Solar Energy Technologies

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Photovoltaic Solar panels

- Physics behind Photovoltaic systems
- I-V curve
- Effect of temperature
- System calculation
- MPPT: Maximum power point tracker
- Inverter
- Charge Controller
- Grid Connected Systems
- Standalone Systems
    - Battery Charging
    - Direct Connected Load

PV Systems – 1.st configuration

- Grid-connected systems

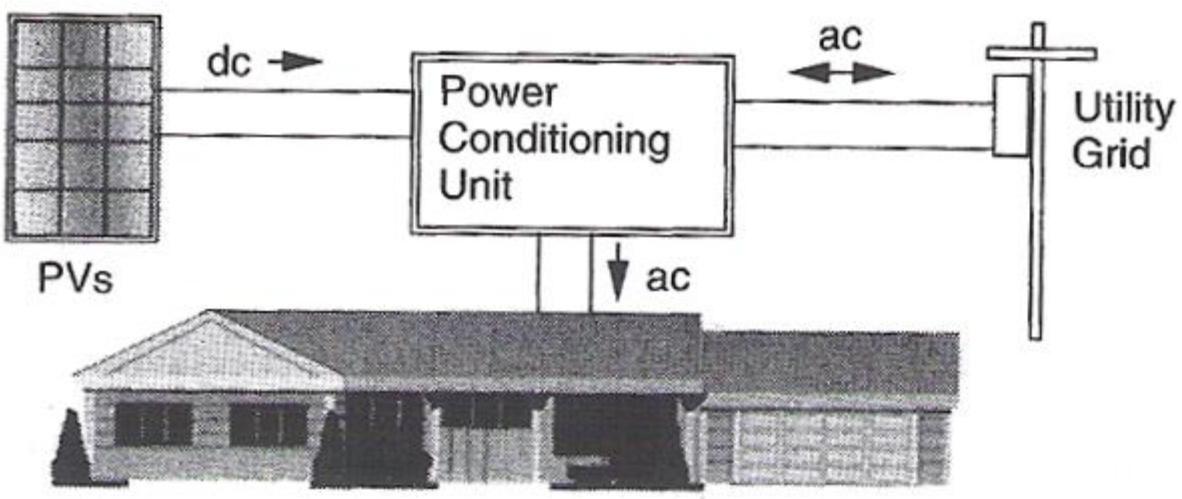


Figure 9.1 Simplified grid-connected PV system.

PV Systems – 2.nd configuration

- Stand-alone systems which charge batteries

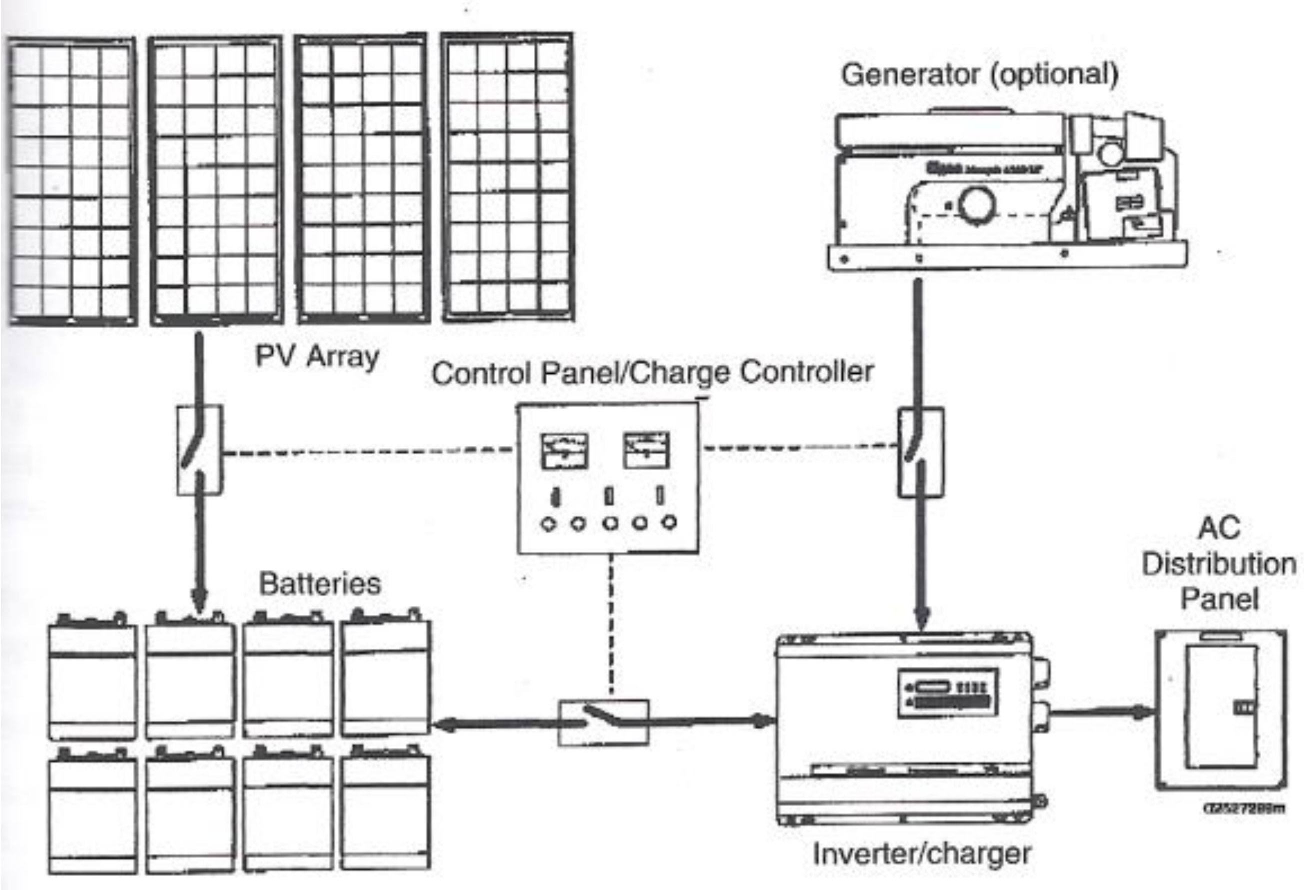


Figure 9.2 Example of a stand-alone PV system with optional generator for back-up.

PV Systems – 3.rd configurations

- Stand-alone systems with directly-connected loads

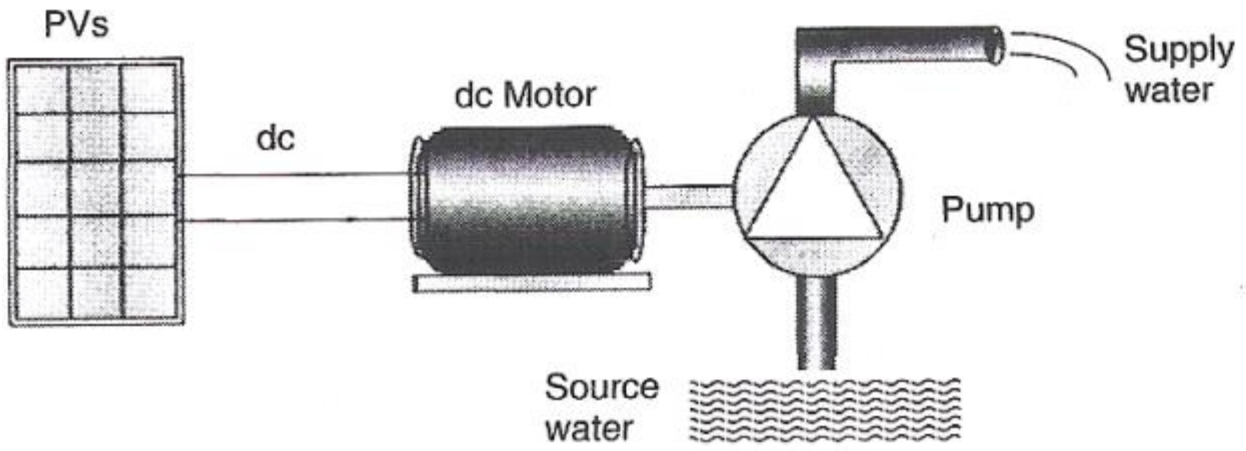


Figure 9.3 Conceptual diagram of a photovoltaic-powered water pumping system.

Load I-V Curves

- PV panels have I-V curves and so do loads
- Intersection of the two curves to tell where the system is actually operating
- Operating point – the intersection point at which the PV and the load I-V curves are satisfied

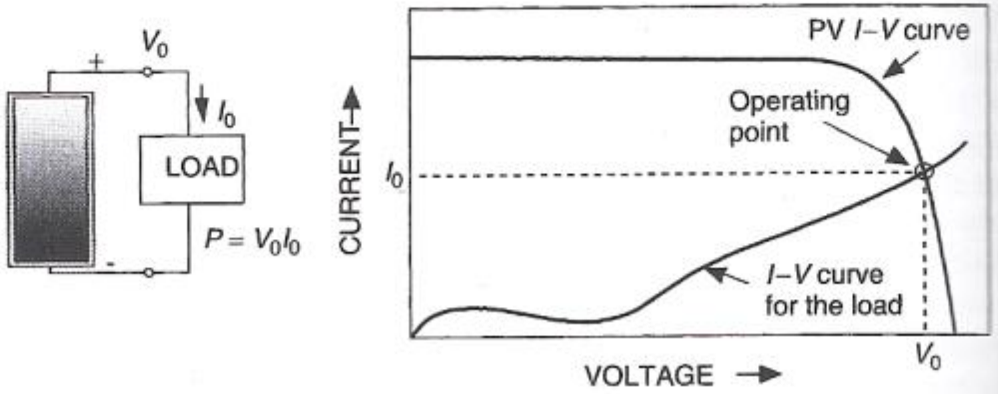


Figure 9.4 The operating point is the intersection of the current–voltage curves for the load and the PVs.

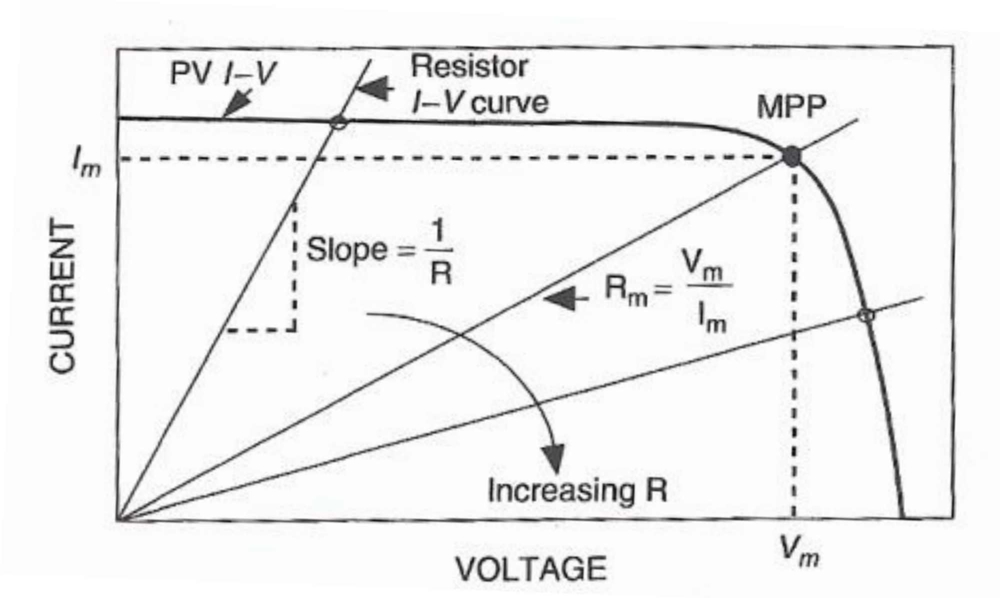
Resistive Load I-V Curve

$$V = IR \Rightarrow I = \left(\frac{1}{R}\right)V \qquad (9.1)$$

- Straight line with slope 1/*R*
- As *R* increases, operating point moves to the right

- Can use a potentiometer to plot the PV module's IV curve
- Resistance value that results in maximum power

$$R_m = \frac{V_m}{I_m} \qquad (9.2)$$



Resistive Load: Maximum power transfer

- Maximum power point (MPP) should occur when the load resistance R = V_R/I_R under 1-sun 25˚C, AM 1.5 conditions

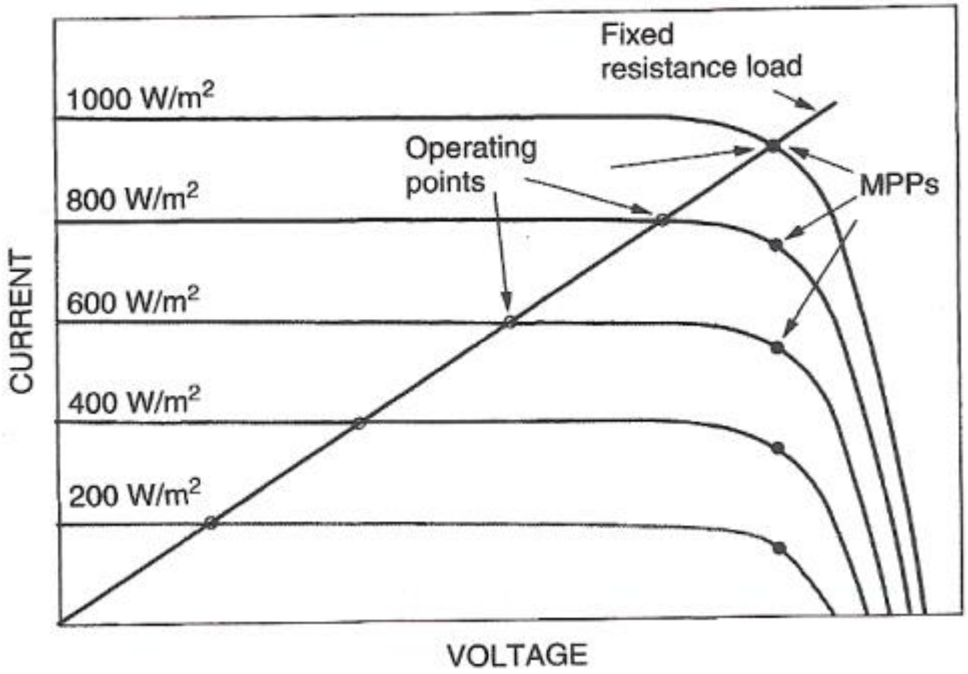


Figure 9.6 The efficiency of a PV module with a fixed resistance load designed for 1-sun conditions will decline with changing insolation. The solid maximum power point (MPP) dots show the operating points that would result in maximum PV efficiency.

- A MPP tracker maintains PV system's highest efficiency as the amount of insolation changes

DC Motor I-V Curve

- DC motors have an I-V curve similar to a resistor

$$V = IR_a + k\omega \qquad (9.3)$$

- $e = k\omega$ is back emf, R_a is armature resistance

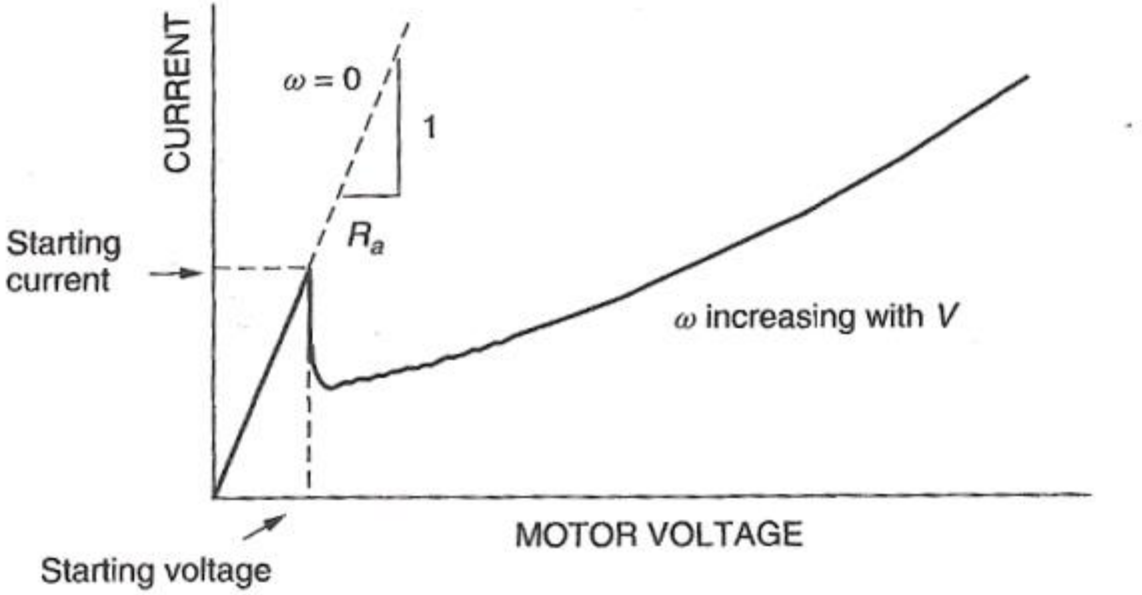


Figure 9.8 Electrical characteristics of a permanent-magnet dc motor.

DC Motor I-V Curve

Linear Current Booster (LCB) helps the motor be able to start in low sunlight

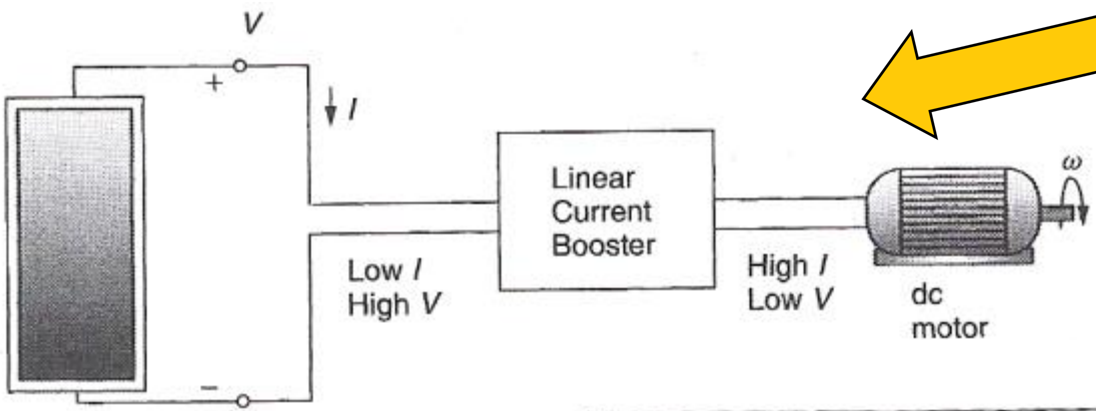
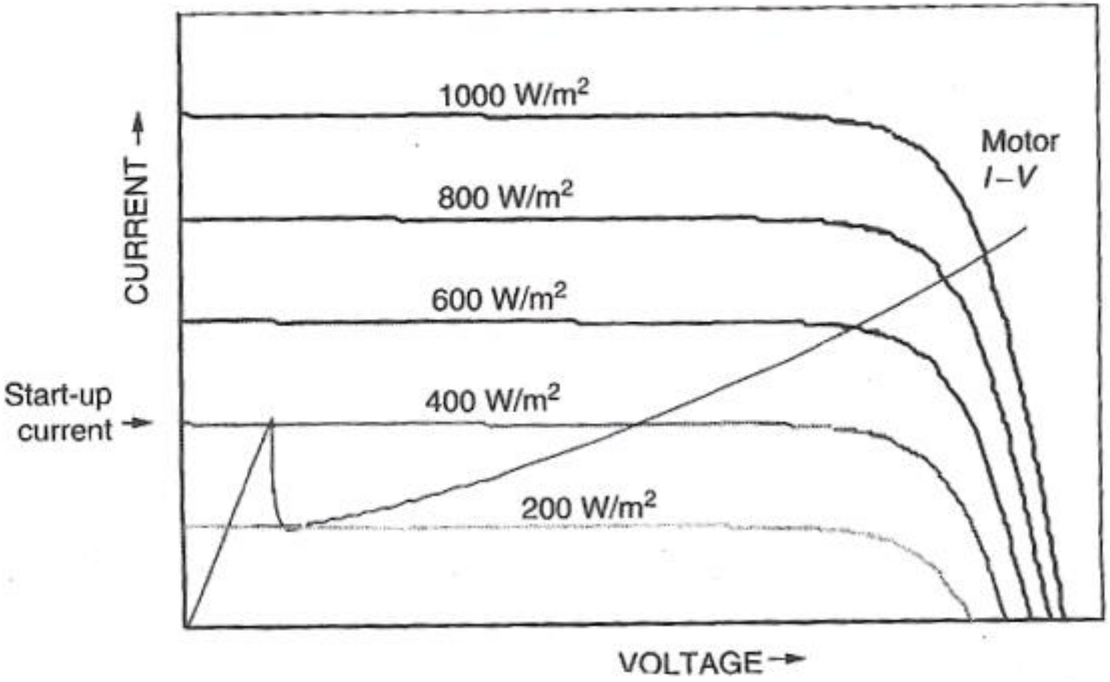


Figure 9.10



Battery I-V Curves

- Energy is stored in batteries for most off-grid applications
- An ideal battery is a voltage source V_B
- A real battery has internal resistance R_i

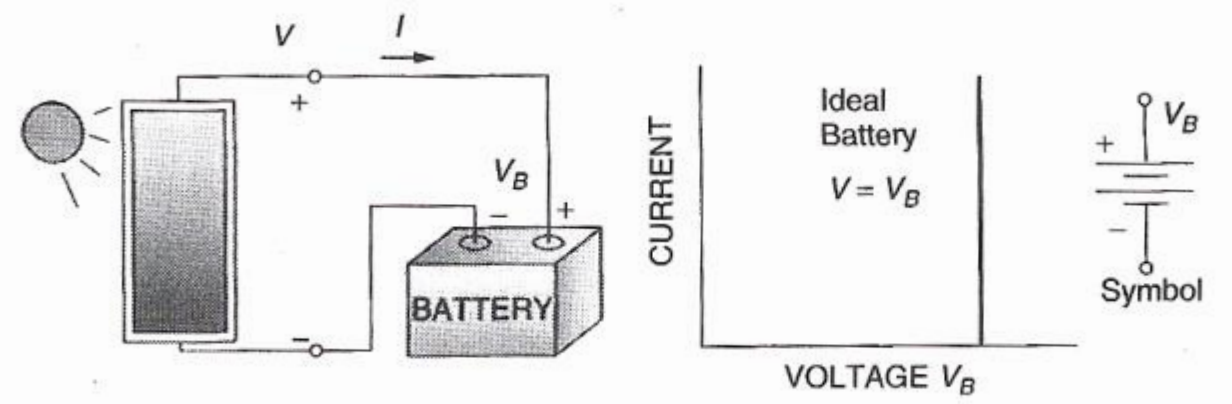
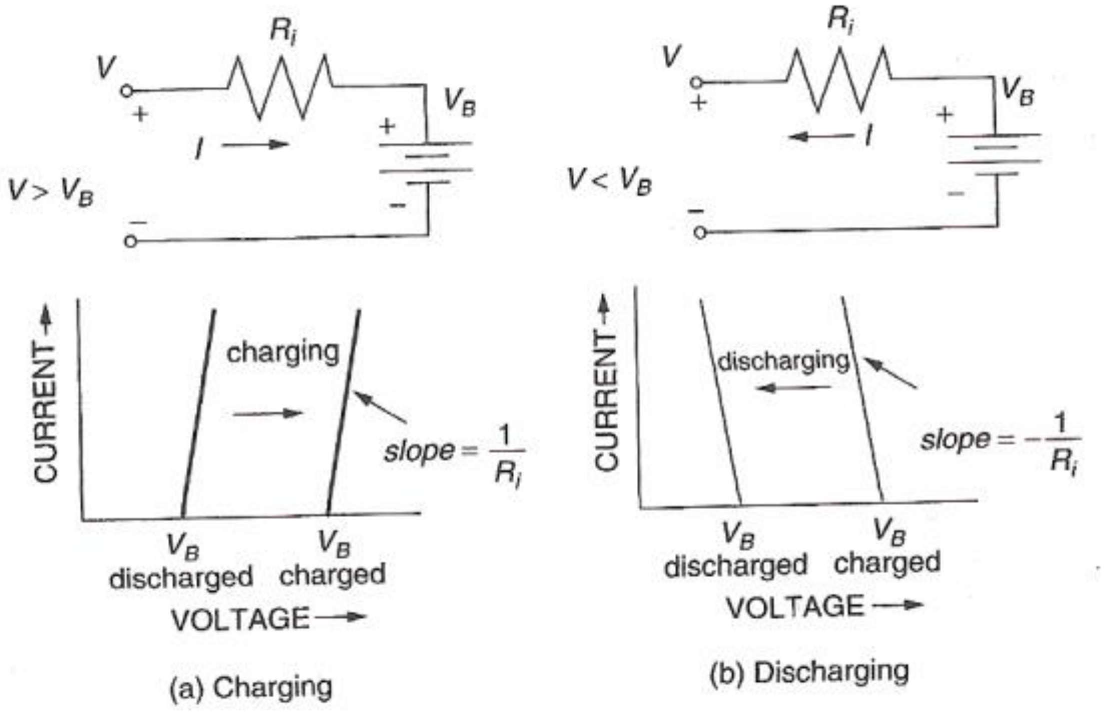


Figure 9.11 An ideal battery has a vertical current–voltage characteristic curve.

$$V = V_B + R_i I \qquad (9.4)$$

Battery I-V Curves

- Charging– I-V line tilts right with a slope of 1/R_i, applied voltage must be greater than V_B
- Discharging battery- I-V line tilts to the left with slope 1/R_i, terminal voltage is less than V_B



(a) Charging

(b) Discharging

Figure 9.12

Maximum Power Point Trackers

- Maximum Power Point Trackers (MPPTs) are often a standard part of PV systems, especially grid-connected
- Idea is to keep the operating point near the knee of the PV system’s I-V curve
- Buck-boost converter – DC to DC converter, can either “buck” (lower) or “boost” (raise) the voltage
- Varying the duty cycle of a buck-boost converter can be done such that the PV system will deliver the maximum power to the load

MPPTs – Example 9.2

- A PV module has its maximum power point at V_m = 17 V and I_m = 6A.
- What duty cycle should its MPPT have if the module is delivering power to a 10Ω resistance?

- Max power delivered by the PVs is 17V*6A = 102W

$$P = \frac{{V_R}^2}{R} \qquad V_R = 31.9V$$

MPPTs – Example 9.2

- The converter must boost the 17 V PV voltage to the desired 31.9 V
- Solving gives:

$$\frac{V_0}{V_i} = -\left(\frac{D}{1-D}\right) \qquad (9.9) \qquad \frac{31.9}{17} = \left(\frac{D}{1-D}\right) = 1.88$$

$$D = 0.65$$

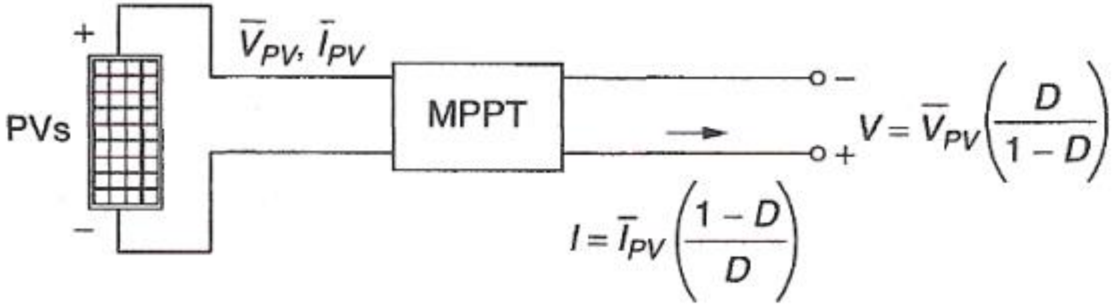


Figure 9.16 The MPPT bumps the PV voltages and currents to appropriate values for the load (one goes up, the other down).

Hourly I-V Curves

- Current at any voltage is proportional to insolation
- V_{OC} drops as insolation decreases
- Can just adjust the 1-sun *I-V* curve by shifting it up or down

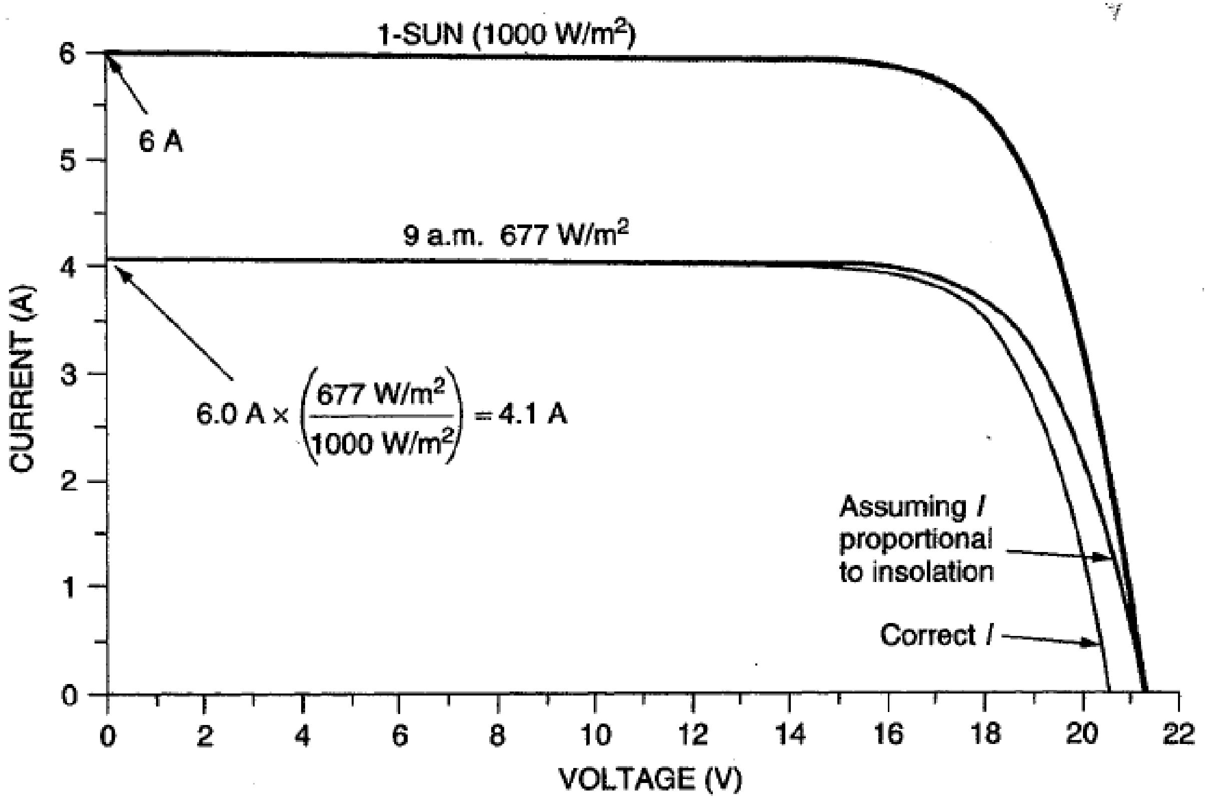


Figure 9.18 The 1-sun $I-V$ curve with two $I-V$ curves when insolation is 677 W/m^2: One is drawn under the simplifying assumption that I is proportional to insolation; the other accounts for the drop in V_{OC} as insolation decreases. For voltages below the knee, there is very little difference.

Grid-Connected Systems

- Can have a combiner box and a single inverter or small inverters for each panel
- Individual inverters make the system modular
- Inverter sends AC power to utility service panel
- Power conditioning unit (PCU) may include
    - MPPT
    - Ground-fault circuit interrupter (GFCI)
    - Circuitry to disconnect from grid if utility loses power
    - Battery bank to provide back-up power

Components of Grid-Connected PV

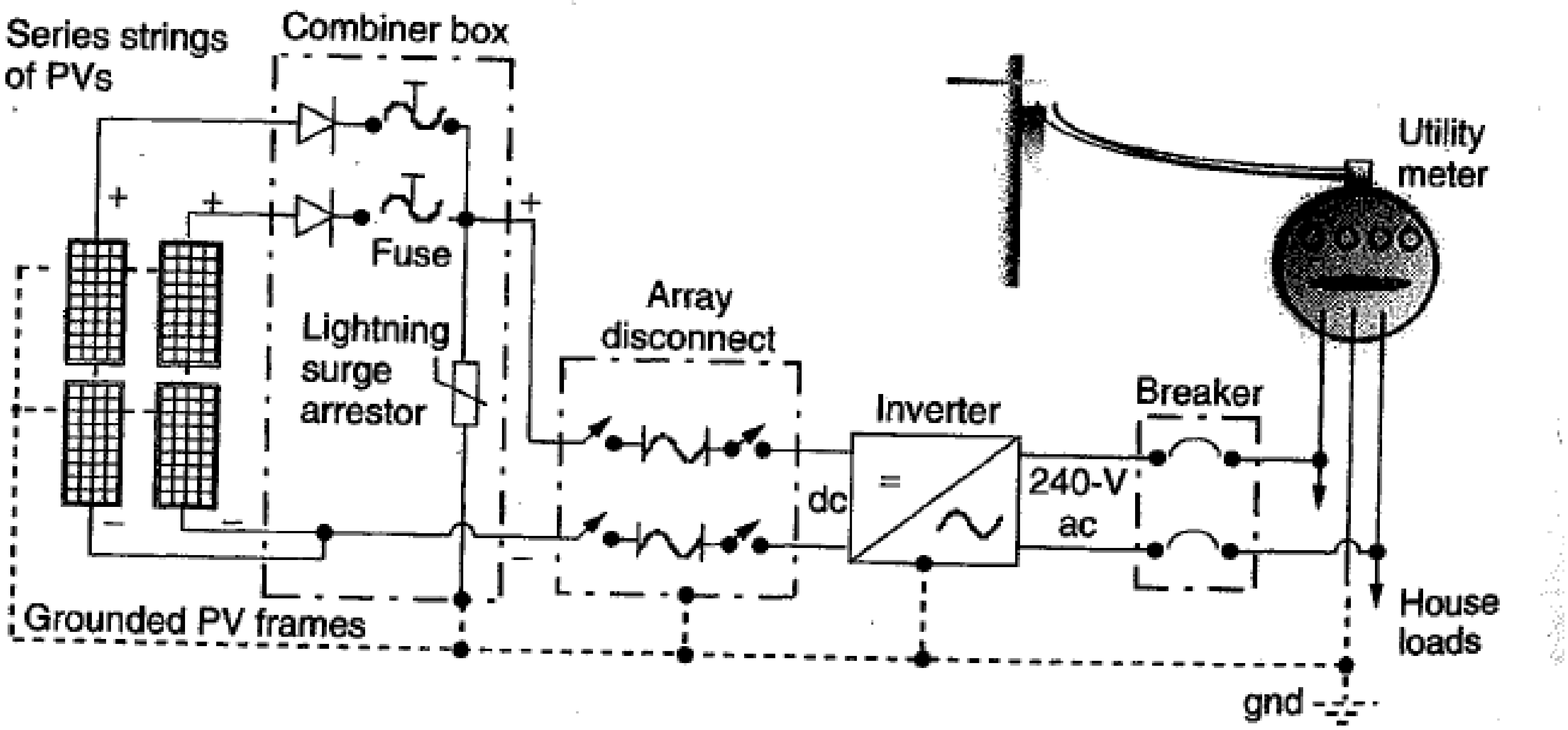


Figure 9.20 Principal components in a grid-connected PV system using a single inverter.

Individual Inverter Concept

- Easily allow expansion
- Connections to house distribution panel are simple
- Less need for expensive DC cabling

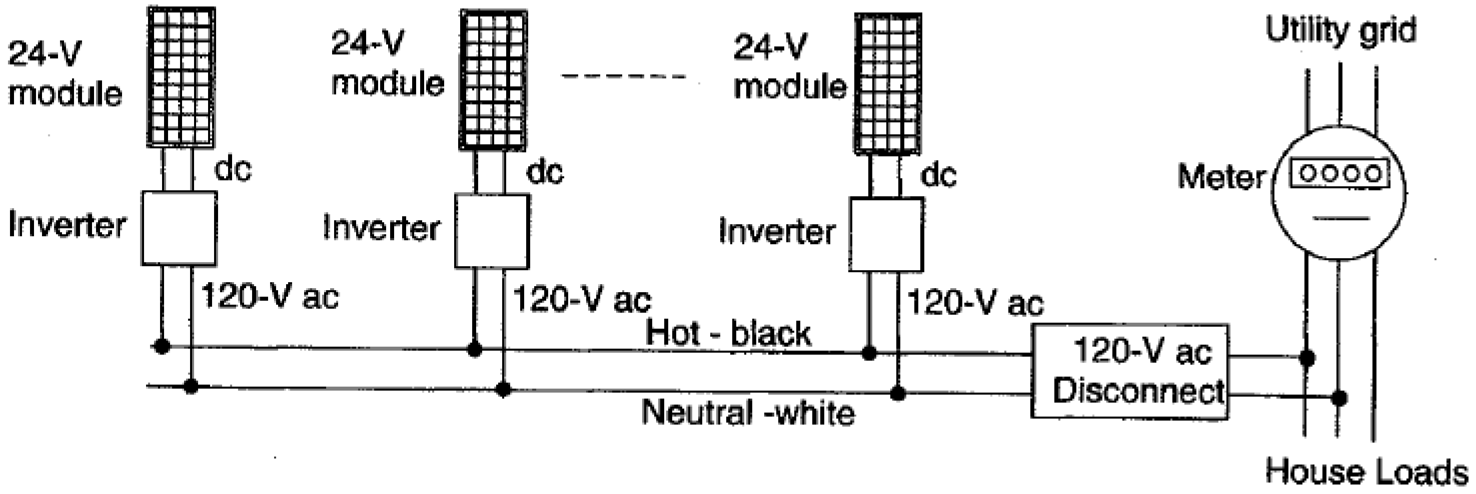
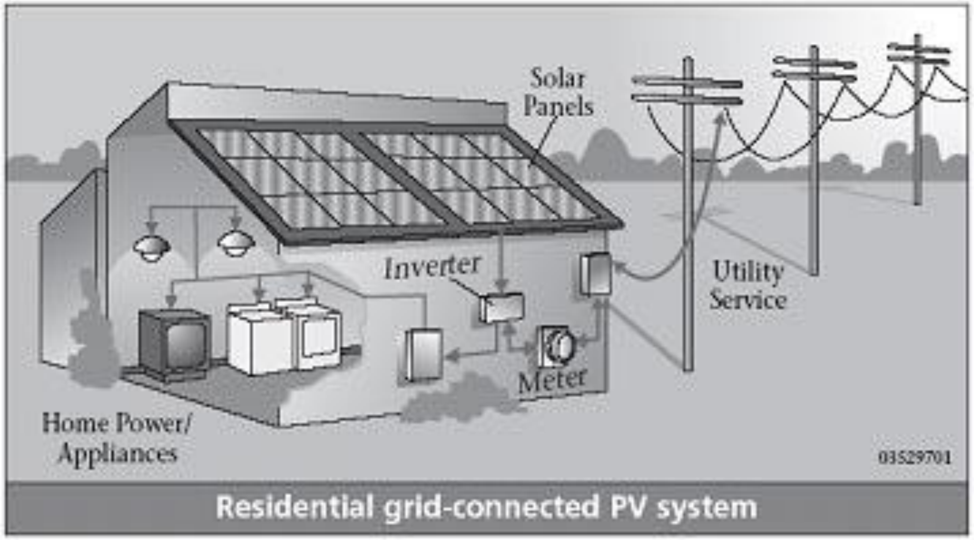


Figure 9.21 AC modules each have their own inverters mounted on the backside of the collector, allowing simple system expansion at any time.

Interfacing with the Utility

- Net metering – customer only pays for the amount of energy that the PV system is unable to supply
- In the event of an outage, the PV system must quickly and automatically disconnect from the grid

- A battery backup system can help provide power to the system’s owners during an outage
- Good grid-connect inverters have efficiencies above 90%



Residential grid-connected PV system

http://www.pasolar.ncat.org/lesson05.php

DC and AC Rated Power

- Estimating the AC output power under varying conditions is necessary.

$$P_{ac} = P_{dc,STC} \times (\text{Conversion Efficiency}) \qquad (9.10)$$

- $P_{dc,STC}$ = DC power of array from adding module ratings under standard test conditions (STC) (1-sun, AM 1.5, 25˚C)
- Conversion efficiency – includes losses from inverter, dirty collectors, mismatched modules, and differences in ambient conditions
- These losses can derate power output by 20-40%, even in full sun

Losses from Mismatched Modules

- Illustrates the impact of slight variations in module *I-V* curves
- Only 330 W is possible instead of 360 W

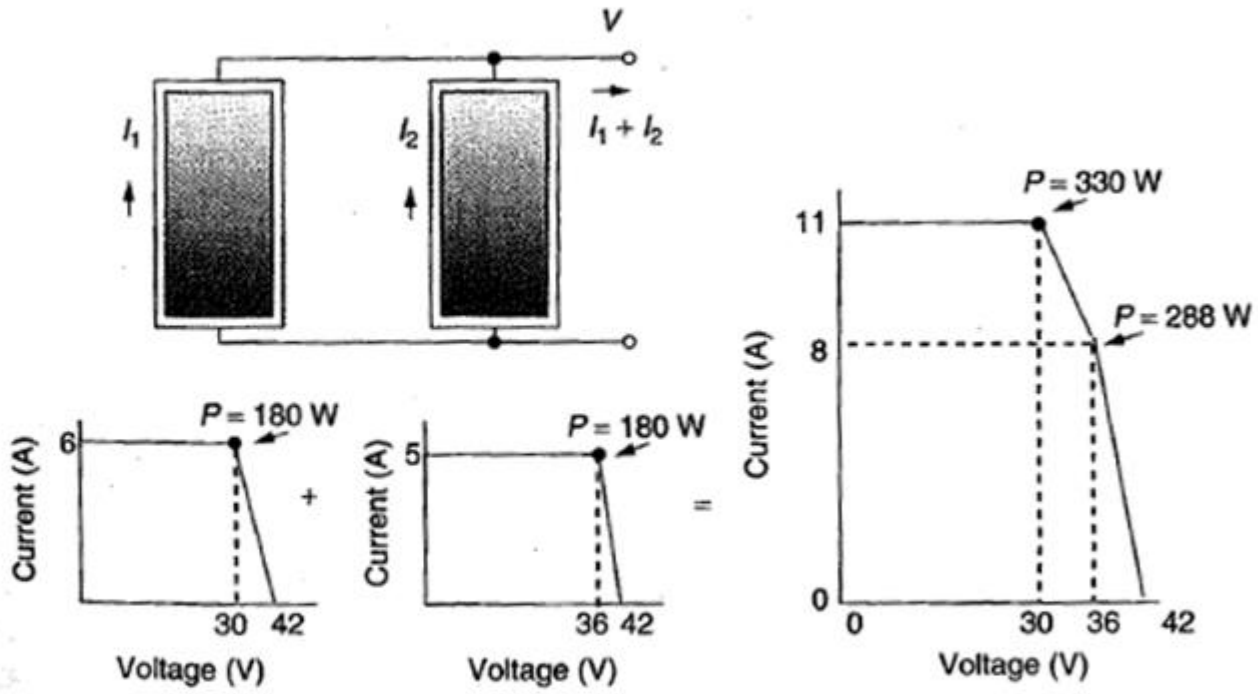


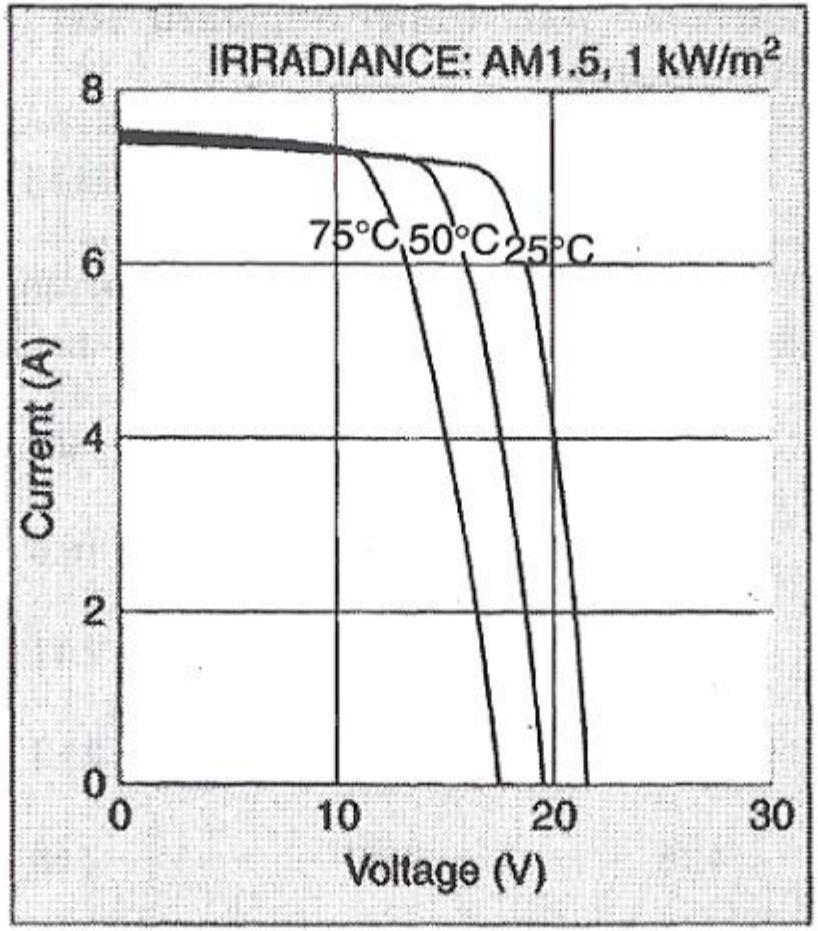
Figure 9.24 Illustrating the loss due to mismatched modules. Each module is rated at 180 W, but the parallel combination yields only 330 W at the maximum power point.

Losses due to Cell Temperature

- As temperature increases, power decreases
- PVUSA test conditions (PTC) – 1-sun insolation in plane of array, 20˚C ambient temperature, wind-speed of 1 m/s
- $P_{ac(PTC)}$ AC output of an array under PTC test conditions is a better indicator of actual power delivered in full sun than the more commonly used $P_{dc(STC)}$
- Describing a system based on $P_{dc(STC)}$ without correcting for temperature and the inverter is misleading

Impact of Temperature

- V_{OC} decreases by ~0.37% per ˚C for crystalline silicon cells
- I_{SC} increases by about 0.05% per ˚C
- NOCT – Normal Operating Cell Temperature



$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20°C}{0.8} \right) \cdot S \qquad (8.24)$$

https://www.pveducation.org/pvcdrom/modules-and-arrays/nominal-operating-cell-temperature

Example - PV Derating using PTC

- A PV array has rating of 1 kW under standard test conditions (STC). Nominal operating temperature (NOCT) from is 47˚C
- DC power output drops by 0.5%/ ˚C above the STC temperature of 25˚C
- Mismatched module loss= 3%
- Dirt loss = 4%
- Inverter efficiency = 90%

- Estimate $P_{ac(PTC)}$, the AC output power under PVUSA test conditions (PTC)

Example– “1 kW PV system” PTC Rated AC Power

- The estimated cell temperature is

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20°C}{0.8} \right) \cdot S \qquad (8.24)$$

$$T_{cell} = 20 + \left(\frac{47 - 20°C}{0.8} \right) \cdot 1 = 53.8°C$$

- With DC losses at 0.5%/ ˚C above 25˚C,

$$P_{dc,(PTC)} = 1\text{ kW}\left[1 - 0.005(53.8 - 25)\right] = 0.856\text{ kW}$$

- Including inefficiencies, estimated AC rated power at PTC is

$$P_{ac,(PTC)} = 8.56\text{ kW} \times 0.97 \times 0.96 \times 0.90 = 0.72\text{ kW}$$

“Peak-Hours” Approach

- 1-sun is 1 kW/m^2
- We can say that 5.6 kWh/(m^2-day) is 5.6 hours of “peak sun”
- If we know P_{ac}, computed for 1-sun, just multiply by hours of peak sun to get kWh
- If we assume the average PV system efficiency over a day is the same as the efficiency at 1-sun, then

$$\text{Energy (kWh/day)} = P_{ac}\ \text{kW} \cdot \left(\text{h/day of "peak sun"}\right) \qquad (9.14)$$

Capacity Factor of PV

$$\text{Energy}\left[\text{kWh/yr}\right]=P_{ac}\ \text{kW}\cdot\text{CF}\cdot 8760\ \left[\text{h/yr}\right]\quad(9.15)$$

$$\text{CF}=\frac{\left(\text{h/day of "peak sun"}\right)}{24\ \text{h/day}}\quad(9.16)$$

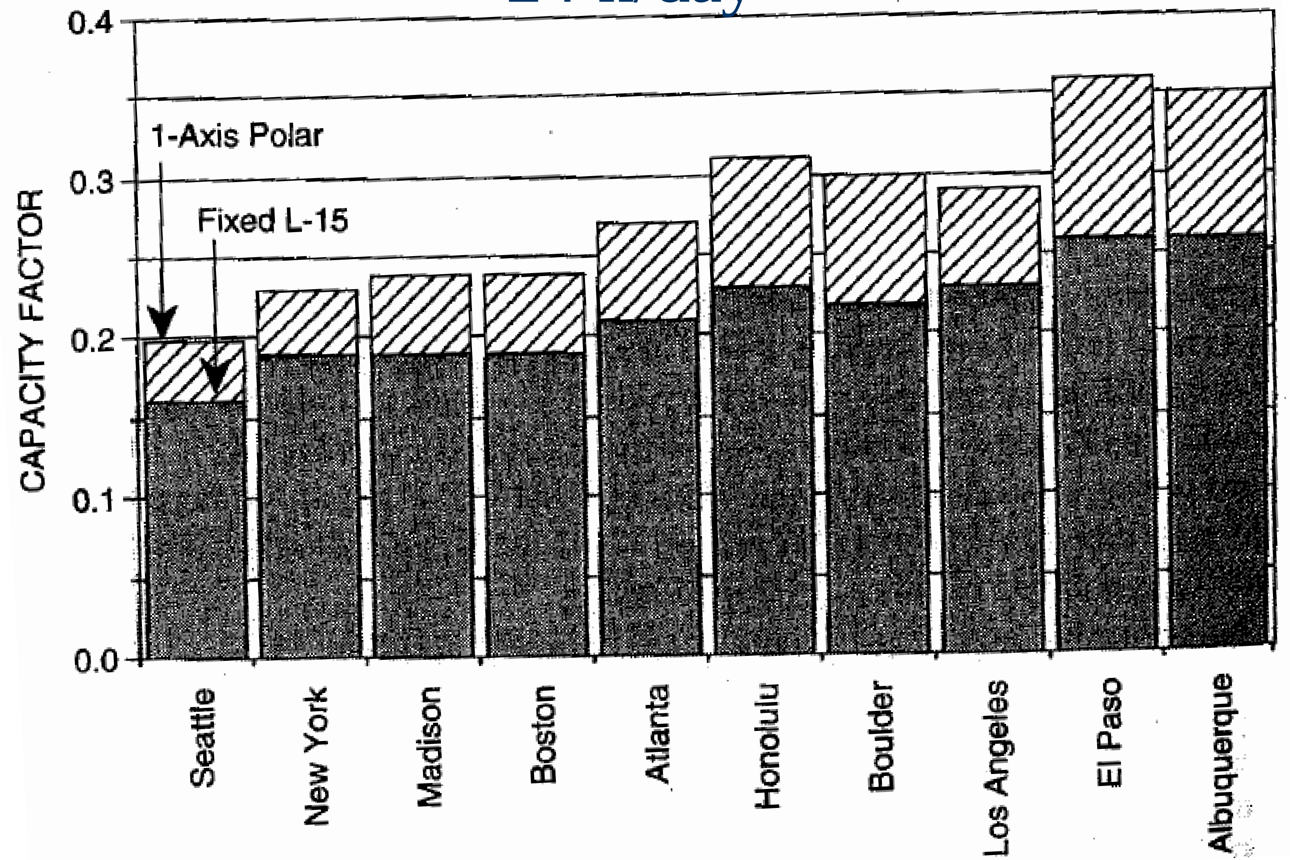


Figure 9.28 PV Capacity Factors for US cities

Stand-Alone PV Systems

- When the grid isn’t nearby, the extra cost and complexity of a stand-alone power system can be worth the benefits
- System may include batteries and a backup generator

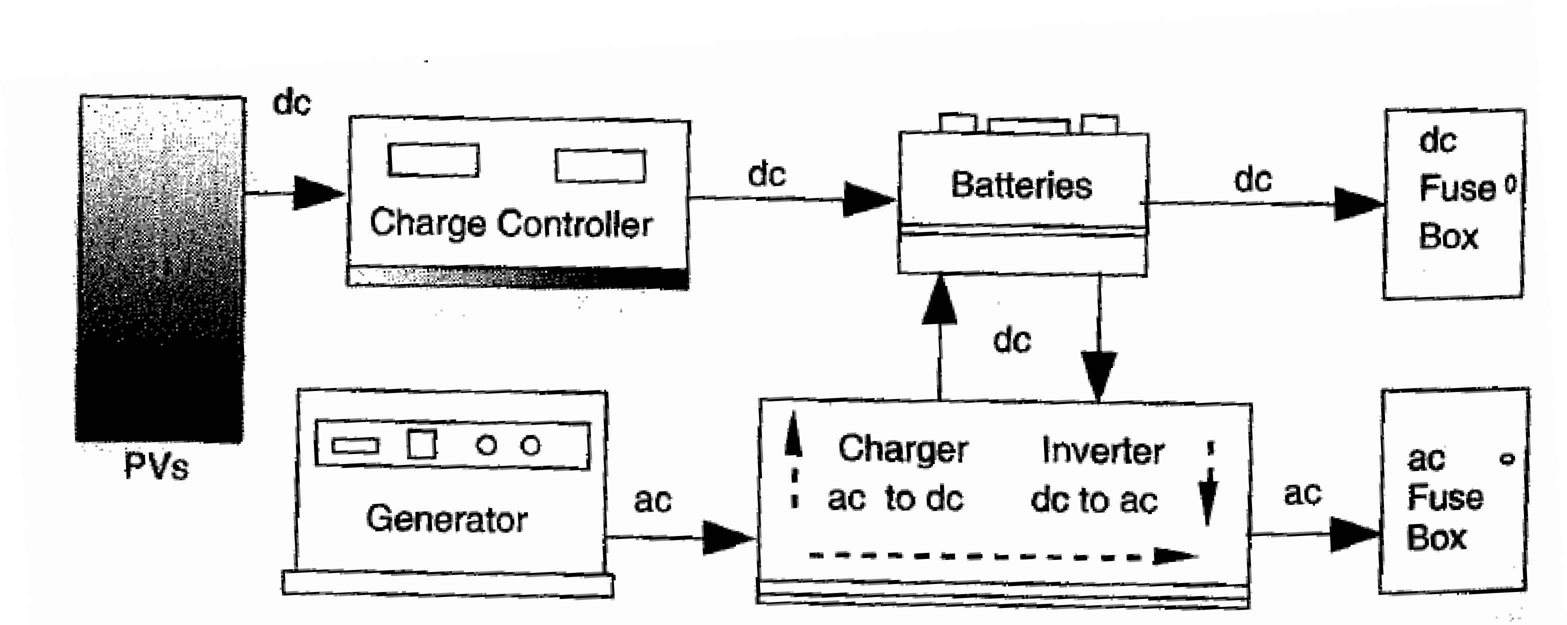
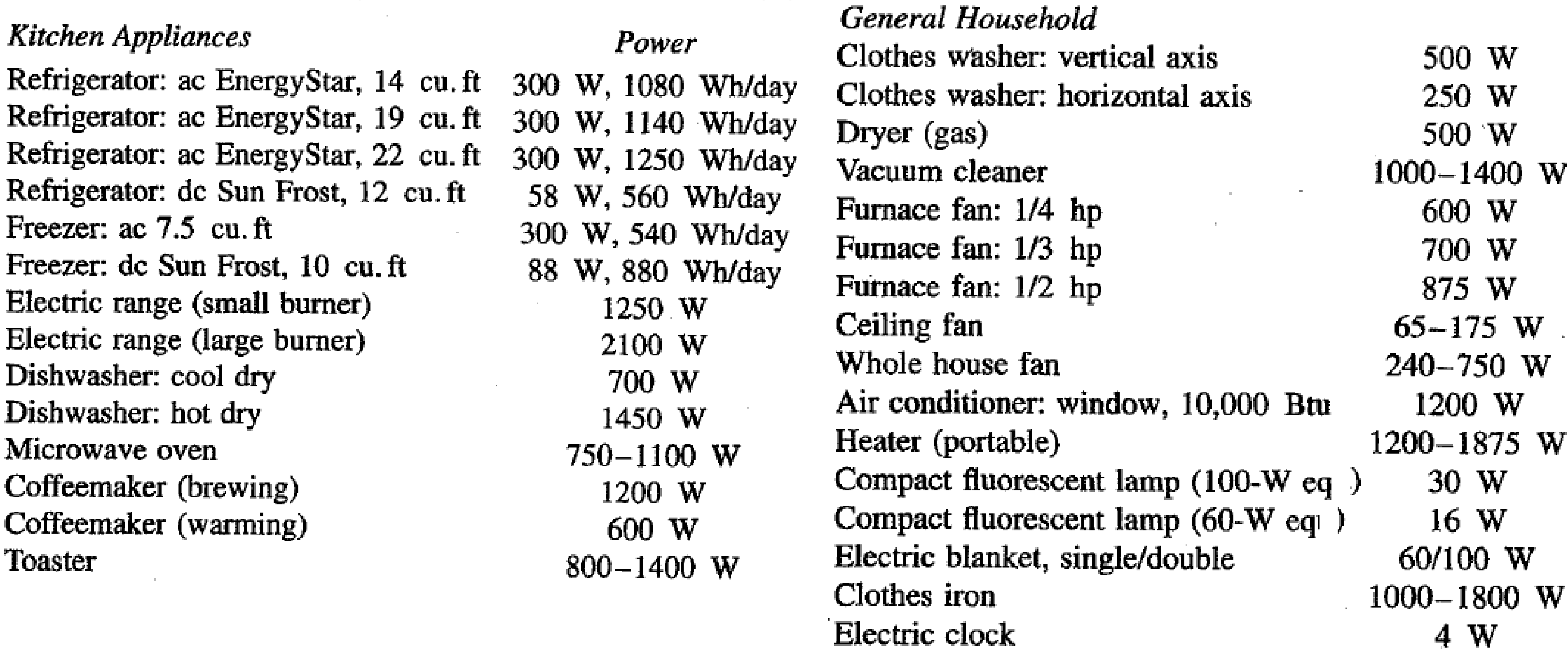


Figure 9.35 A stand-alone system with back-up generator and separate outputs for dc and ac loads.

Stand-Alone PV - Considerations

- PV System design begins with an estimate of the loads that need to be served by the PV system
- Tradeoffs between more expensive, efficient appliances and size of PVs and battery system needed
- Should you use more DC loads to avoid inverter inefficiencies or use more AC loads for convenience?
- What fraction of the full load should the backup generator supply?
- Power consumed while devices are off
- Inrush current used to start major appliances

Power Requirements of Typical Loads



Kitchen Appliances	*Power*
Refrigerator: ac EnergyStar, 14 cu. ft	300 W, 1080 Wh/day
Refrigerator: ac EnergyStar, 19 cu. ft	300 W, 1140 Wh/day
Refrigerator: ac EnergyStar, 22 cu. ft	300 W, 1250 Wh/day
Refrigerator: dc Sun Frost, 12 cu. ft	58 W, 560 Wh/day
Freezer: ac 7.5 cu. ft	300 W, 540 Wh/day
Freezer: dc Sun Frost, 10 cu. ft	88 W, 880 Wh/day
Electric range (small burner)	1250 W
Electric range (large burner)	2100 W
Dishwasher: cool dry	700 W
Dishwasher: hot dry	1450 W
Microwave oven	750–1100 W
Coffeemaker (brewing)	1200 W
Coffeemaker (warming)	600 W
Toaster	800–1400 W

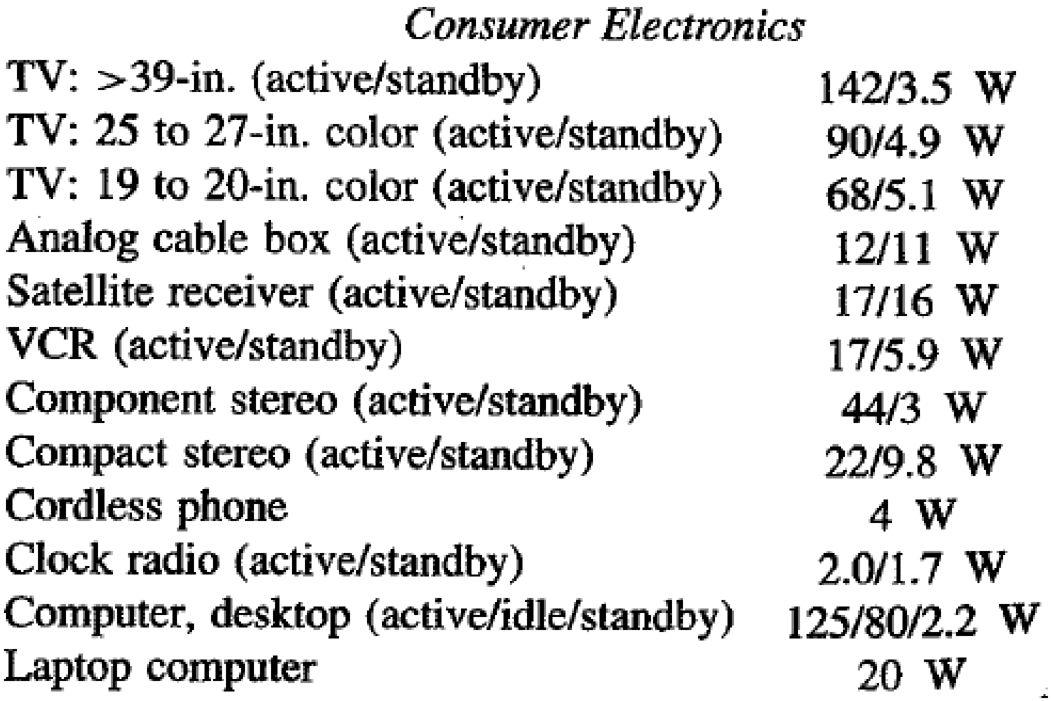
General Household	
Clothes washer: vertical axis	500 W
Clothes washer: horizontal axis	250 W
Dryer (gas)	500 W
Vacuum cleaner	1000–1400 W
Furnace fan: 1/4 hp	600 W
Furnace fan: 1/3 hp	700 W
Furnace fan: 1/2 hp	875 W
Ceiling fan	65–175 W
Whole house fan	240–750 W
Air conditioner: window, 10,000 Btu	1200 W
Heater (portable)	1200–1875 W
Compact fluorescent lamp (100-W eq)	30 W
Compact fluorescent lamp (60-W eq)	16 W
Electric blanket, single/double	60/100 W
Clothes iron	1000–1800 W
Electric clock	4 W

Table 9.10 – Power Requirements of some typical loads

Note that these tables are useful for getting an idea of the average values, but the best data comes from actual measurements!

Consumer Electronics as Loads

- Consider the power when the device is actively used
- Also consider the power consumed when device is in standby



Consumer Electronics

TV: >39-in. (active/standby)	142/3.5 W
TV: 25 to 27-in. color (active/standby)	90/4.9 W
TV: 19 to 20-in. color (active/standby)	68/5.1 W
Analog cable box (active/standby)	12/11 W
Satellite receiver (active/standby)	17/16 W
VCR (active/standby)	17/5.9 W
Component stereo (active/standby)	44/3 W
Compact stereo (active/standby)	22/9.8 W
Cordless phone	4 W
Clock radio (active/standby)	2.0/1.7 W
Computer, desktop (active/idle/standby)	125/80/2.2 W
Laptop computer	20 W

Table 9.10 – Power requirements of some consumer electronics

Batteries and PV Systems

- Batteries in PV systems provide storage, help meet surge current requirements, and provide a constant output voltage
- Lead-acid batteries are still the most commonly-used batteries for PV systems
- The lead-acid battery is an electrical storage device that uses a reversible chemical reaction to store energy.
- Lead-acid batteries date back to the 1860s

Basics of Lead-Acid Batteries

Positive Plate: $\mathrm{PbO_2 + 4H^+ + SO_4^{2-} + 2}e^- \rightarrow \mathrm{PbSO_4 + 2H_2O}$ (9.21)

Negative Plate: $\mathrm{PbO_2 + SO_4^{2-} \rightarrow PbSO_4 + 2e^-}$ (9.22)

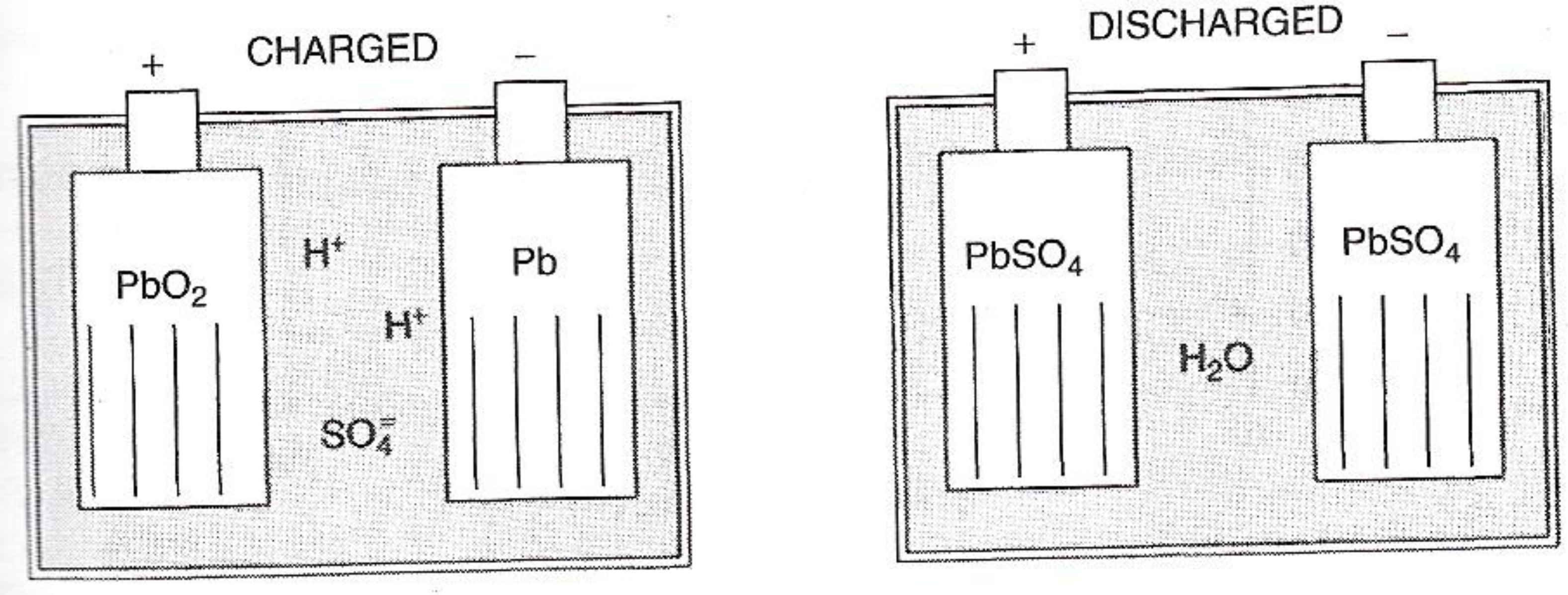
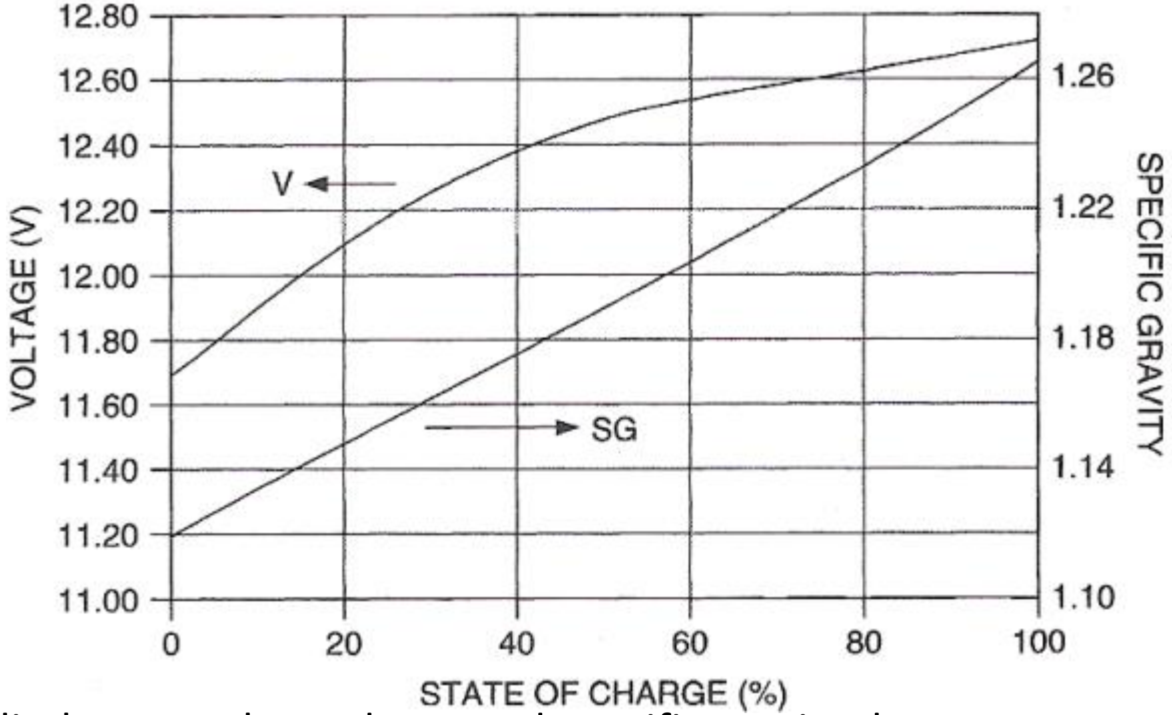


Figure 9.40 A lead-acid battery in its charged and discharged states.

Basics of Lead-Acid Batteries



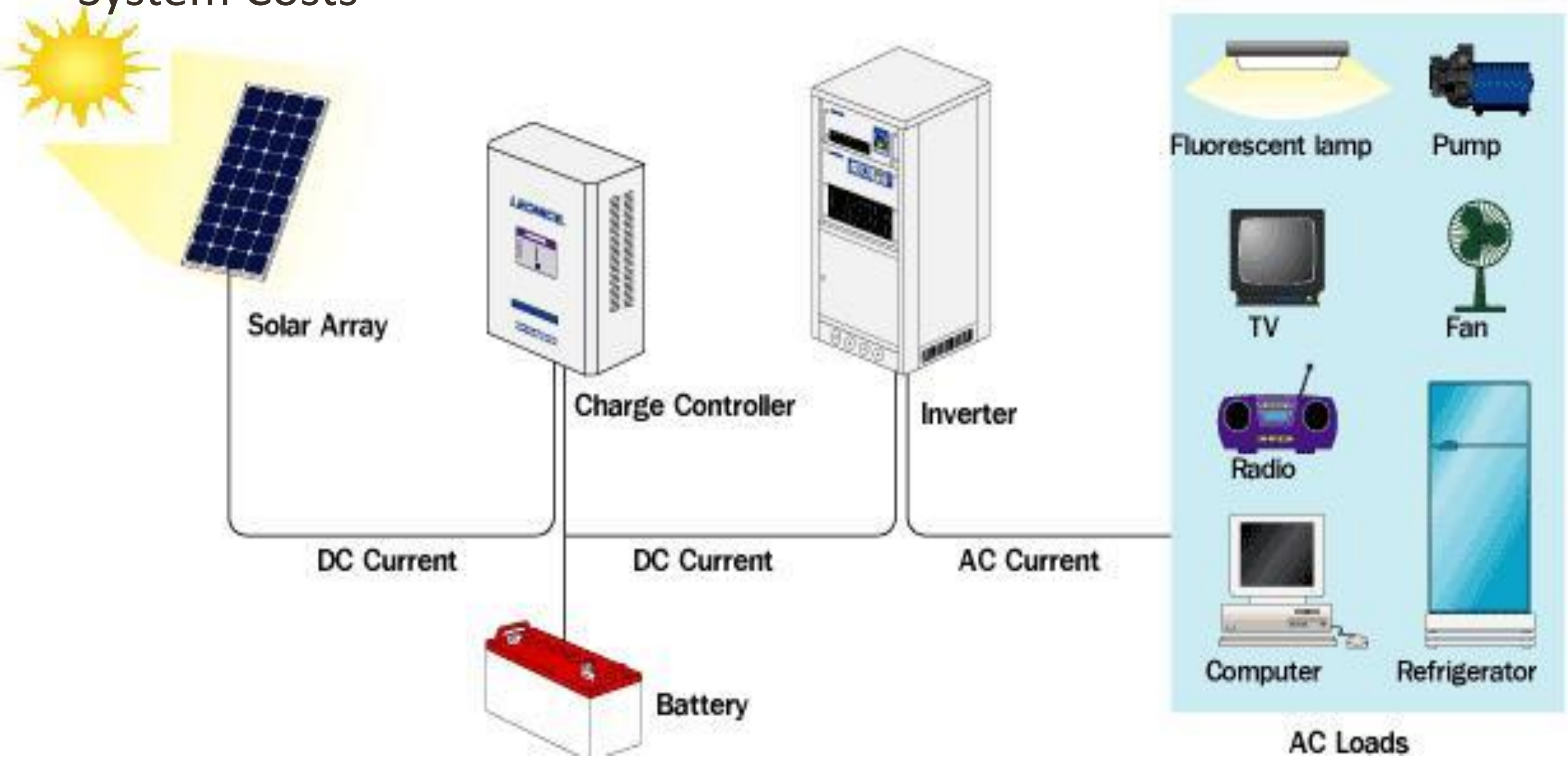
- During discharge, voltage drops and specific gravity drops
- Sulfate adheres to the plates during discharge and comes back off when charging, but some of it becomes permanently attached

Stand-Alone PV Systems – Design Summary

- Analysis of load
    - Determine daily demands for power and energy
    - What fraction of the worst month “design month” should you cover with the PV system? How much should you cover with a backup generator?
    - What PV system voltage should you have?
    - Convert total DC load to amp hours @ system voltage
- PV sizing
    - Pick a PV module based on insolation data for the site for the design month
    - Determine how many parallel strings of modules and how many modules in each string

Stand-Alone PV Systems – Design Summary

- Battery Sizing – How many days of storage needed?
- Generator Sizing
- System Costs



http://www.ecosolarenergy.com.au/How_a_Standalone_System_Works-28.htm