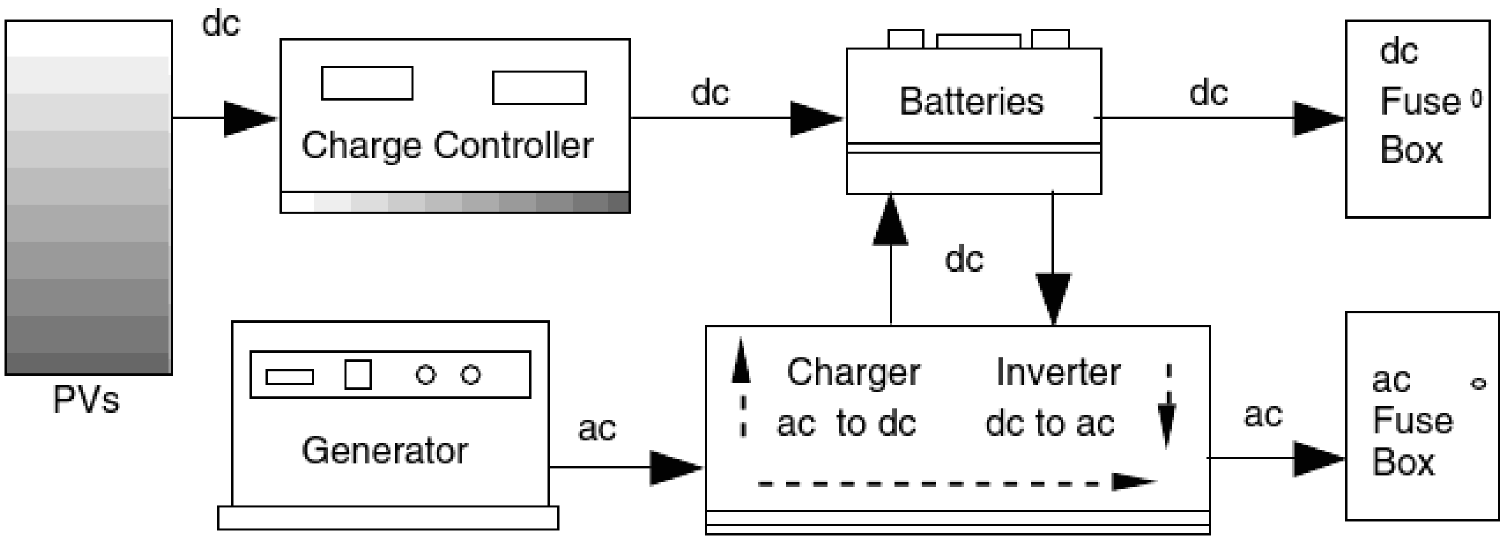
Photovoltaic Systems III

EE 446/646

Stand-alone PV System



- Stand alone PV system with generator back-up and separate outputs for DC and AC loads.
- The charger– inverter unit may include an automatic transfer switch that allows the generator to supply ac loads directly whenever it is running.

Stand-alone PV Systems

- When the grid isn't nearby, electricity becomes much more valuable and the extra cost and complexity of a self-sufficient, stand-alone power system can provide enormous benefit.
  - Instead of competing with 10-cent utility power, a PV– battery system competes with 50-cent gasoline or diesel-powered generators.
  - Or it competes with the cost of bringing the grid to the site, which may run many thousands of dollars per mile.
- Off-grid systems must be designed with great care to assure satisfactory performance. Users must be willing to
  - check and maintain batteries,
  - adjust their energy demands as weather and battery charge vary,
  - fuel and fix a noisy generator,
  - take responsibility for the safe operation of the system.

Sizing a stand-alone PV system

- Power needed by the load, as well as energy required over time by that load, is important for system sizing.
  - Various iterations will follow in which trade-offs are made between more expensive, but more efficient, appliances and devices in exchange for fewer PVs and batteries.
  - Lifestyle adjustments need to be considered in which some loads are treated as essentials that must be provided for, and others are luxuries to be used only when conditions allow.
  - A key decision involves whether to use all dc loads to avoid the inefficiencies associated with inverters, or whether the convenience of an all ac system is worth the extra cost,
  - Another important decision is whether to include a generator back-up system and, if so, what fraction of the load it will have to supply.

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

Power requirements of typical loads (cont.)

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 equivalent)	30 W
Compact fluorescent lamp (60-W equivalent)	16 W
Electric blanket, single/double	60/100 W
Clothes iron	1000–1800 W
Electric clock	4 W
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

Power requirements of typical loads (cont.)

Ink-jet printer	35 W
Dot-matrix printer	200 W
Laser printer	900 W
Shop	
Circular saw, 7 1/4″	900 W
Table saw, 10-in.	1800 W
Hand drill, 1/4″	250 W
Water Pumping	
Centrifugal pump: 36 Vdc, 50-ft @ 10 gpm	450 W
Submersible pump: 24 Vdc, 100-ft @ 1.6 gpm	100 W
Submersible pump: 48 Vdc, 300-ft @ 1.5 gpm	180 W
DC pump (house pressure system), typical use 1–2 h/day	60 W

Source: Rosen and Meier (2000) and others.

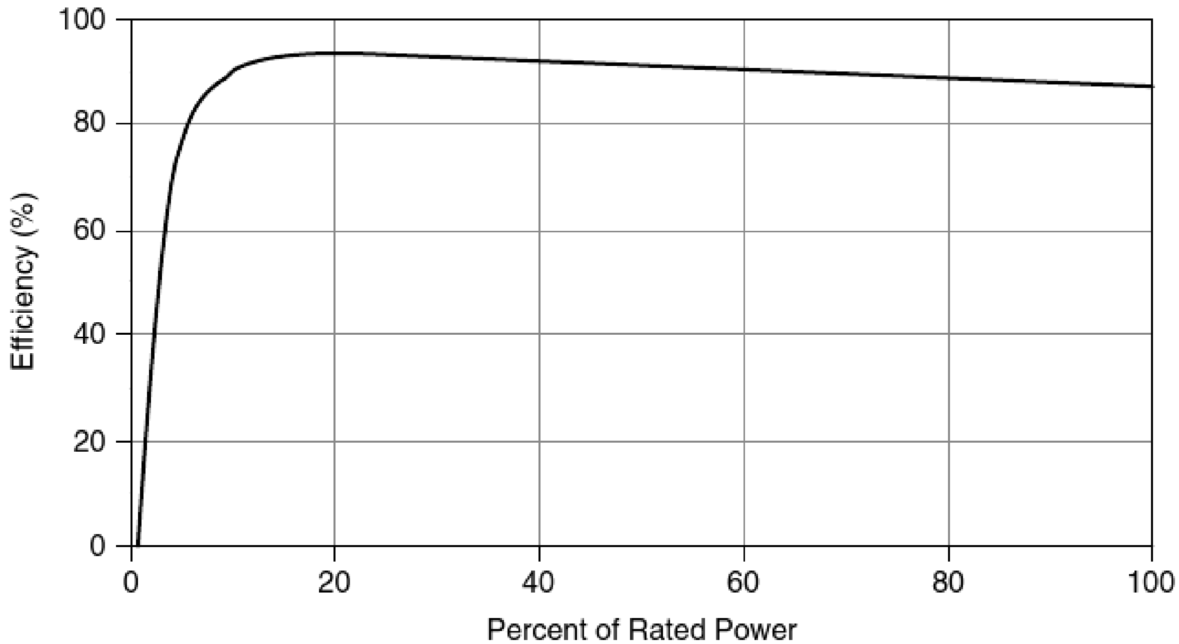
Example 1: A Modest Household Demand

- Estimate the monthly energy demand for a cabin with all ac appliances, consisting of a 19-cu. ft refrigerator, six 30-W compact fluorescents (CFLs) used 5 h/day, a 19-in. TV turned on 3 h/day and connected to a satellite, a cordless phone, a 1000-W microwave used 6 min/day, and a 100-ft deep well that supplies 120 gallons/day.
- *Answer:*

Appliance	Power (W)	Hours	Watt-hours/day	Percentage
Refrigerator, 19 cu. ft	300		1140	37%
Lights (6 @ 30 W)	180	5	900	29%
TV, 19-in., active mode	68	3	204	7%
TV, 19-in., standby mode	5.1	21	107	3%
Satellite, active mode	17	3	51	2%
Satellite, standby mode	16	21	336	11%
Cordless phone	4	24	96	3%
Microwave	1000	0.1	100	3%
Washing machine	250	0.2	50	2%
Well pump, 100 ft, 1.6 gpm	100	1.25	125	4%
Total			3109	100%

Accounting for inverter losses

- the load calculation needs to be modified to account for losses in the dc-to-ac inverter.
  - The inverter's efficiency is a function of the magnitude of the load it happens to be supplying at that particular instant.
  - Most inverters now operate at around 90-95% efficiency over most of their range. For calculations, an overall inverter efficiency of about 85% is considered to be a conservative default assumption.



Example 2

- Suppose that a dc refrigerator that uses 800 Wh/day is being considered instead of the 1,140 Wh/day given in Example 1. Estimate the dc load that the batteries must provide if an 85% efficient inverter is used (a) with all loads running on ac and (b) with everything but the refrigerator running on ac.
- *Answer:*
  - *With all loads running on ac,*

    battery load = 3,109/.85 = 3,658 Wh/day
  - *With all loads running on ac, except the refrigerator,*

    battery load = 800 + (3,109-1,140)/.85 = 3,116 Wh/day

  → 15% reduction in the size and cost of the photovoltaic array and the batteries. But an economic analysis would be needed to determine the right decision (since dc powered appliances are generally more expensive, plus the cost of running extra wires)

Inverter rating

- Inverters are specified by their
  - dc input voltage
  - ac output voltage,
  - continuous power handling capability,
  - amount of surge power they can supply for brief periods of time.
- The inverter's dc input voltage, which is the same as the voltage of the battery bank and the PV array, is usually 12 V, 24 V, or 48 V.
  - Higher voltages need less current, making it easier to minimize wire losses.
- See guideline used to pick the system voltage (while keeping the current below 100 A) in next slide.

Inverter rated power

TABLE 9.11 Suggested System Voltages Based on Limiting Current to 100 A

Maximum ac Power	System dc Voltage
<1200 W	12 V
1200–2400 W	24 V
2400–4800 W	48 V

- The maximum ac power that the inverter needs to deliver is estimated by adding the power demand of all of the loads that will ever be anticipated to be operating simultaneously.
  - For the house in example 1, the total power is 1,919 W. Hence the choice for the system dc voltage is 24 V.

Steady-state and surge power requirements of example loads

Load	Steady State (watts)	Surge (watts)
Refrigerator (ac)	300	1500
Refrigerator (dc)	58	700
Dishwasher	700	1400
Jet pump (1/3 hp) (ac)	750	1400
Submersible pump (ac)	1000	6000
Clothes washer (vertical axis)	650	1150
Clothes washer (horizontal axis)	250	750
Dryer (gas)	500	1800
Furnace fan 1/4 hp	600	1000
Furnace fan 1/3 hp	700	1400
Furnace fan 1/2 hp	875	2350
Air conditioner, window 10 kBtu	1200	1500
Worm drive 7 1/4″ saw	1800	3000
Table saw, 10″	1800	4500

Source: Real Goods (2002).

Inverter electrical specifications

OUTPUT POWER

CONTINUOUS POWER	SURGE POWER	NO LOAD POWER	OUTPUT VOLTAGE	OUTPUT CURRENT	WEIGHT LBS.
125W	150W	5W	100 +/-6%	1.2	2
125W	150W	5W	117 +/-6%	1.1	2
250W**	300W	6W	100 +/-6%	2.5	5
250W**	300W	6W	117 +/-6%	2.1	5
250W**	300W	7W	230 +/-6%	1.1	5
600W**	1100W	8W	100 +/-6%	6.0	6.5
600W**	1100W	8W	117 +/-6%	5.1	6.5
600W**	1100W	9W	230 +/-6%	2.7	6.5
1100W**	2200W	20W*	100 +/-6%	11.0	10
1100W**	2200W	20W*	117 +/-6%	9.5	10
1100W**	2200W	20W*	230 +/-6%	4.8	10
2000W	4000W	12W	100 +/-2%	20.0	15
2000W	4000W	12W	120 +/-2%	16.7	15
2000W	4000W	12W	230 +/-2%	8.7	15

*10W with X2 option , **remote switchable

INPUT POWER

MODEL VOLTAGE	MINIMUM[1] (TYPICAL)	SYSTEM (TYPICAL)	MAXIMUM[1] (TYPICAL)	TYPICAL EFFICIENCY @ FULL POWER	PEAK EFFICIENCY @ 1/3 POWER
**12V	10.4/10.6*	13.8V	16.5V	85%	87%
24V	19/21V*	27.6V	33V	87%	89%
32V	26.5/28V*	36.8V	44V	88%	90%
48V	41.5/42.5V	55.2V	62V	87%	89%
66V	57.5/58.5V*	75.9V	91V	88%	90%
108V	94/95V*	125V	149V	87%	90%

*Indicates typical cut-off voltage/warning buzzer voltage
[1] +/- 3%   ** Output Power derated for XPX

Batteries

- Among the many possible battery technologies, it is the lead-acid battery that continues to be the workhorse of PV systems.
- Competitors to conventional lead-acid batteries include nickel– cadmium, nickel– metal hydride, lithium– ion, lithium– polymer, and nickel– zinc technologies.
  - Conventional car batteries (SLI) are not designed for deep discharge; therefore, they are inappropriate for PV systems.

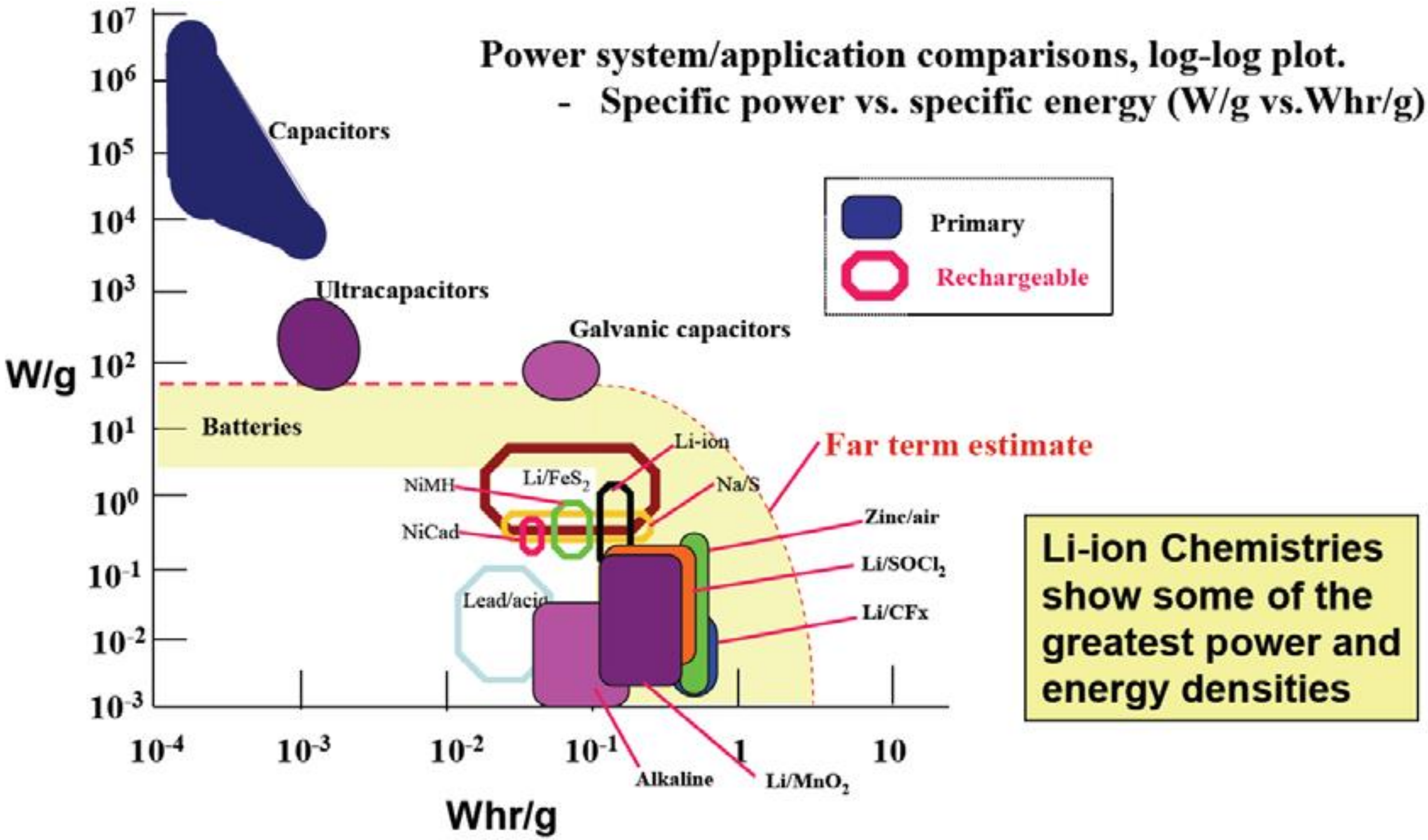
TABLE 9.14 Rough Comparison of Battery Characteristics[a]

Battery	Max Depth Discharge	Energy Density (Wh/kg)	Cycle Life (cycles)	Calendar Life (years)	Efficiencies Ah %	Efficiencies Wh %	Cost ($/kWh)
Lead-acid, SLI	20%	50	500	1–2	90	75	50
Lead-acid, golf cart	80%	45	1000	3–5	90	75	60
Lead-acid, deep-cycle	80%	35	2000	7–10	90	75	100
Nickel–cadmium	100%	20	1000–2000	10–15	70	60	1000
Nickel–metal hydride	100%	50	1000–2000	8–10	70	65	1200

[a] Actual performance depends greatly on how they are used.

Source: Linden (1995) and Patel (1999).

Specific power and energy of different energy storage technologies



Li-ion Chemistries show some of the greatest power and energy densities

Chemical Reaction in Lead Acid Batteries

- A lead acid battery consists of a negative electrode made of porous lead and a positive electrode which consists of lead oxide. Both electrodes are immersed in a electrolytic solution of sulfuric acid and water.
- Lead acid batteries store energy by the reversible chemical reaction shown below.

$$PbO_2 + Pb + 2H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O$$

- At the negative terminal the charge and discharge reactions are:

$$Pb + SO_4^{2-} \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} PbSO_4 + 2e^-$$

- At the positive terminal the charge and discharge reactions are:

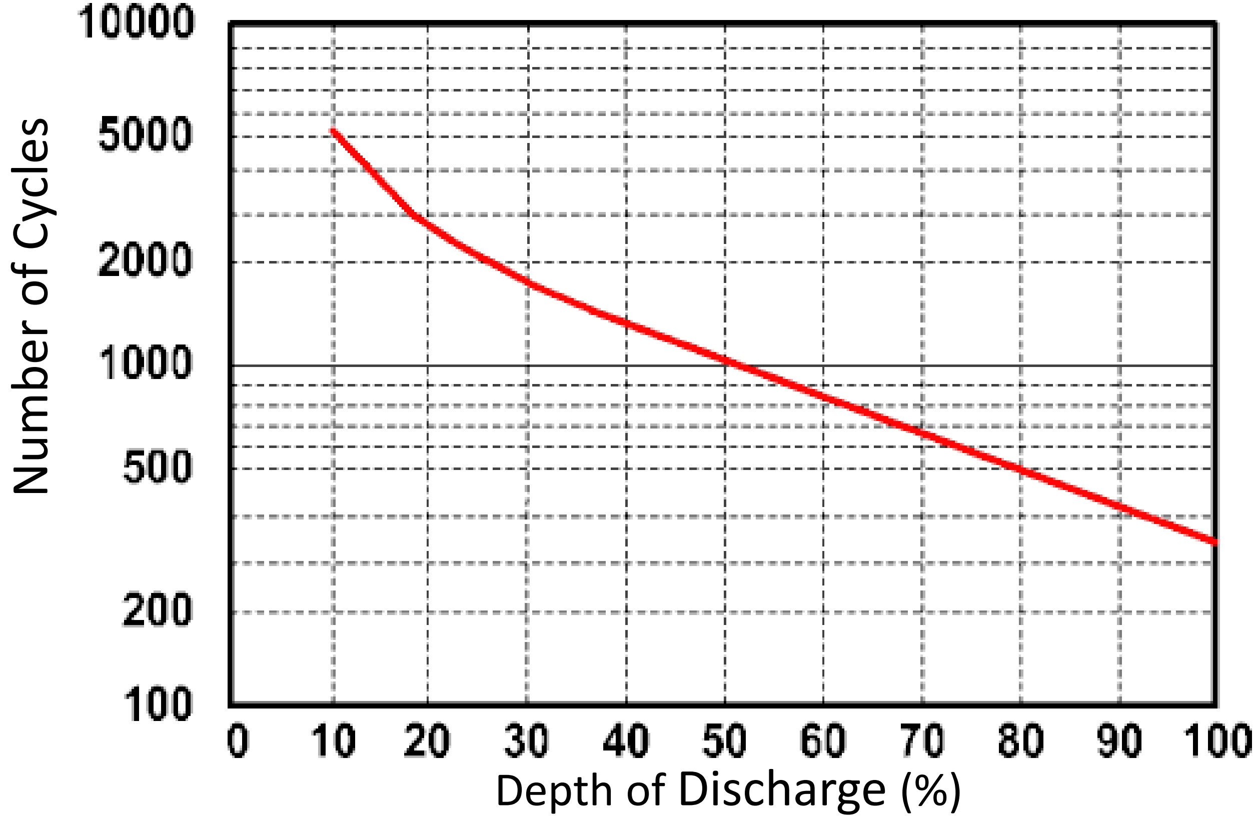
$$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} PbSO_4 + 2H_2O$$

- Unfortunately, not all of the lead sulfate returns to solution, and each battery charge/discharge cycle leaves a little more sulfate permanently attached to the plates – this sulfation is the primary cause of a battery finite lifetime.

Impact of depth of discharge on number of cycles

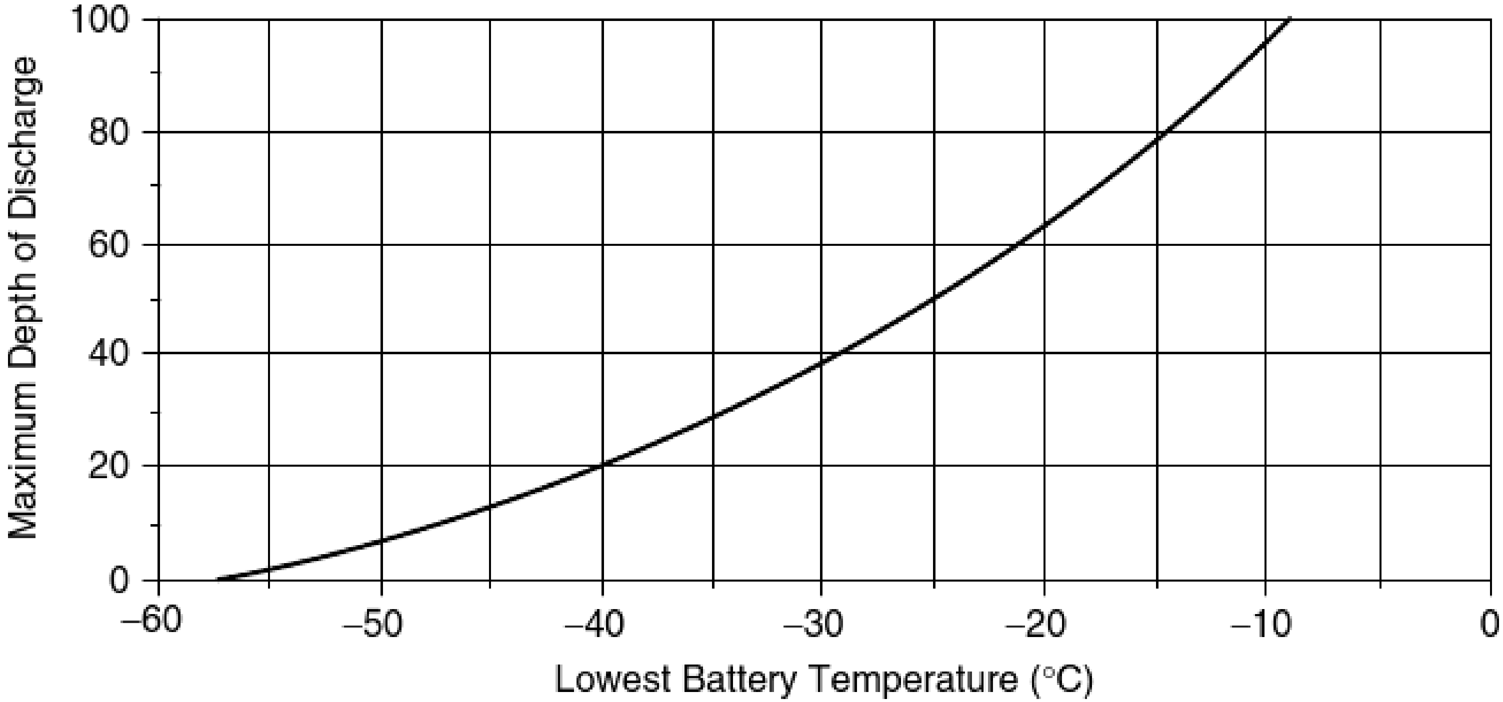
- The deeper the depth of discharge, the shorter is the battery life.
- Relation between state of charge and depth of discharge:

SOC (%) = 100 –DOD (%)



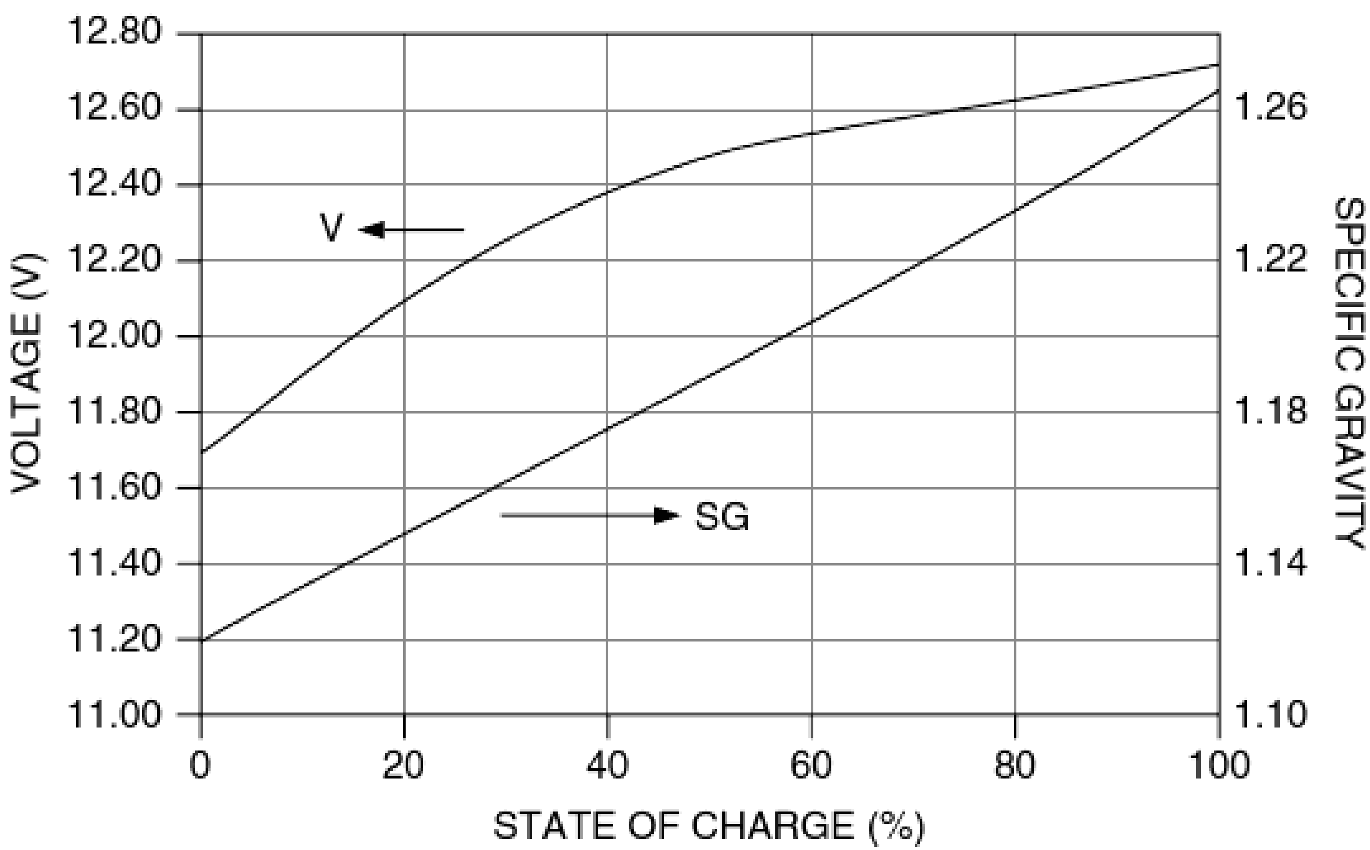
allowable depth of discharge of a lead-acid battery in cold climates

- The battery is more vulnerable to freezing in its discharged state since the anti-freeze action of the sulfuric acid is diminished when there is less of it present.



Determining the battery state-of-charge (SOC) by measuring terminal voltage or specific gravity (SG) of electrolyte

- For accurate results, the battery must be at rest for several hours, at 25°C and the electrolyte is well-mixed. For sealed batteries, voltage reading is the only option.



Battery storage capacity

- Energy storage in a battery is typically given in units of amp-hours (Ah) at some specified discharge rate.
- Manufacturers typically specify the amp-hour capacity at a discharge rate that would drain a 2 V cell down to 1.75 V (or 12 V down to 10.5 V) over a specified period of time at a temperature of 25^{o}C.
- *Example:* a 12 V battery that is rated at 200 Ah at 10-hour rate, is expected to deliver 20 A for 10 hours. It is said that it is discharging at rate of C/10 (i.e., 200Ah/10h = 20 A)
  - At C/4, the battery will have a capacity lower than 200 Ah
  - At C/20, the battery will have a capacity higher than 200 Ah

    → Battery Ah capacity depends on the rate of discharge!
- It is not easy to specify how much energy the battery delivered during its discharge: Energy is volts x amps x hours, but the voltage varies throughout the discharge period.

Battery Capacity at different discharge rates

- Deep-cycle batteries intended for photovoltaic systems are often specified at different discharge rates (with C/20 being the most common rating).

Specification

Nominal Voltage		12 volts	
Nominal Capacity		77° F (25° C)	
20-hr. (12.50A)		230 Ah	
10-hr. (23.25A)		232.5 Ah	
5-hr. (42.50A)		212.5 Ah	
1-hr. (150.00A)		150 Ah	
Approximate Weight		154 lbs (70 kgs)	
Internal Resistance (approx.)		4 mOHMS	
Shelf Life (% of normal capacity at 77° F (25° C))			
3 Months	6 Months	12 Months	
91%	82%	64%	
Temperature Dependancy of Capacity		(20 hour rate)	
104° F	77° F	32° F	5° F
102%	100%	85%	65%

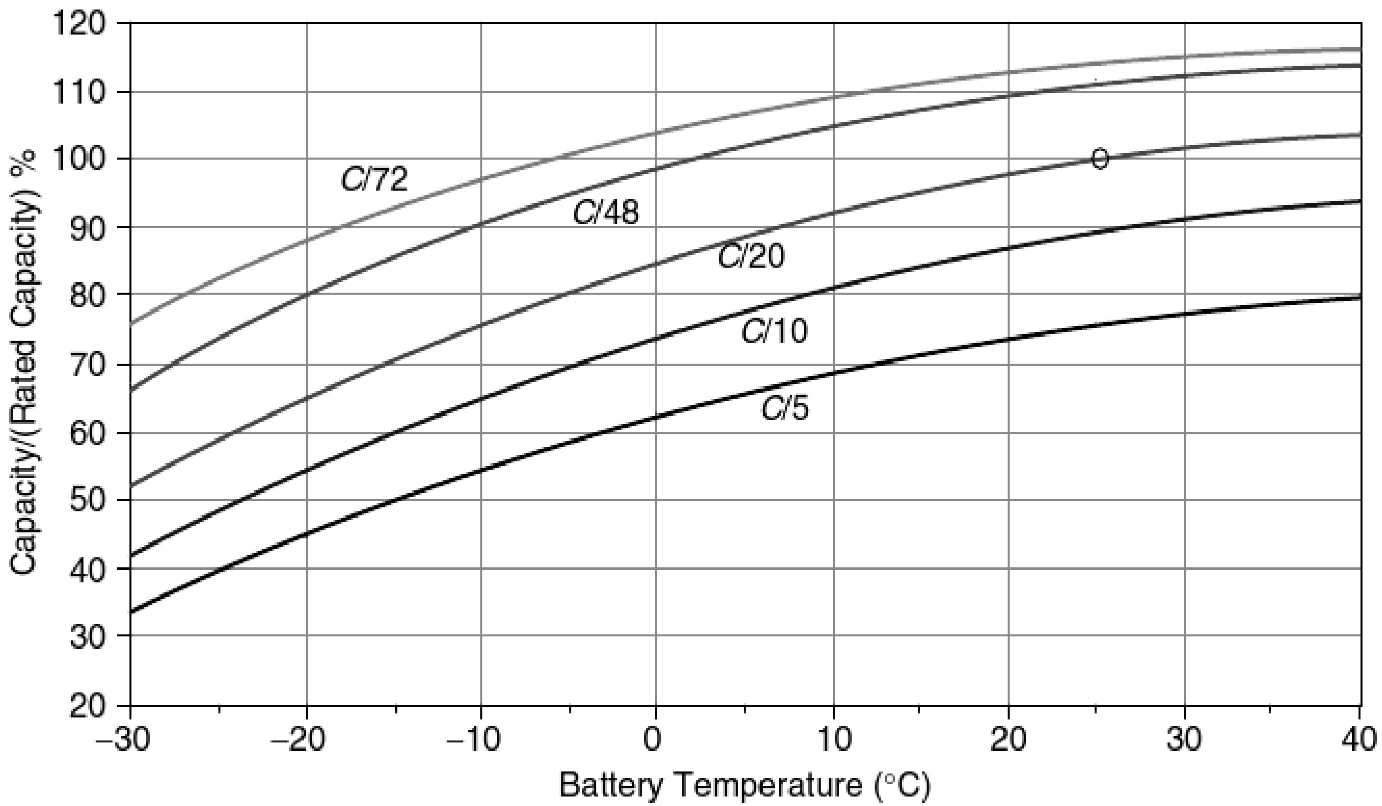
Charge Method (Constant Voltage)	
Cycle Use (Repeating Use)	
Initial Current	87.5 A or smaller
Control Voltage	14.5 - 14.9 V
Float Use	
Control Voltage	13.6 - 13.8 V

Battery capacity

- Note the specified battery capacity (Ah) below applies only for a specific discharge rate (i.e., 11.6 A for 20 hours).
- If the battery is discharged at 75 A, it will last for only 2 hours, (i.e., its capacity drops from 232 Ah down to 152 Ah).

Capacity dependence on temperature

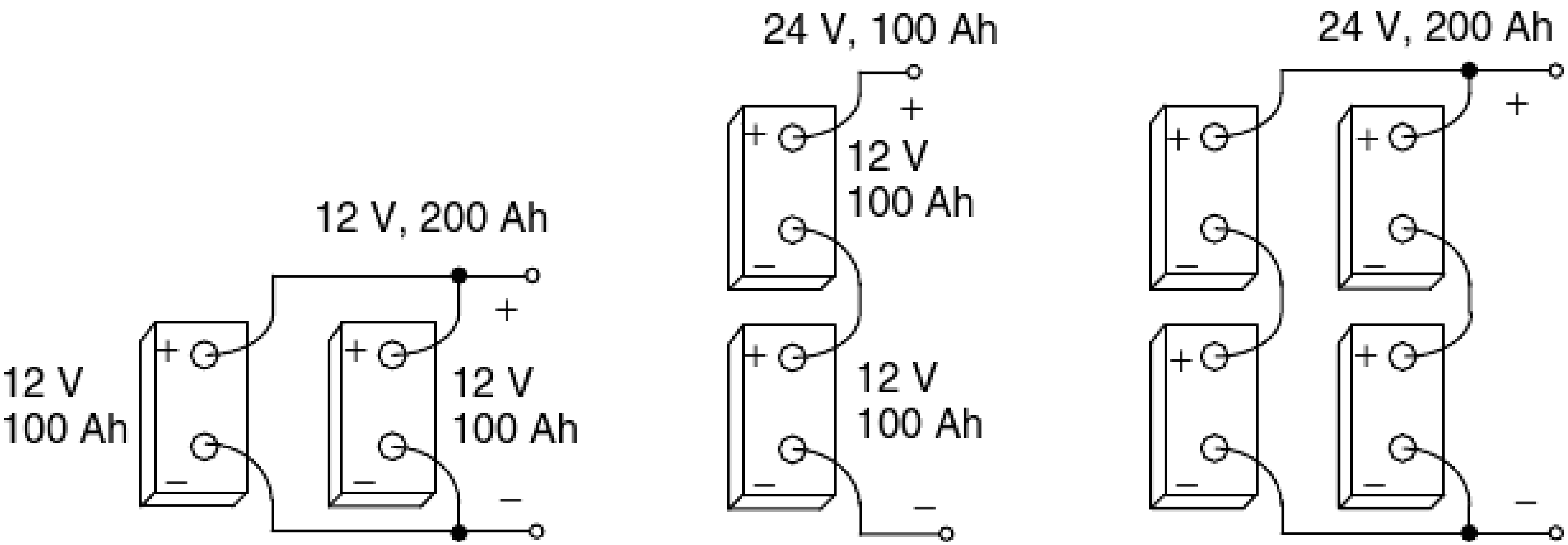
- Battery capacity depends not only on discharge rate, but also on temperature.
  - In cold temperatures, the battery capacity is reduced.
  - In warm temperatures, the battery capacity is increased.



Ratio is based on a rated capacity at C/20 and 25°C

Battery connections

a) For batteries wired in parallel, amp-hours add up
b) For batteries in series, voltages add up
c) For series/parallel combinations, both voltages and amp-hours add up



(a) Parallel, Amp-Hrs add (b) Series, Voltages add (c) Series/Parallel

Coulomb, voltage and Energy Efficiency

- The round trip energy efficiency of a battery is given by

$$\text{Energy efficiency} = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{V_D I_D \ \Delta T_D}{V_C I_C \ \Delta T_C}$$

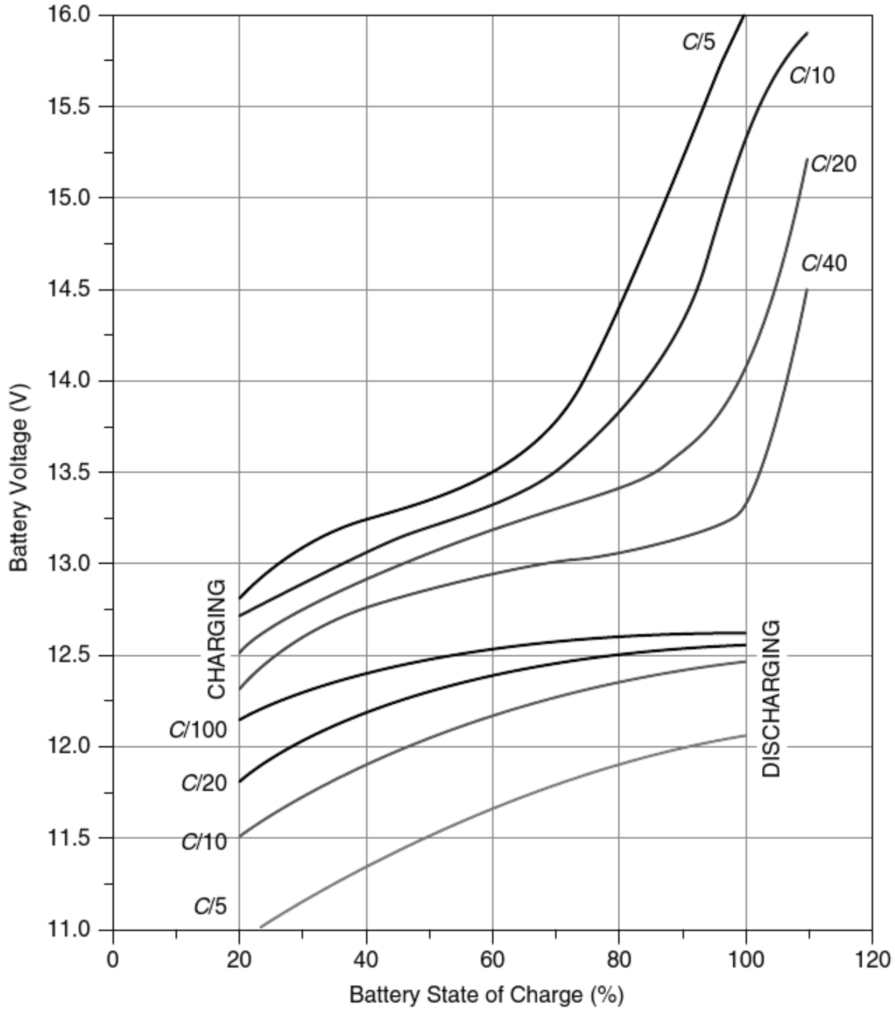
$$\text{Energy efficiency} = (\text{Voltage efficiency}) \times (\text{Coulomb efficiency})$$

- where subscripts “D” and “C” are respectively associated with discharging and charging
- **Example A:** a battery is charged for one hour at a voltage and current of 14 V and 10 A. It is then discharged for one hour at a voltage and current of 9 A and 12 V. its energy efficiency is (12/14)*(9/10) = (0.86)*(0.9)=0.77 (or 77%).
- The power loss occurs in the battery internal resistance (I^2R_i) and in the electrolysis process (i.e., breaking water molecules into hydrogen and oxygen atoms).

Battery voltage during charging and discharging as a function of SOC

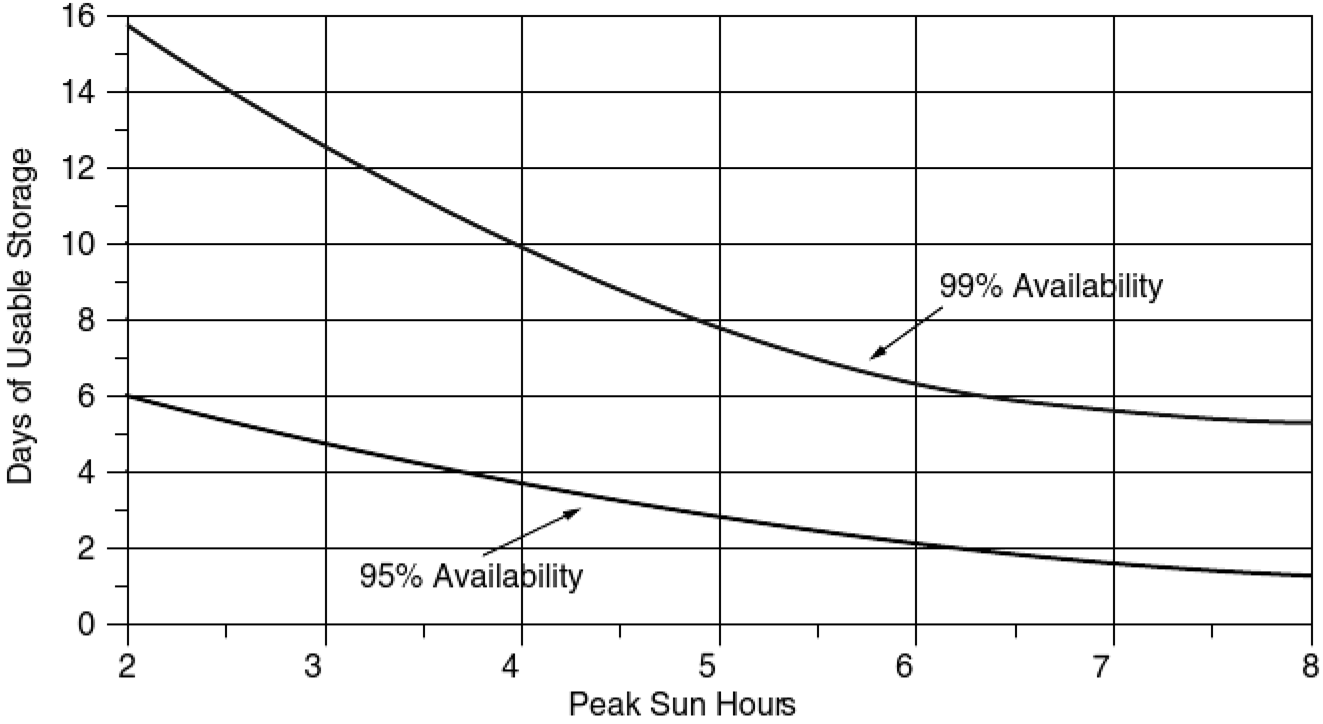
During charging, the voltage rises faster with the rate of charge, as the battery nears 80% SOC.

- This is when electrolysis that removes water from the battery takes place.
- It also creates a potentially dangerous situation since hydrogen gas is so explosive. → Proper ventilation of battery storage systems is important.
- Some lead-acid batteries (VRLA) use pressure-relief valves that allow up to 95% of the gases formed during gassing to recombine with lead .
- Charge controllers are designed to slow the charging rate as the battery approaches its fully charged condition.



Battery Sizing

- Given the statistical nature of weather, there are no set rules about how best to size battery storage.
- Sizing a storage system to meet the demand 99% of the time can easily cost triple that of one that meets demand only 95% of the time.



1. Peak sun hours are for the worst month of the year and availability is on an annual basis (Source: SNL, 1995).
2. Days of "usable storage," means after accounting for impacts associated with maximum allowable battery discharge, Coulomb efficiency, battery temperature, and discharge rate.

Battery Sizing

- The relationship between usable storage and nominal, rated storage (at C/20, 25ºC) is given by

$$\text{Nominal } (C/20, 25^\circ\text{C}) \text{ battery capacity} = \frac{\text{Usable battery capacity}}{(\text{MDOD})(\text{T, DR})}$$

- where MDOD is the maximum depth of discharge (default: 0.8 for lead-acid - subject to freeze constraints) and (T, DR) are the temperature and discharge-rate factor (refer to capacity-temp graph).
- **Example B:** size a battery for 95% availability for a cabin in Salt Lake City, UT, where the AC load demand is 3 kWh/day during the worst winter month. Assume the temperature may reach as low as −10◦C, the system voltage is to be 24 V, and the inverter overall efficiency is 85%.

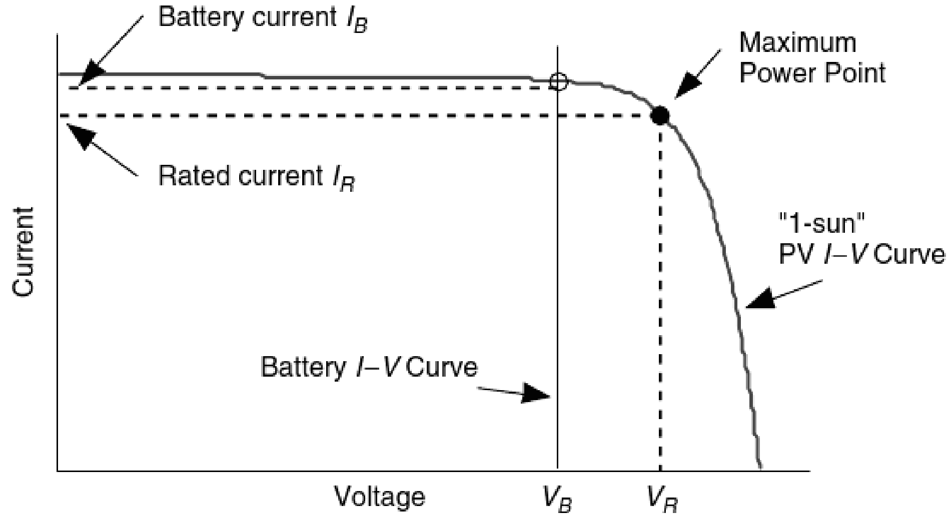
Tilt	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Year
Lat − 15	2.9	4.0	5.0	5.9	6.6	7.2	7.3	7.0	6.3	5.0	3.3	2.5	5.2
Lat	3.2	4.3	5.2	5.8	6.2	6.6	6.7	6.7	6.4	5.4	3.7	2.9	5.3
Lat + 15	3.4	4.4	5.1	5.4	5.5	5.6	5.8	6.1	6.1	5.5	3.9	3.1	5.0

Example B (cont.)

- *Answer:*
  - *Daily Ah needed: (3000/0.85)/24 = 147 Ah*
  - *Worst insolation: 3.1 kWh/m2/day (Dec.)*
  - *Number of storage days needed: 4.6 days*
  - *Useable storage: 4.6x147 = 676 Ah*
  - *DoD allowed: 95%, but we will use the standard value of 80%*
  - *DR at specified temperature: 0.97*
  - *Nominal battery capacity = 676/(0.8x0.97)=871 Ah @24V*
  - *If we choose the Trojan 6 V, 225 Ah, T-105. 1 string of 4 batteries will give 225 Ah @ 24V. Four of such strings in parallel will give 900 Ah @ 24V*

Array Sizing

- A simple sizing procedure is be based on the same “peak hours” approach used for grid-connected systems, except that it is applied to current rather than power, i.e., use the rated current I_R of the PV array at 1-sun, times peak hours of sun, gives us the Ah provided to the batteries.
- It is common practice to apply a de-rating of about 10% to account for dirt and gradual aging of the modules. The temperature and module-mismatch factors are usually ignored because the operating point for battery systems is far enough away from the knee of the I – V curve that those variations are minimum.



Array Sizing

- The current delivered to the batteries needs to multiplied by the Coulomb efficiency (Ah_{out} /Ah_{in}) to give Ah delivered from the batteries to the load:

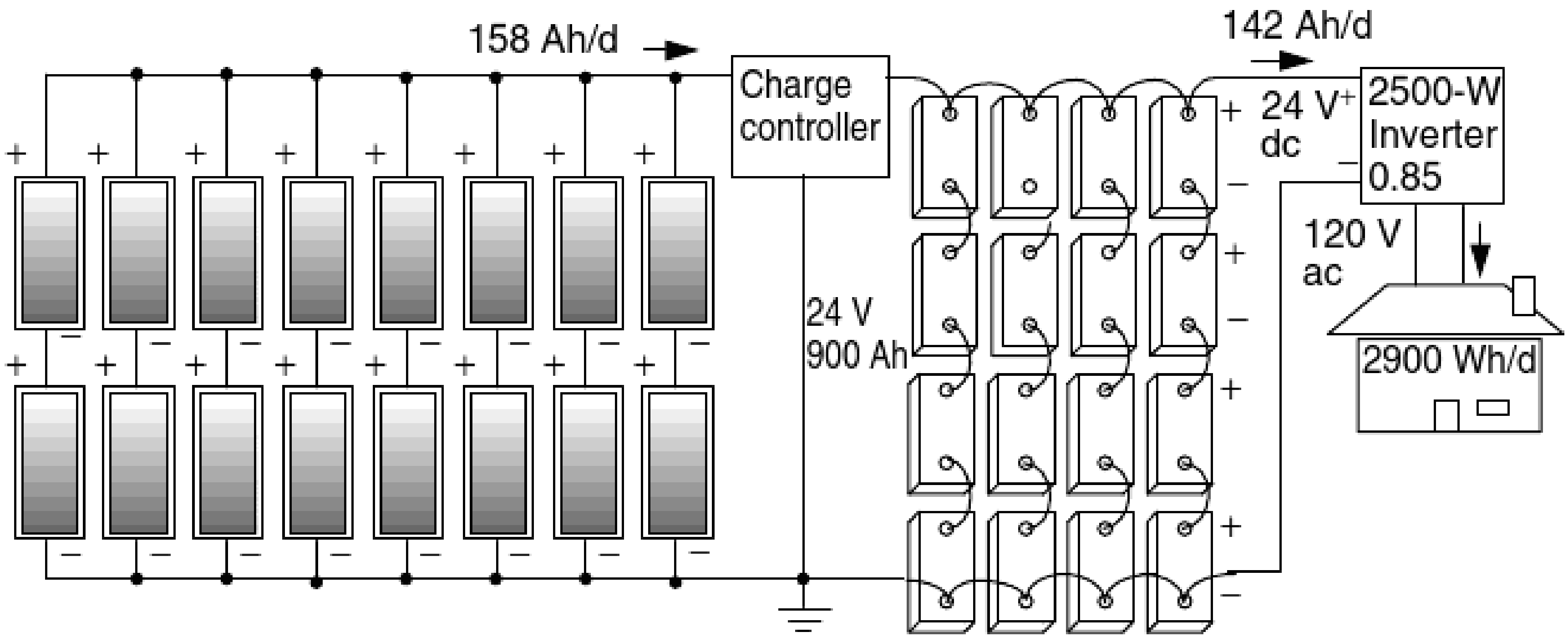
$$\text{Ah to load} = I_R \times \text{Peak sun hours} \times \text{Coulomb efficiency} \times \text{De-rating factor}$$

- **Example B (cont.):** For a 24-V system voltage, 90% Coulomb efficiency, 10% de-rating , size a PV array using Kyocera KC120 modules (with rated voltage and current equal to 16.9V and 7.1A
- *Answer:*
  - *One module will deliver in December about: 7.1x3.1x.9x.9 = 17.83 Ah/day*
  - *Inverter DC input: (3000Wh/day)/(.85x24) = 147 Ah/day @ 24V*
  - *Number of parallel strings (each with two modules in series): 147/17.83 = 8.25 strings*

Example B (cont.)

– *Suppose we undersize to 8 parallel strings: 8x7.1x3.1x.9 =158 Ah/day, battery output: 158x.9=142 Ah/day@24V, inverter output = 142x24x.85 = 2900 Wh/day @ 120Vac – just shy of 3000 Wh/day.*

- Energy values shown below are for the design month of December.



Example B (cont.)

- A PV– battery system sized to cover the worst month delivers much more energy than is needed during the rest of the year.
- After figuring out the cost of a system that has been designed to be completely solar, a buyer may very well decide that a hybrid system with most of the load covered by PV-battery and the remainder supplied by a generator is worth considering.