EE 495-695
Grid-Tied PV Systems

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Applicable Codes & Standards

- Most Important:
  - NEC
  - IEEE Std 1547

Reference #	Title/Contents
NEC 2008	*National Electrical Code*/Wiring methods (comprehensive)
IEEE 928	IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems
IEEE 929	IEEE Recommended Practice for Utility Interface of Residential and Intermediate Photovoltaic Systems
IEEE 937	IEEE Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic Systems
IEEE 1013	IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic Systems
IEEE 1144	Sizing of Industrial Nickel Cadmium Batteries for PV Systems
IEEE 1145	IEEE Recommended Practice for Installation and Maintenance of Nickel Cadmium Batteries for Photovoltaic Systems
IEEE 1187	Recommended Practice for Design and Installation of Valve-Regulated Lead-Acid (VRLA) Storage Batteries for Stationary Applications
IEEE 1262	Recommended Practice for Qualification of Photovoltaic Modules
IEEE 1361	Recommended Practice for Determining Performance Characteristics and Suitability of Batteries in Photovoltaic Systems
IEEE 1373	Recommended Practice for Field Test Methods and Procedures for Grid-Connected Photovoltaic Systems
IEEE 1374	Guide for Terrestrial Photovoltaic Power System Safety
IEEE 1479	Recommended Practice for the Evaluation of Photovoltaic Module Energy Production
IEEE 1513	Recommended Practice for Qualification of Concentrator Photovoltaic Receiver Sections and Modules
IEEE 1526	Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems
IEEE 1547	IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems
IEC TC-82	A compendium of 25 standards relating to the electrical and mechanical performance testing and measurement of PV systems
ISO 9001	An international quality standard, comprising of 20 segments, dealing with all aspects of design, manufacturing, and delivery of service
UL 1741	Standard for Static Inverters and Charge Controllers for Use in Photovoltaic Power Systems
ANSI Z97.1	Relates to safety relating to potential glass breakage
ASCE 7-05	Minimum Design Loads for Buildings and Other Structures
ASTM	A compendium of tests and standards that may apply to building integrated photovoltaic systems

Summary of Content of NEC

Section	Contents	*NEC* Cross References
I	**General**: Scope, Definitions, Installation, Ground-fault protection, ac modules	Article 240
II	**Circuit Requirements**: Maximum voltage, Circuit sizing and current, Overcurrent protection, Stand-alone systems	Articles 110, 210, 240
III	**Disconnecting Means**: Conductors, Additional provisions, PV equipment, Fuses, Switches and circuit breakers, Installation and service	Article 230
IV	**Wiring Methods**: Methods permitted, Component interconnections, Connectors, Access to boxes	Articles 310, 339, 400
V	**Grounding**: System grounding, Point of system grounding connection, Equipment grounding, Size of equipment grounding conductor, Grounding electrode system	Article 250
VI	**Marking**: Modules, ac modules, PV power source, Point of common connection	
VII	**Connection to Other Sources**: Identified interactive equipment, Loss of interactive system power, Ampacity of neutral conductor, Unbalanced interconnections, Point of connection	Article 230
VIII	**Storage Batteries**: Installation, Charge control, Battery interconnections	Articles 400, 480
IX	**Systems Over 600 V**: General, Definitions	Article 490

NEC (Voltage Drop Requirement)

- NEC requires that the voltage drop in the circuit cannot exceed 5%.

$$\%VD = \frac{0.2d}{V_s} R$$

where *R* is the resistance of the wire (per 1,000 ft) and *d* is the distance from the source to the load.

- Table 4.2. below show the maximum current allowed for different copper wire sizes (with THWN-2 insulation)

Table 4.2 Properties of Copper Conductors with 90°C Insulation

Size	18	16	14	12	10	8	6	4
dc Ω/kft	7.77	4.89	3.07	1.93	1.21	0.764	0.491	0.308
I_{max} (A)	14	18	25	30	40	55	75	95
Size	3	2	1	0	00	000	0000	250 kcm
dc Ω/kft	0.245	0.194	0.154	0.122	0.0967	0.0766	0.0608	0.0515
I_{max} (A)	110	130	150	170	195	225	260	290

IEEE Std. 1547 Requirements for Abnormal Voltage and Frequency and Current Harmonic Content

Table 4.4 Required Clearing Times for PV Inverters under Abnormal Grid Voltage Conditions

Voltage Range in % of Base Voltage	<50%	50% to 88%	110% to 120%	≥120%
Clearing Time (s)	0.16	2.0	1.0	0.16

Table 4.5 Required Clearing Times for PV Inverters under Abnormal Grid Frequency Conditions

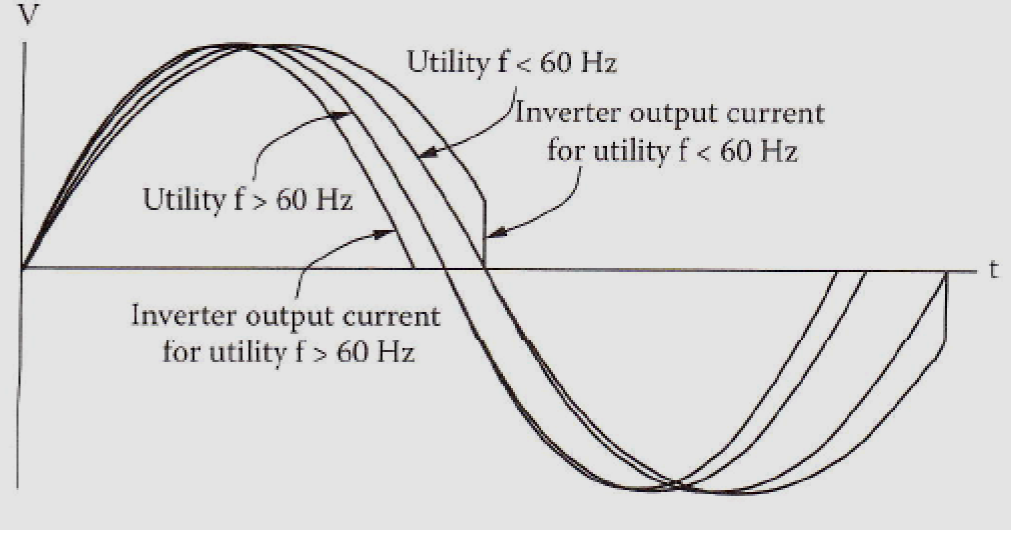
Inverter Size (kW)	Frequency Range (Hz)	Clearing Time (s)
≤30 kW	>60.5	0.16
	<59.3	0.16
>30 kW	>60.5	0.16
	<(59.8–57.0) (adjustable)	Adjustable 0.16–300
	<57.0	0.16

Table 4.6 Maximum Allowable Harmonic Amplitudes for PV Inverter Output in Percent of Maximum Load Current

Harmonic Range	$n < 11$	$11 \le n < 17$	$17 \le n < 23$	$23 \le n < 35$	$35 \le n$
% of Rated Current	4.0	2.0	1.5	0.6	0.3

Inverter Islanding Detection

- The inverter is disconnected for 5 minutes when it sense over-voltage, under-voltage, over-frequency, and under-frequency using UV,OV,UF,OF relays.
- In rare situations (when the power produced by the PV matches that of the local load), the above relays do not sense any deviation in voltage nor frequency, and islanding may occur.
  - In this case, other means to detect an island are needed. A popular example of such islanding detection techniques is the Sandia Frequency Shift (SFS).



Islanding (cont.)

- Another rare situation is when resonance in the islanded circuit occurs. This can be evaluated by an under-damped parallel RLC circuit.

$$v(t) = V_m e^{-\alpha t} \cos(\omega_d t + \phi)$$

$$\alpha = \frac{1}{2RC}, \quad \omega_o = \frac{1}{\sqrt{LC}}, \quad \omega_d = \sqrt{\omega_o^2 - \alpha^2}$$

$$Q = \frac{\omega_o}{2\alpha} = \omega_o RC.$$

- Question: For how many cycles does it take for the voltage to decrease to the inverter trip limit (0.5 V_m) as a function of the quality factor Q? Answer:

$$t = \frac{2\ln 2}{\omega_d}\sqrt{Q^2 - 0.25}$$

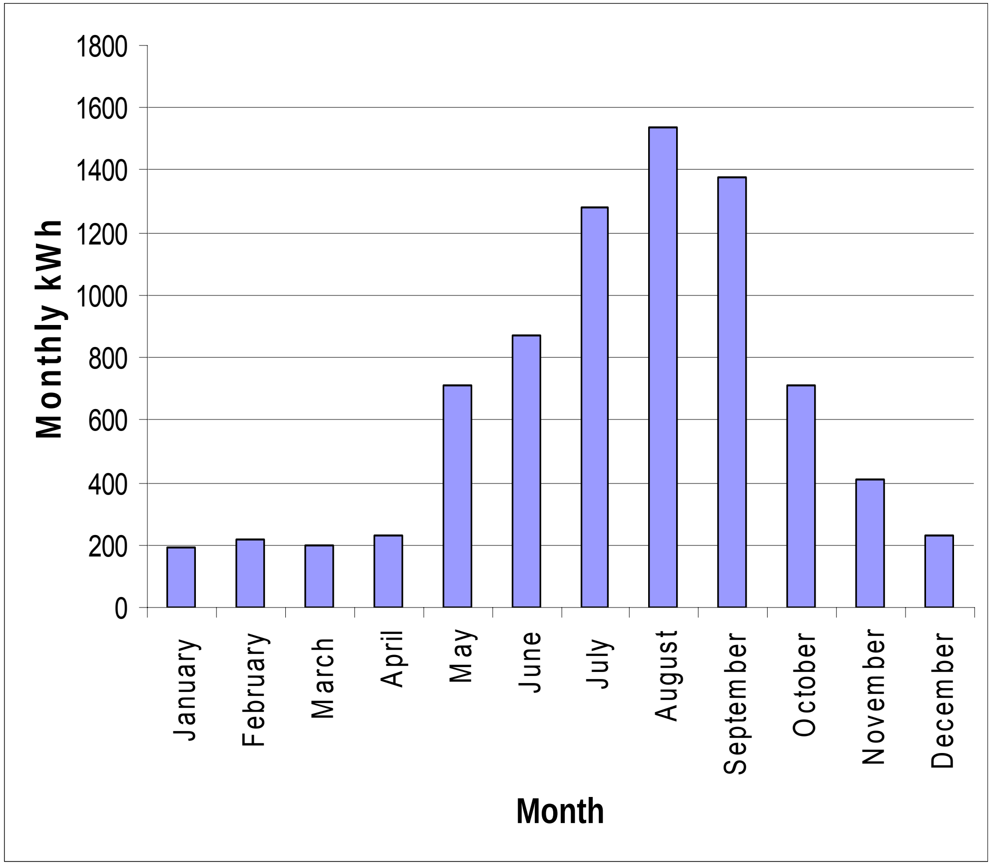
Other Issues Related to Grid-Tied PV Systems

- During a fault, PV inverters contribute a little more than the rated current to the fault. On the other hand, rotating generators generally contributes 5 to 10 times their rated current.
- Aesthetics of PV installation are of particular concern to architects, building owners, and the community.
- Electromagnetic Interference (EMI): both conducted and radiated EMI must be contained and meet Part 15 of the FCC Code.
- Surge protection on both the AC and DC side of a PV system is required per NEC (article 280). A Metal Oxide Varistor (MOV) is used for protection against lightning and switching surges.

PV System Sizing:
Example of Electric Usage (kWh/month) in Las Vegas

- Jan: 190 kWh
- Feb: 220 kWh
- March: 200kWh
- April: 230kWh
- May: 710kWh
- June: 870kWh
- July: 1280kWh
- Aug: 1540kWh
- Sept: 1380kWh
- Oct: 710kWh
- Nov: 410kWh
- Dec: 230kWh

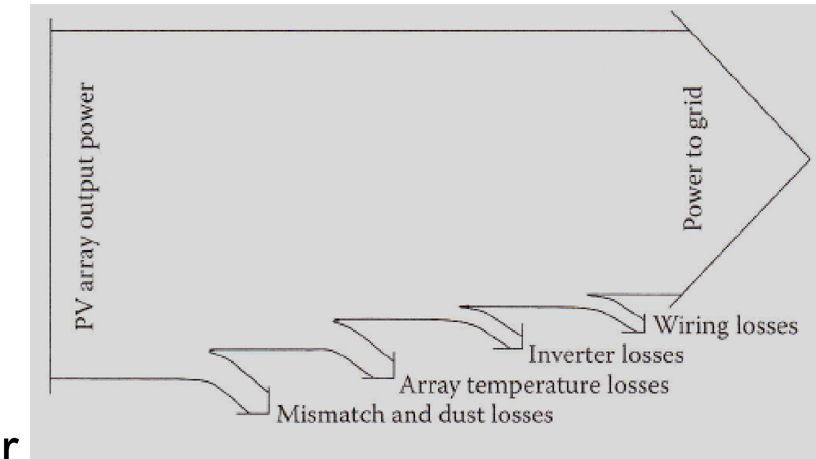
Total: 7,970 kWh



System Sizing – Rough Calculation

Assumptions:

- PV System de-rating:
  - The PV peak power is de-rated by 10% since it is expected to operate at a higher temperature that 25^o.
  - 5% loss due to dust/debris/mismatch
  - 2% loss due to losses in the wires
  - 6% loss due to losses in the inverter



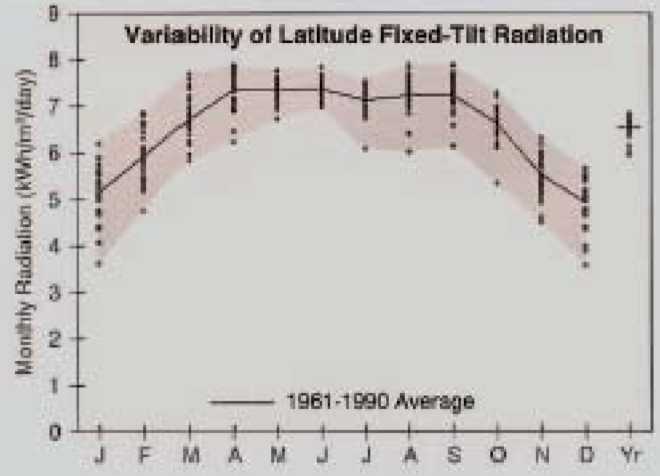
- Hence, a 100 W PV module is expected to produce 77 W of AC power in the real world.
- The roof faces south with 21^o tilt angle. The average daily solar energy received is 6.4 kWh/m^2 (or 6.4 peak sun hours).

Las Vegas, NV

WBAN NO. 23169

LATITUDE: 36.08° N
LONGITUDE: 115.17° W
ELEVATION: 664 meters
MEAN PRESSURE: 938 millibars

STATION TYPE: Primary



Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.0	4.0	5.4	6.9	7.8	8.4	7.9	7.2	6.2	4.7	3.4	2.8	5.7
	Min/Max	2.3/3.4	3.4/4.5	4.8/6.1	6.1/7.4	7.2/8.3	7.8/8.9	6.6/8.4	6.0/7.8	5.4/6.7	4.0/5.1	3.0/3.7	2.2/3.1	5.3/5.8
Latitude -15	Average	4.4	5.3	6.4	7.5	7.8	8.1	7.7	7.5	7.1	6.1	4.8	4.2	6.4
	Min/Max	3.2/5.3	4.4/6.1	5.6/7.3	6.4/8.0	7.2/8.3	7.6/8.6	6.5/8.2	6.2/8.2	6.1/7.7	5.0/6.7	4.0/5.4	3.1/4.8	5.9/6.7
Latitude	Average	5.1	5.9	6.7	7.4	7.3	7.4	7.1	7.2	7.2	6.6	5.5	4.9	6.5
	Min/Max	3.6/6.2	4.8/6.8	5.8/7.7	6.2/7.9	6.7/7.8	7.0/7.8	6.1/7.5	6.0/7.9	6.1/7.9	5.3/7.3	4.5/6.3	3.6/5.7	5.9/6.8
Latitude +15	Average	5.6	6.1	6.6	6.8	6.5	6.3	6.2	6.5	7.0	6.8	5.9	5.4	6.3
	Min/Max	3.8/6.8	4.9/7.2	5.7/7.6	5.7/7.3	5.9/6.8	6.0/6.7	5.3/6.5	5.5/7.2	5.9/7.6	5.4/7.5	4.7/6.8	3.8/6.2	5.7/6.6
90	Average	5.0	5.1	4.7	3.9	3.0	2.6	2.6	3.4	4.5	5.3	5.2	5.0	4.2
	Min/Max	3.4/6.2	4.0/6.0	4.0/5.4	3.3/4.1	2.8/3.1	2.4/2.7	2.4/2.7	2.9/3.7	3.8/4.9	4.2/5.9	4.1/6.1	3.5/5.8	3.7/4.5

Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with a North-South Axis (kWh/m²/day), Uncertainty ±9%

Axis Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	4.6	5.9	7.8	9.8	10.9	11.6	10.8	10.1	9.0	7.1	5.1	4.2	8.1
	Min/Max	3.3/5.6	4.6/7.0	6.2/9.3	8.2/10.9	9.8/11.9	10.5/12.5	8.2/11.8	8.1/11.3	7.1/10.1	5.7/7.9	4.1/6.0	3.0/4.9	7.2/8.5
Latitude -15	Average	5.7	6.9	8.5	10.3	11.0	11.5	10.8	10.4	9.7	8.1	6.2	5.3	8.7
	Min/Max	3.9/6.9	5.3/8.2	6.9/10.2	8.5/11.4	9.9/12.0	10.4/12.4	8.2/11.8	8.4/11.7	7.7/10.9	6.4/9.1	4.9/7.3	3.7/6.2	7.7/9.1
Latitude	Average	6.2	7.3	8.8	10.2	10.6	11.1	10.4	10.3	9.8	8.6	6.7	5.9	8.8
	Min/Max	4.3/7.7	5.6/8.7	7.1/10.5	8.4/11.3	9.6/11.6	10.0/11.9	7.8/11.4	8.2/11.5	7.8/11.1	6.7/9.5	5.3/7.9	4.1/6.9	7.8/9.3
Latitude +15	Average	6.5	7.5	8.7	9.8	10.0	10.3	9.8	9.8	9.6	8.7	7.0	6.2	8.7
	Min/Max	4.4/8.1	5.7/9.0	7.0/10.4	8.1/10.9	9.0/11.0	9.3/11.1	7.3/10.7	7.8/11.0	7.6/10.9	6.7/9.7	5.4/8.3	4.3/7.3	7.6/9.1

Solar Radiation for 2-Axis Tracking Flat-Plate Collectors (kWh/m²/day), Uncertainty ±9%

Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
2-Axis	Average	6.6	7.5	8.8	10.3	11.1	11.8	11.0	10.5	9.8	8.7	7.1	6.3	9.1
	Min/Max	4.5/8.2	5.7/9.0	7.1/10.5	8.5/11.4	10.0/12.1	10.6/12.7	8.3/12.1	8.4/11.8	7.8/11.1	6.7/9.7	5.5/8.3	4.3/7.4	8.1/9.6

- **What percent of the Annual energy needs is expected from 3 kW roof-mounted PV system?**
  - A 3 kW (peak) is de-rated to: 3x0.77 = 2.31 kW
  - The average daily energy production is: 2.31x6.4 =14.8 kWh
  - The yearly energy production is: 14.8 x 365 = 5,396 kWh
  - The above amount represents: 100 x 5,396/7970 = 67% or 2/3 of the annual energy needs.
- **What system size is needed to generate all the annual energy needs?**
  - Annual energy to be produced by the PV: 7,970/0.77 = 10,350 kWh
  - Average daily energy production: 10,350/365 = 28.3 kWh
  - PV system size: 28.3/6.4 = 4.43 kW

More Accurate Sizing Tool: PV-Watts

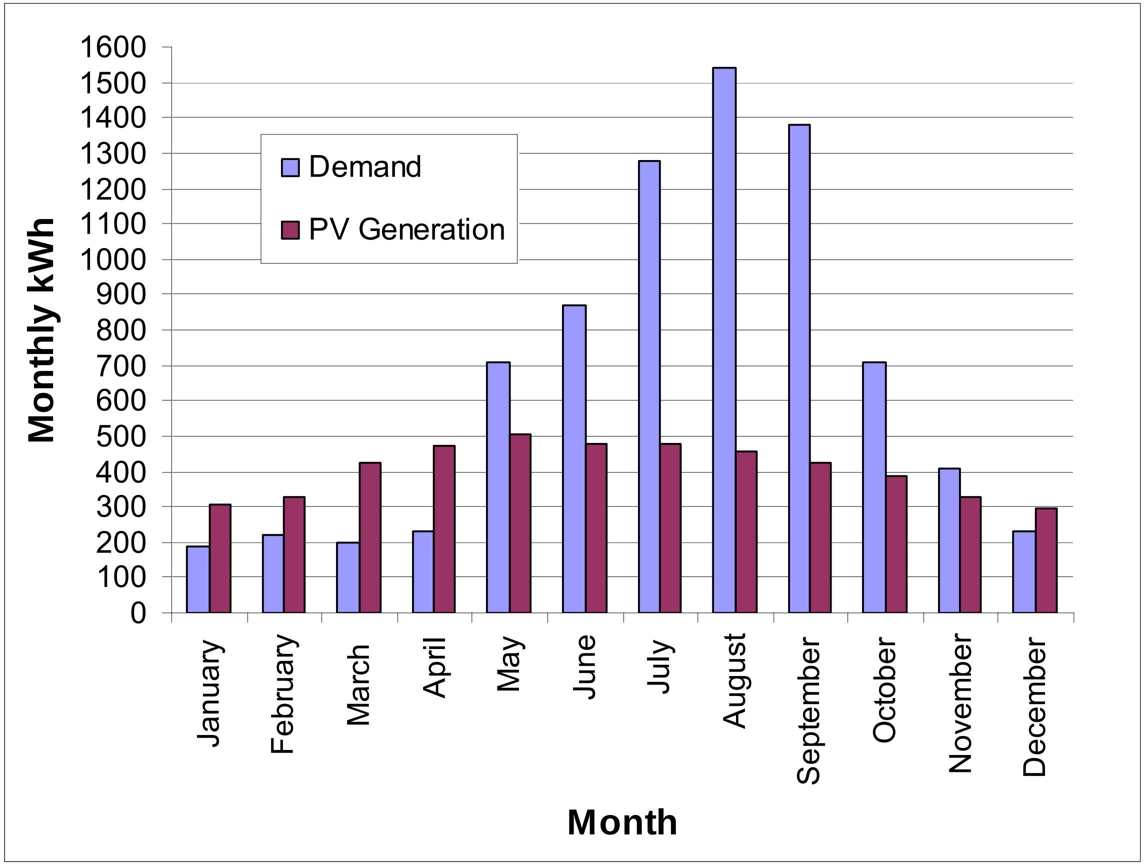
http://www.nrel.gov/rredc/pvwatts/version1.html

PV Watts

A Performance Calculator for Grid-Connected PV Systems

PV-Watts performs an hour-by-hour calculation using TMY weather data, with corrections for things such as the PV module temperature's impact on PV efficiency and inverter efficiency as a function of power generation.

Simulate Previous Example with PV-Watts Using 3 KW Array (61% of energy needs)



Results			
Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value ($)
1	4.47	307	38.38
2	5.40	328	41.00
3	6.30	423	52.88
4	7.45	474	59.25
5	7.95	503	62.88
6	8.08	478	59.75
7	7.98	480	60.00
8	7.56	457	57.12
9	7.14	423	52.88
10	6.01	388	48.50
11	4.99	325	40.62
12	4.27	293	36.62
Year	6.47	4879	609.88

Simulate Previous Example with PV-Watts using 4.9 KW Array (100% of energy needs)

Station Identification	
City:	Las_Vegas
State:	Nevada
Latitude:	36.08° N
Longitude:	115.17° W
Elevation:	664 m
PV System Specifications	
DC Rating:	4.9 kW
DC to AC Derate Factor:	0.770
AC Rating:	3.8 kW
Array Type:	Fixed Tilt
Array Tilt:	21.0°
Array Azimuth:	180.0°
Energy Specifications	
Cost of Electricity:	12.5 ¢/kWh

Results			
Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value ($)
1	4.47	501	62.62
2	5.40	536	67.00
3	6.30	690	86.25
4	7.45	774	96.75
5	7.95	822	102.75
6	8.08	781	97.62
7	7.98	784	98.00
8	7.56	746	93.25
9	7.14	691	86.38
10	6.01	634	79.25
11	4.99	531	66.38
12	4.27	479	59.88
Year	6.47	7970	996.25

You can Write Your Own Calculator in Excel

- Obtain the actual hourly global solar radiation data S_{sun} and ambient temperature T_c: http://www.nrel.gov/midc/unlv
- Compute the following each clock hour (CT) for each day *n* of the year:
- The declination angle δ:
- The equation of time E:
- The solar time ST:
- The hour angle ω:
- The sun altitude angle α and azimuth angle ψ:
- Solar radiation received by the array (specify orientation): S_{pv}
- Approximate temperature of the PV cells:
- PV system de-rating in terms of rated power, temperature coefficient, inverter and other losses.

$$P_{PV} = P_{rated} \frac{G_{PV}}{850} K_{conv} [1 - K_T (T_c - 25^o)]$$

Array Installation

- Maximum annual energy production is achieved when the array faces south with a tilt angle equal latitude angle.
- Little energy is lost if the array is within ± 20^o of south and tilt angle is within ± 15^o of latitude.
- **Homework:** Use PVWatts to plot the annual energy produced by a 2.5 kW PV array in Las Vegas, NV for the following orientations and tilt angles:
  - (south-20^o, Latitude – 20^o), (south-20^o, Latitude – 10^o), (south-20^o, Latitude), (south-20^o, Latitude +10^o), (south-20^o, Latitude + 20^o).
  - (south-10^o, Latitude – 20^o), (south-10^o, Latitude – 10^o), (south-10^o, Latitude), (south-10^o, Latitude +10^o), (south-10^o, Latitude + 20^o).
  - (south, Latitude – 20^o), (south, Latitude – 10^o), (south, Latitude), (south, Latitude +10^o), (south, Latitude + 20^o).
  - (south+20^o, Latitude – 20^o), (south+20^o, Latitude – 10^o), (south+20^o, Latitude), (south+20^o, Latitude +20^o), (south+20^o, Latitude + 20^o).

Example of Design of System based on Specific Energy Needs

- Energy needed in Oklahoma City: 3,996 kWh/year
- According to PVWatts, a 2.842 kW array (with 22.6^o tilt facing south) is needed.
- Module selection: Modules 1-4: 190 W, 175 W, 200W, 230W

Table 4.9 Electrical Characteristics of Four Different PV Modules

Module #	V_{OC} (V)	I_{SC} (A)	V_m (V)	I_m (A)	$\Delta V_{OC}/\Delta T$ (%/°C)	$\Delta V_m/\Delta T$ %/°C	NOCT (°C)
1	32.8	8.05	26.7	7.12	−0.35	−0.49	47
2	44.4	5.30	35.8	4.89	−0.33	−0.47	46
3	68.7	3.83	55.8	3.59	−0.25	−0.29	47
4	48.7	5.99	41.0	5.61	−0.27	−0.38	46

- Assume ambient temperature range between -20^{o}C and +38^{o}C

Table 4.10 Tabulation of V_{OC}(max) and V_m(min) for the Modules of Table 4.9

Module #	Max V_{OC}	Min V_m
1	38.0	20.6
2	51.0	28.1
3	76.4	48.2
4	54.6	33.8

Inverter Selection:

- Inverter must have a UL 1741 listing
- Input and output performance characteristics of two compatible inverters:
  - Rated AC Power, and output voltage
  - Peak efficiency
  - Maximum Array Power and DC voltage
  - Maximum power tracking voltage range

Table 4.8 Input and Output Performance Characteristics of Two Different Inverters

Inverter #	Rated ac Power (W)	Max Array Power (W)	Max dc V_{in} (V)	V_{in} MPPT Range (V)	I_{in} Max (A)	V_{ac} Out (V)	I_{ac} Out Max
1	2800	3100	600	$195 < V_m < 550$	15.4	240	11.7
2	3000	3750	500	$200 < V_m < 400$	17	240	13

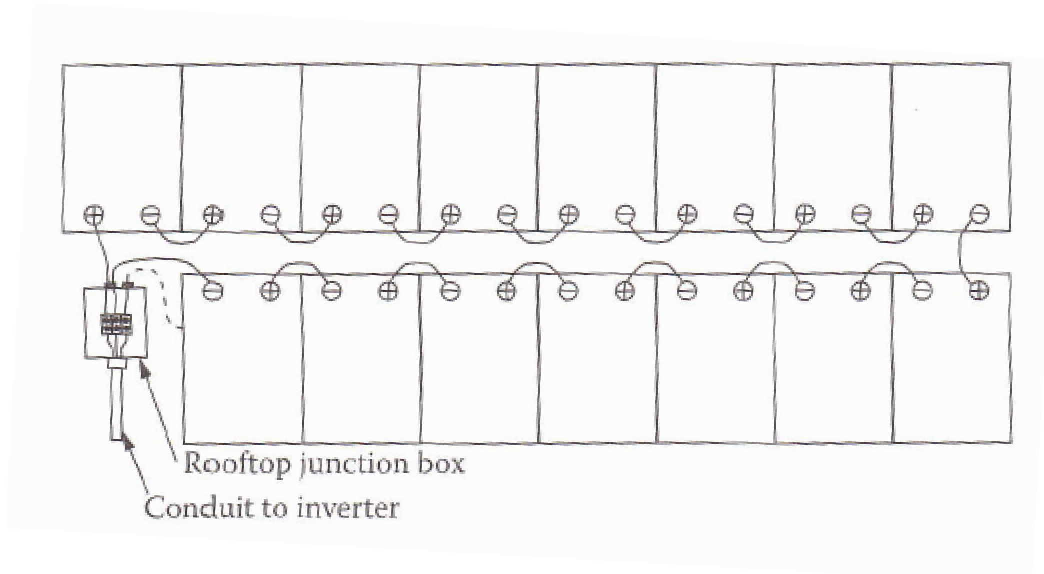
Which Combination to Use?

- Determine minimum (maximum) number of module to be connected in series by dividing the minimum MPPT voltage (maximum array DC voltage) by the minimum voltage at maximum power (maximum module open circuit voltage).
- Determine the number of modules that most closely match the required array power: module 1: 15, module 2: 17, module 3: 15, module 4: 13. … best selection: module 1 and inverter 1

Table 4.11 Summary of Allowed Numbers of Modules That Fall within Inverter Input Voltage Limits

Inverter	Allowed # of Module #1	Allowed # of Module #2	Allowed # of Module #3	Allowed # of Module #4
Inverter #1 with:				
One source circuit	10, 11, 12, 13, 14, or 15	7, 8, 9, 10, or 11	5, 6, or 7	6, 7, 8, 9, or 10
Two source circuits	20, 22, 24, 26, 28, or 30	14, 16, 18, 20, or 22	10, 12, or 14	12, 14, 16, 18, or 20
Inverter #2 with:				
One source circuit	10, 11, 12, or 13	8 or 9	5 or 6	6, 7, 8, or 9
Two source circuits	20, 22, 24, or 26	16 or 18	10 or 12	12, 14, 16, or 18

Rooftop Arrangement & Balance of System



- The modules come with 36” long leads (#10 USE-2): total wire length: 90’.
- Assume 75’ from rooftop junction box to inverter:
- Wire size must satisfy ampacity and voltage drop:
  - Minimum ampacity: 156% of short circuit current (8.05 A) per NEC 690.8(A).
  - Conductor de-rating when operating at higher temperatures.

Temperature correction factors

- Assume conduit height is 3.5” above rooftop, the 22^{o}C are added to the maximum ambient temperature: 38^{o}+22^{o} = 60^{o}C
- Hence a de-rating factor of 71% applies.

Table 4.12 Summary of Ambient Temperature Correction Factors for Wire with 90°C Insulation

Temp (°C)	21–25	26–30	31–35	36–40	41–45
Correction	1.04	1.00	0.96	0.91	0.87
Temp (°C)	46–50	51–55	56–60	61–65	66–70
Correction	0.82	0.76	0.71	0.58	0.41

Source: Based on data from *NFPA 70 National Electrical Code, 2008 ed.*, National Fire Protection Association, Quincy, MA, 2007.

Table 4.13 Ambient Temperature Correction Factors for Conduit Run across Rooftops

Height of Conduit above roof (in.)	0–0.5	0.5–3.5	3.5–12	>12
Add to ambient (°C)	33	22	17	14

Source: Based on data from *NFPA 70 National Electrical Code, 2008 ed.*, National Fire Protection Association, Quincy, MA, 2007.

Conductor Size

- In this example, it is assumed the conduit leaving the junction box goes directly into the attic, hence the derating is 91%. Furthermore, no derating of conduit fill since the number of current carrying conductors is 2.
- Note that a #10 wire is more than adequate.
- Voltage drop: %VD = 0.517% (using Im = 7.12 A, Vm = 400.5 V, resistively = 1.21 Ω/kft, d = 45+75)

Table 4.15 Determination of Conductor Size for PV Source Circuits and/or Output Circuits

I_{SC}	$1.25I_{SC}$	$1.56I_{SC}$	Wire Size	30°C Ampacity	Amb Temp	Amb Derate	Cond Fill	Fill Derate	Derated Ampacity
8.05	10.06	12.58	10	40	38	0.91	2	1.0	36.40

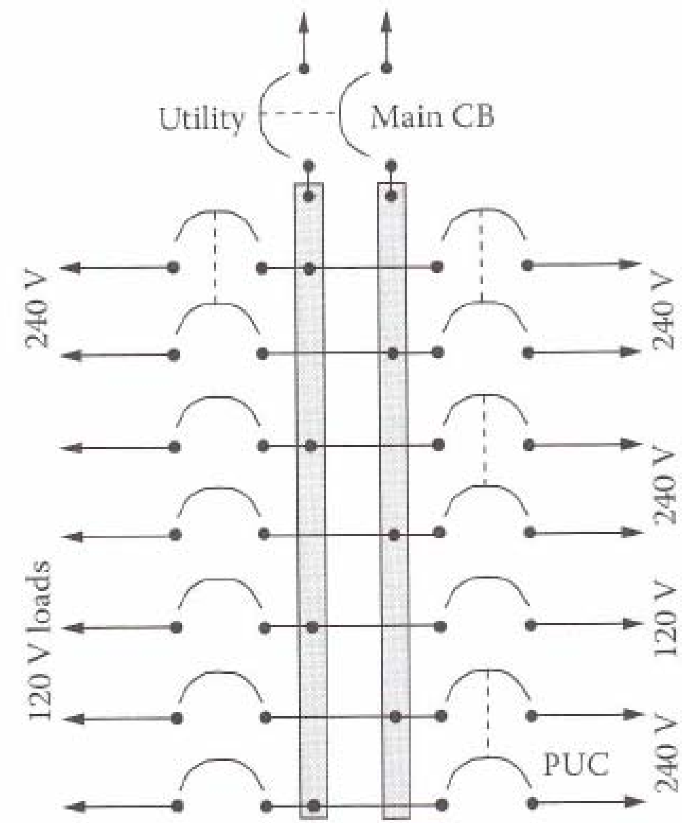
Table 4.14 Derating Factors Based on Conduit Fill

Number of current-carrying conductors	0–3	4–6	7–9	10–20	21–30
Derating factor	1.0	0.8	0.7	0.50	0.45

Source: Based on data from *NFPA 70 National Electrical Code, 2008 ed.*, National Fire Protection Association, Quincy, MA, 2007.

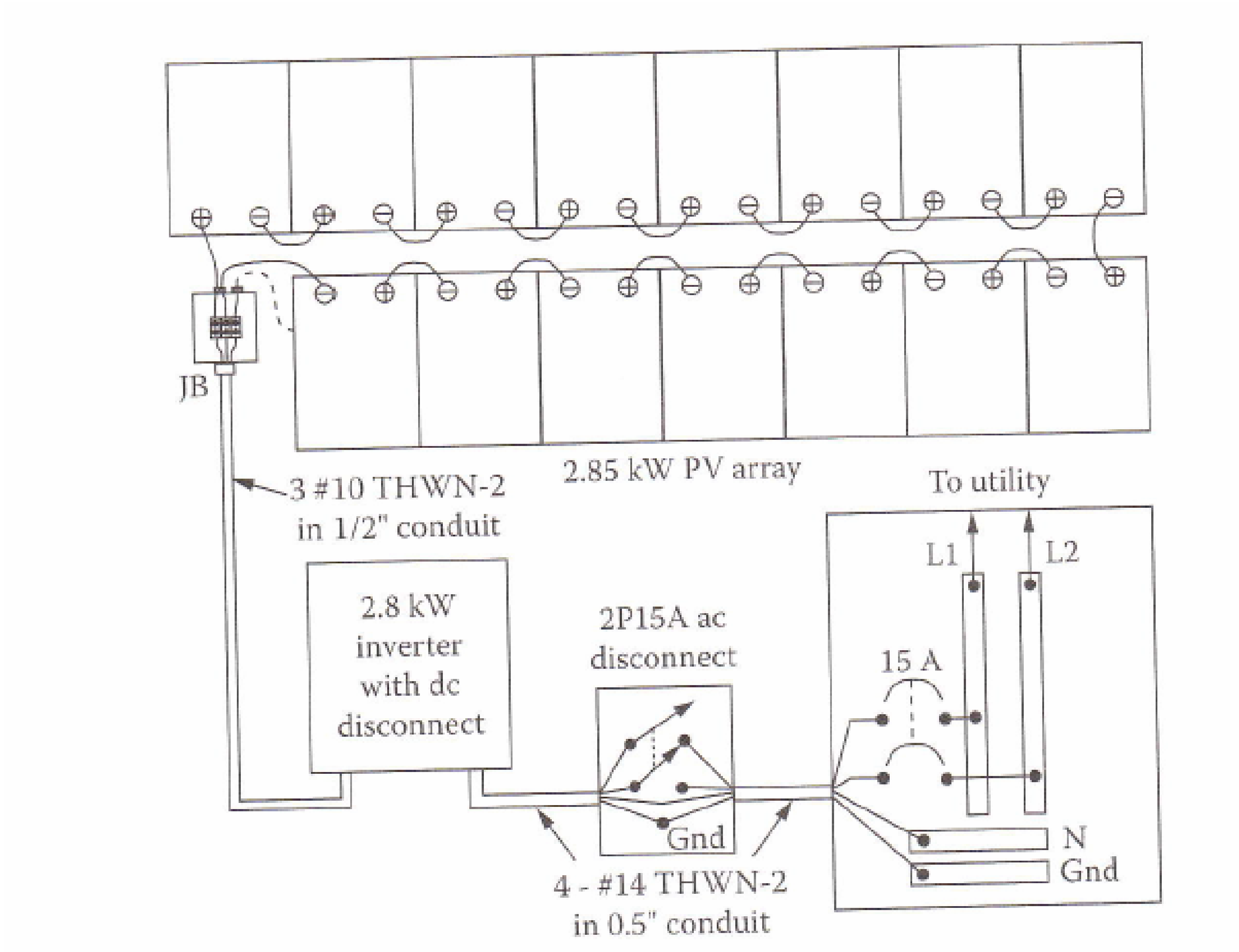
AC and DC Disconnect and Utility Interconnection

- Grid-tied Inverters usually come with DC Disconnects.
- Inverter 1 is rated at 11.7 A@ 240 V on the AC side. The AC disconnect must be rated at not less than125% of the rated output current (i.e., 14.6 A). Hence a 15 A disconnect switch is satisfactory.
- Further, # 14 wire rated at 20 A, may be used to connect the inverter to the utility panel through the disconnect switch.



Neutral and gnd not shown.

Final Electrical Schematic Diagram



Voltage Drop in 3-Phase Circuit

- When ignoring the cable reactance, the voltage drop can be approximated by

$$\%VD = 100IR/V_{phase} = 100\sqrt{3}IR/V_{line}$$

where $V_{line} = \sqrt{3}V_{phase}$ and $R = (\Omega/kft)d/1000$