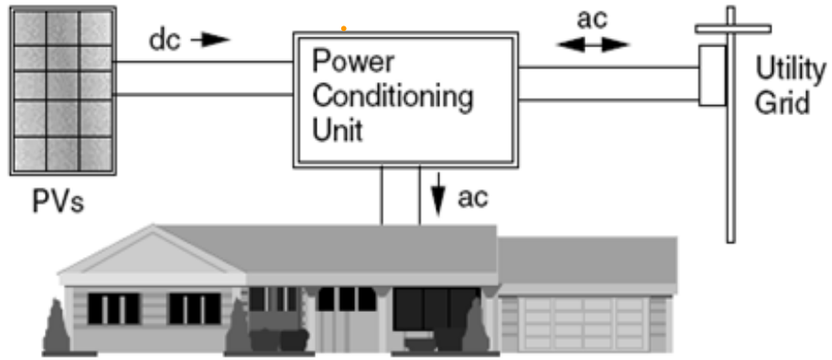
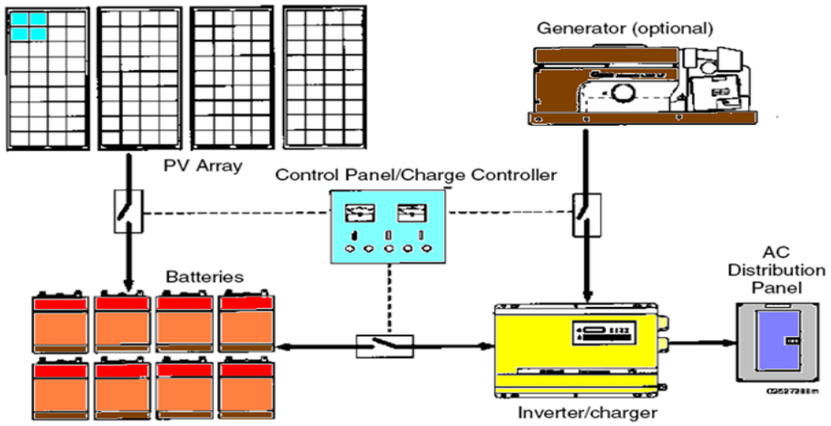
Chapter 9: Photovoltaic (PV) Systems

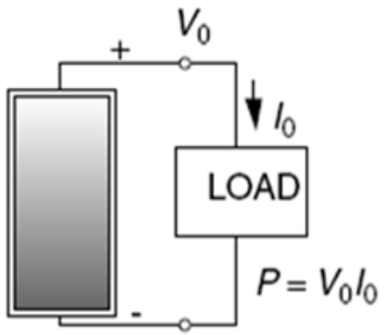


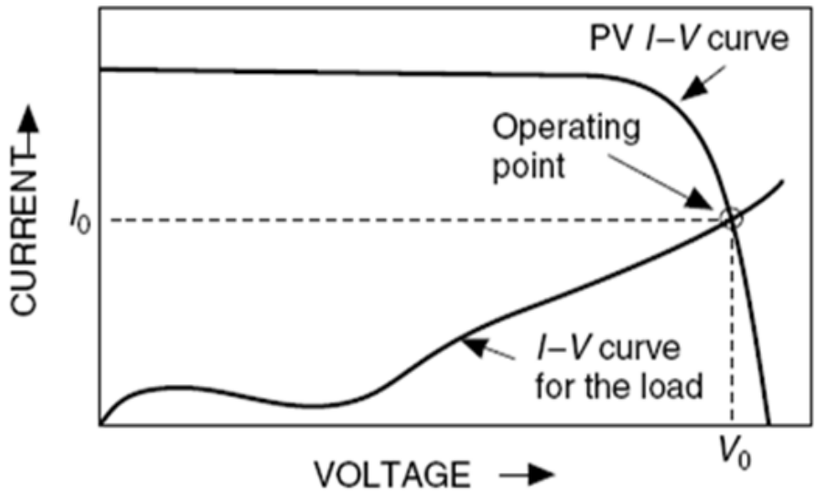
⌘ **Utility connected PV System:**



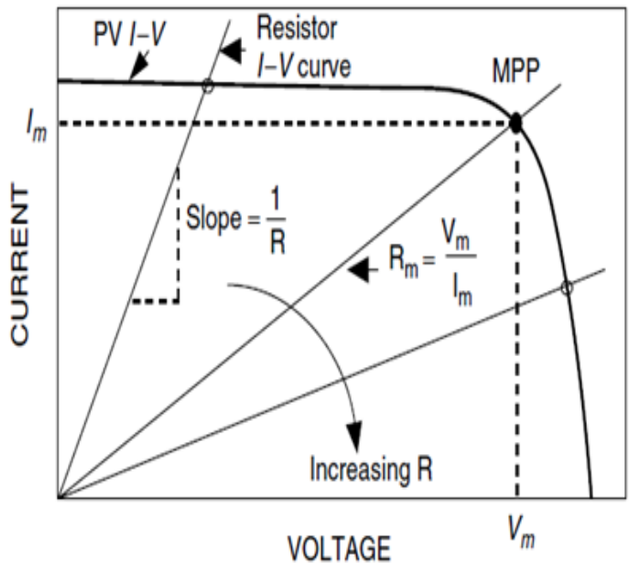
⌘ **Stand-alone system:**

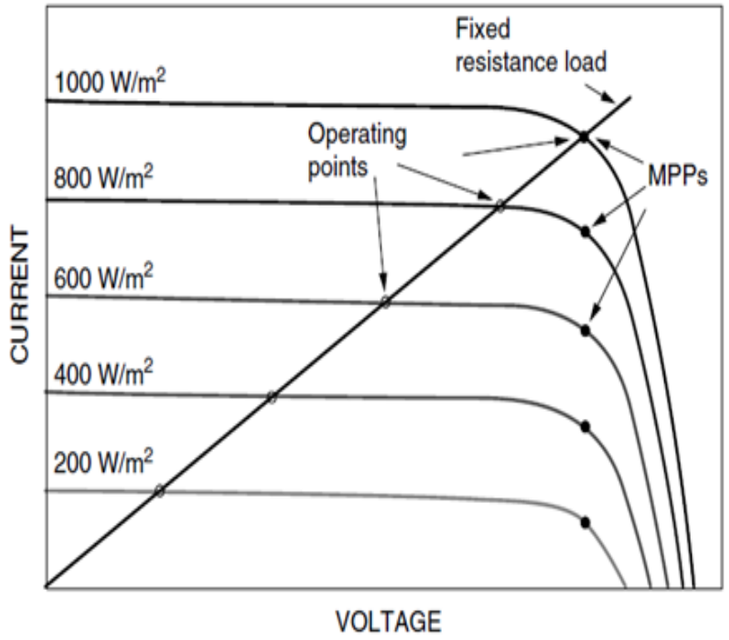
Operating Point



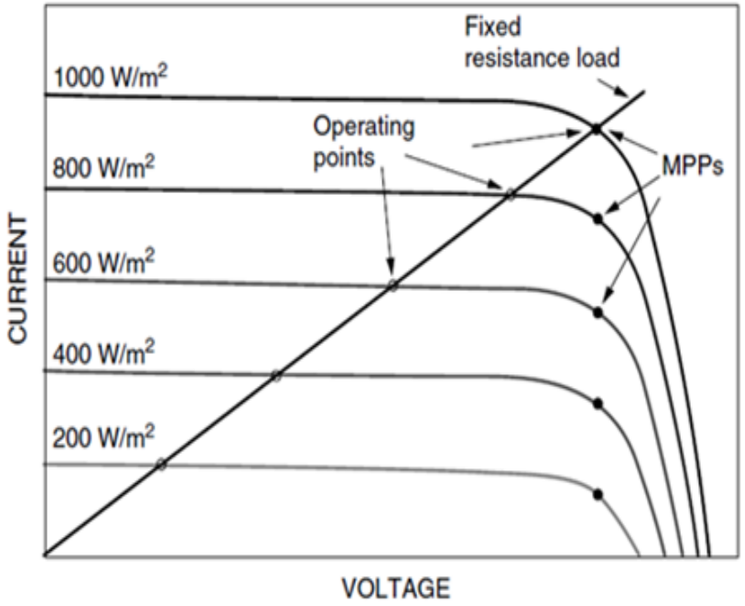


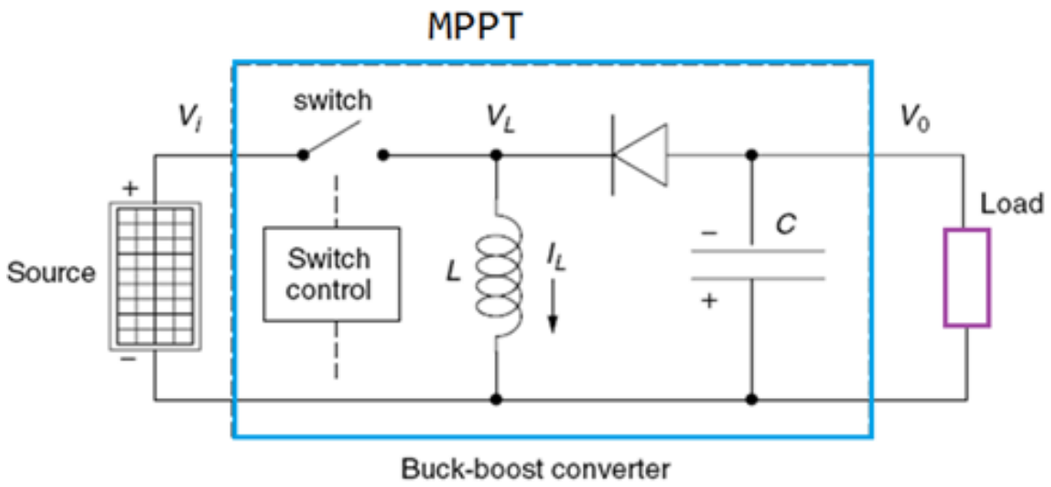
I-V Curve of Resistive Load

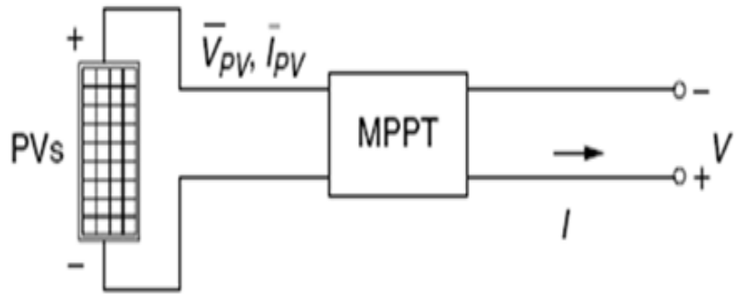




Maximum Power Point Tracker



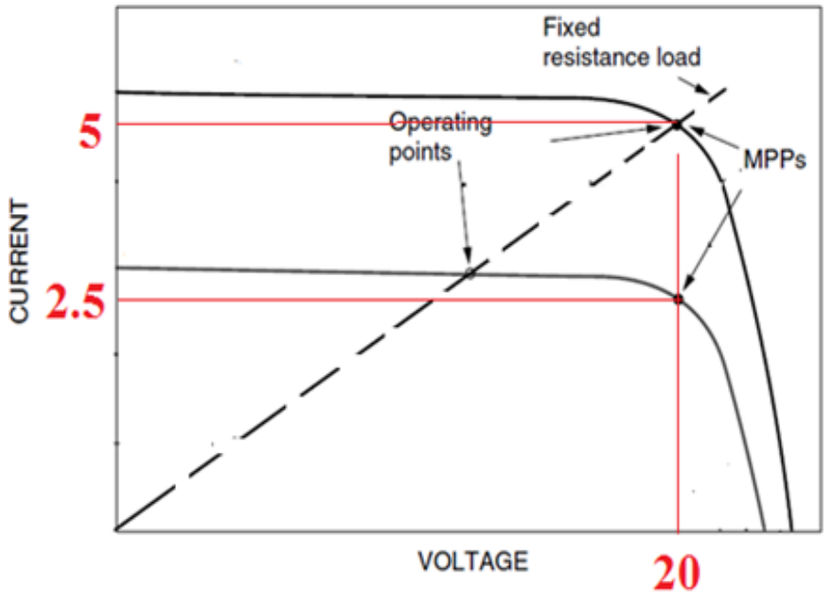


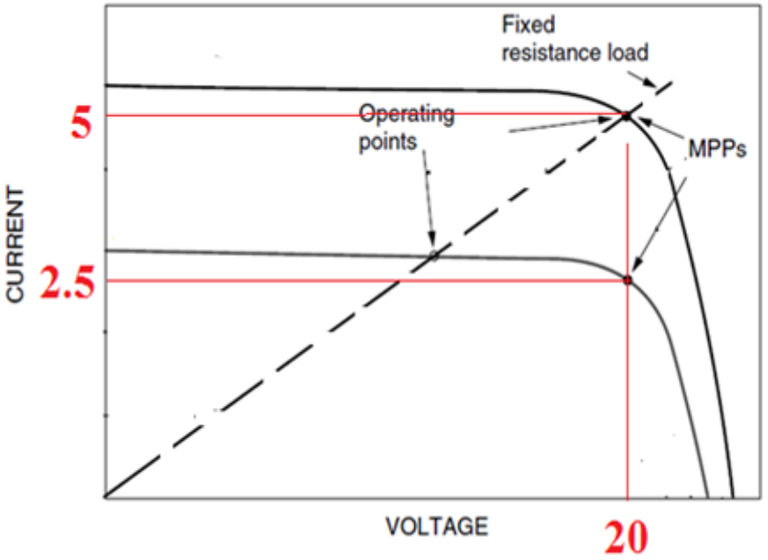


Maximum Power Point Tracker

MPPT - Example

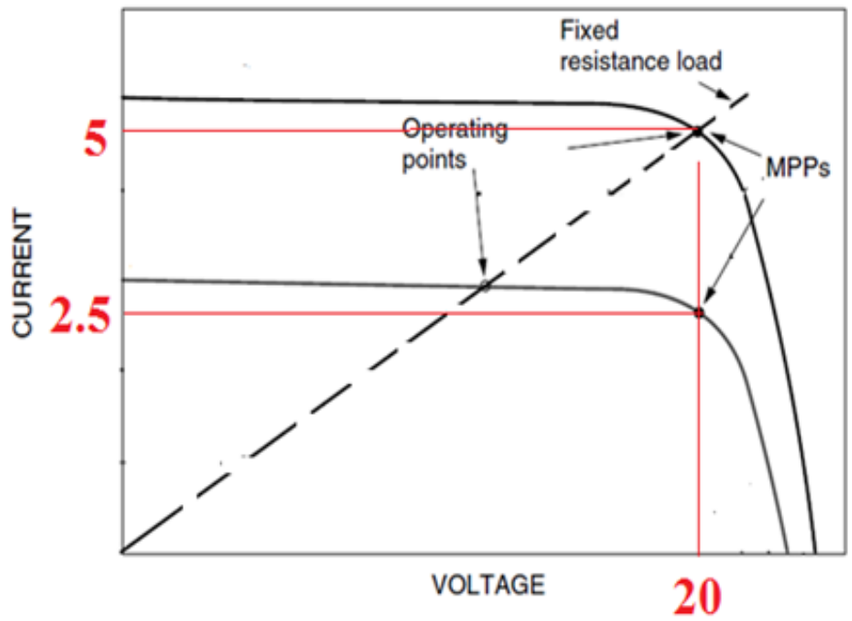
- A PV module is delivering power to a resistive load of 4 ohms. Under an 1-sun condition, a PV module has its maximum power point at V_m=20 volts and I_m = 5 A. In the late afternoon (under ½ sun) , the maximum power point moves to I_m = 2.5 A and V_m=20 volts. (a) What is the power delivered to the load under 1-sun, (b) What is the power deliver to the load under ½ sun, (c) In ½ sun, what should be the output voltage to deliver maximum power to the load ?





1/2- sun condition

MPPT condition for maximum power to the load.



PV System Sizing
(a) Grid-Connected (b) Stand-Along System

(a) Grid-Connected PV System Design

- How much ac kWh/yr are required?
- How much peak watts of dc PV power are needed to provide that amount?
- How much area will that system require?
- What real components are available ?

⌘ Design Steps

Grid-Connected PV System Design

⌘ Example

- A house in Fresno, CA (Latitude at 22°) plans to build a grid-connected PV system with a rooftop PV array, which faces south with fixed tilt angle of L – 15°, that will displace all of the 3600 kWh/yr of electricity on 100V that the home uses. It is assumed that DC-to-AC conversion efficiency of PV array is 75%, and PV array's average 1-sun efficiency is 12.5%.
- **Question:** Design a PV system for the Fresno house.
- How many kW (dc, STC) of PV panels & Inverter will be required and how much area will be needed?

Step 1 – Pdc Estimation

Solar Radiation Data Manual
for
Flat-Plate and Concentrating Collectors

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	2.1	3.2	4.7	6.3	7.5	8.1	8.0	7.2	5.9	4.3	2.7	1.9	5.2
	Min/Max	1.7/2.7	2.5/3.9	3.7/5.5	5.1/7.0	6.6/8.0	7.4/8.7	7.6/8.4	6.3/7.6	5.2/6.3	3.9/4.6	2.0/3.2	1.4/2.6	4.7/5.4
Latitude -15	Average	2.8	4.1	5.5	6.8	7.6	7.8	7.9	7.5	6.8	5.5	3.6	2.5	5.7
	Min/Max	1.9/3.9	3.1/5.3	4.2/6.6	5.4/7.5	6.6/8.1	7.2/8.3	7.5/8.2	6.6/7.9	5.9/7.3	4.8/6.0	2.4/4.5	1.6/3.9	5.1/6.0

Step 2- Selection of PV Module

$P_{dc} = 2.307$ kW

$P_{ac} = 1.73$ [kW]

Module:	Kyocera KC158G
Material:	Multicrystal
Rated power $P_{dc,STC}$:	158 W
Voltage at max power:	23.2 V
Current at max power:	6.82 A
Open-circuit voltage V_{OC}:	28.9 V
Short-circuit current I_{SC}:	7.58 A
Length:	1.290 m
Width:	0.990 m
Efficiency:	12.4%

- Check if the energy requirement is met

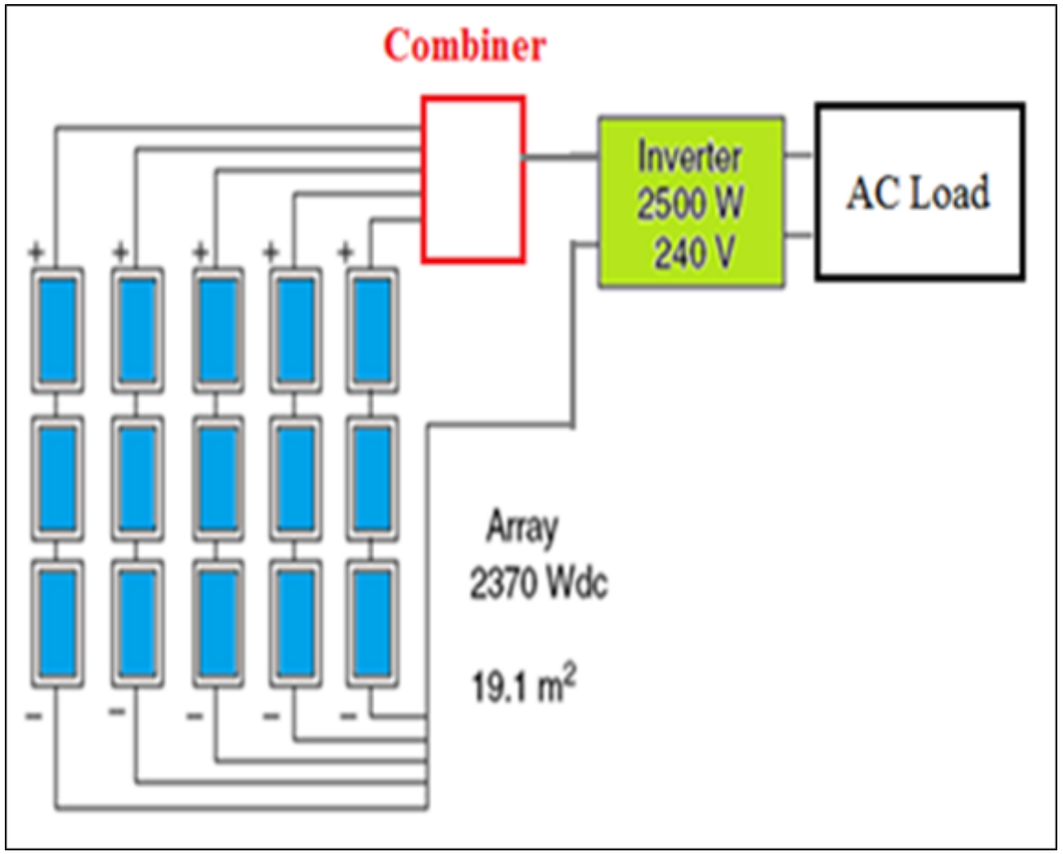
Step 3 – Selection of Inverter Module

☒ 3-string: 23.2x3=69.6V

Manufacturer:	Xantrex	Xantrex	Xantrex	Sunny Boy	Sunny Boy
Model:	STXR1500	STXR2500	PV 10	SB2000	SB2500
AC power:	1500 W	2500 W	10,000 W	2000 W	2500 W
AC voltage:	211–264 V	211–264 V	208 V, 3Φ	198–251 V	198–251 V
PV voltage range MPPT:	44–85 V	44–85 V	330–600 V	125–500 V	250–550 V
Max input voltage:	120 V	120 V	600 V	500 V	600 V
Max input current:	—	—	31.9 A	10 A	11 A
Maximum efficiency:	92%	94%	95%	96%	94%

Step 4 – Installation

NEC Article 690



Step 5 – Energy Cost Calculation

- **PV System Cost Analysis (Example)**
- 1) 15 Kyocera PV modules: $ 15,000
- 2) 1 PV-inverter: $ 4,000
- 3) Rooftop PV installation: $3,000
- 4) Electric Installation: $3,000
- Grand Total: $25,000

3600 kWh/yr of electricity

- Financing (Example)
  - Principal= $25,000
  - O&M Cost: $0
  - Interest rate: 6%
  - Lifespan: 30 years
  - Annual Loan Payment (A):

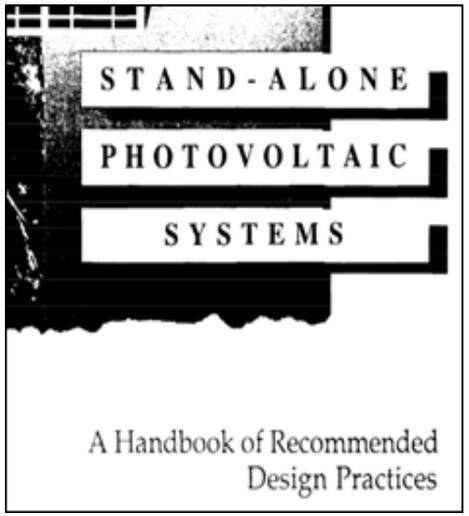
(b) Stand-Alone PV System

- How do **we design for the Fresno house** as a **stand-alone PV system**?
- **Add** a battery
- **How to size a battery?**
  - (a) Daily energy need **kWh/day**
  - (b) Days of storage need
  - (c) Usable Capacity
  - (d) Nominal Capacity
  - (e) Battery Selection

Battery Sizing Step 1 - Daily Energy Need

rooftop PV array, which faces south with fixed tilt angle of L – 15°, that will displace all of the 3600 kWh/yr of electricity that the home uses. It is assumed that DC-to-AC conversion

Battery Sizing Step 2 – Days of Storage Need



Worst-Month
peak-Sun hours

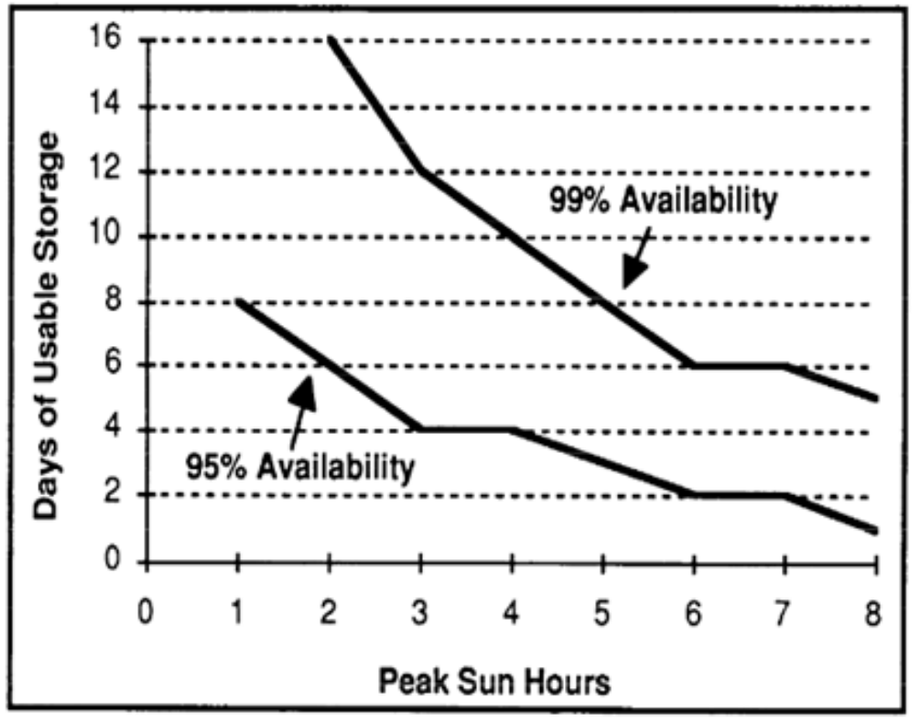


Figure 4. Days of Storage.

Fresno, CA
WBAN NO. 93193

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	2.1	3.2	4.7	6.3	7.5	8.1	8.0	7.2	5.9	4.3	2.7	1.9	5.2
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Latitude -15	Average	2.8	4.1	5.5	6.8	7.6	7.8	7.9	7.5	6.8	5.5	3.6	2.5	5.7
	Min/Max	1.9/3.9	3.1/5.3	4.2/6.6	5.4/7.5	6.6/8.1	7.2/8.3	7.5/8.2	6.6/7.9	5.9/7.3	4.8/6.0	2.4/4.5	1.6/3.9	5.1/6.0
Latitude	Average	3.1	4.4	5.7	6.7	7.1	7.2	7.3	7.3	6.9	6.0	4.1	2.8	5.7
	Min/Max	2.0/4.5	3.3/5.8	4.3/6.9	5.2/7.4	6.2/7.6	6.6/7.6	7.0/7.6	6.4/7.7	6.1/7.5	5.1/6.5	2.6/5.1	1.7/4.6	5.1/6.1
Latitude +15	Average	3.2	4.5	5.6	6.2	6.3	6.1	6.3	6.6	6.7	6.1	4.2	3.0	5.4
	Min/Max	2.0/4.8	3.3/6.1	4.1/6.9	4.8/6.9	5.4/6.7	5.7/6.4	6.0/6.5	5.8/6.9	5.8/7.2	5.1/6.6	2.6/5.4	1.7/5.0	4.7/5.8

Battery Sizing Step 3 – Usable Capacity

- Inverter efficiency = 94%
- System voltage: 69.6V → **60V for Battery & inverter**
- Storage Energy Need in AC

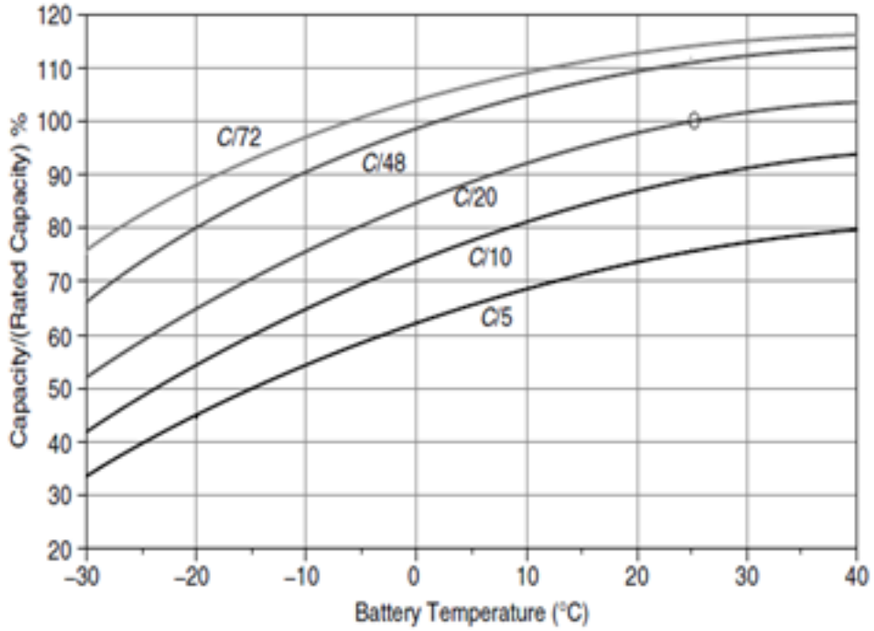
Daily Energy Need

- Storage Energy Need in DC
- **Batt Usable Capacity In DC**

  Conversion to Ah (Ampere-Hour) in 60 V system

Battery Sizing step 4 – Nominal Capacity

Relationship between the **usable battery capacity** and the **nominal battery capacity**

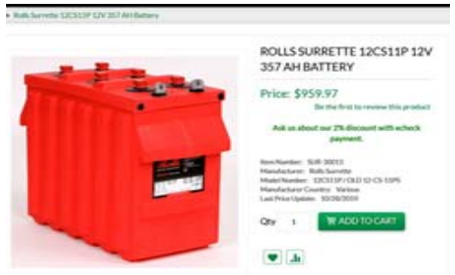


Battery Sizing Step 5- Battery Selection

Nominal Batt capacity $= \frac{2450\ Ah}{(0.8)(0.95)} = 3224\ Ah$ @ 60 V

Example 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



Stand-alone PV System – Energy Cost Calculation

- **PV System Cost Analysis**
- 1) 15 Kyocera PV modules: $ 15,000
- 2) 1 PV-inverter: $ 4,000
- 3) Rooftop PV installation: $3,000
- 4) Electric Installation: $3,000
- 5) 50 Surette 12CS11PS battery: $50,000
- Grand Total: $75,000

- Financing
  - Principal= $75,000
  - O&M Cost: $0
  - Interest rate: 6%
  - Lifespan: 30 years
  - Annual Loan Payment (A):