L15
محاضرة تعويض
27/4/2021

L11-
PV System Sizing and Design

+ L16 part 2
Project Task 2
Details
28/4/2021

Introduction

- **For electrical systems that use PV arrays as their only source of electricity, system sizing is critical.**
- **The size of the array, battery bank, and other major components necessary to adequately meet the load requirements must be carefully calculated.**
- **Sizing procedures are an important part of planning any PV system, but are especially stringent for stand-alone systems.**
- **Worksheets can be used to organize information and guide system-sizing calculations for most simple systems,**
- **More complex or hybrid systems may require computer models or simulation software.**

Sizing Grid Connected PV Systems

- These systems require relatively simple calculations and allow the widest variance in component sizing.
- These systems operate in parallel with utility service, sizing is not critical because failure of the PV system to produce energy does not affect operation of electrical loads, the PCU draws power from the grid .
- Excess Energy is sent into the grid

PCU: Power Conditioning Unit includes an MPPT and a DC-AC inverter

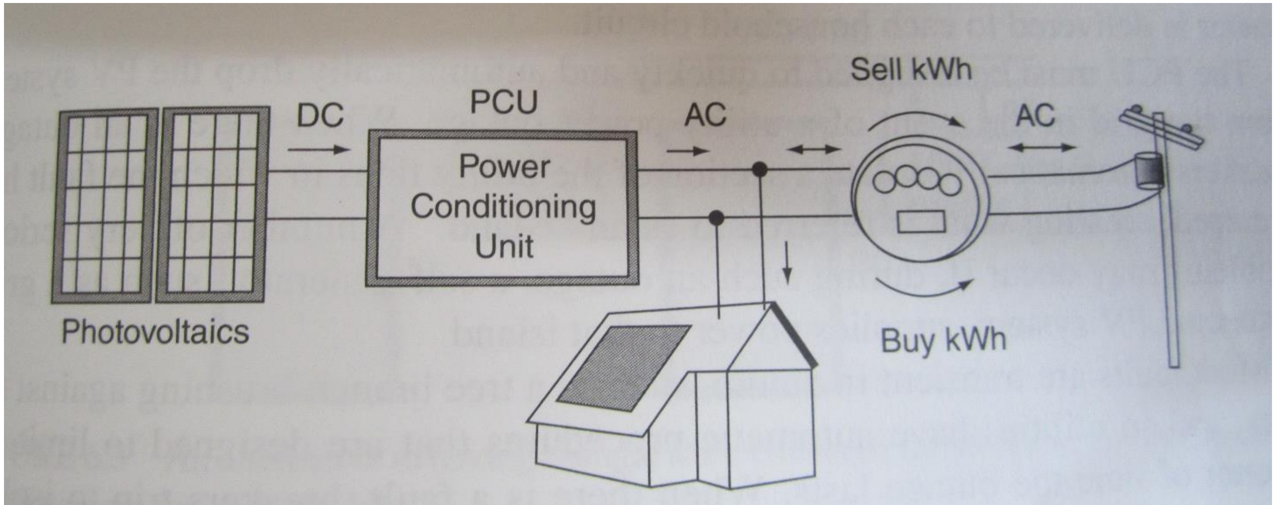


FIGURE 6.1 Simplified grid-connected PV system with net metering.

Sizing Grid Connected PV Systems

- Additional energy can be imported from the utility at any time.
- **Sizing interactive systems begins with the specifications of a PV module chosen for the system.**
- Module ratings at Standard Test Conditions (STC) are used to calculate the total expected array DC power output per peak sun hour

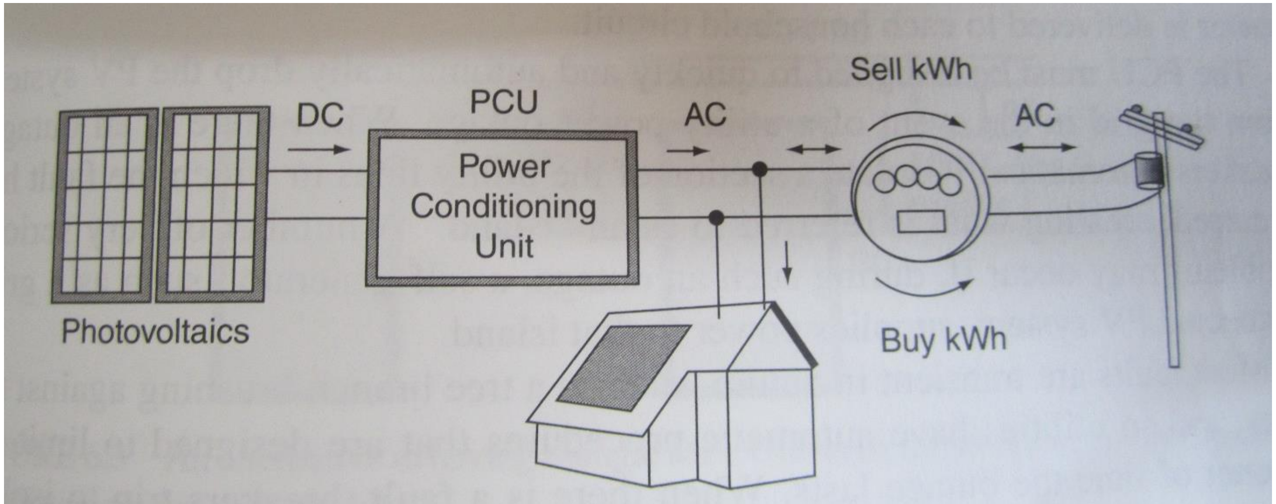


FIGURE 6.1 Simplified grid-connected PV system with net metering.

Sizing Interactive PV Systems (Grid Tied)

- This Power at STC is then de-rated for various losses and inefficiencies in the system, which includes the following:
  1) Guaranteed module output that is less than 100%
  2) Array operating temperature
  3) Array wiring and mismatch losses
  4) Inverter power conversion efficiency
  5) Inverter MPPT efficiency
- The result is **a final AC power output** that is substantially lower but realistically accounts for expected real-world conditions

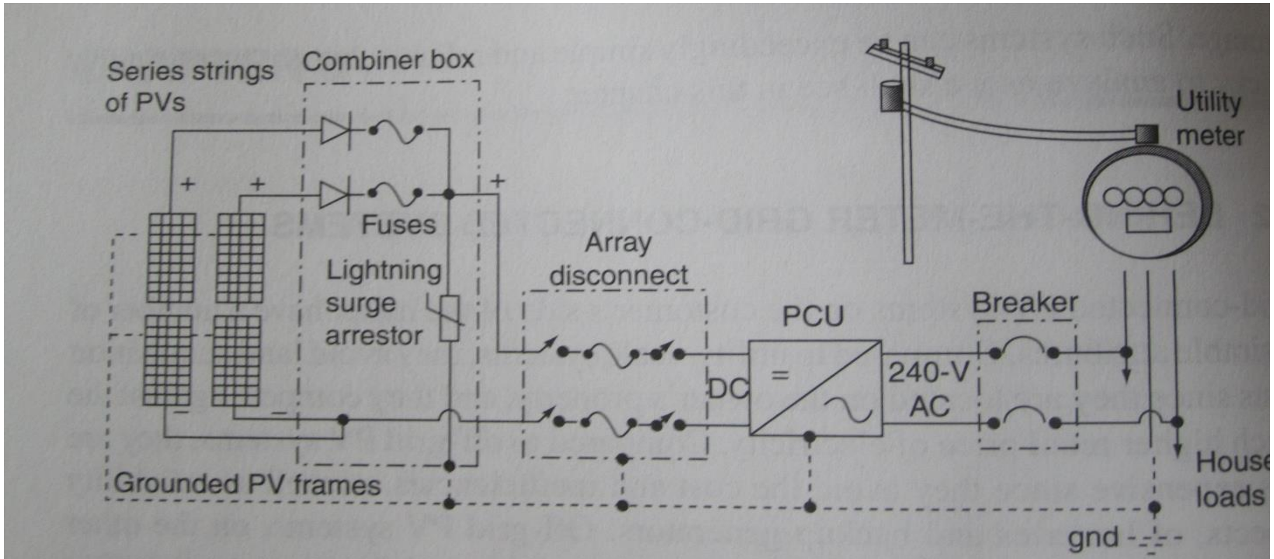
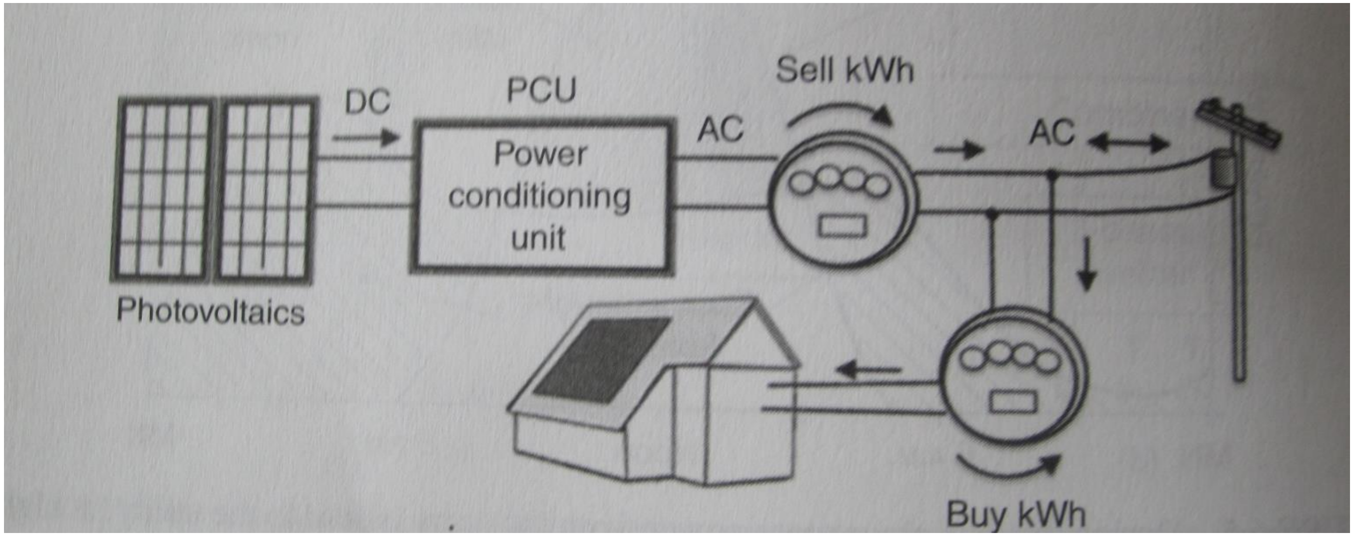


FIGURE 6.2 Principal components in a grid-connected PV system using a single inve and a single utility meter.

Item	Range	PVWATTS Default
PV module nameplate DC rating	0.80–1.05	0.95
Inverter and Transformer	0.88–0.98	0.92
Module mismatch	0.97–0.995	0.98
Diodes and connections	0.99–0.997	1.00
DC wiring	0.97–0.99	0.98
AC wiring	0.98–0.993	0.99
Soiling	0.30–0.995	0.95
System availability	0.00–0.995	0.98
Shading	0.00–0.995	1.00
Sun tracking	0.95–1.00	1.00
Age	0.70–1.00	1.00
Total derate factor without NOCT		0.770



- **A Two-meter system allows a feed-in tariff to provide separate rates for power generated by PV and power used by customers**

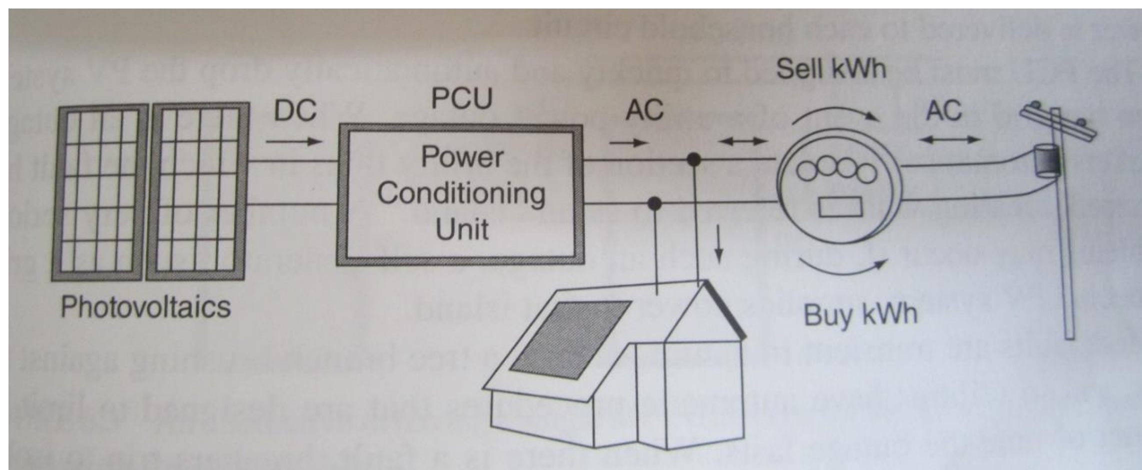


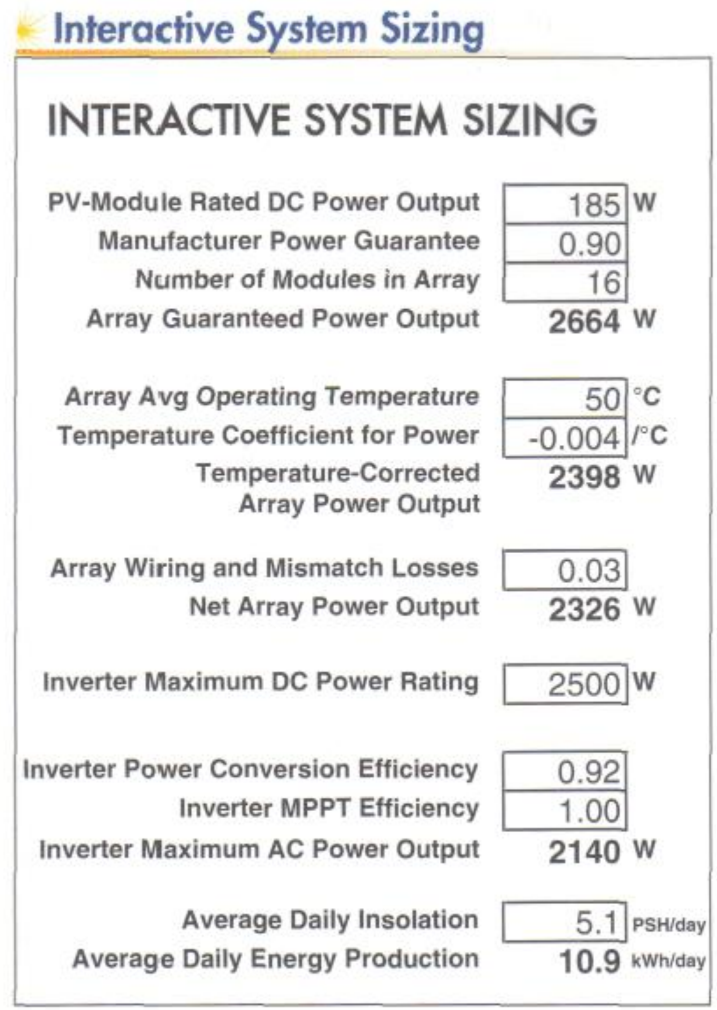
FIGURE 6.1 Simplified grid-connected PV system with net metering.

System Sizing

- A grid connected system is built with the following details:
- Module Wp=185 W,
- Total used 16 modules, 80% power guarantee after 20 years,
- Average operating Temp 50 deg, Temp derating for power =-0.004/C,
- Wiring and mismatch losses 3%,
- Inverter efficiency assumed 92%,
- MPPT 100%,
- PSH=5.1/day
- Determine the expected energy production per day?

System Sizing

- To determine the expected energy production per day, the final AC power output is multiplied by the insolation for the month or year.
- For example, if the calculated AC power output is 2140 W per peak sun hour and the average annual insolation is 5.1 peak sun hours (kWh/m2/day),
- Then the average energy production is expected to be 10.9 kWh/day. (2140 W x 5.1 h/day =10914 wh)
- If the final system power output is not within the desired range, such as above a minimum size requirement for an incentive program, different module and/or inverter choices can be made.
- Also, various system configurations can be compared with their associated system costs for a value-based analysis.



- **The size of an interactive system is primarily limited by the space available for an array and the owner's budget.**
- **However, financial incentive requirements, net metering limits, and existing electrical infrastructure may also influence system size decisions.**

A Grid connected PV System is to be designed using twenty 250- W modules. The array delivers power to a 5500 W inverter. The key specification parameters of the inverter and modules is given in the table below:

Inverter Specification			PV Module Specification	
Max. AC Power	5500 W		Rated Power Pdc	250 W
Input voltage range at MPP	250-700 V		Open circuit voltage Voc	37.38 V
Maximum Input Voltage	1000 V		Short Circuit Current Isc	8.72 A
Maximum Input Current	50 A		Voltage at MPP	30.64 V
Efficiency	97%		Current at MPP	8.16 A
Guarantee	10 years		Power guarantee after 20 years	80%

A. What are the possible arrangement/connection of modules in series /parallel?
   For example one possible arrangement is (5S,4P):
   (5S, 4P) means the system consists of four strings in parallel (P) , each consists of 5 series connected modules (S).

B. Which one of the combinations in part A are recommended? Explain why?

C. If the cost of PV system is 0.85 $/W for the panels, inverter cost 2300 $, wires and circuit breakers 500 $, one time installation cost 500 $, annual maintenance 100$/year. Assume the cost of electricity is 0.2 $/ kWh, what would be the pay-back period (years) of the system (assume life time of project 20 years and psh=6). Is the investment in this project recommended?

A. What are the possible arrangement/connection of modules in series /parallel?

For example one possible arrangement is (5S,4P):

(5S, 4P) means the system consists of four strings in parallel (P), each consists of 5 series connected modules (S).

Module	
Pdc	250
Voc	37.38
Isc	8.72
Vmp	30.64
Imp	8.16
Pow_guar	0.8
Inverter	
Pmax	5500
Vmp	250-700
Vmax	1000
Imax	50
eff	0.97

		250-700	1000	50	50	
Ns	Np	Vmp	Vmax	Imp	Imax	ok?
20	1	612.8	747.6	8.16	8.72	√√
10	2	306.4	373.8	16.32	17.44	√
5	4	153.2	186.9	32.64	34.88	x
4	5	122.56	149.52	40.8	43.6	x
2	10	61.28	74.76	81.6	87.2	x
1	20	30.64	37.38	163.2	174.4	x

Choice (20S, 1P) or (10S, 2P) are valid choice

Total Cost				
Panels	20	250	0.85	4250
Inverter	2		2300	4600
maintainance	20		100	2000
installaion	1		500	500
wires	1		500	500

Sum = 11850 $

Production	
psh	6
Life_derating	0.9
Inv_derating	0.97
Power_rated (W)	5000
Power _derated (W)	4365
Energy_year (kW)	9559.35
Energy revenu/year ($)	1911.87
PayBack Period (year)= total cost/revenue per year	=11850/1911 =6.19812

Example 2

- Choosing The right Inverter
- Give 14 panels of 300W rating from sharp and Inverters from Fronius IG3000, IG4000 and IG5000
- Choose the right inverter and show best module connection (number of strings)

NU-AC300B

NU-AC Series

300 W Black
The Design Solution

Limit values	
Maximum system voltage	1,000 VDC
Over-current protection	15 A
Temperature range	-40 to 85 °C

Electrical data (STC)

		NU-AC300B	
Maximum power	P_{max}	300	W_p
Open-circuit voltage	V_{oc}	40.03	V
Short-circuit current	I_{sc}	9.71	A
Voltage at point of maximum power			V
Current at point of maximum power			A
Module efficiency			%

STC = Standard Test Conditions: irradiance 1,000 W/m², AM 1.5, c
Rated electrical characteristics are within ±10% of the indicated
Reduction of efficiency from an irradiance change of 1,000 W/m²

Temperature coefficient	
P_{max}	-0.375%/°C
V_{oc}	-0.273%/°C
I_{sc}	0.037%/°C

Electrical data (NMOT)

		NU-AC300B	
Maximum power	P_{max}	224.13	W_p
Open-circuit voltage	V_{oc}	37.94	V
Short-circuit current	I_{sc}	7.87	A
Voltage at point of maximum power	V_{mpp}	30.50	V
Current at point of maximum power	I_{mpp}	7.35	A

NMOT = Nominal Module Operating Temperature: 45 °C, irradiance 800 W/m², air temperature of 20 °C, wind speed of 1 m/s.

FRONIUS IG 2000 / 3000 / 2500-LV

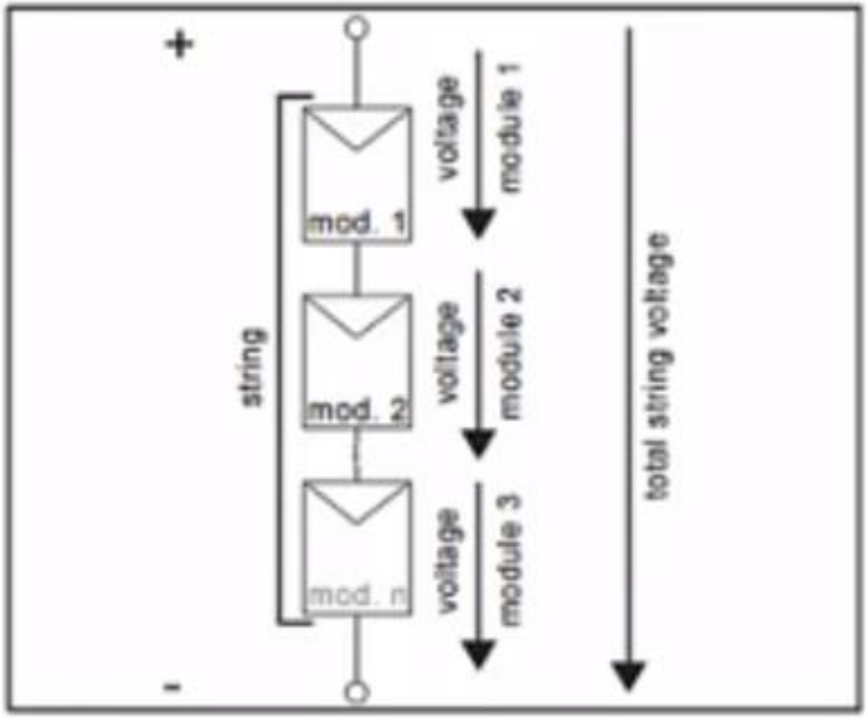
Input data	IG 2000	IG 3000	IG 2500-LV
Recommended PV power	1500-2500 Wp	2000-3300 Wp	1800-3000 Wp
MPP-voltage range		150 - 400 V	
Max. input voltage (at 1000 W/m² / 14 °F in no-load operation)		500 V	
Nominal input voltage		270 V	
Nominal input current	7.2 A	10.0 A	8.6 A
Maximum usable input current	13.6 A	18 A	16.9 A
Max. array short circuit current	25 A	25 A	25 A

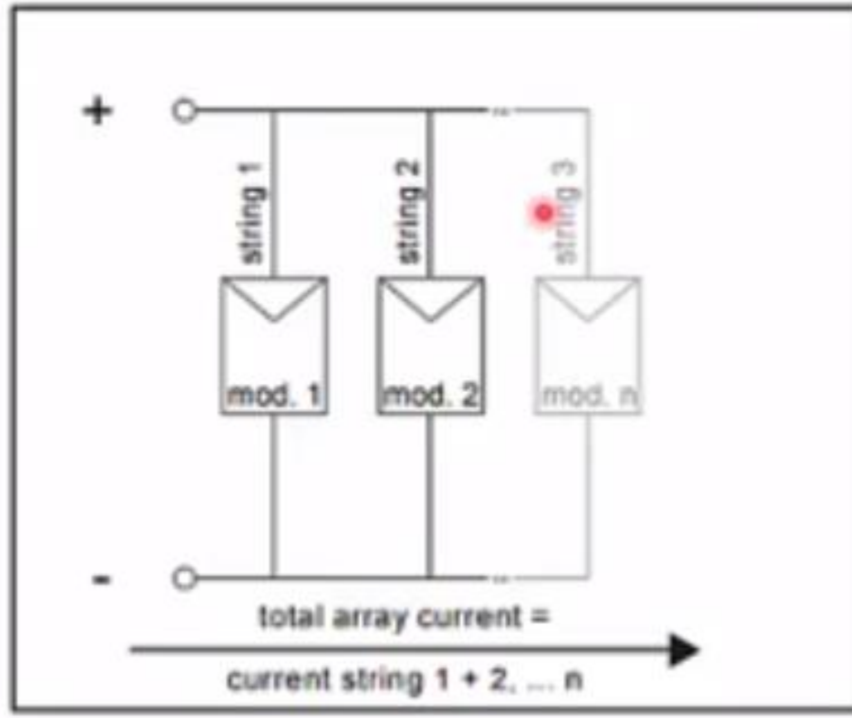
FRONIUS IG 4000 / 5100 / 4500-LV

Input data	IG 4000	IG 5100	IG 4500-LV
Recommended PV power	3000-5400 Wp	4000-6300 Wp	3600-5500 Wp
MPP-voltage range		150 - 400 V	
Max. input voltage (at 1000 W/m² / 14 °F in no-load operation)		500 V	
Nominal input voltage		270 V	
Nominal input current	16.3 A	20.8 A	18.3 A
Maximum usable input current	26.1 A	33.2 A	29.3 A
Maximum array short circuit	40 A	40 A	40 [illegible]

General data	IG 2000	IG 3000	IG 2500-LV
Maximum efficiency	95.2 %	95.2 %	94.4 %
Consumption in standby (night)		< 0.15 W	
Consumption during operation		7 W	
Cooling		controlled forced ventilation	
Protection type		NEMA 3R	
Size l x w x h		18.5 x 16.33 x 8.71 in. (470 x 418 x 223 mm)	
Weight		26 lb. / 11.8 kg	
Admissible ambient temperature		-4 to +122 °F (-20 to 50 °C)	

General data	IG 4000	IG 5100	IG 4500-LV
Maximum efficiency	95.2 %	95.2 %	94.4 %
Consumption in standby (night)		< 0.15 W	
Consumption during operation		15 W	
Cooling		controlled forced ventilation	
Protection type		NEMA 3R	
Size l x w x h		28.34 x 16.46 x 8.78 in. (720 x 418 x 223 mm)	
Weight		41.8 lb. / 19 kg	
Admissible ambient temperature		-4 to +122 °F (-20 to 50 °C)	


+
-
string
mod. 1
mod. 2
mod. n
voltage module 1
voltage module 2
voltage module 3
total string voltage


+
-
string 1
string 2
string 3
mod. 1
mod. 2
mod. n
total array current =
current string 1 + 2, ... n

Calculation For an array of 14 modules

1. Power of one string =14 modules

   Pdc_array=14*300*0.95*0.95

   = 3790 W

2. Voltage of Array

   Vsystem= 14*Vmpp

   = 14*32.68

   =457.5 V

3. Current of Array

   Isystem= 1*Isc

   = 1*9.71

   =9.71 A

4. First Guess of Inverter: (14S, 1P)

One String:

Pmax	**3790 W**
I max	**9.71 A**
Vmpp	**457.5**
V(oc_string)	**560.4**

Inverter Type	Pmax		Max usable DC input current (A)		Max DC input voltage (V)		MPP voltage (V)	
IG 3000	2500-3300	3790 W	18	9.71 A	500	560.4	150-400	457.5
IG 4000	3000-5400	3790 W	26.1	9.71 A	500	560.4	150-400	457.5
IG 5000	4000-6300	3790 W	33.2	9.71 A	500	560.4	150-400	457.5

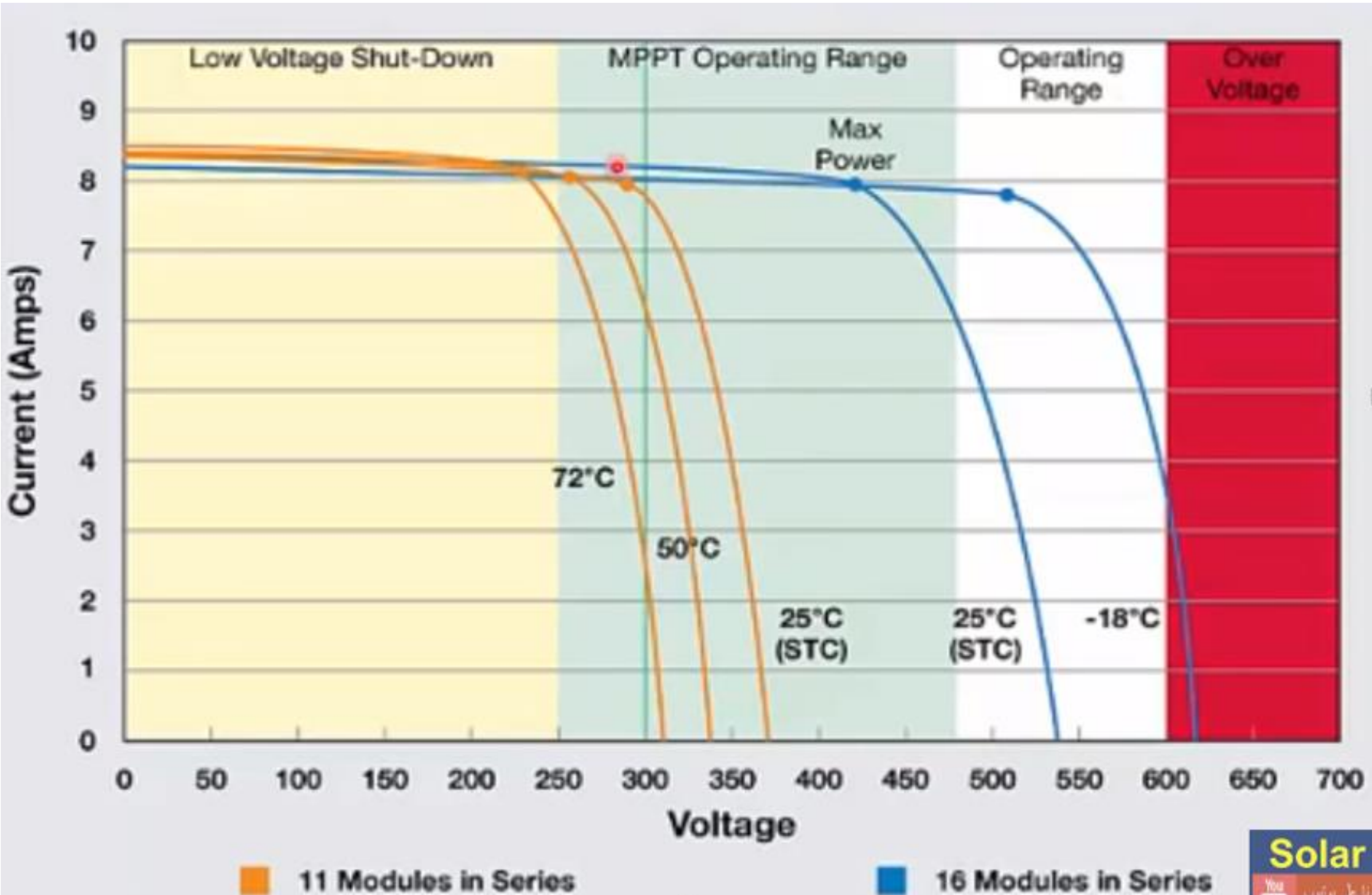
For Two Strings: 7//7 (or 7S, 2P)

Pmax	3790 W
I max	19.42 A
Vmpp	213.8
V(oc_string)	280.2

Inverter Type	Pmax		Max usable DC input current (A)		Max DC input voltage (V)		MPP voltage (V)	
IG 3000	2500-3300	3790 W	18	19.42	500	280.2	150-400	213.8
IG 4000	3000-5400	3790 W	26.1	19.42	500	280.2	150-400	213.8
IG 5000	4000-6300	3790 W	33.2	19.42	500	280.2	150-400	213.8

Choice : IG 4000

Coldest Day Calculation



5. Coldest Day Calculation: assume -10 deg C

Temperature coefficient	
P_{max}	-0.375%/°C
V_{oc}	-0.273%/°C
I_{sc}	0.037%/°C

- Temperature Difference ΔT:

ΔT = -10-25= -35 degrees

Temperature Coeff for voltage =-0.273%/C

Voltage % Rise = ΔT* Temperature Coeff

=-35 C* -0.273%/C=9.55%

Vmax(oc)= **280.2 (1+0.0955)=307V √**

For one string =614 V X

5. Hottest Day Calculation: assume +50 deg C

Temperature coefficient	
P_{max}	-0.375%/°C
V_{oc}	-0.273%/°C
I_{sc}	0.037%/°C

- Temperature Difference ΔT:

ΔT = 50-25= 25 degrees

Temperature Coeff for voltage =-0.273%/C

Voltage % Rise = ΔT* Temperature Coeff

=25 C* -0.273%/C=-6.83%

Vmin(oc)= **280.2 (1-0.0683)= 261 √** **(one string =522 V X)**

Isc(max)=19.42(1+25*0.00037)=19.42*1.00925=19.6 A √

Conclusions

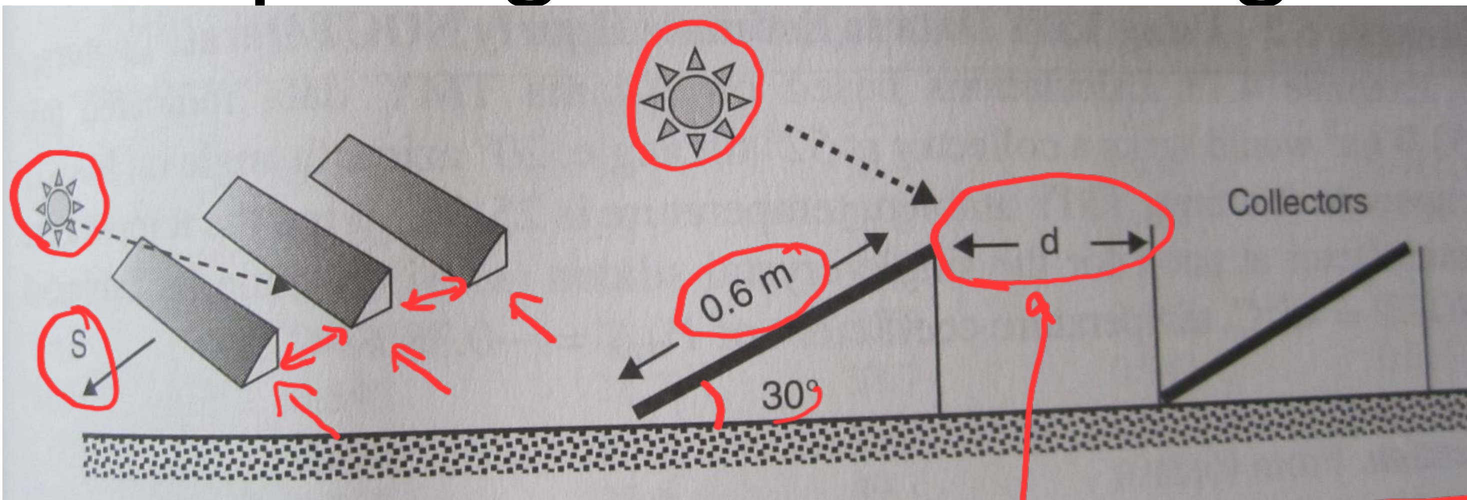
- One String choice is not possible (14S, 1P)
- Two string choice is better (7S,2P)
- Inverter IG 4000 is the best choice, note that

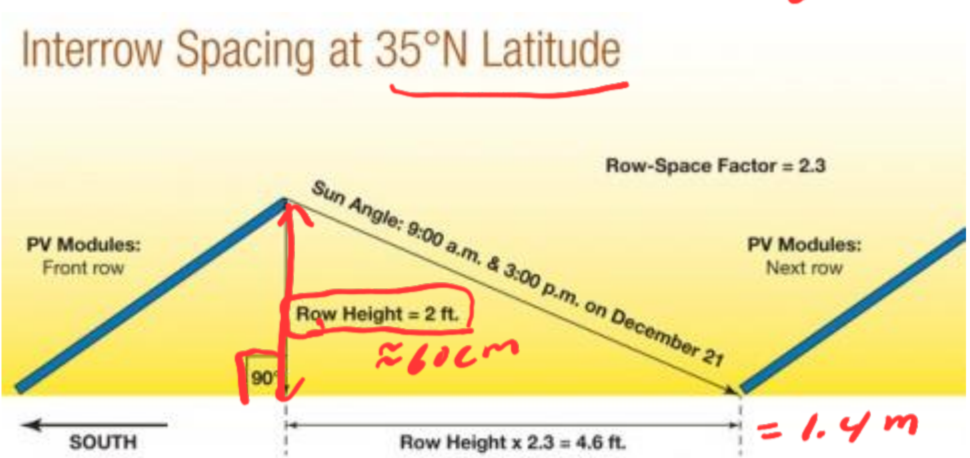
IG 4000	3000-5400	3790 W	26.1	19.42	500	280.2	150-400	213.8

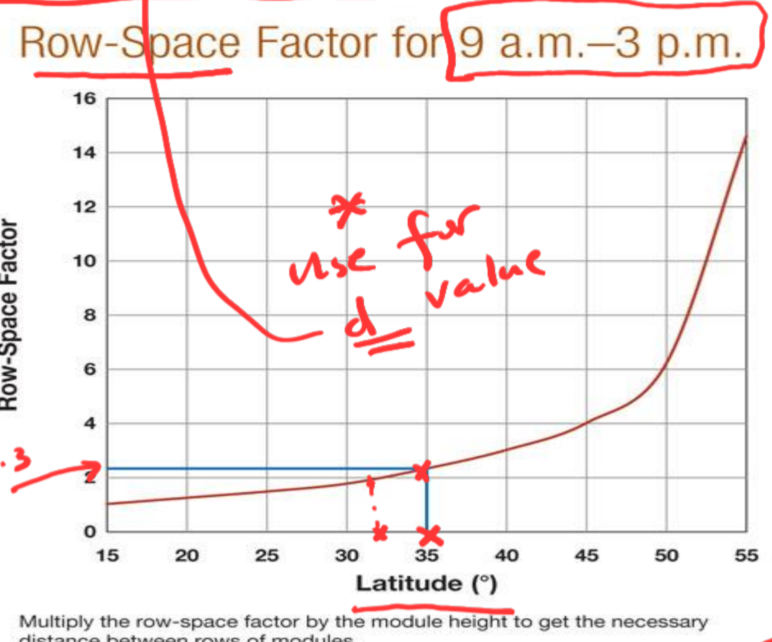
- Must pay attention to the voltage which might be reduced due to shading or aging of PV modules
- Other possibilities like (2S,7P) cannot be used since voltage will not be enough

End of L15 27/4/2021

Spacing due to shading







- https://www.youtube.com/watch?v=5DpXIfz38R4

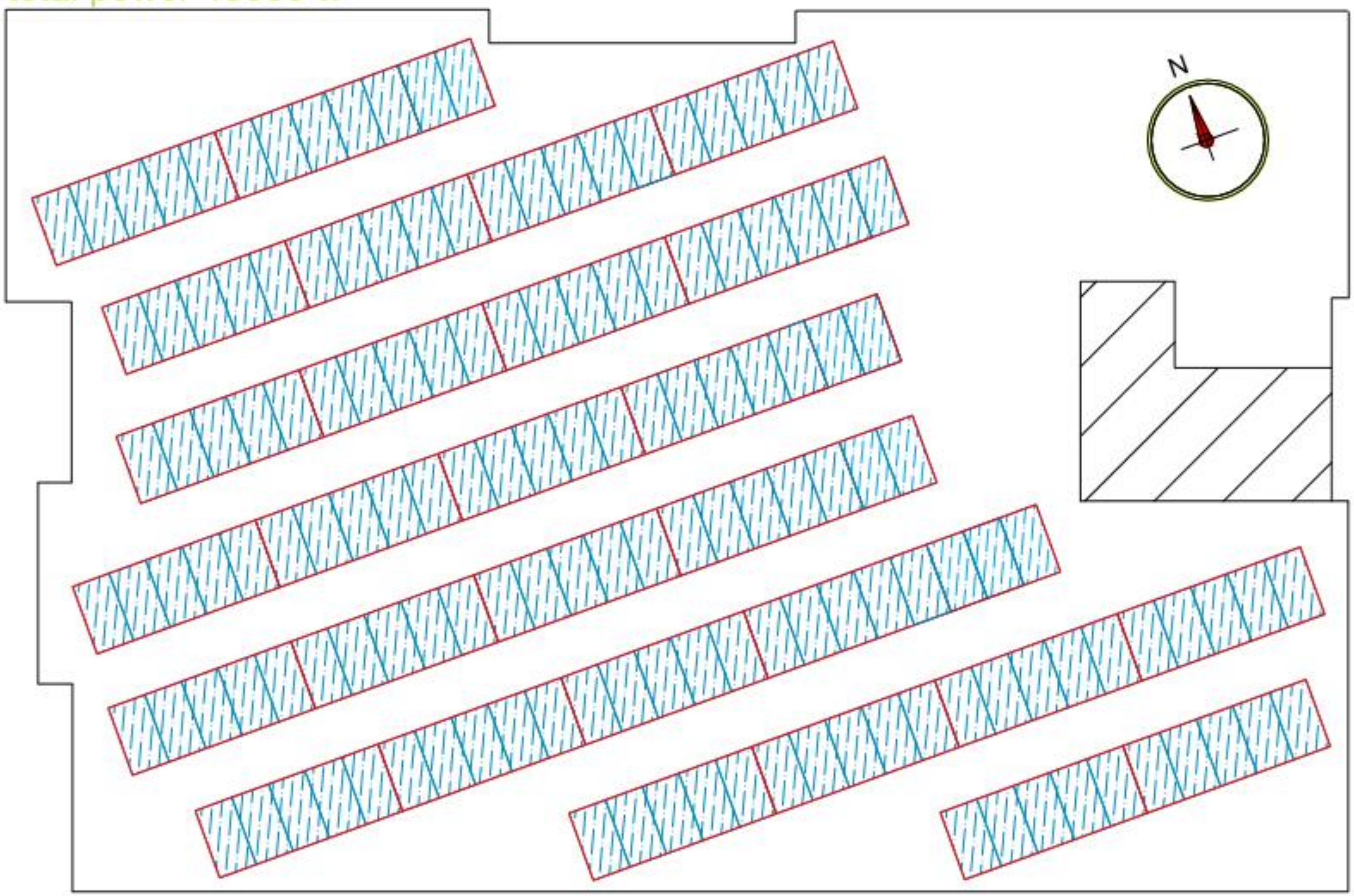
Example PV System Design- مبنى مصنع الادوية في جامعة بير زيت

Meteorological Information	
Daily horizontal irradiation	5.66kWh/m2/day
Ambient Air Temperature (Min)	0 C
Ambient Air Temperature (Max)	42 C
Orientation	
Place of Installation	BirZeit-Palestine
Total Area	700 m2
Orientation	South
Fixed system	inclination=22 deg
Module-Inverter Details	
Module Type	Polycrystalline
Module capacity	320Wp
Module Efficiency	16.49 %
Total Installed Module capacity	48 kWp
Number of modules	150
Inverters Capacity	48-kW
Inverter Efficiency	98%
Number of inverters	3
Grid connection	
JEDCO	Net metering

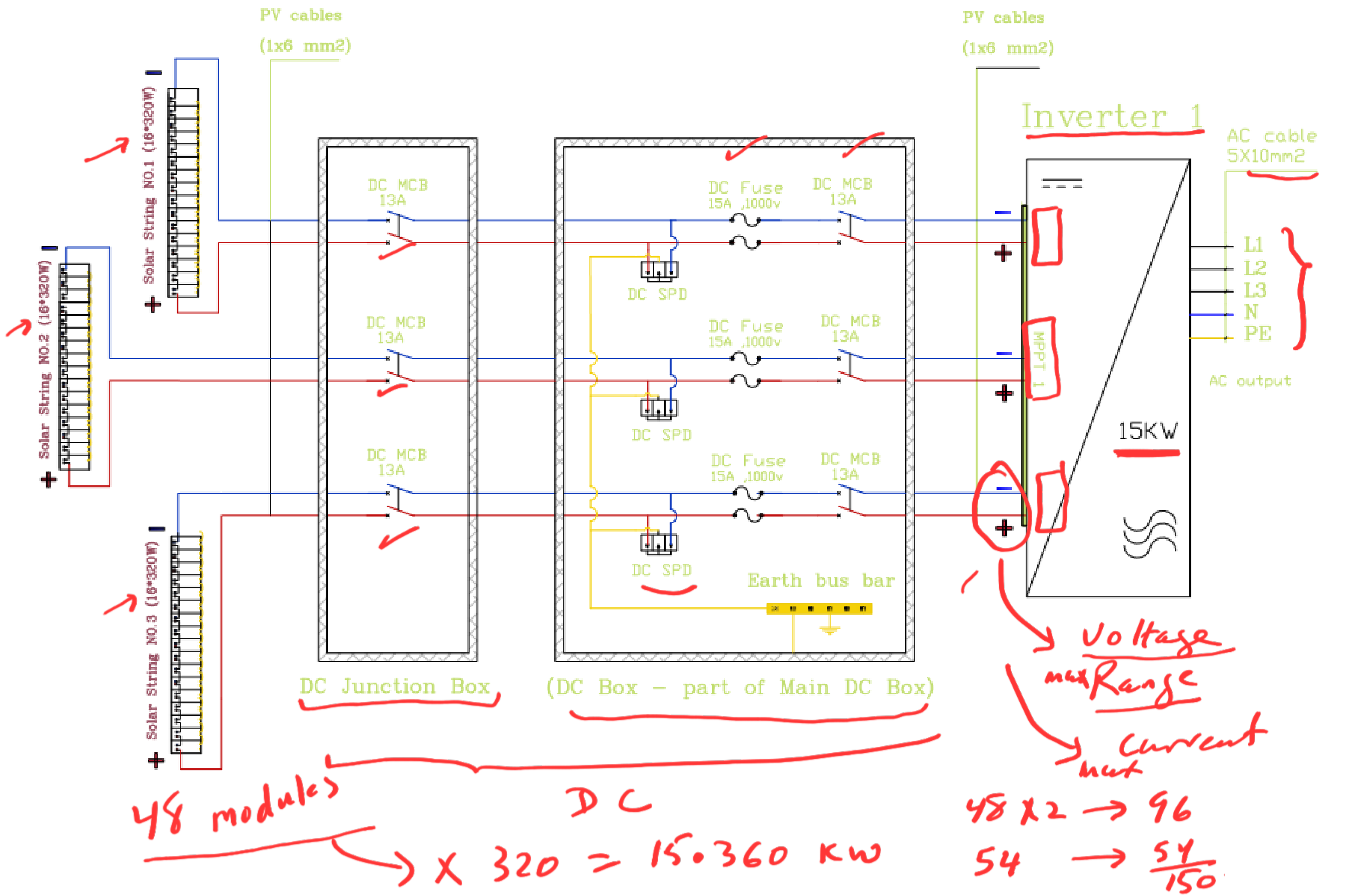
Table 1: Summary of the basic design parameters for the 48-KW grid-connected solar PV system

2D module placement

150 modules *320w
total power 48000 w



3 D module placement



PV cables
(1x6 mm2)
Solar String NO.1 (16*320W)
Solar String NO.2 (16*320W)
Solar String NO.3 (16*320W)
DC MCB
13A
DC Fuse
15A ,1000v
DC SPD
Earth bus bar
DC Junction Box
(DC Box – part of Main DC Box)
Inverter 1
MPPT 1
15KW
AC cable
5X10mm2
L1
L2
L3
N
PE
AC output
Voltage
max Range
max current
48 modules
DC
x 320 = 15.360 KW
48 x 2 → 96
54 → 54/150

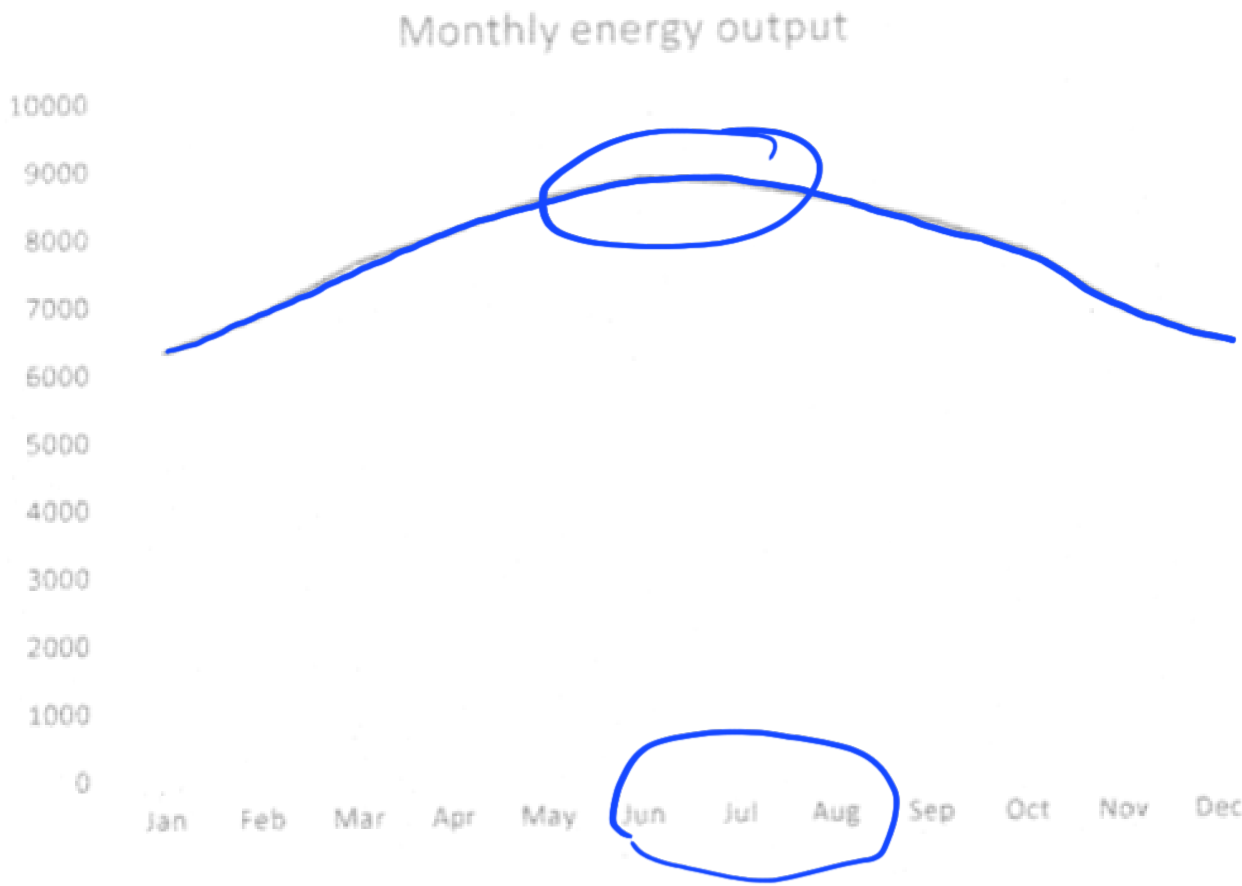
- Estimated losses due to temperature and low irradiance: 10.9% (using local ambient temperature)
- Estimated loss due to angular reflectance effects: 2.1%
- Other losses (cables, inverter etc.): 9.0%
- Combined PV system losses: 22%

Month	Ed	Em	Hd	Hm
Jan	143.0	4433.6	3.8	118.4
Feb	168.1	4707.0	4.3	125.7
Mar	220.9	6847.8	5.9	182.9
Apr	243.0	7289.6	6.5	194.7
May	273.3	8472.7	7.3	226.3
Jun	290.9	8727.3	7.8	233.1
Jul	288.3	8936.9	7.7	238.7
Aug	281.2	8716.4	7.5	232.8
Sep	260.2	7806.2	7.0	208.5
Oct	222.8	6905.8	6.0	184.5
Nov	178.6	5357.7	4.8	143.1
Dec	147.5	4572.9	3.9	122.1
Average	226.5	6897.8	6.05	184.2
Total for Year		82773.85 →	KWh	

Best summer yeild

psh
6.05 kwh/day

- Ed: Average daily electricity production from the given system (kWh).
- Em: Average monthly electricity production from the given system (kWh).
- Hd: Average daily sum of global irradiation per square meter received by the modules of the given System (kWh/m2).
- Hm: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m2)



Monthly energy output from fixed-angle PV system

The economic analysis of the 48-KW grid-connected solar PV system was carried out to assess the cost and intended benefits of the project. Simulating the net present value and simple payback period as well as estimating the greenhouse gas saving potential of renewable energy projects over their entire operational life. The NPV and simple payback period will help determine how feasible the project will be. The total investment cost comprises the following components; module, inverter, cables, mounting structures, engineering and project management, labor and miscellaneous costs. The PV modules and inverter cost alone makes up about 60% of the total investment cost. The total investment cost for the 48-KW project is estimated at US$ 61733(1286.5 US$/1KW).

≈ 1.3 $/W

Solar PV system energy production	82773KW/year
Solar PV system cost	61733 US $
Operating and Maintenance Cost	0.02 US $/KW/Day
Total for Maintenance Cost	1752 US $/ 5Year
Project Life	25 year
KW Price (Tariff)	0.180 US$/KW
Total cost for energy production	14899 US $/Year
Payback period (Maximum)	4.14 Years

Economic Analysis Table

psh = 4.72?

psh = 6.05 × 0.78

4.72

4.72 psh × 365 × 48kW ≈ 82700

Payback period = cost / Revenue/year

Analyses of the simulation results show that, the project when implemented will supply about 82773 kw/year electricity annually, which is about ...% of BirZeit annual electricity consumption.

The project also stands the chance of saving about 32398 tons of CO_2 which would have been emitted by a crude oil fired thermal power plant generating the same amount of electricity. Therefore, the other non-financial benefits like the greenhouse gas emissions savings can, in the long run, help mitigate the adverse effects of the climate change problem plaguing the entire earth.

تأجيل Project-part 1 ← لأسبوع من التاريخ السابق

Project part2-Design task1

- Design a grid-connected system with maximum possible Capacity. to be used on top of a building located in Jerico and oriented south with available space area (40 mX40 m) –see sketch   tilt ?
- Calculate the usable area taking into account no shading from 9am-3 pm. Consider the proper orientation and tilt of the panels for maximum summer months energy yield (June, July and August) (provide a sketch for the placement)   2D & 3D
  x 0.3 = 105$ panel
- Use modules rated at 350 Wp or more, assume cost is 0.3$/Watt $ (make sure modules are available in Pvsyst and do not forget to check the guaranteed power and life time of the modules.

Project part2-Design task1

1:1 ✓
1.2
Batteries

- **Available inverters-guaranteed for 10 years (https://www.europe-solarstore.com/solar-inverters/sma/sunny-tripower.html)**

do not use

Technical data	Sunny Tripower 3.0	Sunny Tripower 4.0	Sunny Tripower 5.0	Sunny Tripower 6.0
Input (DC)				
Max. PV array power	6000 Wp	8000 Wp	9000 Wp	9000 Wp
Max. input voltage	850 V	850 V	850 V	850 V
MPP voltage range	140 V to 800 V	175 V to 800 V	215 V to 800 V	260 V to 800 V
Rated input voltage	580 V			
Min. input voltage / initial input voltage	125 V / 150 V			
Max. input current input A / input B	12 A / 12 A			
Max. DC short-circuit current input A/input B	18 A / 18 A			
Number of independent MPP inputs / strings per MPP input	2/A: 1; B: 1			
Output (AC)				
Rated power (at 230 V, 50 Hz)	3000 W	4000 W	5000 W	6000 W
Max. apparent power AC	3000 VA	4000 VA	5000 VA	6000 VA
Nominal AC voltage	3/N/PE; 220 V / 380 V 3/N/PE; 230 V / 400 V 3/N/PE; 240 V / 415 V			
AC voltage range	180 V to 280 V			
AC grid frequency / range	50 Hz / 45 Hz to 55 Hz 60 Hz / 55 Hz to 65 Hz			
Rated grid frequency / rated grid voltage	50 Hz / 230 V			
Max. output current	3 x 4.5 A	3 x 5.8 A	3 x 7.6 A	3 x 9.1 A
Power factor at rated power / Displacement power factor, adjustable	1 / 0.8 overexcited to 0.8 underexcited			
Feed-in phases / connection phases	3 / 3			
Efficiency				
Max. efficiency / European efficiency	98.2% / 96.5%	98.2% / 97.1%	98.2% / 97.4%	98.2% / 97.6%

Use these inverters

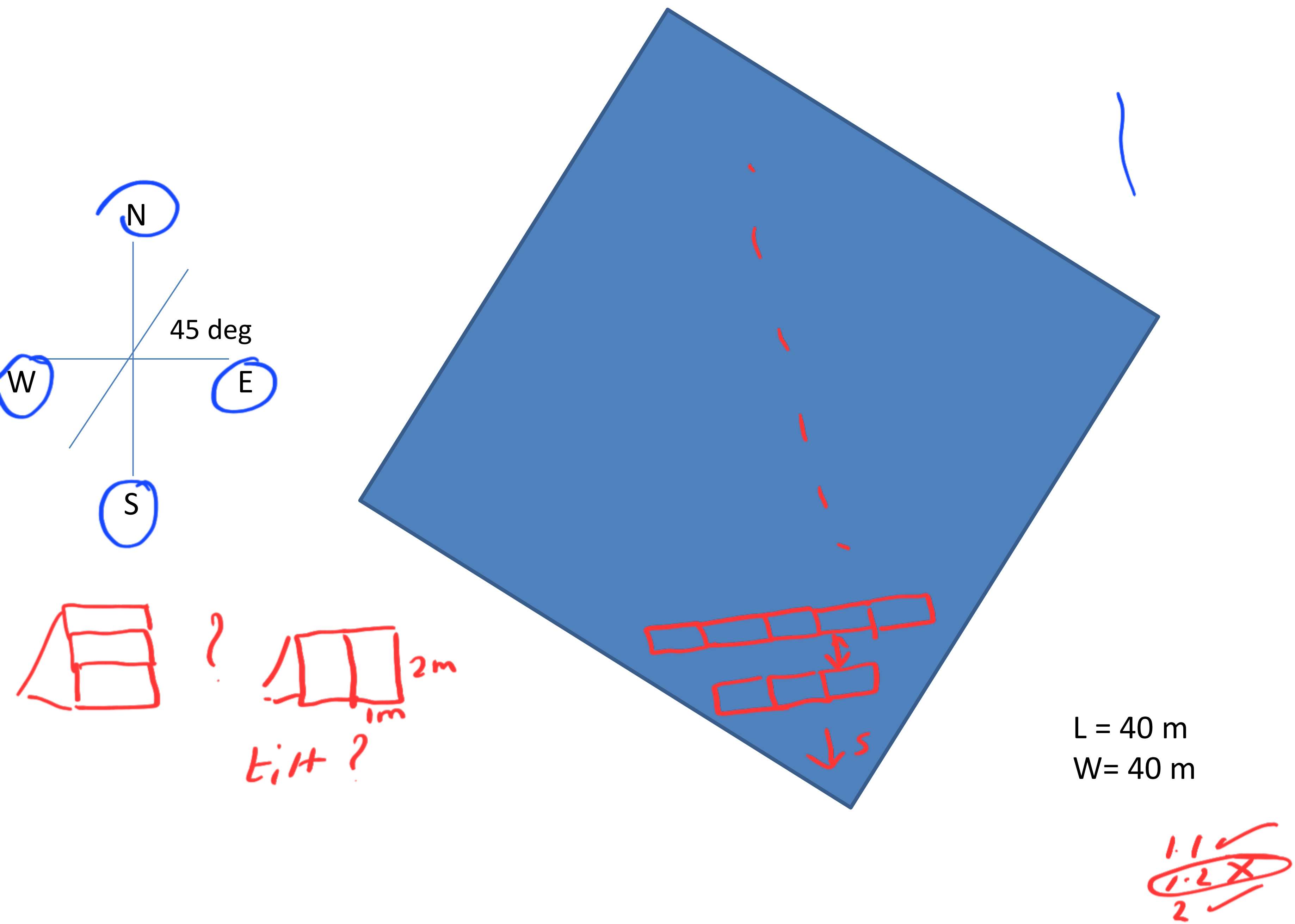
Technical Data	Sunny Tripower 15000TL	Sunny Tripower 20000TL	Sunny Tripower 25000TL
Input (DC)			
Max. DC power (at cos φ = 1) / DC rated power	15330 W / 15330 W	20440 W / 20440 W	25550 W / 25550 W
Max. input voltage	1000 V	1000 V	1000 V
MPP voltage range / rated input voltage	240 V to 800 V / 600 V	320 V to 800 V / 600 V	390 V to 800 V / 600 V
Min. input voltage / start input voltage	150 V / 188 V	150 V / 188 V	150 V / 188 V
Max. input current input A / input B	33 A / 33 A	33 A / 33 A	33 A / 33 A
Number of independent MPP inputs / strings per MPP input	2 / A:3; B:3	2 / A:3; B:3	2 / A:3; B:3
Output (AC)			
Rated power (at 230 V, 50 Hz)	15000 W	20000 W	25000 W
Max. AC apparent power	15000 VA	20000 VA	25000 VA
AC nominal voltage	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V	
AC voltage range	180 V to 280 V	180 V to 280 V	
AC grid frequency / range	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz	
Rated power frequency / rated grid voltage	50 Hz / 230 V	50 Hz / 230 V	
Max. output current / Rated output current	29 A / 21.7 A	29 A / 29 A	36.2 A / 36.2 A
Power factor at rated power / Adjustable displacement power factor	1 / 0 overexcited to 0 underexcited	1 / 0 overexcited to 0 underexcited	
THD	≤ 3%	≤ 3%	
Feed-in phases / connection phases	3 / 3	3 / 3	
Efficiency			
Max. efficiency / European Efficiency	98.4% / 98.0%	98.4% / 98.0%	98.3% / 98.1%

Take the prices of inverters and any other information related to the inverters from the link provided in previous page

- Balance of system (BOS) components, wiring, installation, monitoring cost (0.2 $ per watt dc)
- Calculate the payback period of the system if the Utility would buy the electricity at 0.16$/kWh
- After you finish the design, verify it using PVSYST
- Sketch the placement of the panels and the connection diagram of the panels (Sketches must be done using any software tool or online applications)
- ~~Extra~~ task : 1.2

Assume we want to provide storage for 2 days autonomy of 10% of the project capacity, calculate Battery bank. Assume ambient temperature extremes are -5 to + 45 degrees .

task to be done after finishing Battery topic


N
W
E
S
45 deg
2m
1m
tilt ?
S
L = 40 m
W= 40 m
1.1
1.2
2

Project part2-Design task2 → 2) ✓

- You are employed as a PV design Engineer and your company wants to invest in the PV power generation sector by implementing a 2 Mega Watt DC project. The project will be connected to local electricity grid.

1. Assume the location will be in any rural area in Palestine with cost of Land 10 thousand Jordanian Dinars per donum . سعر الدونم الواحد)
2. Provide a complete design proposal for the project, it is better to have more than one option to propose to your company's CEO. Of course you need to provide cost of project and payback period.
3. You must show number and ratings of panels, inverters and all system components. (provide specs for the used components)

Project part2-Design task2

4. Use Pvsyst to help in your design and to show different alternatives. (generate reports from PVSYST)

5. Consider placement of the PV panels with shading free from 9am to 3 pm and calculate total land area needed.

6. You can divide your system into arrays and make it a modular system, then provide a sketch (2D and 3D) for at least one array.

Project Rules and deadlines:

-Groups consist of 4 students

-Must provide a report, a power point presentation showing summary of **work and record a 5-10 minute video with all group members participating in the video**

-Each group should provide details of who did what in the project?

Deadlines: 31-5-2021

L11-part 2

to be covered after Batteries

PV System Sizing and Design (Standalone Systems)

Batteries

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

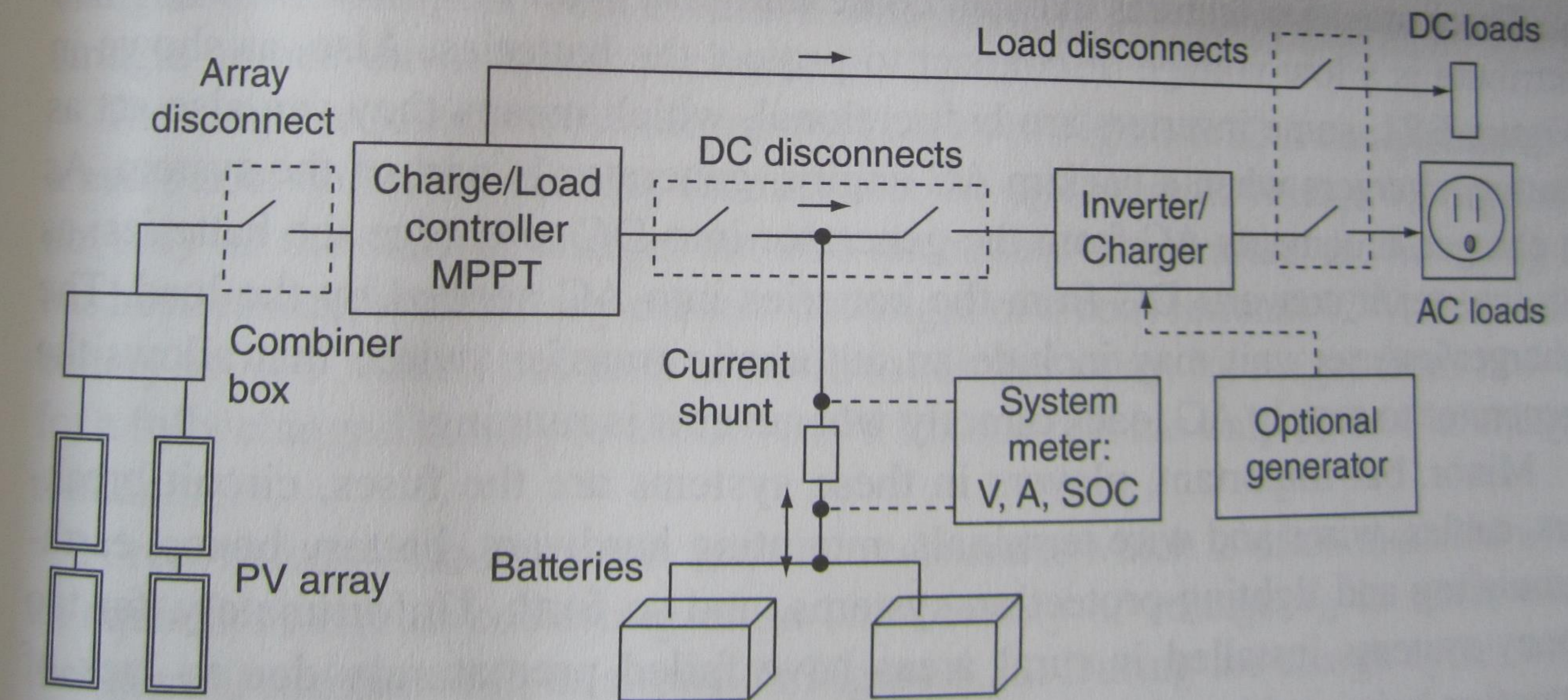


FIGURE 6.21 A "one-line" diagram of the important components in a stand-alone PV system.

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

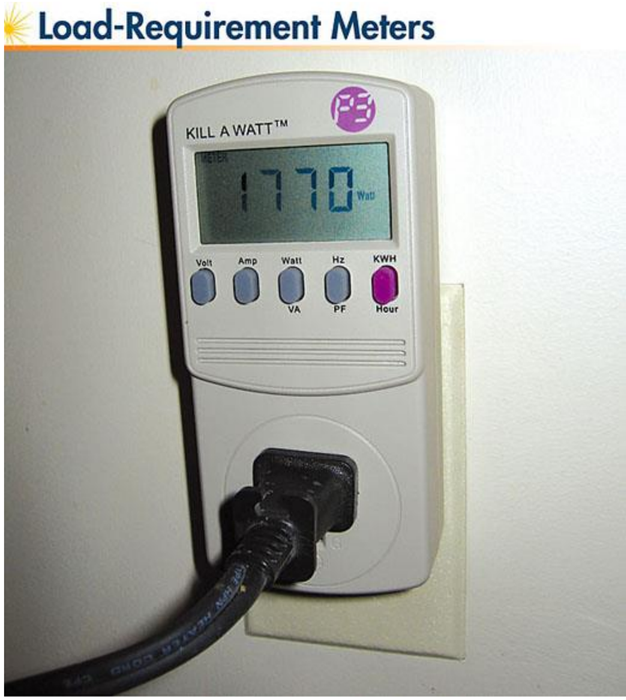
Load Description	Qty	Power Rating (W)	Operating Time (hr/day)	Energy Consumption (Wh/day)

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.

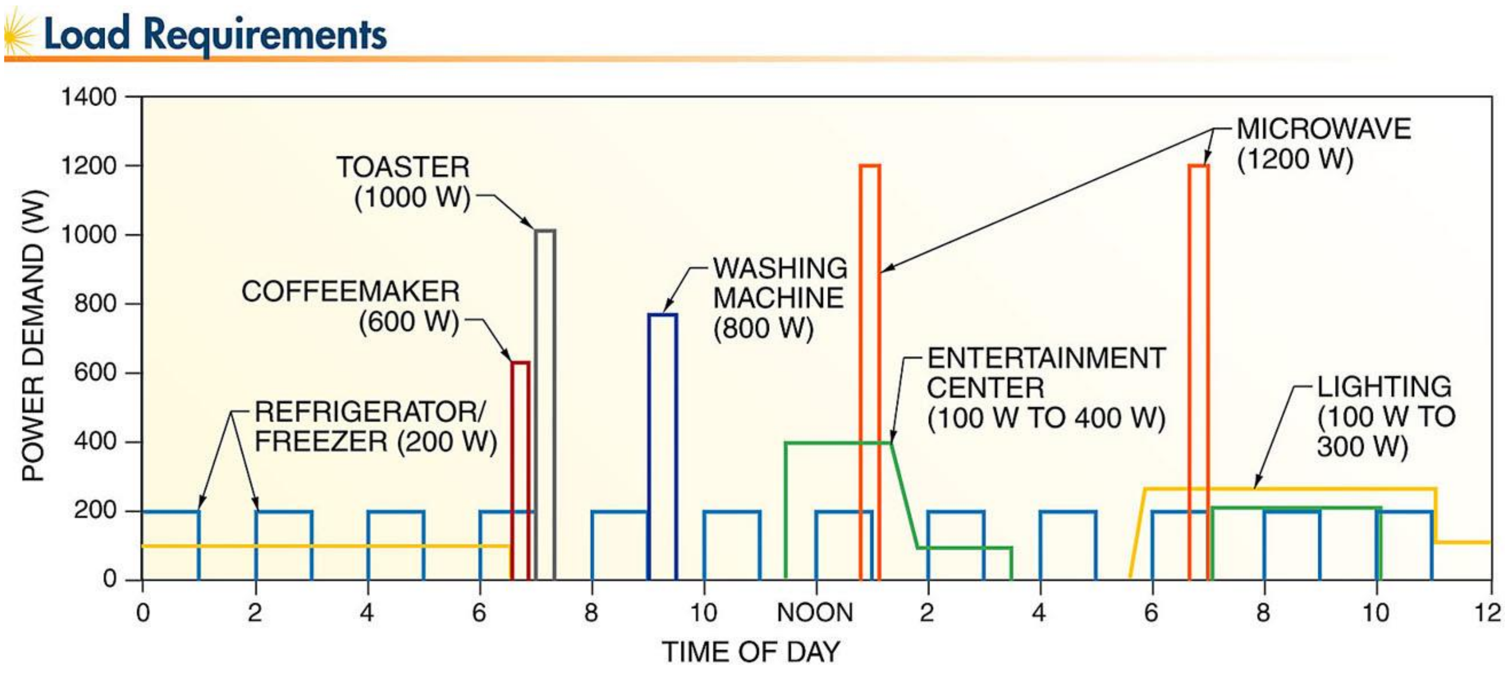


Power Demand & Energy Consumption

- 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?

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

$$t_{op} = \frac{(2400x4) + (1000x7)}{2400 + 1000}$$

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

- 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.

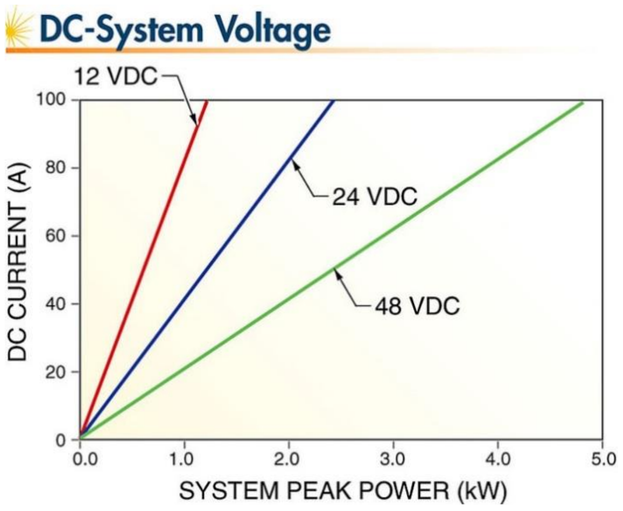
DC-System Voltage

- 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

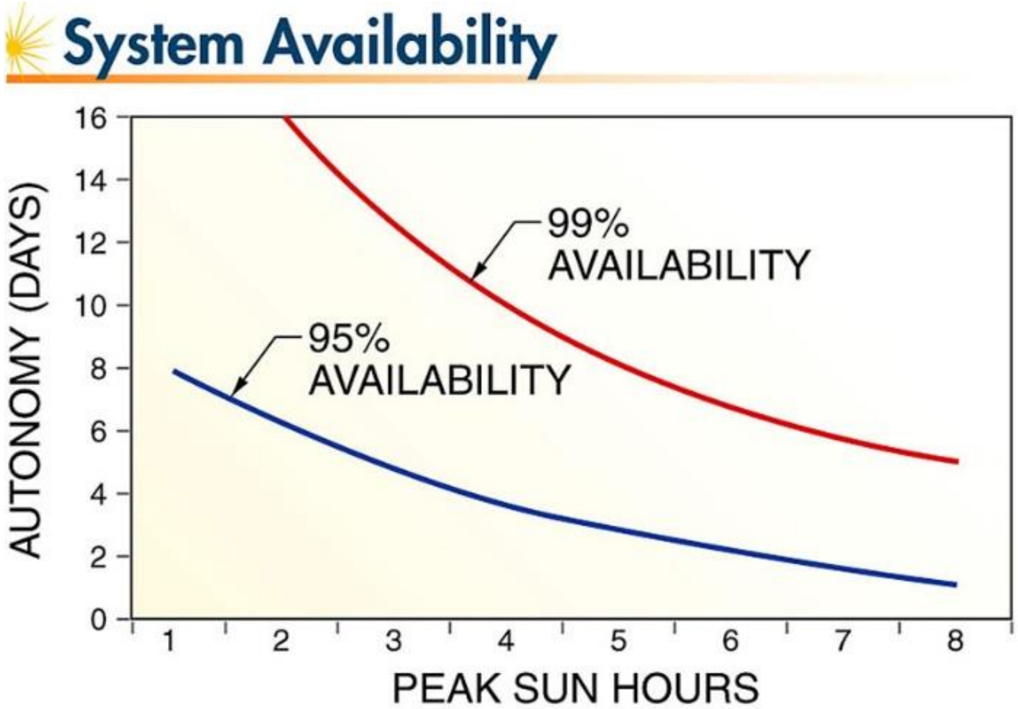
•DC-system voltage is chosen in proportion with the array size and to keep the operating current below 100 A.

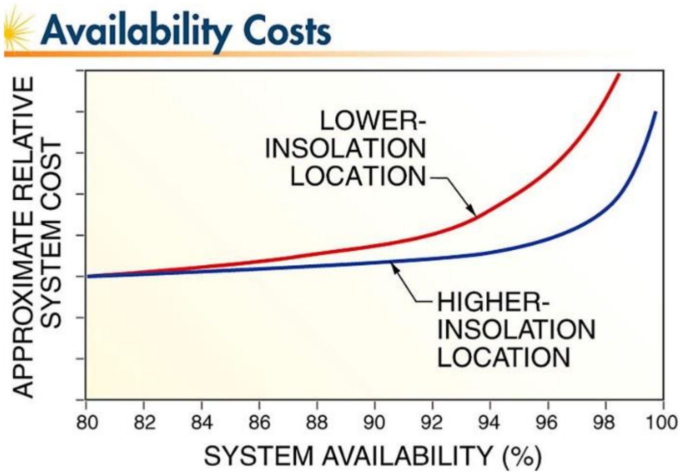
- As a rule of thumb, stand-alone systems up to 1 kW use a minimum 12V battery-bank voltage, which limits DC currents to less than 84 A.
- Similarly, battery voltages of at least 24 V are used for systems up to 2 kW,
- and at least 48 V for systems up to 5 kW.
- Very large standalone systems may use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

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

- where
- B_{out} = required battery-bank output (in Ah)
- E_{crit} = daily electrical-energy consumption during critical design month (in Wh/day)
- t_a = autonomy (in days)
- 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 hr)
- *top =* weighted average operating time (in hr/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?

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

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

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

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

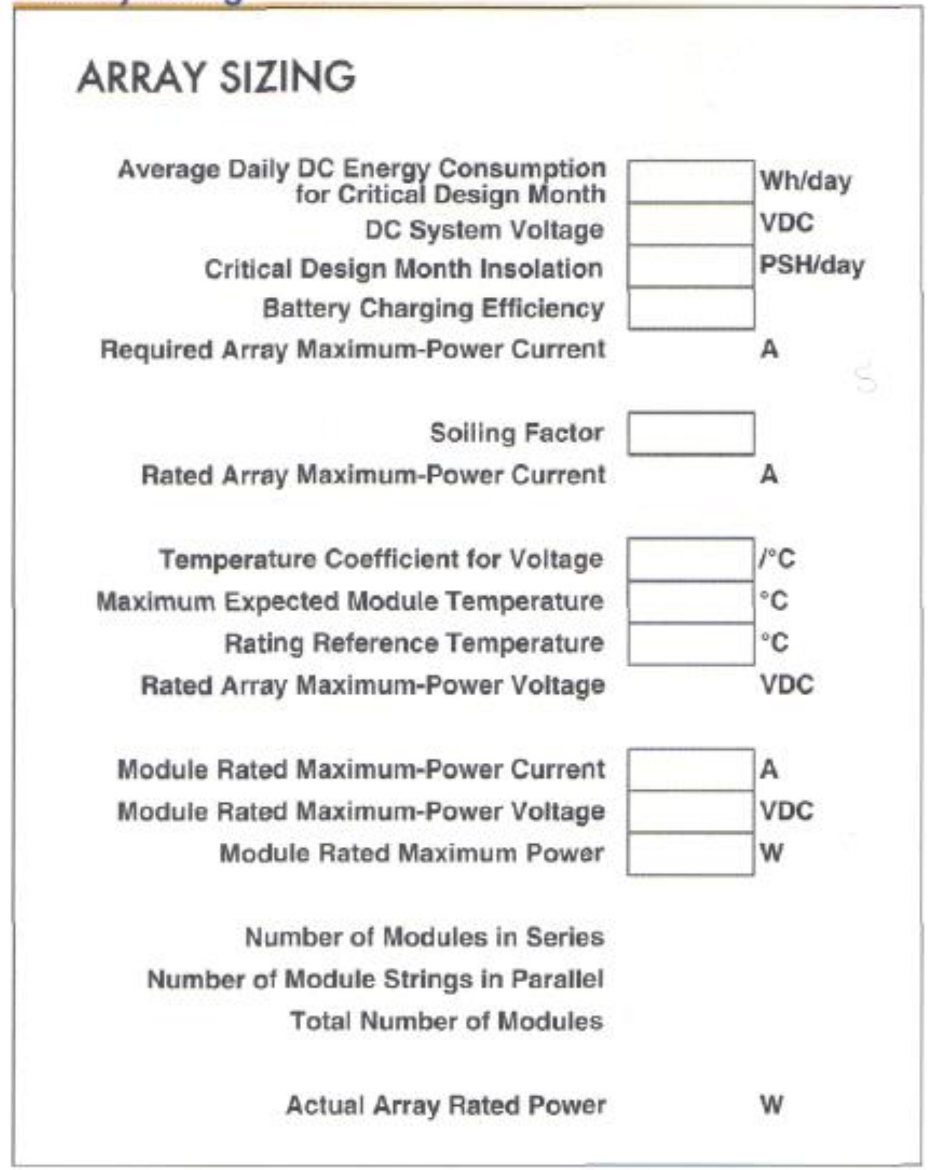


Figure 9-18. *The array sizing worksheet uses insolation data and load requirements to size the array.*

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:

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

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.
- 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

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

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

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

- 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

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

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

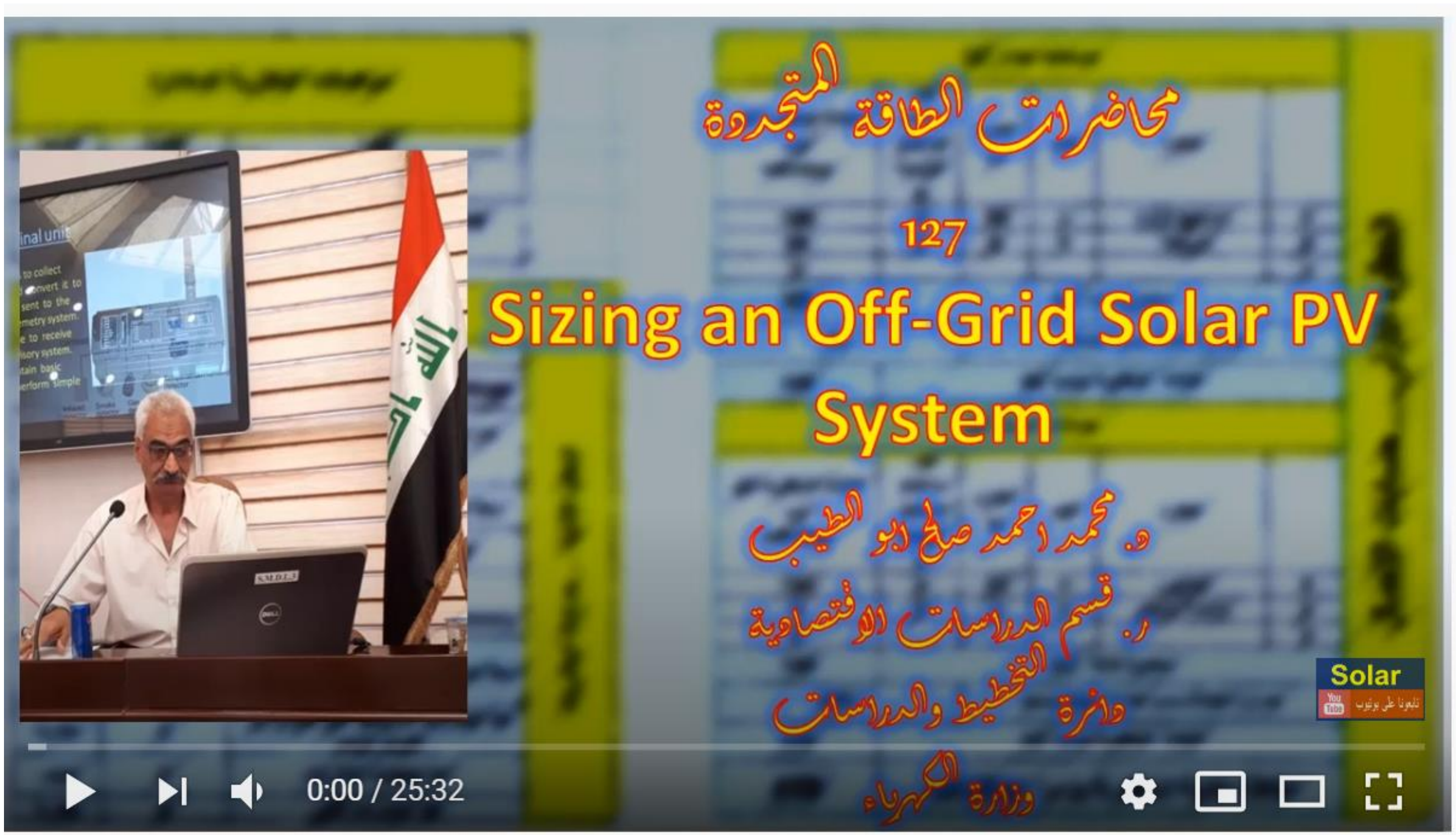
$$V_{array\_rated} = 1.2x\{(V_{SDC}) - [(V_{SDC}).(C_{\%V}).(T_{max} - T_{ref})]\}$$
$$= 1.2x\{(48) - [(48).(-0.004\%/V).(50-25)]\}$$
$$= 63.4 \text{ V}$$

- 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



https://www.youtube.com/watch?v=qyEtLIelZHo