



UNIVERSITÉ DES
MASCAREIGNES

SAVOIR, C'EST POUVOIR



Session 3:

Design of Solar Power Systems

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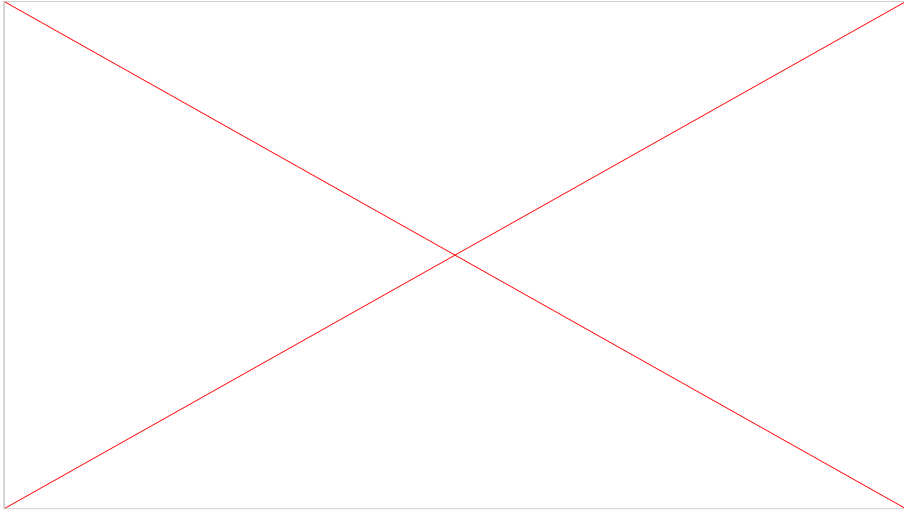
SESSION CONTENT

- 1. On-Grid System Design**
- 2. Off-Grid System Design**
- 3. Hybrid System Design**



1. On-Grid System Design

1.1. Load Analysis



Determine Daily Power Consumption

- Check the monthly power consumption in electricity bill

Monthly Power Consumption = 170 kWh

- Daily power consumption = Monthly power consumption / 30

Daily Power Consumption = 170 kWh/30 = 5.67 kWh

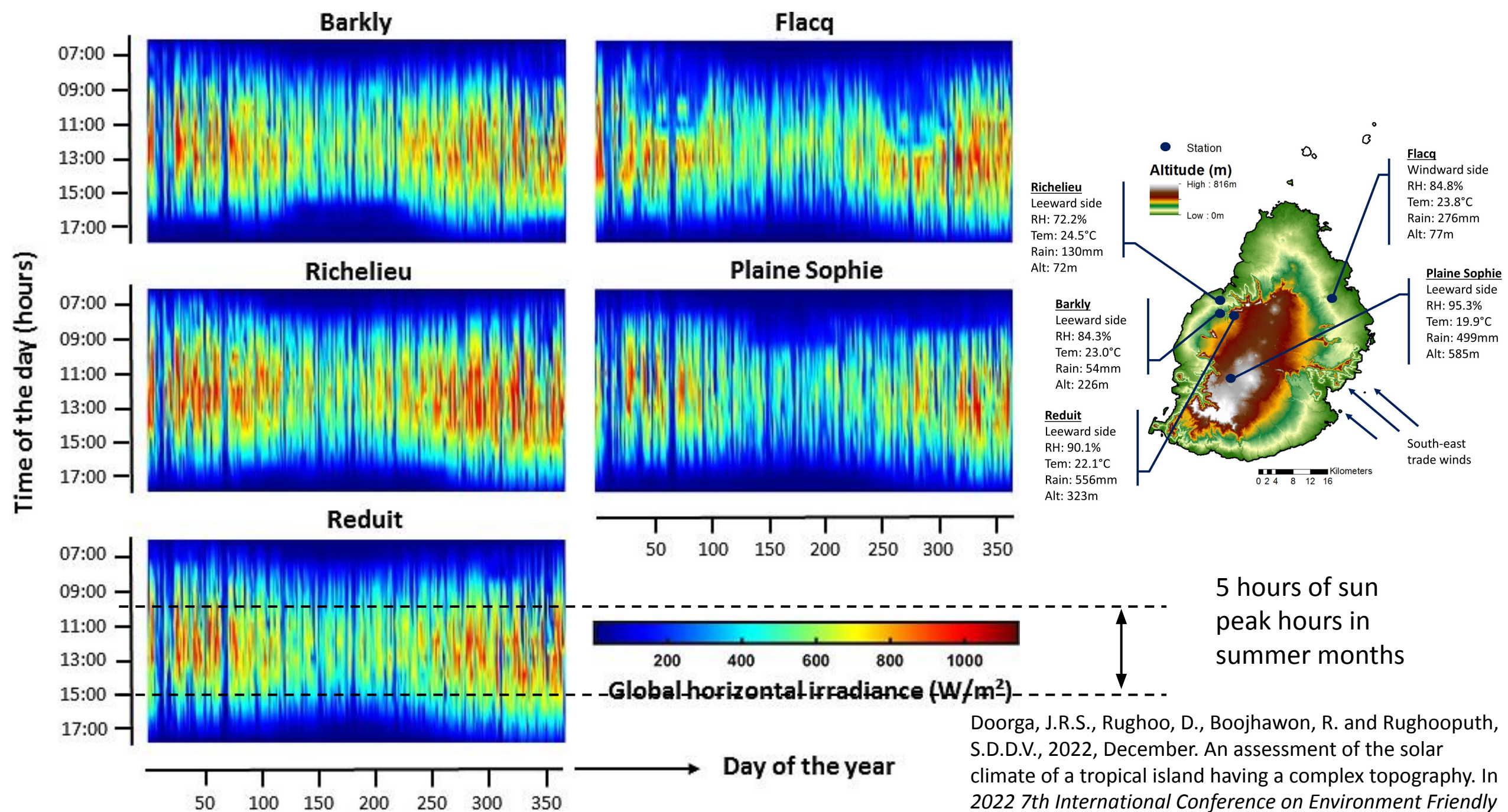
1.2. Sizing of Solar PV Panels

- Check the sun peak hour of the site

A peak sun hour is any hour of the day when the sunlight's intensity is an average of 1000 W/m²

Sun peak hours = 5 hours (Reduced in summer)

Sun Peak hours varies from place to place



Doorga, J.R.S., Rughoo, D., Boojhawon, R. and Rughooputh, S.D.D.V., 2022, December. An assessment of the solar climate of a tropical island having a complex topography. In *2022 7th International Conference on Environment Friendly Energies and Applications (EFEA)* (pp. 1-6). IEEE.

- Required Capacity of Solar Panel

$$PV \text{ Power} = \text{Daily Power Consumption} / \text{Sun Peak hours} \times 1.3$$

$$PV \text{ Power} = 5.67 \text{ kWh} / 5 \text{ h} \times 1.3$$

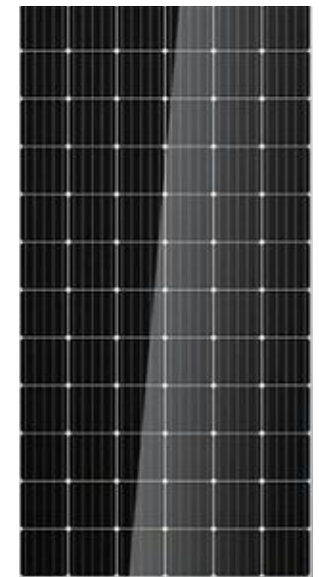
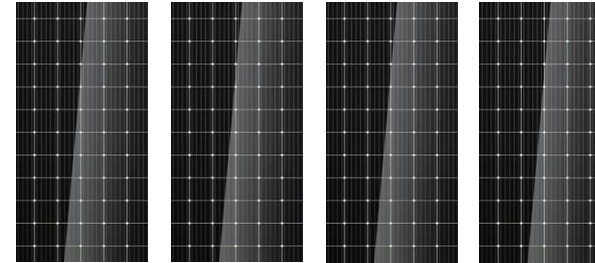
$$PV \text{ Power} = 1.475 \text{ kW} = 1,475 \text{ W} \text{ (Daily power required from PV System)}$$

- Number of Solar Panels

$$\text{No. of PV Panels} = PV \text{ Power} / PV \text{ Panel Rating}$$

$$\text{No. of PV Panels} = 1,475 \text{ W} / 380 \text{ W}$$

$$\text{No. of PV Panels} = 3.88 \text{ (~ 4 panels)}$$



$P_R = 380 \text{ W}$
 $V_{OC} = 48.8 \text{ V}$
 $I_{SC} = 9.94 \text{ A}$
 $\text{Eff} = 19.5\%$

1.3. Sizing of Inverter

- To size the inverter we need to take the PV power output of the actual PV array

$$\text{Maximum PV Power} = PV \text{ Panel Rating} \times \text{No. of PV Panels}$$

$$\text{Maximum PV Power} = 380 \text{ W} \times 4$$

$$\text{Maximum PV Power} = 1,520 \text{ W}$$

$W_p = 2,200 \text{ W}$
 $\text{Max } V_{DC} \text{ Input} = 400 \text{ V}$
 $\text{Max Input Current} = 10 \text{ A}$

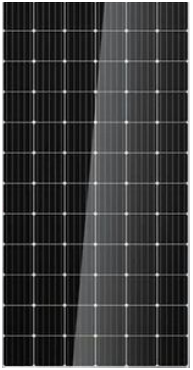
- Choose an inverter with a maximum power (W_p) > Maximum PV Power (1,520 W)

$$\text{Inverter Rating} = 2,200 \text{ W}$$



2,200 W
on-grid inverter

- Check if voltage and current from PV system does not exceed voltage and current of inverter rating



$P_R = 380 \text{ W}$
 $V_{OC} = 48.8 \text{ V}$
 $I_{SC} = 9.94 \text{ A}$
 $\text{Eff} = 19.5\%$

Suppose connect PV Panel in series

$$PV \text{ Array } V_{OUT} (\text{series}) = V_{OC} \times \text{No. of PV panels}$$

$$PV \text{ Array } V_{OUT} (\text{series}) = 48.8 V_{DC} \times 4$$

$$PV \text{ Array } V_{OUT} (\text{series}) = 195.2 V_{DC}$$

$$PV \text{ Array } V_{OUT} [195.2 V_{DC}] < \text{Max } V_{DC} \text{ input of inverter } [400 V_{DC}]$$

$W_P = 2,200 \text{ W}$
 $\text{Max } V_{DC} \text{ Input} = 400 \text{ V}$
 $\text{Max Input Current} = 10 \text{ A}$

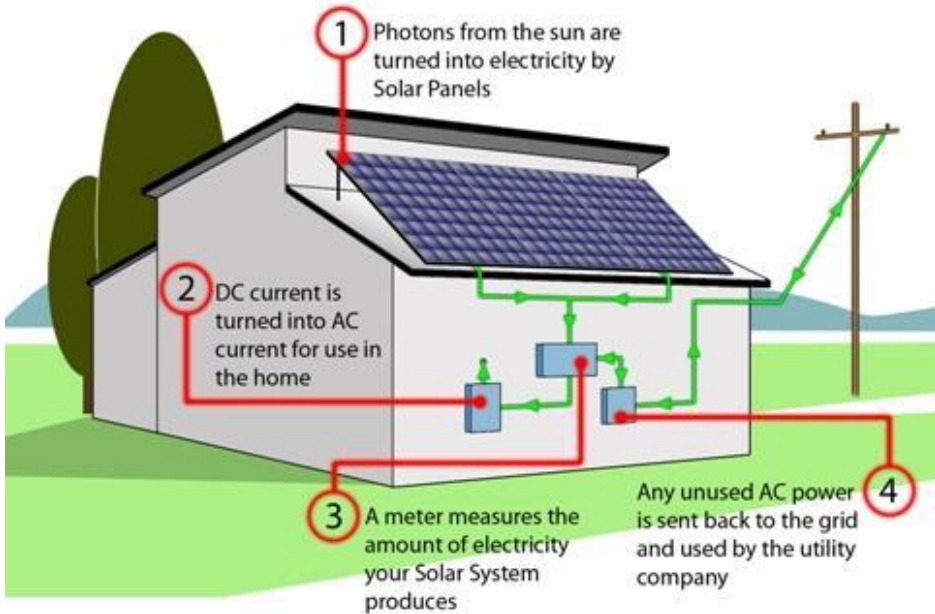


This inverter can handle the amount of voltage coming out of the solar PV array

$$PV \text{ Array } I_{SC} (\text{series}) [9.94 \text{ A}] < \text{Max input current of inverter } [10 \text{ A}]$$

This inverter can handle the amount of current coming out of the solar PV array

Grid-tied Solar Power System



During the day if solar electricity production > household energy consumption = Excess is fed to the power grid

When this occurs electrical meter spins backward [Most gov system has a credit system in place that requires utility companies to buy this electricity back – Feed-in Tariff]

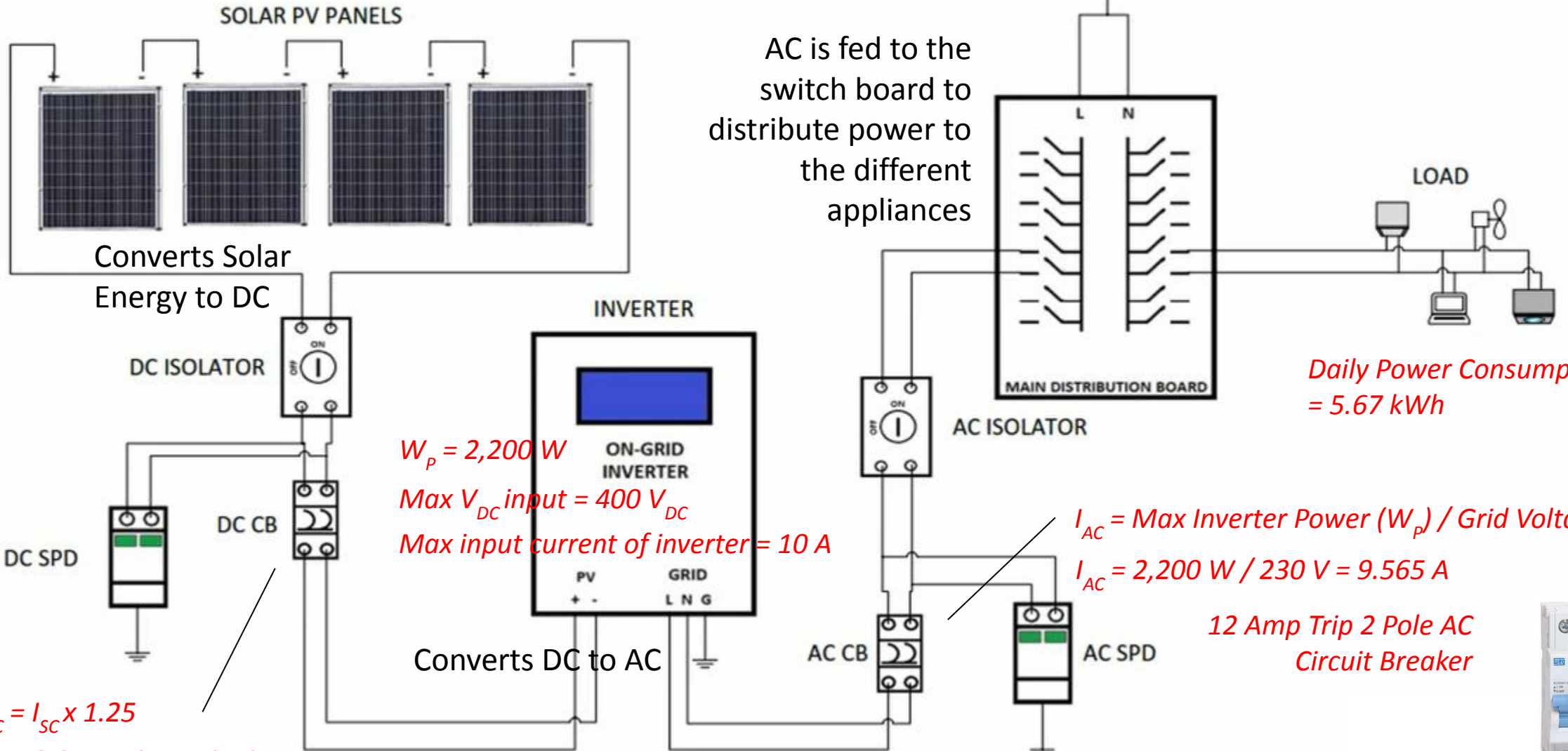
Net metering is an electricity billing mechanism that allows consumers who generate their own electricity to use that electricity anytime

During the day/night if solar electricity production < household energy consumption = Extra energy is powered from the grid

On-Grid System

Maximum PV Power = 1,520 W
PV Array V_{OUT} (series) = 195.2 V_{DC}
PV Array I_{SC} (series) = 9.94 A

The system is also connected to the grid (utility)



AC is fed to the switch board to distribute power to the different appliances

Daily Power Consumption = 5.67 kWh

$W_p = 2,200 W$
Max V_{DC} input = 400 V_{DC}
Max input current of inverter = 10 A

$I_{AC} = \text{Max Inverter Power } (W_p) / \text{Grid Voltage}$
 $I_{AC} = 2,200 W / 230 V = 9.565 A$

12 Amp Trip 2 Pole AC Circuit Breaker

$I_{DC} = I_{SC} \times 1.25$
 $I_{DC} = 9.94 \times 1.25 = 12.425 A$

14 Amp Trip 2 Pole DC Circuit Breaker



2. Off-Grid System Design

Category of use	Appliance	Power (W)	Average utilization	Number of appliance	Monthly consumption (kWh)
Comfort/Leisure	Air conditioner	1500	3 hours/day	1	135
	Television	85	4 hours/day	1	10
	Fan	60	6 hours/day	1	10
Refrigeration	Refrigerator	100	Continuous	1	36
	Lighting	15	Everyday	10	32
Cooking	Rice cooker	200	Once per day	1	3
	Electric kettle	1200	Twice per day	1	6
Washing	Microwave oven	600	20 minutes/day	1	6
	Washing machine	500	2 hours/week	1	4
Others	Computer	100	1 hour/day	1	3
	Vacuum cleaner	450	1 hour/week	1	2

Total Monthly Consumption = 247 kWh

Total daily Consumption = 8,2 kWh

Add some buffer capacity to PV system in case of cloudy skies, for example. 1.3 means adding 30% more capacity

1 panel polycrystalline 330 W; 48 V ~ Rs 7000

PV Panels:

Daily Consumption = 8.2 kWh

Sun Peak Hours= 5 hours

$$\text{PV Power} = \frac{\text{Daily consumption}}{\text{Sun Peak Hours}} \times 1.3$$

$$\text{PV Power} = \frac{8.2 \text{ kWh}}{5 \text{ h}} \times 1.3 = 2.1 \text{ kW}$$

Typical modules are rated between 250 to 400 watts.

Assume use of solar panel with power rating of 330 W.

$$\text{Number of Panel} = \frac{\text{PV Power}}{\text{PV Panel rating}}$$

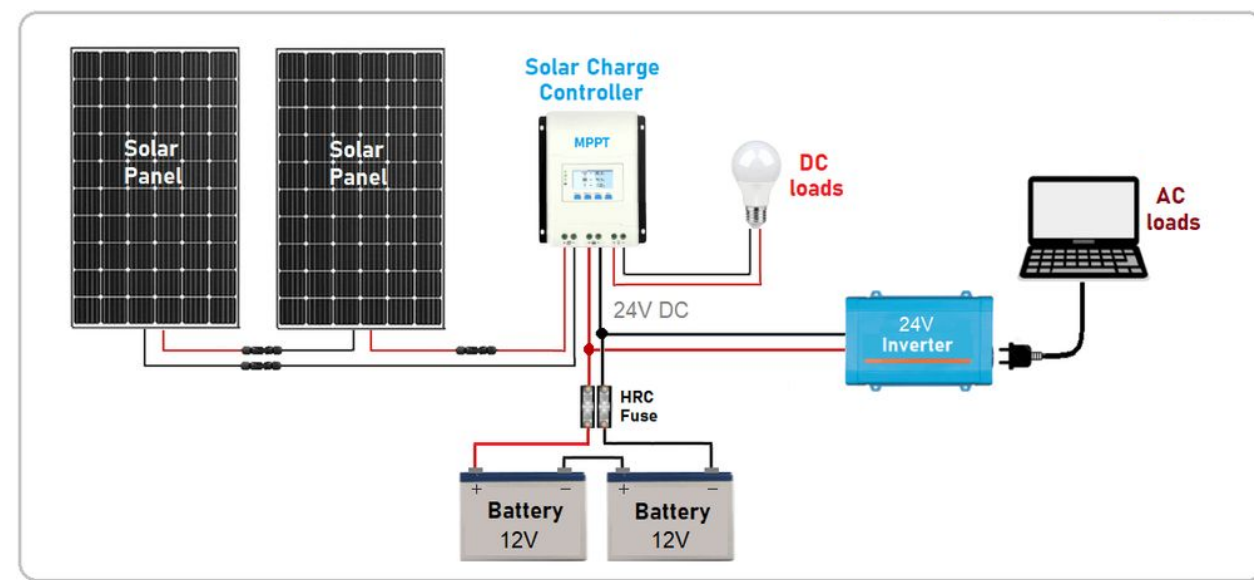
$$\text{Number of Panel} = \frac{2,100}{330} = 6.4$$

Number of Panels required = 7

Battery Bank:



Voltage Rating = 12 V
 Battery Rating = 100 Ah
 Depth of discharge = 50%
 Efficiency = 95%



$$\text{Battery bank capacity} = \frac{\text{Daily consumption}}{\text{Depth of discharge} \times \text{Efficiency} \times \text{System Voltage}}$$

Guidelines for System Voltage:

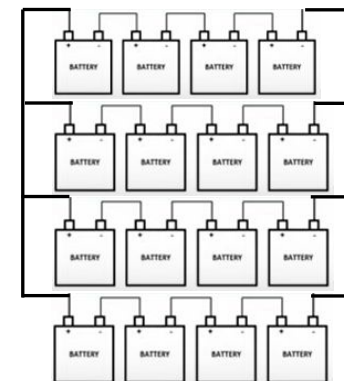
- 12 V – Small installations (< 1200 W)
- 24 V – Medium sized installation (1200 W – 2400 W)
- 48 V – Large installations (> 2400 W)

For this case, the system (Total load = 4945 W) > 2400 W. Therefore 48 V

$$\text{Battery bank capacity} = \frac{8.2 \text{ kWh}}{0.5 \times 0.95 \times 48 \text{ V}} = 359.6 \text{ Ah}$$

$$\begin{aligned} \text{Number of Strings} \\ &= \frac{\text{Battery Capacity}}{\text{Battery Rating}} = \frac{359.6}{100} = 3.6 \sim 4 \end{aligned}$$

$$\begin{aligned} \text{Number of Series} \\ &= \frac{\text{System Voltage}}{\text{Voltage Rating}} = \frac{48}{12} = 4 \end{aligned}$$



Number of Strings = 4
(Parallel connections)

Number of Series = 4

1 Battery = Rs 24,200

Inverter: Converts the variable direct current (DC) output of a PV panel into a utility frequency alternating current (AC)

Category of use	Appliance	Power (W)	Number of appliance	Total Power (W)	Multiplier	Total Power with Allowances (W)
Comfort/Leisure	Air conditioner	1500	1	1500	3	4500
	Television	85	1	85	1.3	110.5
	Fan	60	1	60	1.3	78
Refrigeration	Refrigerator	100	1	100	2	200
	Lighting	15	10	150	1.3	195
Cooking	Rice cooker	200	1	200	2	400
	Electric kettle	1200	1	1200	3	3600
Washing	Microwave oven	600	1	600	3	1800
	Washing machine	500	1	500	3	1500
Others	Computer	100	1	100	2	200
	Vacuum cleaner	450	1	450	3	1350

Minimum Inverter Power = 13,934 W

Rated Inverter Power (15,000 W) is greater than Minimum Inverter Power (13,934 W) and is suitable

Inverter Price = Rs 38,500

We account for surge power (sudden increase in power when switching on appliance) by multiplying the total power of each appliance type by a multiplying factor

For

- Lighter load multiply by 1.3
- Intermediate load x 2
- Heavier load x 3



Inverter Power Rating = 15 kW

Voltage Rating = 48 V

Solar Charge Controller:

A solar charge controller manages the power going into the battery bank from the solar array. It ensures that the deep cycle batteries are not overcharged during the day, and that the power doesn't run backwards to the solar panels overnight and drain the batteries.

Solar PV connection:

$$\text{Number of series} = \frac{V_{max}}{V_{oc}} = \frac{150 V}{48.8 V} = 3.07 \sim 3$$

$$\text{Number of strings} = \frac{\text{Number of PV panels}}{\text{Number of series}} = \frac{7}{3} = 2.33 \sim 3 \text{ (parallel connection)}$$

$$\begin{aligned} \text{Current generated by solar panel array} &= I_{sc} \times \text{Number of Strings} \times 1.25 \\ &= 9.94 \times 3 \times 1.25 \\ &= 37.3 A \end{aligned}$$

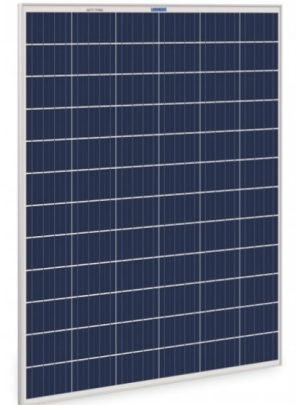
Rated I_{cc} of charge controller (70 A) is greater than current generated by solar panel array (37.3 A) and is suitable

Rs 31,250



V_{max} = 150 V

Current Charge Controller (I_{cc}) = 70 A



Buffer

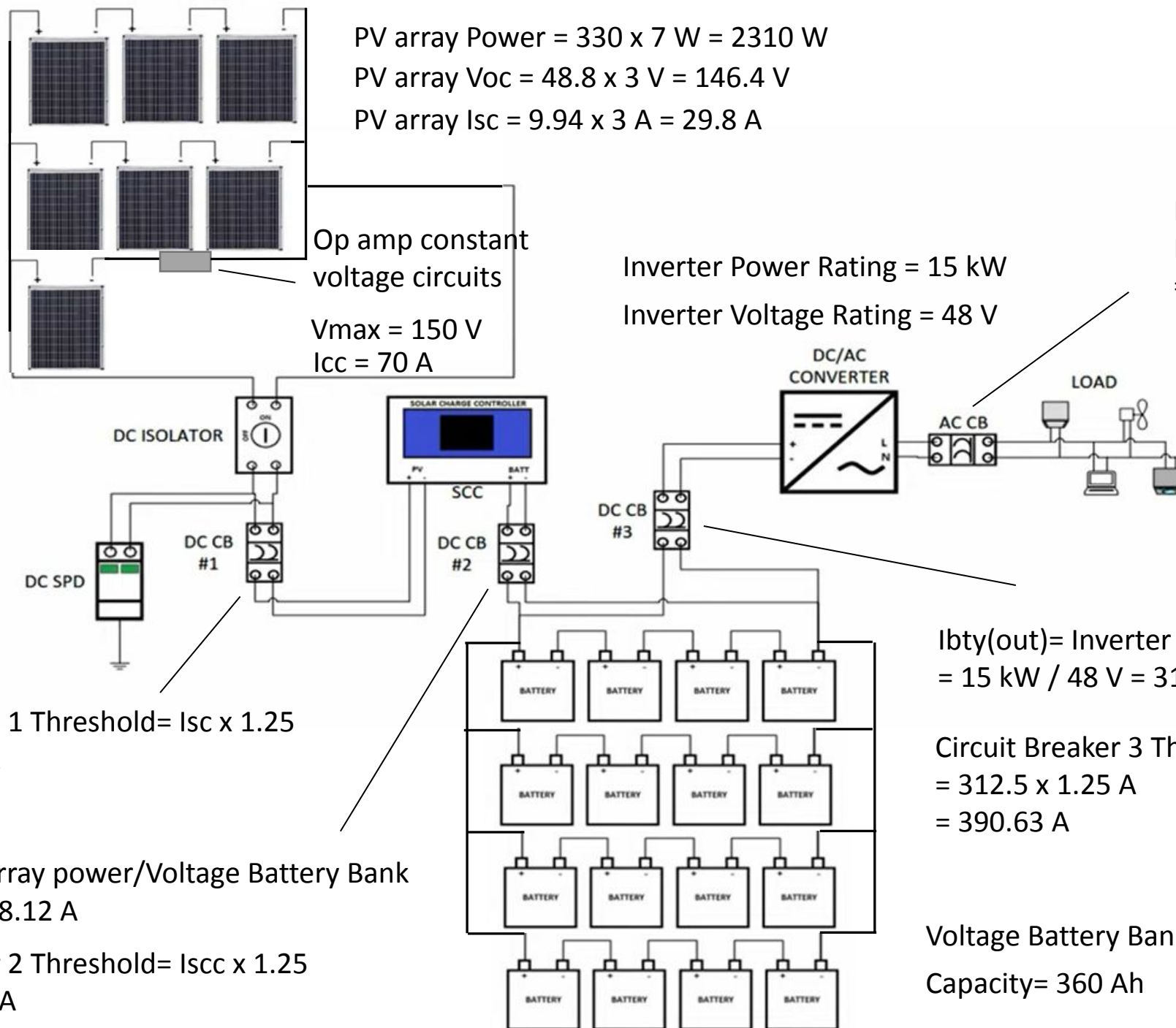
Rated Power = 330 W

Open Circuit Voltage (V_{oc}) - 48.8V

Short Circuit Current (I_{sc}) - 9.94A

Efficiency = 17%

Schematic of circuit:



PV array Power = $330 \times 7 \text{ W} = 2310 \text{ W}$
 PV array Voc = $48.8 \times 3 \text{ V} = 146.4 \text{ V}$
 PV array Isc = $9.94 \times 3 \text{ A} = 29.8 \text{ A}$

Op amp constant
voltage circuits

 $V_{\text{max}} = 150 \text{ V}$
 $I_{\text{cc}} = 70 \text{ A}$

Inverter Power Rating = 15 kW
 Inverter Voltage Rating = 48 V

$I_{\text{inv}}(\text{out}) = \text{Inverter Power Rating} / \text{Grid Voltage}$
 $= 15 \text{ kW} / 230 \text{ V} = 65.2 \text{ A}$

Circuit Breaker 4 Threshold
 $= I_{\text{inv}} \times 1.25$
 $= 65.2 \times 1.25 \text{ A}$
 $= 81.5 \text{ A}$

Circuit Breaker 1 Threshold = $I_{\text{sc}} \times 1.25$
 $= 29.8 \times 1.25 \text{ A}$
 $= 37.25 \text{ A}$

$I_{\text{sc}}(\text{out}) = \text{PV array power} / \text{Voltage Battery Bank}$
 $= 2310 / 48 = 48.12 \text{ A}$

Circuit Breaker 2 Threshold = $I_{\text{sc}} \times 1.25$
 $= 48.12 \times 1.25 \text{ A}$
 $= 60.15 \text{ A}$

$I_{\text{bt}}(\text{out}) = \text{Inverter Power Rating} / \text{Voltage Battery}$
 $= 15 \text{ kW} / 48 \text{ V} = 312.5 \text{ A}$

Circuit Breaker 3 Threshold = $I_{\text{bt}} \times 1.25$
 $= 312.5 \times 1.25 \text{ A}$
 $= 390.63 \text{ A}$

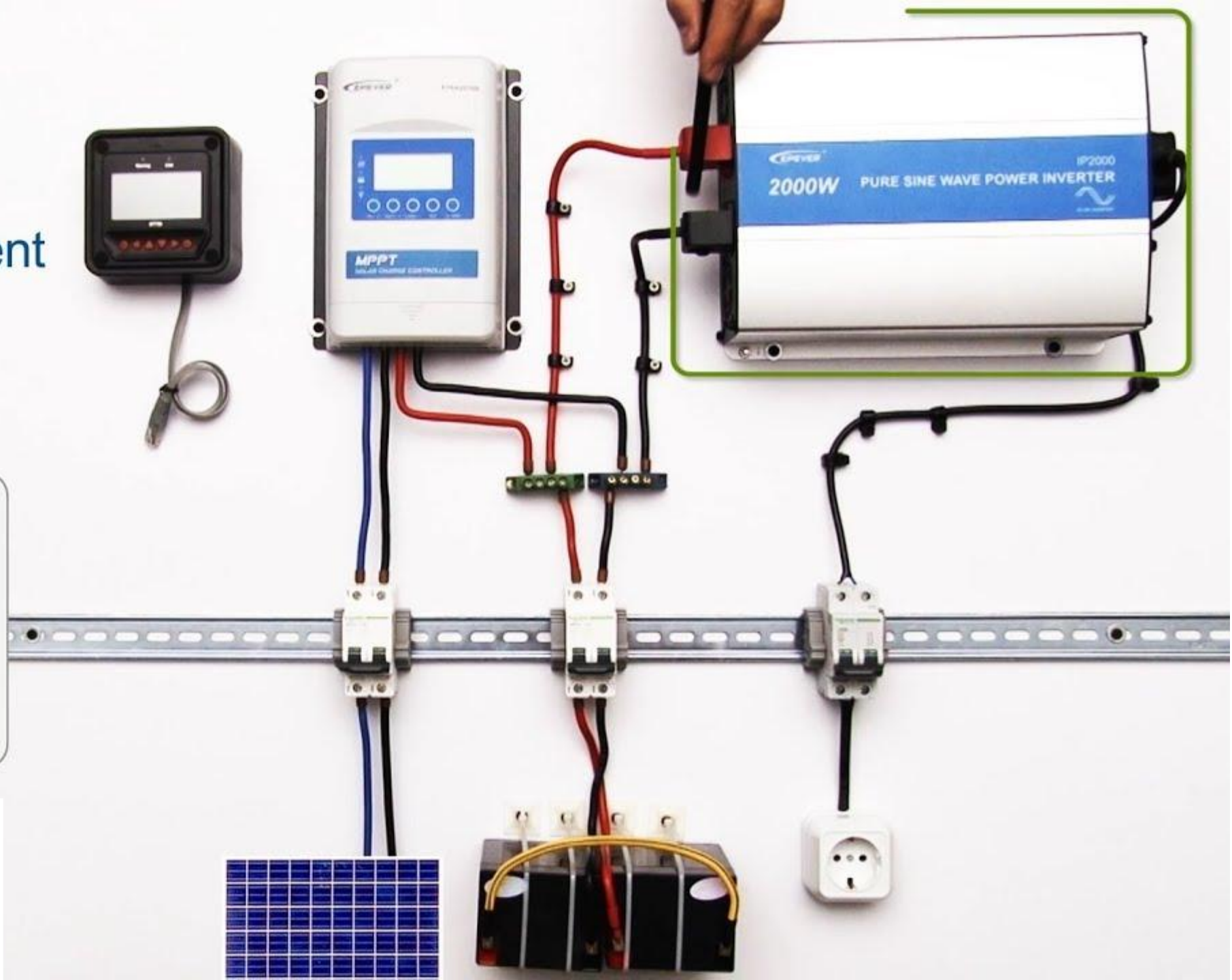
Voltage Battery Bank = $12 \text{ V} \times 4 = 48 \text{ V}$
 Capacity = 360 Ah

Inverter

Converting DC current
to AC current



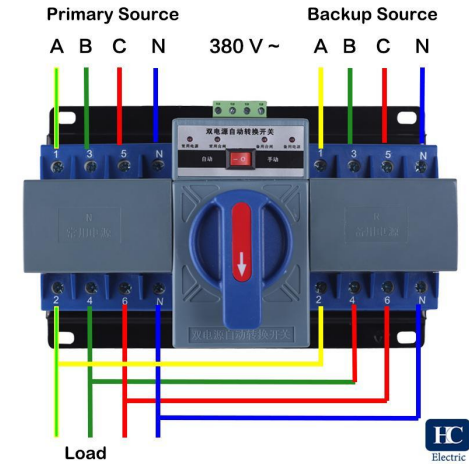
Off-grid solar
electric system



3. Hybrid System Design

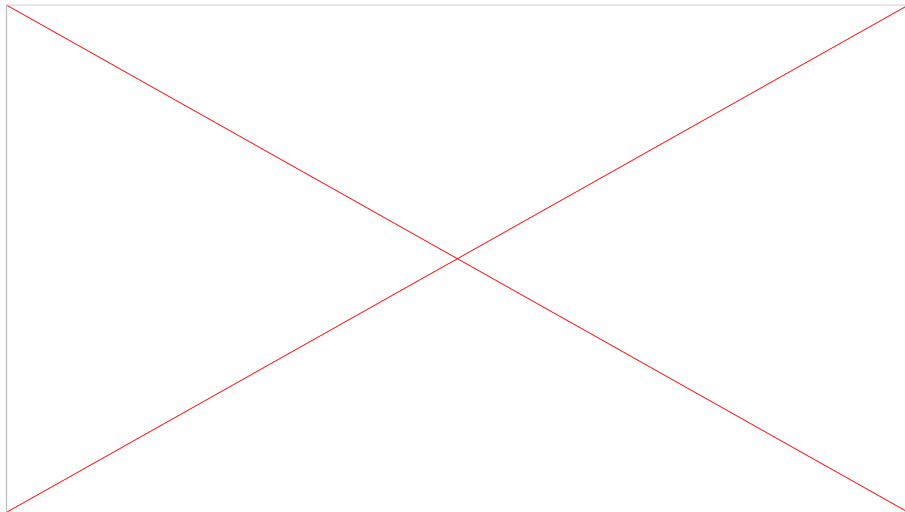
Hybrid case is similar to off-grid sizing apart from the fact that now the solar charge controller and inverter is combined into one equipment

There is also one additional equipment: Automatic Transfer Switch (ATS) – Ensures switch between primary power source and reserve power source



When stored energy of batteries is depleted, the ATS will automatically switch to backup source (grid)

3.1. Load Analysis



Determine Daily Power Consumption

- Check the monthly power consumption in electricity bill

$$\text{Monthly Power Consumption} = 170 \text{ kWh}$$

- Daily power consumption = Monthly power consumption / 30

$$\text{Daily Power Consumption} = 170 \text{ kWh} / 30 = 5.67 \text{ kWh}$$

3.2. Sizing of Solar PV Panels

- Check the sun peak hour of the site

A peak sun hour is any hour of the day when the sunlight's intensity is an average of 1000 W/m²

Sun peak hours = 5 hours (Reduced in summer)

Sun Peak hours varies from place to place

- Required Capacity of Solar Panel

PV Power = Daily Power Consumption / Sun Peak hours x 1.3

PV Power = 5.67 kWh / 5 h x 1.3

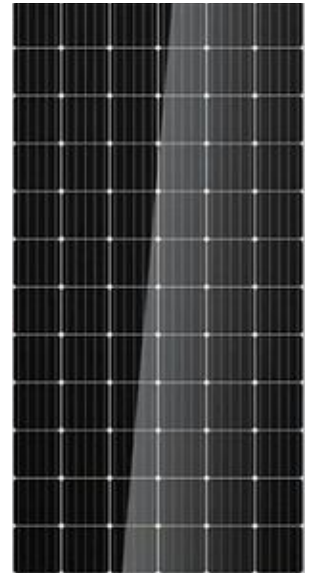
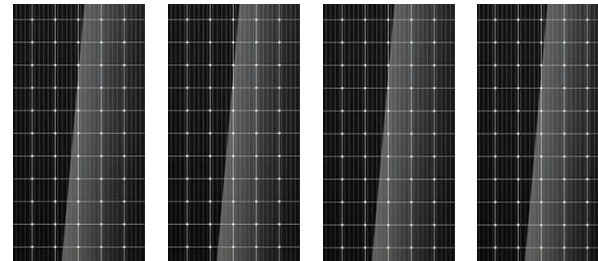
PV Power = 1.475 kW = 1,475 W (Daily power required from PV System)

- Number of Solar Panels

No. of PV Panels = PV Power / PV Panel Rating

No. of PV Panels = 1,475 W / 380 W

No. of PV Panels = 3.88 (~ 4 panels)



$P_R = 380 \text{ W}$
 $V_{OC} = 48.8 \text{ V}$
 $I_{SC} = 9.94 \text{ A}$
 $\text{Eff} = 19.5\%$

3.3. Sizing of Hybrid Inverter

- To size the inverter we need to take the PV power output of the actual PV array

Maximum PV Power = PV Panel Rating x No. of PV Panels

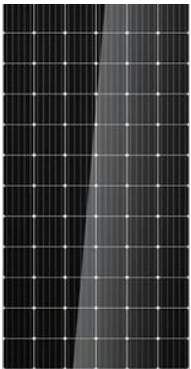
Maximum PV Power = 380 W x 4

Maximum PV Power = 1,520 W

- Choose an inverter with a maximum power (W_p) > Maximum PV Power (1,520 W)

Hybrid Inverter Rating = 3,000 W

- Check if voltage and current from PV system does not exceed voltage and current of inverter rating



$P_R = 380 \text{ W}$
 $V_{OC} = 48.8 \text{ V}$
 $I_{SC} = 9.94 \text{ A}$
Eff = 19.5%

Suppose connect PV Panel in series

PV Array V_{OUT} (series) = V_{OC} x No. of PV panels

PV Array V_{OUT} (series) = $48.8 V_{DC} \times 4$

PV Array V_{OUT} (series) = $195.2 V_{DC}$

PV Array V_{OUT} [$195.2 V_{DC}$] < Max V_{DC} input of inverter [$500 V_{DC}$]

PV Array I_{SC} (series) [9.94 A] < Max input current of inverter [18 A]

3.4. Sizing the Battery Bank

Equipment	Power (W)	Qty	Total Power (W)	Duration (Hrs)	Power Consumption (Wh)
LED Lights	9	4	36	7	252
LED TV	80	1	80	5	400
Electric Fan	65	2	130	8	1,040
Fridge	250	1	250	10	2,500
Laptop	80	1	80	4	320
Washing Machine	250	1	250	2	500
TOTAL					5,012 Wh/day



$$\text{Battery bank capacity} = \frac{\text{Daily consumption}}{\text{Depth of discharge} \times \text{Efficiency} \times \text{System Voltage}}$$

Guidelines for System Voltage:

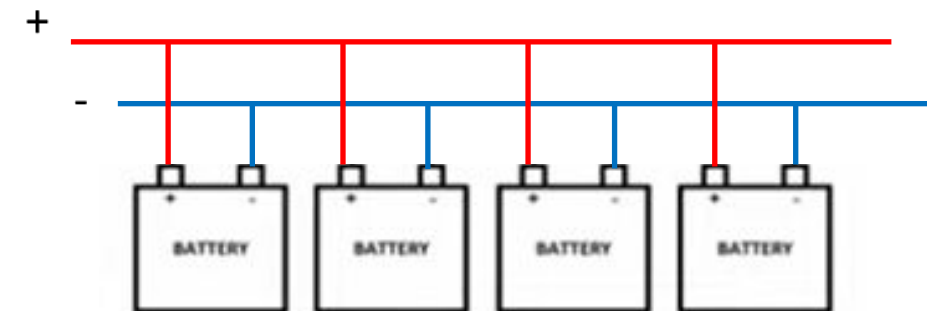
- 12 V – Small installations (< 1200 W)
- 24 V – Medium sized installation (1200 W – 2400 W)
- 48 V – Large installations (> 2400 W)

For this case, the system (Total load = 826 W) < 1200 W. Therefore 12 V

$$\text{Battery bank capacity} = \frac{5.012\text{ kWh}}{0.5 \times 0.85 \times 12\text{ V}} = 982.7\text{ Ah}$$

$$\begin{aligned} \text{Number of Strings} \\ &= \frac{\text{Battery Capacity}}{\text{Battery Rating}} = \frac{982.7}{250} = 3.9 \sim 4 \end{aligned}$$

$$\begin{aligned} \text{Number of Series} \\ &= \frac{\text{System Voltage}}{\text{Voltage Rating}} = \frac{12}{12} = 1 \end{aligned}$$

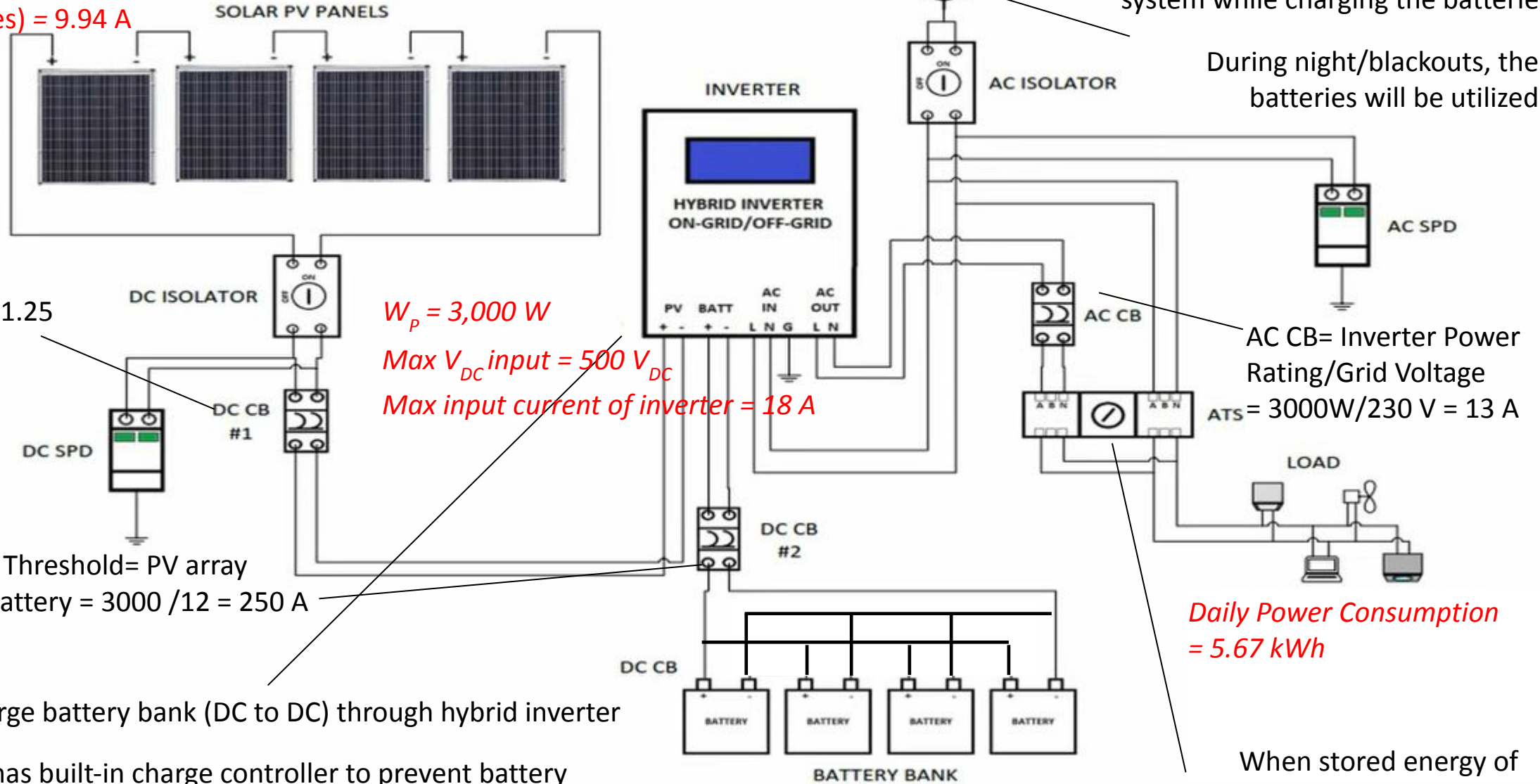


Parallel Connection

Maximum PV Power = 1,520 W

PV Array V_{OUT} (series) = 195.2 V_{DC}

PV Array I_{SC} (series) = 9.94 A



Circuit Breaker 1
Threshold = $I_{sc} \times 1.25$
= 9.94×1.25 A
= 12.425 A

Circuit Breaker 2 Threshold = PV array
power/Voltage Battery = $3000 / 12 = 250$ A

$W_p = 3,000$ W
 $Max V_{DC} input = 500$ V_{DC}
 $Max input current of inverter = 18$ A

Solar panels charge battery bank (DC to DC) through hybrid inverter

Hybrid inverter has built-in charge controller to prevent battery bank from overcharging

Hybrid inverter also converts DC to AC for use by appliances

Hybrid system connected to grid so that during day it can function as on-grid system while charging the batteries

During night/blackouts, the batteries will be utilized

AC CB = Inverter Power Rating / Grid Voltage
ATS = $3000W / 230 V = 13$ A

Daily Power Consumption = 5.67 kWh

When stored energy of batteries is depleted, the ATS will automatically switch to backup source (grid)

Voltage Rating = 12 V
Capacity = 250 Ah

