Chapter 9

System Sizing

Sizing Principles ● Interactive vs. Stand-Alone Systems ● Calculations and Software Tools

Overview

- Establishing the purpose and basic principles for sizing PV systems.
- Identifying the steps and considerations for sizing and estimating the performance of utility-interactive PV systems.
- Determining the electrical loads and the size of battery and PV array required for stand-alone PV systems.

Sizing Objectives

- Sizing is the basis for PV system electrical designs, and establishes the sizes and ratings of major components needed to meet a certain performance objective.
- The sizing of PV systems may be based on any number of factors, depending on the type of system and its functional requirements.

Sizing Principles

- **The sizing principles for interactive and stand-alone PV systems are based on different design and functional requirements.**

- **Utility-Interactive Systems (without energy storage):**
  - Provide supplemental power to facility loads.
  - Failure of PV system does not result in loss of loads.

- **Stand-Alone Systems (with energy storage):**
  - Designed to meet a specific electrical load requirement.
  - Failure of PV system results in loss of load.

Sizing Interactive PV Systems

- **The sizing for interactive systems without energy storage generally involves the following:**

- **Determining the maximum array power output.**
  - Based on the available area, efficiency of PV modules used, array layout and budget.

- **Selecting one or more inverters with a combined rated power output 80% to 90% of the array maximum power rating at STC.**
  - Inverter string sizing determines the specific number of series-connected modules permitted in each source circuit to meet voltage requirements.
  - The inverter power rating limits the total number of parallel source circuits.

- **Estimating system energy production based on the local solar resource and weather data.**

Sizing Interactive PV Systems

- The sizing of interactive PV systems is centered around the inverter requirements.

Inverter size is determined by the PV array maximum power

PV array size is limited by available space, budget and inverter voltage requirement

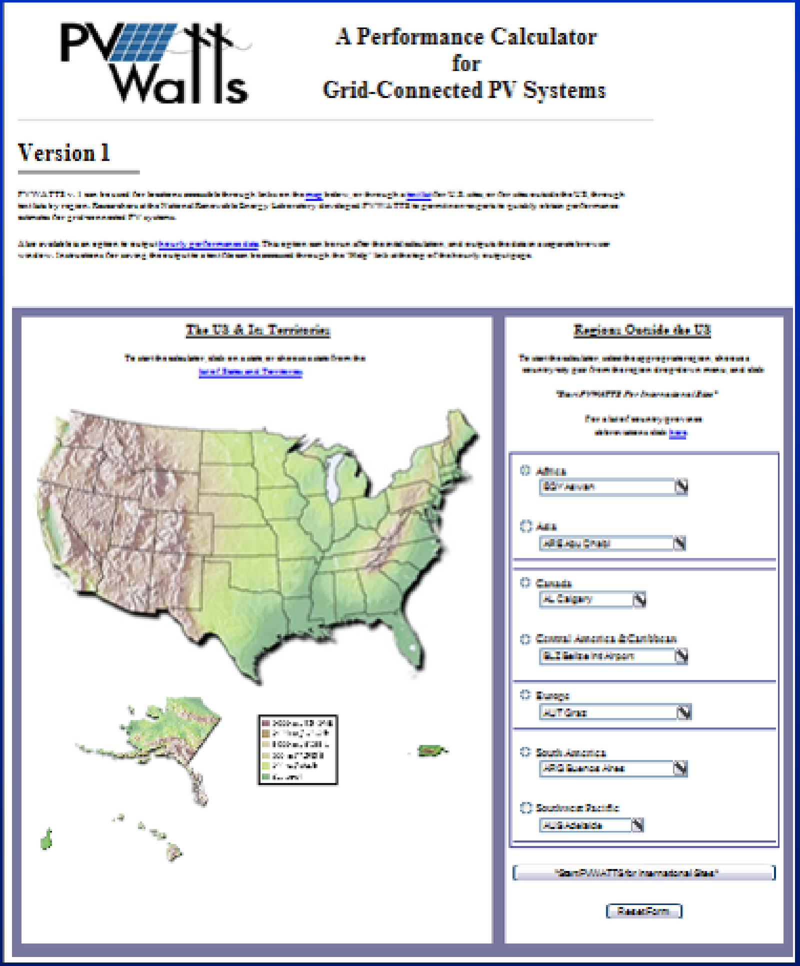
Size of utility service limits maximum system output

Estimating Energy Production

INTERACTIVE PV SYSTEM PERFORMANCE WORKSHEET	
Estimating and Verifying System AC Energy Production	
PV Array DC Power Rating at STC - 1000 W/m^2, 25 °C (kW)	**10**
Derating Factors	
Nameplate Ratings	0.95
Inverter and Transformer	0.95
Module Mismatch	0.98
DC Wiring	0.98
AC Wiring	0.99
Soiling	1.00
Shading	0.85
Sun Tracking	1.00
Age	1.00
Combined Derating Factors	0.73
Estimated System AC Power Output at STC - 1000 W/m^2, 25 °C (kW)	7.3
Temperature Adjustments	
Array Power-Temperature Coefficient (%/°C)	-0.5
Average Array Operating Temperature (°C)	45
Estimated System AC Power Output at 1000 W/m^2 and Average Operating Temperature (kW)	6.6
Solar Radiation Received	
Solar Irradiation in Plane of Array (kWh/m^2/day)	5
Estimated System AC Energy Output at Average Operating Temperature (kWh/day)	**29.5**

PVWATTS Performance Calculator

- Used to estimate the performance of simple grid-tied PV systems, based on user inputs and historical weather and solar radiation data.
- User selects state and city from map, and enters size of PV system, array orientation and derating factors.
- Results give monthly and annual solar energy received and PV system AC energy production.



NREL

PVWATTS

- **How it Works:**
  - Users select location, system size, and array type, orientation and tilt angle.
  - PVWATTS estimates the solar radiation incident on the PV array and the PV cell temperature for each hour of the year.
  - The average DC power for each hour is calculated from the PV system DC rating, the incident solar radiation, and corrected for PV cell temperature.
  - The average AC power for each hour is calculated by multiplying the average DC power by the DC-to-AC derate factor and adjusting for inverter efficiency.
  - Hourly average values of AC power (watt-hours) are then summed to calculate monthly and total annual AC energy production.

PVWATTS Output

AC Energy & Cost Savings

Cautions for Interpreting the Results

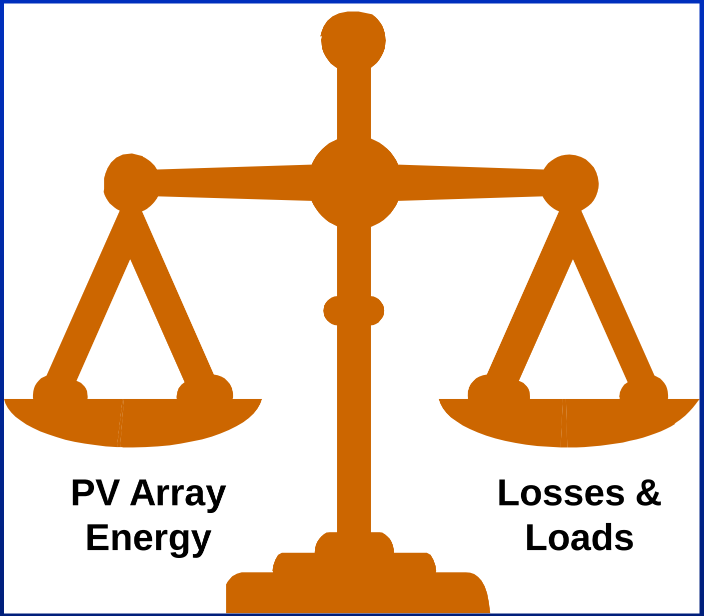
Station Identification	
City:	Daytona Beach
State:	FL
Latitude:	29.18° N
Longitude:	81.05° W
Elevation:	12 m
PV System Specifications	
DC Rating:	500.0 kW
DC to AC Derate Factor:	0.750
AC Rating:	375.0 kW
Array Type:	Fixed Tilt
Array Tilt:	29.2°
Array Azimuth:	180.0°
Energy Specifications	
Cost of Electricity:	9.0 ¢/kWh

Results

Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value ($)
1	4.34	47442	4269.78
2	4.96	49473	4452.57
3	5.81	63084	5677.56
4	6.14	62707	5643.63
5	5.98	62491	5624.19
6	5.67	56218	5059.62
7	5.74	59329	5339.61
8	5.65	58791	5291.19
9	5.51	55536	4998.24
10	4.84	51063	4595.67
11	4.67	48783	4390.47
12	4.23	46323	4169.07
Year	5.30	661241	59511.69

Sizing Stand-Alone Systems

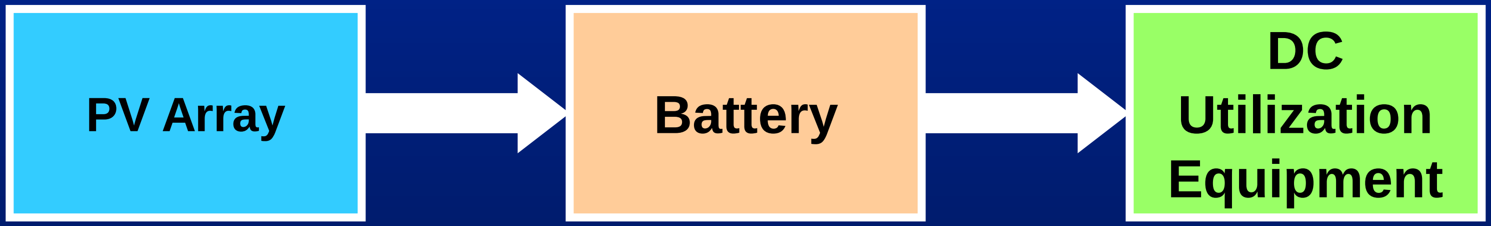
- The sizing objective for any type of stand-alone PV system is a critical balance between energy supply and demand.
- The PV array must provide enough energy to meet the load plus system losses under the worst case conditions.
- Consequently, the efficiency of the electrical loads is a critical concern.



Sizing Stand-Alone PV Systems

- Stand-alone PV systems can be considered a type of banking system.
- The battery is the bank account. The PV array produces energy (income) and charges the battery (deposits), and the electrical loads consume energy (withdrawals).

Battery is sized for desired days of storage



PV array is sized to meet average daily load under worst conditions

System loads determine the size of battery and PV array

Sizing Stand-Alone Systems

- **Stand-alone PV systems are sized to meet specific load requirements, and involve the following key steps:**
  - Determine the average daily load requirements for each month.
  - Conduct a critical design analysis to determine the month with the highest load to solar insolation ratio.
  - Size battery bank for system voltage and required energy storage capacity.
  - Size PV array to meet average daily load requirements during period with lowest sunlight and highest load (usually winter).

Sizing Stand-Alone PV Systems

- Sizing stand-alone PV systems begins with determining the electrical load, and then sizing the battery and PV array to meet the average daily load during the critical design month.

Determine Avg. Daily Electrical Load for Each Month

↓

Determine Load and Insolation for Critical Design Month

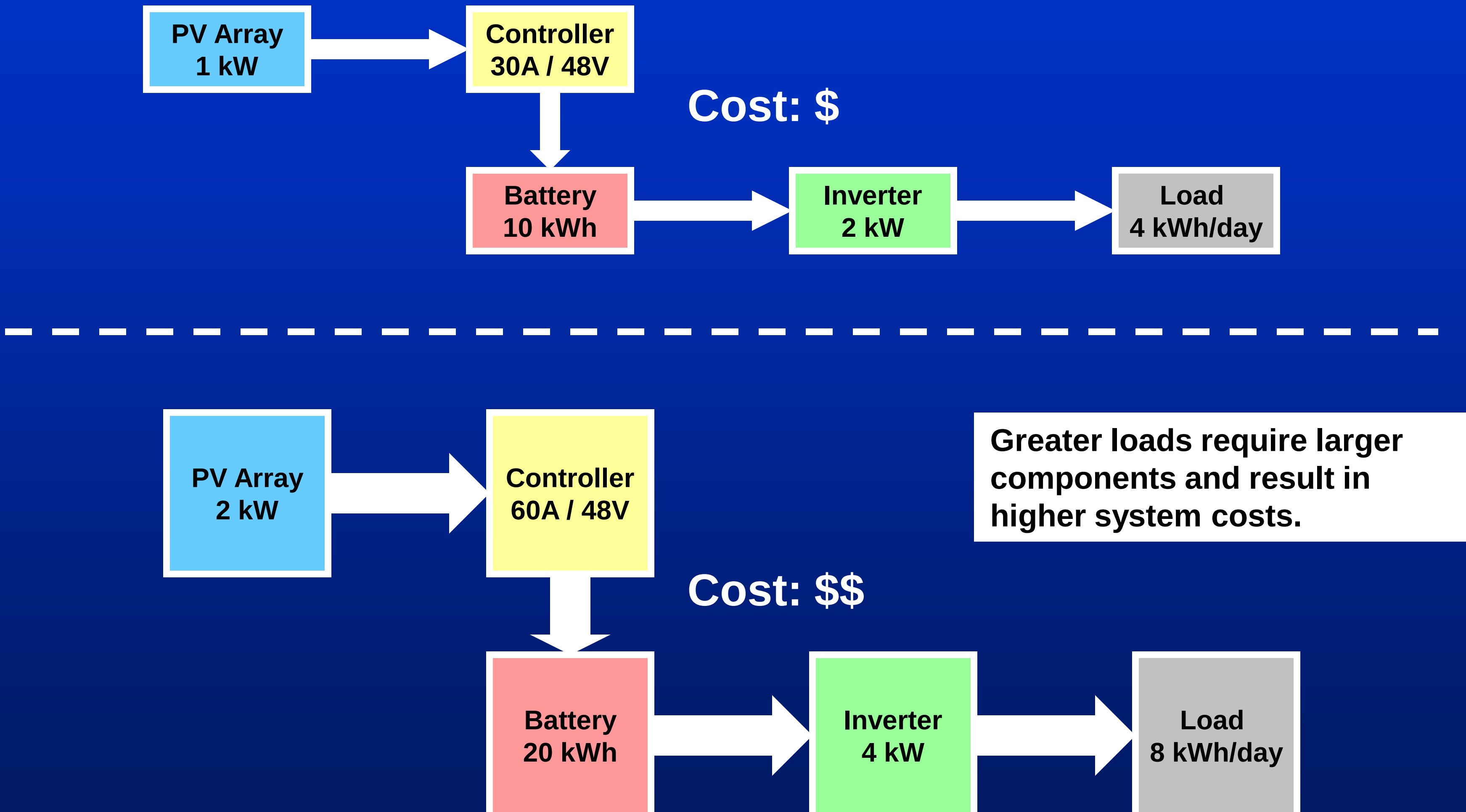
↓

Size Battery to Meet Load for Desired Days of Autonomy

↓

Size PV Array to Meet Loads for Critical Design Month

Load Effects on Stand-Alone System Size and Costs



Load Analysis

- **The energy consumption for electrical loads is estimated on an average daily basis for each month of the year.**
- **Use worksheets to list each load, its average power, daily time of use and compute energy consumption.**
  - List AC and DC loads separately, and apply inverter efficiency to determine the DC energy required for AC loads.
  - The daily DC energy required is used to size the battery and PV array.
  - The peak AC power demand dictates the size of inverter required.
- **Explore opportunities for improvements in load efficiency and end-use practices to reduce size and costs of PV system required.**

Critical Design Analysis

- A critical design analysis evaluates the ratio of the average daily load energy requirements and available solar insolation for each month.
- Use a worksheet to list the average daily loads for each month, and divide the loads by the available solar insolation for different array tilt angles.
- The critical design month is the month with the highest ratio of load to solar insolation, and defines the optimal tilt angle that results in the smallest array possible.
- For constant loads, the critical design month is the month with the greatest average daily load.

Selecting the System DC Voltage

- The DC voltage for stand-alone PV systems is selected based on the operating voltages for DC utilization equipment, including loads and inverters.
- Higher DC voltages are used for systems with higher power loads to reduce the system currents and the size of the conductors and switchgear required.
- Smaller stand-alone systems used for residential and small off-grid application typically use 12 V, 24 V or 48 V systems, while larger systems may use even higher DC voltages.

Selecting an Inverter

- **Selecting an inverter for stand-alone systems is based on the following:**
  - Nominal system DC voltage (battery)
  - AC output voltage
  - Peak AC power required for cumulative load
  - Surge current requirements, if any
  - Additional features (battery charger, etc.)

System Availability

- System availability is a statistical parameter, and represents the percentage of time over an average year that a stand-alone PV system meets the system loads.
- The sizing of stand-alone PV systems is based on long-term averages for solar insolation, and invariably, 100% load availability can never be achieved.
- Higher system availability can be achieved by increasing the size of the PV array and/or battery.

Sizing the Battery

- **Batteries for stand-alone systems are sized to store energy produced by the array for use by the system loads as required.**
- **The total amount of rated battery capacity required depends on the following:**
  - Desired days of storage to meet system loads with no recharge from PV
  - Maximum allowable depth-of-discharge
  - Temperature and discharge rates
  - System losses and efficiencies
- **The system voltage defines the number of series-connected battery cells required.**
- **The total capacity needed defines the number of parallel battery strings required.**

Autonomy

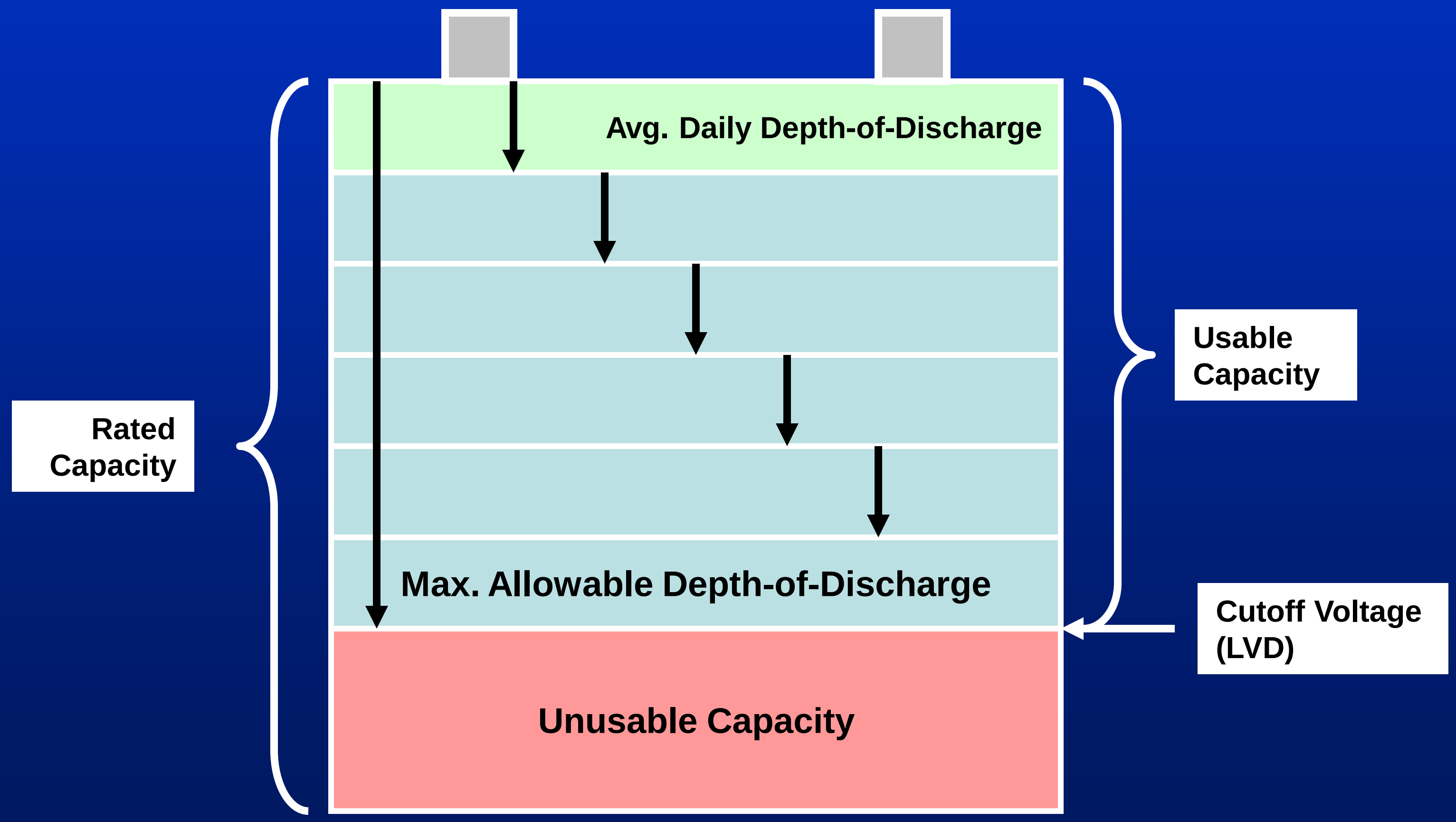
- Autonomy is the number of days that a fully charged battery can meet the system loads without any recharge from the PV array.
- The specified autonomy and maximum allowable depth-of-discharge define the total amount of battery capacity required for a given system load.
- Greater autonomy periods are used for more critical applications and increase system availability, but at higher cost due to the larger battery required.

Factors Affecting Battery Sizing

- **Greater autonomy periods increase the size of the battery and increase availability, and decrease average daily depth-of-discharge.**
- **Maximum depth-discharge defines the usable battery capacity and is defined by the load cutoff voltage.**
  - Greater allowable DOD provides greater system availability, but at the expense of battery health.
  - Depth-of-discharge must be limited in cold climates to protect lead-acid batteries from freezing.
- **Rated battery capacity is affected by temperature, discharge rate and age of the battery.**

Sizing the Battery

- Battery sizing is based on rated capacity and specified limits of operation.

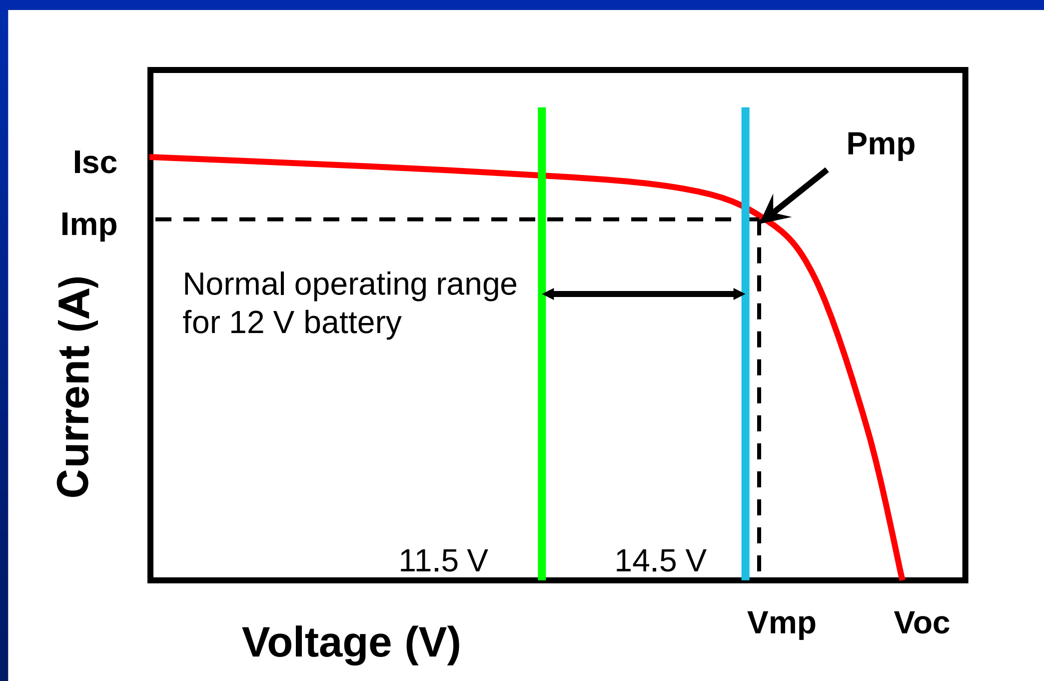


Sizing the PV Array

- The PV array for stand-alone systems is sized to meet the average daily load during the critical design month.
- System losses, soiling and higher operating temperatures are factored in estimating array output.
- The system voltage determines the number of series-connected modules required per source circuit.
- The system power and energy requirements determine the total number of parallel source circuits required.

PV Array Battery Charging

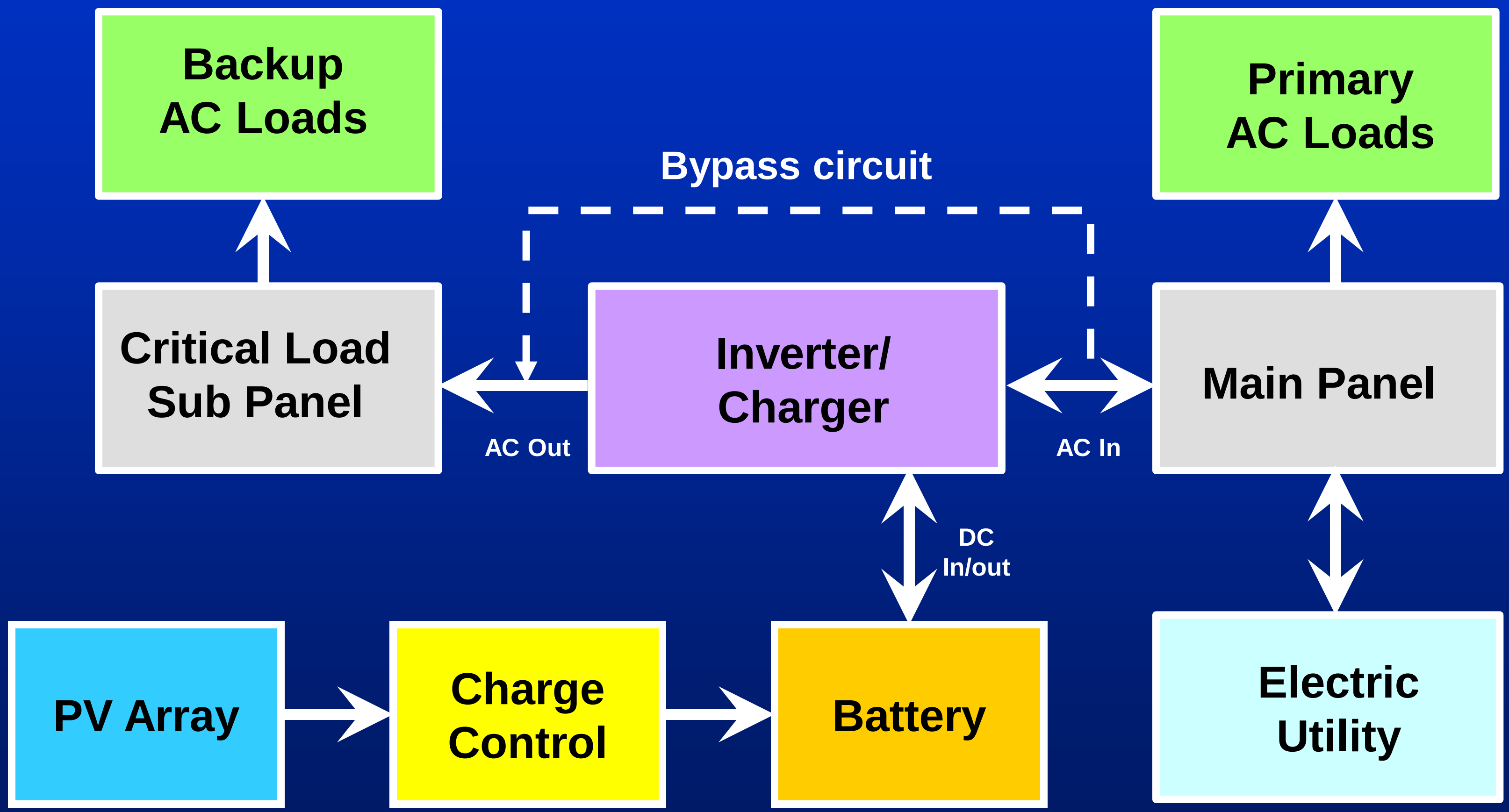
- **Standard silicon PV modules with 36 series-connected cells are optimally suited for charging a nominal 12 V lead-acid battery.**



Sizing Bimodal Systems

- **Bimodal interactive systems with battery storage are primarily sized for stand-alone operation, based on the critical loads to be powered in grid backup mode.**
- **The inverter must also be sized for the maximum array output during interactive operations.**

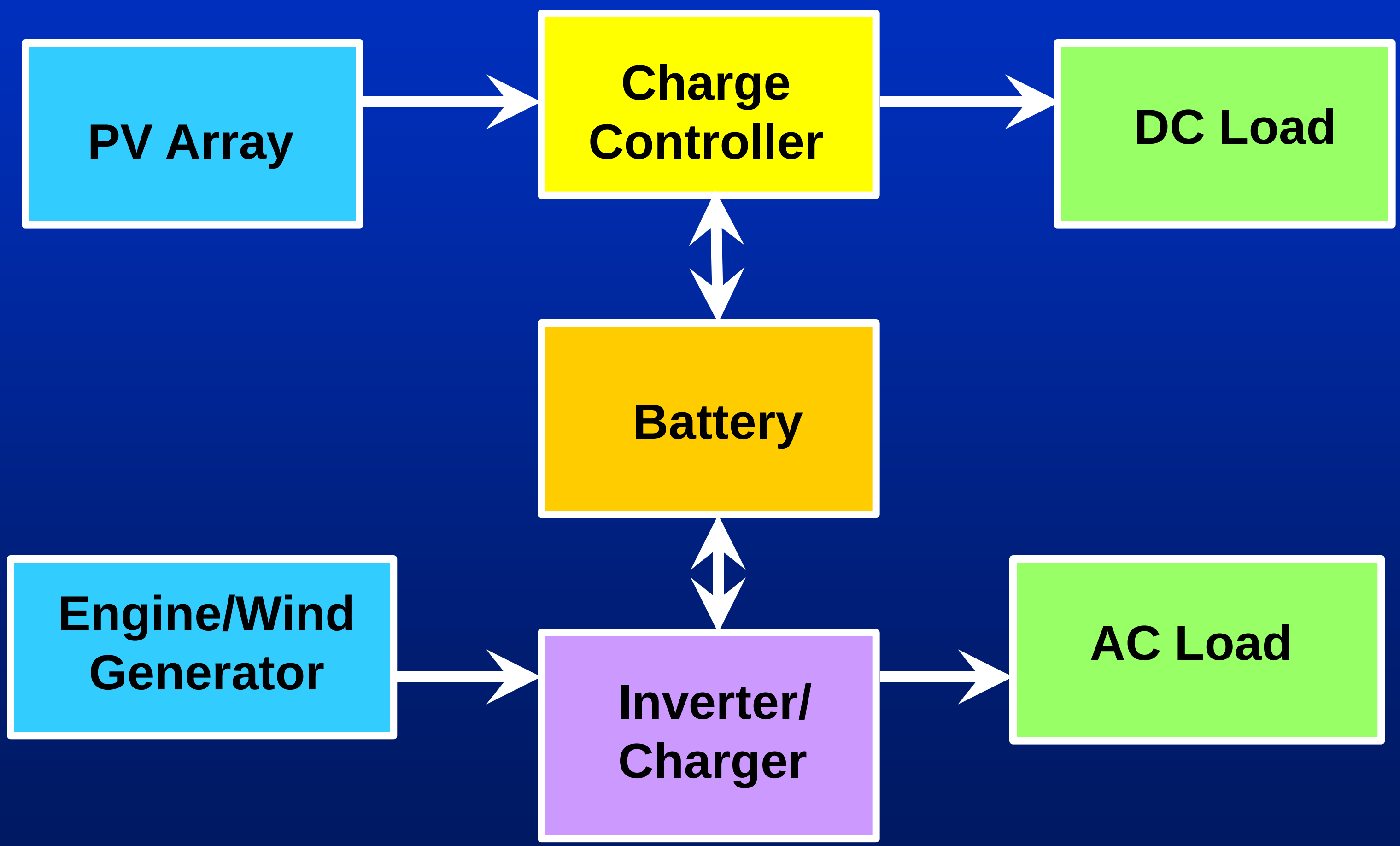
Utility-Interactive PV System with Energy Storage



Sizing Hybrid Stand-Alone Systems

- Hybrid stand-alone systems rely on other energy sources in addition to a PV array in meeting system loads.
- Consequently, the sizing of the PV array and battery are less critical.
- The relative size of the PV array and other energy sources is flexible, and depends on the desired design objectives, such as minimizing costs, or fuel and maintenance for generators.

Hybrid System



PV System Sizing and Estimating Software

- **Public Domain (NREL/DOE)**
  - PVWATTS: www.nrel.gov/rredc/pvwatts/
  - HOMER: www.analysis.nrel.gov/homer/
  - In-My-Backyard (IMBY): www.nrel.gov/analysis/imby
  - Solar Advisor Model (SAM): www.nrel.gov/analysis/sam/
- **Commercial**
  - Clean Power Estimator: www.cleanpower.com
  - PVSYST: www.pvsyst.com
  - OnGrid: www.ongrid.net
  - PVSol: www.solardesign.co.uk/
  - PV F-Chart: www.fchart.com
  - Maui Solar Software: www.mauisolarsoftware.com/
- **Manufacturers**
  - Inverter string sizing and various system sizing and design tools

Summary

- **Sizing PV systems is an iterative process used to determine the relative sizes and configurations for major components needed to meet the functional requirements and performance objectives.**
- **Interactive PV systems are sized independently of loads.**
- **Stand-alone PV systems are sized based on load requirements.**
  - The battery is sized to meet system average daily load for a specified number of days (autonomy).
  - The PV array is sized to meet the average daily load during the worst case insolation and load conditions.

Questions and Discussion