EELE408 Photovoltaics

Lecture 21: Stand Alone Designs

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Stand Alone PV System Design

- Determine Average Daily PV System Load
- Determine Battery Needs
- Determine Array Sizing and Tilt

Determination of the Average Daily PV System Load

- 1. Identify all loads to be connected to the PV System
- 2. For each load determine its voltage, current, power and daily operating hours
  - For some loads the operation may vary on a daily, monthly or seasonal basis
  - If so accounted by calculating daily averages
- 3. Separate AC Loads from DC Loads

Determination of the Average Daily PV System Load (Continued)

- 4. Determine average daily A-h for each load from current and operating hours data
- 5. Add up the A-h for the DC loads, being sure all are at the same voltage
- 6. If some DC loads are at a different voltage and require a DC-DC converter then the conversion efficiency of the converter needs to be included

Determination of the Average Daily PV System Load (Continued)

- 7. For AC loads, the DC input to the inverter must be determined and the DC A-h are then determined from the DC input current
  - The DC input current is determined by equating the AC load power to the DC input power and then dividing by the efficiency of the inverter
- 8. Add the A-h for the DC loads to the A-h for the AC loads, then divide by the wire efficiency factor and the battery efficiency factor.
  - This gives the corrected average daily A-h for the total load

Determination of the Average Daily PV System Load (Continued)

- 9. The total AC load power will determine the required size of the inverter.
  - Individual load powers will be needed to determine wire sizing to the loads
  - Total load current will be compared to the total array current when sizing wire from battery to controller

Battery Selection Procedure

- 1. Determine the number of days storage
  - Depending on whether the load is noncritical or critical
- 2. Determine the amount of storage required in A-h
  - This is the product of the corrected A-h per day and the number of days of storage required.
  - May vary with season

Battery Selection Procedure (continued)

- 3. Determine the allowable level of discharge
  - Divide the required A-h by the allowed depth of discharge
  - This results in the total corrected A-h required for storage
- 4. Check to see if whether an additional correction for discharge rate will be needed.
  - If so apply it to results of (3)

Battery Selection Procedure (continued)

- 5. Check to see whether a temperature correction factor is required
  - If so apply this to the results of (3) or (4)
- 6. Check to see whether the rate of charge exceeds the rate specified by the battery manufacturer.
  - If so multiply the charging current by the rated number of hours for charging
  - If this number is larger than (7) this is the required battery capacity

Battery Selection Procedure (continued)

- 7. Divide the final corrected battery capacity by the capacity of the chosen battery.
- 8. If more than 4 batteries are required in parallel, it is better to consider a higher capacity batteries to reduce the number in parallel to provide for better balance of battery currents

Array Sizing and Tilt Procedure

- 1. Determine the design current for each month of the year by dividing the corrected A-h load of the system each month by the monthly average peak sun hours at each array tilt angle
- 2. Determine the worst-case (highest monthly) design current for each tilt angle

Array Sizing and Tilt Procedure (continued)

- 3. For a fixed mount, select the tilt angle that results in the lowest worst case design current
- 4. If tracking mounts are considered, then determine the design current for one- and two- axis trackers.
- 5. Determine the derated array current by dividing the design current by the module derating factor

Array Sizing and Tilt Procedure (continued)

- 6. Select a module that meets the illumination and temperature requirements of the system as well as having a rated output current and voltage at maximum power consistent with system needs
- 7. Determine the number of modules in parallel by dividing the derated array current by the rated module current.
  - Round up or down as deemed appropriate

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Array Sizing and Tilt Procedure (continued)

- 8. Determine the number of modules in series by dividing the nominal system voltage by the lowest anticipated module voltage of a module supplying power to the system
  - It is almost always necessary to round up
- 9. The total number of modules is the product of the number in parallel and the number in series

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Applications

- Rural Electrification
- Water Pumping and Treatment
- Health Care System
- Communications
- Agriculture
- Transport Aids
- Security
- Corrosion Protection
- Satellite Power
- Miscellaneous

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Rural Electrification

- Lighting and power supplies for remote buildings
- Power supplies for remote villages
- Battery charging stations
- Portable power for nomads

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LED PV Lighting

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EETS Ltd. Hybrid Wind-Solar

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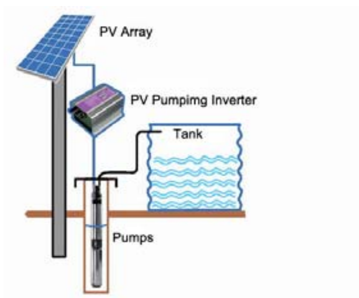
PV Lighting Virgin Islands

Water Pumping and Treatments Systems

- Pumping for drinking water
- Pumping for irrigation
- De-watering and drainage
- Ice production
- Saltwater desalination systems
- Water purification
- Water circulation in fish farms

PV pumping system



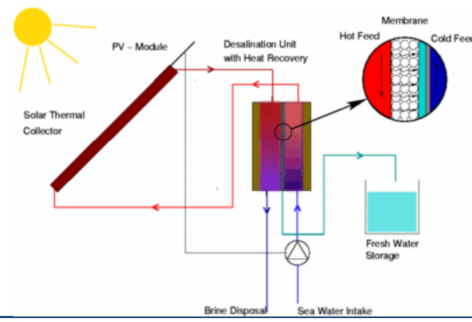
PV Drinking Water

PV Pumping Kit

PV Well

PV Cistern

PV Desalination System

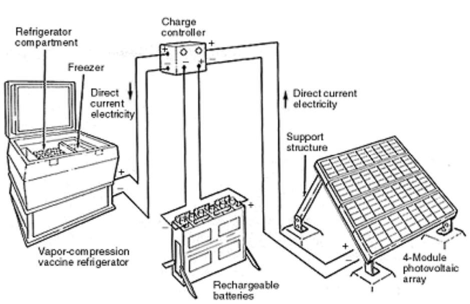


PV Desalination

Health Care Systems

- Lighting in rural clinics
- UHF transceivers between health centers
- Vaccine refrigeration
- Ice pack freezing for vaccine carriers
- Sterilizers
- Blood storage refrigerators

PV Vaccine Refrigerator Schematic



PV Vaccination Refrigerator

Communications

- Radio repeaters
- Remote TV and radio receivers
- Remote weather measuring
- Mobile radios
- Rural telephone kiosks
- Remote data acquisition and transmission
- Emergency telephones

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PV Communications

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PV Phone Booth (London)

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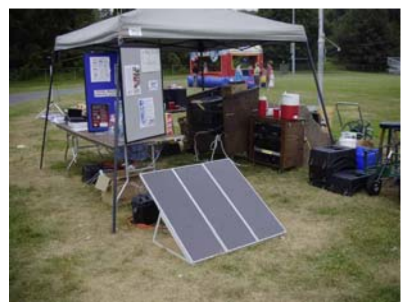
PV Ham Radio



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PV Repeaters

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PV Radios

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Agriculture

- Livestock watering
- Irrigation pumping
- Electrical livestock fencing
- Stock tank ice prevention

Livestock Trough

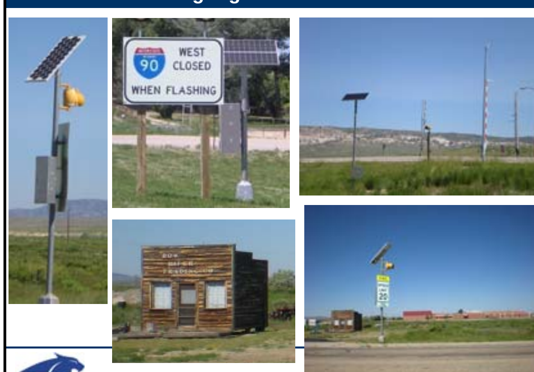
PV Well Sheep

Transport Aids

- Road sign lighting
- Railway crossing signals
- Hazard and warning lights
- Navigation buoys
- Fog horn
- Runway lights
- Terrain avoidance lights
- Road markers

PV Radar Speed Display

PV Road Warning Signs and Gates



PV Buoys


PV Railroad Cars?

Emergency & Security Systems

- Security lighting
- Remote alarm system
- Emergency phones

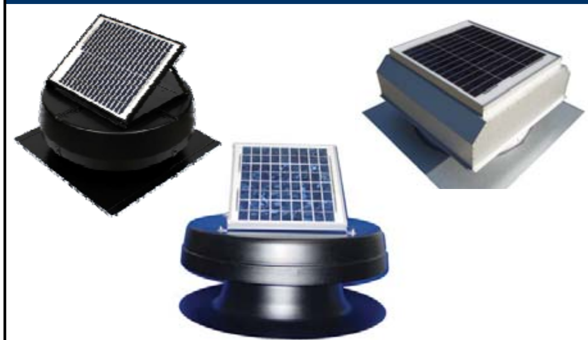
Corrosion Protection System

- Cathodic protection for bridges
- Pipeline protection
- Well-head protection
- Lock gate protection
- Steel structure protection

Miscellaneous

- Ventilation systems
- Camper and RV power
- Calculators
- Automated feeding system on fish farms
- Solar water heater circulation pumps
- Path lights
- Yacht/boat power
- Vehicle battery trickle chargers
- Earthquake monitoring systems
- Battery charging
- Fountains
- Emergency power for disaster relief
- Aeration systems for stagnant lakes

Solar Attic Fans



Solar Fan

Solar Calculators

Solar Flashlights

Solar Battery Chargers

Battery charges via USB or solar power

Solar Fountain

PV Aeration

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PV Solar Compactor

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Electric Power for Satellites

- Telecommunications
- Earth observations
- Scientific missions
- Large Space Stations

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PV Satellites

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PV Satellites

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Space Applications: Primary Power Source

- Are Solar Arrays the correct choice?
- Choice governed by:
  - Power level
  - Operating location
  - Life expectancy
  - Orientation requirements
  - Radiation tolerance
  - Cost
- What are the options?

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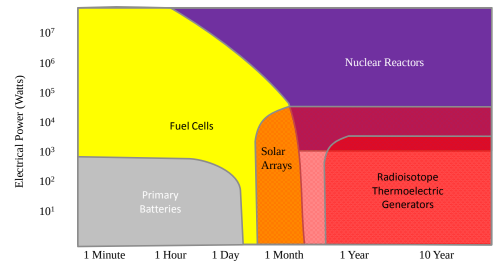
Operating Regimes of Spacecraft Power Sources



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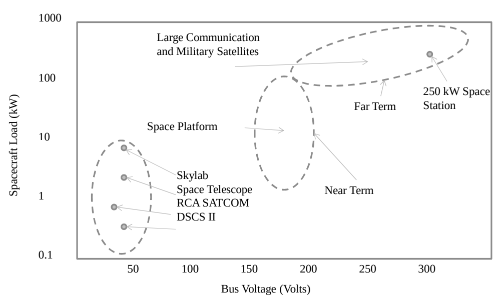
Trends in Spacecraft Power



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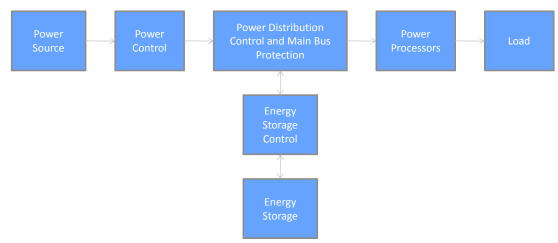
Power Subsystem Functional Block Diagram



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Power System Elements

- Power Source
  - Solar Voltaic
  - Radioisotope Thermoelectric Generator
  - Nuclear Reactor
  - Fuel Cells
  - Primary Batteries
- Source Control
  - Shunt Regulator
  - Series Regulator
  - Shorting Switch Array
- Energy Storage Control
  - Battery Charge Control
  - Voltage Regulator
- Power Conditioning
  - DC-DC Converters
  - DC-AC Inverters
  - Voltage Regulation

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Power System Design Considerations

- Customer/User
- Target Planet/Solar Distance
- Spacecraft Configuration
  - Mass Constraints
  - Size
  - Launch Constraints
  - Thermal Dissipation Capability
- Payload Requirements
  - Power type, current, voltage
  - Duty Cycle, Peak Loads
  - Fault Protection
- Lifetime
  - Total
  - % in various modes/power levels
- Attitude Control
  - 3 axis stabilized
  - Gravity Gradient
  - Pointing Requirements
- Orbital Parameters
  - Altitude
  - Inclination
  - Eclipse Cycle
- Mission Constraints
  - Maneuver Rates
  - G loads

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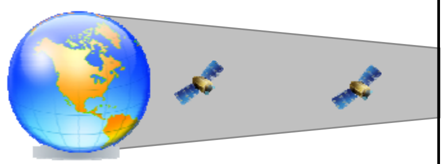
Eclipse Cycle



Batteries

- Charge Capacity
  - Total electric charge stored in the battery measured in ampere – hours (40A for 1hr = 40A-h)
- Energy Capacity
  - Total energy stored in the battery equal to the charge capacity times the average discharge voltage – measured in Joules or Watt – hours
- Average Discharge Voltage
  - Number of cells in series times cell discharge voltage (typically 1.25 V)
- Depth of Discharge (DOD)
  - Percentage of battery capacity used in the discharge cycle (75% DOD means 25% capacity remaining, DOD is usually limited to promote long cycle life)
- Charge Rate
  - Rate at which the battery can accept charge (measured in amperes per unit time)
- Energy Density
  - Energy per unit mass (J/kg or W-h/kg) stored in the battery

Primary Batteries

- Long installed storage required
  - Missiles in silos
  - Interplanetary missions
- Often dry without electrolyte prior to activation
  - Pyrotechnic valve fires to allow electrolyte to enter the battery from a separate reservoir
- Highly reliable quick reaction power source
- No maintenance
- Uses:
  - Activate pyrotechnic charges and other deployment devices
  - Electromechanical actuators and sensors that require isolation from other noisy circuits and power drains
- Most common type is Silver-Zinc

Secondary Batteries

- Rechargeable
- Generally has a lower energy density
- Limits on the depth of discharge and lifetime

Silver-Zinc (Ag-Zn)

- Commonly used in early space systems, still popular
- Good energy density
  - 175 W-h/kg – primary
  - 120-130 W-h/kg – secondary
- Limited cycle life
  - 2000, 400, 75 @ 25, 50, 75% DOD
- 1.5 V/cell

Silver Cadmium (Ag-Cd)

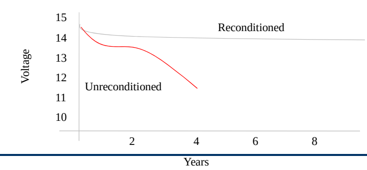
- Better cycle life than Ag-Zn
- Better energy density than Ni-Cd
- Fair energy density
  - 60-70 W-h/kg – secondary
- Limited cycle life
  - 3500, 800, 100 @ 25, 50, 75% DOD
- 1.1 V/cell

Nickel Cadmium (Ni-Cd)

- Most common secondary battery in use
- Good deep discharge tolerance
- Can be reconditioned to extend life
- Low energy density
  - 20-30 W-h/kg
- Long cycle life
  - 20,000, 3000, 800 @ 25, 50, 75% DOD
- 1.25 V/cell

NiCad reconditioning

- Reconditioning consists of a very deep discharge to the point of voltage reversal followed by a recharge under carefully controlled conditions
- Increases Battery Lifetime



Nickel Hydrogen (Ni-H_2)

- High internal pressure requires bulky pressure vessel configuration
- No reconditioning required
- Good energy density
  - 60-70 W-h/kg
- Long cycle life
  - 15,000, 10,000, 5000 @ 25, 50, 75% DOD
- 1.30 V/cell

Nickel –Metal Hydride (Ni-MH)

- Same chemistry as nickel-hydrogen
- Hydrogen adsorbed in metal hydride to reduce pressure
- Improved packaging relative to nickel-hydrogen
- Good energy density
- Limited cycle life
- 1.30 V/cell

Lithium Batteries

- Several Types:
  - Li-$SOCl_2$, Li-V_2O_5, Li-SO_2
- Both primary and secondary designs available
- Very high energy density
  - 650 W-h/kg, 250 W-h/kg, 50-80 W-h/kg
- Higher Cell Voltage
- 2.5 – 3.4 V/cell

Nominal Bus Voltage

- Most spacecraft systems flown to date have used 28 VDC as the Bus Voltage
- Satisfactory for relatively small low-powered spacecraft
- Higher voltage systems have become popular for larger spacecraft
  - Reduces current handling requirements of wire harness
  - Reduces weight of harness
  - Reduces resistive losses (heating) goes as current squared

Depth of Discharge Tradeoff

- Tradeoff between battery mass due to unused capacity and battery degradation and lifetime reduction due to repeated deep discharge
- Low-altitude, low inclination orbits have most severe usage due to eclipse on each orbit
  - Battery will be discharged and charged 12-16 times per day
  - 10,000 cycles in a few years
- Eclipse time as high as 40% of orbital period ~ 35 minutes

Depth of Discharge

$$DOD = \frac{\text{Energy required during eclipse}}{\text{Stored battery energy}}$$

$$DOD = \frac{P_L t_d}{C_{chg} V_{ave}} = \frac{P_L t_d}{E_{bat}}$$

$\mathrm{P_L}$ = Load power in watts

$\mathrm{t_d}$ = Discharge time in hours

$\mathrm{C_{chg}}$ = Charge capacitiy in ampere hours

$\mathrm{V_{avg}}$ = Battery average discharge voltage in volts

$\mathrm{E_{bat}}$ = Total battery energy capacity

Charge Rate

- Rule of thumb: $R_{chg} = \frac{C_{chg}}{15h} = I_{chg}$
- Charge rate also drives battery size
  - Power input level that is too high can result in overheating of the battery and if carried to extremes explosive destruction
- Trickle Charge:
- This is quite conservative higher charge rates may be acceptable, use manufacture's specifications as ultimate guide

$$R_{chg} = \frac{C_{chg}}{45h} = I_{chg}$$

Charge voltage

- Battery must be charged at a slightly higher voltage than V_{ave} or a full charge cannot be restored.
- Typically charging voltages are 20% higher than average discharge voltage
- This impacts solar array design

Example 1

- What is the required size of a NiCad battery to support a 1500 W payload in geostationary orbit?
- Given:
  - Bus Voltage 28 VDC
  - Peak Load 1500 W
  - Maximum Load Duration 1.2 h
  - Battery Energy Density 15 (W-h)/lb at 100% DOD
  - Average Cell Voltage 1.25 V
  - Maximum DOD 70%

Example 1: Solution

- Number of Cells: $N_{cell} = \frac{V_{bus}}{V_{cell}} = \frac{28}{1.25} = 22.4$
- Can choose either 22 or 23 cells
  - Selecting 22 saves mass and results in an acceptable bus voltage of 27.5 VDC
- Total Charge Capacity and Battery Energy Density:

$$C_{chg} = \frac{P_L t_d}{(V_{avg} DOD)} = \frac{(1500W)(1.2h)}{(27.5V)(0.7)} = 93.5(A-h)$$

$$E_{bat} = C_{chg} V_{avg} = (93.5A-h)(27.5V) = 2571(W-h)$$

$$\text{Battery Mass}: \frac{E_{bat}}{e_{bat}} = \frac{2571(W-h)}{15(W-h)/lb} = 171(lb)$$

Example 1: Solution (Cont.)

- It may be desirable to split battery into 2 or 3 individual battery packs for ease in packaging, placement, and balance
- Each battery pack must contain 22 series-connected cells to maintain proper voltage
- Redundancy management issues have been ignored.

Primary Power

- Solar Array
  - Viable choice out to Mars Orbit (1.5 AU)
  - Inverse-square law renders solar energy too diffuse to be useful
  - Concentrators may extend capability to a limited degree
  - Seriously degraded by extensive exposure to radiation

Example 2

- What is the size of a solar array to support a 1500 W load, plus a suitable level of battery charging (Example 1) if we assume 2 x 4 cm cells? How many are needed?
- Given:
  - Cell efficiency 11.5% @ 301 K
  - Maximum operating temp. 323 K
  - End of Life Degradation (10 yrs) 30%
  - Worst Case Sun Angle 6.5º off normal
  - Solar Intensity 1350 W/m^2 at 1 AU
  - Temperature coef. -0.5%/K (power)
  - Packing factor 90% (10% loss for spacing)
  - Battery capacity 90Ah

Example 2: Solution

- Array voltage must exceed battery voltage, rule of thumb 20%
- Battery Charging Power
- End of Life (EOL) Power is Load + battery charging power

$$V_{array} = (1.2)(V_{bat}) = (1.2)(27.5V) = 33(V)$$

$$P_{chg} = V_{chg} I_{chg} = V_{chg} R_{chg} = \frac{V_{chg} C_{chg}}{15h} = \frac{(33V)(90Ah)}{15h} = 198(W)$$

$$P_{EOL} = 1500W + 198W = 1698W \approx 1700(W)$$

Example 2: Solution (Cont.)

- Compensate for other lost efficiency factors
- Temperature:

$$\eta_{temp} = 1 - \frac{0.005}{K}(323K - 301K) = 1 - 0.11 = 0.89$$

- Radiation exposure:

$$\eta_{rad} = 1 - 0.3 = 0.7$$

- Incident angle:

$$\eta_{angle} = \cos(\theta) = \cos(6.5^\circ) = 0.9766$$

Example 2: Solution (Cont. 2)

- The End of Life Power is the result of applying the losses to the Beginning of Life array power

$$P_{EOL} = \eta_{rad}\eta_{temp}\eta_{angle}P_{BOL} = 1700W$$

$$P_{BOL} = \frac{1700W}{(0.7)(0.89)(.9766)} = 2794W \approx 2800W$$

Example 2: Solution (Cont. 3)

- Need to calculate the total cell area to produce the required power.
- Then calculate the array size that will produce the required cell area

$$P_{BOL} = \eta_{Si} I_S A_{cell} = (0.115)(1350W/m^2)A_{cell} = 2800W$$
$$A_{cell} = 18(m^2)$$

$$A_{cell} = \eta_{pack} A_{array} \Rightarrow A_{array} = \frac{A_{cell}}{0.9} = \frac{18m^2}{0.9} \approx 20m^2$$

Example 2: Solution (Cont. 4)

- Need to calculate the number of cells.
- Design array to hold the required cells

$$N_{cell} = \frac{A_{cell}}{Unit\ cell\ Area} = \frac{20m^2}{.02m \times .04m} = 25{,}000$$