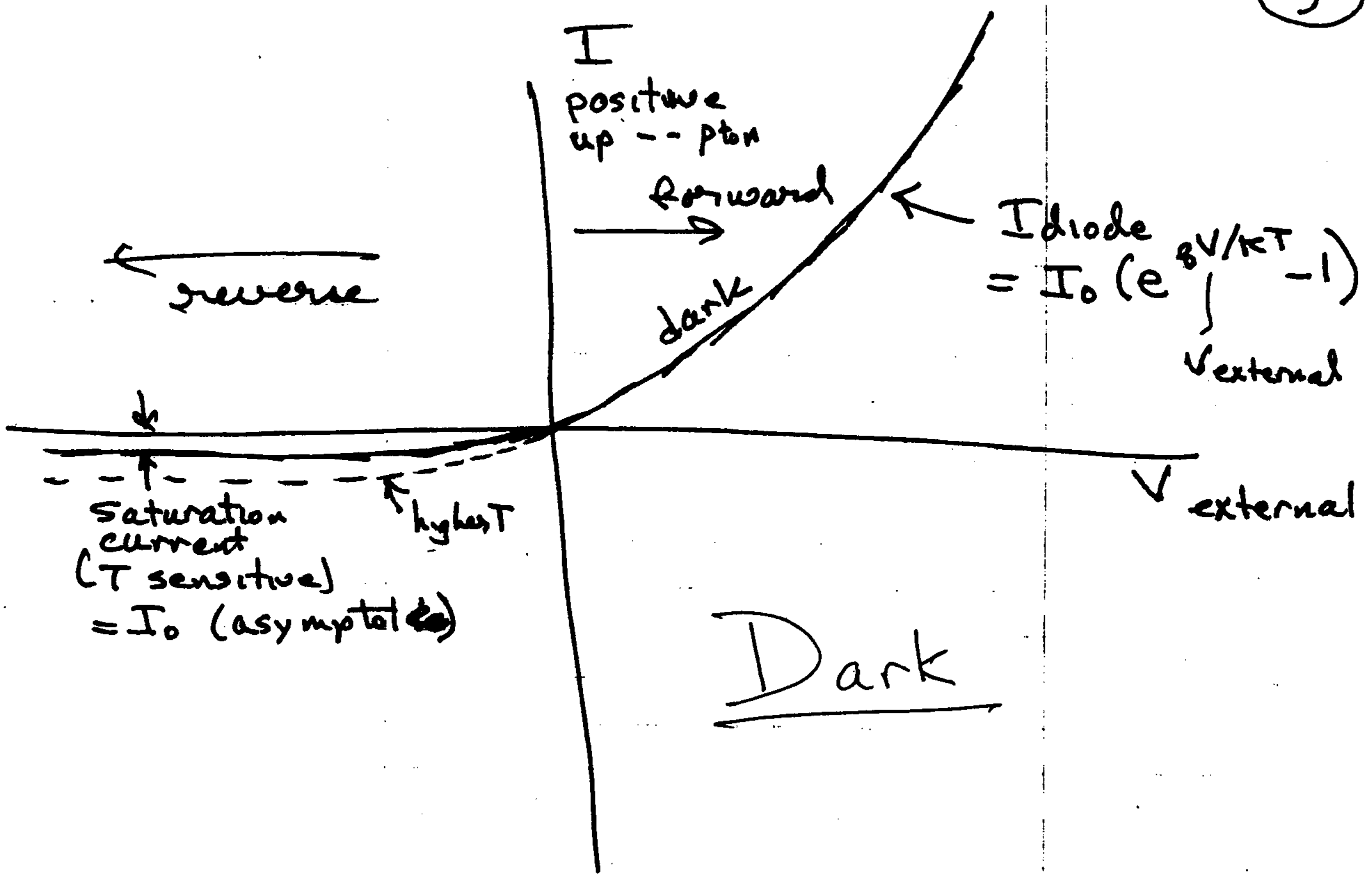
Now, switch the external voltage



We have made net upward diffusion of ⊕ easier

$I_r \gg I_g$

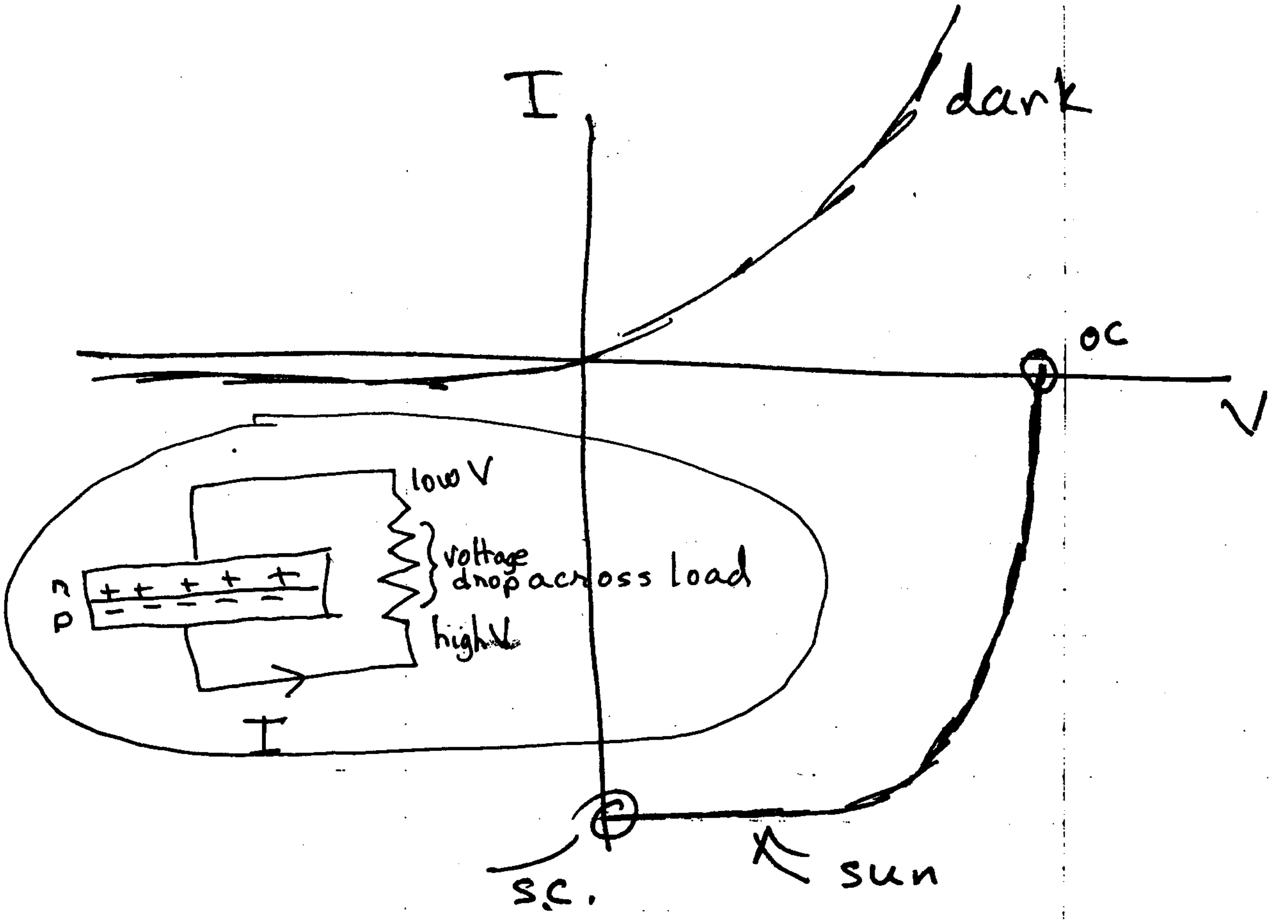
Forward bias



Now let the sun fall on the solar cell (n-p junction). The sun light creates a downward (n to p) current. This is a negative current on our diagram.

$$I = I_{diode} - I_{sun} = I_0(e^{qV/kT} - 1) - I_{sun}$$

The voltage is like the forward biasing case; since there is a voltage drop across the load, the voltage on P-side > voltage on n-side



If the load is a very thick wire (very small resistance) connecting the p to n side, the Voltage drop is essentially zero — — short circuit.

Then $I_{diode} = I_0\left(e^{q\overset{\to 0}{V}/KT} - 1\right) = I_0(1-1) = 0$

and $I = I_{Load} = -I_{sun} = I_{sc}$

Max current, but since $V = 0$, Power $= IV = 0$. No electrical work is being done on load.

As the resistance of the load is increased, its voltage drop increases, V increases in our equation and I diode increases. The net I (I through load) is starting to drop (become more upwards in cell, moving towards I=0). However, we don't notice this effect much until the external resistance becomes very large, i.e. as we approach "open circuit".

At open circuit, $I_{Load} = 0$

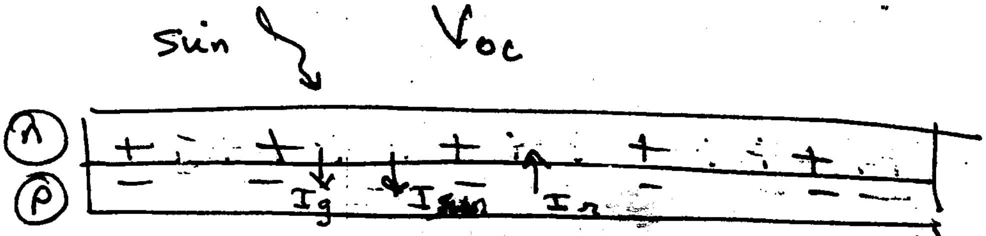
and

$$I = 0 = I_0(e^{qV/kT}-1) - I_{sun}$$

Thus

$$I_0(e^{q\underset{\big\downarrow}{V}/kT}-1) = I_{sun} = -I_{sc}$$

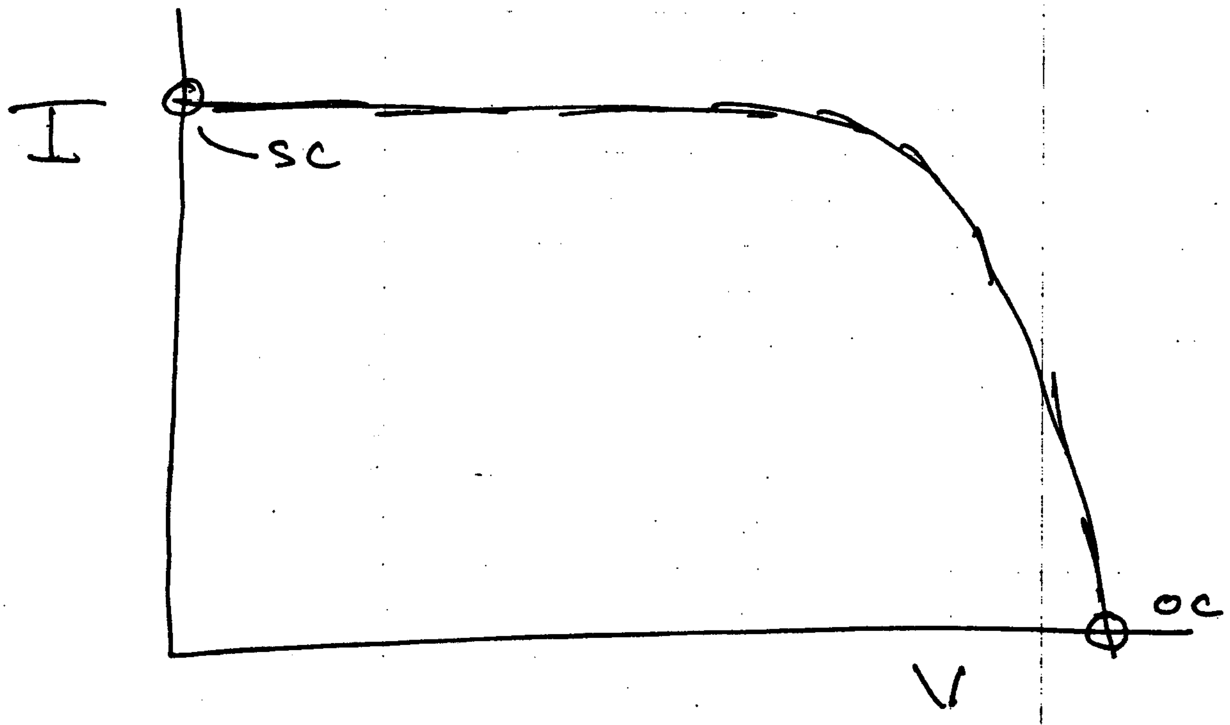
V_{oc}



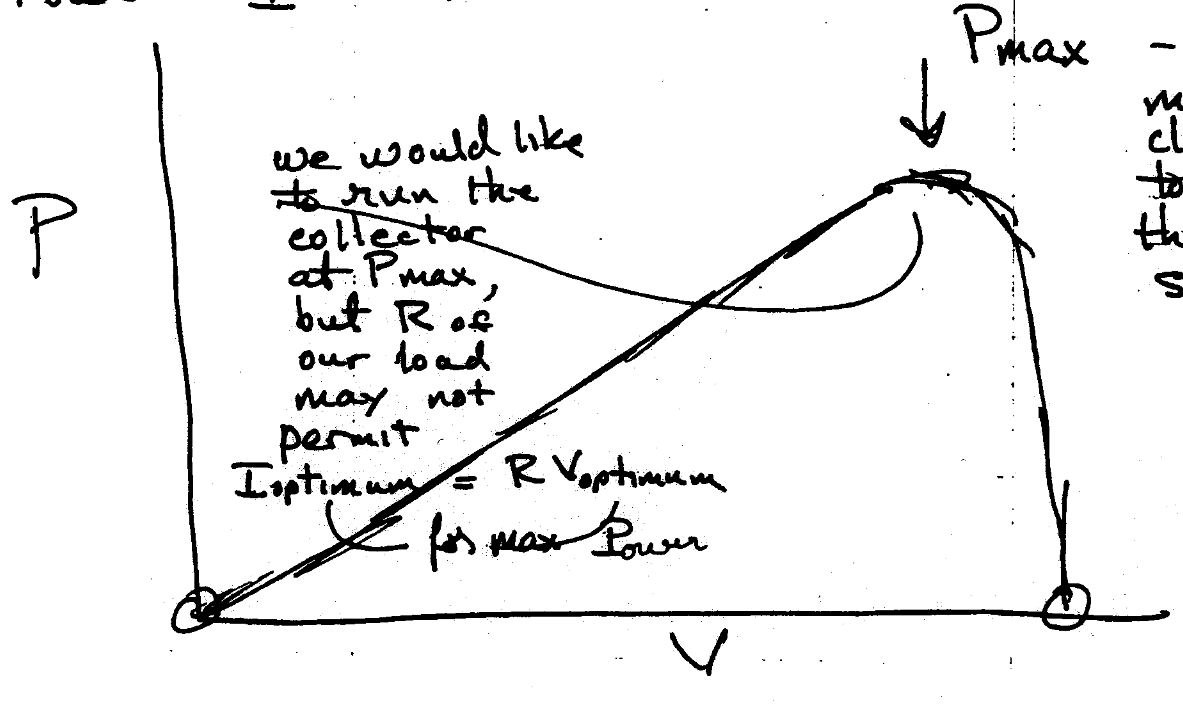
essentially (since I_g is small), we have balance of I_{sun} with I_r

Redo the plot:
Switch I_{load} to positive

$$I = I_{load} = I_{sun} - I_{diode}$$
$$= I_{sun} - I_0\left(e^{qV/kT} - 1\right)$$



Power = $P = VI$



we would like to run the collector at Pmax, but R of our load may not permit

$I_{optimum} = R\,V_{optimum}$ for max Power

-- much closer to oc that sc

There are "trackers" that permit running at P_{max} -- they adjust R to keep system at P_{max} -- electric power tracker instead of sun tracker

Called power point tracking

Cell to Panel:

Panel is a number of cells wired in series, typically 30 to 40 cells

$V_{panel} = V_{cell} \times \text{number of cells}$

$I_{panel} = I_{cell}$

Typical size (for largest of panels)

Panel ~ $1 m^2$

Cell ~ $250 cm^2$ 16 cm x 16 cm or 18 cm diameter

For panel, want to know

$$\left.\begin{array}{l} V_{oc}\\ I_{sc}\\ V_{maxP} \sim .75\,V_{oc}\\ I_{maxP}\\ P_{max}\end{array}\right] \text{for rated sunlight and panel } T=25^\circ C$$

See page 96 of text for example.

Cell rated @ 25°C

AM 1.5 radiation of 1000 W/m²

$$1.5 = \frac{1}{\cos\underbrace{\theta_Z}_{48^\circ}}$$

Note: since I_0 increases with T,
I_{diode} increases with T
and I_{Load} drops with T

For crystalline Si cells,
0.4% drop in Power for each degree C above 25°C.

A cold, strongly radiated cell would give the most power.

Factors affecting efficiency:

1. Top surface contact obstruction : loss ~ 3%
2. Top surface reflection : loss ~ 1%
3. Photon energy insufficient: loss ~ 23%
4. Excess photon energy : loss ~ 33%
5. Voltage factor - voltage produced at junction less than band gap energy : loss ~ 20%
6. Curve factor loss, #1

   i.e. $P \neq V_{oc} \times I_{sc}$

   $$\text{Fill factor} = \frac{P_{max}}{V_{oc} I_{sc}}$$ (.88 max for silicon

   loss ~ 4%
7. Curve factor loss #2

   $I = I_{sun} - I_o (e^{qV/KT} - 1)$

   not quite followed

   loss ~ 5%

Delivered Power Si

10 to 17%

System Cost

Panels	Cost/m^2	Efficiency
Single-crystal Si	↓	↓
Multi & poly crystal Si		
Thin film Si		
Thin film alloys	decreasing	decreasing

Thus Cost/watt doesn't change that much, stays around $4.5 → $5.5/Watt peak for small systems.
Maybe $3.50/Wp for large systems

Balance of System and its Cost

How much electrical power?

Example:

Specify a 8 panel, 1000 watt system for your home.

This means in rated sunlight of 1000 w/m^2 normal to the panels, and for panel $T = 25°C$ the system would produce 1000 watts (1 kw) of electricity.

Suppose the efficiency of the panels based on full area is 12.5%.

$$1000\ w/m^2 \times A \times 0.125 = 1000\ w$$

$$\Rightarrow A = 8\ m^2$$

$$\text{or } A_{\text{one panel}} = 1\ m^2$$

Sunlight:

$1000\ w/m^2 \times 8m^2 = 8000\ w$

Electricity: 1000 w

On average, it is daylight only ½ the time, 12 hrs. But the early and late hours of the day don't offer much solar energy, especially for panels set at one tilt angle, so we are down to about 8 hrs of useful daylight

Thus $1000\ w \times \frac{8}{24} = 333$ average watts

Now, it is cloudy some of the time. For a place like Phoenix, the result is about 200^+ watts average power (i.e. $20^{+}\%$ capacity factor)

For place like Seattle,

capacity factor is about
12 % ⟹ 120 watts average

The 8 panels probably cost
at least $4000 -- maybe
as much as $6000,
and we need balance of system:
biggest item is inverter

Total Cost: $7000 to $12000
for our 1000 watts system

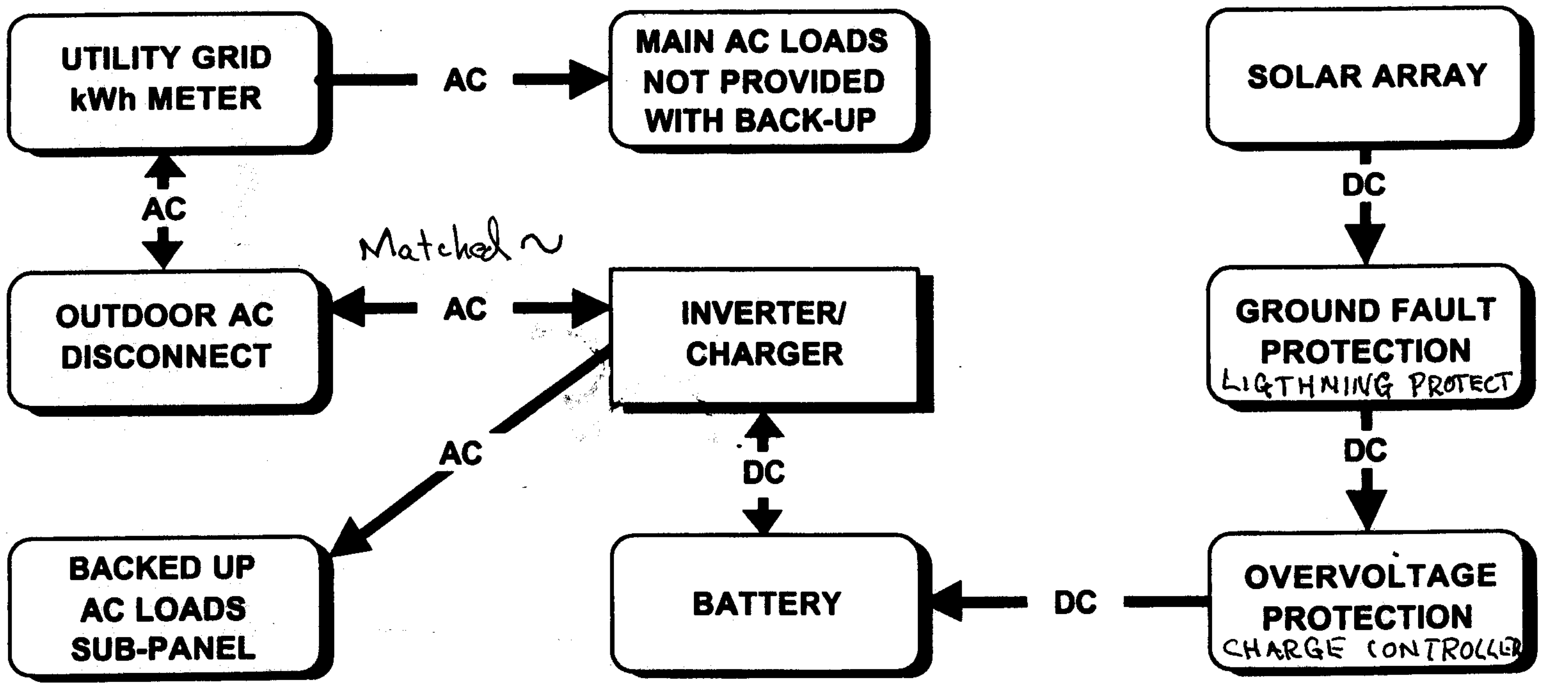
Simple cost

$$\frac{120\overset{200^{+}}{-}\text{watts} \times 8760\ \text{hr/yr} \times 20\overset{30}{-}\text{yrs}}{\$7000 - \$12000}$$

⟹ 12 ¢/kwh – 57 ¢/kwh

Phoenix @ best case (200+, 30, $7K) Seattle @ worst case (120, 20, $12K)

SYSTEM


UTILITY GRID
kWh METER
AC
MAIN AC LOADS
NOT PROVIDED
WITH BACK-UP
SOLAR ARRAY
DC
AC
Matched ~
OUTDOOR AC
DISCONNECT
AC
INVERTER/
CHARGER
GROUND FAULT
PROTECTION
LIGTHNING PROTECT
DC
AC
DC
BACKED UP
AC LOADS
SUB-PANEL
BATTERY
DC
OVERVOLTAGE
PROTECTION
CHARGE CONTROLLER