5. Renewable Energy Sources

Part B2: Solar Electricity - 2

Charles Kim, “Lecture Note on Analysis and Practice for Renewable Energy Micro Grid Configuration,” 2013. www.mwftr.com

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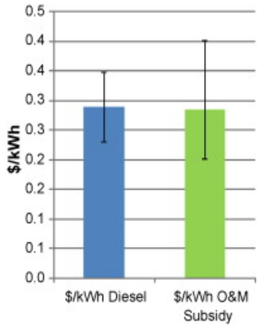
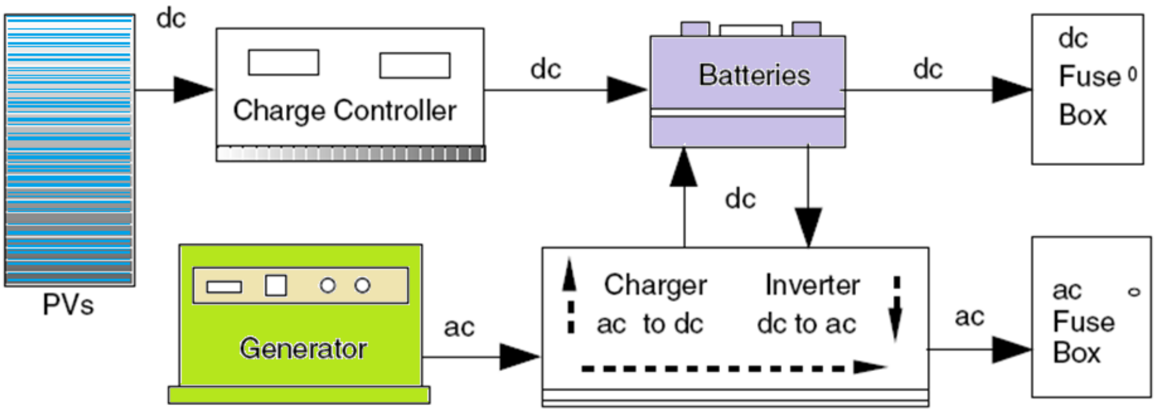
Stand-Alone PV Systems

- When grid is not nearby, electricity becomes more valuable, and stand-alone power system can provide enormous benefit, and complete, instead of $0.1/kWh utility power, with $0.5/kWh gasoline or diesel generators.
- A general stand-alone PV system with back-up generator and separate outputs for AC and DC loads.





Design Process for Stand-Alone System

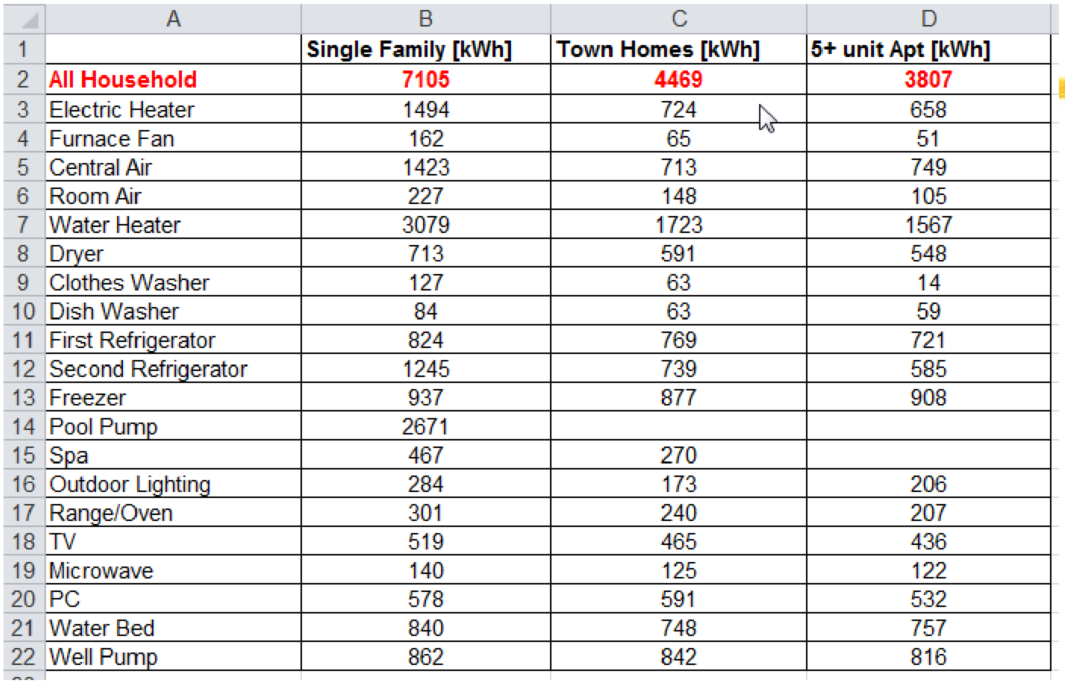
- Load study
  - Know your object and (future) target : P_{ac}
- Inverter and System Voltage (12, 24, or 48V)
  - Relevant to PV output voltage
- PV Sizing
  - P_{dc}, efficiency, Area, V_{oc}, and I_{sc}.
- Battery Sizing
- Hybrid PV System (Generator Sizing)
- System Cost Analysis
  - COE ($/kWh)

Load Study

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

- TV: 100 W Vacuum Cleaner: 1000 W Ceiling Fan: 100 W
- Computer: 125 W Laptop: 20 W Clothes Washer: 250 W
- Window A/C: 1200 W Iron: 1000 W Component Stereo: 40 W
- Clock Radio: 2 W Electric Blanket: 60 W Microwave: 1000 W

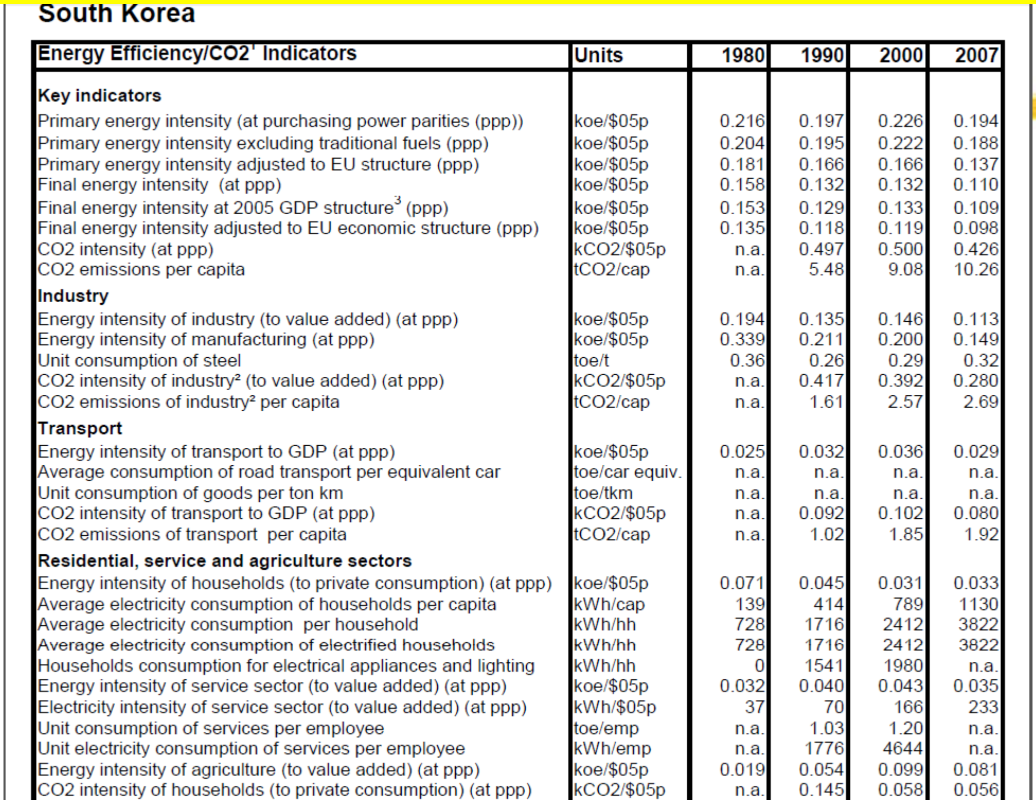
CA Residential Load Study



	A	B	C	D
1		**Single Family [kWh]**	**Town Homes [kWh]**	**5+ unit Apt [kWh]**
2	**All Household**	**7105**	**4469**	**3807**
3	Electric Heater	1494	724	658
4	Furnace Fan	162	65	51
5	Central Air	1423	713	749
6	Room Air	227	148	105
7	Water Heater	3079	1723	1567
8	Dryer	713	591	548
9	Clothes Washer	127	63	14
10	Dish Washer	84	63	59
11	First Refrigerator	824	769	721
12	Second Refrigerator	1245	739	585
13	Freezer	937	877	908
14	Pool Pump	2671		
15	Spa	467	270	
16	Outdoor Lighting	284	173	206
17	Range/Oven	301	240	207
18	TV	519	465	436
19	Microwave	140	125	122
20	PC	578	591	532
21	Water Bed	840	748	757
22	Well Pump	862	842	816

- California Statewide Residential Appliance Saturation Study, 2004

Energy Consumption Data



South Korea

Energy Efficiency/CO2[1] Indicators	**Units**	**1980**	**1990**	**2000**	**2007**
Key indicators					
Primary energy intensity (at purchasing power parities (ppp))	koe/$05p	0.216	0.197	0.226	0.194
Primary energy intensity excluding traditional fuels (ppp)	koe/$05p	0.204	0.195	0.222	0.188
Primary energy intensity adjusted to EU structure (ppp)	koe/$05p	0.181	0.166	0.166	0.137
Final energy intensity (at ppp)	koe/$05p	0.158	0.132	0.132	0.110
Final energy intensity at 2005 GDP structure[3] (ppp)	koe/$05p	0.153	0.129	0.133	0.109
Final energy intensity adjusted to EU economic structure (ppp)	koe/$05p	0.135	0.118	0.119	0.098
CO2 intensity (at ppp)	kCO2/$05p	n.a.	0.497	0.500	0.426
CO2 emissions per capita	tCO2/cap	n.a.	5.48	9.08	10.26
Industry					
Energy intensity of industry (to value added) (at ppp)	koe/$05p	0.194	0.135	0.146	0.113
Energy intensity of manufacturing (at ppp)	koe/$05p	0.339	0.211	0.200	0.149
Unit consumption of steel	toe/t	0.36	0.26	0.29	0.32
CO2 intensity of industry[2] (to value added) (at ppp)	kCO2/$05p	n.a.	0.417	0.392	0.280
CO2 emissions of industry[2] per capita	tCO2/cap	n.a.	1.61	2.57	2.69
Transport					
Energy intensity of transport to GDP (at ppp)	koe/$05p	0.025	0.032	0.036	0.029
Average consumption of road transport per equivalent car	toe/car equiv.	n.a.	n.a.	n.a.	n.a.
Unit consumption of goods per ton km	toe/tkm	n.a.	n.a.	n.a.	n.a.
CO2 intensity of transport to GDP (at ppp)	kCO2/$05p	n.a.	0.092	0.102	0.080
CO2 emissions of transport per capita	tCO2/cap	n.a.	1.02	1.85	1.92
Residential, service and agriculture sectors					
Energy intensity of households (to private consumption) (at ppp)	koe/$05p	0.071	0.045	0.031	0.033
Average electricity consumption of households per capita	kWh/cap	139	414	789	1130
Average electricity consumption per household	kWh/hh	728	1716	2412	3822
Average electricity consumption of electrified households	kWh/hh	728	1716	2412	3822
Households consumption for electrical appliances and lighting	kWh/hh	0	1541	1980	n.a.
Energy intensity of service sector (to value added) (at ppp)	koe/$05p	0.032	0.040	0.043	0.035
Electricity intensity of service sector (to value added) (at ppp)	kWh/$05p	37	70	166	233
Unit consumption of services per employee	toe/emp	n.a.	1.03	1.20	n.a.
Unit electricity consumption of services per employee	kWh/emp	n.a.	1776	4644	n.a.
Energy intensity of agriculture (to value added) (at ppp)	koe/$05p	0.019	0.054	0.099	0.081
CO2 intensity of households (to private consumption) (at ppp)	kCO2/$05p	n.a.	0.145	0.058	0.056

Example Electricity Demand

- A modest household monthly energy demand for a cabin:
  - 19-cu ft refrigerator
  - 6 30W compact fluorescent lamp (5h/day)
  - 19 in TV (3h/day) connected to a satellite
  - Cordless phone
  - 1000W Microwave (6 min/day)
  - 250W Washing machine (30 min/day)
  - 100W pump for 100ft deep well that supplies 120 gallons/day (1.25 h/day)
- Power and Energy Demand (3.11kWh/day)

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%

System Voltage

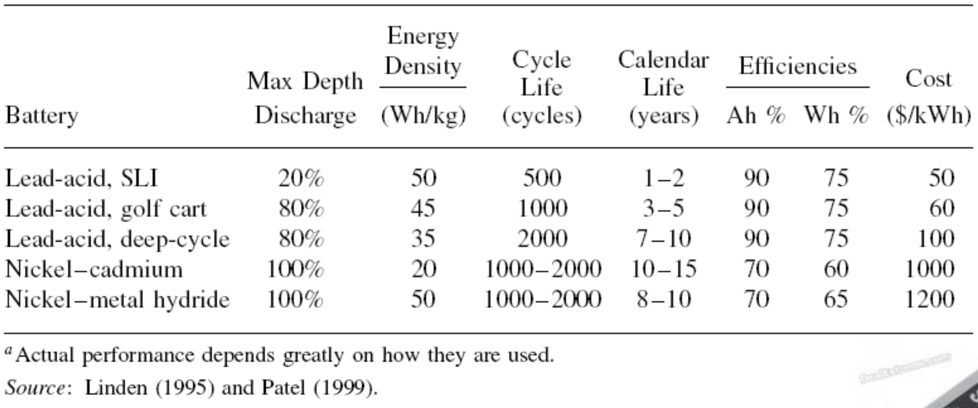
- System voltage: Inverter dc input voltage = **battery bank voltage** = PV array voltage
- High voltage:
  - low current → minimize wire loss
  - More batteries in series
- A guideline:
  - Keep the maximum steady-state current drawn below around 100A → readily available electrical hardware and wire size can be used
  - Suggest system voltage

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

- **BOS (Balance of System):** Balance of equipment necessary to integrate PV array with site load, which includes the array circuit wiring, fusing, disconnects, and inverter

Batteries

- Comparison of Battery Characteristics
- SLI: engine **S**tarting, vehicle **L**ighting, and engine **I**gnition



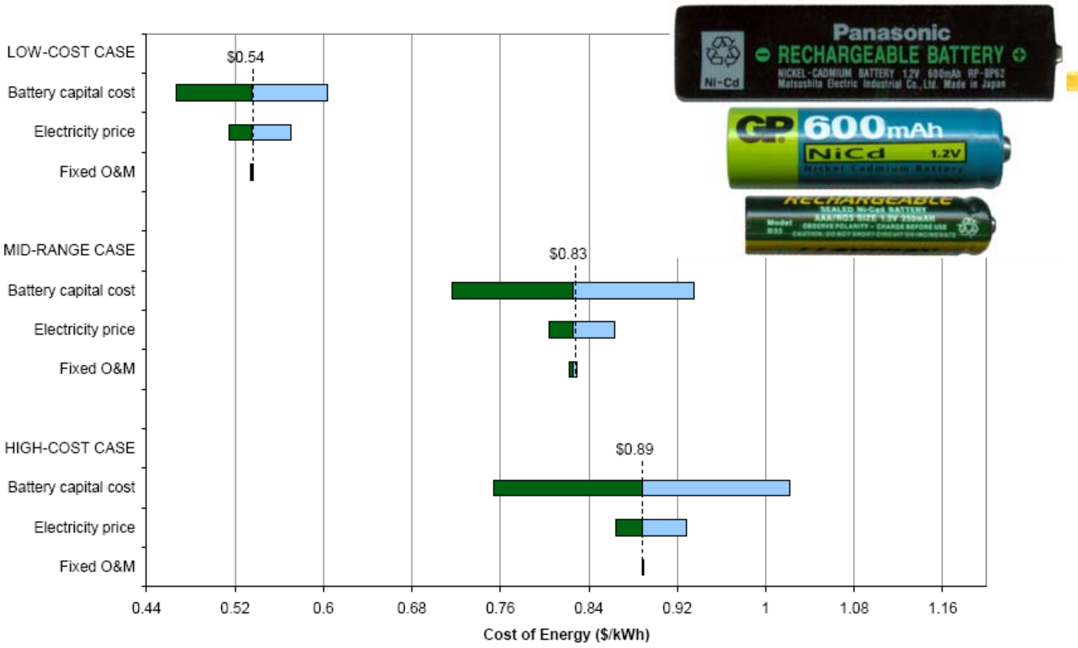
Battery	Max Depth Discharge	Energy Density (Wh/kg)	Cycle Life (cycles)	Calendar Life (years)	Efficiencies Ah %	Efficiencies Wh %	Cost ($/kWh)
Lead-acid, SLI	20%	50	500	1–2	90	75	50
Lead-acid, golf cart	80%	45	1000	3–5	90	75	60
Lead-acid, deep-cycle	80%	35	2000	7–10	90	75	100
Nickel–cadmium	100%	20	1000–2000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

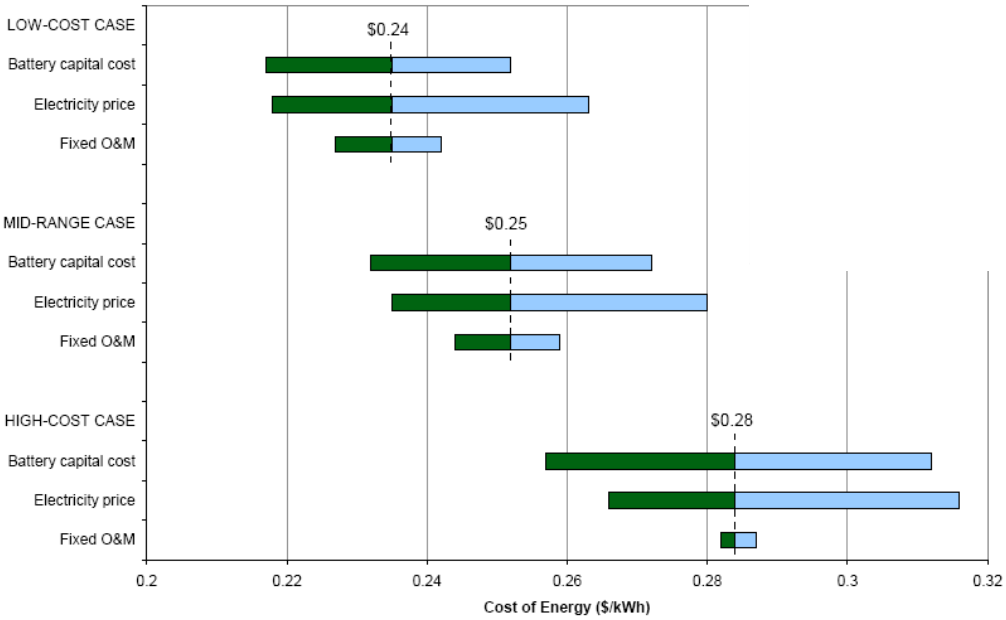
Source: Linden (1995) and Patel (1999).

- Lead-Acid: Cheapest, highest efficiency
- NiCd: Expensive, longer life cycle, dischargeable 100% without damage, more forgivable when abused
- Lithium Iron:

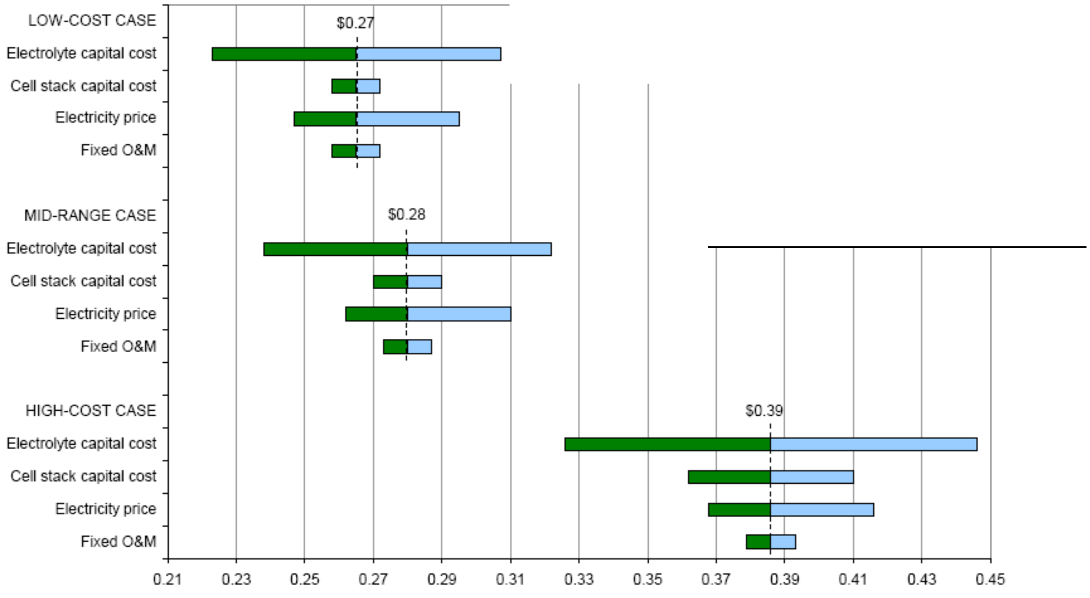
Nickel Cadmium Battery



Sodium Sulfur Battery



Vanadium Redox (Reduction-Oxidation) Battery

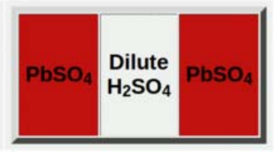


Lead-Acid Batteries

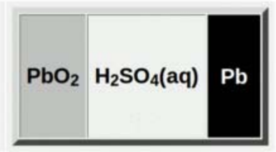
- 1860s: Raymond Gaston Plante first fabricated battery cells with corroded lead-foil electrodes and a dilute solution of sulfuric acid and water
- Chemical reaction in discharge

$$\text{Positive plate}: \quad PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$$

$$\text{Negative plate}: \quad Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$



Fully Discharged



Fully Charged

Compound State Symbols
(s): Solid
(l): liquid
(g): gaseous
(aq): aquaeius - solution

- ¾ of the $30 B global market are for automobile SLI (400 – 600 A for starting, after that alternator quickly recharges the battery. Not for deep discharge)
- 2 V per cell
- Deep Discharge type: thicker plates, greater space around the plates, big and heavy, can be discharged by 80%
- Biggest utility battery bank: 10MW (5000A at 2kV) for 4 hours in to grid (Chino, CA)

Installed Large Scale Battery Energy Storage

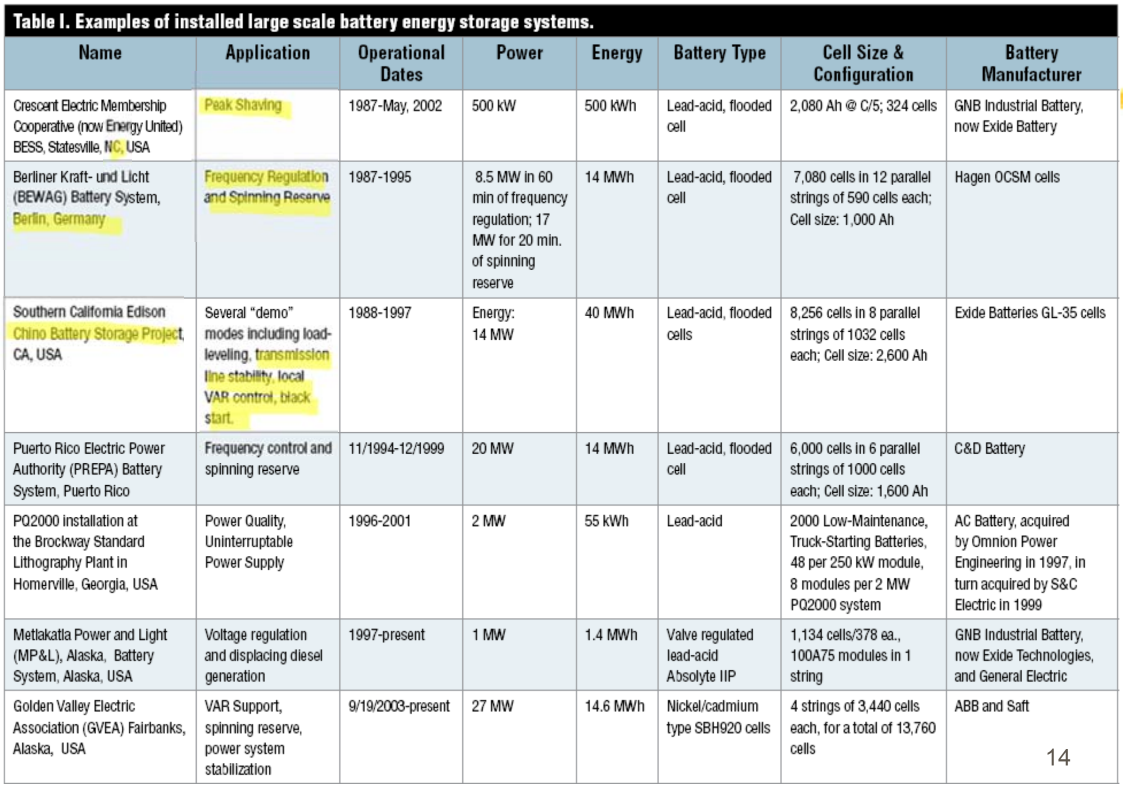


Table I. Examples of installed large scale battery energy storage systems.

Name	Application	Operational Dates	Power	Energy	Battery Type	Cell Size & Configuration	Battery Manufacturer
Crescent Electric Membership Cooperative (now Energy United) BESS, Statesville, NC, USA	Peak Shaving	1987-May, 2002	500 kW	500 kWh	Lead-acid, flooded cell	2,080 Ah @ C/5; 324 cells	GNB Industrial Battery, now Exide Battery
Berliner Kraft- und Licht (BEWAG) Battery System, Berlin, Germany	Frequency Regulation and Spinning Reserve	1987-1995	8.5 MW in 60 min of frequency regulation; 17 MW for 20 min. of spinning reserve	14 MWh	Lead-acid, flooded cell	7,080 cells in 12 parallel strings of 590 cells each; Cell size: 1,000 Ah	Hagen OCSM cells
Southern California Edison Chino Battery Storage Project, CA, USA	Several "demo" modes including load-leveling, transmission line stability, local VAR control, black start.	1988-1997	Energy: 14 MW	40 MWh	Lead-acid, flooded cells	8,256 cells in 8 parallel strings of 1032 cells each; Cell size: 2,600 Ah	Exide Batteries GL-35 cells
Puerto Rico Electric Power Authority (PREPA) Battery System, Puerto Rico	Frequency control and spinning reserve	11/1994-12/1999	20 MW	14 MWh	Lead-acid, flooded cell	6,000 cells in 6 parallel strings of 1000 cells each; Cell size: 1,600 Ah	C&D Battery
PQ2000 installation at the Brockway Standard Lithography Plant in Homerville, Georgia, USA	Power Quality, Uninterruptable Power Supply	1996-2001	2 MW	55 kWh	Lead-acid	2000 Low-Maintenance, Truck-Starting Batteries, 48 per 250 kW module, 8 modules per 2 MW PQ2000 system	AC Battery, acquired by Omnion Power Engineering in 1997, in turn acquired by S&C Electric in 1999
Metlakatla Power and Light (MP&L), Alaska, Battery System, Alaska, USA	Voltage regulation and displacing diesel generation	1997-present	1 MW	1.4 MWh	Valve regulated lead-acid Absolyte IIP	1,134 cells/378 ea., 100A75 modules in 1 string	GNB Industrial Battery, now Exide Technologies, and General Electric
Golden Valley Electric Association (GVEA) Fairbanks, Alaska, USA	VAR Support, spinning reserve, power system stabilization	9/19/2003-present	27 MW	14.6 MWh	Nickel/cadmium type SBH920 cells	4 strings of 3,440 cells each, for a total of 13,760 cells	ABB and Saft

Installed Large Scale Battery - Continued

AEP Sodium Sulfur Distributed Energy Storage System at Chemical Station, N. Charleston, WV, USA	Substation upgrade deferral	2006-present	1.0 MW	7.2 MWh	Sodium/Sulfur	50 kW NAS battery modules, 20 ea	NGK Insulators LTD (battery)/ S & C Electric Co. (balance of system)
Long Island, New York Bus Terminal Energy Storage System, NY, USA	Load Shifting	2008-present	1.2 MW	6.5 MWh	Sodium/Sulfur	20 ea. 50 kW (60kW peak) NAS battery modules	NGK Insulators LTD (battery)/ABB Inc. (integration and balance of system)
Vanadium-Redox Battery at the Sumitomo Densetsu Office, Osaka, Japan	Peak Shaving	2000-present	3 MW	800 kWh	Vanadium-Redox Flow Battery	50 kW Sumitomo battery modules	Sumitomo Electric Industries (SEI) of Osaka, Japan
Pacificorp Castle Valley, Utah Vanadium-Redox Battery (VRB) System, Utah, USA	Distribution line upgrade deferral, voltage support	March 2004-present	250 kW	2 MWh	Vanadium-Redox Flow Battery	50 kW Sumitomo battery modules, 250 kW for 8 hours	VRB Power Systems (purchased by Prudent Energy Co., Beijing, China in 2009)

- *Exterior and interior views of the 2MWh VRB system at Castle Valley, UT.*

NaS Battery Project

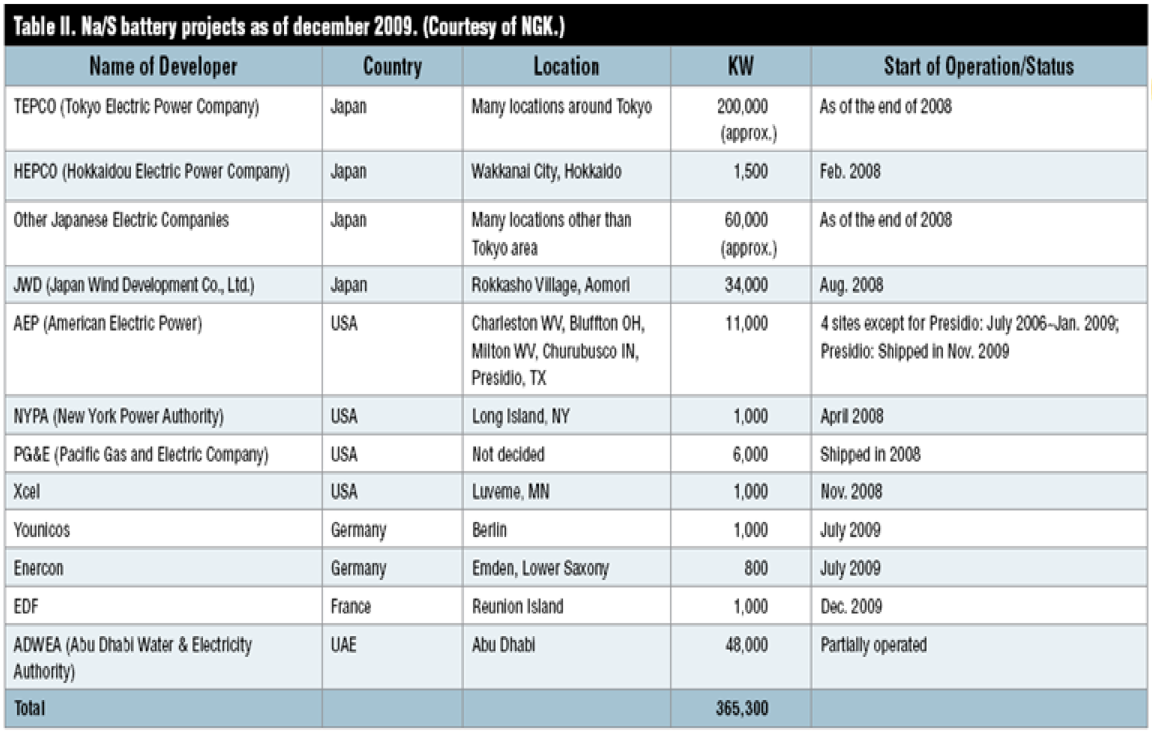


Table II. Na/S battery projects as of december 2009. (Courtesy of NGK.)

Name of Developer	Country	Location	KW	Start of Operation/Status
TEPCO (Tokyo Electric Power Company)	Japan	Many locations around Tokyo	200,000 (approx.)	As of the end of 2008
HEPCO (Hokkaidou Electric Power Company)	Japan	Wakkanai City, Hokkaido	1,500	Feb. 2008
Other Japanese Electric Companies	Japan	Many locations other than Tokyo area	60,000 (approx.)	As of the end of 2008
JWD (Japan Wind Development Co., Ltd.)	Japan	Rokkasho Village, Aomori	34,000	Aug. 2008
AEP (American Electric Power)	USA	Charleston WV, Bluffton OH, Milton WV, Churubusco IN, Presidio, TX	11,000	4 sites except for Presidio: July 2006–Jan. 2009; Presidio: Shipped in Nov. 2009
NYPA (New York Power Authority)	USA	Long Island, NY	1,000	April 2008
PG&E (Pacific Gas and Electric Company)	USA	Not decided	6,000	Shipped in 2008
Xcel	USA	Luverne, MN	1,000	Nov. 2008
Younicos	Germany	Berlin	1,000	July 2009
Enercon	Germany	Emden, Lower Saxony	800	July 2009
EDF	France	Reunion Island	1,000	Dec. 2009
ADWEA (Abu Dhabi Water & Electricity Authority)	UAE	Abu Dhabi	48,000	Partially operated
Total			**365,300**	

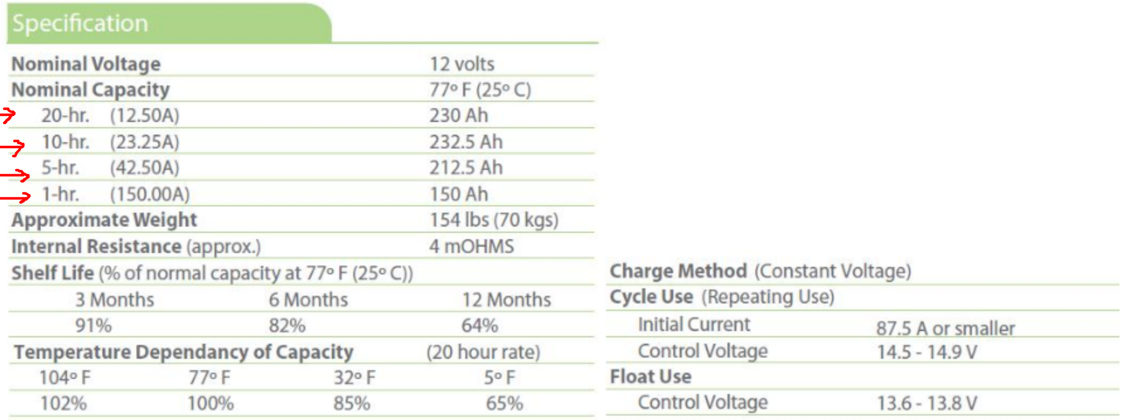
Battery Storage Capacity

- Energy Storage: Amp-hour (Ah) at **a nominal voltage** and at a specified **discharge rate**
- Ah capacity [C] that would drain from **2V** {full charge} to **1.75V** {full discharge} **(87.5%)**
- 12-V 10-h 200-Ah: delivers 20A for 10 h, then the voltage drops to 6x1.75=**10.5** V, considered as **fully discharged**.
- Discharging rate: C/h ←delivering current
- ***C/20* rate** is standard in PV system
- Example of Deep-Cycle Lead-Acid Battery Characteristics

BATTERY	Voltage	Weight (lbs)	Ah @ *C*/20	Ah @ *C*/100
Concorde PVX 5040T	2	57	495	580
Trojan T-105	6	62	225	250
Trojan L16	6	121	360	400
Concorde PVX 1080	12	70	105	124
Surette 12CS11PS	12	272	357	503

Battery Capacity Example

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))

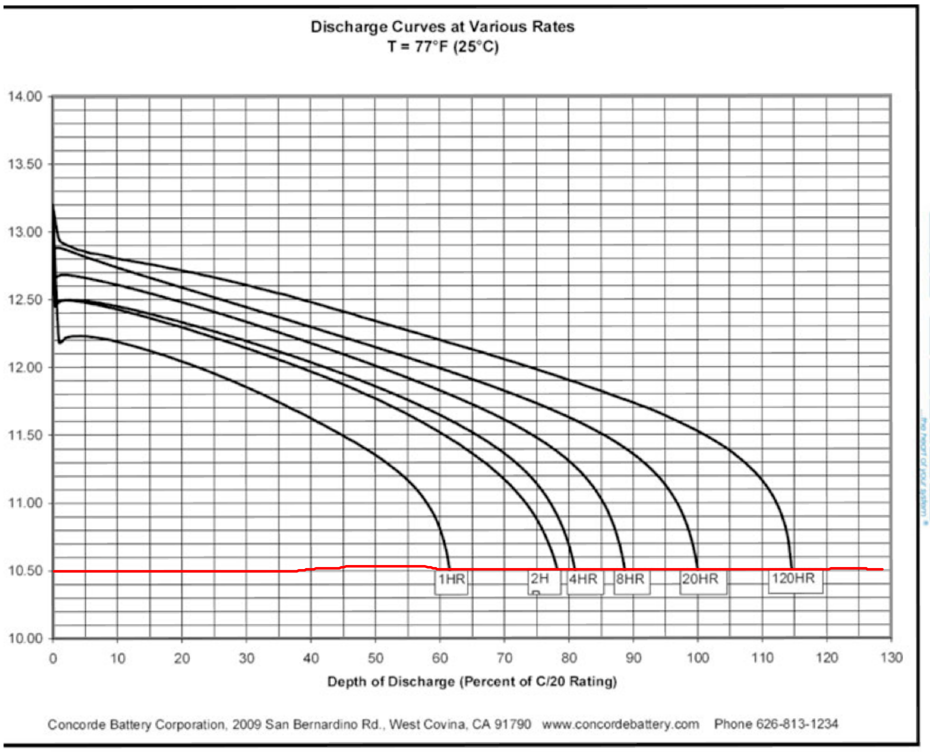
3 Months	6 Months	12 Months
91%	82%	64%

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

Discharge Curves at Different Rates

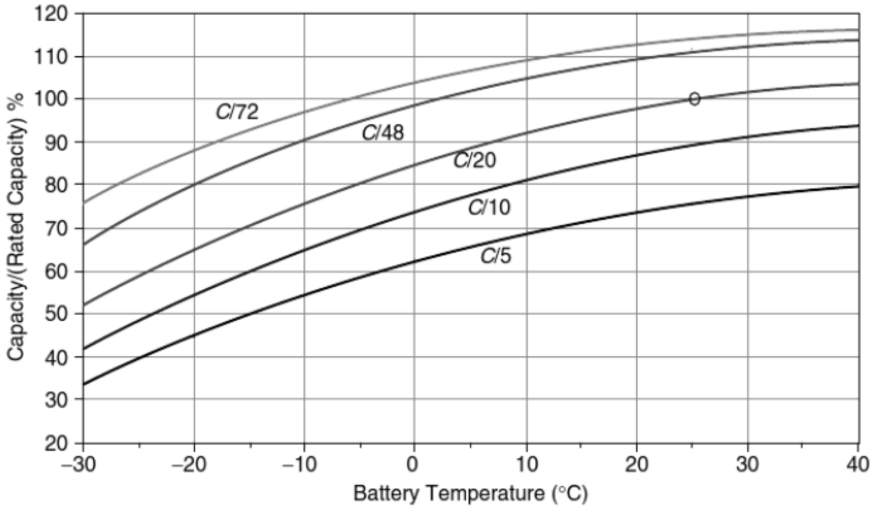

Discharge Curves at Various Rates
T = 77°F (25°C)

Concorde Battery Corporation, 2009 San Bernardino Rd., West Covina, CA 91790 www.concordebattery.com Phone 626-813-1234

Temperature Dependency

In cold temperatures, the battery capacity is reduced.

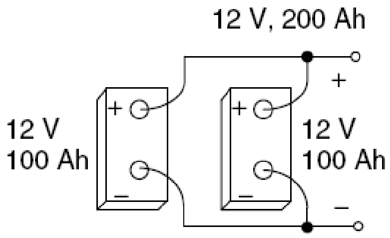
In warm temperatures, the battery capacity is increased.



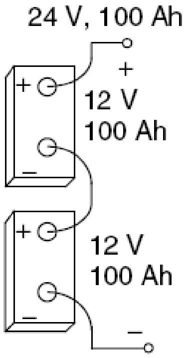
Ratio is based on a rated capacity at C/20 and 25°C

Battery Wiring

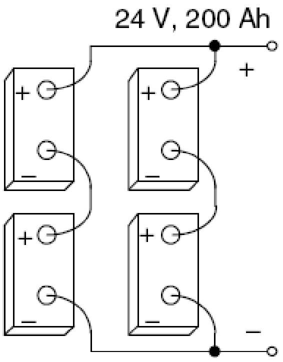
- Series: Voltages add → Ah remains the same
- Parallel: Currents add → Ah adds



(a) Parallel, Amp-Hrs add



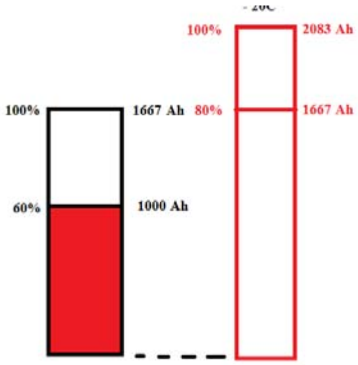
(b) Series, Voltages add



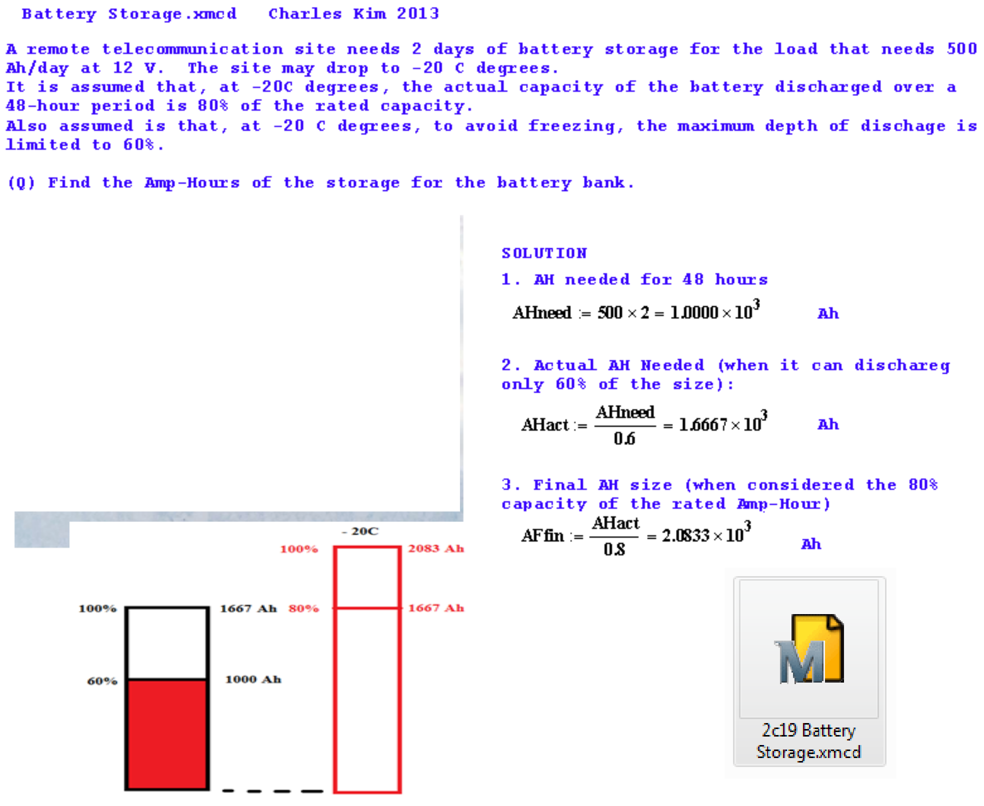
(c) Series/Parallel

Battery Storage Calculation

- Example
  - Suppose that batteries located at a remote telecommunications site may drop to −20◦C. If they must provide 2 days of storage for a load that needs 500 Ah/day at 12 V, how many amp-hours of storage should be specified for the battery bank?
  - Assume that, to avoid freezing, the maximum depth of discharge at −20◦C is 60%.
  - Also, assume that the actual capacity of the battery at −20◦C discharged over a 48-h period is about 80% of the rated capacity.
- Solution:
  - 1. Energy need for 2 days: 500x2 = 1000 Ah
  - 2. Battery storage for 2 days with discharge no more than 60% (which means that 60% of the stored energy must be able to cover the energy need): Battery storage= 1000Ah/0.6 = 1667 Ah
  - 3. Since the actual capacity is only 80%: Battery storage = 1667 Ah/0.8 = 2083 Ah



MathCad Solution



Battery Storage.xmcd   Charles Kim 2013

A remote telecommunication site needs 2 days of battery storage for the load that needs 500 Ah/day at 12 V. The site may drop to -20 C degrees.
It is assumed that, at -20C degrees, the actual capacity of the battery discharged over a 48-hour period is 80% of the rated capacity.
Also assumed is that, at -20 C degrees, to avoid freezing, the maximum depth of dischage is limited to 60%.

(Q) Find the Amp-Hours of the storage for the battery bank.

SOLUTION

1. AH needed for 48 hours

$AHneed := 500 \times 2 = 1.0000 \times 10^3$ Ah

2. Actual AH Needed (when it can dischareg only 60% of the size):

$AHact := \frac{AHneed}{0.6} = 1.6667 \times 10^3$ Ah

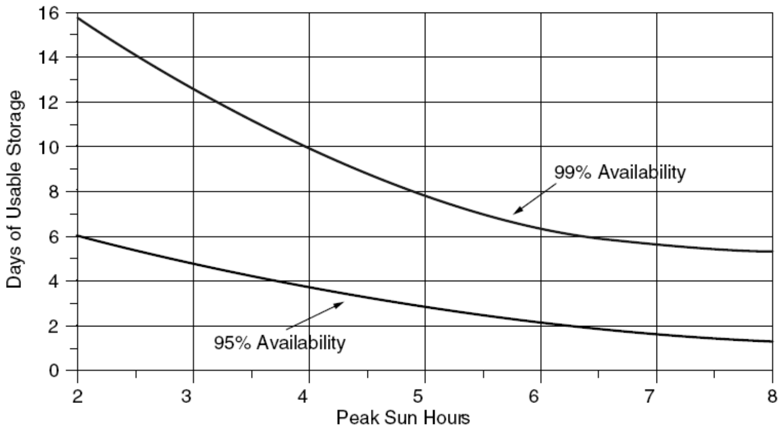
3. Final AH size (when considered the 80% capacity of the rated Amp-Hour)

$AFfin := \frac{AHact}{0.8} = 2.0833 \times 10^3$ Ah

2c19 Battery Storage.xmcd

Battery Sizing

- Statistical nature of weather
- No set rules about how best to size battery storage except the cost trade-off
- Battery system of meeting demand 99% of the time may be 3 times higher in cost than that of meeting 95% of the time.
- The number of days of storage to supply a load in the design month [the month with the worst combination of insolation and load]
- **Days of "usable battery storage**" needed for a stand-alone system

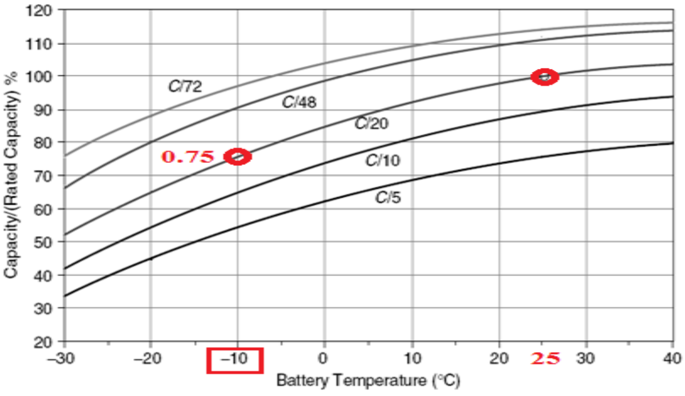


Battery Sizing

- Nominal rated storage vs. usable storage:

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

- Variables:
  - MDOD (maximum depth of discharge): <u>0.8 for lead-acid;</u> 0.25 for auto SLI
  - (T,DR): **Discharge Rate Factor** under a given Temperature



Battery Sizing Example

- A cabin near Salt Lake City, Utah, has an ac demand of 3000 Wh/day in the winter months. A decision has been made to size the batteries such that a 95% system availability will be provided, and a back-up generator will be kept in reserve to cover the other 5%. The batteries will be kept in a ventilated shed whose temperature may reach as low as −10◦C. The system voltage is to be 24 V, and an inverter with overall efficiency of 85% will be used.
- SOLUTION APPROACH
  - 1. AC load → DC load demand (with 85% inverted efficiency)
  - 2. Battery Capacity (Ah)
  - 3. Usable storage (Ah)
  - 4. Nominal capacity (Ah)
    - Assumption: 80% deep discharge ←MDOD
    - Assumption: 97% discharge rate ← (T,DR)
  - 5. Battery Bank Design

SOLUTION - details

$$\text{DC load} = \frac{\text{AC load}}{\text{Inverter efficiency}} = \frac{3000\ \text{Wh/day}}{0.85} = 3529\ \text{Wh/day}$$

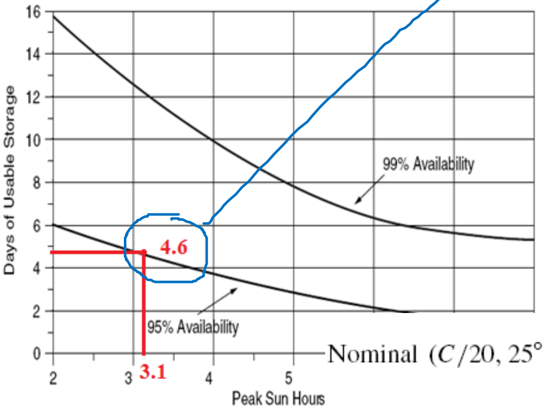
$$\text{Load} = \frac{3529\ \text{Wh/day}}{24\ V} = 147\ \text{Ah/day} \ @\ 24\ \text{V}$$

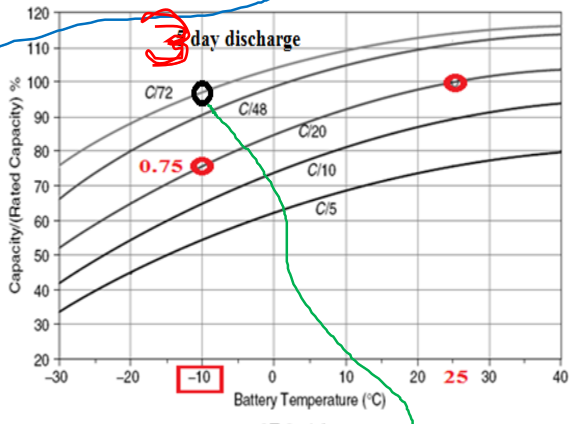
Correction: general 3 days

$$\text{Usable storage} = 147\ \text{Ah/day} \times \cancel{4.6}\ \text{day} = 676\ \text{Ah}$$

peak-sun

Tilt	Jan	Feb	Nov	Dec	Year
Lat − 15	2.9	4.0	3.3	2.5	5.2
Lat	3.2	4.3	3.7	2.9	5.3
Lat + 15	3.4	4.4	3.9	$\boxed{3.1}$	5.0





$$\text{Nominal } (C/20, 25°\text{C}) \text{ battery capacity} = \frac{676\ \text{Ah}}{0.80 \times 0.97} = 871\ \text{Ah (at 24 V)}$$

Solution in MathCad

Battery Sizing.xmcd Charles Kim 2013

A Cabin near Salt Lake City, Utah, has an AC energy demand of 3 kWh per day in the winter months. With a battery system, a 95% availability will be provided, while a back-up generator will be kept to cover the other 5%. The battery system will be kept in a ventilated shed where the tempeatue may go as low as - 10 C degrees. The system voltage is 24 V, and an inverter efficiency is 85%. Assume 80% deep discharge (MDOD) and 95 % discharge rate (T,DR)

(Q) Calculate the size of the battery system.

2c26 Battery Sizing.xmcd

MDOD := 0.8

TDR := 0.95

Eac := 3 kWh / day

D2A := 0.85 Inverter Efficiency

Bvolt := 24 Battery System Voltage

40.7500° N, 111.8833° W

Salt Lake City, Coordinates

SOLUTION
=========

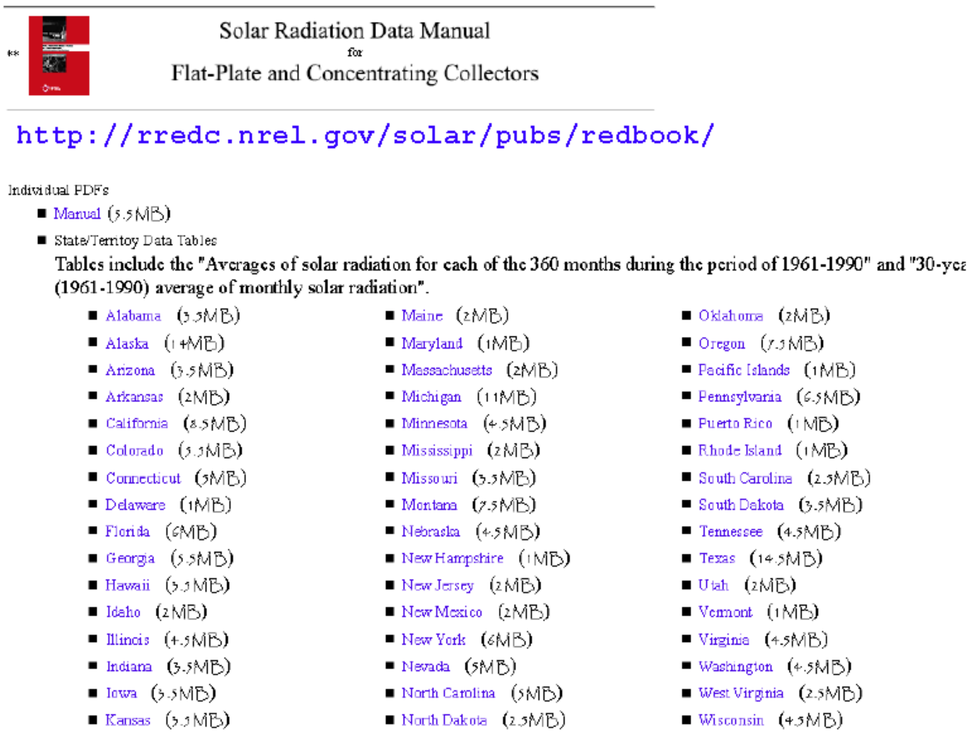
1. DC energy demand (Edc):

$Edc := \frac{Eac}{D2A} = 3.5294$ kWh /day

2. Expression of the energy demand in terms of Amp-Hour per day. Remember that Energy=Power*Time = V*A*time, ==> A*hour = Wh/V

$AH := \frac{Edc \times 1000}{Bvolt} = 147.0588$ Ah/day

MathCad



Solar Radiation Data Manual
for
Flat-Plate and Concentrating Collectors

http://rredc.nrel.gov/solar/pubs/redbook/

- Individual PDFs
  - Manual (5.5MB)
  - State/Territoy Data Tables

    Tables include the "Averages of solar radiation for each of the 360 months during the period of 1961-1990" and "30-yea (1961-1990) average of monthly solar radiation".

    - Alabama (3.5MB)
    - Alaska (14MB)
    - Arizona (3.5MB)
    - Arkansas (2MB)
    - California (8.5MB)
    - Colorado (5.5MB)
    - Connecticut (5MB)
    - Delaware (1MB)
    - Florida (6MB)
    - Georgia (5.5MB)
    - Hawaii (5.5MB)
    - Idaho (2MB)
    - Illinois (4.5MB)
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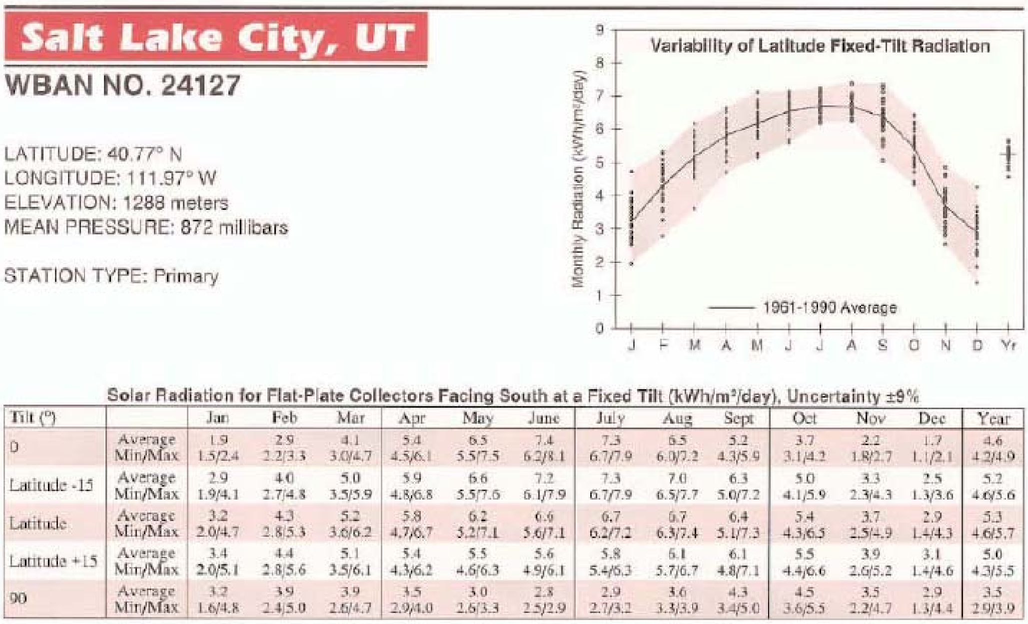
    - Washington (4.5MB)
    - West Virginia (2.5MB)
    - Wisconsin (4.5MB)

MathCad



Salt Lake City, UT

WBAN NO. 24127

LATITUDE: 40.77° N
LONGITUDE: 111.97° W
ELEVATION: 1288 meters
MEAN PRESSURE: 872 millibars

STATION TYPE: Primary

Variability of Latitude Fixed-Tilt Radiation

Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	1.9	2.9	4.1	5.4	6.5	7.4	7.3	6.5	5.2	3.7	2.2	1.7	4.6
	Min/Max	1.5/2.4	2.2/3.3	3.0/4.7	4.5/6.1	5.5/7.5	6.2/8.1	6.7/7.9	6.0/7.2	4.3/5.9	3.1/4.2	1.8/2.7	1.1/2.1	4.2/4.9
Latitude -15	Average	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
	Min/Max	1.9/4.1	2.7/4.8	3.5/5.9	4.8/6.8	5.5/7.6	6.1/7.9	6.7/7.9	6.5/7.7	5.0/7.2	4.1/5.9	2.3/4.3	1.3/3.6	4.6/5.6
Latitude	Average	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
	Min/Max	2.0/4.7	2.8/5.3	3.6/6.2	4.7/6.7	5.2/7.1	5.6/7.1	6.2/7.2	6.3/7.4	5.1/7.3	4.3/6.5	2.5/4.9	1.4/4.3	4.6/5.7
Latitude +15	Average	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
	Min/Max	2.0/5.1	2.8/5.6	3.5/6.1	4.3/6.2	4.6/6.3	4.9/6.1	5.4/6.3	5.7/6.7	4.8/7.1	4.4/6.6	2.6/5.2	1.4/4.6	4.3/5.5
90	Average	3.2	3.9	3.9	3.5	3.0	2.8	2.9	3.6	4.3	4.5	3.5	2.9	3.5
	Min/Max	1.6/4.8	2.4/5.0	2.6/4.7	2.9/4.0	2.6/3.3	2.5/2.9	2.7/3.2	3.3/3.9	3.4/5.0	3.6/5.5	2.2/4.7	1.3/4.4	2.9/3.9

MathCad

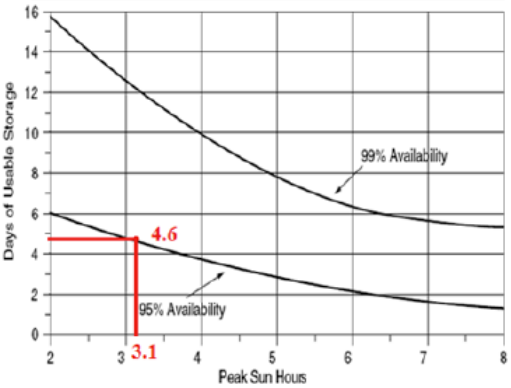
3. Find the usable storage Ah at -10 C degree (use the graph)

a. Peak-Sun-Hour information

b. Find the # of days of usuable storage(Dus) on the 95% availability curve

peak-sun

Tilt	Jan	Feb	Nov	Dec	Year
Lat − 15	2.9	4.0	3.3	2.5	5.2
Lat	3.2	4.3	3.7	2.9	5.3
Lat + 15	3.4	4.4	3.9	3.1	5.0



From the curve, we find for Dus:

Dus := 4.6 days

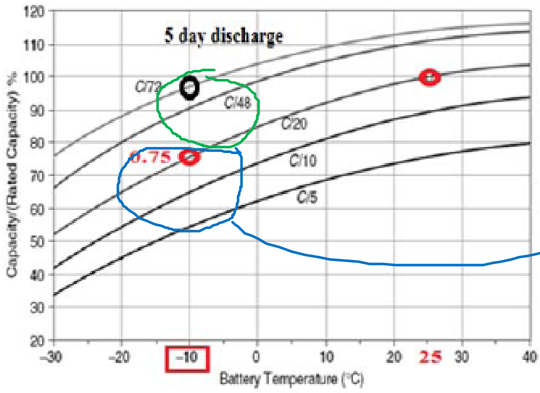
MathCad

c. Now we calculate the Usuable Storage Amp-Hour (AHus)

$$AHus := AH \times Dus = 676.4706$$ Ah

d. Finally, the nominal (C/20, 25 C) capacity:

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



$MDOD = 0.8000$

$TDR = 0.9700$

$MDOD \times TDR = 0.7760$

$$AHnorm := \frac{AHus}{MDOD \times TDR} = 871.7404$$ Ah

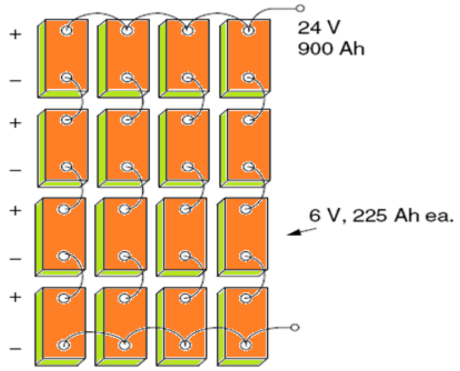
Cf.

With Dus=4.6 (~ 5) days = 72 hours,C/72 Rate, at -10 C, the value is 0.97.

Battery Selection - Example

- 871 Ah @ 24V

BATTERY	Voltage	Weight (lbs)	Ah @ $C/20$	Ah @ $C/100$
Concorde PVX 5040T	2	57	495	580
Trojan T-105	6	62	225	250
Trojan L16	6	121	360	400
Concorde PVX 1080	12	70	105	124
Surette 12CS11PS	12	272	357	503

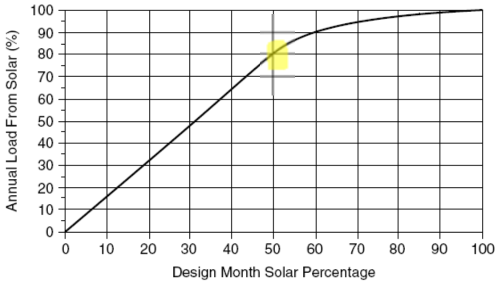


Battery Types: T-105 and L16

- T-105
  - Trojan Battery Company
  - Basic Golf-Cart-Style battery
  - Light (62 lb.), cheap ($90 - $100), 3 - 6 years or longer
- L16
  - More rugged than T-105
  - Popularized by Trojan but other companies too
  - Heavy (120 lb), expensive ($220), 8 or more years

Hybrid PV Systems

- Supplying load in the worst month (“design month”) is much more demanding than the rest of the year
- Hybrid system option: Most of the load covered by PV and the remainder supplied by a **generator**
- Key decision: relationship between **shrinking the PV system size** and **increasing the fraction of the load carried by the generator**
- Example (Salt Lake City case) of significant reduction in PV size while covering high fraction of the annual load.

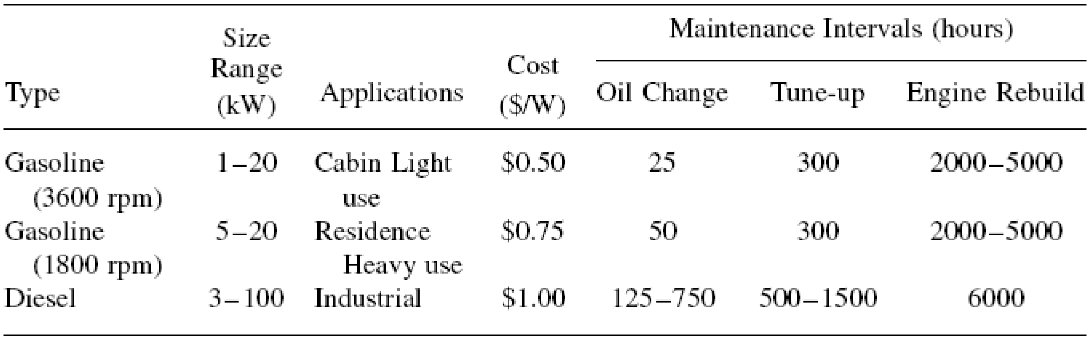


- PV system designed to deliver only 50% of the load in the design month will still cover about 80% of the annual load

---

Batteries and Generators for Hybrid PV Systems

- Battery Storage Bank:
  - can be smaller since the generator can charge during the poor weather condition
  - nominal 3-day storage system is often recommended
- Generators: 5 kWh/gallon



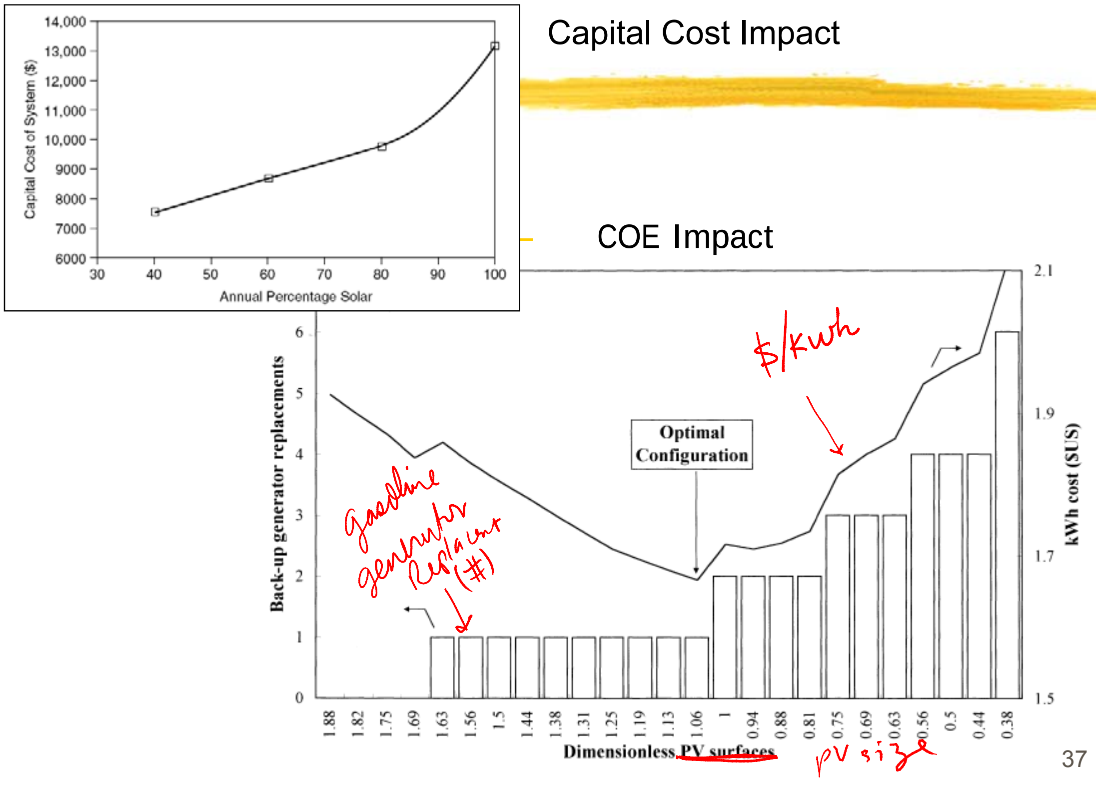
Type	Size Range (kW)	Applications	Cost ($/W)	Maintenance Intervals (hours)		
				Oil Change	Tune-up	Engine Rebuild
Gasoline (3600 rpm)	1–20	Cabin Light use	$0.50	25	300	2000–5000
Gasoline (1800 rpm)	5–20	Residence Heavy use	$0.75	50	300	2000–5000
Diesel	3–100	Industrial	$1.00	125–750	500–1500	6000

Source: Sandia National Laboratories (1995).

Capital Cost Reduction in Hybrid PV

Capital Cost Impact

COE Impact



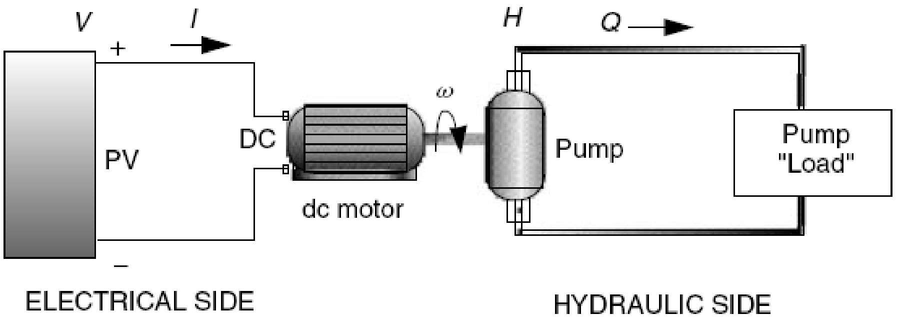
$/kwh

gasoline generator Replacement (#)

PV size

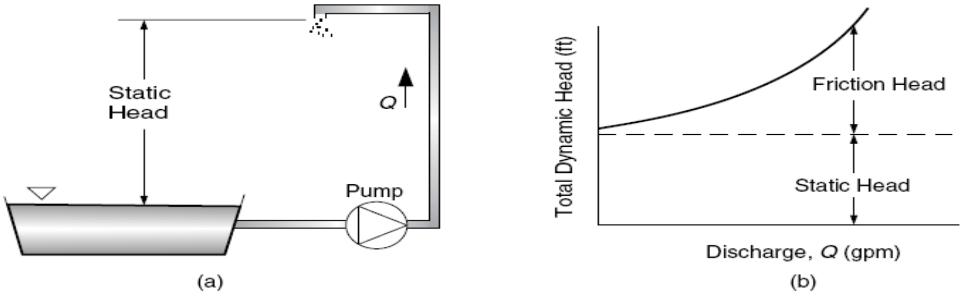
PV-Powered Water Pumping (Solar Pump)

- Most economically viable PV application
- Water pumping in remote areas: raise water from a well or spring and store it in a tank → irrigation, cattle watering, village water supply
- PV Array directly attached to a DC pump
- No battery is required
- Simple, low cost, and reliable



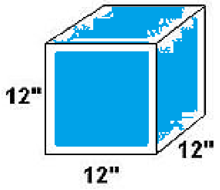
Solar Pumps

Hydraulic System Curves



(a) (b)

- Static Head (“feet of water”)



1-ft cube weighing 62.4 lb would exert on its 144 square inches

$$1 \text{ ft of head} = 62.4 \text{ lb}/144 \text{ in.}^2 = 0.433 \text{ psi}$$

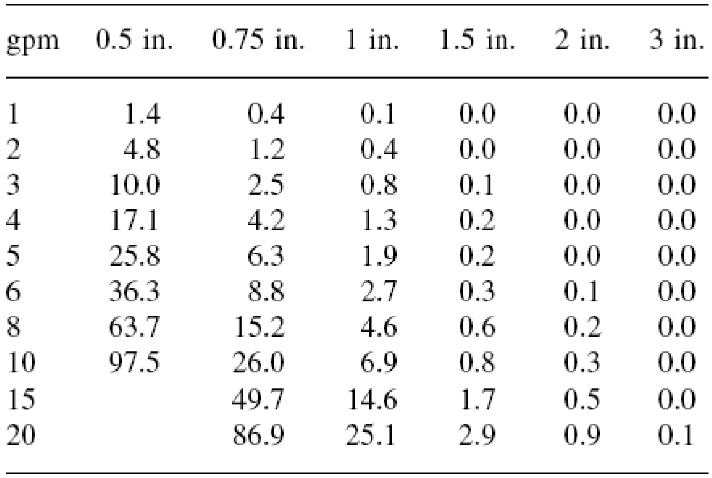
pounds per square inch (psi)

$$1 \text{ psi} = 2.31 \text{ ft of water.}$$

  - **Typical city water pressure = 60 psi = 140 feet of water**
- Friction in the Pipe system (roughness inside the pipes, # of bends, valves, etc)

Pressure Loss due to Friction

- Plastic Pipe
- Feet of Water per 100ft of Tube for various tube diameters

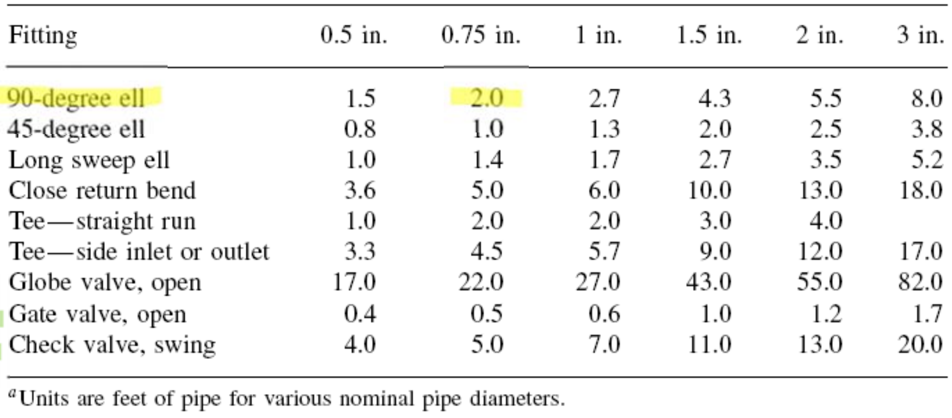


gpm	0.5 in.	0.75 in.	1 in.	1.5 in.	2 in.	3 in.
1	1.4	0.4	0.1	0.0	0.0	0.0
2	4.8	1.2	0.4	0.0	0.0	0.0
3	10.0	2.5	0.8	0.1	0.0	0.0
4	17.1	4.2	1.3	0.2	0.0	0.0
5	25.8	6.3	1.9	0.2	0.0	0.0
6	36.3	8.8	2.7	0.3	0.1	0.0
8	63.7	15.2	4.6	0.6	0.2	0.0
10	97.5	26.0	6.9	0.8	0.3	0.0
15		49.7	14.6	1.7	0.5	0.0
20		86.9	25.1	2.9	0.9	0.1

- gpm: Gallons per minute

Friction Loss in Elbows and Valves

- Friction loss expressed as equivalent lengths of tube



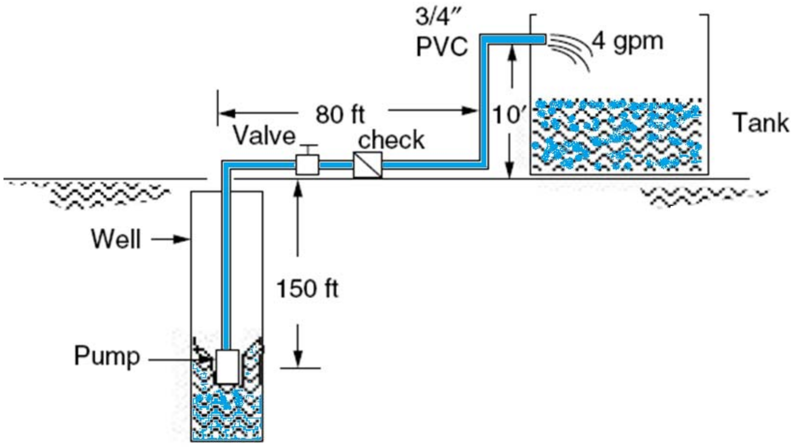
Fitting	0.5 in.	0.75 in.	1 in.	1.5 in.	2 in.	3 in.
90-degree ell	1.5	2.0	2.7	4.3	5.5	8.0
45-degree ell	0.8	1.0	1.3	2.0	2.5	3.8
Long sweep ell	1.0	1.4	1.7	2.7	3.5	5.2
Close return bend	3.6	5.0	6.0	10.0	13.0	18.0
Tee—straight run	1.0	2.0	2.0	3.0	4.0	
Tee—side inlet or outlet	3.3	4.5	5.7	9.0	12.0	17.0
Globe valve, open	17.0	22.0	27.0	43.0	55.0	82.0
Gate valve, open	0.4	0.5	0.6	1.0	1.2	1.7
Check valve, swing	4.0	5.0	7.0	11.0	13.0	20.0

[a] Units are feet of pipe for various nominal pipe diameters.

- Interpretation: 0.75in 90-degree elbow adds to the pressure drop of the same amount as would 2.0ft of straight pipe.
- Static Head + Friction Head = Total Dynamic Head (H)

Pumping Head Calculation Example

- A pump is required to deliver 4 gpm from a depth of 150 ft. The well is 80 ft from the storage tank, and the delivery pipe rises another 10 ft. The piping is 3/4-in.diameter plastic, and there are three 90◦ elbows, one swing-type check valve, and one gate valve in the line.
- Q: What is the pumping head?



Solution

- Length of pipe = 150+80+10=240 ft
- Equivalent pipe length for 3 elbows: 3x2.0=6 ft
- Eq. pipe length for check valve: 5.0 ft
- Eq. pipe length for the gate valve (open): 0.5 ft
- Total Eq. Pipe Length: 240+6+5+0.5=251.5 ft

Fitting	0.5 in.	0.75 in.
90-degree ell	1.5	2.0
45-degree ell	0.8	1.0
Long sweep ell	1.0	1.4
Close return bend	3.6	5.0
Tee—straight run	1.0	2.0
Tee—side inlet or outlet	3.3	4.5
Globe valve, open	17.0	22.0
Gate valve, open	0.4	0.5
Check valve, swing	4.0	5.0

- Pressure drop at 4 gpm per 100ft pipe: 4.2 ft
- Therefore, the Friction head = [4.2 x 251.5] / [100] = 10.5 ft
- Static Head = 150+10 = 160 ft
- Total Head = 160 + 10.5 = 170.5 ft of water pressure

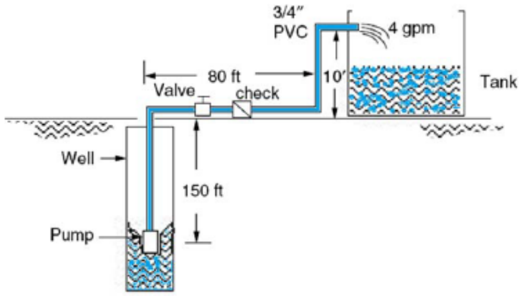
gpm	0.5 in.	0.75 in.
1	1.4	0.4
2	4.8	1.2
3	10.0	2.5
4	17.1	4.2
5	25.8	6.3
6	36.3	8.8
8	63.7	15.2
10	97.5	26.0
15		49.7
20		86.9

Solution by MathCad

Pumping head.xmcd   Charles Kim 2013

A pump is required to deliver at 4 GPM from a depth of 150 ft. The well is 80 ft from the storage tank, and the delivery pipe rises another 10 ft. The piping is 3/4 in. diameter plastic and there are three 90 degree elbows, one swing-type valve, and one gate valve in the line.

(Q) What is the pumping head



Per 100 ft

Fitting	0.5 in.	0.75 in.
90-degree ell	1.5	2.0
45-degree ell	0.8	1.0
Long sweep ell	1.0	1.4
Close return bend	3.6	5.0
Tee—straight run	1.0	2.0
Tee—side inlet or outlet	3.3	4.5
Globe valve, open	17.0	22.0
Gate valve, open	0.4	0.5
Check valve, swing	4.0	5.0

gpm	0.5 in.	0.75 in.
1	1.4	0.4
2	4.8	1.2
3	10.0	2.5
4	17.1	4.2
5	25.8	6.3
6	36.3	8.8
8	63.7	15.2
10	97.5	26.0
15		49.7
20		86.9

2c43 pumping head.xmcd

SOLUTION
=========

1. Length of Pipe

$Lp := 150 + 80 + 10 = 240.0000$ ft

2. Eq Length of pipe of 3 elbows

$Lel := 3 \times 2.0 = 6.0000$ ft

MathCad

3. Eq pipe Length of a check valve

$Lck := 1 \times 5.0 = 5.0000$ ft

4. Eq pipe Length of gate valve (open) $Lgt := 1 \times 0.5 = 0.5000$ ft

5. Total Eq Pipe Length $Ltot := Lp + Lel + Lck + Lgt = 251.5000$ ft

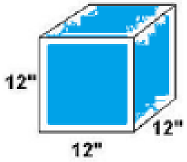
6. Pressure drop length of the total eq pipe (per 100ft): $Lfr := 4.2$ ft

7. Dynamic Head $Hd := \frac{Ltot}{100} \times Lfr = 10.5630$ ft

8. Static Head $Hs := 150 + 10 = 160.0000$ ft

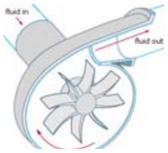
9. Total Head $Ht := Hs + Hd = 170.5630$ ft of water pressure

2c43 pumping head.xmcd



Hydraulic Pumps

- Different flow rate will results in different pump head
- To determine the actual flow for a given pump, we need to know the characteristics of the pump
- 2 types of pump for PV-power system

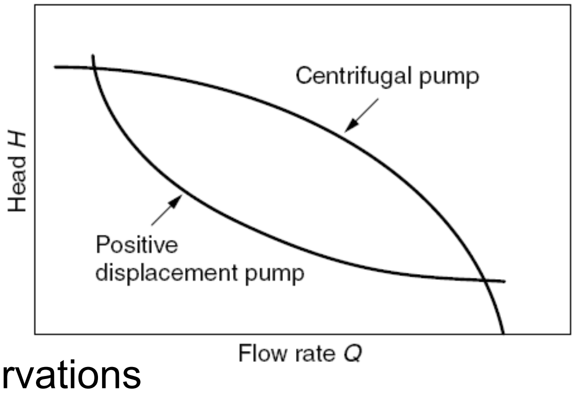


  - Centrifugal pump
    - Fast spinning impellers create suction input side of the pump and create pressure on the delivery side, which throw water out of the pump
    - Limited by the ability of atmosphere pressure to push up water into the suction side of the pump – theoretical max is 32 ft.
  - Positive displacement pump
    - Helical pumps: rotating shaft to push water up a cavity
    - Jack pumps: oscillating arm drives shaft up and down (like the classic oil-rig pumper)
    - Diaphragm pumps: rotating cam opens and closes valves
    - Most useful in low volume applications

Centrifugal	Positive Displacement
High-speed impellers	Volumetric movement
Large flow rates	Lower flow rates
Loss of flow with higher heads	Flow rate less affected by head
Low irradiance reduces ability to achieve head	Low irradiance has little effect on head
Potential grit abrasion	Unaffected by grit

Hydraulic Pump Curve

- Graphical relationship between head (H) and flow (Q)



- Observations
  - Centrifugal pump: Raising the open end of the hose higher and higher (increasing the head) will result in less and less flow until a point is reached at which there is no flow at all.
  - Positive displacement pump: Flapper valve, diaphragm, or rotating screw in a positive displacement pump holds up the water column mechanically, so their flow rates are much less affected by increasing head.

Some Solar (Sun) Pump

SR2 Aluminum Pump.
Part # (535472-2)

$ 820.00 (NO additional controller required!)

2 Piston brushless motor submersible solar pump.

Over volt protection. Thermal over load protection to help from over heating and causing damage. Abrasion & Corrosion resistant.

Aluminum Housing and Head.
Reverse polarity protection.

Brushless Motor 12-40 volts operating range.

Max gpm 3 at no lift or pressure, flows decrease as lift and pressure increase.

SR4 Aluminum Pump
Part # (535474-2)

$930.00 (NO additional controller required!)

4 Piston brushless motor submersible solar pump.
2 yr. warranty

Over volt protection. Thermal over load protection to help from over heating and causing damage. Abrasion & Corrosion resistant.

Aluminum Housing and Head.
Reverse polarity protection.

Brushless Motor 12-40 volts operating range.

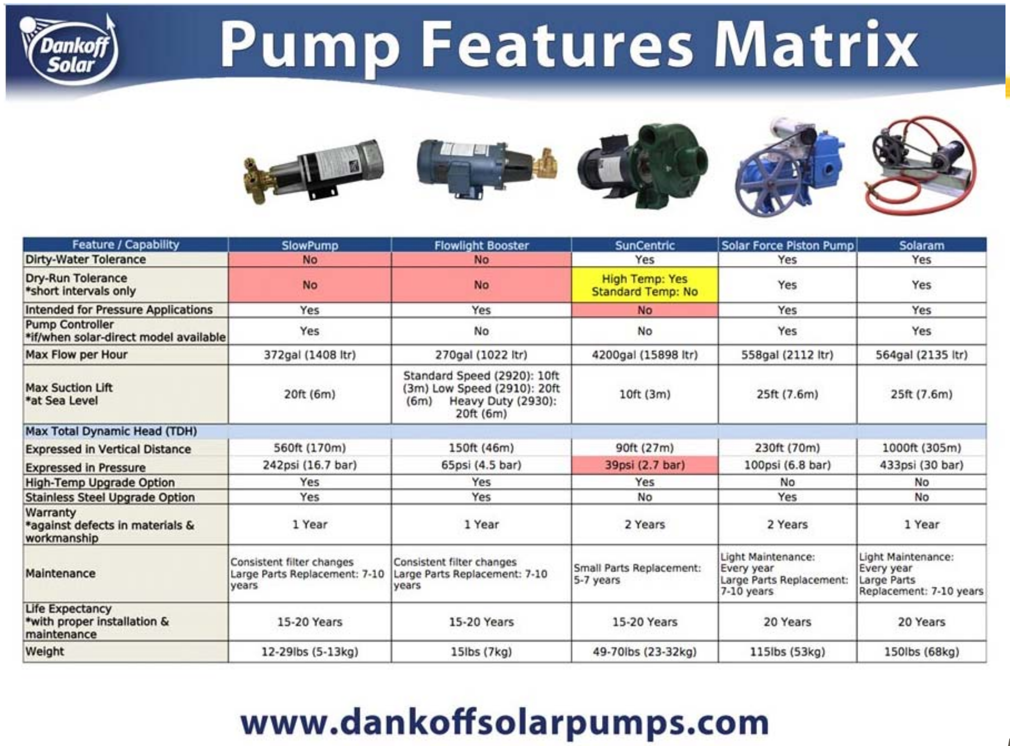
Max gpm 3.75 at no lift or pressure, flows decrease as lift and pressure increase.

These SR series aluminum pumps come with a 2 yr. warranty.

Factory rebuildable. Designed CNC Aluminum parts. Positive displacement pumps. Lightweight and durable. Temporary run dry capability. Come standard with 100ft. of wire attached so no under water splice is needed. (actual product appearance or color may vary)

SR4 Pumps require a 5" diameter or larger well casing.
SR2 Pumps require a 4" or larger diameter well casing.

Solar Pumps



Dankoff Solar

Pump Features Matrix

Feature / Capability	SlowPump	Flowlight Booster	SunCentric	Solar Force Piston Pump	Solaram
Dirty-Water Tolerance	No	No	Yes	Yes	Yes
Dry-Run Tolerance *short intervals only	No	No	High Temp: Yes Standard Temp: No	Yes	Yes
Intended for Pressure Applications	Yes	Yes	No	Yes	Yes
Pump Controller *if/when solar-direct model available	Yes	No	No	Yes	Yes
Max Flow per Hour	372gal (1408 ltr)	270gal (1022 ltr)	4200gal (15898 ltr)	558gal (2112 ltr)	564gal (2135 ltr)
Max Suction Lift *at Sea Level	20ft (6m)	Standard Speed (2920): 10ft (3m) Low Speed (2910): 20ft (6m) Heavy Duty (2930): 20ft (6m)	10ft (3m)	25ft (7.6m)	25ft (7.6m)
Max Total Dynamic Head (TDH)					
Expressed in Vertical Distance	560ft (170m)	150ft (46m)	90ft (27m)	230ft (70m)	1000ft (305m)
Expressed in Pressure	242psi (16.7 bar)	65psi (4.5 bar)	39psi (2.7 bar)	100psi (6.8 bar)	433psi (30 bar)
High-Temp Upgrade Option	Yes	Yes	Yes	No	No
Stainless Steel Upgrade Option	Yes	Yes	No	Yes	No
Warranty *against defects in materials & workmanship	1 Year	1 Year	2 Years	2 Years	1 Year
Maintenance	Consistent filter changes Large Parts Replacement: 7-10 years	Consistent filter changes Large Parts Replacement: 7-10 years	Small Parts Replacement: 5-7 years	Light Maintenance: Every year Large Parts Replacement: 7-10 years	Light Maintenance: Every year Large Parts Replacement: 7-10 years
Life Expectancy *with proper installation & maintenance	15-20 Years	15-20 Years	15-20 Years	20 Years	20 Years
Weight	12-29lbs (5-13kg)	15lbs (7kg)	49-70lbs (23-32kg)	115lbs (53kg)	150lbs (68kg)

www.dankoffsolarpumps.com

Power delivered by pump

$$\boxed{P = \rho H Q \qquad \rho \text{ is fluid density}}$$

conversion factors...
453.54 g = 1 lb
1000 mL = 1L
1000 L = 264.17 gal

conversion equation...
(1.00g/mL) x (1lb / 453.54g) x (1000 mL / 1L) x (1000 L / 264.17 gal)
= 8.35 lbs/gal

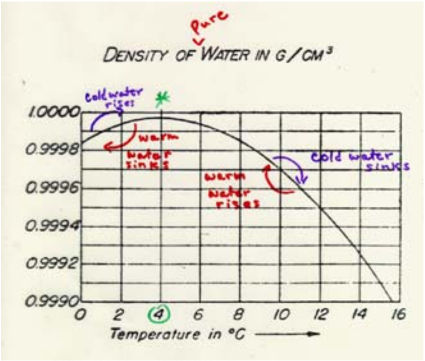
In American units

$$P(\text{watts}) = 8.34 \text{ lb/gal} \times H(\text{ft}) \times Q(\text{gal/min}) \times (1 \text{ min}/60 \text{ s})$$

$$\times\, 1.356 \text{ W/(ft-lb/s)}$$

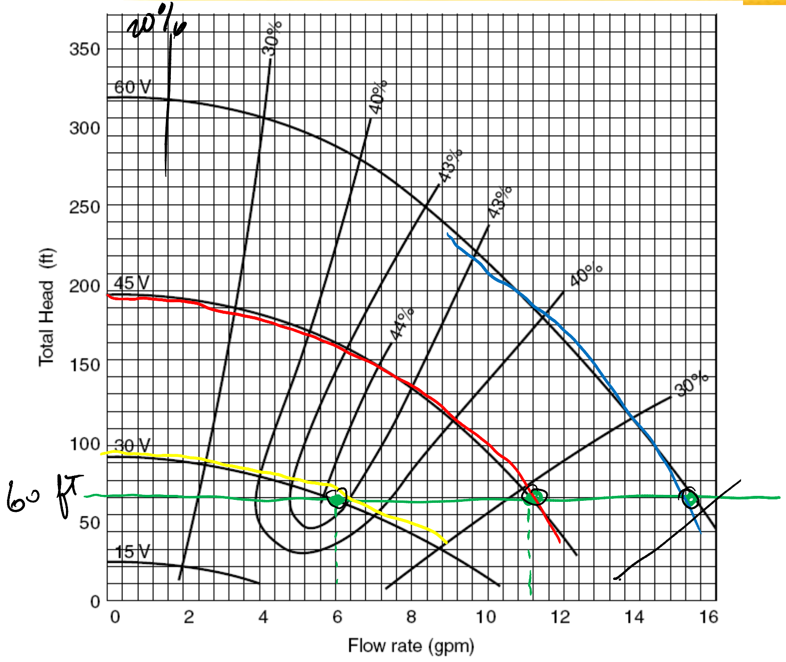
$$\boxed{P(\text{watts}) = 0.1885 \times H(\text{ft}) \times Q(\text{gpm})}$$

In SI units, $\boxed{P(\text{watts}) = 9.81 \times H(\text{m}) \times Q(\text{L/s})}$



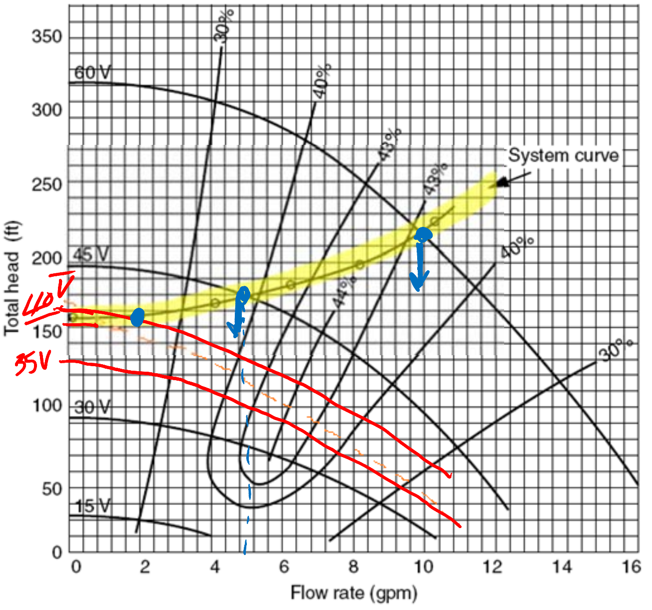
Pump curves under different input voltages

- Example gpm and pump efficiency
  - Jacuzzi SJ1C11 DC Centrifugal Pump for PV application



Combination of Hydraulic System Curve and Pump Curve

- Q-H System curve
  - Well System (Situation)
- Q-H pump curve
  - Pump Capability
- Determine the hydraulic operating point
- Observation
  - Pump will not deliver any water unless the voltage applied to the pump is at least 36V
  - At 45V, about 5 gpm would pumped
  - At 60V, the flow would be 9.5 gpm
  - **Which one is better? Higher Efficiency?**



PV-Pump Design Process 1

- 1. Determine the water production goal (gallons/day) in the design month (highest water need and lowest insolation)
- 2. Use the design month insolation (hours at 1-sun) as the hours of pumping, and find the pumping rate Q (gpm):

$$Q\,(\text{gpm}) = \frac{\text{Daily demand (gal/day)}}{\text{Insolation(h/day@1-sun)} \times 60\ \text{min/h}}$$

- 3. Find the total dynamic head H at Q. Friction head may be assumed to be 5% of the static head
- 4. Find a pump capable of delivering the desired head and flow Q. Note the input power and the nominal voltage. Pump efficiency for suction pumps is 25% and submersible pumps 35%.

$$P_{\text{in}}\ (\text{W})\ \text{to pump} = \frac{\text{Power to fluid}}{\text{Pump efficiency}} = \frac{0.1885 \times H(\text{ft}) \times Q(\text{gpm})}{\eta_p}$$

PV-Pump Design Process 2

- 5. The number of PV modules in series (15V PV module) from the pump voltage

$$\text{Modules in series} = \frac{\text{Pump voltage(V)}}{15 \text{ V/module}}$$

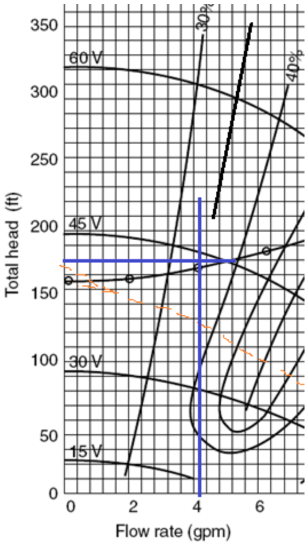
- 6. The number of PV strings in parallel using pump input power, and PV rated current (IR), and de-rating factor (for dirt and temperature effect) with 0.80.

$$\#\text{ strings} = \frac{\text{Pump input power } P_{\text{in}}(\text{W})}{\#\text{ mods in series} \times 15 \text{ V/mod} \times I_R(\text{A}) \times \text{de-rating}}$$

- 7. Estimate the water pumped.

$$Q(\text{gal/day}) = 15 \text{ V/mod} \times I_R \ (\text{A}) \times (\#\text{ mods}) \times (\text{Peak h/day}) \times 60 \ \text{min/h} \times \text{de-rating} \times \eta_P / [0.1885 \times H(\text{ft})]$$

PV-Pump System Design Example



- **Sizing an Array for a 150-ft Well in Santa Maria, California.**
  - Goal: pump at least 1200 gallons per day from the 150-ft well.
  - Directions
    - Use Jacuzzi SJ1C11 pump
    - **Use Siemens SR100 15-V PV modules with rated current 5.9 A**
    - The worst month (December) insolation is 4.9 kWh/m^2-day
  - Question: Size the PV array

Sol.

- 1. $$Q = \frac{1200 \text{ gal/day}}{4.9 \text{ (h/day @1-sun)} \times 60 \ \text{min/h}} = 4.1 \text{ gpm}$$
- 2. @4.1 gpm, the hydraulic curve shows that about 170 ft of head is needed and at the operating point the pump efficiency is about 34% → estimated pump input power

$$P_{\text{in}}(\text{W}) = \frac{0.1885 \times H(\text{ft}) \times Q(\text{gpm})}{\text{Pump efficiency}} = \frac{0.1885 \times 170 \times 4.1}{0.34} = 386 \text{ W}$$

Example-Solution (continued)

- 3. At the above operating point, the pump voltage required is a little under 45V → 3 15-V modules in series
- 4. Number of Parallel Strings (de-rating at 80%) (5.9A – rated current)

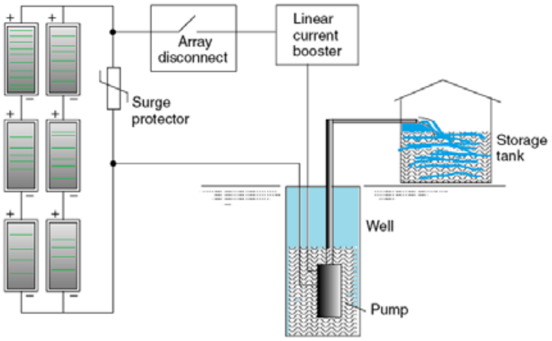
$$\#\ \text{strings} = \frac{386\ \text{W}}{3\ \text{modules string} \times 15\ \text{V/module} \times 5.9\ A \times 0.80} = 1.8$$

So 2 parallel strings.

- 5. Estimated water delivery in December

$$Q \approx \frac{15\ \text{V} \times 5.9\ \text{A} \times 6\ \text{modules} \times 4.9\ \text{h/day} \times 60\ \ \text{min}/\text{h} \times 0.80 \times 0.34}{0.1885 \times 170\ \text{ft}}$$

$$= 1325\ \text{gal/day}$$



Buck Converter as Linear Current Booster

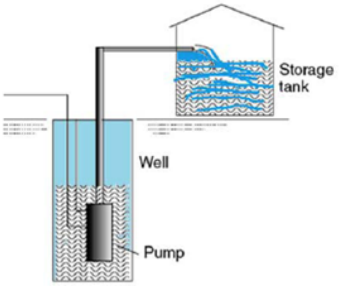
- Low sun → not enough torque to pump
- Lower voltage and increase current → lower speed pumping, but pumping anyway

Solution by MathCad

2c56 Solar Pump System Design.xmcd

Solar Pump System Design.xmcd   Charles Kim 2013

Design a solar pump system for a 150 ft well located in Santa Maria, CA, which pums at least 1200 gallons per day. The worst month (December) insolation at the site is 4.9 Peak Sun Hours. (or 4.9 kWh/m²-day).
Use Jacussi SJ1C11 pump.
Use Siemens SR100 15-V PV Modules (rated current 5.9A)
(Q) Size the PV array for the pump system.




Santa Maria

City

Nickname(s): BBQ Capital of California

Location in Santa Barbara County and the state of California

Location in California

Coordinates: 34°57′5″N 120°26′0″W

SOLUTION
========

$Qreq := 1200$ gpd

$PSH := 4.9$

$Vr := 15$ PV rated voltage

$Hs := 150$ ft Static Head

$Hd := 20$ ft Friction/Dynamic Head

$H := Hs + Hd = 170.0000$ Total Water Head

$\eta p := 0.34$ pump efficiency

$Ir := 5.9$ PV Rated Current

$Rd := 0.8$ PV De-rating factor

MathCad

1. Required Pumping Rate (Qgpm):

$$Qgpm := \frac{Qreq}{PSH \times 60} = 4.0816 \quad gpm$$

$$Q(\text{gpm}) = \frac{\text{Daily demand (gal/day)}}{\text{Insolation(h/day@1-sun)} \times 60 \ \text{min/h}}$$

2. Pump Power Input Calculation (Pw)

$$P_{\text{in}}\ (\text{W})\ \text{to pump} = \frac{\text{Power to fluid}}{\text{Pump efficiency}} = \frac{0.1885 \times H(\text{ft}) \times Q(\text{gpm})}{\eta_p}$$

$$Pw := \frac{0.1885 \times H \times Qgpm}{\eta p} = 384.6939 \quad W$$

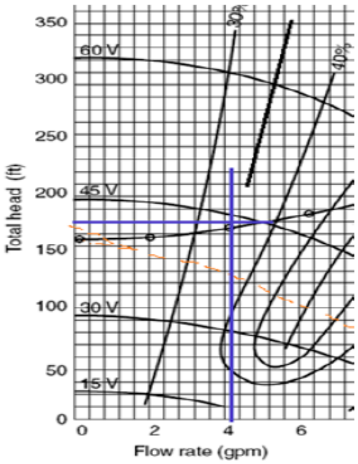
3. Number of 15-V 5.9-A PV modules. From the graph, the operating point is made just below 45V

$$PVseries := \frac{45}{Vr} = 3.0000$$

4. Number of Parallel PV calculation. Power = 384 W, Voltage=45, so the required current is? (with De-rating factor of 0.8)

$$PVparallel := \frac{Pw}{45} \times \frac{1}{Ir \times Rd} = 1.8112$$

$$PVparallel := \text{round}(PVparallel) = 2.0000$$



MathCad

2c56 Solar Pump System Design.xmcd

5. Estimation of the actual water pumped

$$Q\,(\text{gal/day}) = 15\ \text{V/mod} \times I_R\ (\text{A}) \times (\#\ \text{mods}) \times (\text{Peak h/day}) \times 60\ \ \text{min}/\text{h} \times \text{de-rating} \times \eta_P/[0.1885 \times H\,(\text{ft})]$$

$$\text{PVmod} := \text{PVseries} \times \text{PVparallel} = 6.0000$$

$$\text{Qest} := \frac{\text{Vr} \times \text{Ir} \times \text{PVmod} \times \text{PSH} \times 60 \times \text{Rd} \times \eta\text{p}}{0.1885 \times \text{H}} = 1.3251 \times 10^3 \quad \text{gpd}$$

This is more than 1200 gpd required so the design meets the project goal.