Photovoltaic Systems Engineering

Solar radiation: Refer to Lectures 5 & 6 of EML 4450 Fall 2006.

Irradiance & Irradiation

Irradiance is given in *W/m^2 and is represented by the symbol G.*

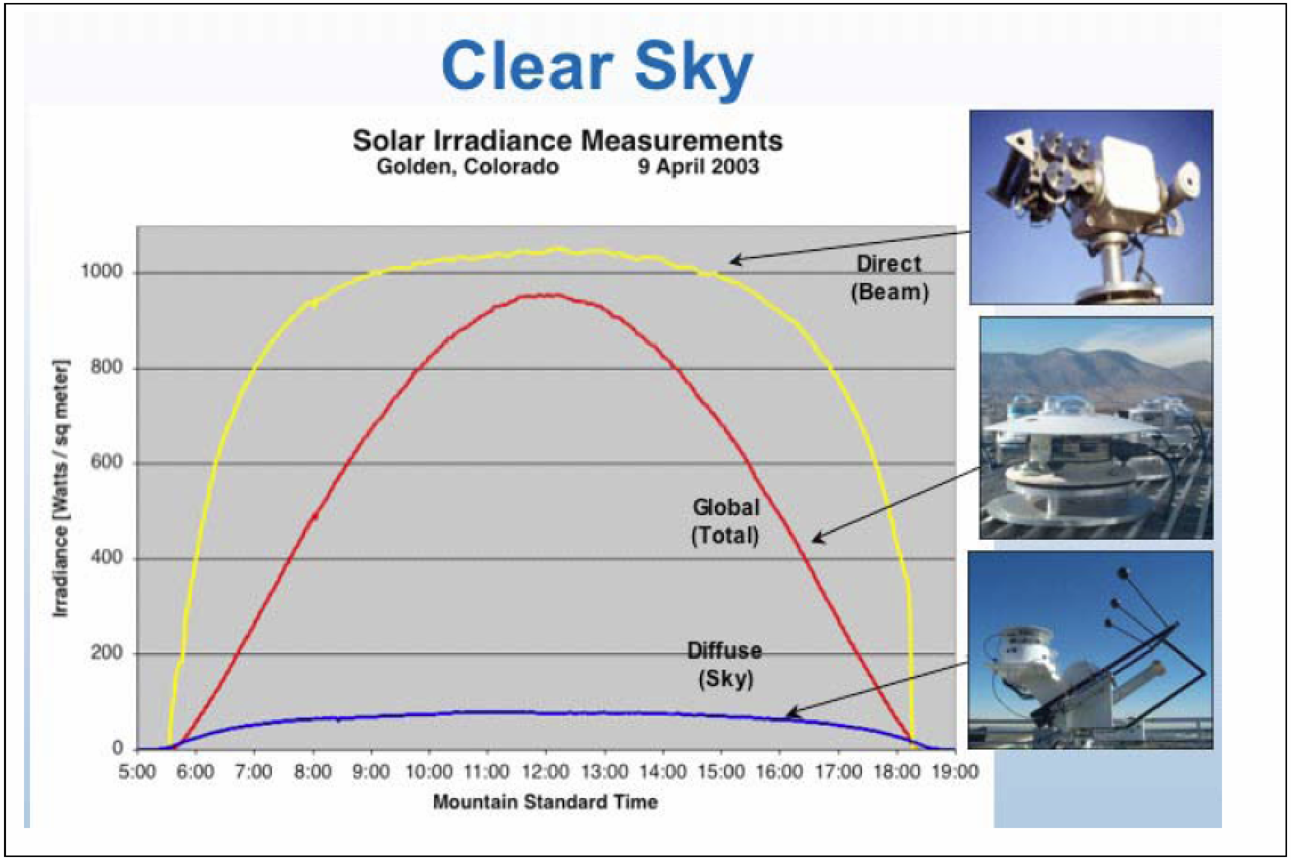
The rate at which radiant energy is incident on a surface per unit area of surface.

Irradiation is given in *J/m^2* and is the incident energy per unit area on a surface - determined by integration of irradiance over a specified time, usually an hour or a day.

Insolation is a term used to solar energy irradiation

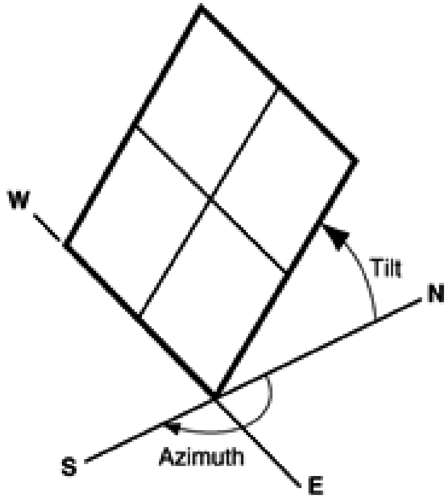
Radiosity is the rate at which radiant energy leaves a surface, per unit area, by combined emission, reflection and transmission.

Typical Solar Irradiance

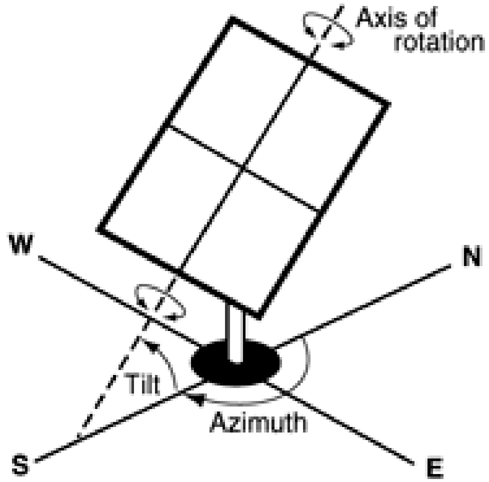


Measurement	Method	Application
Direct (Beam)	Pyrheliometer tracking the sun all day	Concentrating collectors for PV or solar thermal
Global (Total)	Pyranometer viewing the entire sky dome (as plotted) or tilted towards the south like a solar collector	Thermal performance of buildings, biomass, PV, solar thermal, and climatology
Diffuse (Sky)	Shaded pyranometer (beam is blocked by a shade ball or disk)	Daylighting, biomass, and PV

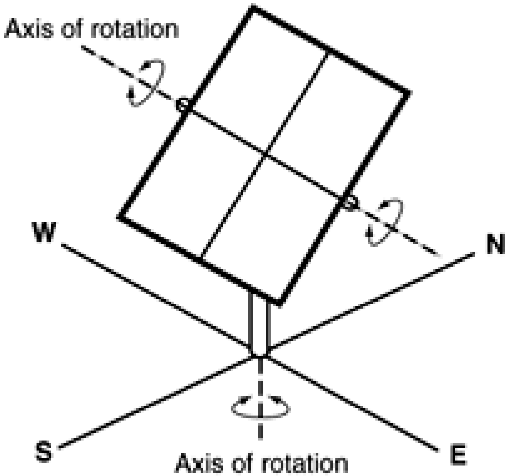
PV Panel Orientation



PV array facing south at fixed tilt.

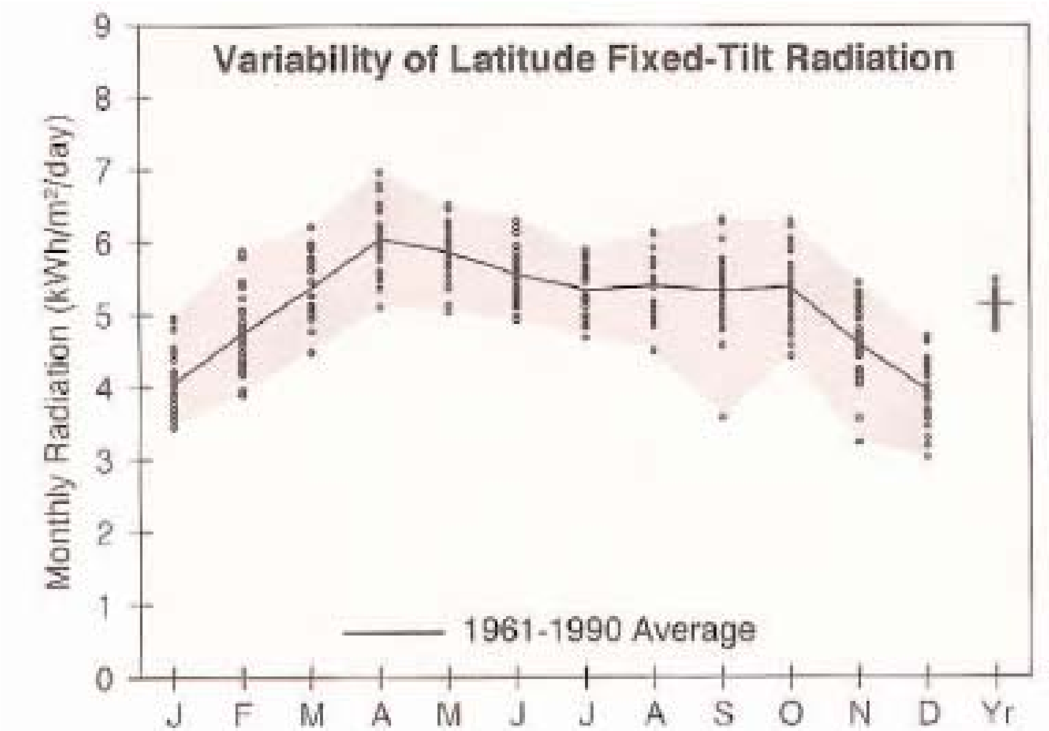


One axis tracking PV array with axis oriented south.



Two-axis tracking PV array

Tallahassee Solar Radiation Data



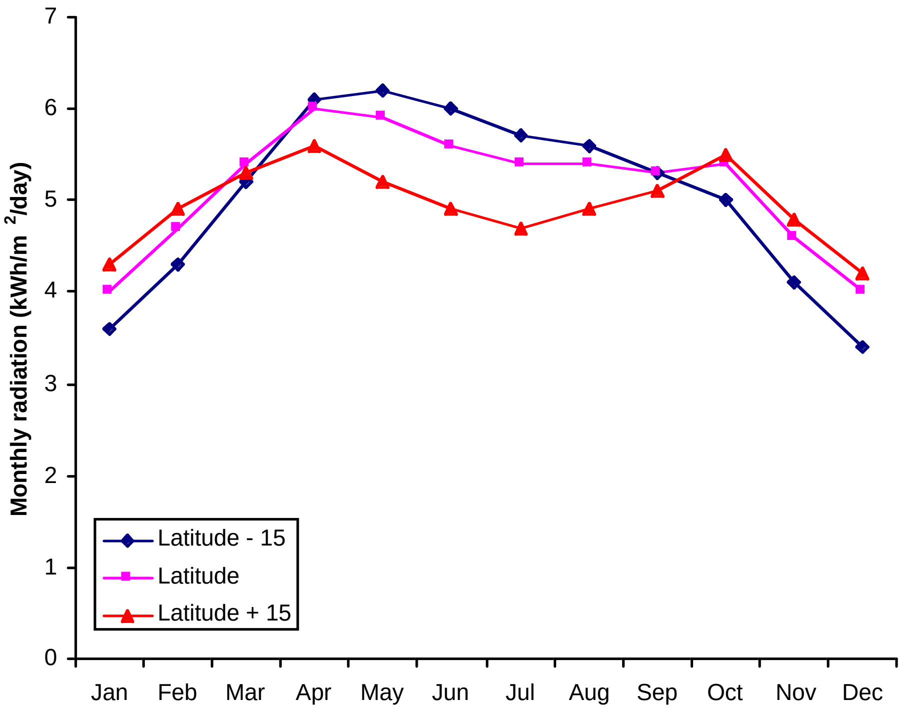
LATITUDE: 30.38° N
LONGITUDE: 84.37° W
ELEVATION: 21 meters
MEAN PRESSURE: 1016 millibars

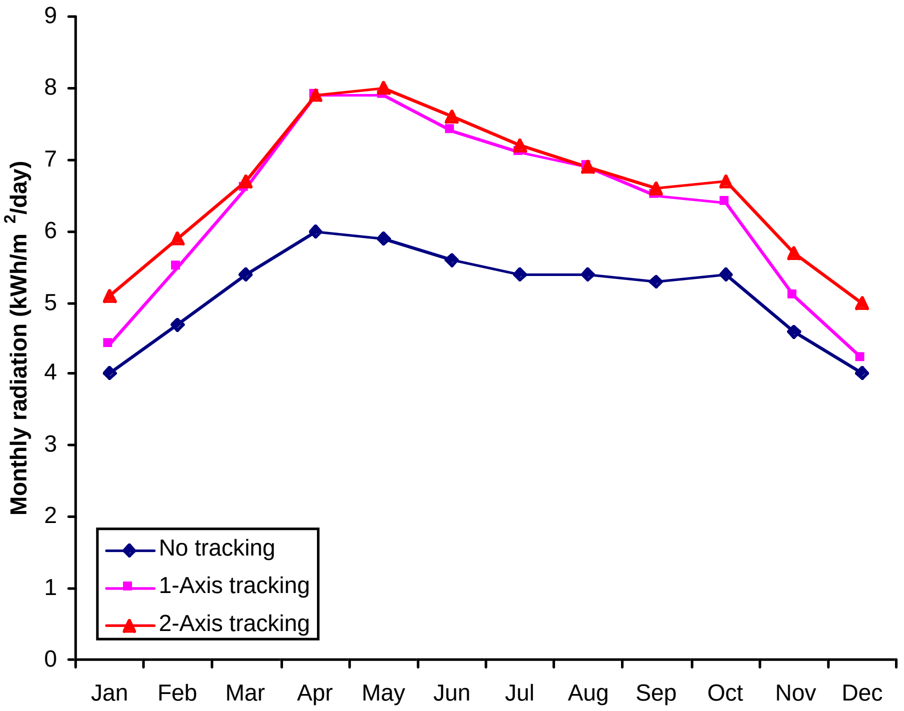
Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	2.9	3.7	4.7	5.9	6.3	6.1	5.8	5.5	4.9	4.3	3.3	2.7	4.7
	Min/Max	2.5/3.4	3.1/4.4	4.0/5.3	5.1/6.7	5.5/6.9	5.4/7.0	5.2/6.4	4.6/6.2	3.5/5.7	3.7/5.0	2.6/3.8	2.3/3.1	4.4/5.0
Latitude -15	Average	3.6	4.3	5.2	6.1	6.2	6.0	5.7	5.6	5.3	5.0	4.1	3.4	5.0
	Min/Max	3.1/4.3	3.6/5.3	4.3/5.9	5.2/7.1	5.3/6.9	5.3/6.8	5.0/6.3	4.7/6.3	3.6/6.2	4.2/5.8	3.0/4.7	2.7/4.0	4.7/5.4
Latitude	Average	4.0	4.7	5.4	6.0	5.9	5.6	5.4	5.4	5.3	5.4	4.6	4.0	5.1
	Min/Max	3.5/5.0	3.9/5.9	4.5/6.2	5.1/7.0	5.0/6.5	4.9/6.3	4.7/5.9	4.5/6.1	3.6/6.3	4.4/6.3	3.2/5.4	3.0/4.7	4.8/5.5
Latitude +15	Average	4.3	4.9	5.3	5.6	5.2	4.9	4.7	4.9	5.1	5.5	4.8	4.2	5.0
	Min/Max	3.6/5.3	4.0/6.1	4.3/6.1	4.7/6.5	4.5/5.8	4.3/5.5	4.2/5.2	4.1/5.6	3.4/6.1	4.4/6.4	3.3/5.8	3.2/5.1	4.6/5.3
90	Average	3.6	3.7	3.4	2.9	2.2	1.9	2.0	2.4	3.1	4.0	4.0	3.7	3.1
	Min/Max	3.0/4.7	3.1/4.8	2.8/4.0	2.5/3.2	1.9/2.4	1.7/2.0	1.8/2.1	2.1/2.5	2.0/3.6	3.2/4.7	2.6/4.9	2.7/4.5	2.9/3.3

http://rredc.nrel.gov/solar/pubs/redbook/PDFs/FL.PDF

Tallahassee Monthly Solar Insolation





Annual Global Irradiance

For clear sky condition

$$E_{global} = \left[650 \left(\sin \frac{4}{3\alpha} - 30 \right) + 325 \right] \times \left(8 \times 10^{-5} \times h + 1 \right) \quad \mathrm{W/m^2}$$

Where α is the solar altitude in degrees and h is the geographic altitude in meters (Tallahassee: 21 m).

To find the solar altitude go to the following site:

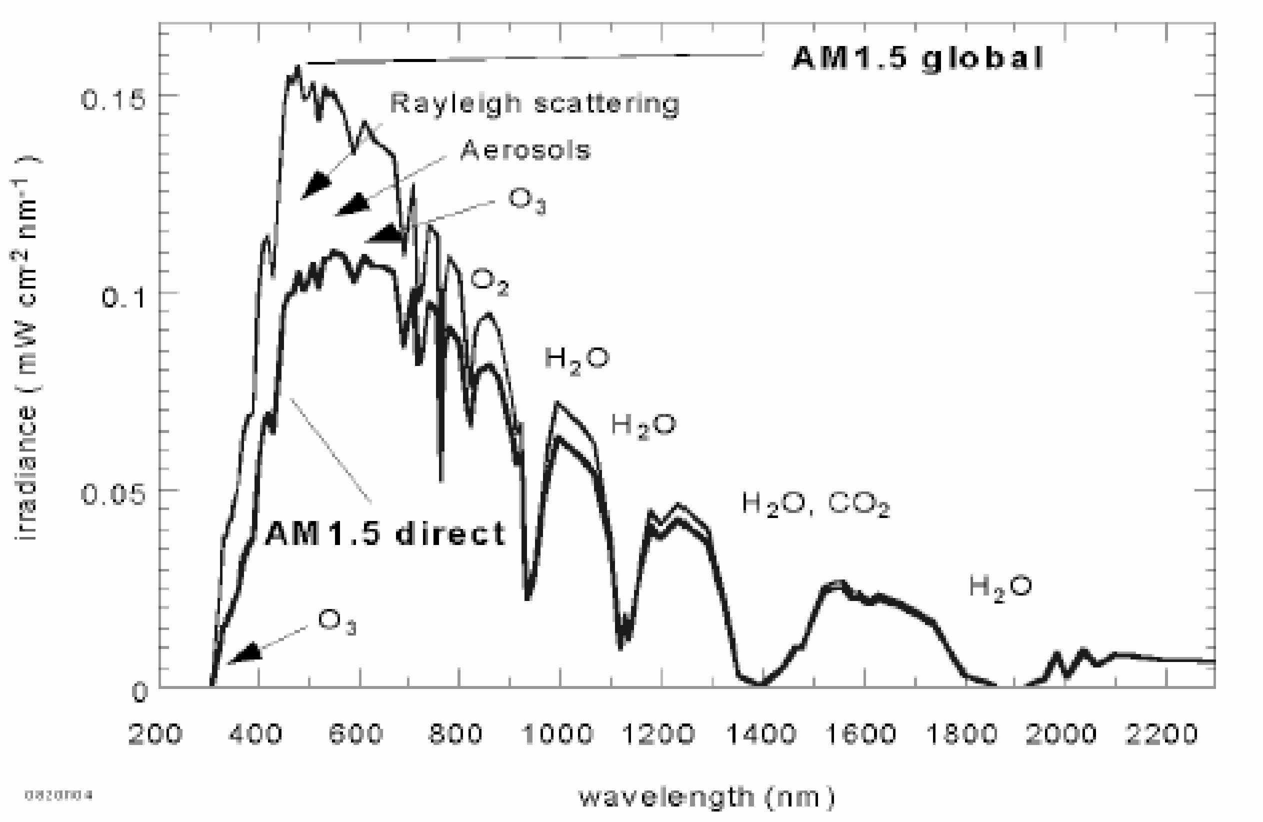
http://aa.usno.navy.mil/data/docs/AltAz.html

Source: Masato Oki & Hiroyuki Shiina, “Preliminary study on an estimation method for annual solar irradiance at various geological altitudes”, Eighth International IBPSA Conference, Eindhoven, Netherlands, August 2003.

Algorithm

Ibrahim Reda & Afshin Andreas, “Solar Position Algorithm for Solar Radiation Applications”, NREL/TP-560-34302, November 2005. http://www.nrel.gov/docs/fy06osti/34302.pdf

Global Radiation



The global spectrum comprises the direct plus the diffused light.

AM 1.5d Spectrum Energy Distribution

(eV) :	4.1	3.5	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.24	1.18	1.13	1.08	1.03	0.99	0.95	0.69	0.62	0.5
(nm):	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1800	2000	2500
300	0	0.7	2.9	7.6	14	21	28	35	42	48	54	59	64	67	70	74	77	79	81	84	86	96	96	100
350		0	2.2	6.9	14	21	28	35	41	47	53	58	63	66	69	73	77	78	80	83	85	95	96	99
400			0	4.7	11	18	25	33	39	45	51	56	61	64	67	71	74	76	78	81	83	93	93	97
450				0	6.7	14	21	28	34	40	46	51	56	59	62	66	70	71	73	76	78	88	89	92
500					0	7.0	14	21	28	34	39	44	50	52	56	60	63	64	67	69	72	81	82	86
550						0	7.1	14	21	27	32	37	42	45	49	53	56	57	60	62	65	74	75	79
600							0	7.1	14	20	25	30	35	38	42	46	49	50	52	55	58	67	68	72
650								0	6.5	13	18	23	28	31	35	39	42	43	45	48	51	60	61	65
700									0	6.1	12	17	22	25	28	32	35	37	39	42	44	54	54	58
750										0	5.6	11	16	19	22	26	29	30	33	35	38	48	48	52
800											0	5.1	10	13	16	20	24	25	27	30	32	42	43	46
850												0	5.1	8.0	11	15	19	20	22	25	27	37	37	41
900													0	2.9	6.3	10	13	15	17	20	22	32	32	36
950														0	3.3	7.3	11	12	14	17	19	29	29	33
1000															0	3.9	7.2	8.4	11	13	16	26	26	30
1050																0	3.2	4.5	6.8	9.5	12	22	22	26
1100																	0	1.2	3.5	6.2	8.7	18	19	23
1150																		0	2.3	5.0	7.5	17	18	21
1200																			0	2.7	5.2	15	15	19
1250																				0	2.5	12	13	16
1300																					0	10	10	14
1800																						0	0.5	4.3
2000																							0	3.8
2500																								0

Silicon solar cells with a bandgap of 1.13ev can maximally absorb 77% of the terrestrial solar energy.

PV Electricity Applications
(market share in 2002)

- Grid connected systems (71%)
- Off-grid industrial applications (15%)
- Rural electrification in developing countries (7%)
- Consumer applications (7%)

Net producer of energy: generating between 5 and 12 times more energy over their lifetime than is required for their manufacture.

Ideally suited for distributed generation of electricity and easily scalable.

PV Economics

Grid connected PV competes with retail electricity. Unlike grid power, customers incur a high upfront cost and, depending on the level of customer incentives offered by state or utility programs, a high LCOE over the project life to invest in PV.

This economic disadvantage of PV is reduced significantly through government incentives and a growing market for PV environmental attributes such as green tag trading.

In terms of a purchase decision, different economic metrics are used, such as:

- upfront cost   - payback period   - internal rate of return

-net present value   - levelized cost of electricity

- years till cumulative positive cash flow

Economic Metrics

Residential Segment	• The most common factor considered for residential applications is the *simple payback period*. • Retrofit applications are implemented by home owners while new construction applications are mainly implemented by home developers and influenced by architects. • In the case of new construction applications, home developers will typically not consider installing PV systems if it costs more than 1-2% of the cost of the house.
Commercial Segment	• Commercial customers tend to take a longer term perspective in considering an investment, and hence take into account a life cycle cost approach. However, budget constraints may adversely impact the decision to invest in PV even if it is a worthwhile investment. • The most common metric used is a measure of ***return on investment***, such as the ***internal rate of return***. Some customers also consider ***simple payback period***.

http://www.ef.org/documents/EF-Final-Final2.pdf

System Price Drivers

- PV Module
- Inverter
- Mounting Structure
  - Function of type of mounting systems
  - Varies for retrofit versus new construction installations
- Meters, Switches, Panels
- Installation Material (electrical, hardware)
- System Design and Engineering
- Installation Labor
  - Varies by location
  - Varies for retrofit versus new construction installations
- Other (Inspection, vehicle rental, building permit and review fees, etc.)

→ PV Installed System Price

http://www.ef.org/documents/EF-Final-Final2.pdf

Performance Factors

PV Technology – Efficiency, crystalline silicon, thin film etc.

PV System Tilt - latitude

Orientation – south facing

Tracking System - none

System location – insolation and utility rates

Energy Economics

Life Cycle Cost of a Energy System

1. Acquisition Costs
2. Operating Costs
3. Maintenance Costs
4. Replacement Costs

Refer all costs to the time of acquisition.

Simple Payback Period

Simple payback = Extra first cost / Annual savings

Ex: Energy efficient washer that cost an extra $500 and which saves $ 100/year in electricity would have a simple payback of about 5 years. This method does not consider the longevity of the system. It generally makes an investment look worse than it is.

Initial simple rate of return = Annual savings / Extra first cost

This is the inverse of a simple payback period and it makes the investment look good with a 20% initial rate of return in the above example. It is a convenient indicator of “minimum threshold”. If an investment has an initial rate of return below the threshold, there is no need to proceed any further.

Time Value of Money

Inflation rate - i

*Discount rate - d (*relates to the amount of interest that can be earned on principal that is saved*)*

Where d is the percentage rate expressed as a fraction - $100d$ % per year

Initial amount of money = N_o

Number of years = n

The final value of investment = N

$$N(n) = N_o (1+d)^n$$

Time Value of Money

Initial cost of the item: C_o

Inflation rate : $100i$ %

Cost of the item after n years:

$$C(n) = C_o (1+i)^n$$

Present Worth

Present Worth Factors and Present Worth:

Present worth factor, Pr is defined by

$$\mathrm{Pr} = \left(\frac{1+i}{1+d}\right)^n$$

For an item to be purchased n years later, the present worth is given by

$$PW = (\mathrm{Pr})\, C_o$$

Present Worth

Present worth of a recurring expense:

Example: Diesel fuel of a diesel generator or yearly maintenance costs of a system

The costs are incurred at the beginning of each year

The present worth is:

$$PW = C_o + C_o\left(\frac{1+i}{1+d}\right) + C_o\left(\frac{1+i}{1+d}\right)^2 + C_o\left(\frac{1+i}{1+d}\right)^3 + \text{............} + C_o\left(\frac{1+i}{1+d}\right)^{n-1}$$

Let

$$x = \left(\frac{1+i}{1+d}\right)$$

Present Worth

Cumulative present worth factor:

$$PW = C_0\left(1 + x + x^2 + \ldots\ldots\ldots + x^{n-1}\right)$$

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 + \ldots\ldots\ldots\ldots\ldots = \sum_{i=0}^{\infty} x^i$$

$$Pa = \frac{PW}{C_o} = \frac{1}{1-x} - \sum_{i=n}^{\infty} x^i = \frac{1}{1-x} - x^n \sum_{i=0}^{\infty} x^i$$

$$Pa = \frac{1-x^n}{1-x}$$

Life Cycle Cost

Life Cycle Cost (LCC):

Assume that the *PW* of all cost categories are known.

LCC is simply the sum of the *PW's* of all the components.

Example:

Refrigerator A costs $600 and uses 150 kWh/month. Designed to last 10 years with no repairs.

Refrigerator B costs $800 and uses 100 kWh/month. Designed to last 10 years with no repairs.

Cost of electricity: $0.07/kWh or $0.15/kWh

Discount rate: 10%

Electrical cost inflation rate: 3%

Which is the better buy?

Example

Example: continued

First year electrical costs:

Refrigerator A - 12 x 150 x 0.07 = $126

Refrigerator B - 12 x 100 x 0.07 = $84

Cumulative present worth factor, Pa

$$Pa = \frac{1-x^n}{1-x}$$

$$x = \frac{1+i}{1+d}$$

$$PW = Pa \times C_o$$

Table 5.1 Life cycle cost analysis for two refrigerators at $0.07/kWh and $0.15/kWh.

	Refrigerator A			Refrigerator B		
	first year	PW	PW	first year	PW	PW
Purchase Price	$600	$600	$600	$800	$800	$800
Electrical cost @ $.07/kWh	$126	$954		$84	$636	
Electrical cost @ $.15/kWh	$270		$2045	$180		$1363
LCC		$1554	$2645		$1436	$2163

Example

Example 2: PV vs gasoline generator

Load: 2 kWh/day

Operation: 24 hrs a day with minimal downtime

Lifespan: 20 years

Average power requirement = 83 W

PV system:

500 W array at a cost of $5/W

Batteries = $900 (need to be replaced every five years)

Charge controller = $300

System maintenance costs= $100/year

Gasoline generator:

500 W generator cost = $250 (running well under rated load)

Performance= 2.5 kWh/gallon

Annual fuel = 300 gallons

Annual maintenance cost = $400

it must be replaced after five years

Inflation rate = 3%; Discount rate = 10%

Example

PV system:

Present worth calculated for 5, 10 & 15 years (because of Battery replacement) using

$$\Pr = \left(\frac{1+i}{1+d}\right)^n$$

$$Pa = \frac{1-x^n}{1-x}$$

Maintenance costs:

$$Pa_1 = x + x^2 + x^3 + \ldots\ldots + x^n = xPa = x\frac{1-x^n}{1-x}$$

Generator:

Pr is calculated for 5, 10 and 15 years

Pa is used to calculate fuel and maintenance costs.

For given i and d, we have x = 0.9364, Pa =11.5 and Pa_1 = 10.77

Example

Cost Comparison

PV System			Generator System			
Component	Initial Cost	PW	Component	Initial Cost	Ann Cost	PW
Array	$2500	$2500	Generator	$250		$250
Controller	$300	$300				
Batteries	$900	$900	Fuel		$375	$4313
Batt 5 yr Batt 10 yr Batt 15 yr	$900 $900 $900	$648 $466 $336	Gen 5 yr Gen 10 yr Gen 15 yr	$250 $250 $250		$180 $130 $93
Annual Maintenance	$100	$1077	Annual Maintenance		$400	$4600
LCC		$6227	LCC			$9566

Example

Annualized Life Cycle Cost:

For system components

$$ALCC = \frac{LCC}{Pa} \; or \; \frac{LCC}{Pa_1}$$

For the PV system in the previous example:

ALCC = $6227/10.77 =$578

For the generator:

ALCC = $9566/11.5 = $832

Example

Unit Electricity Cost (UEC):

Unit cost of electricity produced by an electrical generating system. It is given by

$$UEC = ALCC/(\text{annual electrical production in kWh})$$

For the PV system

$$UEC = \$578/730 = \$0.792/kWh$$

For gasoline generator

$$UEC = \$832/730 = \$1.14/kWh$$

Borrowing Money

Loan amount = C_o

Interest rate $= i$

Number of years $= n$

Annual payment is given by the expression:

$$ANN.PMT. = C_o i \left(\frac{(1+i)^n}{(1+i)^n - 1} \right)$$

Table 5.3 Breakdown of portions of loan payment allocated to principle and interest.

Yr	Pmnt on Prin	Interest Payment	Total Payment	Balance of Principle
1	A_1	iC_o	$A_1 + iC_o$	$C_o - A_1$
2	A_2	$i(C_o - A_1)$	$A_2 + i(C_o - A_1)$	$C_o - A_1 - A_2$
3	A_3	$i(C_o - A_1 - A_2)$	$A_3 + i(C_o - A_1 - A_2)$	$C_o - A_1 - A_2 - A_3$
n	A_n	$i(C_o - \ldots - A_{n-1})$	$A_n + i(C_o - \ldots - A_{n-1})$	0

Subsidies

Green Power: A form of subsidy for the acquisition of sustainable energy sources

Tax Breaks: Deduct a fraction of the cost from the federal income tax ($2000 in 2006).

The California Public Utility Commission's program will provide about $2.8 billion in solar subsidies over the next decade. It could put solar panels on the roofs of 1 million California houses and generate 3,000 megawatts of power.

Effective July 1, 2006, the program is paying $2.60 per watt for professionally installed photovoltaic systems. Owner-installed PV systems are rebated at 15% less, or $2.21 per watt.

Philadelphia Million Solar Roofs Community Partnership

PV grants up to $25,000 will be available for PV systems that are purchased and installed by a PECO Energy distribution company customer (regardless of customer class) that are sized between 1 kW and 5 kW (nominal dc watts at Standard Test Conditions).

The PV grants will be paid to the owner of a qualifying system in two installments. The first payment will be equal to $4 per watt dc (based on the nominal STC rating), up to a maximum payment of $20,000.

This first payment to the system owner will be made upon inspection and approval of the installed system. At the completion of the first 12 months of operation, the system will again be inspected and a reading taken of how many kilowatt-hours (kWh) the system has produced. A second payment will be made at that time to the owner equal to $1 per kWh generated by the system in its first 12 months of operation, up to a maximum payment of $5,000. At the same time, a payment will be made to the system installer equal to $0.10 per kWh generated by the system during these 12 months of operation, up to a maximum payment of $250 per system. These two payments will give both the owner and the installer a significant incentive to monitor system performance and to make certain that the system is performing well.

http://www.phillysolar.org/pv_program.htm

Home Energy Efficiency

Go to the following site:

http://hes.lbl.gov/hes/region/sa.html

Project 1: PV system design

Home size: 2000 ft^2 (186 m^2)

(4 bedrooms ; 2.5 bathrooms; living room; family Room; dining Room, kitchen and two car garage)

Two working adults and two children (ages 10 & 12)

Utility electricity rate: $0.14/kWh

All energy star appliances

1. Estimate annual electricity use
2. Determine the appropriate PV panel size to meet the required demand with net metering*

* Net metering allows your electricity meter to spin forward when electricity flows into your building and also backwards when your PV system produces a surplus of electricity that is not immediately used. Your meter will add up all of those additions and deductions like a calculator Your excess electricity is "banked" on the utility grid. You can use an equivalent amount of electricity later without cost to you. All decent utility offer owners of PV systems the option of interconnecting with the electrical power grid on a net-metering basis.

Project 1: PV system design

1. Estimate the LCOE of lighting and HVAC with and without energy star ratings appliances. Determine the net savings over a PV life of 20 years.
2. Consider the 1st and 2nd generation PV technologies and assesses net cost of energy in terms of $/kWh.

   The report should be thorough enough to convince yourself whether you are willing to consider installing a PV system on your house. What kind of government subsidy is reasonable to make the system viable.