DESIGNING PHOTOVOLTAIC SYSTEMS

Renewable Energy
Lecture 16: DESIGNING PHOTOVOLTAIC SYSTEMS

Grade: 4th Class

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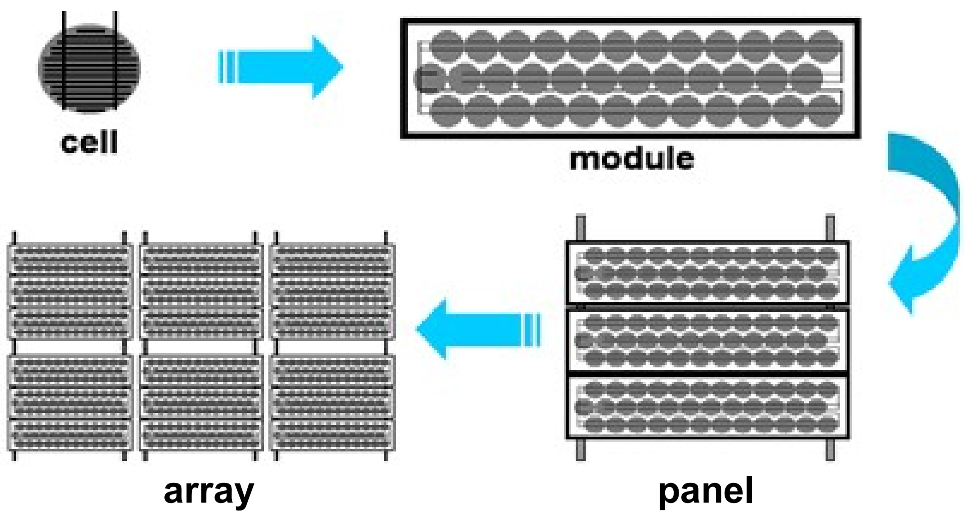
Module, Panel and Array

Module: PV cells are connected electrically in series and/or parallel circuits to make a module to produce higher voltages, currents, and power levels.

Panel: PV panels include one or more PV modules assembled as a pre-wired, field-installable unit.

Array: A PV array is the complete power-generating unit, consisting of any number of PV modules and panels.



Effect of Shading on Module Performance

When one module in an array is shaded, the output of the entire array can be drastically reduced. The use of a diode can minimize the effect of shading.

The diode can be used for several functions:

1. **Blocking Diode:** Placed between the module and battery to stop the module from leaking to the battery current from reversing the flow from the battery to the array at night or cloudy weather.

2. **Bypass Diode:** Wired in parallel with a module to divert current around the module in the event of shading.

Types of PV Systems

PV systems can be designed:

- To provide DC and/or AC power service.
- Can operate interconnected with or independent of the utility grid.
- Can be connected with other energy sources and energy storage systems.

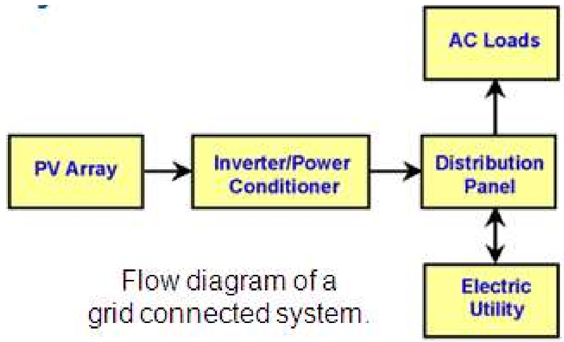
The two principal classifications of PV systems are the following:

- **Grid-connected or utility-interactive systems, and**
- **Stand-alone systems.**

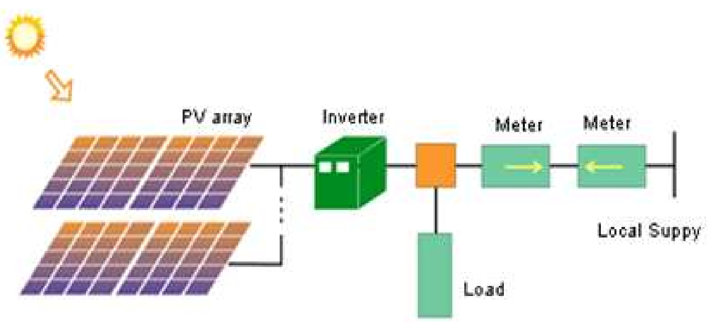
Types of PV Systems *(cont.)*

Grid-Connected PV System

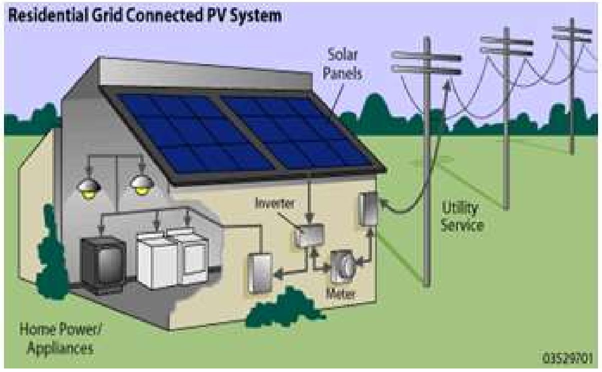
Grid-connected or utility-interactive PV systems are designed to operate in parallel with and interconnected with the electric utility grid. The primary component in grid-connected PV systems is the inverter, or power conditioning unit (PCU).



Flow diagram of a grid connected system.



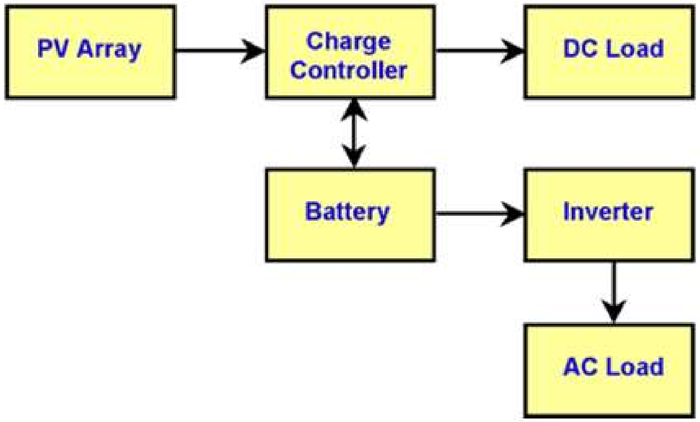
Single inverter grid connected system.

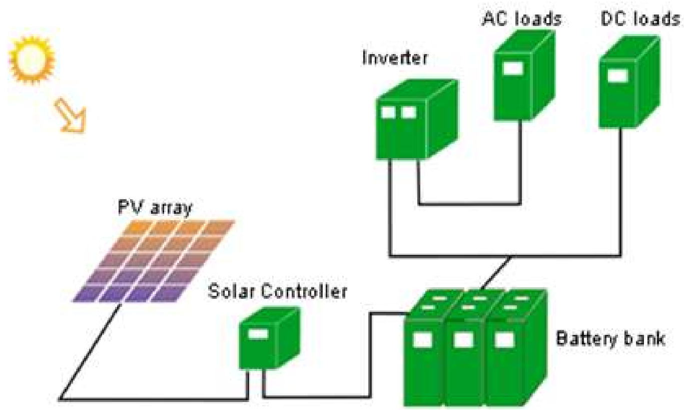


Types of PV Systems *(cont.)*

Stand-Alone PV System

Stand-alone PV systems are designed to operate independent of the electric utility grid, and they are generally designed and sized to supply certain DC and/or AC electrical loads.

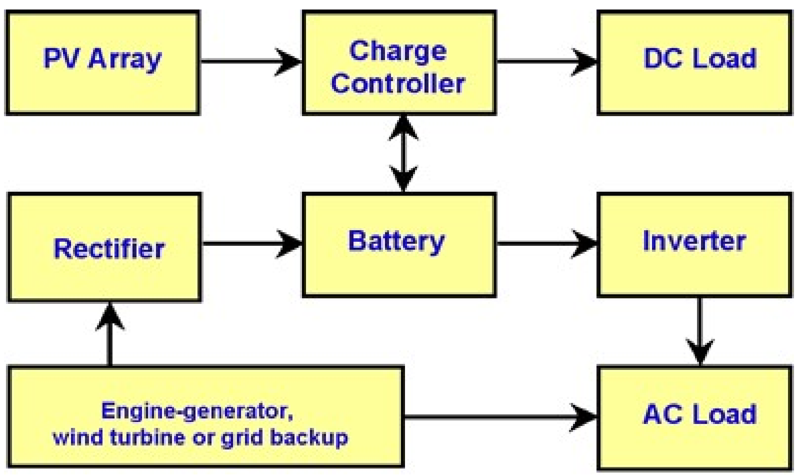


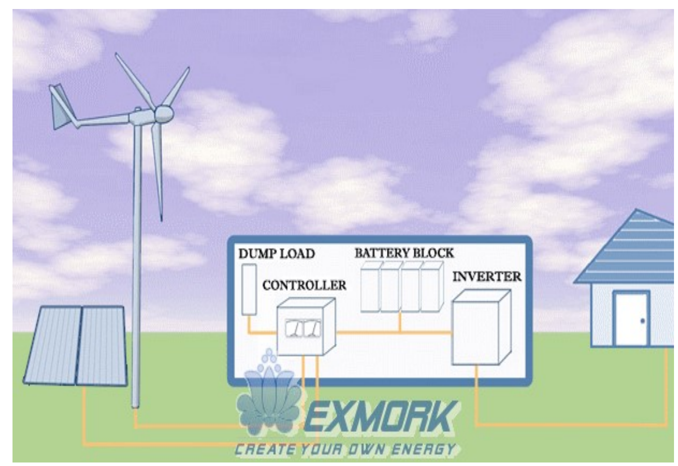


Types of PV Systems *(cont.)*

Hybrid System

A hybrid renewable energy system is a system in which two or more supplies from different renewable energy sources (e.g., solar-thermal, solar-photovoltaic, wind, biomass, hydropower) are integrated to supply electricity to the same demand.





Other PV system parts

Batteries

Batteries store DC electrical energy in chemical form.

Batteries are rated as Amp-hour (Ah). A common battery specification is the number of hours that are discharged.

A battery with more than 20 hours discharge is said to have a discharge of C/20. More than 5 hours is C/5. Most batteries are rated at the C/20.

Other PV system parts *(cont.)*

Types of Batteries:

1. **Lead acid**
   - Liquid vented: Automobile battery
   - Sealed (VRLA, “valve regulated lead acid”): have no caps, but they are not totally sealed; a valve allows excess pressure to escape in case of overcharging.

2. **Alkaline batteries**

   The electrolyte is potassium hydroxide. One advantage over other batteries is that it is not affected by temperature.

   There are two types:

   - Nickel cadmium
   - Nickel iron

Other PV system parts *(cont.)*

Charge Controller

It is a voltage regulator used to:

- Prevent the battery from being overcharged by the PV array.
- To protect the battery from being overly discharged by the load.

Inverter

It is used to change the DC electricity produced by PV modules and stored in the batteries to AC electricity to finally power an AC load.

There are two categories of inverters:

1. Synchronous or line-tied inverter used in grid-connected systems.
2. Stand-alone or static inverter used for independent systems.

Another classification for inverters is the type of waveform they produce. The three most common waveforms are the following:

1. Square wave.
2. Modified square wave.
3. Sine wave.

PV System Design for a Residence in Kuwait

Site Climate and Solar Radiation

Location: 29° 22’ 10” N latitude, 47° 58’ 41” W longitude

Temperature range (° C): 5 – 45

Relative humidity (%): 45 – 65

Global solar radiation: 5.5 – 7.8 kWh/m^2/day

Sunshine hours: More than 3000 hrs/year

Sizing Procedure

Step 1: Electric load estimation

Step 2: Battery sizing

Step 3: Array sizing

Step 4: Controller specification

Step 5: Inverter specification

Step 6: System wiring sizing

Step 1: Electric Load Estimation

The house load comprises the following:

1. **10 fluorescent lights (20 watt each), operates 6 hr/day**
2. **1 washing machine (400 watt), operates 0.3 hr/day**
3. **1 clothes dryer (1000 watt), operates 0.35 hr/day**
4. **1 microwave oven (800 watt), operates 0.5 hr/day**
5. **1 toaster (1000 watt), operates 0.15 hr/day**
6. **1 air conditioner (1000 watt), operates 10 hr/day**

Each load and the number of daily operating hours should be identified to calculate the average daily electrical energy use in watt-hours, as well as total connected watts.

Step 1: Electric Load Estimation *(cont.)*

Individual Load	Qty x	Volt x	Amps =	Watts AC	Watts DC x	Use h/d x	Use d/wk ÷	7 days =	W.h AC	W.h DC
Light Fluorescent	10	220	0.091	200		6	7	7	1200	
Washing machine	1	220	1.82	400		0.3	3	7	51.5	
Cloth dryer	1	220	4.55	1000		0.35	3	7	150	
Microwave oven	1	220	3.64	800		0.5	7	7	400	
Toaster	1	220	4.55	1000		0.15	7	7	150	
Air conditioner	1	220	8.2	1000		10	7	7	10000	

AC Total Connected Watts: 4,400 W

AC Average Daily Load: 11,951.5 W-h

DC Total Connected Watts:

DC Average Daily Load:

Step 2: Battery Sizing

Table 2. Battery Sizing Worksheet

AC Average Daily Load ÷	Inverter Efficiency ÷	DC Average Daily Load ÷	DC System Voltage =	Average Amp-h/d
11951.5	0.9	N/A	24	553.3
Average Amp-h/d x	Days of Autonomy ÷	Discharge Limits ÷	Battery Ah Capacity =	Batteries in Parallel
553.3	3	0.8	200	11
DC System Voltage ÷	Battery Voltage =	Batteries in Series x	Batteries in Parallel =	Total Batteries
24	6	4	11	44
Battery Specifications: 6 V, 200 AH				

Step 3: Array Sizing

Table 3. Array Sizing Worksheet

Average A-h/d	÷	Battery Efficiency	÷	Peak Sun h/d	=	Array Peak Amps		
553.3		0.8		6.5		106.4		
Array Peak Amps	÷	Maximum Amps/module	=	Modules in Parallel	=	Modules Short Circuit Current		
106.4		2.23		48		2.4		
DC System Voltage	÷	Nominal Module Voltage	=	Modules in Series	x	Modules in Parallel	=	Total Modules
24		12		2		48		96

Module Specifications:

Power at STC (25°C & 1 000 W/m^2)	=	27 Watt
Nominal Voltage	=	12 V
Voltage at STC	=	12 V
Current at STC	=	2.23 A
Short-Circuit Current	=	2.4 A

Step 4: Controller Specification

Table 5. Controller Sizing Worksheet

Module Short Circuit Current x	Modules in Parallel x	1.25 =	Array Short Amps	Controller Array Amps	Listed Desired Features
2.4	**48**	**1.25**	**141**	**141**	**LVD, metering**
DC total Connected Watts ÷	**DC System Voltage =**	**Maximum DC Load Amps**	**Controller Load Amps**		
Controller Specifications: if we choose a controller with 30 A rated current, therefore we need 5 controllers to be connected in parallel (24 V &30 A each).					

Step 5: Inverter Specification

Table 4. Inverter Sizing Worksheet

AC Total Connected Watts ÷	DC System Voltage =	Maximum DC Amps Continuous	Estimated Surge Watts	Listed Desire Features
4400	24	183.3	13200	Modified Sine
Inverter Specifications: sine-wave output, 24 /220 V, 50 Hz and 90% efficiency.				

Step 6: System Wire Sizing

Wiring information:

- **25 ft from the array to controller**
- **10 ft from controller to the battery**
- **10 ft from batteries to inverter**
- **10 ft from inverter to AC load**
- **Wire type THWN in conduit, 2% voltage drop**

Step 6: System Wire Sizing *(cont.)*

1- Wires from PV combiner box to controller

A. NEC requirement **Isc of module x # of modules in parallel = Total Amp x 1.25 x1.25 = NEC requirement** **1.24 x 48 = 115.2 x 1.25 x 1.25 = 180.0 A** **Amperage satisfying NEC = <u>180.0 A</u> Wire size from table = #1/0 AWG**
B. Voltage drop requirement **System voltage: 24 V Total Amps: 115.2 A** **One way distant: 25 ft Voltage drop (%): 2** **Wire from tables: # 2/0 AWG**
If this equal to or greater than the size wire needed for safety? No **Therefore the correct wire size is #2/0 AWG**

Step 6: System Wire Sizing *(cont.)*

2- Wires from controller to batteries

C. NEC requirement

Isc of module x # of modules in parallel = Total Amp x 1.25 x1.25 = NEC requirement

2.4 x 48 = 115.2 x 1.25 x 1.25 = 180.0 A

Amperage satisfying NEC = <u>180.0 A</u>   Wire size from table = #1/0 AWG

D. Voltage drop requirement

System voltage: 24 V   Total Amps: 115.2 A

One way distant: 4 ft   Voltage drop (%): 2

Wire from tables: # 2 AWG

If this equal to or greater than the size wire needed for safety? No
Therefore the correct wire size is #1/0 AWG

Step 6: System Wire Sizing *(cont.)*

3- Wires from batteries to inverter

E. NEC requirement

Inverter watt ÷ Inverter efficiency ÷ DC voltage = Inverter Amps x1.25 = NEC required amps

4400	**÷**	**0.9**	**÷**	**24**	**= 203.0**	**x 1.25 = 254.6 A**

Amperage satisfying NEC = 254.6 A **Wire size from table = #2/0 AWG**

F. Voltage drop requirement

System voltage: 24 V **Total Amps: 203.0 A**

One way distant: 4 ft **Voltage drop (%): 2**

Wire from tables: #1/0 AWG

If this equal to or greater than the size wire needed for safety? No

Therefore the correct wire size is #2/0 AWG

Step 6: System Wire Sizing *(cont.)*

4- System grounding

4.1- System ground **Wire type: Standard copper** **Wire size: # 1/0 AWG** **Type of earth ground: Ground rod**
4.2 Equipment ground **Wire type: Standard copper** **Wire size: # 1/0 AWG** **Type of earth ground: Ground rod**

Step 6: System Wire Sizing *(cont.)*

5- Inverter to AC load (AC wire sizing)

System voltage: 220 V

Maximum current: 24 A

Length of wire: 10 ft

Wire size: # 10 AWG THWN

Life-Cycle Cost (LCC) Analysis

LCC analysis gives the total cost of the PV system, including all expenses incurred over the life of the system.

Two reasons to do this analysis:

1. **To compare different power options**

2. **To determine the most cost-effective system designs.**

$$LCC = C + M_{pw} + E_{pw} + R_{pw} - S_{pw}$$

where:

C = Capital cost of the project includes the initial cost of equipment, the system design, engineering and installation.

M = Sum of all yearly scheduled operation and maintenance (O&M) costs. It includes operator's salary, inspection, insurance, property tax, and all scheduled maintenance.

Life-Cycle Cost (LCC) Analysis *(cont.)*

E = Energy cost (fuel) of the system.

R = Replacement cost is the sum of all repair and equipment replacement cost over the life of the system.

S = Salvage value of the system in final year of life-cycle period (usually 20%).

pw = present worth of each factor.

Future cost must be discounted because of the lifetime value of the money. One dollars received today is worth more than the promise of $1 next year, because the $1 today can be invested and earn interest.

Life-Cycle Cost (LCC) Analysis *(cont.)*

PV System

The PV system consisted of:

- 4.4-kW array,
- A 44-battery bank of 200 Ah each,
- A controller and 5-kW inverter.
- The system cost is assumed to be US$8000 per kW, with a total cost of US$41,600.
- The only future system cost is replacing the batteries every 10 years and a yearly inspection cost of US$100 per year.

Life-Cycle Cost (LCC) Analysis *(cont.)*

Life-cycle cost analysis					
PV system					
Economic parameters: 1. Years in life cycle: 25 2. Investment rate: 7% Net discount rate (7-4) = 3%			3. General inflation rate: 4% 4. Fuel inflation rate: 5% Differential fuel inflation (5-4) = 1%		
Item worth	Single present Worth year	Uniform present worth year	Dollar amount	present worth factor (tables)	present amount
1.Capital cost			35,200	1	= 35,200
2.Maintenance					
. labor: yearly inspection		25	100 X	17.413	= 1741.3
. material others					
3.Energy cost					
4.Repair replacement					
. Battery bank	10		6600 X	0.744	= 4910.4
. Inverter	10		5000 X	0.744	= 3720.0
. Battery bank	20		6600 X	0.554	= 3656.4
. Inverter	20		5000 X	0.554	= 2770.0
5. Salvage					
20% of capital cost	25		7040 x	0.478	= 3365.1
Total life cycle cost		(Items 1+2+3+4-5)			= 48633.0
Notes:					
Notes:					

Life-Cycle Cost (LCC) Analysis *(cont.)*

The proposed generator system consisted of:

- 4.5-kW generator,
- 4.5-kW inverter,
- 44 batteries of 200 Ah capacities each.
- The generator system initial cost is estimated to be US$15000, including design and engineering.
- The generator would consume US$500 per year, require annual inspection of US$1200, and have to be rebuilt every 5 years with a cost of US$2000 per year.
- In addition, the battery bank has to be replaced every 10 years.

Life-Cycle Cost (LCC) Analysis *(cont.)*

Life-cycle cost analysis					
Generator system					
Economic parameters:					
I. Years in life cycle: 25			3. General inflation rate: 4%		
2. Investment rate: 7%			4. Fuel inflation rate: 5%		
Net discount rate (7-4) = 3%			**Differential fuel inflation (5-4)= 1%**		
Item worth	**Single present Worth year**	**Uniform present worth year**	**Dollar amount**	**present worth factor (tables)**	**present amount**
1.Capital cost			15000.00	1	= 15000.00
2.Maintenance					
. labor: yearly inspection		25	1200 X	17.413	= 20400.00
. material others					
3.Energy cost		25	500.00	17.413	= 8706.5
4.Repair replacement					
. Battery bank	10		6600 X	0.744	= 4910.4
. Inverter	10		5000 X	0.744	= 3720.0
. Battery bank	20		6600 X	0.554	= 3656.4
. Inverter	20		5000 x	0.554	= 2770.0
. Generator rebuild	5		2000 x	0.863	= 1726.0
. Generator rebuild	10		2000 x	0.744	= 1488.0
. Generator rebuild	15		2000 x	0.642	= 1284.0
. Generator rebuild	20		2000 x	0.554	= 1108.0
5. Salvage					
20% of capital cost	25		3000 x	0.478	= 1434.0
Total life cycle cost		(Items 1+2+3+4-5)			= 63335.3
Notes:					

Life-Cycle Cost Comparison

Life-cycle cost comparison		
Item	Present Worth PV system	Present Worth Generator system
1.Capital cost	35200.00	15000.00
2.Maintenance		
. labor: yearly inspection	1741.30	20400.00
. material		
.others		
3.Energy cost		8706.5
4.Repair replacement		
. Battery bank 10	4910.40	4910.4
. Inverter 10	3720.00	3720.0
. Battery bank 20	4910.40	3656.4
. Inverter 20	2770.00	2770.0
. Generator rebuild 5		1726.0
. Generator rebuild 10		1488.0
. Generator rebuild 15		1284.0
. Generator rebuild 20		1108.0
5. Salvage		
20% of capital cost 25	3365.10	1434.0
Total life cycle cost (Items 1+2+3+4-5)	49887.00	63335.3
Note: Go Solar		

ASSIGNMENT 1 – PV SYSTEM DESIGN

Find a location and design this system

Appliance	AC or DC Watts		Hours Used/ Day		Watt Hours/ Day
Ceiling Fan	100	x	8.0	=	800
Coffee Maker	600	x	0.3	=	180
Clothes Dryer	4,856	x	0.8	=	3,885
Computer	75	x	2.0	=	150
Computer Monitor	150	x	2.0	=	300
Dishwasher	1,200	x	0.5	=	600
Lights, 4 Compact Fluorescents	4x15	x	5.0	=	300
Microwave Oven	1,300	x	0.5	=	650
Radio	80	x	4.0	=	320
Refrigerator	600	x	9.0	=	5,400
Television	300	x	8.0	=	2,400
Vacuum Cleaner	600	x	0.2	=	120
VCR	25	x	8.0	=	200
Washing Machine	375	x	0.5	=	188
Total					15,493