AC Bus Hybrid System Workshop

Introduction

- Walkthrough of design of AC bus Hybrid system with the following design decisions:
  - Generator used daily to meet demand
  - PV array is connected via a PV inverter
- Generator design and installation guidance can be found within Hybrid Design and Installation Guideline, however sizing of PV array and battery bank is covered in Off-grid PV system Design Guideline

Hybrid System Overview

- Any system that includes two charging sources is a hybrid system.
- This overview is only considering hybrid system comprising a fuel generator and PV array.
- The generator could just be for back-up when the solar is insufficient to meet the energy demand (e.g. during periods of bad weather) or it could be required to meet some of the energy demand each day.

Scenario Where Generator is Used Daily

- A village with 250 households is being powered by a diesel generator operating 24 hours a day, with a second generator onsite for redundancy.
- This village is receiving funding via an aid project to build a PV and battery system to supplement its current diesel generator power plant.
- The aim of the PV system is to reduce generator operation to 6pm – 11pm nightly.

Customer Requirement

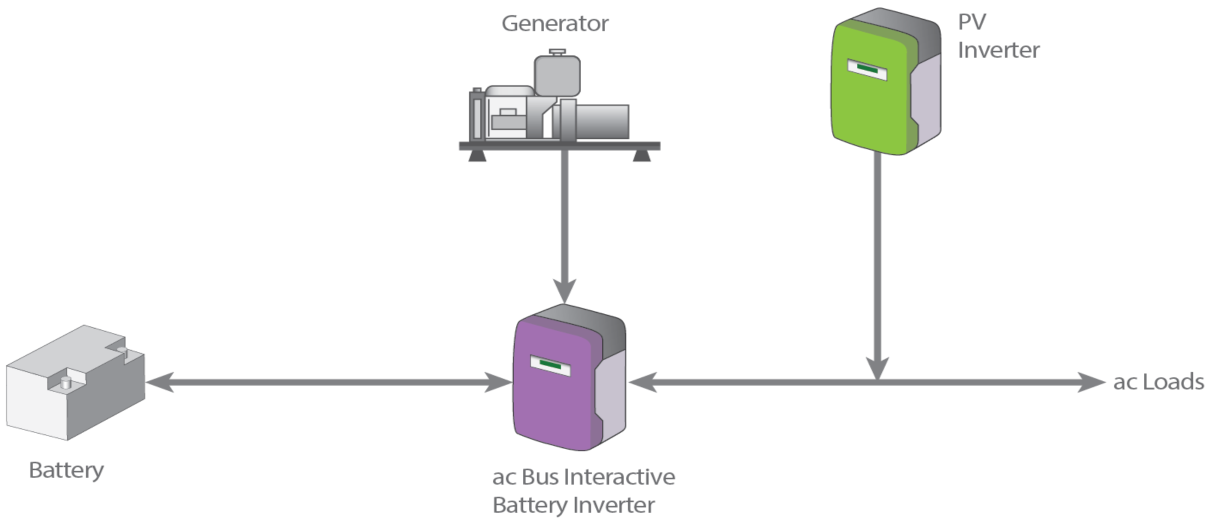
- Generator to operate nightly from 6pm to 11pm
- Sealed lead-acid batteries to be used.
- Batteries to have 3000 cycles with daily depth of discharge (DoD) no greater than 50%.

Site Information

- Two 110kVA diesel generators, derated by 10% due to temperature to 99kVA.
- Site location: Vanuatu, 15°S
- Annual irradiation deficit due to shadowing (horizontal): 0%
- Optimal array angle: 15° tilt
- Irradiation for design month (May) is 4.59kWh/m^2 or 4.59PSH
- Average temperature of May is 26.8^{o}C

System arrangement: Parallel System- ac Bus

- Nominal battery voltage: 48V
- Inverter waveform – Pure sine wave for proper operation of all electronic equipment
- Inverter type – ac bus interactive inverters from SMA's Sunny Island Range—3 single phase inverters in a 3-phase arrangement



Site Load Assessment

- Peak demand: 40kVA
- Average daily energy use: 450kWh
- Energy usage between 6pm and 11pm: 100kWh
- Percentage of daily use occurring between 6pm and 11pm: 22%
- It is assumed that the load is the same all year
- The load is the greatest in the daytime due to a number of daytime commercial operations. It then remains high during the evening peak.

Determine battery bank capacity

Given:

- Average daily energy use: 450kWh
- Energy usage between 6pm and 11pm: 100kWh
  - i.e. Generator in new system will supply 100kWh daily between 6pm and 11pm

Battery bank capacity = Average energy use – energy used when generator is running

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Determine energy provided by PV array and battery bank

Battery bank energy requirement = Average daily energy use – energy used when generator is running

Therefore:

- Energy that must be supplied by battery bank daily is 450kWh – 100kWh = 350 kWh

Determining the capacity of the Battery bank

The battery bank must be sized to meet the whole daily load that is being supplied by the PV array and battery bank, as there will be days where the solar irradiation is not available.

The equation used to calculate the energy required at the battery is:

$$E_{BATT}\,(Wh) = E_{BATT\_DAY} \div (DOD \times \eta_{INV})$$

Where

E_{BATT} = energy required from the battery bank
E_{BATT_DAY} = Total daily energy required from the battery
η_{INV} = *inverter efficiency*

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Determining the capacity of the Battery bank

Assumptions:

• Battery Inverter efficiency	94%
• Battery coulombic efficiency	90%
• Watt-hour efficiency of the battery	80%

Given:

- Client request DOD of 50%

Therefore:

$$E_{BATT} = E_{BATT\_DAY} \div (DOD \times \eta_{INV})$$

E_{BATT} = 350kWh / (0.5 x 0.94)

= 744.68 kWh

Determining the capacity of the Battery bank (Cont'd)

For lead-acid batteries, the amp-hour (Ah) battery capacity is calculate with:

$$C_x = E_{BATT} \div (V_{dc})$$

Where

C_x = capacity rating for given Cx. C_{10} rating should be used for lead acid battery.

V_{dc} = dc voltage of system

Determining the capacity of the Battery bank (Cont'd)

For lead-acid batteries, the amp-hour (Ah) battery capacity is calculate with:

$$C_x = E_{BATT} \div (V_{dc})$$

Where

V_{dc} = *48 V (safe voltage)*

C_{10} = 744.63kWh/48V

= *15,514kAh*

= *15514 Ah*

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Selecting the inverter

- From site load assessment:
  - Peak demand = 40kVA but only 35kVA during the times from 6pm to 11pm.

- Apply safety factor of 10%
  - Peak demand = 44kVA

- Peak demand required per phase is:

  = 44kVA / 3

  = 14.6 kVA

Selecting the inverter

- Peak demand required per phase is:

  = 14.6 kVA

  Two options: 3 x Sunny Island 8.0H(3 x 6 kW = 18kW), or

  4 x Sunny Island 6.0H (4 x 4.6kW = 18.4kW)

Technical Data	Sunny Island 4.4M	Sunny Island 6.0H	Sunny Island 8.0H
Operation on the utility grid or generator			
Rated grid voltage / AC voltage range		230 V / 172.5 V to 264.5 V	
Rated grid frequency / permitted frequency range		50 Hz / 40 Hz to 70 Hz	
Maximum AC current for increased self-consumption (grid operation)	14.5 A	20 A	26 A
Maximum AC power for increased self-consumption (grid operation)	3.3 kVA	4.6 kVA	6 kVA
Maximum AC input current	50 A	50 A	50 A
Maximum AC input power	11500 W	11500 W	11500 W
Stand-alone or emergency power operation			
Rated grid voltage / AC voltage range		230 V / 202 V to 253 V	
Rated frequency / frequency range (adjustable)		50 Hz / 45 Hz to 65 Hz	
Rated power (at Unom, fnom / 25 °C / cos φ = 1)	3300 W	4600 W	6000 W
AC power at 25 °C for 30 min / 5 min / 3 sec	4400 W / 4600 W / 5500 W	6000 W / 6800 W / 11000 W	8000 W / 9100 W / 11000 W
AC power at 45 °C continuously	3000 W	3700 W	5430 W
Rated current / maximum output current (peak)	14.5 A / 60 A	20 A / 120 A	26 A / 120 A
Total harmonic distortion output voltage / power factor at rated power	< 5% / −1 to +1	< 1.5% / −1 to +1	< 1.5% / −1 to +1
Battery DC input			
Rated input voltage / DC voltage range	48 V / 41 V to 63 V	48 V / 41 V to 63 V	48 V / 41 V to 63 V
Maximum battery charging current / rated DC charging current / DC discharging current	75 A / 63 A /75 A	110 A / 90 A / 103 A	140 A / 115 A /130 A

Selecting the inverter

- Sunny Island 8.0H chosen, partitioned into groups (clusters) of 3 inverters to form a 3-phase grid.
- 3 clusters needed to exceed 14.6kVA per phase
- 9 inverters needed in total

Technical Data	Sunny Island 4.4M	Sunny Island 6.0H	Sunny Island 8.0H
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Battery DC input			
Rated input voltage / DC voltage range	48 V / 41 V to 63 V	48 V / 41 V to 63 V	48 V / 41 V to 63 V
Maximum battery charging current / rated DC charging current / DC discharging current	75 A / 63 A /75 A	110 A / 90 A / 103 A	140 A / 115 A /130 A
Battery type / battery capacity (range)	Li-Ion[1], FLA, VRLA / 100 Ah to 10000 Ah (lead-acid) 50 Ah to 10000 Ah (li-Ion)		

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Selecting a Battery Model

- The battery bank will is selected from the Sonnenschein Solar range of batteries due to it meeting the 3000+ cycle at 50% DoD requirement.

- The required battery capacity is 15514Ah, the largest battery in this range has a capacity of 3036Ah at C_{10} , so three parallel banks will be required. (15514/3036 =5.11 (Round up to 6)> 2)

- Therefore each string should have capacity greater than:

  = 15514/6 = 2585.6 Ah.

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Selecting a Battery Model

From the table below the battery that is greater than 2586 Ah at C_{10} is the model number A602/3920 with 3036Ah

- Six strings (connected to 3 cluster of inverters) would provide a battery bank of 6 x 3036= 18216Ah. 17% greater than required.
- Model A602/3270 has a C_{10} rating of 2530Ah but is smaller and only about 2.2% less than the energy required. (6 x 2530 Ah = 15180Ah, 15180/15514 = 0.978)
- In this case, A602/3270 is acceptable, but in other situations final decision may come down to undertake full life cycle analysis in real life events

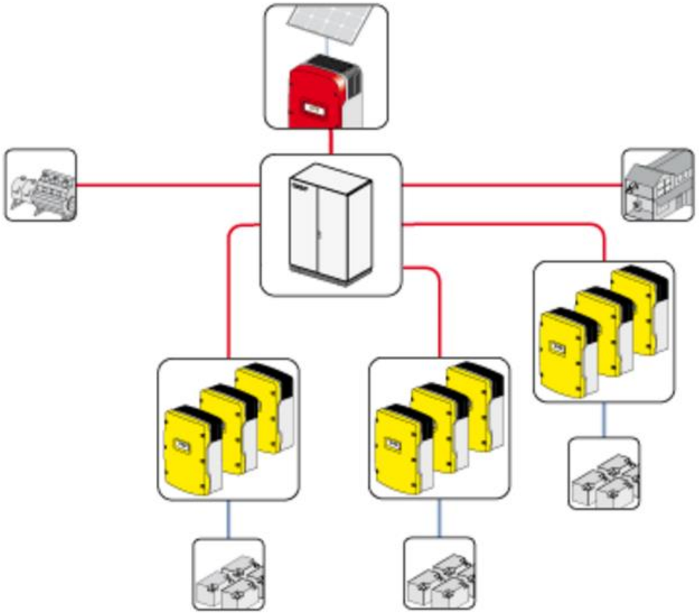
Capacities C_1 - C_{120} (20 °C) in Ah

Type	C_1 1.67 Vpc	C_3 1.75 Vpc	C_5 1.77 Vpc	C_{10} 1.80 Vpc	C_{24} 1.80 Vpc	C_{48} 1.80 Vpc	C_{72} 1.80 Vpc	C_{100} 1.85 Vpc	C_{120} 1.85 Vpc
A602/295 SOLAR	124	167	193	217	248	273	289	285	294
A602/370 SOLAR	155	209	241	272	310	342	362	357	367
A602/440 SOLAR	186	251	289	326	372	410	434	428	440
A602/520 SOLAR	229	307	342	379	435	471	503	505	519
A602/625 SOLAR	275	369	410	455	523	565	604	606	623
A602/750 SOLAR	321	431	479	531	610	659	705	707	727
A602/850 SOLAR	368	520	614	681	729	782	827	822	845
A602/1130 SOLAR	491	694	818	908	973	1043	1102	1096	1126
A602/1415 SOLAR	614	867	1023	1135	1216	1304	1378	1370	1408
A602/1695 SOLAR	737	1041	1228	1362	1459	1565	1654	1644	1689
A602/1960C SOLAR	867	1222	1371	1593	1803	1942	2016	1957	1994
A602/2600 SOLAR	1047	1548	1782	2024	2276	2472	2599	2547	2613
A602/3270 SOLAR	1309	1935	2227	2530	2846	3090	3249	3184	3266
A602/3920 SOLAR	1571	2322	2673	3036	3415	3708	3899	3821	3919

Battery arrangement

6 strings of battery bank, 2530 Ah and 48V each, need to be connected to 3 clusters of 3-phase inverter.

- Battery capacity to be spread as evenly across inverters as possible
- Each inverter clusters connected to 2 x 2530 Ah banks in parallel



Sizing the Battery Charger

Check Generator availability

- Each night the generator will operate for 5 hours. The generator is derated to 99kVA while the maximum (peak demand) during the hours that the generator operates is 35kVA.
- **Therefore, the minimum available capacity available for charging the batteries**

= 99kVA-35kVA = 63kVA

Nameplate capacity of system inverters

= 9 x 6kVA = 54kVA < 63kVA

Sizing the Battery Charger

Calculate maximum charge current

- The chosen inverter, SMA Sunny Island 8.0H has a maximum charge current of 140A at full rating of 6kW. Three inverters making three phases gives the maximum charge current of

  = 3 x 140A = 420A

Sizing the Battery Charger

- The maximum charging current for a battery is 0.1x C10 capacity rating. The maximum charge current for the selected battery bank is

= 0.1 x 5060

= 506A each for two parallel strings connected to an inverter cluster

Sizing the Battery Charger

- Each inverter clusters' maximum charge current is 420A;
- The battery bank can accept up to 506A of charge current.
- As 506A > 420A, the battery can accept the inverter's maximum charge current.

Daily energy charged by generator

Estimate charging current

- Sunny Island 8.0H has a maximum charge current of 140A, at 1.8V per cell for 24 cells, this gives 6048kVA.
- However as the battery voltage rises the current will decrease.
- To be conservative we assume that the average charging current while the genset is operating is 110A per inverter.
- The estimated charge current for the whole system would be:

= 110A x 9

= 990A

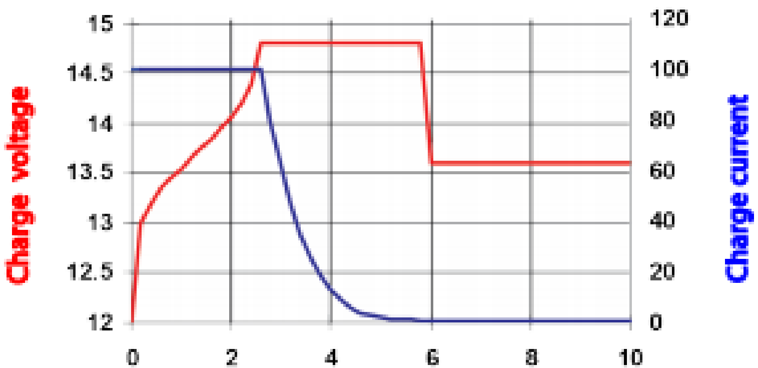


Fig. 3: Three step charge curve

Daily energy charged by generator

Calculate charge capacity

- The charge capacity = charge current x charging duration. Therefore the charge capacity of the battery bank if it is charged for 5 hours is

= 5h x 990Ah = 4950Ah

Daily energy charged by generator

Calculate energy supplied by generator via battery

- With a battery columbic efficiency of 90%, DC interactive inverter efficiency of 94% and battery system voltage of 48V, the daily energy that will be supplied by the batteries which is charged by the generator is

E_{GEN_BATT}= (4950 x 0.9 x 0.94 x 48)/1000

= 201.009 kWh

= 201 kWh

Determine the portion of energy that is to be supplied by the PV array

- For a hybrid system where the generator is operating daily, the total daily energy requirement is determined as follows:

$$E_{LOAD} = E_{GEN} + E_{GEN\text{-}BATT} + E_{PV\text{-}DIR} + E_{PV\text{-}BATT}$$

- *Where*
  - *E_{LOAD} = Total daily energy*
  - *E_{GEN} = Portion of daily energy being supplied directly by generator*
  - *E_{BATT_GEN} = Portion of daily energy being provided by battery bank being charged by generator.*
  - *E_{PV_DIR} = Portion of daily energy that will be provided by the PV array*
  - *E_{PV_BATT} = Portion of daily energy being provided by battery bank being charged by PV array*

Determine the portion of energy that is to be supplied by the PV array

- Rearrange the equation, the portion of daily energy that will be provided by the PV array is

$$E_{PV} = E_{PV\text{-}DIR} + E_{PV\_BATT} = E_{LOAD} - E_{GEN} - E_{GEN\_BATT}$$

We know that

$$E_{LOAD} = 450\text{kWh}$$

$$E_{GEN} = 100\text{kWh}$$

$$E_{GEN\_BATT} = 201\text{kWh}$$

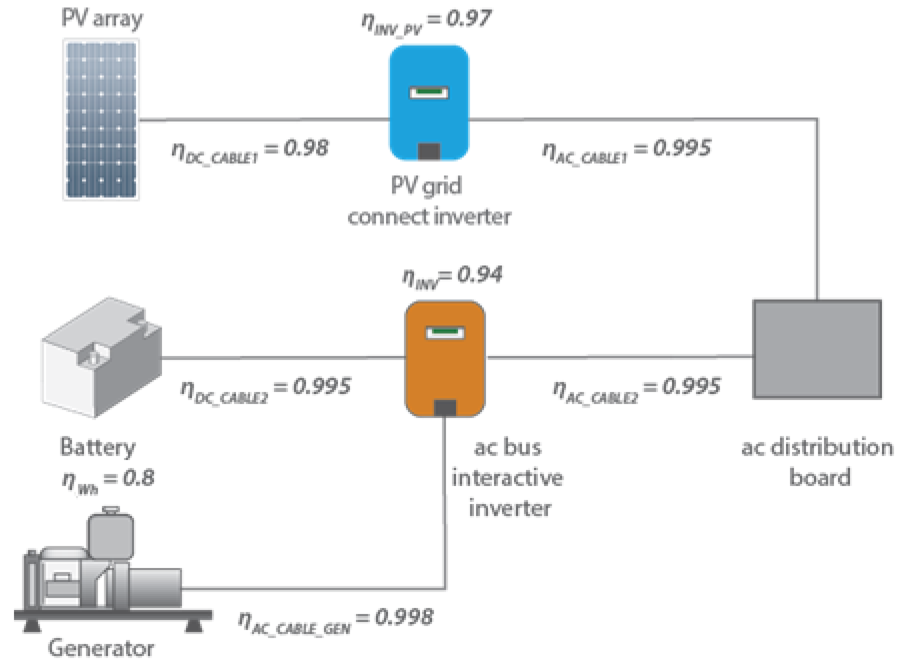
Therefore

$$E_{PV} = 450 - 100 - 201$$

$$= 149 \text{ kWh}$$

Determining Size of PV Array

- The AC load to be supplied by the PV array is 149kWh
- The irradiation is 4.59 kWh/m²/day.
- A block diagram is useful to show all major losses.
- Many principles in this section are covered in grid-connect and off-grid PV systems design guidelines



System Information

System efficiencies

- Battery coulombic efficiency (η_{COUL}) 90%
- Watt-hour efficiency of the battery (η_{WH}) 80%
- Inverter efficiency(η_{INV}) 94%
- Inverter efficiency when acting as charger (η_{INV_CHG}) 94%
- PV inverter efficienc (η_{PV}) 97%
- Oversize coefficient (f_o) 1
- Dirt de-rating(f_{DIRT}) 95%
- Ambient Temperature 26.8°C

System characteristics

- Nominal power rating (P_{STC}) 290W_p
- Power tolerance (f_{MAN}) +0W to 5W Equivalent to
- P_{max} Temp Co-efficient(γ) -0.39% / °C

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Calculate PV Module Derated Power

PV module power is effected by temperature

To calculate temperature derating factor:

$$F_{\text{TEMP}} = 1 + [\gamma \times (T_{\text{CELL-EFF}} - T_{STC})]$$

Where

$T_{\text{CELL-EFF}}$ = ambient temperature + 25 °C

= 26.8 °C + 25 °C

Therefore

F_{TEMP} = 1+[-0.39/100×(26.8°C+25 °C−25°C)]

= 0.896

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Calculate PV Module Derated Power

PV Module power, derated for local condition, is calculated by the equation:

$$P_{MOD} = P_{STC} \times F_{MAN} \times F_{TEMP} \times F_{DIRT}$$

P_{MOD} = 290 W × 1 × 0.896 × 0.95

= 246.7 W

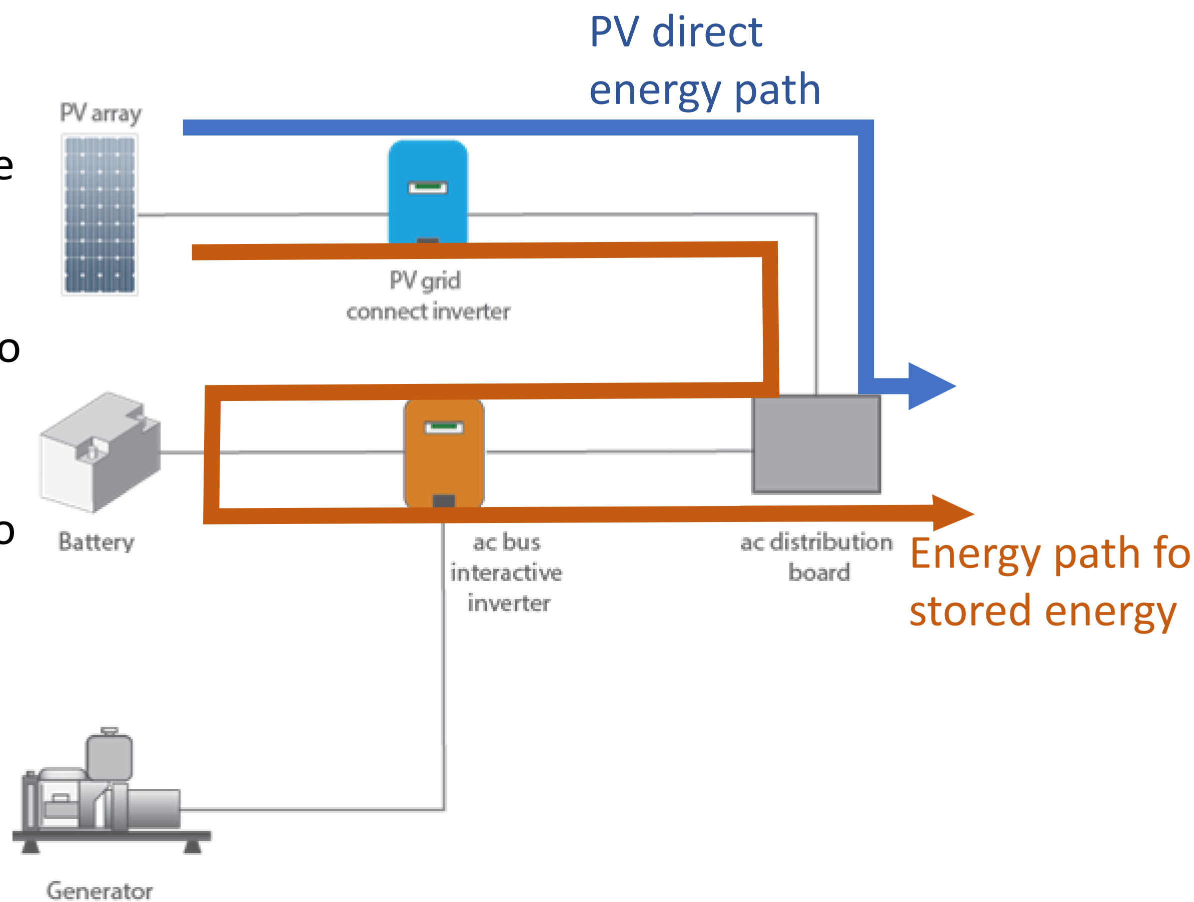
= 247W

Calculate PV Array Required

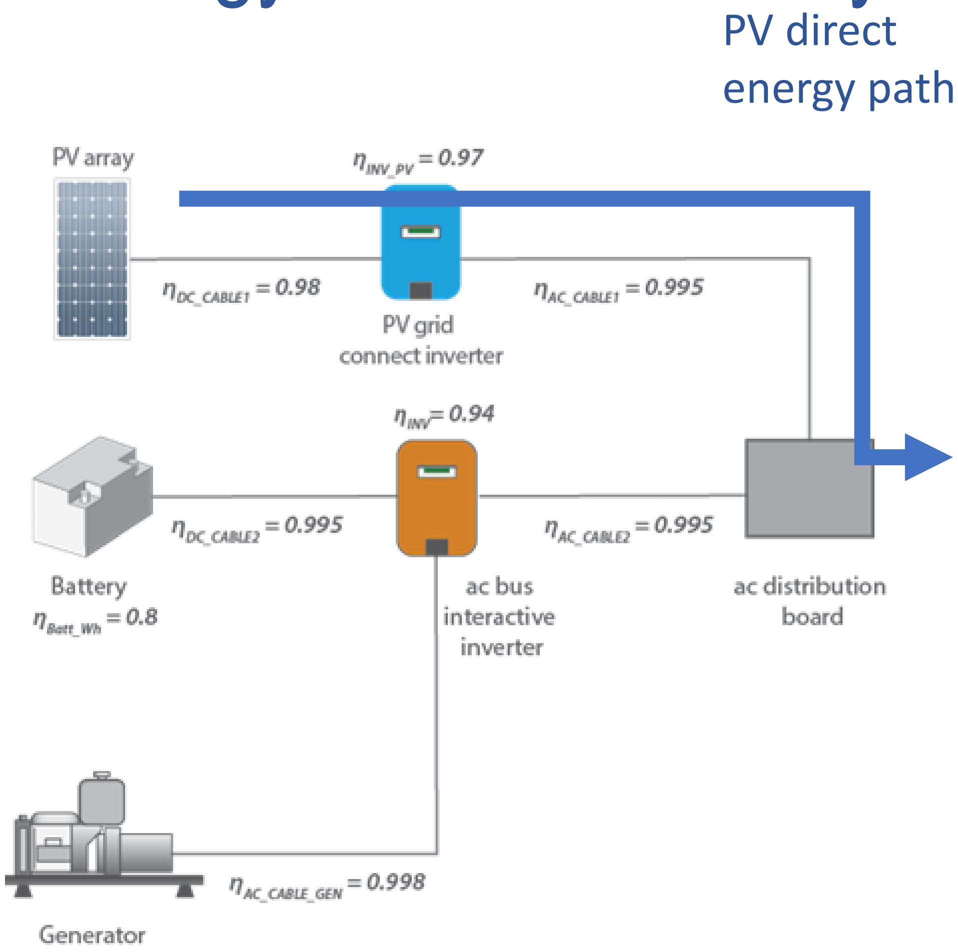
The PV array need to provide 149kWh/day. There are two ways this can happen:

- Provide energy directly to loads during the day
- Provide extra energy to battery during the day, to discharge from battery during the night

Energy losses is greater for charging battery for later use, therefore the PV array requirement needs to be separately calculated.



Calculate Number of Modules Needed for Energy from PV Directly



Calculate Number of Modules Needed for Energy from PV Directly

The energy directly supplied by the PV array is calculated by:

$$E_{PV\_DIR} = E_{ac5} = P_{MOD} \times N \times H_{TILT} \times \eta_{PV} \times \eta_{PV\text{-}Load}$$

where:

- E_{ac5} = ac energy directly supplied by PV Array (Wh)
- P_{MOD} = derated power from a module (W)
- N = number of modules in the array (Dimensionless)
- H_{ILT} = daily irradiation (in *PSH*) for the specified tilt angle and orientation (hour)
- η_{PV} = PV Inverter efficiency (dimensionless)
- $\eta_{PV\text{-}Load}$ = cable (transmission) efficiency (dimensionless)

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Calculate Number of Modules Needed for Energy from PV Directly

Rearrange the equation, The number of solar modules required in the arrays is determined as follows:

$$N_{PV\_DIR} = E_{PV\_DIR} / (P_{MOD} \times H_{TILT} \times \eta_{PV} \times \eta_{PV\_LOAD})$$

where:

P_{MOD} = 247W

H_{TILT} = 4.59 PSH

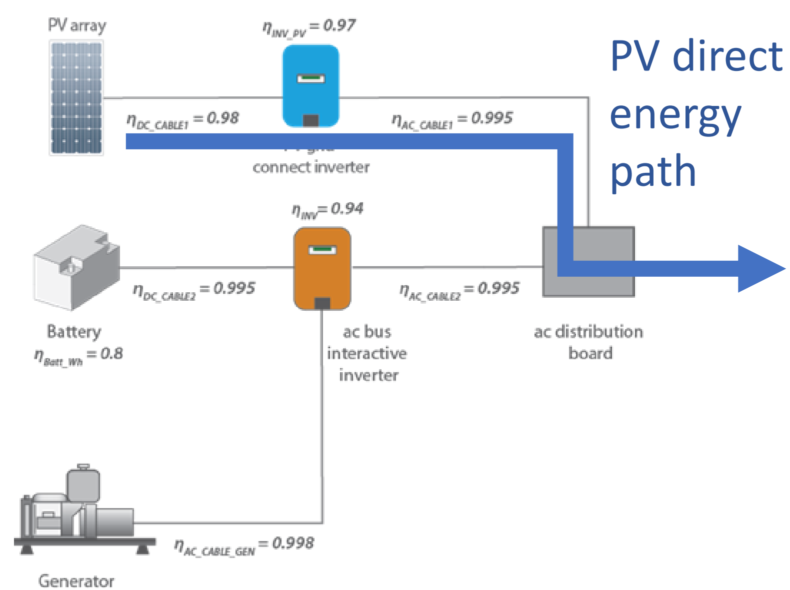
η_{PV} = 0.97

η_{PV_LOAD}

$= \eta_{ac\_cable1} \times \eta_{dc\_cable1}$

$= 0.995 \times 0.98$

$= 0.9751$



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Calculate Number of Modules Needed for Energy from PV Directly

- Assume that 100% of the remaining load can be met directly with PV
- i.e. E_{PV_DIR} = 149kW = 149,000W
- Number of modules required would be:

$$N_{PV\_DIR} = E_{PV}/(P_{MOD} \times H_{TILT} \times \eta_{PV} \times \eta_{PV\_Subsys})$$

$$=149000/(247 \times 4.59 \times 0.97 \times 0.9751)$$

= 138.95

= 139 modules

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Calculate Number of Modules Needed for Energy from PV Directly

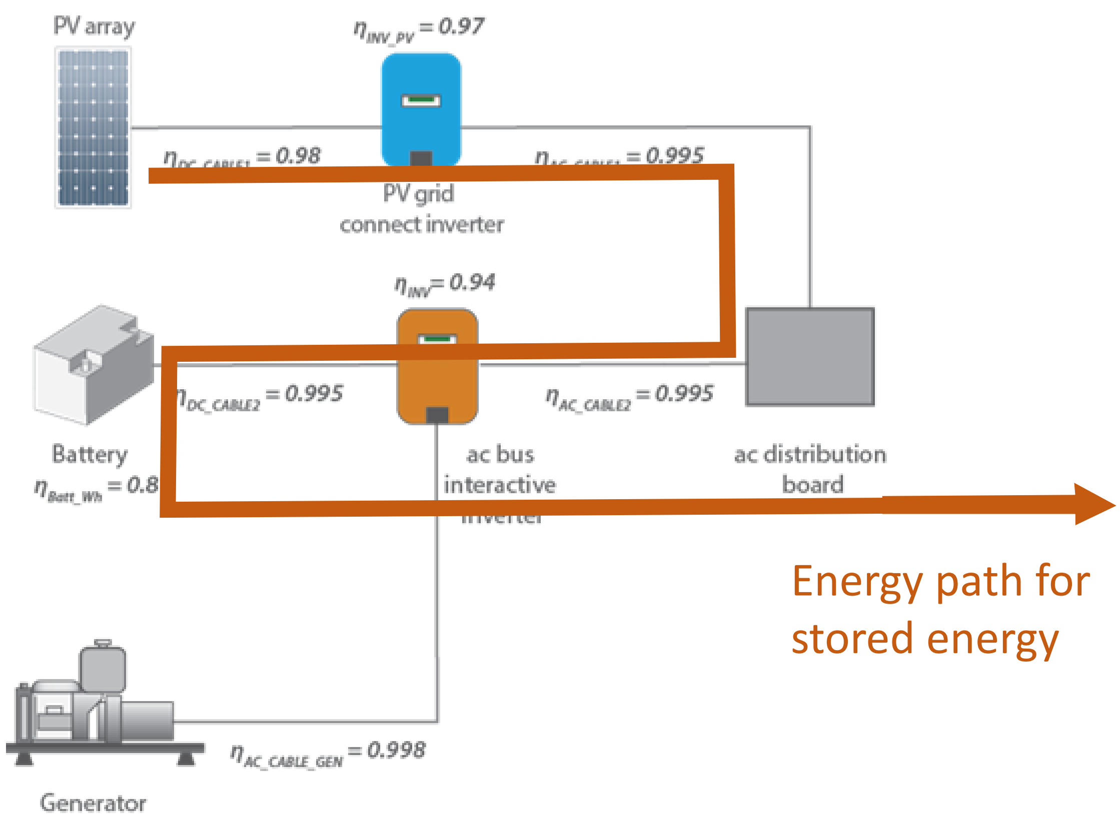
- Assume that 100% of the remaining load can be met directly with PV
- Array Size would be

  139 modules × 290W

  = 40310Wp

  = 40.31 kWp

Calculate Number of Modules Needed for Energy from PV via Battery



Calculate Number of Modules Needed for Energy from PV via Battery

The energy supplied by the PV array via the battery is calculated by:

$$E_{PV\_BATT} = E_{ac6} = P_{MOD} \times N \times H_{TILT} \times \eta_{PVINV} \times \eta_{INV\text{-}CHG} \times \eta_{WH} \times \eta_{INV} \times \eta_{PV\text{-}Load}$$

where:

- E_{ac6} = ac energy directly supplied by battery bank charged by PV Array (Wh)
- P_{MOD} = derated power from a module (W)
- N = number of modules in the array (Dimensionless)
- H_{TILT} = daily irradiation (in *PSH*) for the specified tilt angle and orientation (hour)
- η_{WH} = Watt-Hour efficiency of the battery (dimensionless)
- η_{PV} = PV Inverter efficiency (dimensionless)
- η_{INV_CHG} = Inverter efficiency acting as battery charger (dimensionless)
- η_{INV} = Inverter efficiency (dimensionless)
- $\eta_{PV\text{-}Load}$ = cable (transmission) efficiency (dimensionless)

Calculate Number of Modules Needed for Energy from PV via Battery

Rearrange the equation, The number of solar modules required in the arrays is determined as follows:

$$N_{PV} = E_{PV}/(P_{MOD} \times H_{TILT} \times \eta_{PV} \times \eta_{INV\text{-}CHG} \times \eta_{WH} \times \eta_{INV} \times \eta_{PV\_LOAD})$$

where:

P_{MOD} = 247W

H_{TILT} = 4.59 PSH

η_{PV} = 0.97

$\eta_{INV\text{-}CHG}$ = 0.94

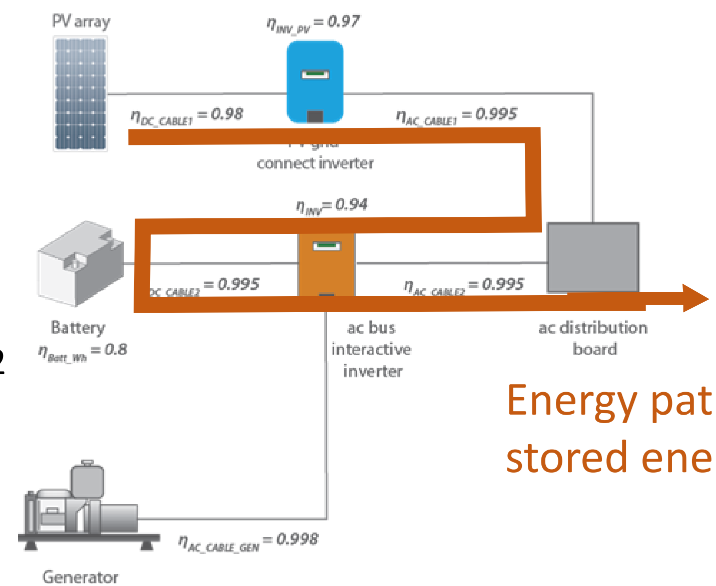
η_{WH} = 0.8

η_{INV} = 0.94

$\eta_{PV\_LOAD} = \eta_{dc\_cable1} \times \eta_{ac\_cable1} \times \eta_{ac\_cable2} \times \eta_{dc\_cable2} \times \eta_{dc\_cable2} \times \eta_{ac\_cable2}$

= 0.98 x 0.995^5

= 0.9557



Energy path for stored energy

Calculate Number of Modules Needed for Energy from PV via Battery

- Assume that 100% of the remaining load will be met with stored battery energy charged from the PV array
- i.e. E_{PV_BATT} = 149kW = 149,000W
- Number of modules required would be:

$$N_{PV\_BATT} = E_{PV\_BATT} / (P_{MOD} \times H_{TILT} \times \eta_{PV} \times \eta_{INV\text{-}CHG} \times \eta_{WH} \times \eta_{INV} \times \eta_{PV\_LOAD})$$

$$= 149000/(247 \times 4.59 \times 0.97 \times 0.94 \times 0.8 \times 0.94 \times 0.9751)$$

$$= 196.57$$

= 197 modules

Calculate Number of Modules Needed for Daytime load

- Assume that 100% of the remaining load will be met with stored battery energy charged from the PV array
- Array Size would be

$$197 \text{ modules} \times 290\text{W}$$

$$= 57130 \text{ Wp}$$

$$= 57.13 \text{ kWp}$$

PV Array Size Summary

- If 100% of the remaining load will be met by the PV array, required PV array size is:

  40.31 kWp

- If 100% of the remaining load will be met with stored battery energy charged from the PV array, required PV array size is:

  57.13 kWp

PV Array Sizing

- What if we assume 50% of PV array energy will directly supply load and 50% of PV array energy will be supplied via battery?

  N_{PV_DIR} = 69.475

  N_{PV_BATT} = 98.25

- Total number of modules required would be:

  $N_{PV\_DIR} + N_{PV\_BATT} = 167.725$

  = 168 modules

- Array size would be

  = 168 x 290Wp

  = 48720 Wp

  = 48.72 kWp

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System Summary

Generator run time: 6-11pm

Spare capacity from generator during run-time is used to charge battery

Inverter model: SMA Sunny Island 8.0H

Inverter arrangement: 3 clusters of inverter, each cluster consisting of one inverter in each phase

Battery bank capacity: three 5060 Ah banks, one connected to each 3-phase inverter cluster

Battery bank arrangement: 2 x 48V strings

Minimum PV array size: 48.72kW$_P$ (Assumes 50% of PV energy is directly consumed)

Discussion: Ratio of PV array providing direct energy and PV array charging battery

- ac bus PV array suffer more efficiency losses to store energy in battery than to deliver energy directly.
- A sizing program can be used to compare PV array size and genset run times to optimise the system.
- Site requirements could be anywhere between readily available CAPEX and low OPEX, which favours PV, to low availability of CAPEX and somewhat higher OPEX, which favours a genset.

Discussion: System dc Voltage, Maximum Demand, Battery Capacity and Configuration

- The appropriate system voltage

depends on the maximum charge or discharge rate that the batteries will experience, which

depends on the size and type of inverter chosen, which in turn

depends on the system load and also

depends on the system configuration (ac vs dc bus)

Note: **Typically** the d.c. voltage range of the chosen inverter could dictate the battery voltage.

Questions?


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