Several types of operating modes

- **Stand Alone systems**
  - No grid connection needed or wanted
- **Distributed Grid tied**
  - Small residential type systems
- **Centralized power plant**
  - Large PV system located in an optimum location, feeding into the grid

Application Areas

Photovoltaic System Basics

- Photovoltaic Systems
  - Cell → Panel → Array
  - Balance of System (BOS)
    - Mounting Structures
    - Storage Devices
    - Power Conditioners
  - Load
    - DC
    - AC

Specifications of PV Modules

- **Type**
  - c-Si, a-Si:H, CdTe
- **Rated Power Max:** \( P_{\text{max}} \) (Wp)
- **Rated Current:** \( I_{\text{MP}} \) (A)
- **Rated Voltage:** \( V_{\text{MP}} \) (V)
- **Short Circuit Current:** \( I_{\text{SC}} \) (A)
- **Open Circuit Voltage:** \( V_{\text{OC}} \) (V)
- **Configuration (V)**
- **Cells per Module (#)**
- **Dimensions (cm x cm)**
- **Warranty (years)**
Storage Devices (Batteries)

- Advantages
  - Back up for night and cloudy days
- Disadvantages
  - Decreases the efficiency of PV system
  - Only 80% of energy stored retainable
  - Adds to the expense of system
  - Finite Lifetime ~ 5 - 10 years
  - Added floor space, maintenance, safety concerns

Power Conditioners (Inverters)

- Limit Current and Voltage to Maximize Power
- Convert DC Power to AC Power
- Match AC Power to Utilities Network
- Protect Utility Workers during Repairs

Simple DC

- Direct Powering of Load
- No Energy Storage

Small DC

- Home and Recreational Use

Large DC

- Home and Recreational Use
- Industrial Use

Large AC/DC

- Both AC and DC loads
Utility Grid Connected

- No On-Site Energy Storage

   ![Diagram of Utility Grid Connected System]

   - Inverter
   - AC Load
   - Multiple Panels
   - Electric Grid

Hybrid System

- Supplement Generator

   ![Diagram of Hybrid System]

   - Inverter
   - DC Load
   - Multiple Panels
   - Charge Regulator
   - AC Generator (Wind turbine)
   - Multiple Batteries

PV System Design Rules

1. Determine the total load current and operational time
2. Add system losses
3. Determine the solar irradiation in daily equivalent sun hours (EHS)
4. Determine total solar array current requirements
5. Determine optimum module arrangement for solar array
6. Determine battery size for recommended reserve time

Photovoltaic System Design Block Diagram

- Battery
- AC Load
- Power Conditioning
- DC Load
- Photovoltaic Generator
- Back-up Generator
- Grid
- Not all the subsystems will be necessary

Direct PV driven System

- Photovoltaic Generator
- Power Conditioning
- DC Load

Example: Attic Fans

Stand Alone DC System

- Battery
- DC Load
- Photovoltaic Generator
- Power Conditioning

Example: Small Consumer Devices
Grid Tied System

Photovoltaic Generator → Power Conditioning → AC Load

Example: Most Home Systems

Grid Tied with Battery backup

Photovoltaic Generator → Power Conditioning → Battery → DC Load

Not all the subsystems will be necessary

Remote Area Power System

Battery → Power Conditioning → AC Load

Photovoltaic Generator → Power Conditioning (DC Load)

Back-up Generator

Example: remote cabin

Batteries

• Requirements
  – Long life
  – Very low self-discharge
  – Long duty cycle
  – High charge storage efficiency
  – Low cost
  – Low maintenance

• Efficiencies
  – Coulombic or Charge
    • Amount of charge able to retrieve from the battery (85%)
  – Voltage
    • Charge is retrieved from battery at a lower voltage than input voltage (85%)
  – Energy
    • Product of coulombic and voltage efficiencies (72%)

Batteries 2

• Power rating
  – Maximum rate of charge and discharge (Amps)
• Battery capacity
  – Maximum amount of energy that can be extracted from the battery without the battery voltage falling below a prescribed value
  – Ampere-hrs at a constant discharge rate

• Depth of Discharge
  – Percentage of the rated capacity withdrawn from the battery
  – Battery life is a function of the average state of charge of the battery
  – Trade-off between cycling depth of discharge and size of battery and lifetime

Lead Acid Batteries

Most common used in home systems
Nickel-Cadmium Batteries

- **Advantages**
  - Can be overcharged
  - Can be fully discharged
  - More rugged
  - Excellent low temperature performance
  - Low internal resistances
  - Uniform voltage over discharge
  - Long life
  - Low maintenance

- **Disadvantage**
  - More expensive (2-3x)
  - Lower charge storage efficiencies (60-70%)
  - Memory, inability to deep discharge
  - Much lower capacity

Power Conditioning and Regulation

- **Diodes**
  - Bypass: prevents hot-spotting and module performance reduction
  - Blocking: protects the battery from short circuits in the array and prevent battery from discharging through the solar cells when not illuminated

- **Battery Voltage Regulators or Charge Controllers**

- **Charge Controllers**
Shunt Controller
- Variable resistant element in parallel with the battery usually a MOSFET or BJT
- As resistance is reduced more current from array is diverted through resistor and less through the battery
- May need to dissipate a large amount of power

Series
- Regulator placed in series with battery
- Dissipates much less power
  - Low voltage across regulator when charging
  - Low current through regulator when charged

Series Pulse Width Modulation
- Switch set to open at battery voltage and close at another battery voltage

Sub-array Switching
- Used in large systems
- Array disconnected as charging currents increase towards midday
- Reconnected as charging currents fall later in the day

Inverter
- Convert power from DC to AC
  - 12, 24, 48 VDC to 110 VAC
- Self Commutating Fixed Frequency Inverter:
  - use of transistor switches to reverse polarity of supply under internal control
- Line Commutated Fixed Frequency Inverter:
  - uses thyristor switches that require an alternating load voltage from an external source (Grid) to turn switches off
- Inverter failure remains one of the primary causes of PV system failure
A. Input to the sizing procedure

• 1-3. Determine the energy input
  - The radiation data for the site, along with the panel orientation are used to determine the incident solar radiation on the panel for a typical day for every month of the year

• 4-6. Determine the load demand
  - The load specification or typical load for a similar system
  - Allow for battery efficiencies
  - \( f \): fraction of load stored in battery before use
    \[ n_{\text{battery}} = \frac{1}{1 - f(1 - n_{\text{battery}})} \]

B. Number of Series-connected Modules

• 7. The DC operating bus bar voltage \( V_{\text{DC}} \) of the system is specified. (For home systems it is usually a multiple of 12V)

• 8. The number (\( N_s \)) of modules connected in series is directly determined by the DC operating voltage
  - \( V_m \) is the operating voltage of one module
    - Usually 36 cells in string for a 12V system
    \[ V_{\text{DC}} = \frac{V_m}{N_s} \]

C. Number of parallel strings

• The number is determined by the current requirement of the load

• 9. The equivalent load current is calculated
  - \( I_{\text{peak}} \) is the current drawn by the load
  - \( V_{\text{DC}} \) is the DC operating voltage
  - \( N_s \) is the number of modules in series
  \[ E_i (Wh / day) = (PSH I_{\text{PV}} V_{\text{DC}}) \Rightarrow I_{\text{PV}} = \frac{24 I_i}{PSH} \]

D. Sizing the storage subsystem

• 13. The daily and seasonal charge deficits are calculated. Excess energy generated and not used must be stored. Daily Charge/Discharge percentages of the battery must not exceed safety value

• 14. The energy balance for the year is set such that the summer excess can be stored to cover the energy deficit during the winter
  - \( Q_w \): total energy storage
  \[ Q_w = \frac{AE}{V_{\text{DC}}} \]

• 15. Allow for number of days of operation without energy input
  - Maintenance
  - Service
  - Lack of sunshine (Bad storm)
Final Lab Report (Wafer Number)

- **Background**
  - Fabrication Sequence
  - Device Cross Section

- **Measurements**
  - N+ Final Sheet Resistivity
  - P+ Final Sheet Resistivity
  - Front Al Sheet Resistivity
  - Back Al Sheet Resistivity
  - Front Al Thickness

- **Device Testing**
  - IV curves (4)
    - Resistance Estimation
    - Fill Factor
    - Efficiency Estimations
  - Dark I-V curves (SDA)
    - Linear
    - Semilog

- **Analysis**
  - 4 solar cell data table
  - Series resistance calculations
  - Annealing impact
  - Class Data Table
  - 4 devices Variances
  - Comparison of Class Data

- **Summary**
  - Results
    - Maximum Voltage
    - Maximum Current Density
    - Maximum Fill Factor
    - Efficiency
  - Course recommendations