EELE408 Photovoltaics

Lecture 20: Photovoltaic Systems

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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

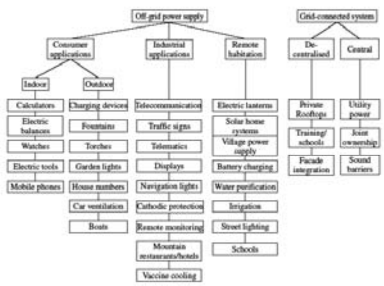
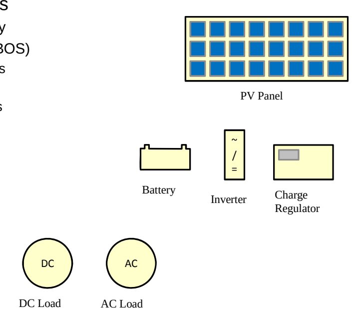


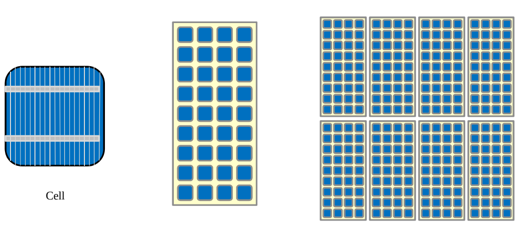
Figure 17.1 Application areas of photovoltaic systems. The applications are subdivided into "off-grid" and "grid-connected" systems

Photovoltaic System Basics

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



Modularity: Solar Cell to Array



- **Cell (c-Si 10×10 cm² η=15% P=1.5Wp V=0.5V I=3A)**
- **Solar panel (36 c-Si cells P=54Wp I=3A V=18V)**
- **Solar array**

Specifications of PV Modules

- Type
  - c:Si, a-Si:H, CdTe
- Rated Power Max: P_{max} (W_p)
- Rated Current: I_{MPP} (A)
- Rated Voltage: V_{MPP} (V)
- Short Circuit Current: I_{SC} (A)
- Open Circuit Voltage: V_{OC} (V)
- Configuration (V)
- Cells per Module (#)
- Dimensions (cm x cm)
- Warranty (years)

Storage Devices (Batteries)

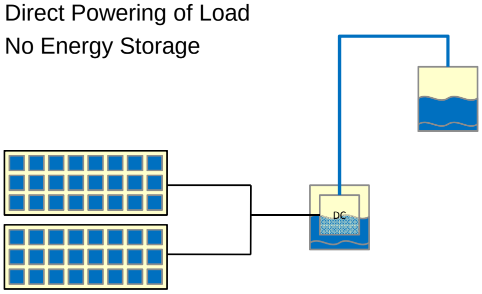
- Advantages
  - Back up for night and cloudy days
- Disadvantages
  - Decreases the efficiency of PV system
  - Only 80% of energy stored retainable
  - Adds to the expense of system
  - Finite Lifetime ~ 5 - 10 years
  - Added floor space, maintenance, safety concerns

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

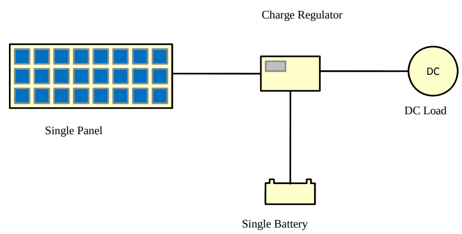
Simple DC

- Direct Powering of Load
- No Energy Storage



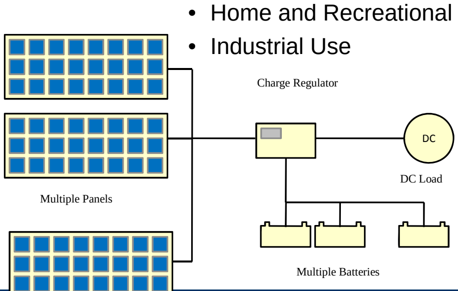
Small DC

- Home and Recreational Use



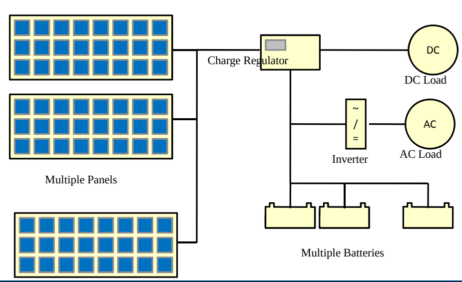
Large DC

- Home and Recreational Use
- Industrial Use



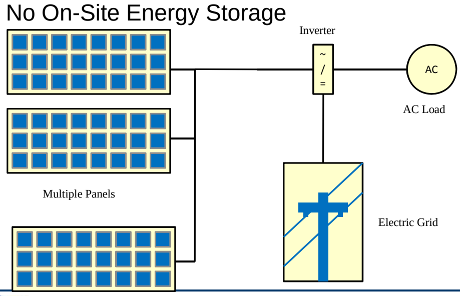
Large AC/DC

- Both AC and DC loads



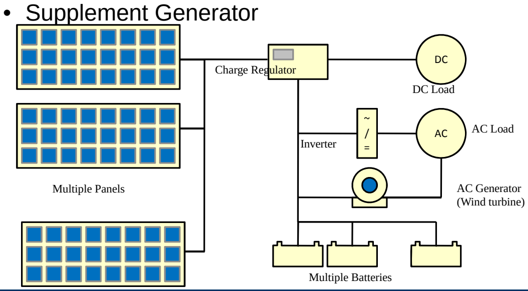
Utility Grid Connected

- No On-Site Energy Storage



Hybrid System

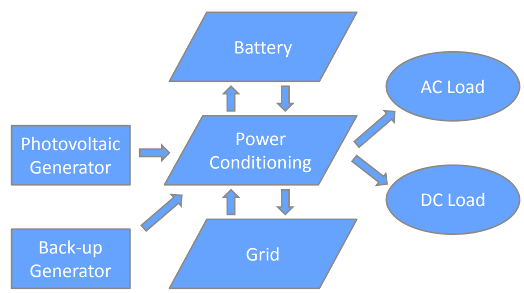
- Supplement Generator



PV System Design Rules

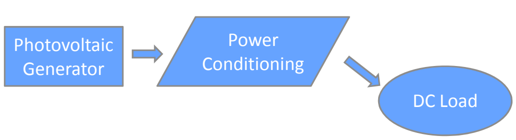
- 1. Determine the total load current and operational time
- 2. Add system losses
- 3. Determine the solar irradiation in daily equivalent sun hours (EHS)
- 4. Determine total solar array current requirements
- 5. Determine optimum module arrangement for solar array
- 6. Determine battery size for recommended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

Photovoltaic System Design Block Diagram



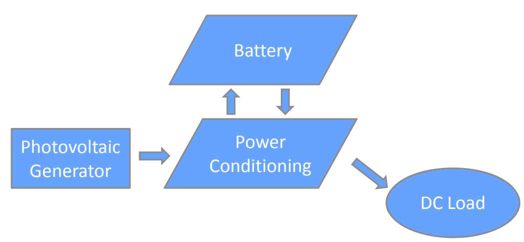
Not all the subsystems will be necessary

Direct PV driven System



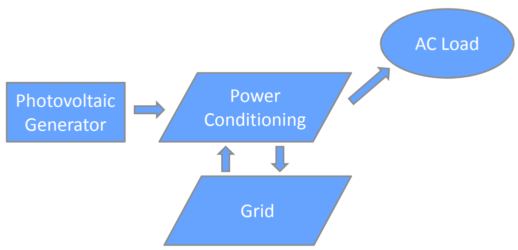
Example: Attic Fans

Stand Alone DC System



Example: Small Consumer Devices

Grid Tied System



Example: Most Home Systems

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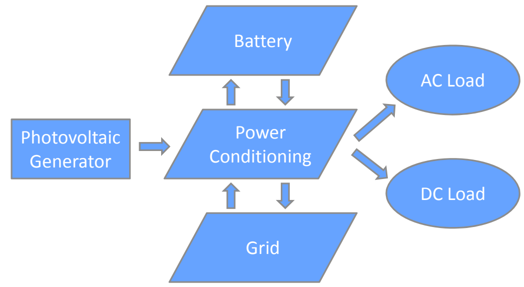
Grid Tied with Battery backup



Not all the subsystems will be necessary

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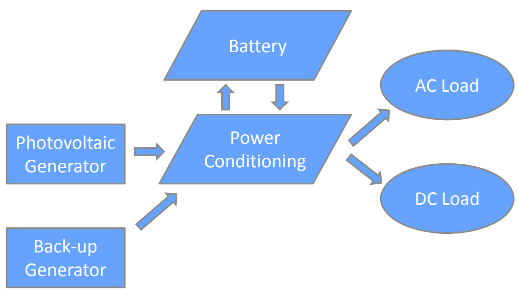
Remote Area Power System



Example: remote cabin

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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%)

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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

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Lead Acid Batteries

Most common used in home system

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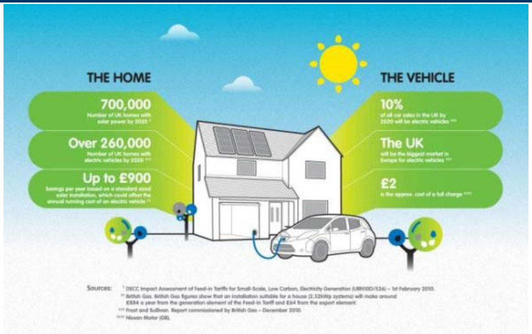
BEV and Home



Energy Management

Nickel-Cadmium Batteries

Used in household appliances

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

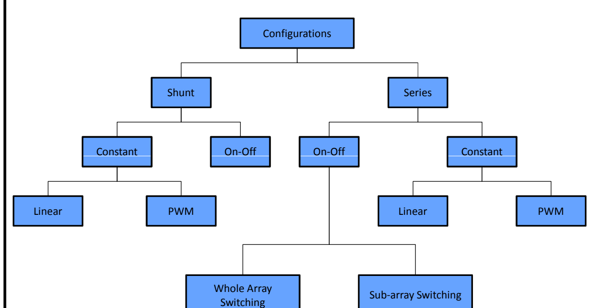
Power Conditioning and Regulation

- 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

Power Conditioning and Regulation

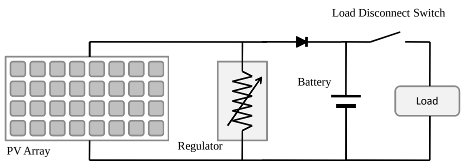
- Battery Voltage Regulators or Charge Controllers
  - Shuts down the load when the battery reaches a prescribed state of discharge
  - Shuts down the PV array when the battery is fully charged

Charge Controllers



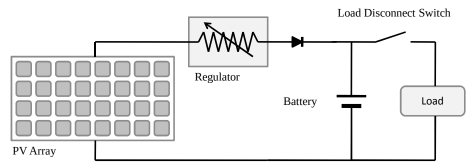
Shunt Controller

- 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



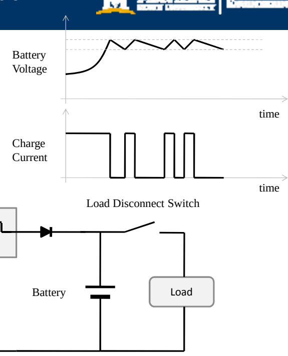
Series

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



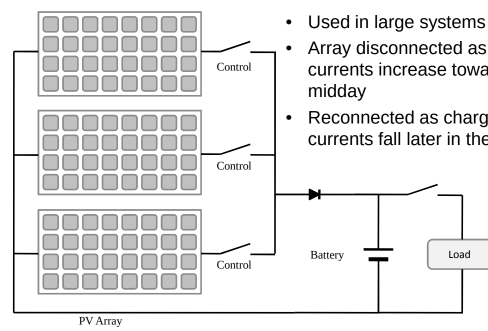
Series Pulse Width Modulation

- Switch set to open at battery voltage and close at another battery voltage



Sub-array Switching

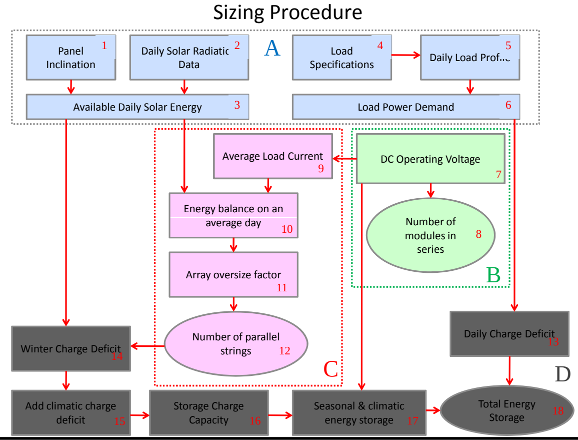
- Used in large systems
- Array disconnected as charging currents increase towards midday
- Reconnected as charging currents fall later in the day



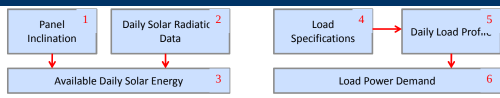
Inverter

- Convert power from DC to AC
  - 12, 24, 48 V_{DC} to 110 V_{AC}
- **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

Sizing Procedure



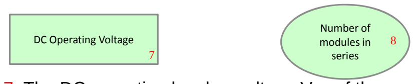
A. Input to the sizing procedure



- 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

$$\frac{\eta_{battery}}{1-f\left(1-\eta_{battery}\right)}$$

B. Number of Series-connected Modules



- 7. The DC operating bus bar voltage V_{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

$$N_s = \frac{V_{DC}}{V_m}$$

C. Number of parallel strings

- The number is determined by the current requirement of the load
- 9. The equivalent load current is calculated

$$I_L(A) = \frac{E_L(Wh/day)}{24V_{DC}}$$

Hours in a day — Typical power requirement

- 10. Define the nominal current required from the PV generator when irradiated with AM1.5 (1kW/m²) (PSH: Peak Solar Hours)

$$E_L(Wh/day) = (PSH)(I_{PV})(V_{DC}) \Rightarrow I_{PV} = \frac{24I_L}{PSH}$$

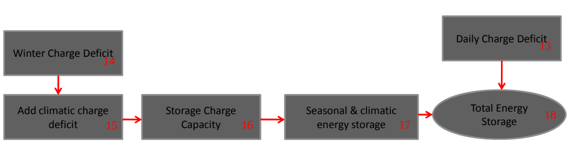
C. Number of parallel strings

$$E_L(Wh/day) = (PSH)(I_{PV})(V_{DC}) \Rightarrow I_{PV} = \frac{24I_L}{PSH}$$

- The average load current x number of hours in a day = nominal PV current x number of peak solar hours
- 11,12. The number of modules in parallel is calculated by:
- Isc is the short circuit current under standard illumination
- SF is a sizing factor to oversize the array

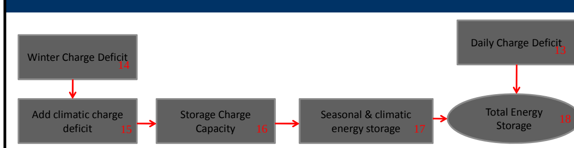
$$N_p = (SF)\frac{I_{PV}}{I_{SC}}$$

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

D. Sizing the storage subsystem

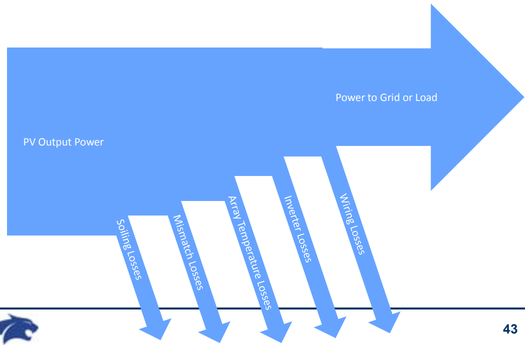


- 14. The energy balance for the year is set such that the summer excess can be stored to cover the energy deficit during the winter

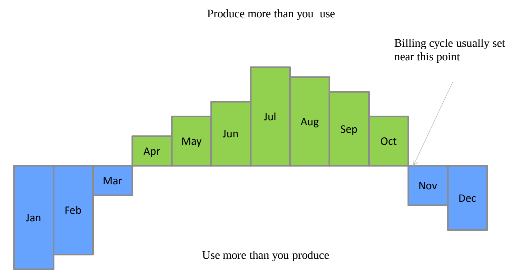
$$Q_{yd} = \frac{\Delta E}{V_{DC}}$$

- 15. Allow for number of days of operation without energy input
  - Maintenance
  - Service
  - Lack of sunshine (Bad storm)

Loss Mechanisms



Annual Energy Balance



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