DC Bus Hybrid System Workshop

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Introduction

- Walkthrough of design of dc bus Hybrid system with the following design decisions:
  - Generator used as backup only
- 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

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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.

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System when Generator is Back-up

- In these systems the design of the solar system will be the same as previously covered in the design guidelines.
- The generator will then operate during periods of bad weather or if the loads energy is exceeding that be in provided by the solar array.

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Customer requirement

- A guesthouse owner is looking to install a dc bus hybrid system as their generator is due for replacement. They would like:
  - A battery bank with 2 days of autonomy without needing to run the generator in the event of bad weather.
  - A new generator that would meet the maximum demand of the loads but will also provide maximum charging current possible from the inverters and the selected battery bank
- This hybrid system will therefore use the generator as a back-up only.

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Site information

- Site location: Vanuatu,15°S
- Large available roof facing North
- Occupants, 4 adults full time (owners + 2 staff)
- 4 guest rooms for up to 12 guests.

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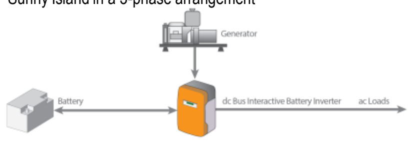
System Arrangement: dc Bus Hybrid

- The following dc bus hybrid system has been selected:
  - Three-phase system
  - Nominal battery voltage: 48V
  - Inverter waveform: Pure sine wave for proper operation of all electronic equipment
  - Inverter type – dc bus interactive inverters—3 single phase SMA Sunny Island in a 3-phase arrangement



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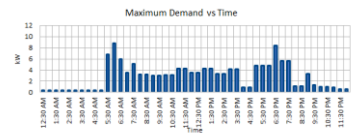
Load Assessment

- A data-logger was used to measure demand and energy consumption over a typical day with full occupancy
- Results:
  - Average daily consumption: 50kWh
  - Max Demand: 9 kVA
  - Surge demand: 12kVA (not shown)



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Determine required capacity of inverter

- **Max demand**

Assuming the loads are balanced across the system, divide the site's max demand by the number of phases to obtain the max demand per phase

= 9,000VA / 3 = 3000 VA

Applying a 10% safety factor

Inverter minimum required max demand = 1.1 * 3000 = 3300 VA

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Determine required capacity of inverter

- **Surge demand**

Assuming the loads are balanced across the system, divide the site's surge demand by the number of phases to obtain surge demand per phase.

= 12,000 / 3 = 4000 VA

Applying a 10% safety factor

Inverter minimum rated surge demand = 1.1*4000 = 4400 VA

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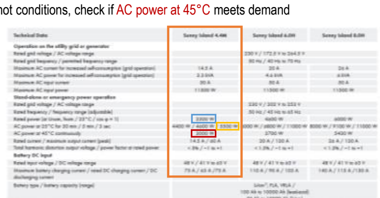
Select the Inverter

- The inverter's continuous demand rating should meet the required maximum demand. Its surge demand should meet the required surge demand
- Inverter power output can be assumed as unity, ie 1W = 1VA
- From the datasheet provided below, Sunny Island 4.4M meet the surge demand (5500W> 4400 Required) and continuous demand (3300W = 3300W required)
- In hot conditions, check if AC power at 45°C meets demand



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Determine Battery Bank Capacity

- 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.
- *To calculate the energy required at the battery, use the equation:*

$$E_{BATT} = E_{AC} / \eta_{INV}$$

Where:

E_{BATT} = energy required from the battery bank
E_{AC} = Total daily energy (no dc load)
η_{INV} = *inverter efficiency*

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Determine Battery Bank Capacity

$E_{BATT} = E_{AC} / \eta_{INV}$

E_{BATT} = 50,000 / 0.94
= 53,191 Wh/day

Assumptions:

Battery Inverter efficiency	94%
Battery Inverter efficiency when acting as charger	94%
Watt-hour efficiency of the battery	80%
Maximum Depth of Discharge (DOD)	70%

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Determine Battery Bank Capacity Cont'd

- Battery capacity is the energy required per day times the days of autonomy required, divided by system voltage and specified depth of discharge. i.e.

Battery Capacity (Ah) = (E_{BATT} x T_{aut})÷ (V_{dc} × DOD)

T_{aut} = specified days of autonomy
V_{dc} = Battery Bank dc voltage
DOD = depth of discharge

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Determine Battery Bank Capacity Cont'd

Given:

- 2 days as per customer's requirements,
- 48V battery voltage (inverter DC input voltage constraint),
- and DOD of 70% (design decision),

The required battery bank is:

Battery Capacity = 53,191Wh x 2 /(0.7x48)
= 3,166Ah.

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Size and Select Battery Model

- The battery bank will is selected from the Sonnenschein Solar range of batteries due to its heavy cycling capabilities.
- The required battery capacity is 3166Ah, the largest battery in this range has a capacity of 3036Ah at C_{10} , so two parallel banks will be required. (3166/3036 > 1)
- Therefore each string should have capacity greater than:
  = 3166/2 = 1583 Ah.

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Selecting a Battery Model

From the table below the battery that is greater than 1583 Ah at C_{10} is the 1593Ah. That is model number A602/1960C.

Two parallel banks would provide a battery bank of 2 x 1593= 3186Ah.

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

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Battery Array Arrangement

- Each battery cell is nominal 2V.
- To make 48 volts, the number of cells in the string is

$N_{series} = V_{dc}$ / Cell Voltage

N_{SERIES} = 48 / 2
= 24 cells in series per string

- The total number of cells in the battery bank is:
  = 24 cells in series per string x 2 strings in parallel
  = 2 x 24 = 48 cells

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Size and Select PV Array

The PV array will be sized for the month with the lowest irradiation, June. The PSH in June for the site is 4.33kWh/m^2 (PSH) with an average temperature of 26.1°C. As the generator is for backup only, this system is designed similar to an offgrid PV system.

Assume:

- Site's daily consumption is 50 kWh/day
- No PV array oversizing required because there is a generator

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Size and Select PV Array

System efficiencies and characteristics:

- Average solar resource at 15° tilt (H_{tilt}) 4.33 PSH/day
- PV module rated capacity (P_{STC}) 300W
- Derating factor due to dirt (F_{DIRT}) 95%
- Derating factor due to manufacturer's tolerance (F_{MAN}) 95%
- Watt-hour efficiency of the battery 80%
- P_{MP} Temp Co-efficient(γ) -0.39%/°C

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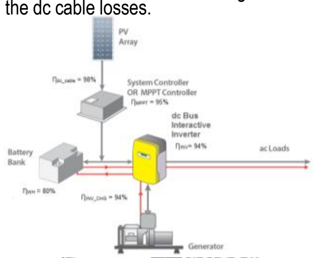
System block diagram

- It is helpful to draw out a system block diagram with major components and their efficiencies. The diagram below also calculated the dc cable losses.



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Derating PV Modules for Local Condition

- Temperature derating factor

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

Cell effective temperature $T_{CELL\text{-}EFF}$ can be calculated by adding 25°C to site average ambient temperature

For this site:

F_{TEMP} = 1+[-0.39/100×(26.1°C+25°C−25°C)]

= 0.898 (i.e. 10.2% decrease)

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Derating PV Modules for Local Condition

PV module derated power is calculated by:

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

- Module nominal power at Standard Test Condition (P_{STC}) and manufacturer's derating factor (F_{MAN}) is obtained from the module datasheet.
- F_{TEMP} was calculated on the previous page based on local average temperature
- Evaluate dirt derating factor F_{DIRT} on a case by case basis. 5%(0.95) is good assumption unless area is extra dusty

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Derating PV Modules for Local Condition

From previous calculation, local condition, and information from manufacturer:

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

= 300 W×0.95×0.898×0.95

= 243.1W

= 243W

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Calculate Number of Modules Needed

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

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

Where:

H_{TILT} = 4.33 PSH
E_{AC} = 50,000kWh
F_o = 1 (generator present, no oversizing required)

Inverter subsystem efficiency η_{pv_subsys}

$= \eta_{INV} \times \eta_{WH} \times \eta_{MPPT} \times \eta_{dc\_cable}$

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Inverter Sub-system Efficiency

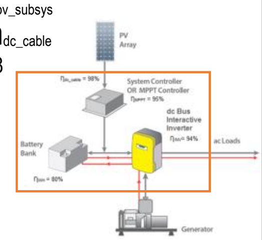
Inverter subsystem efficiency η_{pv_subsys}

$= \eta_{INV} \times \eta_{WH} \times \eta_{MPPT} \times \eta_{dc\_cable}$

= 0.94 x 0.8 x 0.95 x 0.98

= 0.70

Note: This efficiency factor assumes the worst case scenario, where all PV array energy goes through the battery bank before ac loads.



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Calculate Number of Modules Needed for Daytime load

- The number of solar modules required in the arrays is determined as follows:

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

Where:

H_{TILT} = 4.33 PSH
E_{AC} = 50,0001kWh
F_o = 1 (generator present, no oversizing required)
Inverter sub-system efficiency η_{pv_subsys}
= 0.70

N_{pv} = (50,000 x 1) / (243 x 4.33 x 0.7)
= 67.88 = 68 modules

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Calculating Array Size

The nominal array size is:
= 68 x 300 W_p
= 20,400 W_p = 20.4 kW_p

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Sizing the PV array using an MPPT

- Choosing MPPT model
  - Choose from nominal battery voltage – system voltage is 48V
  - Look at last column
- Assume
  - lowest temperature for the site is 15 °C
  - maximum cell temperature is 70 °C
  - Module V_{oc} is 39.3V
  - Module V_{mp} is 32.1V

Technical data	Sunny Island Charger 40	
	24 V	48 V
Input (PV generator)		
Max. PV power	1250 W	2100 W
Max. DC voltage	140 V DC	140 V DC
Optimal MPPT voltage range	40 V - 80 V	70 V - 100 V
Number of MPP trackers	1	1
Max. PV current	40 A	30 A
Output (battery)		
Nominal DC power up to 40 °C	1200 W	2000 W
Nominal battery voltage	24 V	48 V
Nominal voltage range	16 V - 31.5 V	36 V - 65 V
Battery type	flooded and sealed lead acid batteries	
Max. charging current / continuous charging current	50 A / 50 A	40 A / 40 A
Charge control	IUoU	IUoU
Efficiency		
Max. efficiency	98 %	98 %
Euro ETA	97.3 %	97.3 %
Device protection		
DC reverse polarity	●	●
Short-circuit proof	●	●
Overload protection	●	●
Over- and undervoltage protection	●	●
Over- and undertemperature protection	●	●
General data		
Dimensions (W / H / D) in mm	421 / 310 / 143	421 / 310 / 143
Weight	10 kg	10 kg
Protection class (according IEC 60529)	IP65	IP65
Operating temperature range	-25 °C ... +60 °C	-25 °C ... +60 °C
Air humidity	0 % - 100 %	0 % - 100 %
Daytime operating consumption	< 5 W	< 5 W
Internal consumption at night	< 3 W	< 3 W

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Maximum Number of Modules in String

- The maximum V_{oc} of the module at coldest temperature is:

$$V_{MAX\_OC} = V_{OC\_STC} \times \{1 + [\beta \times (T_{MIN} - T_{STC})]\}$$

V_{MAX_OC} = 39.3 × {1+[(-0.30/100) × (15-25)]} = 40.48

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Maximum Number of Modules in String

- Maximum number of modules in the string is

$$N_{MAX\_OC} = V_{ARRAY\_MAX\_V\_OC} / V_{MAX\_OC}$$

$V_{ARRAY\_MAX\_VOC}$ is read off MPPT datasheet, which is 140V

N_{MAX_OC} = 140/40.48

= 3.46, round down to 3 modules

Technical data	Sunny Island Charger 40	
	24 V	48 V
Input (PV generator)		
Max. PV power	1250 W	2100 W
Max. DC voltage	140 V DC	140 V DC
Optimal MPPT voltage range	40 V – 80 V	70 V – 100 V
Number of MPP trackers	1	1
Max. PV current	40 A	30 A

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Minimum Number of Modules in String

- The minimum V_{mp} of the module at hottest temperature is:

$$V_{MIN\_MP} = V_{MP\_STC} \times \{1 + [\gamma\ (T_{MAX} - T_{STC})]\}$$

V_{MIN_MP} = 32.1 × {1 +[(-0.39/100)× (70-25)]} =26.46V

- The PV array's minimum voltage at the MPPT is de-rated by the voltage drop and is calculated as follows:

$$V_{MIN\_MP\_MMPT} = V_{MIN\_MP} \times [1 - \text{voltage drop}]$$

$V_{MIN\_MP\_MPPT}$ = 26.46 x 0.99 = 26.20 V

Note: effect of voltage drop depends on cable run. In this case it's assumed to be 1% drop

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Minimum Number of Modules in String

- For the MPPT to work effectively the V_{mp} of the array should also be greater than the battery voltage.
- The data sheet above states minimum MPPT voltage (V_{MIN_MPPT}) is 70V.

Technical data	Sunny Island Charger 40	
	24 V	48 V
Input (PV generator)		
Max. PV power	1250 W	2100 W
Max. DC voltage	140 V DC	140 V DC
Optimal MPPT voltage range	40 V – 80 V	70 V – 100 V
Number of MPP trackers	1	1
Max. PV current	40 A	30 A

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Minimum Number of Modules in String

Note: In this case this is also the minimum array MP voltage, i.e. $V_{ARRAY\_MIN\_MP} = V_{MIN\_MPPT}$

- The minimum number of modules per string is then determined by the following equation (round **up**):

$$N_{MIN\_MP} = V_{ARRAY\_MIN\_MP} / V_{MIN\_MP\_MPPT}$$

= 70/26.2

= 2.67 rounded up to 3

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Calculate Array Size per MPPT

- Allowable string size is 3 modules per string.
- The power rating of each string

= 3 x 300 = 900W

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Calculate Array Size per MPPT

- Each MPPT has a recommended power of the array = 2100W @ 48V. Therefore The number of strings per MPPT is

= 2100/900=2.3 rounded to 2

- The number of modules per MPPT = 2 x 3 = 6
- Array power rating per MPPT = 6 x 300 = 1800

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Calculate total array size

- Minimum number of module needed was 68modules
- Number of modules per MPPT = 6
- So number of MPPTS= 68/6= 11.3 rounded up to 12

Note: The 12th one only required 0.3 of 6 modules, which is 2, but minimum modules per string is 3, hence there are 3 modules in the 12th MPPT.

- Actual number of modules = 11 x 6 + 3
  = 69

The nominal array size is:
= 69 x 300 W_p
= 20,700 W_p = 20.7 kW_p

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Sizing a Fuel Generator

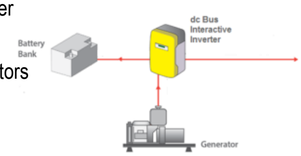
Should be able to meet the demand of all the load—similar to sizing the battery inverter (See first step)

PLUS

Meet the battery charging demand, either via a separate battery charger or via inverter/charger

THEN

Apply generator derating factors



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Calculating Battery Charging Demand

The demand can be calculated if battery charger max power is given. If it is not, then it can be worked out from looking at battery charger's max voltage and current as P = IV

Battery charger max current (& check battery can handle max charge current)

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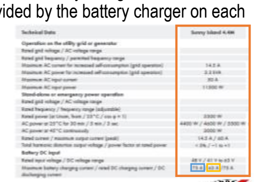
Calculating Battery Charging Demand

Battery Charger Max Current

From datasheet, each SMA Sunny Island 4.4M inverter has a maximum charge current of 75A but a rated current of 63A.

The maximum charge current from the battery charger is the sum of maximum current that can be provided by the battery charger on each phase, i.e.

I_{bc} = 3 x 75= 225 Adc



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Calculating Battery Charging Demand

The selected battery bank comprises two parallel banks of A602/1960C SOLAR with a combined C_{10} capacity of 2 x 1593= 3186Ah. The battery's charge current is 0.1 x its C_{10} rating, i.e.

battery design maximum charging current
= 0.1 x 3186A = 318.6A.

This is smaller than Inverter's maximum battery charging current I_{bc}. Which means the battery bank can accept the maximum charging current from the inverters.

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Calculating Battery Charging Demand

Battery Charger Max Voltage

Assume the maximum charge voltage per cell is 2.4V.

Maximum charge voltage can be calculated as:

V_{bc} = cell voltage x N_{series}
= 2.4 x 24 = 57.6 Volts

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Calculating Battery Charging Demand Cont'd

- Battery charging demand from the point of view of the generator is the power the battery charger delivers divided by the battery charger efficiency and power factor,

$$S_{bc} = (I_{bc} \times V_{bc}) / (\eta_{bc} \times pf_{bc})$$

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Calculating Battery Charging Demand Cont'd

- Assume for this example:
  - Battery charger nominal efficiency (η_{bc}) is 0.94
  - Battery charger nominal power factor (pf_{bc}) is 1

S_{bc} = $(I_{bc} \times V_{bc}) / (\eta_{bc} \times pf_{bc})$
= (225 x 57.6) / (0.94 x 1.0)
= 13,333 VA = 13.3 kVA

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Calculating Battery Charging Demand Cont'd

- The13.3 kVA is theoretical because the continuous rating of the inverter is 3.3kW. So three inverters would only represent 9.9kVA NOT 13.3 kVA .
- The reason is that the maximum current would not occur at the maximum voltage of 57.6V. The VA of 75A x 57.6V is 4320VA this is eevn higher than the ½ rating of the inverter (600) .
- So we would know use 9.9kVA.

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Calculate Generator Capacity

- Generator needs to be sized to meet the maximum demand it can experience
- In this case it is:

Delivering full AC load + charging battery at max battery charger demand

- It can be written as

$$S_{GEN} = (S_{BC} + S_{MAX\_CHG}) \times F_{GO}$$

Where:
S_{GEN} = Minimum apparent power rating of the generator (kVA)
S_{BC} = Maximum apparent power consumed by the battery charger under conditions of maximum output current and typically maximum charge voltage (kVA)
S_{MAX_CHG} = Maximum ac demand from ac loads during battery charging (kVA),In this case it's the site's max demand
F_{GO} = Generator oversize factor (dimensionless

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Calculate Generator Capacity (Cont'd)

If the generator oversize factor is decided as 10%, then the minimum capacity of the generator required so that it can meet the battery charging load and maximum demand at the same time is:

S_{GEN} = $(S_{BC}+S_{MAX\_CHG}) \times F_{GO}$
S_{GEN} = (9.9 + 10) * 1.1 = 21.9kVA)

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Generator derating factor

- Generators will perform at a reduced level with high air temperature, altitude, or humidity.
- If derating factors are not available from the manufacturer, the following table (from Hybrid Guideline) can be used as a substitute

Site factor		Derating
Air Temperature		Derate 2.5% for every 5°C above 25°C
Altitude		Derate 3% for every additional 300 m above 300 m altitude
Humidity	Air Temperature between 30°C and 40°C	Derate 0.5% for every 10% above 60% humidity
	Air Temperature between 40°C and 50°C	Derate 1.0% for every 10% above 60% humidity
	Air Temperature between 50°C and 60°C	Derate 1.5% for every 10% above 60% humidity

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Applying Generator Derating

The guesthouse is located at 100m altitude, with maximum air temperature is 28°C and humidity is 78%.

- Altitude derating does not apply, the site is less than 300m above sea level
- Temperature derating: (28 °C -25 °C)/5*2.5 = 1.5%.

Note: temperature derating would be higher if generator is not located in a well-ventilated space

- Humidity derating does not apply, this site's air temperature is below 30°C
- Total derating:
  =1.5%

The derating factor would be 1 – 0.015 = 0.985

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Required Generator Capacity accounting for derating factor

- Generator required capacity S_{GEN} = 21.9kVA
- Site specific derated required capacity = 21.9/0.985 = 22.23kVA

Note:

- Generator is likely to be underloaded most of the time based on this sizing; it would only be running at full capacity during morning and evening peak. This is acceptable for this case since it's expected that the generator will not be running often.
- If generator is expected to be used more frequently, a smaller generator may be selected and operated such that battery charging never happens during maximum demand times

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System summary

Generator required capacity: 22.23kVA

Generator is only used for prolonged days without sun.

PV Array Size:20.7kW$_p$, 69 modules rated at 300W

Array connected to 12 MPPT chargers and battery bank

Battery bank capacity: 3186Ah

Battery bank arrangement: 2 x 48V strings

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Discussion: Maximum Charge Rate

- The maximum charge rate is generally less than the maximum discharge rate,
- The batteries have to be capable of providing the maximum demand drawn from them by the inverter.

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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.

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Questions?

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The End

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