L19
part 2

L11-part 2
PV System Sizing and Design
(Standalone Systems)

Sizing Standalone Systems

- Stand-alone PV systems are designed to power **specific on-site loads**, so the size of these systems is directly **proportional to the load** requirements.
- If the system is too small, there will be losses in load availability and system reliability.
- If the system is too large, excess energy will be unutilized and wasted.
- Therefore, sizing of stand-alone systems requires a fine balance between energy supply and demand.
- Because of this necessary balance, sizing stand-alone systems requires more analysis and calculations than are required for interactive systems.
- Most of these calculations build upon one another as the analyses proceed.
- Moreover, sizing stand-alone systems is an iterative process.
- That is, if the final calculations indicate that the components are improperly sized, the starting values must be changed and the calculation process repeated until the system output matches the load requirements

Sizing Standalone Systems

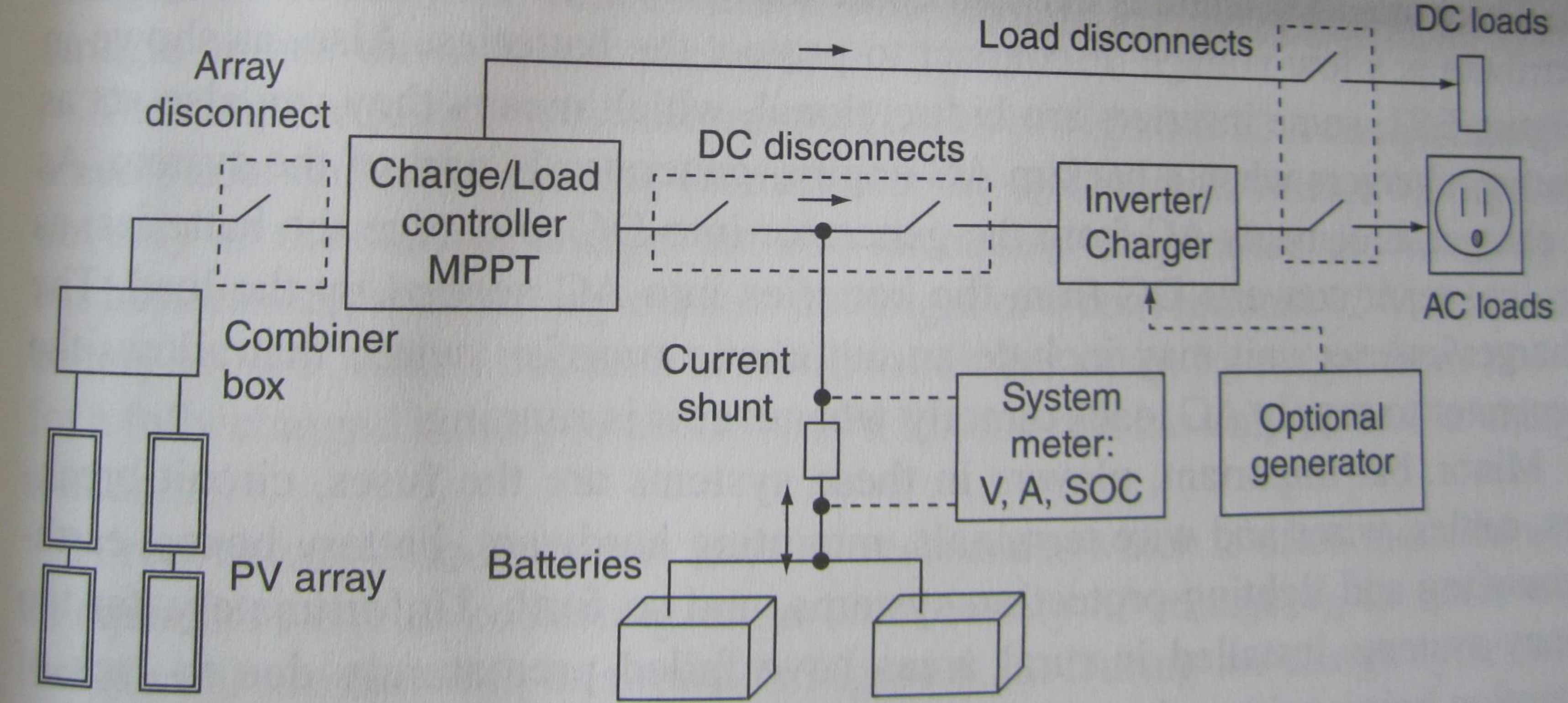


FIGURE 6.21 A "one-line"diagram of the important components in a stand-alone PV system.

Sizing Calculations –Standalone system

- Sizing PV systems for stand-alone operation involves four sets of calculations.

➔ **First, a load analysis** determines the electrical load requirements.

➔ Then, **monthly load requirements** are compared to the local insolation data to determine the critical design month.

➔ Next, the battery bank is sized to be able to independently supply the loads for a certain length of time, such as if cloudy weather educes array output.

➔ Finally, the PV array is sized to fully charge the battery bank under the critical conditions

Load Analysis

- Analyzing the electrical loads is the first and most important step in PV-system sizing.
- The energy consumption dictates the amount of electricity that must be produced.
- All existing and potential future loads must be considered. Underestimating loads will result in a system that is too small and cannot operate the loads with the desired reliability.
- However, overestimating the load will result in a system that is larger and more expensive than necessary.
- Comprehensive yet conservative load estimates will ensure that the system is adequately sized.

Load Analysis

- A load analysis tabulates the various kinds of loads and their power and electrical-energy requirements.

Load Analysis

LOAD ANALYSIS

Month:

AC LOADS

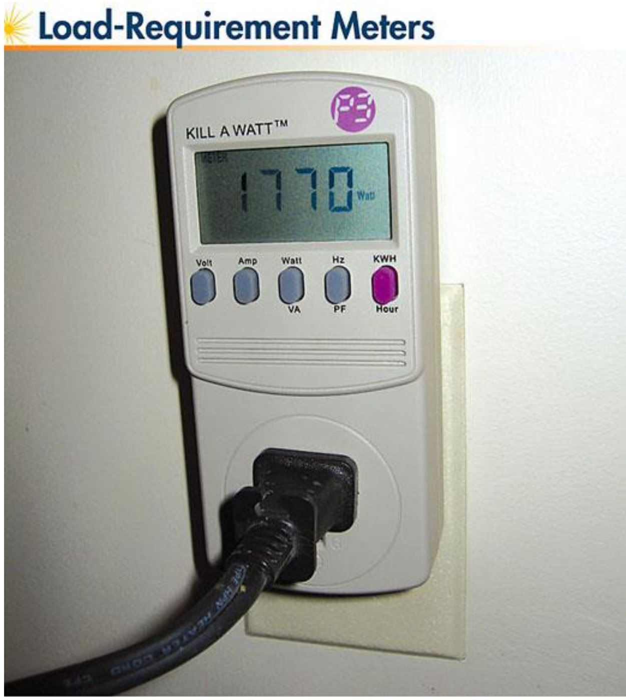
Load Description	Qty	Power Rating (W)	Operating Time (hr/day)	Energy Consumption (Wh/day)

DC LOADS

Total AC Power		W
Total DC Power		W
Total Daily AC Energy Consumption		Wh/day
Total Daily DC Energy Consumption		Wh/day
Weighted Operating Time		hr/day
Inverter Efficiency		
Average Daily DC Energy Consumption		Wh/day

Power Demand

- Peak-power information is usually found on appliance nameplates or in manufacturer's literature.
- When this information is not available, peak power demand can be estimated by multiplying the maximum current by the operating voltage, though this is less accurate for reactive loads.
- Measurements, meter readings, or electric bills may also be used to help establish existing load requirements.

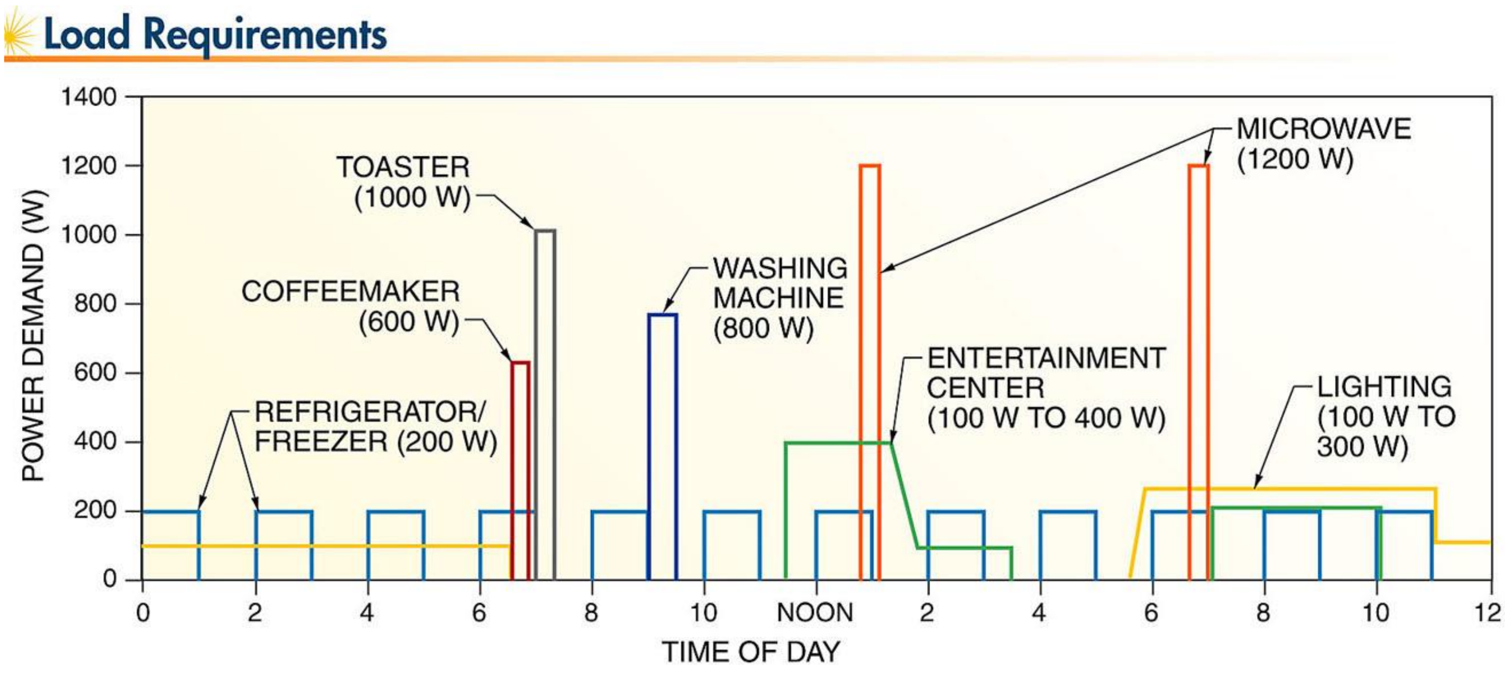


Power Demand & Energy Consumption

- The peak power demands are then summed.
- **The total power demand is considered when determining the required inverter AC-power output rating.**
- **While it is not likely that every load would be ON at the same time, it is recommended to size the inverter with extra capacity.**
- Electrical energy consumption is based on the power demand over time.
- **Loads rarely operate continuously, so each load's operating time must be determined. This is the total number of hours per day that the load is operating.**

Power Demand & Energy Consumption

- Load requirements include the power demand and electrical-energy consumption for all the expected loads in the system



Operating time

- The battery-bank discharge rate will change as various loads turn ON and OFF during the day.
- In this case, a weighted average operating time (t_{op}) is calculated using the following formula:

$$t_{op} = \frac{(E_1 \times t_1) + (E_2 \times t_2) + \ldots + (E_n \times t_n)}{E_1 + E_2 + \ldots + E_n}$$

- E_1 = DC energy required for load 1 (in Wh/day)
- t_1 = operating time for load 1 (in hr/day)

Operating Time

- **For example, one DC load uses 2400 Wh/day and operates for 4 hr and another DC load uses 1000 Wh/day and operates for 7 hr.**
- What is the weighted average operating time?

$$t_{op} = \frac{(E_1 . t_1) + (E_1 . t_1)}{E_1 + E_2}$$

$$t_{op} = \frac{(2400 x 4) + (1000 x 7)}{2400 + 1000}$$

$$t_{op} = 4.9 hr / day$$

- The two loads have a combined effect of a single 694 W load operating for 4.9 hr/day [(2400 Wh + 1000 Wh) / 4.9 hr = 694 W].
- **If the system includes both AC and DC loads, the AC load energy requirement must be first be converted to equivalent DC energy. This is done by dividing each AC energy consumption amount by the inverter efficiency.**

Inverter Selection

- If the system includes AC loads, an inverter must be selected.
- Several factors must be considered when selecting the inverter.
- **First, the inverter must have a maximum continuous power output rating at least as great as the largest single AC load.**
- A slightly oversized inverter is usually recommended to account for potential future load additions.
- **The inverter must also be able to supply surge currents to motor loads, such as pumps or compressors, while powering other system loads.**

Example

$$E_{SDC} = \frac{E_{AC}}{\eta_{inv}} + E_{DC}$$

where

E_{SDC} = required daily system DC electrical energy (in Wh/day)

E_{AC} = AC energy consumed by loads (in Wh/day)

η_{inv} = inverter efficiency

E_{DC} = DC energy consumed by loads (in Wh/day)

For example, if a load analysis determines that a system requires 800 Wh/day for the AC loads and 200 Wh/day for the DC loads and the inverter efficiency is 90%, what is the daily DC electrical energy required by the system?

$$E_{SDC} = \frac{E_{AC}}{\eta_{inv}} + E_{DC}$$

$$E_{SDC} = \frac{800}{0.90} + 200$$

$$E_{SDC} = 889 + 200$$

$$E_{SDC} = \mathbf{1089\ Wh/day}$$

Critical Design Analysis

- A stand-alone system must produce enough electricity to meet load requirements during any month.
- **Therefore, systems are sized for the worst-case scenario of high load and low insolation.**
- A critical design analysis compares these two factors throughout a year, and the data for the worst case is used to size the array.
- **The *critical design ratio* is the ratio of electrical energy demand to average insolation during a period.**
- The load data comes from the load analysis, which is usually performed for each month.
- The insolation data is available from the solar radiation data sets. (or can be estimated for any given location based on previous lectures).
- The ratio is calculated for each month.

Critical Design Month

- **The *critical design month* is the month with the highest critical design ratio.**
- This is the worst-case scenario, and the associated load and insolation data are used to size the rest of the system.
- If the loads are constant over the entire year, the critical design month is the **month with the lowest insolation** on the array surface.
- For most locations in the Northern Hemisphere, this is a winter month, either December or January.
- However, when the load requirements vary from month to month, the critical design month must take into account both the loads and the available insolation.
- Because of these two factors, the critical design month may turn out to be any month of the year.

Critical Design Month

- Sizing for the critical design month typically results in excess energy at other times of the year.
- If this excess is significant, the system designer may want to consider adding diversion loads or changing to a different system configuration, such as a hybrid system, that better matches the available electrical energy to the loads.

Array Orientation

- Since array orientation has a significant effect on receivable solar radiation, array orientation must also be accounted for in a critical design analysis.
- If the mounting surface restricts the array to only one possible orientation, then the analysis is conducted to determine the critical design factors for that orientation.
- However, if multiple orientations are possible, separate analyses are performed for each orientation. A critical design month can be identified for each of the array orientations, since the receivable solar radiation will be different for each.
- Of the resulting critical design months, the one with the smallest design ratio is the best choice.

Array Sizing

- The orientations most commonly used in a critical design analysis are tilt angles equal to the latitude, latitude +15°, and latitude-15°, each at an azimuth of due south.
- **The greater array tilt angle maximizes the received solar energy in winter months, and the smaller array tilt angle maximizes the received solar energy in summer months.**
- For azimuth angles other than due south, the insolation data must be adjusted to obtain the most accurate results.
- **Computer models are available to predict average monthly insolation for alternate orientations**.

- A critical design analysis compares the load requirements and insolation for each month to determine the critical design month.

Critical Design Analysis

CRITICAL DESIGN ANALYSIS

Month	Average Daily DC Energy Consumption (Wh/day)	Array Orientation 1		Array Orientation 2		Array Orientation 3	
		Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio
January							
February							
March							
April							
May							
June							
July							
August							
September							
October							
November							
December							

Critical Design Month

Optimal Orientation

Average Daily DC Energy Consumption **Wh/day**

Insolation **PSH/day**

DC-System Voltage

- The DC-system voltage is established by the battery-bank voltage in battery-based systems.
- This voltage dictates the operating voltage and ratings for all other connected components, including DC loads, charge controllers, inverters, and (for battery-based systems) the array.
- DC voltage in battery-based systems is critically important.
- The DC voltage for battery- based PV systems is usually an integer multiple of 12 V, usually 12 V, 24 V, or 48 V.

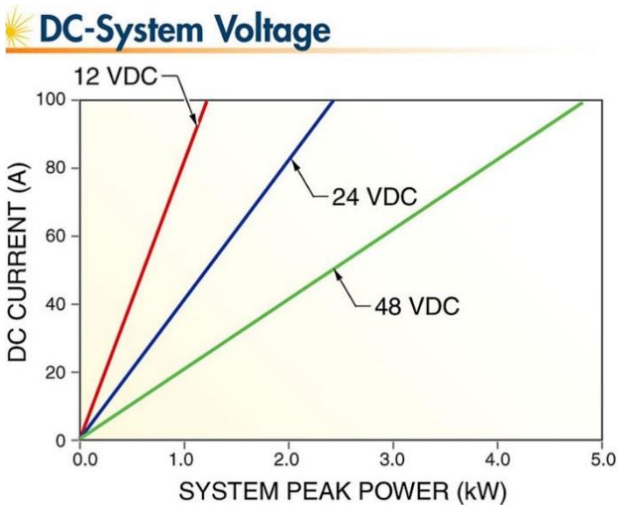
DC-System Voltage

- The selection of the battery-bank voltage affects system currents
- **For example, a 1200 W system operating at 12 V draws 100A(1200W/12 V= 100 A).**
- The same 1200 W system draws only 50 A at 24 V, or 25 A at 48 V.
- Lower current reduces the required sizes of conductors, overcurrent protection devices, disconnects, charge controllers, and other equipment.
- Also, since voltage drop and power losses are smaller at lower currents, higher-voltage systems are generally more efficient.

DC-System Voltage

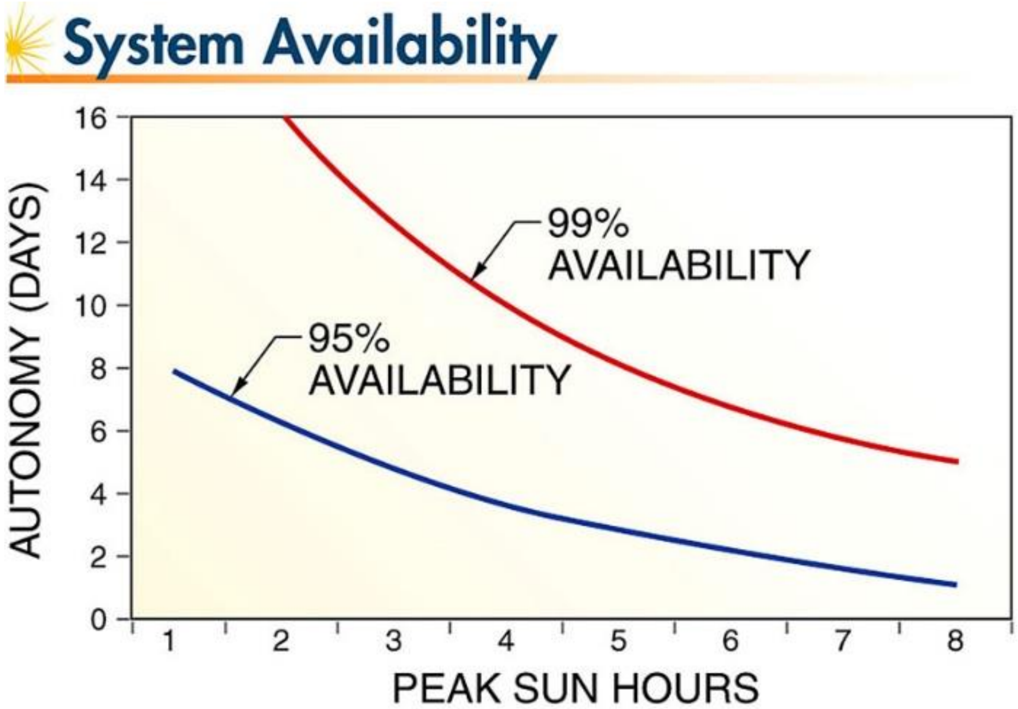
•DC-system voltage is chosen in proportion with the array size and to keep the operating current below 100 A.

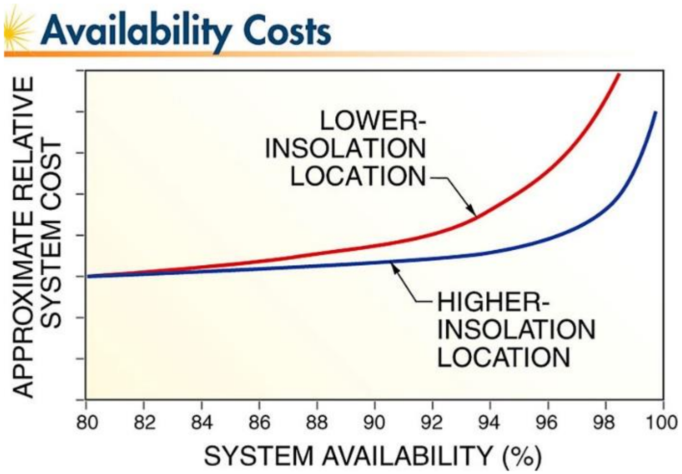
- As a rule of thumb, stand-alone systems up to 1 kW use a minimum 12V battery-bank voltage, which limits DC currents to less than 84 A.
- Similarly, battery voltages of at least 24 V are used for systems up to 2 kW,
- and at least 48 V for systems up to 5 kW.
- Very large standalone systems may use battery voltages of 120 V,
- though battery banks over 48 V involve additional code requirements and safety measures.



Availability

- **System availability is approximated from the local insolation and the autonomy period.**





- **Increasing system availability significantly increases the cost of the system.**

Battery Bank Sizing

- Batteries for stand-alone PV systems are sized to store enough energy to meet system loads for the desired length of autonomy without any further charge or energy contributions from the PV array.
- Greater autonomy requires larger and costlier battery banks, but reduces the average daily depth of discharge, which prolongs battery life.

- The required battery-bank capacity is determined from the electrical-energy requirements to operate the loads during the critical design month for the length of the autonomy period and at the desired battery-system voltage.
- Battery Capacity ***Bout*** is calculated: kWh/day

$$\text{Capacity} = B_{out} = \frac{E_{crit} \times t_a}{V_{SDC}}$$

$I_{dc} < 100$ A

- where
- B_{out} = required battery-bank output (in Ah) or Capacity
- E_{crit} = daily electrical-energy consumption during critical design month (in Wh/day)
- t_a = autonomy (in days) based on availability requirements
- V_{SDC} - nominal DC-system voltage (in V)

The average discharge rate

- The average discharge rate is determined from the total operating time over the period of autonomy, taking the allowable depth of discharge into account.

$$r_d = \frac{t_{op} \times t_a}{DOD_a}$$

- where
- *rd* - average discharge rate (in hours)
- *top* = weighted average operating time (in h/day)
- *ta* = autonomy (in days)
- *DODa* = allowable depth of discharge

- The required capacity is calculated using the following formula:

$$B_{rated} = \frac{B_{out}}{DOD_a \times C_{T,rd}}$$

- where
- *Brated =* battery-bank rated capacity (in Ah)
- *Bout* = battery-bank required output (in Ah)
- *DODa =* allowable depth of discharge
- $C_{T,rd}$ *=* temperature and discharge-rate derating factor

Array Current

- The required PV array current is calculated using the following formula:

$$I_{array} = \frac{E_{crit}}{(\eta_{batt})(V_{SDC})(t_{PSH})}$$

- where

I_{array} required array maximum-power current (in A)

E_{crit} daily electrical-energy consumption during critical design month (in Wh/day)

η_{batt} battery-system charging efficiency

V_{SDC} nominal DC system voltage (in V)

t_{PSH} peak sun hours for critical design month (in hr/day)

For example, consider a nominal 24 V system in a location with 4.9 peak sun hours that must supply 1580 Wh per day. The battery-system charging efficiency is estimated at 0.90. What is the required array current?

$$I_{array} = \frac{E_{crit}}{\eta_{batt} \times V_{SDC} \times t_{PSH}}$$

$$I_{array} = \frac{1580}{0.90 \times 24 \times 4.9}$$

$$I_{array} = \frac{1580}{105.8}$$

$$I_{array} = \mathbf{14.9\ A}$$

Array Sizing

ARRAY SIZING

Average Daily DC Energy Consumption for Critical Design Month		Wh/day
DC System Voltage		VDC
Critical Design Month Insolation		PSH/day
Battery Charging Efficiency		
Required Array Maximum-Power Current		A
Soiling Factor		
Rated Array Maximum-Power Current		A
Temperature Coefficient for Voltage		/°C
Maximum Expected Module Temperature		°C
Rating Reference Temperature		°C
Rated Array Maximum-Power Voltage		VDC
Module Rated Maximum-Power Current		A
Module Rated Maximum-Power Voltage		VDC
Module Rated Maximum Power		W
Number of Modules in Series		
Number of Module Strings in Parallel		
Total Number of Modules		
Actual Array Rated Power		W

Figure 9-18. *The array sizing worksheet uses insolation data and load requirements to size the array.*

Array Rated Output and Soiling Factor

- *Soiling* is the accumulation of dust and dirt on an array surface that shades the array and reduces electrical output. The magnitude of this effect is difficult to accurately determine, but estimates will account for most of this effect.
- A derating factor of 0.95 is used for light soiling conditions with frequent rainfall and/or a higher tilt angle, and a derating factor of 0.90 or less is used for heavy soiling conditions with long periods between rainfalls or cleanings.
- The rated array maximum-power current is calculated using the following formula:

- Cs – soiling factor

$$I_{rated} = \frac{I_{array}}{C_S}$$

Temperature Effect

- High temperature reduces voltage output. A temperature coefficient of -0.004/°C is applied to voltage, indicating that voltage falls by about 0.4% for every degree above the reference or rating temperature, which is usually 25°C (77°F).
- In addition, the array voltage must be higher than the nominal battery-bank voltage in order to charge the batteries.
- An array with a 12 V maximum-power voltage will not charge a nominal 12V battery because the actual voltage of a nearly charged battery is about 14.5 V.
- The array voltage must be at least 14.5 V to charge a nominal 12 V battery.
- **Therefore, the rated array maximum-power voltage is multiplied by 1.2 to ensure that the array voltage is sufficient to charge the battery bank.**

- The rated array maximum-power voltage is calculated using the following formula:

PV array

$$V_{rated} = 1.2 \times \{V_{SDC} - [V_{SDC} \times C_{\%V} \times (T_{max} - T_{ref})]\}$$

V_{rated} = rated array maximum-power voltage (in V)

V_{SDC} = nominal DC-system voltage (in V)

$C_{\%V}$ = temperature coefficient for voltage (in /°C)

T_{max} = maximum expected module temperature (in °C)

T_{ref} = reference (or rating) temperature (in °C)

- For example, consider an array for a nominal 24 V DC system that must output 18 A.

0.95

- The soiling conditions are expected to be light and the maximum module temperature is estimated at 50°C.
- What are the minimum rated maximum power current and voltage parameters?

$$I_{rated} = \frac{I_{array}}{C_S}$$

$$I_{rated} = \frac{18}{0.95}$$

$$I_{rated} = \mathbf{18.95\ A}$$

$$V_{rated} = 1.2 \times \{V_{SDC} - [V_{SDC} \times C_{\%V} \times (T_{max} - T_{ref})]\}$$

$$V_{rated} = 1.2 \times \{24 - [24 \times -0.004 \times (50 - 25)]\}$$

$$V_{rated} = 1.2 \times [24 - (24 \times -0.004 \times 25)]$$

$$V_{rated} = 1.2 \times (24 + 2.4)$$

$$V_{rated} = \mathbf{31.7\ V}$$

Module Selection

- For each module, three parameters are needed for sizing:

  the maximum power, the maximum-power operating current, and the maximum-power operating voltage.

- As with batteries, modules should be chosen to result in an array that is as close as possible to the desired array ratings, but slightly higher.
- The number of parallel strings of modules required is determined by dividing the rated array current output by the selected module maximum-power current output and rounding up to the next whole number.

Design Example (Standalone System)

- A home is being constructed near Albuquerque, NM and needs standalone power, this home power consumption is detailed in the next slide
- Design a suitable PV system

LOAD ANALYSIS

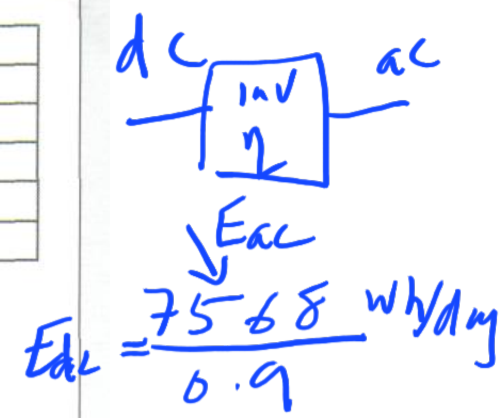
Month: August

AC LOADS

Load Description	Qty	Power Rating (W)	Operating Time (hr/day)	Energy Consumption (Wh/day)
Refrigerator/Freezer	1	200	10	2000
Microwave	1	1200	0.5	600
Toaster	1	1000	0.05	50
Coffeemaker	1	600	0.25	150
Washing Machine	1	800	0.29	232
Entertainment Center	1	200	3	600
Computer System	1	100	2	200
Plug Loads	1	200	1	200
Water Pump	1	800	0.33	264
Ceiling Fans	2	50	24	2400
Fluorescent Lighting	4	15	6	360
Fluorescent Lighting	4	32	4	512

DC LOADS

Total AC Power	5388 W
Total DC Power	0 W
Total Daily AC Energy Consumption	7568 Wh/day
Total Daily DC Energy Consumption	0 Wh/day
Weighted Operating Time	11.2 hr/day
Inverter Efficiency	0.90
Average Daily DC Energy Consumption	**8409** Wh/day



For the month of August, the load analysis yields a total AC-power demand of about 5.4 kW and a daily energy consumption of 7568 Wh/day.

If all loads operate at the same time, the inverter must have a continuous power output rating of at least 5.4 kW. Although it is unlikely that all loads will be operating simultaneously, a 5.5 kW inverter is selected to allow for future load additions.

Since the efficiency of the inverter is 90%, the total average daily DC energy required is **8409 Wh/day.** This number will be used in the critical design analysis, along with energy requirements for every other month, to determine the critical design month. The weighted operating time for the critical design month will be used in the battery-sizing calculations.

Critical Design Analysis

CRITICAL DESIGN ANALYSIS

Month	Average Daily DC Energy Consumption (Wh/day)	Array Orientation 1: Latitude – 15		Array Orientation 2: Latitude		Array Orientation 3: Latitude + 15	
		Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio
January	6532	4.6	1420	5.3	1232	5.8	1126
February	6436	5.4	1192	6.0	1073	6.2	1038
March	6254	6.3	993	6.5	962	6.5	962
April	6197	7.3	849	7.2	861	6.6	939
May	6160	7.7	800	7.2	856	6.3	978
June	7568	7.8	970	7.1	1066	6.1	1241
July	8300	7.4	1122	6.9	1203	6.0	1383
August	8409	7.2	1168	6.9	1219	6.3	1335
September	7834	6.6	1187	6.8	1152	6.5	1205
October	6160	5.9	1044	6.5	948	6.6	933
November	6327	4.8	1318	5.5	1150	5.9	1072
December	6578	4.3	1530	5.0	1316	5.5	1196

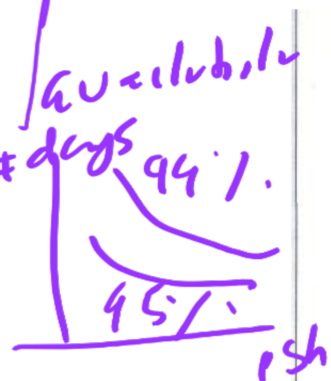
- **Critical Design Month: December**
- **Orientation: Latitude**
- **Average Daily DC Energy Consumption: 6578**
- **Insolation: 5.0 PSH/day**

- The critical design ratio is calculated for each month.
- For each orientation, the highest ratio of load requirement to insolation corresponds to the critical design month. For two of the orientations, the month is December.
- For the latitude + 15° orientation, the month is July.
- Of the three possible critical design months, the month of December at the latitude orientation produces the lowest ratio.
- This indicates the optimal orientation.
- For this designated critical design month, the load requirement value is used for battery-bank sizing and the insolation value is used for array sizing.

Battery Bank

- A 48 V system is used
- Autonomy is set for 3 days
- A small engine generator should be aslo available

given



$$B_{out} = \frac{(E_{crit})(t_a)}{(V_{SDC})} = \frac{(6578)(3)}{(48)} = 411Ah$$

$$B_{rated} = \frac{B_{out}}{(DOD_a)(C_{T,rd})} = \frac{411}{(0.8)(0.9)} = 571Ah$$

$$r_d = \frac{(t_{op})(t_a)}{DOD_a} = \frac{(11.2)(3)}{0.8} = 42\ h$$

- Flooded lead acid batteries with 295 Ah capacity are used , so 4 in series are required to provide 48V bus, and two strings in parallel to provide required capacity

$\frac{48}{12} = 4 = N_s$

$2 = \frac{571\ Ah}{295} = N_p$

BATTERY-BANK SIZING

Average Daily DC Energy Consumption for Critical Design Month	6578	Wh/day
DC System Voltage	48	VDC
Autonomy	3	days
Required Battery-Bank Output	411	Ah
Allowable Depth-of-Discharge	0.80	
Weighted Operating Time	11.2	hrs
Discharge Rate	42	hrs
Minimum Expected Operating Temperature	0	°C
Temperature/Discharge Rate Derating Factor	0.90	
Battery-Bank Rated Capacity	571	Ah
Selected Battery Nominal Voltage	12	VDC
Selected Battery Rated Capacity	295	Ah
Number of Batteries in Series	4	
Number of Battery Strings in Parallel	2	
Total Number of Batteries	8	
Actual Battery-Bank Rated Capacity	590	Ah

In this application, the load fraction is estimated at 0.75. The average daily depth of discharge is 17%. From the manufacturer's data, this battery has an expected life of 4000 cycles at 20% average daily depth of discharge. Correspondingly, at least 10 years of service should be expected in this application.

Array Sizing

$$I_{array\_rated} = \frac{E_{crit}}{(\eta_{batt})(V_{SDC})(t_{PSH})(Cs)} = \frac{6578}{(0.85)(48)(5)(0.95)} = 33.9A$$

$$V_{array\_rated} = 1.2x\{(V_{SDC}) - [(V_{SDC}).(C_{\%V}).(T_{max} - T_{ref})]\}$$

$$= 1.2x\{(48) - [(48).(-0.004\%/V).(50-25)]\}$$

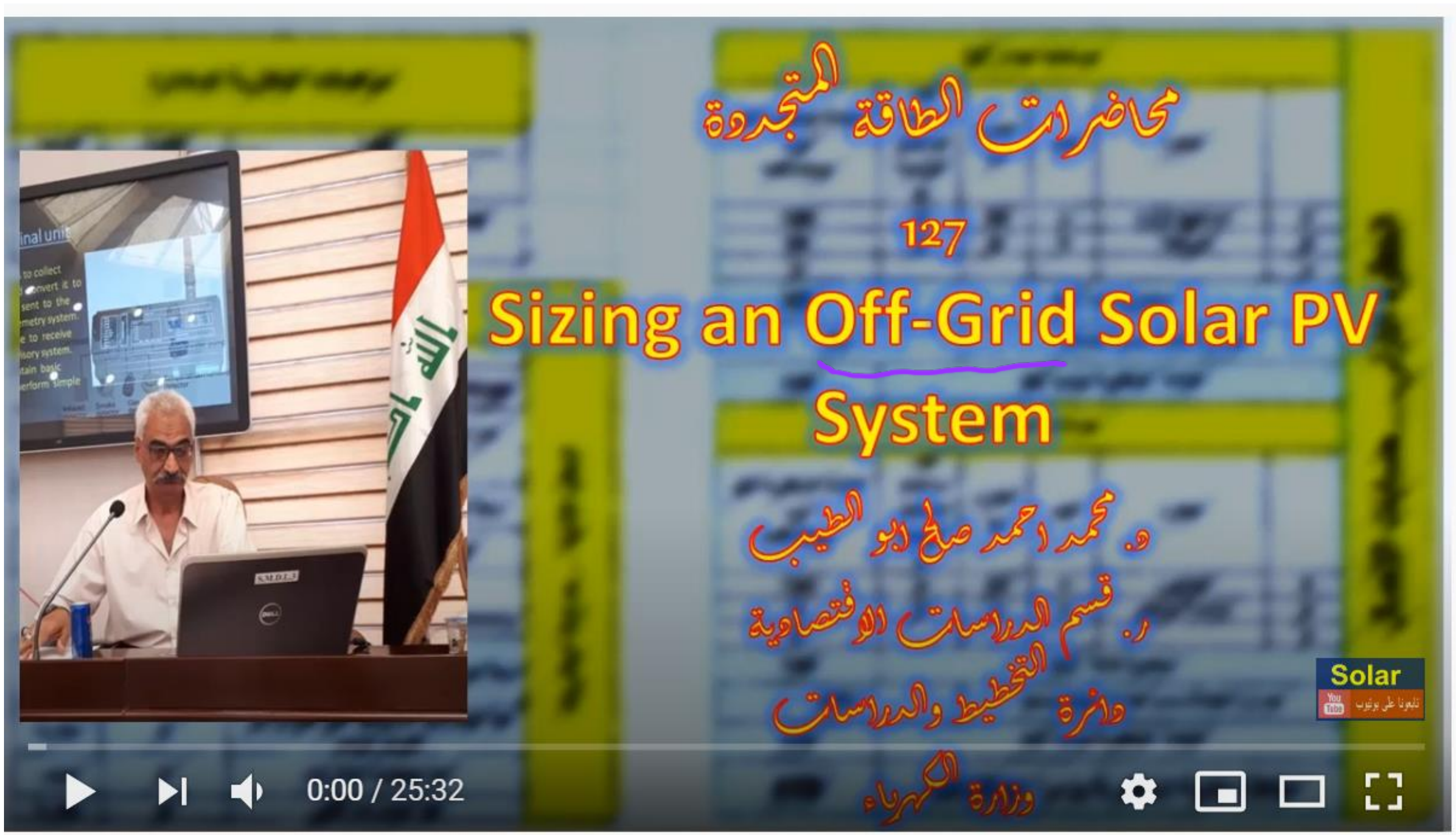
$$= 63.4\ V$$

- A 185 Wp module with
- Imax=5.11 A, Vmax=36.2 V is chosen
- Ns=63.4/36.2=1.74 → Ns=2
- Np=33.9/5.1=6.65 Np=7
- Total modules Nt=Ns*NP=14
- Total rated power= 14*185=2590 W

ARRAY SIZING

Average Daily DC Energy Consumption for Critical Design Month	6578	Wh/day
DC System Voltage	48	VDC
Critical Design Month Insolation	5.0	PSH/day
Battery Charging Efficiency	0.85	
Required Array Maximum-Power Current	32.2	A
Soiling Factor	0.95	
Rated Array Maximum-Power Current	33.9	A
Temperature Coefficient for Voltage	−0.004	/°C
Maximum Expected Module Temperature	50	°C
Rating Reference Temperature	25	°C
Rated Array Maximum-Power Voltage	63.4	VDC
Module Rated Maximum-Power Current	5.11	A
Module Rated Maximum-Power Voltage	36.2	VDC
Module Rated Maximum Power	185	W
Number of Modules in Series	2	
Number of Module Strings in Parallel	7	
Total Number of Modules	14	
Actual Array Rated Power	2590	W

https://www.youtube.com/watch?v=Cm6ks0Rp-z8



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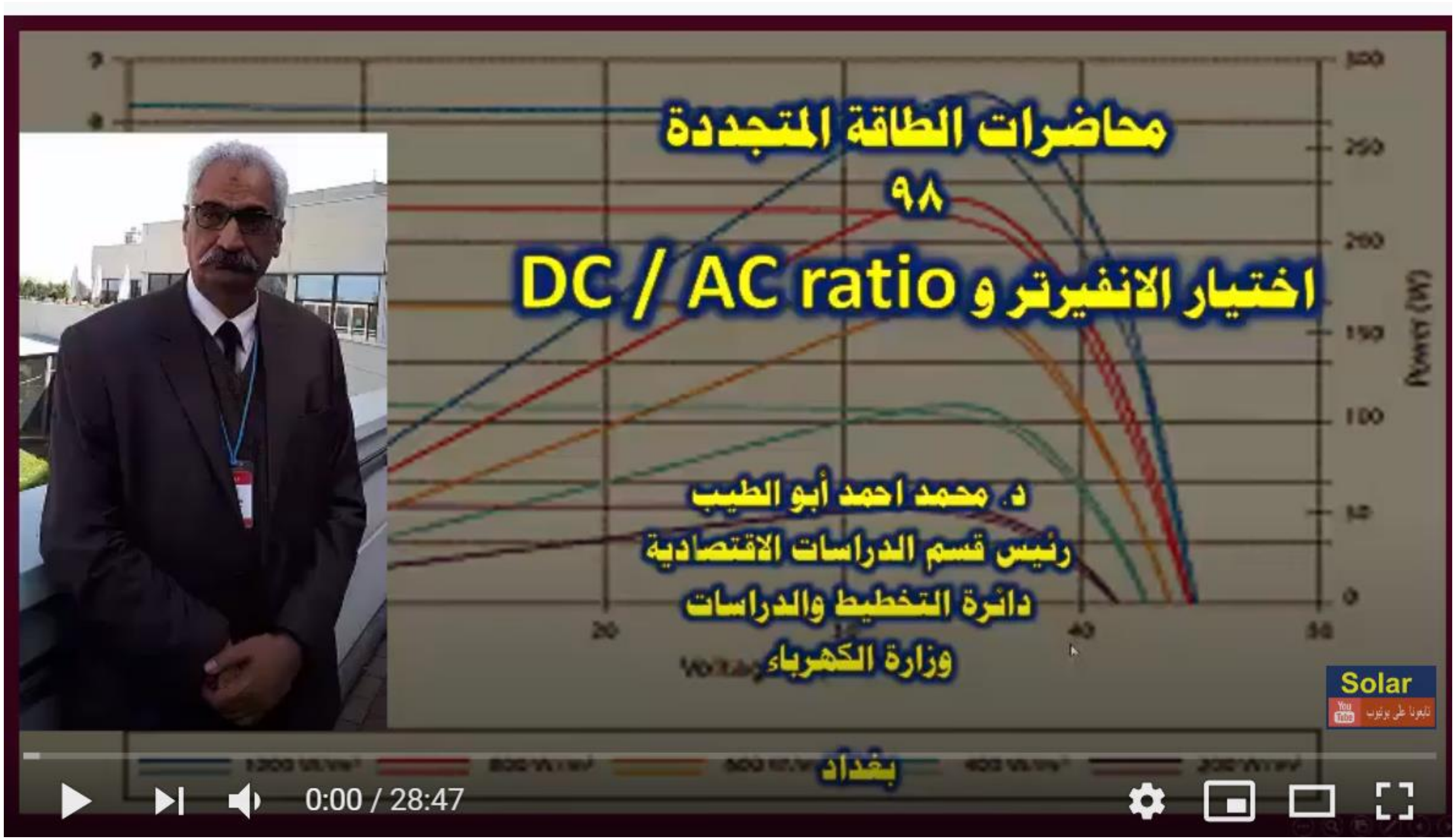

* End of PV Topics

↓ next

Wind Energy