

Photovoltaic Systems



- Central issues in photovoltaic systems
- Characteristics of energy systems & performance characteristics for PV
- Types of PV systems
- Overview of components

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Issues in PV Systems



- Central goal: understand how the interaction and match between the components affects the power produced, cost, and reliability of the PV system.
- Central issues
 - Match between components & losses in components
 - Large range in operating characteristics; variability in input resource, temperature.
 - Reliability of components: PV modules have 20+ year warranties, but what about other components.
 - Trade-off between performance, availability and cost
- Analysis of system and system design are critical

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Energy Systems



- Central issues in energy systems
 - Distribution
 - Costs
 - Reliability
- Current energy system:
 - Electricity (>99%) is generated by mechanical generators. Source of the mechanical energy varies: ~10% hydro, remainder mostly thermal → mechanical energy.
 - Load characteristics:
 - Peak load
 - Base line load

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Characteristics of PV Systems



- Parameters to judge system performance
 - Availability: fraction of time that load is available compared to time load is required.
 - Critical availability requires availability > 99%.
 - Availability of 95% for conventional applications.
 - Loss of load probability = LOLP = $1 - A$ (may also be called loss of power probability, LOPP)
 - Capacity Factor
 - The capacity factor is the ratio of the electrical energy generated, for the period of time considered, to the energy that could have been generated at continuous full-power operation during the same period.
 - The capacity factor is useful in comparing technologies and is a standard figure of merit in electricity generating systems.

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Characteristics of PV Systems



- Parameters to judge system performance
 - Reliability
 - Probability of a system being inoperable due to a breakdown
 - In general, mechanical systems introduce reliability issues.
 - Temperature a contributing factor in reduced reliability.
 - Operating and Maintenance
 - Different than reliability, & in many systems there is a trade-off between the two.
 - The cost of operating and maintenance can vary dramatically.

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Characteristics of PV Systems



- Parameters to judge system performance
 - Modularity and scalability
 - Together, these parameters determine the minimum effective system size.
 - Thermal-based systems are
 - PV systems are both modular and scalable.
 - Power Quality
 - Existing systems are primarily high voltage AC based. Power quality refers to match to a sine wave, voltage within specified limits.

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Characteristics of PV Systems



- Parameters to judge system performance
 - Impact on environment and other system
 - Impact can be quantified by “externalities”
- Cost
 - Initial cost
 - Operating cost
 - Lifecycle cost

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- System performance parameters (con't)
 - Peak Power/Energy ratio: units of W_p / Wh .
 - The W_p is the rating of the array, and the watt-hours is the energy produced during a given time period (usually yearly)
 - Peak Power/Energy rating is substantially a measure of location and array parameters.

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- System performance parameters (con't)
 - Efficiency: Power out/Power in:
 - Central question is at what time and under what conditions.
 - Efficiency: Energy out/Energy In
 - Includes realistic losses and variety of conditions
 - Need to justify time period over which system is measured.
 - Used Solar Fraction:
 - Total amount of the incident solar energy which is used by the load.
 - Cost: both initial cost and lifecycle cost.
 - Average battery state of charge (BSOC)
 - Useful indicator for the life of the batteries (which will in general be the most likely failure point).

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- System performance parameters (con't)
 - Array to load ratio
 - Losses
 - Generation Losses. Loss mechanisms that reduce the power generated by the PV panels from that available under test conditions (AM1.5 at room temperature) are considered generation losses.
 - Component Losses. Any losses in the components themselves, such as the inverter or the battery bank, are categorised as component losses. Many of these losses are covered in individual sections
 - Mismatch Losses Mismatch losses can account for the most significant losses to the power generated by a PV system.
 - Usage Losses

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- Losses due to electrical losses in components: efficiencies of power conditioning, batteries, wiring, etc
- Losses in loads themselves: may not be included in design calculations unless designer also has some input into or control over load.
- Fraction of losses:
 - Losses/Energy Generated
 - If this is calculated, it is a good measure of the mismatch losses in the system, and a useful design parameter
 - Energy used by load/generated by system
 - Similar to losses/generated, but would include losses due to inability to use incident sunlight.
- Specific applications may also have other performance indicators or may use only a subset of these indicators
 - Eg: availability not a useful in residential grid connected PV system.

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PV Systems



- Several types of modes for operating a PV system.
 - Centralized power plant
 - Large PV system located in an optimum location, feeding into the grid.
 - Distributed grid-tied
 - System such as residential PV systems
 - Stand alone systems

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System configurations



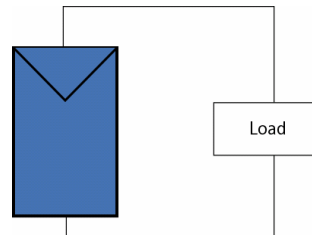
- Types of Systems
 - Direct-coupled PV system:
 - DC PV system with storage
 - DC-AC PV systems
 - Hybrid PV systems
 - Grid-connected PV systems
- Increasing components in a system decreases reliability due to component failure, increases the losses due to inefficiencies in components, but in generally significantly improves the match between various components.
- Adding additional power sources increases the availability and increases fraction of solar power used.
- Increasing components increases cost of a system, but generally reduces the cost to achieve a given availability.

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System configurations



- Direct coupled DC system:
 - Simplest type of system.
 - Low cost, due fewer additional components required.
 - Reliability can be very high.
 - Ability to use direct coupled system depends on:
 - Match between load and solar resource or ability to tolerate low availability
 - Tolerance of load to range of input voltage and currents.
 - Load must have DC as input
 - Examples: some home power systems, direct drive application including water pumping and ventilation systems.

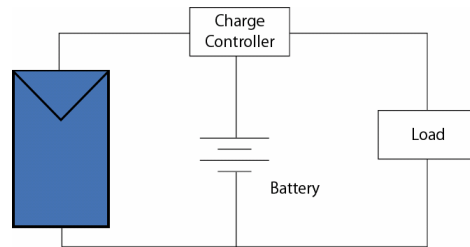


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System configurations



- DC Photovoltaic System:
 - Traditionally most common type of system, still extensively used in smaller systems or specific purpose systems.
 - Requires all DC appliances, but efficiency of DC appliances may be higher than that of conventional appliances.
 - Requires different wiring, connector, fuses, and built to different set of standard.
 - In most cases, charge controller (which may be parallel or series) as well as battery included. Use of a power point tracker depends on load and system.
 - High voltage DC connections and wiring requires caution.
 - Examples: specific use industrial systems, small home power systems.

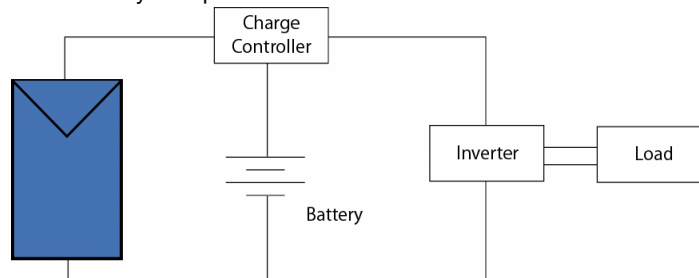


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System configurations



- DC-AC system with storage.
 - Most flexible system: can use any appliance at any time.
 - Now uncommon to include a DC load –usually just AC.
 - Efficiency depends on other components used in system.
 - Maximum power point trackers increase efficiency
 - Efficiency of batteries and inverters (including operating point of inverters) affects system performance.

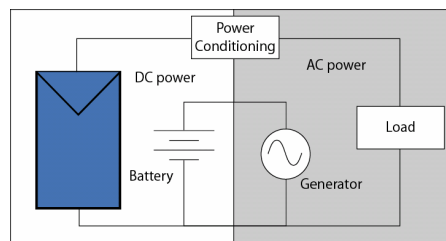


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System configurations



- Hybrid: AC system alternate generating system (usually diesel generator).
 - Diesel only-system performs poorly under part-load conditions, both from efficiency and maintenance standpoint.
 - Addition of batteries reduces requirement to run generator under part load conditions.
 - Addition of solar (or other small generating source) reduces need for diesel.
 - Get high availability system, in which large fraction of solar resource is used.
 - Examples: stand alone home/village systems.

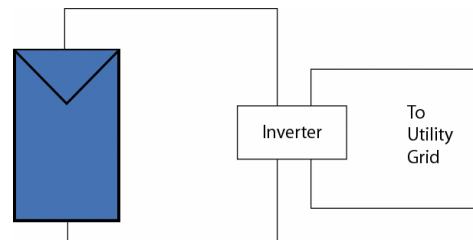


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System configurations



- Grid connected systems:
 - No storage included in systems: when PV system generates, power is either used locally at generation source or fed into the grid.
 - Inverter design must be substantially different for grid-connected systems in order to meet power quality requirements and safety requirements of utility.
 - Key concern is that PV system continues to power grid, causing safety hazard (called islanding).
 - Several types of grid connected systems:
 - Residential PV
 - Building integrated PV
 - Utility-scale PV

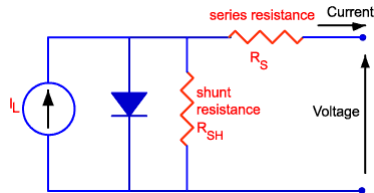


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System Components



- Match between components: equivalent circuit of all components
- Solar cell: diode and current source
- Battery: Voltage source, in which the voltage depends on temperature (and past history of battery)
- Inverters: efficiency dependent of power which they convert

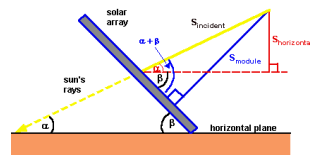


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- Losses in the system compared to generated.
 - Losses in system:
 - Losses in incident radiation due to optical losses and angular losses.

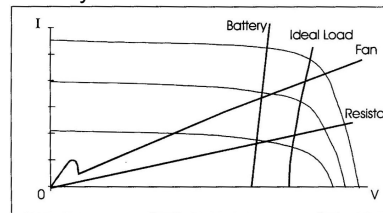
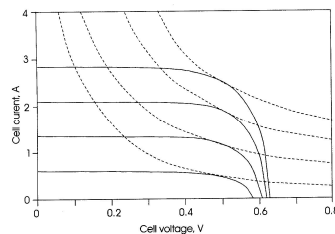


$$S_{horizontal} = S_{incident} \sin(\alpha)$$

$$S_{module} = \frac{S_{horizontal} \sin(\alpha + \beta)}{\sin(\alpha)}$$

$$S_{module} = S_{incident} \sin(\alpha + \beta)$$

- Losses due to operating point of solar array



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- Losses due to temperature (usually calculated separate from design):
 - Solar cells lose power as they increase in temperature

$$\frac{1}{P_m} \frac{dP_m}{dT} \approx -(0.004 \text{ to } 0.005)/^\circ C \text{ for Si}$$

- The operating temperature depends on the ambient temperature, the incident solar radiation, and the temperature loss mechanisms of thermal conduction, convection and radiative cooling.

Thermal conduction $H = \kappa \frac{A}{L} \Delta T$ κ is the thermal conductivity in $W \cdot m^{-1} \cdot Kelvin^{-1}$, T is the temperature differential across some distance L , A is the surface area

Convection $Q = -hA(T_{surf} - T_{amb})$ h is the heat transfer coefficient in $W \cdot m^{-2} \cdot Kelvin^{-1}$, the T 's are the temperatures at the surface and ambient, A is the surface area

Radiative $H = \epsilon \sigma (T_{obj}^4 - T_{amb}^4)$ ϵ is the emissivity (number), σ is the Stefan-Boltzmann constant, and the T 's are the temperature of the object and ambient

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Variability in Solar Resource



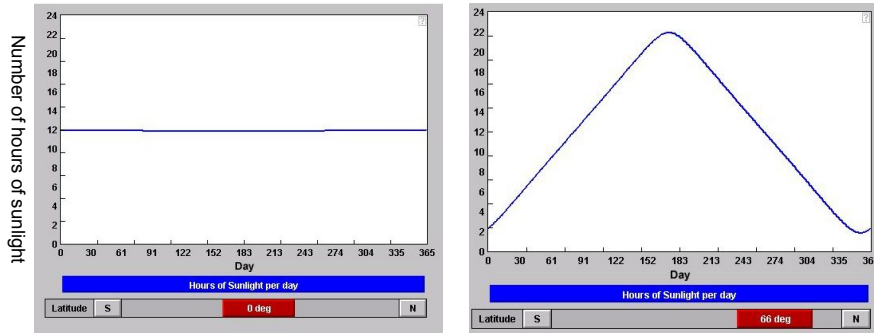
- Impact of variability in solar resource
 - A key element in renewable energy systems is the design of one component that has inherent variation (the solar resource) to drive another component (the load) in which the variation should be minimized as much as possible.
 - The larger the variation in the resource compared to the load, the more difficult the trade-offs.
 - Some loads have a match to solar resources, but often higher loads are encountered in months with lower solar insolation.
 - Large variation in solar radiation means that in order to get higher availability, the system has:
 - a lower solar fraction
 - a substantial storage component.
 - Higher cost.

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Variability in Solar Resource



- Variability due to latitude:
 - Every latitude has on average 12 hours of sunlight, ignoring local cloud cover, etc.
 - High latitude locations have a larger variation in peak sunlight hours between summer and winter.

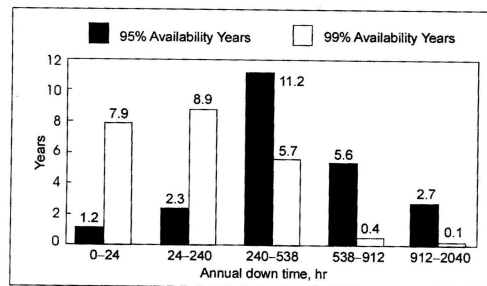


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Variability in Solar Resource



- Variation in photovoltaic systems due to solar resource (con't):
 - Climate: The pattern on the solar resource, as well as the average available depends on the local climate.
- Impact of variability:
 - Design is statistical – 99% availability does not mean that the system will give power 99% of time every year.



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System Design



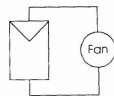
- System Design:
 - Goal is to produce a system within specified cost and power, choosing among trade-offs between availability, the fraction of solar used and system losses.
 - Key trade-off between tilt angle, battery capacity and array size arises from seasonal variability in load.
 - Simplest design:
 - power from array over year = load over year + losses; array tilt = latitude; battery capacity = # cloudy days in a row × load
 - This approach does not work – in most cases, periods with reduced insolation do not have reduced loads, and it is not realistic to make battery capacity such that it stores power generated in summer to be used in winter.
 - Instead, either the array or the battery must be over designed for (usually) summer use to meet availability needs during low insolation periods, meaning substantial power is lost during high insolation periods.
 - Increasing battery size means less over design of PV system, and vice versa.

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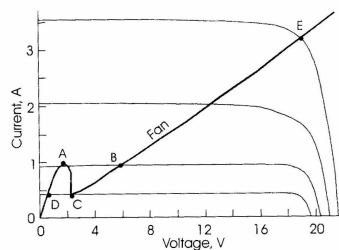
Loads



- Motor Loads:
 - Iron cores or magnetic components in motor loads make them sensitive to harmonic and DC components (affecting choice of inverter)
 - DC component will be dissipated in wire or core (if motor/transformer not design to use DC), causing heating.
 - Motor loads may have different load conditions of start-up that they do when running, requiring higher current on start-up.



a. Connection



b. Operating characteristics of fan and PV

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Photovoltaic Systems



- Types of design procedures:
 - Several different types of design procedures, depending on availability of radiation data and time period over which calculations are performed.
 - 1. “Rule of Thumb”: Determine feasibility/select system topology: rough calculations, no specific location dependant parameters, and usually no comparison, iteration or checking.
 - 2. Worst Month Calculations
 - 3. Time-based simulations, usually hourly, but could also be daily, using detailed solar radiation data and suited to examining battery state of charge. These are usually computer-based.

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1. Rough Design Procedure



- No battery sizing or tilt angle calculations and just calculate rough estimate of array size.
 1. Calculate average load, L in Watts, or the total daily load, D, in Wh
 - For a continuous running load, the load is the average load.
 - Calculate D from appliances ratings or by comparing to similar situations, and then $L = D/24$
 2. Calculate average power need from array.
 - Average load is used for 24 hrs
 - Increase load to account for electrical losses in inverter, batteries, power controller, wiring losses, etc.
$$\text{Power needed (Wh)} = \frac{24L \text{ (Wh)}}{\eta_{\text{batt}} \eta_{\text{inverter}} \eta_{\text{other}}}$$
 - $\eta_{\text{batt}} \approx 0.85$, $\eta_{\text{inverter}} \approx 0.9$, $\eta_{\text{other}} \approx 0.95$

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1. Rough Design Procedure



3. Calculate energy from x Watts of installed photovoltaic power:

$$\text{Power generated (Wh)} = xW \times \text{sunhr} \times \eta_{temp} \times \eta_{opt} \times \eta_{mismatch}$$

For latitudes 20° - 50°, average sunhrs = 6.5 hrs

$$\eta_{temp} \approx 0.9, \eta_{optical} \approx 0.95, \eta_{mismatch} \approx 0.95.$$

4. Calculate amount of installed power needed.

- Power generated must equal power needed by load.

$$\text{Power generated (Wh)} = \text{Power need from load (Wh)}$$

$$xW \times \text{sunhr} \times \eta_{temp} \times \eta_{opt} \times \eta_{mismatch} = \frac{24L \text{ (Wh)}}{\eta_{batt} \eta_{inverter} \eta_{other}}$$

$$x = 6.2L \text{ Watts} \quad \text{Need about 6 times the amount of photovoltaic panels as a continuous load.}$$

1. Rough Design Procedure



- Can find a similar relationship between the needed Watts of PV and the total daily load, D, giving that the amount of PV needed in Watts is the total daily load divided by 4.

$$xW = \frac{D \text{ (Wh)}}{\text{sunhr} \eta_{temp} \eta_{batt} \eta_{temp} \eta_{inverter} \eta_{other} \eta_{mismatch}} \approx \frac{D}{4}$$

- This approach can be tailored to a specific case by putting in known numbers for efficiency and sunhours.
 - In calculations here have used optimum numbers.
- Uses of rough design procedure
 - Get an answer quickly, minimal calculations
 - As this does not include losses due to oversizing to accommodate lower insolation, it can be viewed as an minimum array size.
- Disadvantages:
 - Not a “design” methodology – no trade-offs, no tilt angle calculations, no battery calculations.

2. Worst Month Calculations



- Worst month calculations use specific load and solar radiation data, but only use averages of solar radiation. This ignores the day-to-day variability that determines battery size (and availability), which must then be determined by other means.
- Advantages: very simple calculations and short, simple input data – can calculate by hand, no need for large data sets or computers.
- Disadvantages:
 - No inherent inclusion of statistical analysis of battery systems.
 - If only calculating a one month calculations, then possibility exists for unexpected consequences for other months.

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2. Worst Month Calculations



- Generally calculate system in Amp-hr rather than Watt-hr: Most losses in the system are voltage losses.
 - De-rate current by ~10% to account for reductions in current due to dirt, etc.
 - When converting from Wh to Ah, must use the same system voltage throughout.
- Variations of worst-month approaches, related to how to pick battery. Approaches are:
 - Size the array to meet load during worst month, and then pick battery size based on experience, availability curves, etc.
 - Statistical design of battery size.

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2. Worst Month Calculations



- Average monthly or worst month calculations:
 1. Make initial choice about system topology
 2. Calculate load for each month of the year in Ah.
 - The voltage used in these calculations must be the same as the system voltage
 - Increase load by dividing by battery, inverter, power conditioning efficiency.
 3. Pick a tilt angle, or calculate for several tilt angles.
 - For initial guess, look at load and pick tilt angle that maximized solar radiation on array during month in which load is highest.
 - Array = latitude gives overall maximum power: Constant load or slightly higher load in summer
 - Array = Latitude + 15°: Suited towards winter loads
 - Array = Latitude – 15° : Suited towards summer loads.

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2. Worst Month Calculations



4. Get solar radiation data on chosen tilt angle.
 - a) Find declination angle for mid-point of month (watch for radians vs degrees)

$$\delta = 23.5^\circ \sin B \quad B = \frac{2\pi}{365}(NDY - 81)$$

- b) Find elevation angle at solar noon

$$\alpha = 90^\circ \pm (\phi - \delta) \quad \pm \text{accounts for different hemispheres.}$$

- c) Convert average monthly radiation on horizontal to solar radiation on module.

$$S_{\text{module}} = \frac{S_{\text{horizontal}} \sin(\alpha + \beta)}{\sin(\alpha)}$$

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2. Worst Month Calculations



5. Find total current needed from array.

$$\text{Array current} = \frac{\text{Load (Ah)}}{S_{\text{module}} \text{ Sun Hours (hr)}}$$

6. Find number of panels needed in parallel.

$$\# \text{ Panels} = \frac{\text{Array Current (A)}}{\text{Current from pannel} \times 0.9 \text{ (A)}}$$

- Current from panel is found by looking on manufacturers data sheet at maximum power point current.
- Current from panel is at maximum power point and is de-rated (in this case 10%) to account for reduction in current due to dirt, etc.

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2. Worst Month Calculations



7. Find total number of panels in series to meet system voltage requirements.

- Need to account for
 - Temperature drops due to operating temperature as opposed room temperature, at which module power is usually specified.
 - Diode drops.
 - Changes in battery voltages due to temperature (unless maximum power tracker included).
 - Battery voltage needs to be above 12V (should be ~14V) for a nominally 12V system.
- Total number of panels is number in series.
- Total number of panels = # series \times # parallel

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2. Worst Month Calculations



8. Find battery size.

- Estimate number of days autonomy from statistical analysis of radiation data, existing systems, etc.
- Make a guess as to type of battery to be used
- Determine depth of discharge (DOD) for battery from manufacturers data sheets or estimate from type of battery.
- Determine battery capacity in Ah

$$\text{Battery Capacity (Ah)} = \frac{\text{Load (Ah)} \times \text{Days Autonomy}}{\text{DOD}}$$

- The load in the above equation is the “corrected” load which takes into account battery, inverter inefficiencies

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2. Worst Month Calculations

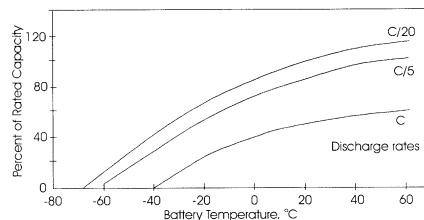


8. Find battery size (con't)

Find total number of batteries:

$$\text{Number Batteries} = \frac{\text{System Voltage (V)} \times \text{Battery Capacity (Ah)}}{\text{Battery Voltage (V)} \times \text{Rated Battery Capacity (Ah)}}$$

- Battery voltage and rated battery capacity are determined from manufacturers' data
- Check and adjust if necessary battery capacity based on temperature, discharge rates, and also make sure make sure battery is used according to specifications.



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2. Worst Month Calculations



9. Specify other parameters.

- Charge controller: handle maximum current and power from array, suited to type of batteries.
- Inverter: Rated power should be just under typical load: Check possibility for peak load.
- BOS components: meet specifications and standards.

10. Check that system makes sense or check for other options.

- Is stand-alone choice and type of power reasonable.
- Tracking: if more than one month has low solar radiation, then tracking may prove useful, but if the month with the lowest insolation is used to calculate the tilt angle, then tracking does not provide a benefit.

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Battery Sizing & LOLP



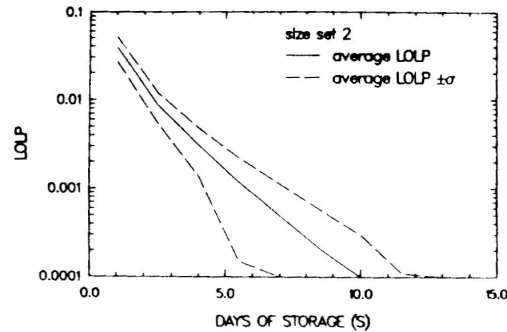
- Loss of load probability (LOLP) for a system in which the array can meet the load & battery charging loads is determined by the number of days storage.
- The number of days storage can be determined by examining the probability of having a certain number of number of cloudy days (< 50% radiation) in a row.
 - Example: probability of having 5 cloudy days in a row is 3%: If battery sized to give 5 days power for load, then LOLP =3% or A = 97%.
 - Assumes that array will recharge battery to a full level before another cloudy period comes (tends to underestimate battery size needed).
 - Ignores the power available to the array during the cloudy days (tends to underestimate the power available and overestimate battery size).

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Battery Sizing & LOLP



- By using such a statistical analysis of the solar radiation, an estimate of the LOLP probability can be included in worst month calculations without requiring daily or hourly system performance calculations.
- Result of analysis is plots that give LOLP as a function of the number

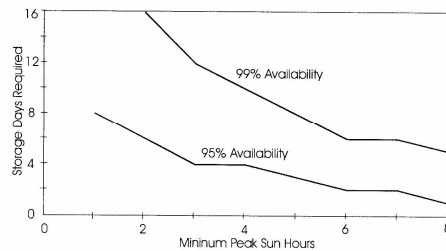


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Battery Sizing & LOLP



- If the plots of days storage and LOLP need to be calculated for each location, then it reduces the utility of simple worst-month calculations.
- However, for a given latitude range, the average number of peak sun hours is correlated to the number of cloudy periods. These in turn tend to have similarly shaped probability functions.
- Means that many locations will behave similarly, and hence plots relating LOLP, average sun hours, and battery storage can be determined.
- If a location has a weather pattern in which # cloudy days not well correlated to average radiation (eg, monsoon), cannot necessarily use generalized plot, but need to calculate LOLP based on analysis of the radiation for that type of climate.



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3. Hourly based PV simulation



- Computer-based calculations
 - Computer allow daily variations in radiation data, and hence allow impact of variation on system design.
 - Accuracy of design in general limited by statistical nature of radiation and inability to predict relevant parameters.
 - Accuracy of computer simulations does not typically limit the system performance, and hence many programs have simple models for temperature dependant, matching and losses that depend on the operating point of the array or batteries.
 - Programs generally restricted to battery/array/tilt trade-offs, and sometimes cases life cycle costing – the specification of other system components, temperature effects, etc still needs to be done and checked.
 - Should perform sensitivity, LCC on system.

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3. Hourly based PV simulation



- Daily simulations require larger set of input specifications and more detailed output specifications.
- Inputs into design process.
 - Location (solar radiation data, including potentially temperature, wind, etc)
 - Load profiles (including potentially effects of small load, surge currents, etc)
 - Specifications of components (Battery efficiency, impact of temperature on battery specs, inverter efficiency curves)
 - Design goals: Should be clear is goal is to have maximum availability, low cost, etc.
- Outputs
 - Array size and tilt angle, type of solar panel, average operating temperature.
 - Other components: battery charger, maximum power tracking, inverter, wiring, generator, etc.
 - Numerical specification of system according to design goals.
 - Documentation, maintenance schedules etc.

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3. Hourly based PV simulation



- Calculations generally follow similar approach to worst month calculations, but on an hourly basis.
 - Calculate solar radiation
 - Calculate radiation on tilted surface and power generated by array. Since done on hourly basis, often use energy flows in Ahr.
 - Determine where energy from array goes: battery, load, lost.
 - Determine where load draws power from: array, battery, or load not powered.
 - Determine BSOC.
 - Calculation system performance indicators (availability, solar fraction used, cost, etc)
 - Vary tilt angle, array size, battery capacity until optimum reached.
- In addition, must calculation life cycle costs, temperature effects, sensitivity to design parameters, other features as required by specifications.