Chapter 17

System Sizing

17.1 Introduction

Before choosing the final components, the system should be roughly sized to allow viewing of approximate component sizes. Later, the components must be sized again by a detailed electrical and mechanical design. The purpose of this chapter is to provide **simple tools** to roughly estimate the needed system size before contacting a PV specialist.

17.2 **Sizing procedure**

In general PV systems in buildings are sized in such a way that the PV system can meet the building loads either fully or partially and still function reliably. In stand-alone and hybrid systems, the batteries and/or backup system (i.e.: diesel generator) must deliver the electricity even during long overcast periods. In grid-connected systems, there is no storage component because the grid acts as an infinite buffer.

The key factors affecting the system sizing are the load size, the operation time (all year, summer only etc.), the location of the system (solar radiation) and a possible sizing safety margin. Besides that, the **available roof or facade area** can restrict the PV array size. Finally, the most important restriction for PV system sizing is the available budget. Roof/facade area and budget are typically the key restrictions for the design of a grid-connected PV house.

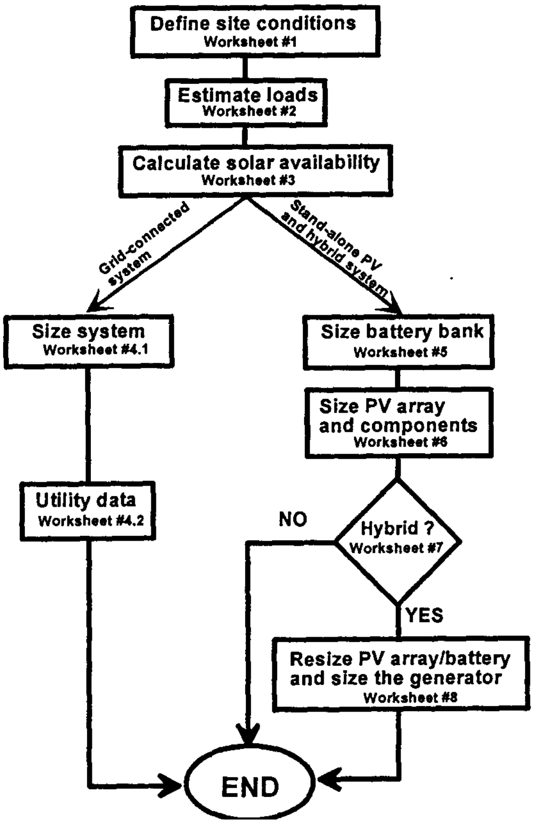

Figure 17.1 Steps of the rough sizing procedure.

Steps involved in the **rough sizing procedures** for different types of PV building systems are presented in Figure 17.1. The approach is to estimate the required component sizes by making assumptions about the efficiency of all key components and by using monthly average weather data. To make the procedure easier, a set of Worksheets (#1-#7) has been prepared for the different steps (see Appendix II).

Specification of site conditions (Worksheet #1)

Define site and weather station location (latitude, longitude) and monthly average values of the global irradiance on the horizontal surface (kWh/m^2) and the annual average *as* well as the minimum and maximum monthly average ambient temperatures. Weather data for several locations are available from Appendix I. The weather station chosen should belong to the same climate zone and it should be as close as possible to the site in question. This is especially important if the PV system site is close to a high mountain or a coast.

Estimation of solar availability (Worksheet #1)

Main factors affecting the solar availability are the orientation (tilt and azimuth angles) and the possible shading caused by the surroundings. By multiplying the horizontal insolation values with a monthly tilt and azimuth angle factor, the monthly radiation values on the module surface can be estimated. In Appendix I, this monthly factor is presented for different locations for horizon shadowing levels of 0, 20 and 40 degrees.

Ground reflection, shadowing of the neighbouring buildings and the PV building itself can affect the solar availability as well. However, these effects are too difficult to consider in this rough sizing procedure. The surface with the highest available radiation (kWh/m2) during the system operation time should be chosen. If that surface is not large enough, other surfaces should be considered.

In Figure 2.5 the dependency of available solar radiation and tilt and orientation angles is shown for Central Europe. If these angles can be chosen freely (e.g. in a new building), the choice should be made on the basis of maximizing the PV production. The annual PV output is maximum when the azimuth angle is within ±45° from the south orientation (in the northern hemisphere) and the tilt angle is ±15° of the latitude angle value. Larger variations are not recommended. In practice, architectural and technical reasons usually limit the possible orientation.

Estimation of the electricity demand (Worksheet #2)

For an existing building, past electricity bills will help to perform this task. For a building not yet constructed, guidelines are given in Chapter 16 on how to estimate energy demand.

Sizing of a grid-connected system (Worksheet #3 I&II)

The optimum size of a grid-connected system also depends on a number of external factors such as: the investment cost of the system, the available budget, governmental subsidies, the energy payback policy of the local utility, and the amount of PV energy directly used by the building. It must be remembered that because of the variable nature of PV power it is seldom used to decrease the peak load demand of the building.

The buyback ratio is the major utility factor affecting the sizing of the PV system. This is the ratio between the price the utility pays for the PV electricity and the price of the electricity bought from the grid. Typically the buyback ratio is less than one (0.5 - 1.0), which means that the utility pays less for PV electricity than the building owner pays for the grid electricity. Therefore, most of the PV system production should be used directly in the building. This use depends on the matching of the PV production with the house lead profile.

The shaded area in Figure 17.2 represents an average result obtained using a typical European and North-American climate and load profile.

Typical sizes of a grid-connected system for a single family house range from 2 to 5 kW (with an annual electricity consumption of 4 - 5 MWh). This means an annual electricity production of 1.5 - 3.8 MWh in Northern Europe, 1.6 - 4.0 MWh in Central Europe and 25 MWh in Japan, assuming optimum orientation and design.

In practice, the nominal size of the PV array should be chosen based on the load size and the budget. The rule of thumb is that an installed grid-connected PV system will cost 10 US\$/W_P (1994 price). The required PV module area APV (m^2) can be calculated from the chosen nominal PV power using the formula

$$A_{PV} = \frac{P_{PV}}{\eta_{PV}}$$

where P_{PV} (kW) is the nominal power of the PV array under standard test conditions (STC) and 1 η_{PV} (fraction) is the efficiency of the modules at STC (see Table 17.2).

The annual energy production of the system can be calculated using the formula below:

$$E_{PV} = \eta_{BOS} K_{PV} P_{PV} S$$

where S (kWh/m^2) is the annual solar radiation on the PV array, K_{PV} is a decreasing factor (-0.9), which takes into account phenomenas like module temperature, dust, array imbalance, circuit losses etc. and η_{BOS} is the balance of system efficiency which is the system efficiency without the PV module efficiency.[1]

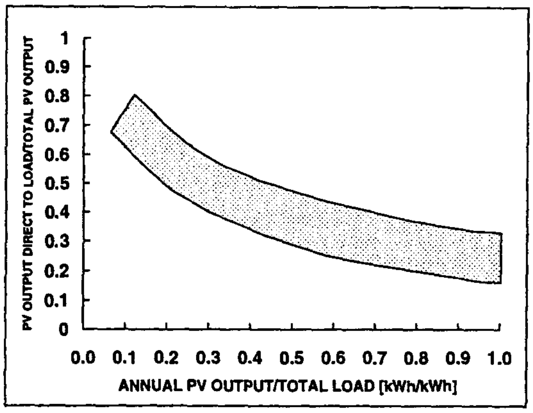

Figure 17.2 Average fraction of directly used PV energy from the total house load as a function of the annual PV electricity output / annual load ratio in Europe and North America with a typical one family house load profile.

In grid-connected systems this efficiency mainly depends on inverter and wiring losses. Typically the wiring losses are 10% and the inverter losses 15%.

Thus the η_{BOS} is approximately 75%. The annual radiation S can be taken from Worksheet #1.

When the total energy production E_{PV} has been determined, the ratio of E_{PV} and E_{load} can be calculated. With this value and Figure 17.2, the amount of directly used energy is estimated.

It must be noted that Figure 17.2 is an average result obtained with average house load profiles and insolation data for Europe and North-America. The calculations can also be performed vice versa by starting from a wanted ratio of directly used PV energy back to PV array size.

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[1] Note: In order to achieve correct results, mentioned units must be used in all formulas and worksheets.

Location	Inverter power ratio $P\,(DC)_{inverter}/P_{PV}$
Northern Europe (55-70°N)	0.7 - 0.8
Central Europe (45-55°N)	0.75 - 0.9
Southern Europe (35-45 °N)	0.85 - 1.0

Table 17.1 Recommended inverter sizes for different locations.

The nominal power of the inverter should be smaller than the PV nominal power. The optimum ratio depends on the climate, the inverter efficiency curve and the inverter/PV price ratio. Computer simulation studies indicate a ratio $P\ (DC)_{Inverter}/P_{PV}$ of 0.7 - 1.0. The recommended inverter sizes for different locations are shown in Table 17.1.

In order to list metering options and other basic information of the grid-connected case as well as for performing the sizing calculations, Worksheets #3 part I and II are prepared and may be found in Appendix II.

Sizing of a stand-alone PV-battery system (Worksheets #4 & 5 & 6)

For stand-alone PV battery systems the sizing must be more accurate than for grid-connected systems, because the available buffer capacity is quite limited. To compensate unexpected long cloudy periods some oversizing of the battery size as well as of the PV array size is needed. This oversizing also reduces the average battery "Depht of Discharge" (DOD) and thus increases the battery life.

After performing the load estimation with the help of Worksheet #2, the required autonomy time is chosen. The autonomy time varies from case to case and depends on latitude, operation season and required percentage of availability (safety margin). In Worksheet #4 (Appendix II) recommendations of autonomy time for different locations are given. Battery capacity is also dependent of discharge current and temperature. In Worksheet #4 this factor is shown as a function of the discharge rate and average storage temperature of the month in which storage is needed most. This derating is especially important, if the battery is located outdoors in cold climates. The maximum allowable DOD depends on battery type and load profile. For a typical lead-acid battery this fraction is between 0.5 - 0.8.

The next step is to size the PV array and the other system components. This is done with the help of Worksheet #5. For PV array sizing the month with the lowest insolation on the array plane is chosen as the design month (from Worksheet #1).

Dividing the average daily load of the design month by the average daily solar insolation and the system component efficiencies, yields the necessary PV array size (kW). The efficiencies to be taken into account are wiring efficiencies (typically 90%), charge regulator efficiency (typically 85%) and battery efficiency (typically 90%). A safety margin is recommended and presented in Worksheet #5. The design array current and the size of the power conditioning unit is then estimated.

The PV array area corresponding to the calculated array power is estimated as in the grid-connected case. The module efficiency is module-type dependent. For rough calculations, average module efficiencies as presented in Table 17.2 can be used.

At this stage it must be confirmed whether a PV battery system is enough to satisfy the load or whether a back-up generator is needed. This can be done with Worksheet #6 "Consider Hybrid," where the array to load ratio is calculated and used for this decision.

Sizing of a stand-alone PV hybrid system (Worksheet #7)

For a PV-hybrid system the PV array sizing procedure is similar to that used for a PV-battery system, but now the battery - generator pair must be sized so that it can back-up the shortfall during the month with the lowest insolation (wintertime).

An experienced designer should be consulted to decide whether a back-up generator is needed. Generally, if there are large seasonal variations in available solar radiation or long overcast periods or if there is a need to supply the load all the time, the back-up generator will be specified.

Figure 17.3 shows a simple chart as guideline for this decision. The figure is based on practical experiences with existing systems. According to the figure, a hybrid system should be preferred when the load is large. This is mainly because of cost considerations. Also, if the PV array size obtained for a corresponding standalone system is large compared to the load, a hybrid system will be most economic and practical.
Examples of sizing procedures for different types of PV systems are presented in chapters 17.4 - 17.6.

Module type	Average efficiency
Amorphous	5 %
Mono-crystalline	13 %
Polycrystalline	12 %

Table 17.2 Average efficiencies of different commercial silicon-based PV module types.

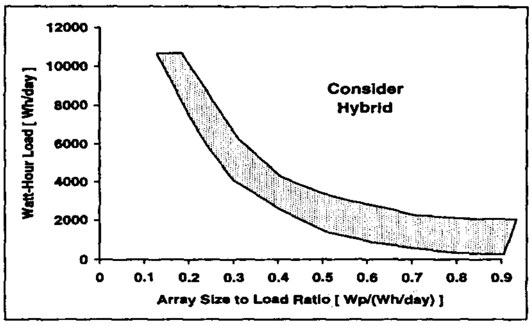


Figure 17.3 A graph showing the relationship of array to load ratio and the load size when a hybrid system should be used.

17.3 Simulation programs

Every field of application has its own requirements to the simulation programs. The PV system salesman requires software to perform initial and lifetime cost analyses of PV systems. PV system designers need software which performs component sizing and gives information about system reliability. The PV researcher needs software which can perform component characterisation and allow for investigation of the effects of different power management strategies on the PV system performance. The end user asks for software to simulate the performance of a PV system given various meteorological and load conditions and allowing the comparison of predicted results with measured data to detect possible faults within the PV system.

The programs may be classified into three categories:

- Programs that use statistical information in order to predict the longterm performance of systems. An example is PV F-CHART using the utilizability concept by Klein and Beckman (TAB);

- Programs that calculate a sequence of states of a predefined system structure (allowing for several options) in constant time steps. Examples are PVS and SOMES (SIM);

- Simulation systems which provide great flexibility in modeling different system structures - examples are TRNSYS and INSEL (SYS).

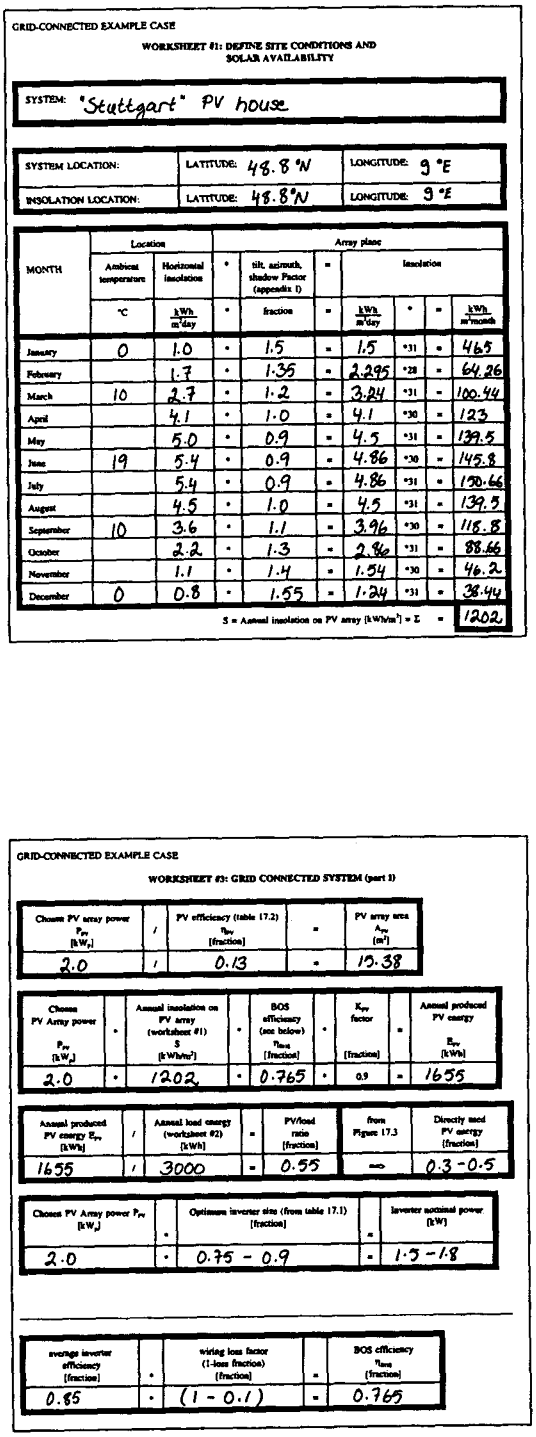
Program	Type	PV	Wind	Stand-alone	Grid-connected	Facade	Pump
ASHLING	SIM	+	-	+	+	-	-
DAST-PVPS	SIM	+	-	+	-	-	+
FWISO 81	SIM	+	+	+	+	-	+
INSEL	SYS	+	+	+	+	-	+
ISEE	DB	+	+	-	-	-	-
ITE-BOSS	SYS	+	-	+	+	-	+
PHOTO	SIM	+	+	+	+	-	-
PV 1.03	SIM	+	-	o	+	-	-
PVcalc 1.03	SIM	+	-	o	+	-	-
PV-DIMM	SIM	+	-	+	-	-	-
PV F-CHART	TAB	+	-	+	+	-	-
PV-TAS	SIM	+	-	+	+	+	-
PVDIM	SIM	+	-	+	+	-	+
PVFORM	SIM	+	-	+	+	-	-
PVnode	SIM	+	-	+	+	+	-
PVPUMP	SIM	+	-	+	-	-	+
PVS	SIM	+	-	+	+	-	-
PVSHAD	SIM	+	-	+	+	+	-
SHADE	SIM	+	-	+	+	+	-
SOMES	SIM	+	+	+	+	-	-
SYSTEMSPEC	SIM	+	-	+	+	-	-
TRNSYS	SYS	+	+	+	+	+	-
WAsP	TAB	-	+	+	+	-	-
WATSUN-PV	SIM	+	-	+	+	-	+

Type of program:	TAB	Statistics-based programs
	SIM	Time step simulators
	SYS	Simulation systems
	DB	Data bases
Type of system:	PV	PV generators
	Wind	Wind generators
	Stand-alone	Stand-alone systems
	Grid-connected	Grid-connected systems
	Facade	Inhomogeneously irradiated generator surfaces (facades)
	Pump	PV pump systems

+	yes
o	conditional
-	no

Table 17.3 Overview of PV simulation programs.

17.4 Sizing example of a grid connected PV building system



GRID-CONNECTED EXAMPLE CASE

WORKSHEET #1: DEFINE SITE CONDITIONS AND SOLAR AVAILABILITY

SYSTEM: "Stuttgart" PV house

SYSTEM LOCATION:	LATITUDE: 48.8 °N	LONGITUDE: 9 °E
INSOLATION LOCATION:	LATITUDE: 48.8°N	LONGITUDE: 9 °E

MONTH	Location		Array plane						
	Ambient temperature	Horizontal insolation	•	tilt, azimuth, shadow Factor (appendix I)	=	Insolation			
	°C	kWh/m²day	•	fraction	=	kWh/m²day	•	=	kWh/m²month
January	0	1.0	•	1.5	=	1.5	•31	=	46.5
February		1.7	•	1.35	=	2.295	•28	=	64.26
March	10	2.7	•	1.2	=	3.24	•31	=	100.44
April		4.1	•	1.0	=	4.1	•30	=	123
May		5.0	•	0.9	=	4.5	•31	=	139.5
June	19	5.4	•	0.9	=	4.86	•30	=	145.8
July		5.4	•	0.9	=	4.86	•31	=	150.66
August		4.5	•	1.0	=	4.5	•31	=	139.5
September	10	3.6	•	1.1	=	3.96	•30	=	118.8
October		2.2	•	1.3	=	2.86	•31	=	88.66
November		1.1	•	1.4	=	1.54	•30	=	46.2
December	0	0.8	•	1.55	=	1.24	•31	=	38.44

S = Annual insolation on PV array [kWh/m²] = Σ = 1202

GRID-CONNECTED EXAMPLE CASE

WORKSHEET #3: GRID CONNECTED SYSTEM (part 1)

Chosen PV array power P_{pv} [kW_p]	/	PV efficiency (table 17.2) η_{pv} [fraction]	=	PV array area A_{pv} [m²]
2.0	/	0.13	=	15.38

Chosen PV Array power P_{pv} [kW_p]	•	Annual insolation on PV array (worksheet #1) S [kWh/m²]	•	BOS efficiency (see below) η_{bos} [fraction]	•	K_{pv} factor [fraction]	=	Annual produced PV energy E_{pv} [kWh]
2.0	•	1202	•	0.765	•	0.9	=	1655

Annual produced PV energy E_{pv} [kWh]	/	Annual load energy (worksheet #2) [kWh]	=	PV/load ratio [fraction]	from Figure 17.3	Directly used PV energy [fraction]
1655	/	3000	=	0.55	⟹	0.3 - 0.5

Chosen PV Array power P_{pv} [kW_p]	•	Optimum inverter size (from table 17.1) [fraction]	=	Inverter nominal power [kW]
2.0	•	0.75 - 0.9	=	1.5 - 1.8

average inverter efficiency [fraction]	•	wiring loss factor (1-loss fraction) [fraction]	=	BOS efficiency η_{bos} [fraction]
0.85	•	(1 - 0.1)	=	0.765

Figure 17.4 Filled-in Worksheets #1 and #3 (part I) for the grid-connected PV system example described in Chapter 17.4.

The general description of a grid-connected example system is as follows:

Location: Stuttgart, 49,9°E, Germany;
Shadow: 10° horizon shadowing;
House: typical one family house, the roof faces south with a tilt angle of 45°, the available roof area is 40 m2;
Load: 3000 kWh/year AC electricity, (energy-efficient house).

First, the solar availability on the roof surface must be defined with the help of Worksheet #1. From Appendix I the solar radiation data of Stuttgart can be found. For monthly tilt, azimuth and shadow angle factors the data of Madison will be used as the best approximate. The 10° shadow of the horizon can be taken into account by calculating the average of the two shadow angle figures for 0° and 20°.

Finally, with simple multiplications, the monthly figures can be written into the Worksheet. Summing up the monthly figures gives a radiation value of 1202 kWh/m^2 on the PV roof surface.

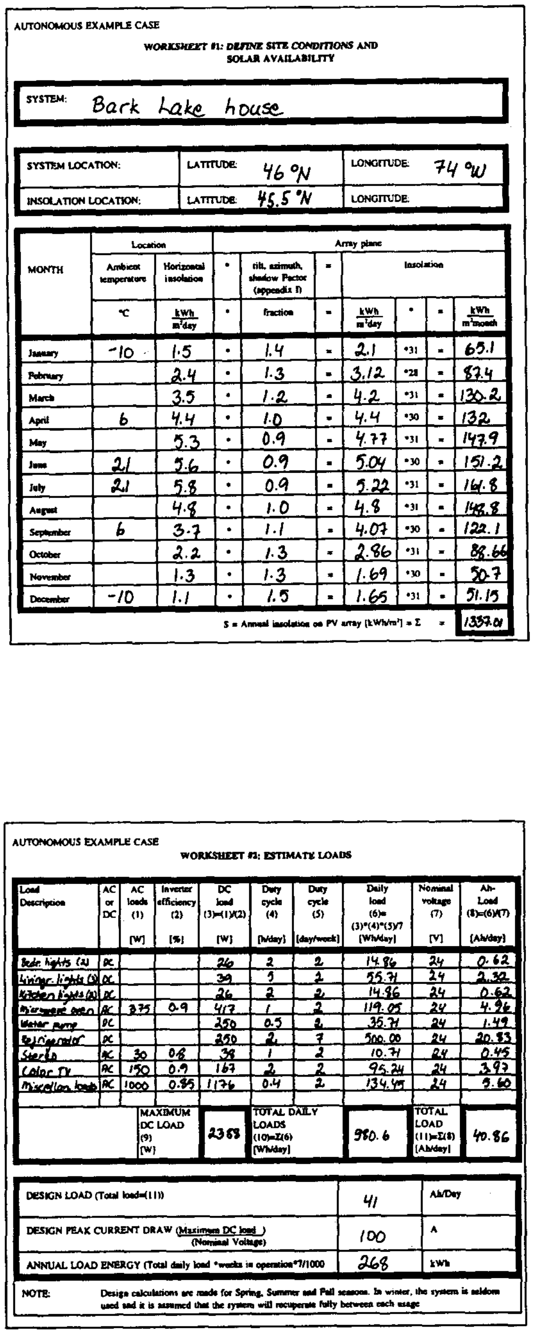
In this case it is not necessary to do any load analysis and efficiency improvements because the house is new and efficient already and the past electrical bills have shown that the electricity consumption is 3000 kWh/year and the profile can be assumed to be roughly constant in this case.

Now the Worksheet #3 is used to size the system components. Let us choose as the PV array nominal power a typical 2 kW size. The PV array area with monocrystalline modules is approximately 16 m^2. A typical average value for a grid-connected inverter efficiency is 85%. Wiring losses are usually 10%. Thus the annually produced energy is 1655 kWh. The directly used PV energy fraction is 30-50%. This means that roughly 60% of the PV electricity is sold to the grid annually. The optimum inverter size is 1.5-1.8 kW. In practice, the available inverters are limited to certain sizes and if a suitable inverter is not found the PV array size might be adjusted slightly.

17.5 Sizing example of an autonomous PV building system

The following case shows an example of an autonomous PV system used to power a remote vacation cabin. The cabin is situated in the heart of the Laurentians near Montreal, Canada, and it is used mainly on weekends and holidays during the summer as well as on an occasional weekend in winter. The cabin is one kilometer away from the grid and the owner enjoys the fact that his cabin is totally isolated. Still, after years of using oil lamps and hauling water by hand, the owner would like to enjoy the benefits of electricity. The description of the case is as follows:

Location:	Bark Lake; 46°N, 74°W, Canada;
Shadow:	20° horizon shadowing;
House:	Small cabin with roof face tilted at 45° angle due south, overlooking a lake in front. Some trees are partially shading the array in the morning and afternoon in the summer;
Loads:	Variable, average of 980 Wh/ day when inhabited. The owner wants to use ordinary AC appliances except for his lighting and refrigeration needs. In winter, the cabin is heated with wood.



AUTONOMOUS EXAMPLE CASE

WORKSHEET #1: DEFINE SITE CONDITIONS AND SOLAR AVAILABILITY

SYSTEM: Bark Lake house

SYSTEM LOCATION:	LATITUDE: 46 °N	LONGITUDE: 74 °W
INSOLATION LOCATION:	LATITUDE: 45.5 °N	LONGITUDE:

MONTH	Location		Array plane						
	Ambient temperature	Horizontal insolation	•	tilt, azimuth, shadow Factor (appendix I)	=	Insolation			
	°C	kWh/m²day	•	fraction	=	kWh/m²day	•	=	kWh/m²month
January	-10	1.5	•	1.4	=	2.1	•31	=	65.1
February		2.4	•	1.3	=	3.12	•28	=	87.4
March		3.5	•	1.2	=	4.2	•31	=	130.2
April	6	4.4	•	1.0	=	4.4	•30	=	132
May		5.3	•	0.9	=	4.77	•31	=	147.9
June	21	5.6	•	0.9	=	5.04	•30	=	151.2
July	21	5.8	•	0.9	=	5.22	•31	=	161.8
August		4.8	•	1.0	=	4.8	•31	=	148.8
September	6	3.7	•	1.1	=	4.07	•30	=	122.1
October		2.2	•	1.3	=	2.86	•31	=	88.66
November		1.3	•	1.3	=	1.69	•30	=	50.7
December	-10	1.1	•	1.5	=	1.65	•31	=	51.15

S = Annual insolation on PV array [kWh/m²] = Σ = 1337.01

AUTONOMOUS EXAMPLE CASE

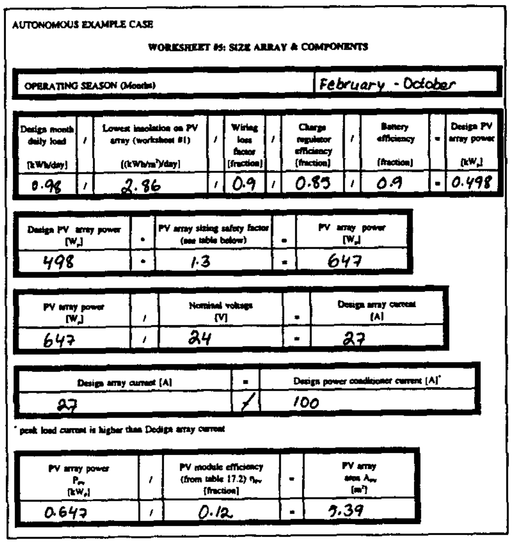
WORKSHEET #2: ESTIMATE LOADS

Load Description	AC or DC	AC loads (1) [W]	Inverter efficiency (2) [%]	DC load (3)=(1)/(2) [W]	Duty cycle (4) [h/day]	Duty cycle (5) [day/week]	Daily load (6)= (3)*(4)*(5)/7 [Wh/day]	Nominal voltage (7) [V]	Ah-Load (8)=(6)/(7) [Ah/day]
Bedr. lights (2)	DC			26	2	2	14.86	24	0.62
Living r. lights (3)	DC			39	5	2	55.71	24	2.32
Kitchen lights (2)	DC			26	2	2	14.86	24	0.62
Microwave oven	AC	375	0.9	417	1	2	119.05	24	4.96
Water pump	DC			250	0.5	2	35.71	24	1.49
Refrigerator	DC			250	2	7	500.00	24	20.83
Stereo	AC	30	0.8	38	1	2	10.71	24	0.45
Color TV	AC	150	0.9	167	2	2	95.24	24	3.97
Miscellan. loads	AC	1000	0.85	1176	0.4	2	134.45	24	5.60
		MAXIMUM DC LOAD (9) [W]		2388	TOTAL DAILY LOADS (10)=Σ(6) [Wh/day]		980.6	TOTAL LOAD (11)=Σ(8) [Ah/day]	40.86

DESIGN LOAD (Total load=(11))	41	Ah/Day
DESIGN PEAK CURRENT DRAW (Maximum DC load / Nominal Voltage)	100	A
ANNUAL LOAD ENERGY (Total daily load *weeks in operation*7/1000	268	kWh

NOTE: Design calculations are made for Spring, Summer and Fall seasons. In winter, the system is seldom used and it is assumed that the system will recuperate fully between each usage

Figure 17.5 Filled-in Worksheets #1 and #2 for the autonomous PV systems example described in Chapter 17.5.



AUTONOMOUS EXAMPLE CASE

WORKSHEET #5: SIZE ARRAY & COMPONENTS

OPERATING SEASON (Months)	February - October

Design month daily load [kWh/day]	/	Lowest insolation on PV array (worksheet #1) [(kWh/m^2)/day]	/	Wiring loss factor [fraction]	/	Charge regulator efficiency [fraction]	/	Battery efficiency [fraction]	=	Design PV array power [kW$_p$]
0.98	/	2.86	/	0.9	/	0.85	/	0.9	=	0.498

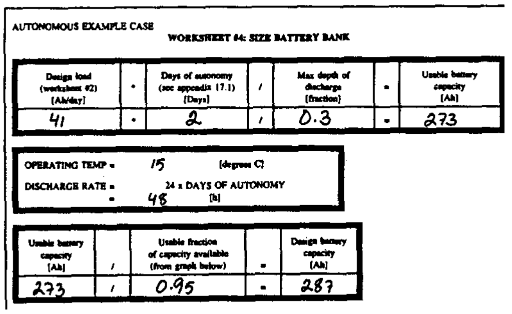
Design PV array power [W$_p$]	•	PV array sizing safety factor (see table below)	=	PV array power [W$_p$]
498	•	1.3	=	647

PV array power [W$_p$]	/	Nominal voltage [V]	=	Design array current [A]
647	/	24	=	27

Design array current [A]	=	Design power conditioner current [A]*
27	≠	100

* peak load current is higher than Design array current

PV array power P_{pv} [kW$_p$]	/	PV module efficiency (from table 17.2) η_{pv} [fraction]	=	PV array area A_{pv} [m^2]
0.647	/	0.12	=	5.39



AUTONOMOUS EXAMPLE CASE

WORKSHEET #4: SIZE BATTERY BANK

Design load (worksheet #2) [Ah/day]	•	Days of autonomy (see appendix 17.1) [Days]	/	Max depth of discharge [fraction]	=	Usable battery capacity [Ah]
41	•	2	/	0.3	=	273

OPERATING TEMP = 15 [degrees C]

DISCHARGE RATE = 24 x DAYS OF AUTONOMY

= 48 [h]

Usable battery capacity [Ah]	/	Usable fraction of capacity available (from graph below)	=	Design battery capacity [Ah]
273	/	0.95	=	287

Figure 17.6 Filled-in Worksheets #4 and #5 for the autonomous PV system example described in Chapter 17.5

The solar availability is estimated using Worksheet #1 with the solar radiation data (Montreal) and the correction factors (Madison) found in Appendix I.

The next step is to define the load for the cabin. Using the load analysis portion of Worksheet #2 the average total load per day is found to be around 980 Wh/day. Note that the total load per day can be as high as 2100 Wh/day during the weekend. The designer should then choose deep cycle batteries because the batteries may discharge completely during the weekend.

Since the owner wants AC loads and the more efficient inverters are working at 24 V, the system will be a 24 V system. Note that the refrigerator is a large part of the load and that it is turned on throughout the summer. However, it is turned off during winter and only put on when the owner is using the cabin.

Since the owner is planning to use his cabin only on weekend holidays, most of the load will be at these times. This in turn means that the battery bank can be relatively small since it would normally be recharged during the week. But, for the same reason, the designer should use a low average for the Maximum Depth of Discharge (DOD) when estimating the capacity of the battery. We can thus calculate an average maximum depth of discharge for the battery at 30% and two days of autonomy. Note that the battery will be located inside a special shed but since the cabin will not be heated in winter, the battery should be allowed to recharge throughout the period. Since little consumption will be drawn from the battery, the system should be well protected against overcharge. The battery sizing is presented in Worksheet #4.

The final step of the sizing (W Worksheet *#5)* requires calculation of the lowest insolation month with the corresponding highest load month. In our example, it is obvious that March or September will be the most demanding months for the system and the array should thus be calculated for these months. In this application the efficiency of the battery must be taken into account.

Thus the resulting system design is as follows:

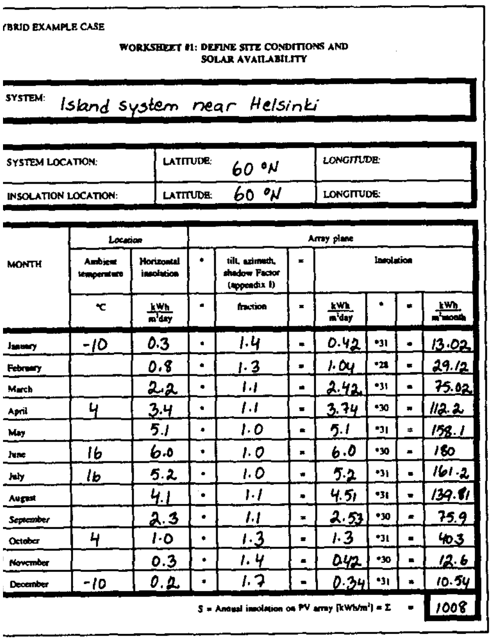
PV Array Size:	650 Wp
PV Array Area:	5.4 m2
Design Array Current:	27 A
Inverter Size:	1600 VA
Battery Size:	300 Ah

17.6 Sizing example of a hybrid PV building system

As an example case of a hybrid PV building system a house located near the Helsinki coast on a small island in Southern Finland will be used. The house is owned by a fisherman and his family. The house is inhabited all year round. The description of the case is as follows:

Location: Island near cost, 60°N, 23°E, Finland;
Shadow: 0° south, 15° north;
House: typical one-family house, the roof faces south-east with a tilt angle of 30°, the available roof area is 60 m2;
Load: roughly constant load profile, 2500 kWh/year AC electricity.

Different approaches can be used to size a photovoltaic-diesel hybrid system. One approach is to size the system assuming that photovoltaics will provide a given percentage of the system electricity need.



YBRID EXAMPLE CASE

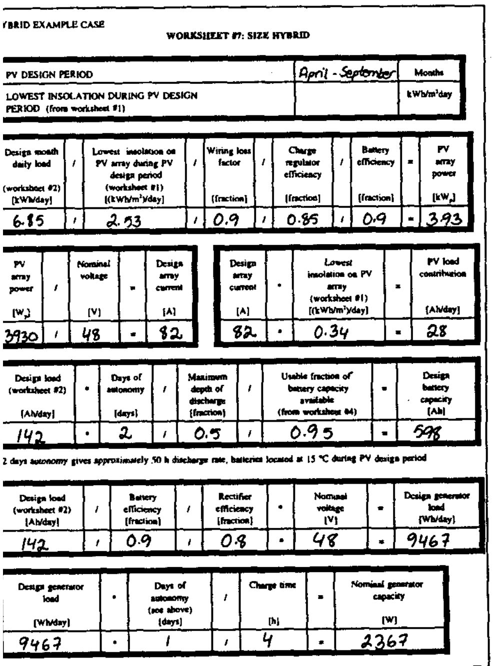
WORKSHEET #1: DEFINE SITE CONDITIONS AND SOLAR AVAILABILITY

SYSTEM: Island system near Helsinki

SYSTEM LOCATION:	LATITUDE: 60 °N	LONGITUDE:
INSOLATION LOCATION:	LATITUDE: 60 °N	LONGITUDE:

MONTH	Location		Array plane						
	Ambient temperature	Horizontal insolation	*	tilt, azimuth, shadow Factor (appendix I)	=	Insolation			
	°C	kWh/m^{2}day	*	fraction	=	kWh/m^{2}day	*	=	kWh/m^{2}month
January	-10	0.3	*	1.4	=	0.42	*31	=	13.02
February		0.8	*	1.3	=	1.04	*28	=	29.12
March		2.2	*	1.1	=	2.42	*31	=	75.02
April	4	3.4	*	1.1	=	3.74	*30	=	112.2
May		5.1	*	1.0	=	5.1	*31	=	158.1
June	16	6.0	*	1.0	=	6.0	*30	=	180
July	16	5.2	*	1.0	=	5.2	*31	=	161.2
August		4.1	*	1.1	=	4.51	*31	=	139.81
September		2.3	*	1.1	=	2.53	*30	=	75.9
October	4	1.0	*	1.3	=	1.3	*31	=	40.3
November		0.3	*	1.4	=	0.42	*30	=	12.6
December	-10	0.2	*	1.7	=	0.34	*31	=	10.54

S = Annual insolation on PV array [kWh/m^2] = Σ = 1008



YBRID EXAMPLE CASE

WORKSHEET #7: SIZE HYBRID

PV DESIGN PERIOD	April - September	Months
LOWEST INSOLATION DURING PV DESIGN PERIOD (from worksheet #1)		kWh/m^{2}day

Design month daily load (worksheet #2) [kWh/day]	/	Lowest insolation on PV array during PV design period (worksheet #1) [(kWh/m^2)/day]	/	Wiring loss factor [fraction]	/	Charge regulator efficiency [fraction]	/	Battery efficiency [fraction]	=	PV array power [kW$_p$]
6.85	/	2.53	/	0.9	/	0.85	/	0.9	=	3.93

PV array power [W$_p$]	/	Nominal voltage [V]	=	Design array current [A]
3930	/	48	=	82

Design array current [A]	*	Lowest insolation on PV array (worksheet #1) [(kWh/m^2)/day]	=	PV load contribution [Ah/day]
82	*	0.34	=	28

Design load (worksheet #2) [Ah/day]	*	Days of autonomy [days]	/	Maximum depth of discharge [fraction]	/	Usable fraction of battery capacity available (from worksheet #4)	=	Design battery capacity [Ah]
142	*	2	/	0.5	/	0.95	=	598

2 days *autonomy* gives approximately 50 h discharge rate, batteries located at 15 °C during PV design period

Design load (worksheet #2) [Ah/day]	/	Battery efficiency [fraction]	/	Rectifier efficiency [fraction]	*	Nominal voltage [V]	=	Design generator load [Wh/day]
142	/	0.9	/	0.8	*	48	=	9467

Design generator load [Wh/day]	*	Days of autonomy (see above) [days]	/	Charge time [h]	=	Nominal generator capacity [W]
9467	*	1	/	4	=	2367

Figure 17.7 Filled-in Worksheets #1 and #7 for the hybrid PV system example described in Chapter 17.6.

Here it is assumed that photovoltaics will satisfy the main electricity demand during certain months, namely from April to September.

The first steps of this case are the same as in the previous cases, starting from solar availability estimations with Worksheet #1 and the solar radiation data and correction factors of Appendix I. For correction factors the data of Copenhagen will be used *as* the best approximate.

The next step would be to use Worksheet #2 for the load estimation. However, the load is given here to be constant 2500 kWh/year, which means 6.85 kWh/day. This results in 6850/48 Ah/day = 142 Ah/day with system voltage of 48 V. The following steps would be to use Worksheets #4 and #5 to estimate the battery and the PV array size and with Worksheet #6 whether a PV-hybrid system should be considered. These steps are omitted here, because in this very northern example case (latitude 60°N) it is evident that a diesel generator is needed if the load has to be guaranteed for the whole year. This can be read from Worksheet #1: during the three darkest winter months the available solar radiation is very small. Thus the sizing can be finished with Worksheet #7. The batteries and diesel genset are located in an insulated cabin so that the battery temperature during the PV design period is roughly 15°C.

The sizing results are:

PV array size: 4000 Wp
Design array current: 82 A
Battery size: 610 Ah
Diesel generator size: 2400 kW

The PV array area with polycrystalline cells is estimated to be 4.0 kW_p/0.12 = 33 m2

Chapter 18

Key Component Selection

18.1 Introduction

Once the PV system has been sized as explained in Chapters 15 through 17, the installation may be planned. This means designing the physical layout of the system, selecting the proper equipment to meet the design requirements and ordering the different parts. In this chapter, criteria and guidelines for the design of a proper layout and selection of equipment available on the market are provided.

The designer should specify components in the following order:

1. Choose place and mounting method for modules, select modules;
2. Choose place for batteries, select battery type (off-grid systems only);
3. Select the necessary power conditioning equipment and inverter;
4. Select back-up system (if needed);
5. Estimate overall system losses and respecify components, if necessary;
6. Specify safety devices and switchgears;
7. Do layout of wiring, specify size and type;
8. Prepare a full list of parts and tools to order.

18.2 Selection of the photovoltaic modules

Photovoltaic modules come in different types, sizes and shapes. During the sizing procedure presented in Chapter 17, the array size has been determined in terms of peak watts delivered at peak sun hours. The designer must now select the actual photovoltaic module type to be used and calculate the number of modules in the array. Physical considerations such as available area, mounting structure type and architectural aspects limit the size of the array and influence the selection of the type of module to be used. Inclination, shadowing and ventilation of the modules will affect the electrical characteristics of the array and may change the design size of the system.

General position of the modules

Photovoltaic modules should always be placed close to the control unit and batteries to minimize voltage drop along wires. Low voltage with high direct currents lead to high ohmic losses and require large size wires. These are bulky, very expensive and hard to work with.

The modules should be mounted in a place where there is no or only a minimum of shading from surrounding objects such as trees and other buildings. Even a small shadow on just one cell can affect the performance of the whole array. If the array cannot be placed without being affected by shading, sizing the array will have to take into account the loss of electricity production due to this shading effect. This in turn will affect the quantity of modules to be used.

In general, if partial shading cannot totally be avoided, the series strings should be arranged in such a way that only one of them is affected.

The array should be positioned in a direction and inclination to produce maximum power during the time when it is needed most and when power production is maximum. These times may not coincide and during the sizing process adjustments must be made to size the system for its optimal design.

Mounting of the array

Photovoltaic modules generate most electricity when facing the sun directly, but the position of the sun changes through the day. It is possible to mount the modules on trackers to improve the power output of the array by allowing the tilt angle and direction of the modules to follow the sun. Their use may significantly improve the power output of the array in regions where direct sunlight is prevalent and thus reduce the size of the array. However, trackers have almost no impact in regions, where diffuse sunlight accounts for more than 50% of the total insolation. Trackers can be very expensive and they are difficult to integrate in a built environment.

Integration of PV modules in a building surface may influence the size of the modules used, the size of the array, its inclination and its direction. When sub-arrays have different sizes and mounting directions, special care must be given to optimize power production so that each sub-array can deliver maximum power to the load.

Other mounting considerations which may affect the size and location of the array are:

- Photovoltaic arrays must be strong enough to withstand wind loads and snow accumulation.
- The modules must be held securely for their lifetime which is estimated to be 2030 years.
- Ease of access to the modules for maintenance and cleaning must be planned at the design stage.

Module types

Many different types of PV modules are commercially available. More efficient modules will lead to smaller arrays.

- Modules made of crystalline silicon cells are most widely used; their efficiencies range from 12 to 15%.
- Modules made of thin-film amorphous silicon are cheaper to produce but their efficiencies range from 5 to 10% only.
- Thin-film materials such as Cadmium Telluride (CdTe) and Copper Indium Diselenide (CIS) are not yet fully commercialized in modules and still expensive although they promise to become a low cost solution. Their efficiencies range from 7 to 10%.

Architectural aspects

PV modules can have different shapes and appearances- depending on the material they are made of and the way they are produced. Modules made of crystalline cells are made of round or square cells encapsulated in glass with a clear or coloured back side. Amorphous silicon cells are usually dark red. Thin-film modules can be micro-perforated to give a defined transmissivity, but this will reduce their efficiencies.

Frame

PV modules come with different frame types and colors and can also be produced frameless to facilitate their integration into a building.

Module size

Choosing the largest module size available will reduce the amount of handling and installation time. There will be fewer electrical and mechanical joints which should improve the tightness of building mounted arrays. On the other hand, large modules are heavy and difficult to handle and can be expensive to replace in case of an accident.

Modules in series

The number of modules in series is determined by dividing the designed system voltage (usually determined by the battery bank or the inverter) with the nominal module voltage that occurs at lower temperatures. The nominal module voltage is often a multiple of 12 V.

Since module voltage decreases with increasing temperature (in the order of 2.2 mV/K/cell for Si), care must be given when integrating the module to a building so that the modules do not overheat because of lack of ventilation. The maximum power point of the series string must be calculated to be in the range of the design system voltage for all operating temperatures.

The number of modules in series, n_s, is calculated by

$$n_s = \frac{V_{system,max.}}{V_{module,corr.}}$$

where

$V_{system,max}$ is the maximum system voltage (at maximum charging current) and
$V_{module,corr}$ is the module voltage corrected for operating conditions.

Strings in parallel

The number of modules in parallel is determined by dividing the designed array output (W_p) by the selected module output (W_p) and the number of strings.

$$n_p = \frac{P_{array,max.}}{n_s * P_{module,max.}}$$

where

$P_{array,max}$ is the peak array power and
$P_{module,max}$ is the module peak power.

Both, the number of modules per series string and the number of parallel strings must be integers. Once the numbers of modules in parallel and in series are known, the total number of modules in the array is found by their product.

18.3 Selection of the storage component (off-grid systems only)

During the design process, it must be decided whether a storage component has to be used in the proposed system. Stand-alone building PV systems always need some form of storage. Notwithstanding the use of mechanical devices to store energy (such as elevating water or compressing air), electrochemical secondary batteries are presently the only commercial means to store electricity for a period of time exceeding a few days. The required battery capacity and nominal battery (system) voltage has been estimated during the sizing process. The decision to use deep or shallow cycling batteries must be made according to the load requirement.

The selection of the type of battery depends on the operation of the system and the environment of the battery. It is important to choose a quality battery well suited for the application, since the battery is the key element which defines the lifetime of the system and most of the maintenance requirements. Care must be taken not to mix batteries with different characteristics, since this will negatively affect the overall performance of the whole system. For the same reason, new batteries should not be used in combination with old ones.

It is important to keep batteries at a moderate temperature of 10 - 25°C for optimum performance. In hot climates, the electrolyte in a battery has a tendency to evaporate or cause deformation of the battery and its efficiency is reduced. Electrode corrosion is also accelerated. In cold climates, the battery is more difficult to charge, the electrolyte may freeze and the battery can be destroyed. Batteries will also need a higher voltage to complete charging in cold weather. Properly insulated enclosures help keep temperature swings from affecting the battery. However, this enclosure must be well ventilated, especially in case of liquid electrolytes, since charging the battery causes some hydrogen production and may cause a deflagration if it is allowed to accumulate. If ventilation is not possible, the use of either gel-type sealed batteries or glass fiber matted batteries will permit the use of an enclosure to protect the batteries.

Protection against vandalism and harmful damage are other considerations which affect the type of battery and its enclosure. Batteries are expensive items and could be used for other than the intended purposes. The use of a battery bank made of 2 V cells will deter thieves looking for suitable vehicle batteries. Large battery capacities will also benefit from using individual 2 V cells which are easier to handle.

Chapter 7 has shown the characteristics of different battery types. In general:

- Lead-acid batteries should be selected for large battery banks because of the lower initial costs. Lead-acid batteries are the most common and the least expensive type of battery. Note that lead-acid batteries are nominally rated at 2 V per cell but that their operation cycle lies between 1.75 to 2.45 V. Equipment connected to these batteries must accept this range.

- Lead-acid batteries with calcium alloy should be selected for shallow cycling with long autonomy periods (50 to 500 hours discharge time) since they are virtually maintenance free.

- Lead-acid batteries with low antimony alloy (0.1 - 2% antimony) should be selected for deep-cycling and daily discharging.

- Lead-acid batteries should have a higher concentrated electrolyte when used in a cold environment (specific gravity of 1.3 kg/dm3 instead of 1.25 kg/dm^3). This influences the charging voltage but keeps the battery from freezing when deeply discharged.

- Nickel-Cadmium batteries are less affected by extreme temperatures and supply a constant voltage through most of their discharge cycle. They also withstand a higher number of cycles than lead-acid batteries. Note that a Ni-Cd cell is rated at 1.2 V and thus requires more cells than a lead-acid battery for the same voltage.

- Gel-type or AGM (Absorptive Glass Mat) batteries should be used in areas where transportation is difficult and where ventilation of the batteries is a problem. Note that these batteries can be positioned in any way and are easier to stack.

After selection of the battery type has been completed, the capacity requirements should be reevaluated to include the efficiency and electrical characteristics of the battery selected. In choosing the size of the battery, select the cell with the amp-hour (Ah) rating nearest to the one calculated. Then determine the number of cells to be connected in -series by dividing the nominal system voltage by the nominal cell voltage. Consider that it may be cheaper to choose a battery cell with half the capacity and use two parallel strings of batteries. Larger capacity cells can be more expensive per capacity and are bulky, heavy and difficult to handle.

18.4 Selection of the power conditioning equipment

Proper selection of the power conditioning equipment ensures that the system will operate in its optimum range and also extends the lifetime of the various components. Improper selections can result in inefficiency, faulty operation, safety hazard, inadequate performance and excessive costs. Included in the general term "Power conditioning equipment" are battery charge regulators, load controllers, maximum power point trackers, auxiliary battery chargers and DC to DC converters. A special section covers DC to AC inverters.

Battery charge regulators and load controllers (off-grid systems only)
Battery charge regulators are electronic devices which control the power output of the array so that it may not overcharge the battery. Sophisticated regulators trickle charge the battery when it is fully charged. They may also automatically compensate for temperature influences. Load controllers protect, on the opposite end, the battery from being completely discharged, by warning the user that his system is reaching a critical level or by cutting off the load. Sophisticated controllers are able to shed the least important loads when the battery capacity level is low. Many battery charge regulators have load controllers incorporated in them. These two electronic devices are essential in extending the lifetime of the battery component and special care must be given to choose the right one for the application and **adjust it properly** before operating the system.

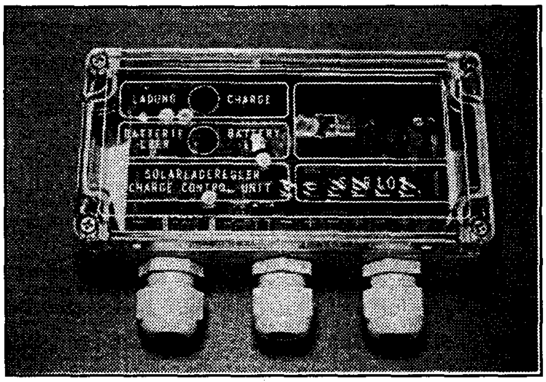


Figure 18.1 Battery charge regulator

The following guidelines can be useful to the designer in making a selection:

- Small PV systems with large battery capacity (15 times the maximum array current) may not need a battery regulator, the internal resistance of the battery will be sufficient to absorb the overcharge current. Note that, when overcharging liquid lead acid batteries, gassing will occur. Special care must then be given to properly ventilate the battery and compensate for water loss periodically.

- Small PV systems with a less than 100 W, array may use a simple shunt regulator which will shunt the current from the array across the battery through a transistor. The advantage of this system is that there is no power loss when the battery is charging. This approach is not recommended for larger systems because the power to be dissipated through the transistor when the battery is full requires the use of a dummy load and can be potentially hazardous.

- For systems above 100 W_p, a series regulator should be used. This device opens the circuit between the array and the battery when the battery is fully charged. Large systems exceeding 30 A should have relays which can avoid forming electric arcs.

- Large PV systems should have regulators which can trickle charge the battery. It may also be necessary to divide the array in sub-arrays and use a charger with a number of relays to charge the battery. As the battery is charged, the regulator switches out the sub-arrays in a planned sequence.

- When batteries are exposed to a wide temperature range, the regulator/controller devices should automatically adjust the charging and discharging set points to compensate for the variable electric characteristics of the battery and protect it from damage.

Maximum power point trackers
Maximum power point trackers (MPPT) are electronic devices which optimize the output of the array or of a number of different sub-arrays to match the electric characteristics of the load. In a uniform array, MPPT are used with loads with variable optimum voltage such as water pumps. In an array with different or variable electrical configuration of sub-arrays, MPPT are used to match the power output of each sub-array to the load so that the energy output of the higher voltage sub-array does not reverse into the sub-array with the lowest voltage. MPPT must be chosen to fit the operating range of the load and its control points must be set carefully to ensure proper operation. Note that most grid-connected inverters have an integrated MPPT.

Auxiliary battery charger (off-grid systems only)
Auxiliary battery chargers are used in hybrid PV/generator systems to charge batteries by the generator when insolation levels are insufficient. The battery charger must be selected according to the power output of the generator and the battery charging requirements. The battery charger output must not exceed the maximum charging rate of the battery but it must be as large as possible in order to minimize the running time of the generator.

DC to DC Converter (off-grid systems only)
DC-DC converters are used where it is necessary to convert from one DC voltage to another when multiple loads with different DC voltage levels are present. A DC-DC converter should be selected according to the power requirement of the load requiring it. Consider that it may be cheaper to use AC equipment and one main inverter if there is more than one DC voltage level or if the power requirement is greater than 1 kW.

18.5 Selecting the inverter

Depending on the nature of the PV system, the inverter converts direct current from the array or from a battery bank to alternating current. In grid-connected systems the inverter permits PV-produced electricity to be fed to the utility grid. In stand-alone (off-grid) systems the inverter permits the operation of common AC appliances from a DC source. Both types of inverters are very different in design and operation and should not be mistaken for another.

Inverters for stand-alone systems with batteries
Inverters for stand-alone PV systems on buildings are usually connected to a battery bank and their voltage input is relatively constant. This voltage is usually low, from 12 to 48 V, but depending on the load size the current requirement can be high. Since the power requirements of the inverter is driven by the load demand, the inverter must be chosen so that it can meet the maximum load demand and still remains efficient at the level it will be used the most. The following points should be addressed when choosing an inverter:

- The input voltage of the inverter must be rated to handle the full range of the battery voltage. A sensing circuit is useful to prevent damage when operation of the inverter is below or beyond its optimal operation points.

- The inverter should be rated at least 20% more than the maximum power requirement of the load to ensure that it can deliver this power for an extended time.
- Inverters for stand-alone applications can have different wave-form output quality. A cheap square wave inverter can be used for small resistive heating loads, hand tools or incandescent lights. Modified sine wave inverters are appropriate for most loads where harmonics in the wave form will not adversely affect the operation of the load (be aware that harmonics will add to the heat generated by power loss in a motor). Sine wave inverters can operate any AC load within their rated power range but are usually more costly.
- Inverters used with motorized appliances should be able to exceed several times their rated capacity for a few seconds to withstand the power surge during start-up. An automatic overload feature which disconnects the inverter after a few seconds is recommended to protect the equipment from failure.
- It may be useful to choose more than one inverter for an application with variable loads in order to have the inverter operating at its maximum efficiency for a range of power requirements. Multiple units connected in parallel (cascaded) to service the same load must be compatible and their frequency must be inter-regulated to be in phase. Some inverters can also produce 3-phase AC output.

Inverters for grid-connected systems Grid-connected inverters directly convert DC electricity from the PV array to AC electricity which is fed into the grid. These inverters must comply with strict grid output requirements so as not to destabilize the line or introduce parasitic harmonics. The wave form of the inverter must be an almost perfect sine-wave shape and its total harmonic distortion must be lower than 3 - 5% following the utility's specification. Their power requirement is dictated by the power output of the array and the inverter should be rated not more than about the maximum power output of the array in order to be in its most efficient range. Special care must be given so that a group of inverters operating on the same line are prevented from feeding electricity to the line if it fails (islanding phenomenon). Please refer to chapter 9 for more information on the different inverters for grid-connected systems.

The following recommended specifications can be used to select a grid-connected inverter:

- High conversion efficiency (> 92%);
- Low start-up and shut-down thresholds;
- Power factor > 0.85 (satisfies local utility requirements);
- Low total harmonic distortion of output current (< 3%);
- Maximum power point operation;
- Current limiting function;
- Low power consumption at night (P_o < 0.5% of Prated);
- Automatic disconnect at utility fault conditions (deviation of V,f);
- Automatic restart after fault is cleared.

18.6 Selection of the back-up system (off-grid systems only)

Selecting the proper diesel or gas driven generator depends on a number of electrical and physical factors.

Electrical factors include the demand characteristics of the load (load variation, peak demand, limits of operation, starting loads) and reliability of the system. Isolated systems will require a back-up system that can come online automatically and require little maintenance.

Physical factors include the location of the system (e.g. exposure to harsh environment), space limitation, noise protection, isolation requirements, engine cooling and ventilation, fuel availability and its storage, starting aids and maintenance requirements. Repair information on all major components of the engine should be readily available.

18.7 Selection of wire size and type

Selection of the proper wiring depends much on the design layout of the system and the different components being used. The following factors should be noted:

- In general, the DC portion of the system will be low voltage. Thus, DC wire runs should be kept as short as possible to minimize cost and voltage drop. Wire selection must be made on the basis of allowed voltage drop. The voltage drop in a cable must be small in order to ensure that power at the correct voltage is delivered to the load. Using electrical code safety standards to select the size of a cable is not sufficient to ensure that the voltage drop will be less than 2 - 5%.

  The following formula can be used to determine the voltage drop 0 V in a cable:

  $$\Delta V = R * 2L * I$$

  where

  R is the wire resistance in Ω/m,
  L is the wire run (one-way) and
  I is the current.

  Please refer to Appendix III for selection of the proper wire size.

- In order to achieve the most economical wiring diameter, one can optimize the counter-current effects of cabling investment costs and PV power losses. The total costs are

$$K = k_L * A + \frac{I^2_{nom}}{g * A} * k_{PV}$$

In order to minimize costs, $\frac{dK}{dA} = 0$ **or**

$$0 = k_L + (-1) * \frac{I^2_{nom}}{g * A^2} * k_{PV}$$

Changing $\frac{I}{A}$ **to current density we get the optimised current density as:**

$$S_{opt} = \frac{\sqrt{k_1 * g}}{k_{...}}$$

Explanation of the symbols used in the formulas:

K Total investment	[$/m]
k_L Cost of cabling	[$/mm2/m]
k_{PV} Cost of the PV array	[$/W]
I_{nom} Nominal current	[A]
g Conductivity of the cable	[m/Ωmm]
S Current density	[A/mm2].

An example calculation for the total costs is illustrated in Figure 18.2 which also clearly shows the optimum.

Resistance of Copper Wire						
Cross Section (mm^2)	1,5	2,5	4	6	10	16
Resistance R (Ω/m)	0.0137	0.0082	0.0051	0.0034	0,0019	0,0013

Table 18.1 Resistance of Copper Wire.

- Appliances should be arranged in separate circuits for effective management and identification. AC and DC circuits must be well identified.

- Flexible cables should be selected in all places which need a lot of work. Cables made with several strands are preferred because a single strand can break more easily after bending.

- All wiring must be done to outlast the life-time of the system. Proper care must be given to cable connectors which will not degrade or loosen with time.

- All wiring should be selected according to the environment it faces and the protection it receives from it. There are many types of wires available. Some may be buried directly in the ground, others may need to be protected against humidity, UV or overheating.

18.8 Specification of safety devices and switchgears

Circuit layout must ensure proper safety for the user, the maintenance crew and the equipment in all conditions of operation. In larger systems, circuit layout should include monitoring points to measure the performance of the system at all times.

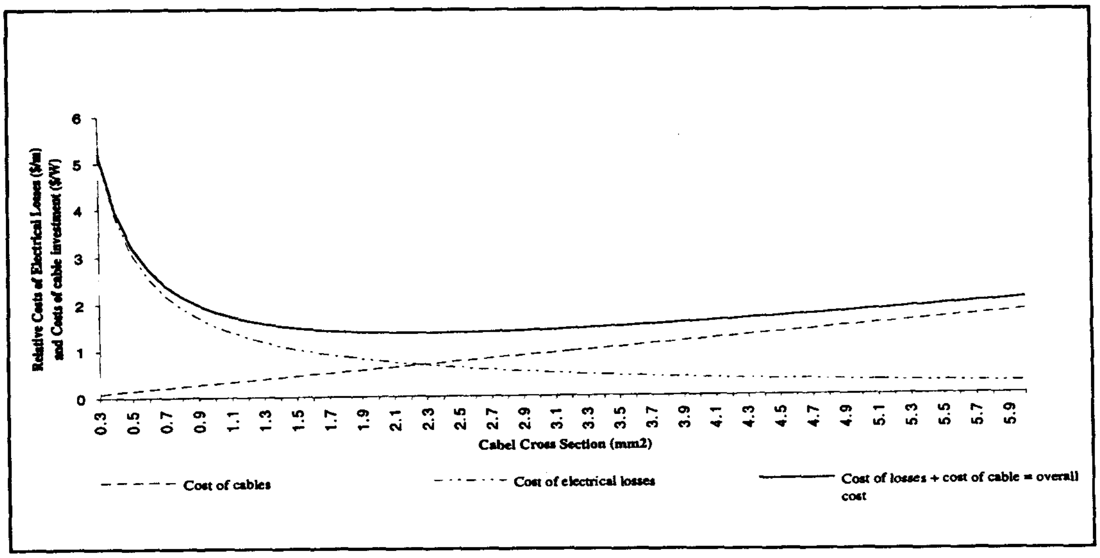


Figure 18.2 Result of a total cost calculation for a typical string cable with a nominal current of 3.5 A (k_L= 0.3 $/$mm^2$m, kPV= 7 $/W).

Switches
Each circuit must be protected against system-failure and short-circuits. The system itself must be rendered inoperational by cutting off a main circuit switch to allow work on the system without danger.

DC circuits must have properly rated DC switches. In switching DC, an arc is formed when a switch is opened and will last till the contacts are some distance apart. If the arc continues for long, it can burn the contacts and shorten their life. High current DC lines can create long arcs which will destroy the switch or the system and can be hazardous to the operator if they are not properly selected.

Switches with a built-in timing mechanism can be useful to cut off an appliance which may be left on inadvertently. Energy efficient techniques are a must for solar systems.

Fuses and breakers
Select fuses and breakers to protect the circuit from shorts and current surges. Each circuit should be properly laid out and connected to a main distribution box to minimize power loss and increase safety of the system.

Surge protection
Circuit layout must include protection of the circuit and of the user from surges derived from lightning and other transient inputs.

Plugs and sockets
Plugs and sockets should be different for DC and AC appliances. DC circuits should use plugs and sockets which identify the polarity of the conductors and prevent the appliance from being reverse connected.

18.9 Checklist of required parts

The following table lists the system parts and important features.

Items	What to look for
Array	
Electrical Specs	W_p, V_{OC}, I_{SC}, I-V curve
Modules	Size, type modularity
Mounting frame	Material, facility of mounting, nuts and bolts
Mounting base	Cement, fastening system
Fence	Protection against vandalism
Connection	Facility of connection
Batteries	
Electrical Specs	Ah capacity, voltage, cycling, discharge capacity, charging treshold
Physical limitation	Size, weight, environmental protection needs, ventilation, frame
Electrolyte	Type, specific gravity, distilled water need
Connection	Ring clamps, grease
Controller	
Electrical Specs	Set points, adjustability, temperature compensation, upgrading
Protection	Fuse, reverse-polarity protection
Connection	Type, ease of connection
Options	Metering/monitoring capability, tamper-proof, alarm, computer-coupling
Back-up generator	
Electrical Specs	Type, VA, voltage, regulation, frequency, THD, surge capacity
Fuel	Diesel, propane, gasoline, availability, consumption
Physical limitation	Size, weight, engine cooling and ventilation, noise, heating requirements
Maintenance	Periodicity, ease, overhaul requirements
Options	Automatic starter, battery charger, shut-down protection
Inverter	
Electrical Specs	DC input voltage, AC output voltage, phase, frequency, THD, surge capacity, shape of curve, power consumption during standby, local code safety requirements.
Physical Specs	Temperature limitation, humidity limitation, size, noise level, ventilation needs.
Utility Requirements	Safety, power quality, trip limits, protection details.
Distribution	
Cables	Distance, voltage drop, flexibility, environment
Conduit	Type, coupler, environment
Connectors	Crimp, ring, wiring terminals, splicing
Safety protection	Fuses, breakers, surge protection, main switch, circuit switches, grounding
Distribution box	Facility of wiring, upgrading, environmental protection, vandalism protection, grounding
Plugs and sockets	Polarity identification and protection

Table 18.2 System parts checklist.

Section E

Installation and Maintenance

Principal Contributors

Chapter 19: **Photovoltaic System Installation Guidelines**

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Chapter 20: **Photovoltaic System Operation and Maintenance**

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1) Extracted from "The Design of Residential Photovoltaic Systems", volume 5 "Installation, Maintenance and Operation Volume", document number SAND 87-1951-5, edited by Dr. Gary Jones and Dr. Michael Thomas.
Contributors to this report were James Huning, John Otte, Elizabeth Rose, Russ Sugimura and Kent Volkmer of the Jet Propulsion Laboratory.

Chapter 19

Photovoltaic System Installation Guidelines

19.1 What the installer needs to know

The installation of a photovoltaic system in a residence should not be an unusually difficult task as long as the few unique characteristics of photovoltaics are well understood. This chapter describes the steps of a typical residential photovoltaic system installation and provides special information useful to the system installer.

Because the DC part of the photovoltaic system is "activated" when modules are illuminated, there is the possibility of electric shock hazard with varying degrees of severity. Safety rules must be followed, and the entire work crew should be instructed about possible shock hazards and how to avoid them.

19.2 Component delivery: inspect, test and protect

To minimize the possibility of theft, vandalism and other risks to handlers, a number of suggestions for storing and handling system components is provided. In addition, suggestions for inspecting and testing components prior to installation are given. Of course, these procedures may vary according to specific site situations and the local construction protocol. A large multiple-unit installation will require variations to the procedures suggested here for an individual residence.

- PV modules generate electricity when exposed to light.
- When wired, PV modules may generate a lethal shock.
- A DC current spark is more dangerous than an AC spark.

Table 19.1 Instruction of work crew about PV unique hazards.

19.2.1 Timing is important - plan the delivery schedule

When a PV system is installed during a new home construction, system components should be ordered to arrive at the site at the appropriate time in the construction sequence. Coordination of building construction with array installation may be especially critical. For example, building codes usually require the roof installation to be completed before the electric wiring may be installed. When the array itself becomes the roof weather seal, as in the case of an "integral" array design, array installation can obviously pace the remainder of the home construction. This consideration will be less important for array designs that do not constitute the roof weather seal.

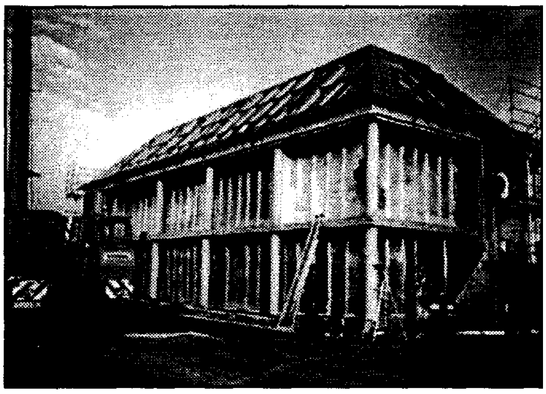


Figure 19.1 Structural glazing: Building without facade.

- Cracked cover glass;
- Bent or dented frame, if applicable;
- Loose or broken wires;
- Check all modules for proper open circuit voltage when exposed to full illumination.

Table 19.2 Inspection of PV modules upon receipt for obvious damage or defects.

Delivery of all PV components at the same time will usually minimise the expense of return visits by installers and the expense of providing secure storage for valuable components awaiting installation.

19.2.2 Component function check prior to installation

Once the photovoltaic modules have been received, care must be exercised in removing them from their shipping containers. If the terminals are exposed, an electric shock is possible. Although the electric shock hazard from a single module is low, it may be sufficient to startle the person handling it and cause her or him to drop and damage the module.

Each module should be visually inspected for damage or obvious defects such as cracked glass or cells. Modules with cracked cover glass or cells, or with bent or dented frames, should not be installed in the array, but returned to the vendor for replacement. Similar visual inspection should be done for other system components as well. This is especially true for the power conditioning unit. If the PCU is damaged during shipment, the manufacturer should be notified as soon as possible so that repair and/or replacement can be made. The damaged shipping container should be saved as evidence in the event the unit must be returned.

A simple check of the module's electrical function is recommended as part of the receiving inspection. Because each module has been electrically tested by the manufacturer, sophisticated testing is not necessary at this step. An I-V (current-voltage) curve is useful at the module level only if the design calls for matching array source circuit power outputs. A simple check of open circuit voltage (V_{OC}) will be sufficient. (Note: This check should be performed only with the module directly facing the sun.) The V_{OC} check is a very rough test to detect only a serious fault or malfunction in the module. The measured value of VOC, even for a properly functioning module, will vary according to its temperature and the intensity of the sunlight. A VOC reading no more than 20 percent below the manufacturer's specified value will generally indicate that the module is functioning correctly. During extended cloudy periods, this check should be dispensed with since results will be too difficult to interpret. Additional electrical testing will be accomplished during the installation and checkout phases.

19.2.3 Protecting PV components

Photovoltaic system components represent a significant investment and merit. Module and power conditioning units should be kept in a secure location to prevent theft or vandalism. In addition, the components should be protected from weather until installation. Modules should not be left in direct sunlight while resting in their open shipping containers. Photovoltaic modules stored in the sun can become extremely hot even if crated. If the installer removes hot modules from the packing crate without using protective gloves, a burn is possible and the module could be dropped and damaged. If possible, excessive stacking of modules, one on top of another, should be avoided. A preferred method is to store modules on their edges.

19.3 Array installation: the key step

Installation of a rooftop array of PV modules will be the most challenging part of residential system installation. A variety of mounting methods are available, which may be used with a number of roof structure styles and designs. Installation of the array requires mechanically mounting the modules, attaching the electrical interconnections, and checking the performance of completed array source circuits. All phases of array installation involve working with electrically active components. Consequently, all workers must be familiar with the potential hazards of installing PV and with the specific procedures appropriate to the system being installed. Each option for mounting and wiring an array will present its own special installation requirements. For this reason, the system designer must provide detailed installation procedures for each system design.

Figure 19.2 Structural glazing: The first facade element is being mounted.

19.3.1 Array mounting options

A number of factors determine which specific array design is selected. Among these factors are:

- Whether the system will be integrated into a new residence or an existing home (retrofit);
- Type of roof construction;
- Roof orientation;
- Local climatic conditions;
- Institutional factors, including local covenants and restrictions.

There are four basic mounting options: direct, integral, stand-off, and rack. In a direct mount, modules are mounted directly on the roof sheathing and shingles.

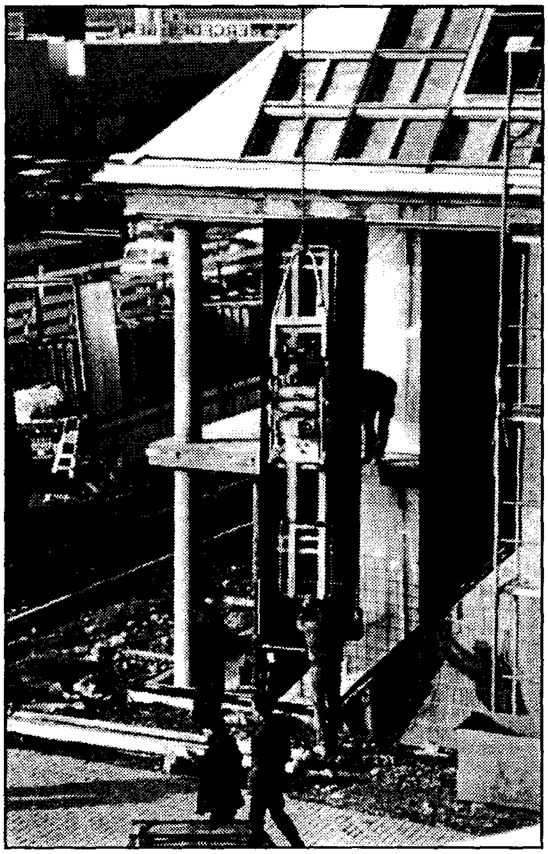


Figure 19.3 Structural glazing: Facade mounting continues.

In an integral mount, the photovoltaic modules replace the roofing material, including sheathing. In this case, modules are mounted directly on the roof rafters and provide the weather seal. In a stand-off mount, the modules are mounted a few inches above and parallel to the roof surface. Finally, in a rack mounted array, a frame or rack is first installed to support the modules. The orientation of the rack can be selected for the most appropriate direction or angle to the sun.

In a new construction, the system designer can select the preferred mounting scheme, which may then influence the overall roof structural design. For example, if an integral mount is selected, rafter and spacing specifications must be made compatible with the proposed module size and attachment methods. With a retrofit, however, the existing roof structure will largely dictate which mounting schemes are feasible. A retrofit application will generally rule out an integral mount because of the cost or unsatisfactory rafter spacing. Or, in another case, an existing roof may depart sufficiently from optimal tilt or orientation such that only a rack mount may be used.

Each option presents special design constraints to the system designer. Because the integral mount becomes part of the roof itself, the builder must give particular attention to scheduling the PV installation, especially the wiring of the array. Such items as how and where to run the electrical wiring, where to place the roof insulation and where to situate the junction boxes, need to be clearly sequenced for the builder. A possible advantage to the other three mounting options - direct, stand-off, or rack - is that the builder has the option of scheduling array installation after the roof structure is completed. This approach may prevent interference between work crews when the array is not being installed by the general contracting crew.

To some degree, local building code requirements also help to determine which mounting options are feasible. The architect and system designer will have identified any local requirements before the final system design is selected. Factors normally addressed by codes include the extra weight and wind loads that modules and any support structure will add to the roof.

Regardless of the mounting option selection, the architect or system designer must give attention to the requirements of installers or service personnel in two particular areas:

- **Accessibility.** The mounting option must allow for safe and effective module removal or maintenance. Any special hardware requirements should be specified by the system designer. The mounting option must not only allow for physical accessibility, it must also allow access to the electrical termination on the backside of standard PV modules. The integral mount is usually superior, since this provides direct access to the back of the modules from inside the building. Direct or stand-off arrangements require partial removal of the module while working on the roof surface to gain electrical access. This operation may require special ladders or scaffolding to prevent standing and working directly on the array surface.

- **Weather sealing.** Any array mounting scheme must provide for, or at least not jeopardise, the roof weather seal. This is most important in the case of the integral mount. Proper attention must be given to casketing and hold-down materials, both during design and during actual installation.

No unusual construction practices are required, although with an integral mount special care must be taken to ensure a weather tight fit. Experimental designs are satisfactory in this regard, although applying liquid sealants may require working in dry, above-freezing weather conditions.

19.3.2 Module attaching methods

The actual procedure used in securing the modules is determined, in part, by the specific array design, including the type of module and mounting option used.

Detailed installation procedures must be provided for each system design. The procedures should emphasise that DC shock is a potential hazard at all times, not only during the array wiring phase. Accordingly, protective equipment such as insulated gloves should be used whenever modules are handled or are being attached to the support structure. If feasible, the modules may be covered to block the light and preclude shock hazard.

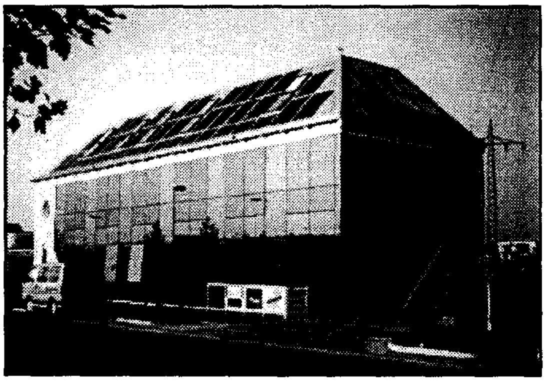


Figure 19.4 Structural glazing: The completed building with PV facade.

Moderate to high velocity winds present difficulty in handling modules on a rooftop and may significantly affect worker safety and installation scheduling. For example, in areas where high wind velocities are a typical occurence in the afternoon, module mounting may have to be scheduled for early morning or early evening.

A work crew consisting of at least two people should be used to install the modules. The modules should not be walked on at any time. Some experimenters have suggested three-person crews, two to handle the module and one to place it in the support structure. Lifting large modules or multimodule panels to the roof may require a hoist or crane.

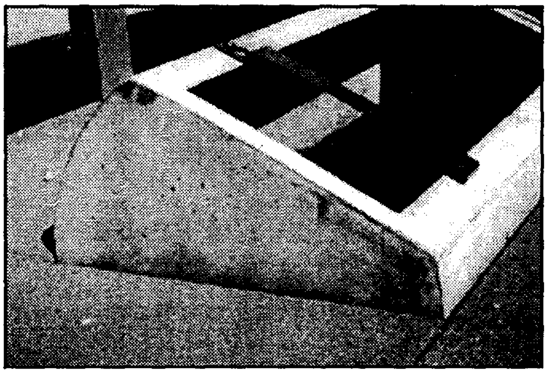


Figure 19.5 Flat roof installation: Concrete block.

With several experimental array schemes, mounting holes had to be drilled to allow the module to be attached to the support structure. Special care is required in measuring for the mounting holes. If one hole is misplaced and the module mounted, each subsequent module will be out of alignment. In some cases, the installer may prefer to drill mounting holes as each module is attached, thereby ensuring that no time will be wasted in having to redrill them.

On sloping roofs, precautions used by experienced roofers, such as a lifeline and safety belt may be required to prevent accidental falls. This is especially true for roofs that are steep or inherently slippery. Hard hats should be worn by those working on the ground during array installation. Non-conducting tools and other support equipment should be used.

19.3.3 Array wiring instructions

Because of the diversity of acceptable array electrical wiring systems and termination methods, it is not possible to describe an installation procedure that addresses every contingency. Therefore, it is especially important that the PV system designer provides detailed procedures and design-specific recommendations to facilitate proper and safe array wiring. This section discusses points that should be addressed in detailed procedures.

Because the wiring system and termination must be installed at the site, local building code requirements must be observed.

The various acceptable array wiring and termination methods require no special mechanical skills or tools beyond those normally found at a construction site. Generally, differences between PV and other wiring installation methods consist of the additional precautions required by PV due to its constantly energized operating characteristics.

Existing National Electrical Code requirements specify that non-current-carrying conductive structures are to be solidly grounded. This is consistent with present design practice and, in general, should be one of the first steps of any PV electrical installation that utilizes a conductive mounting structure for the PV modules. The array design should also ensure that modules or panels with a conductive frame are effectively bonded to ground.

The remaining step in the electrical installation of a PV array consists of manually wiring a number of series-connected modules that will achieve system voltage. This series string of modules, which constitutes the source circuit, is then connected in parallel with other source circuits to form the system output.

Contact with conductors at a voltage greater than about 50 V can result in a lethal shock. In most cases, a residential PV system voltage will be substantially higher - in the order of 200 V. Since PV modules develop full voltage potential at low illumination levels, contact with conductors that connect a series of modules in a source circuit carries the potential of a lethal shock. Remember, unlike more conventional electrical sources, PV modules cannot be "turned off'.

EXTREME CAUTION SHOULD BE EXERCISED WHEN WORKING WITH CONDUCTORS AT THE SOURCE CIRCUIT LEVEL.

Two additional cautions must be emphasised. Because DC arcing is possible when a DC circuit is interrupted, caution must be exercised when a DC connection or termination is broken. Installation procedures should ensure that source circuits will remain open prior to circuit checkout so that no current will flow. If the source circuit is accidentally closed (e.g. by shorting across the terminals of the circuit disconnect switch, or between circuit wiring and the grounded array frame), any subsequent opening of the circuit will produce a large DC arc. (These conditions carry other safety hazards as well and must be avoided.) Even though the arc itself may not be hazardous, the worker could be startled sufficiently by it to fall and be injured.

The second caution is based on the limited availability of short-circuit current and on the problem that protective devices may not function in the presence of a ground fault. This unique characteristic coupled with the fact that the array is electrically energized by the sun demands extra care in installation to prevent shock or fire.

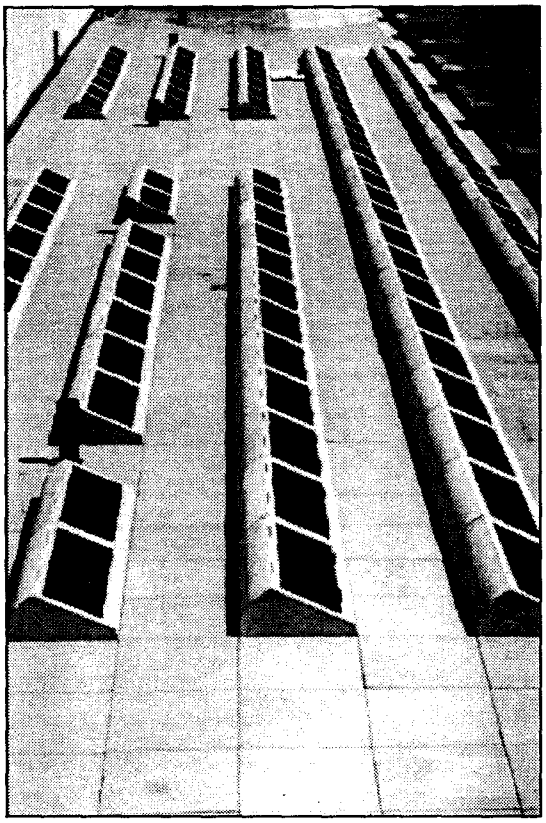


Figure 19.6 Flat roof installation: Roof with concrete blocks.

As installation proceeds, both array wiring and terminations must be tested and checked. Specific procedures for installation and checkout should be written for each wiring and termination method. In general, test and checkout of each source circuit should be performed as early as convenient during installation sequence. Prior to source circuit checkout, proper installation of the structure grounding system should be verified.

During the actual electrical interconnection of modules, particular attention should be paid to maintaining the correct polarity. Any series safety devices (i.e. diodes, fuses) should be checked for proper installation (secure connection, and proper polarity where applicable).

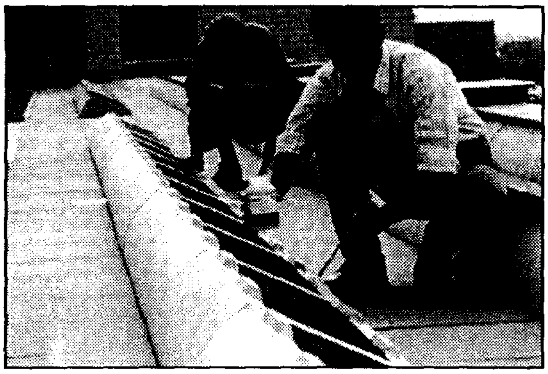


Figure 19.7 Flat roof installation: Cleaning and priming of concrete block

As a minimum, a voltage check should be performed on each source circuit, as well as on the photovoltaic output circuit (the full array). All disconnecting means should be exercised to verify correct operation. This will normally involve only a simple voltage check on the downstream side of each disconnection switch in both the open and closed positions. If voltage remains on the downstream side of a source circuit or array disconnection switch after it has been opened, either the circuit has been wired incorrectly or the switch is faulty. If the circuit proves to be correctly wired, the disconnection switch should be removed and tested with an ohm-meter and replaced if necessary.

Because each specific design should include a set of detailed wiring procedures, only generic procedures have been discussed. The critical issue is that the designer must anticipate the wiring requirements and give the installer sufficient details so that the safety of installers, occupants, and the photovoltaic system is ensured.

193.4 Location of the power conditioning unit

The preferred location of the power conditioning unit will be dictated, in part, by physical characteristics of the PCU, including size, noise production and environmental operating requirements. The unit must be properly mounted to minimise audible noise and vibration, and it must be placed in a secure location to prevent tampering.

The location of the PCU in the building will also depend in part on specific site climate. In areas that experience a large annual or daily temperature variation, the PCU will have to be protected from the weather so that the specified operating temperature range is not exceeded. In areas that have an equable climate, the PCU may be located outside the building, but it must be protected by a weather-proof box. If located outdoors, the ventilation ports on the box may have to be screened to prevent small animals from taking up residence inside the box.

Each PCU has a specified operating temperature and relative humidity range, which should be indicated in the manufacturer's specifications and on the unit itself. The temperature range (min-max) must be determined and the unit located such that exposure to temperatures beyond its safe operating range (e.g. not below freezing or above 38°C) is avoided. All PCUs produce waste heat (as much as 5-10% of nominal Power), which means that adequate ventilation must be ensured.

If temperature requirements dictate an insidethe-building location and the PCU under consideration produces noise, it should be located where noise will not be an environmental nuisance to the occupants. Again, the amount of heat produced must be taken into account if the unit is located in a small area (e.g. closet).

If the power conditioning design permits, attachment to wall studs is generally recommended. In this location it is more accessible for occasional monitoring, less accessible to small children, and less likely to hinder activities in the area. Manufacturers' recommendations should be observed regarding specific mounting methods. Some PCUs are designed for free standing and require no mounting procedures.

Lethal voltages are connected to the power conditioning unit, and it is imperative that individuals be protected from accidental contact with electrically active parts. For this reason, the unit is normally packaged in a cabinet that can be locked or otherwise secured. Other components of the power conditioning subsystem (e.g. an isolation transformer, if separate from the PCU) should be located within a lockable PV service box. "DANGER HIGH VOLTAGE" labels should be placed on and near the power conditioning subsystem, regardless of its location.

19.4 Special protection devices

In addition to the array of PV modules and the power conditioner, several additional devices will be included in the system design to provide protection in case equipment should malfunction. Applicable codes and utility requirements dictate the protection devices that are required in the PV system.

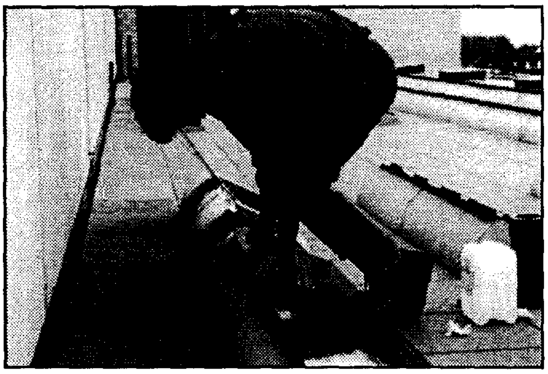


Figure 19.8 Flat roof installation: Glueing of PV modules to concrete block.

- Choose location of PCU that meets temperature and humidity requirements.
- Consider PCU-generated noise when selecting PCU location.
- Ensure adequate ventilation since PCU produces significant heat.
- Avoid public access to live parts.

Table 19.3 Location of Power Conditioning Unit (PCU).

19.4.1 The 1984 U.S. National Electrical Code

Specific recommendations of the US-NEC Article 690 are of general validity and include

- Use of overcurrent protection devices in all PV electrical sources, including the PV source circuit (string), PV output circuit (array), PCU output circuit, and storage battery circuit conductors.
- Protection against possible feedback of current from any source of supply, including the PCU.

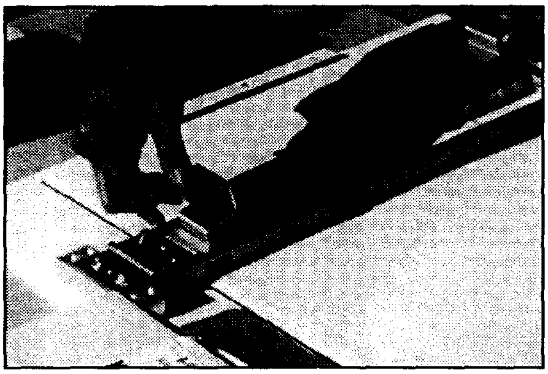


Figure 19.9 Flat roof installation: Bracket glueing to PV module.

- Inclusion of readily accessible, manually operable switch(es) or circuit breaker(s) to disconnect conductors.
- Surge protection and grounding methods.

19.4.2 Additional steps

Several additional steps are recommended to provide protection in the event of any malfunction. These include ground-fault protectors, alarms, system interlocks and disconnects, lockable boxes and special labelling, and specific placement of equipment. These items are not universally addressed in existing PV design guides.

19.4.3 Co-location of PV system components

To facilitate maintenance and protect service personnel, selected components of the PV system (e.g. blocking diodes, fuses, source circuit disconnects) should be co-located in a lockable DC service box. Co-locating equipment minimises wiring and the number of places service personnel must work. It also can provide a lockable barrier between high voltage equipment and untrained persons or children.

To minimise the shock hazard to service personnel during maintenance, it must be possible to electrically isolate the PV system from the utility. In addition, service personnel must be readily able to disconnect the array from the PCU. Lockable disconnects are important when maintenance must be performed on the roof array, away from disconnect switches. The power conditioner, fuses, switches, test points, alarms, and service interlocks may be conveniently located in a dedicated space.

A smoke detector may be used as an indicator of power conditioner faults or electrical wiring shorts that present a possible fire hazard. An ion-sensitive smoke detector is particularly recommended because of its extreme sensitivity. The recommended location for the smoke detector is directly above the power conditioner. The alarm must be audible within the occupied building.

Safety codes recommend an overcurrent protection device such as a fuse in every circuit. Overcurrent and overvoltage protection are now standard features built into today's power conditioners. However, a PV system represents a significant investment, and additional overvoltage surge arrestors may be cost-effective in certain cases.

It is generally agreed that a system cannot be economically protected from a direct lightning strike, although it may be protected against power surges from near strikes by the use of surge arrestors. Surge arrestors provide economical and effective protection and should be installed both line-to-line and line-to-ground. The surge arrestor should be installed on both the positive and negative legs of the array to protect the PCU from damage. Many persons believe air masts and lightning rods provide little additional protection. Lightning surge protection may be unnecessary in areas where electrical storms are rare.- Considering the value of PV system components and the low-cost protection provided by surge arrestors, their use is strongly recommended in all residential installations. The use of surge arrestors on the output of the PCU should also be considered to protect particularly sensitive house loads, such as computers, from occasional transients appearing in the PCU output.

19.4.4 Location of protection devices

The PV system or building design will frequently dictate the best locations for protection devices. Criteria to consider are:

- **Accessibility.** Protection devices must be accessible to service personnel so that they can be actuated (e.g. disconnect) or inspected (e.g. fuses) with a minimum of difficulty.
- **Wiring requirements.** A trade-off may be necessary because extremely accessible locations will generally require considerable additional wiring, and thus cause additional cost and failure risks.

Array and utility disconnects must be located as specified by local code, utility, or fire department requirements, usually in visible outside locations. The array disconnect is most commonly located near the power conditioner. A lockable disconnect should be used to prevent accidental closure during service. The array disconnect should be clearly labelled. In addition, fire department personnel should be notified that the disconnect only interrupts power supplied to the building, and that the roof array remains electrically active when illuminated. The AC disconnect should be located near the utility service entrance in a place accessible to utility personnel.

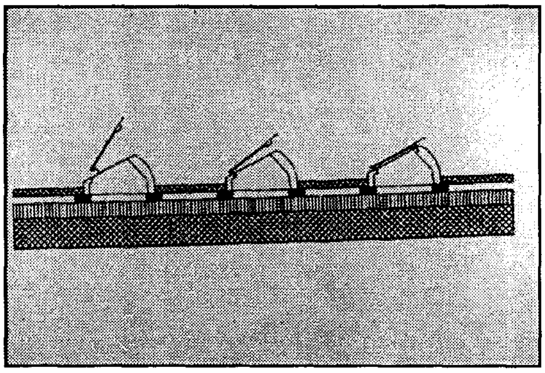


Figure 19.10 Flat roof installation: Attaching PV modules with brackets to concrete blocks.

- Lightning surge protectors should be installed to protect the PCU on both AC and DC sides.
- Locate grounding connection point for lightning power surge protection as close as possible to the device.
- For proper foundation of the devices, they should be placed where the wire enters the building.

Table 19.4 Location of surge protection.

19.4.5 Labels, warnings and instructions

Warning labels and special instructions are important for the occupants' safety in case of a serious system malfunction. In addition, special labelling and instructions should be provided for service personnel and fire-fighters. A sign indicating the presence of a PV system should be placed on the utility pole or vault serving the PV building to alert utility service personnel.

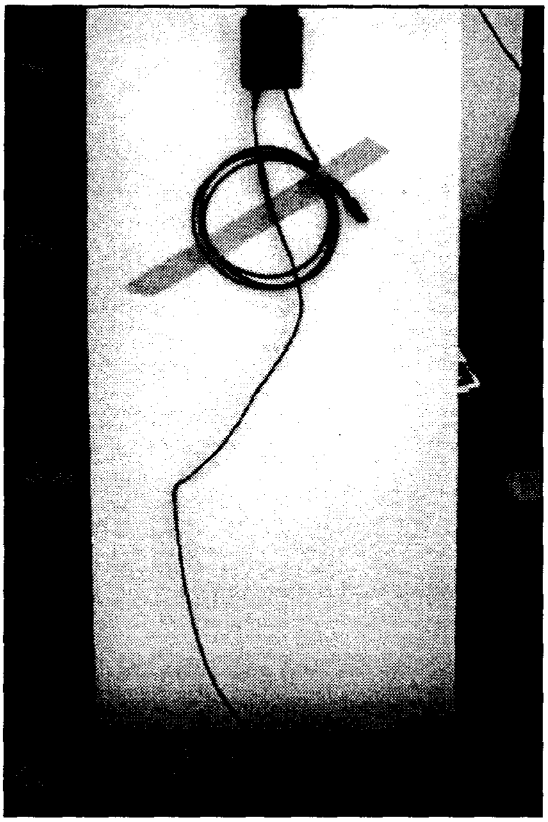


Figure 19.11 Flat roof installation: PV module back side with connection box.

Blocking diodes are used to prevent one source circuit from feeding current back into another source circuit in cases where one circuit voltage is higher than another. The system designer should consider locating these diodes in the PV service box where they will be accessible to service personnel. If diodes and diagnostic test points for each source circuit are located in the PV service box, necessary service can be more easily accomplished. Manual switches that allow each circuit to be independently disconnected (for testing) can also be co-located in the PV service box. Each switch should be clearly labelled to indicate which source circuit it disconnects. All circuits should be identified on the schematic diagram prepared for trained service personnel.

19.5 Inspection of the system

In most countries the newly installed PV system requires building code inspection by local officials. In addition to electrical inspection, structural inspection may be required. A residential photovoltaic system represents a new and unfamiliar technology to most inspectors in local agencies, at least for the near-term future. To preclude possible installation, checkout, and operation delays, necessary inspection requirements must be well understood and action must be taken to meet them at the appropriate times.

19.5.1 Inspection requirements

The electrical and structural inspection requirements vary according to the region of the country, both as a function of administrative jurisdiction (i.e. city or county) and specific utility.

The number of inspections and the level of detail to which a photovoltaic system will be inspected vary according to the region. In some areas, code requirements may be rigorous and followed closely, while in other areas requirements may be more lax. It is imperative that local requirements be clearly known before the design is completed and any inspection requirements be scheduled into the installation and checkout phases.

Because most inspectors will not be familiar with photovoltaic systems, especially the "always-on" characteristic of the array, a thorough briefing of the inspector before a site visit may prove valuable. Informing the inspector regarding what will be seen, why PV differs from other electrical systems, and the protective features that are included in the system should reduce or eliminate any reservations or concerns the inspector may have due to the newness of photovoltaics:

The local fire department station should also be informed about the existence of the photovoltaic system and the "always-on" characteristic of the array. The fire department may not levy specific inspection requirements, but fire department personnel will probably appreciate knowing that a photovoltaic system is planned within their service area.

When residential photovoltaic systems are more common, many of the concerns noted above will disappear. Until then, the architect/system designer should take the initiative to alert regulatory and service agencies to the existence and unique properties of photovoltaic systems.

19.5.2 Utility requirements

Utility requirements vary, but the system designer and builder can be certain that the utility wants assurances that the system will not feed poor quality power into the grid (i.e. power having excessive noise or harmonic content), and that it will shut down in the case of an emergency or loss of utility power. In the initial design stage, the system designer must check with the specific utility to determine its requirements. For the near-term future the utility may even ask to see PCU performance data, but as photovoltaics become more and more common, the utility will likely specify only generic requirements that the system designer must meet. The utility may require a complete single-line diagram delineating control, protection and metering functions as part of the application's procedure. In any case, consult utility representatives before finalising the system design.

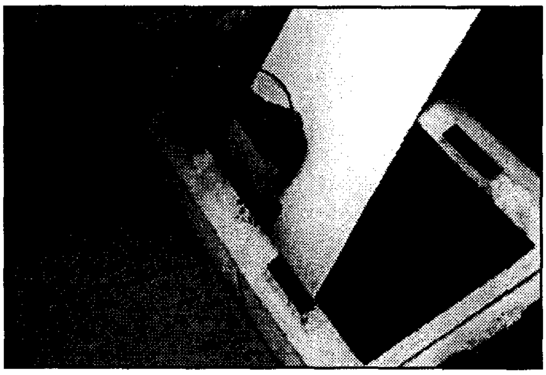


Figure 19.12 Flat roof installation: Electrical connection using plugs.

19.6 Installation summary

Detailed instructions are required for installation personnel, particularly for mounting and electrically wiring the array. These instructions should cover the points outlined below:

19.6.1 Preparation of system installation

- Work crew briefed on PV procedures and safety hazards;
- Components delivery scheduled;
- Components checked upon receipt:
  - Modules
    - No broken glass or cell;
    - Frames straight and undented;
    - Open circuit voltage (V_{OC}) approximately equal to design value;
  - Power conditioning unit
    - No visible damage;
- Components safely stored in weatherproof location until installation.

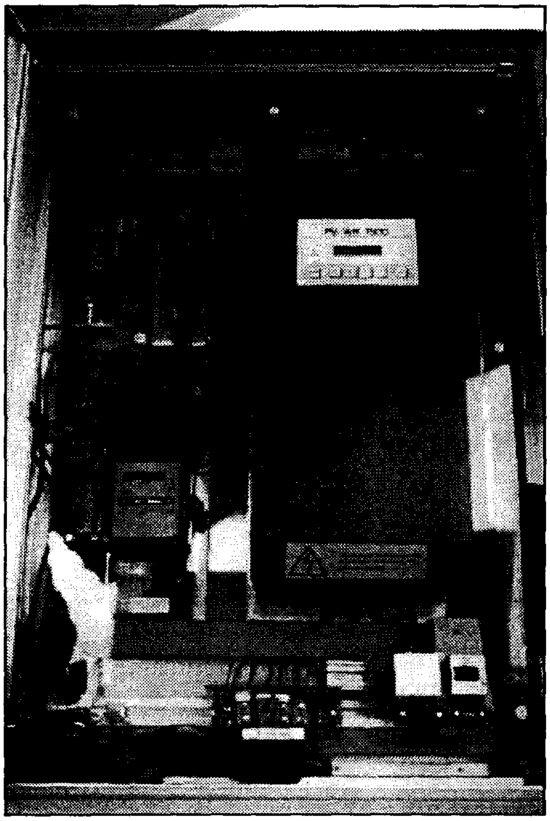


Figure 19.13 Flat roof installation: Inverter.

19.6.2 Installing the array

- Integral mount:
  - Modules installed before house wired;
  - Modules may be wired one at a time as installed, or after all modules are installed;
  - Sealants may require dry, above-freezing weather;

- Direct or stand-off mount:
  - Installed after roof is intact;
  - Modules wired one at a time as installed;

- Rack mount:
  - Installed after roof is intact;
  - Modules may be wired one at a time as installed, or after all modules are installed;

- Safety procedures include:
  - Non-conducting ladders or scaffolding;
  - No walking on module surfaces;
  - Two-person work crew as minimum;
  - No module handling in high wind velocities;
  - Safety line on steep roofs;
  - Briefing on unique design aspects or electrical safety hazards;
  - Prevention against falling down;

- Electrical wiring and checkout:
  - Array frame grounded before module installation;
  - Wiring method and schedule per designer's procedures;
  - Open circuit voltage (V_{OC}) check on each source circuit as wiring is completed;
  - No attachment of array to power conditioner prior to initiating system-level checkout;
  - Array left in open circuit condition.

19.6.3 Installing the power conditioning unit

- Locate to satisfy temperature and humidity specifications, usually done by the designer;

- When possible, stud mount;

- Protect from tampering
  - Verify seal on locked enclosure or
  - Place in lockable service box or
  - Dedicated space;

- Good access for maintenance;

- Allow free air circulation;

- Cable inlet from the bottom.

19.6.4 Installing system protection devices

■ Observe requirements
- Local building or electrical codes;
- Local utility and fire department;

■ Recommendations include
- Overcurrent protection devices in source circuit, array, PCU output;
- Feedback protection from any supply source;
- Accessible, manual disconnects on ungrounded conductors;
- Surge protection and ground;
- Smoke detector above PCU;

■ Co-locate circuit overcurrent protection devices with test points;

■ Labels, warnings, and posted instructions
- AC and DC disconnects;
- System circuit diagram;
- Test point labels and appropriate readings;
- Warnings at points of electrical hazards;
- Sign on utility pole or vault.

19.6.5 Inspecting the entire PV system

■ Brief inspectors and schedule in advance:
- Building and electrical;
- Utility;
- Fire department.

It may be an advantage to install the inverter first and the connection to the grid as well as the DC-cabling. Finally the PV-array can be mounted and start-up procedure can follow immediately.

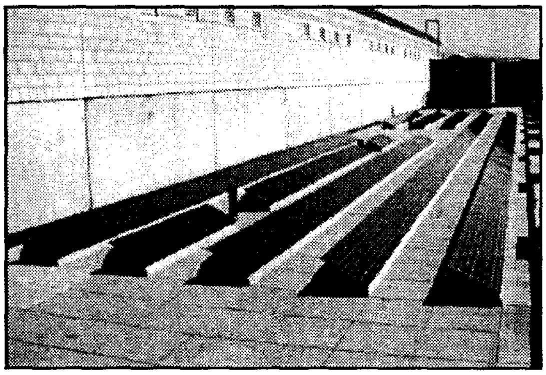


Figure 19.14 Flat roof installation: The completed flat roof installation.

19.7 Installation examples

19.7.1 Structural glazing example

The photovoltaic modules are fully integrated in this commercial building in a rear-ventilated construction. Frameless modules fitted into the balustrades and voids of the window areas were used. The prefabricated facade elements were built into the building within a single day.

Figures 19.1 through 19.4 show steps between beginning and end of installation.

19.7.2 Flat roof installation

This system is an example of how standard photovoltaic elements can be integrated into a flat roof covered by conventional concrete paving stones (50 cm x 50 cm).

A concrete base which occupies a surface equivalent to that of two paving stones (i.e. 100 cm x 50 cm) was developed especially for this purpose. Current ballast norms for PV installations were easily met by the weight of the concrete (60 kg). As this is a pilot installation, the PV modules were attached to the concrete blocks in two different ways._

Figures 19.5 through 19.14 show the construction stages: The gravel of the original roof was removed and paving stones were displaced to make space for the prefabricated concrete module bases (Figure 19.5). It takes two people to move one of these concrete blocks. Once they are in their place (Figure 19.6), the photovoltaic modules can be mounted directly or indirectly:

- direct fixing of the modules to the base is achieved with a double-sided auto-adhesive tape which is applied directly to the concrete. Good weather is necessary for this three-step procedure: first the concrete is cleaned and primed (Figure 19.7), then the auto-adhesive tape is attached to the concrete and finally the PV modules are put into position and secured by pressure (Figure 19.8).

- indirect fixing requires stainless steel brackets, which are glued to the module beforehand (Figure 19.9) and then attached to the concrete base as shown in Figure 19.10.

Both mounting techniques are accompanied by a very simple and efficient wiring system. It is arranged around a connection box with integrated diodes and connectors, which is glued to the back of the PV module (Figure 19.11). When the modules are mounted, the wires between them are laid underneath the concrete bases and simply connected by plugs (Figure 19.12). Thus, the wiring is protected from mechanical damage as well as from UV rays etc. All wires enter the building at the same place. Inside, they are connected to the inverter (Figure 19.13) which feeds the electricity directly into the grid.

This system integrates very elegantly into the building. At the same time it allows easy access for roof maintenance and enough space for people to pass (Figure 19.14).

Chapter 20

Photovoltaic System Operation and Maintenance

20.1 Introduction

Properly designed and installed PV systems require little maintenance due to the absence of moving parts and to the high reliability of their components. Nevertheless periodic maintenance is recommended in order to ensure a good performance of the PV system and extend its useful life.

Although in general all PV systems have similar elements and/or subsystems (PV modules, battery, backup generator, regulator(s), inverter(s), cabling etc.), the level or type of maintenance depends on the complexity of the system and its use. In this chapter the maintenance of PV systems in buildings is discussed. A collection of procedures to be carried out periodically is suggested and described. Since it is good practice to establish a site log to record all maintenance schedules and comments, examples of log reports are presented.

20.2 PV array maintenance

The PV array consists of PV modules, cabling and a mounting structure. This subsystem is very reliable and does not require intensive maintenance.

Dust accumulated on a PV array can decrease its efficiency and performance. Normally rain will be enough to clean the modules if it is not a very dry site.

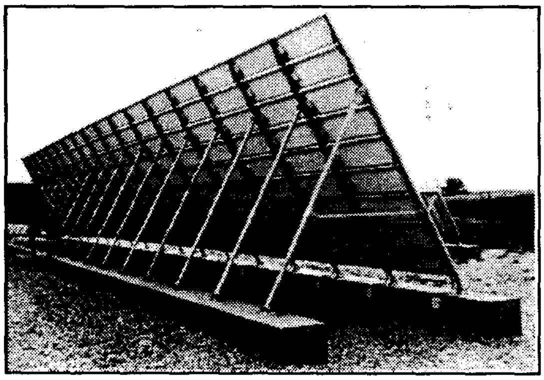


Figure 20.1 Backside view of a PV array.

But in urban or industrial areas or near busy roads where ordinary dust is mixed with heavier and greasy particles, cleaning using detergents is recommended from time to time. Do not use abrasive brushes and/or foams. In most cases a simple water jet from a garden hose mixed with detergent will be sufficient.

Twice per year (following seasonal climate changes) it is recommended to:

- review the structure of the PV array ;
- check PV modules for cracked cells and glazing, delamination and cell interconnect corrosion ;
- check power output of individual array strings;
- check wiring, connection boxes for cracking, rodent damage, fraying etc.;
- check electrical leakage to ground.

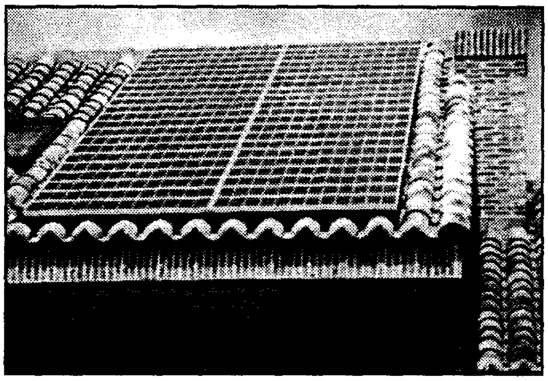


Figure 20.2 PV array roof-integrated.

For cabling and connection boxes of the PV array a quarterly visual inspection is recommended. Replace every box that shows some sign of corrosion or degradation. In addition, the lightning protection (varistors) must be checked regularly especially after stormy weather. Normally varistors have an indicator, which changes colour or position when the protection has worked due to a lightning causing a higher voltage than its nominal value. In such a case, replace it as soon as possible.

A log sheet for maintenance of the PV array is provided in Appendix V.

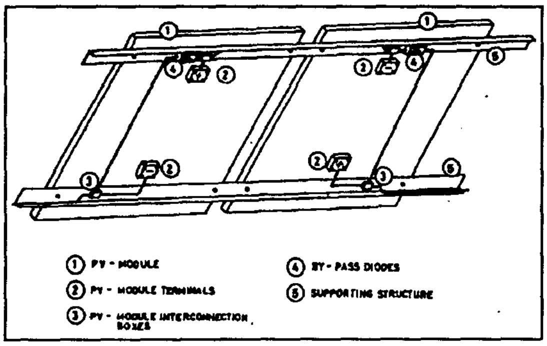


Figure 20.3 Detail of PV modules connection (backside).

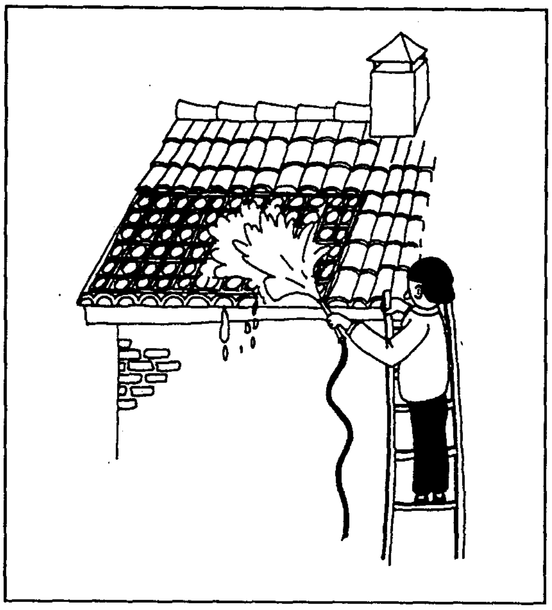


Figure 20.4 PV modules cleaning.
Attention: Short-circuit the output of the PV array through its corresponding switch before cleaning.

20.3 Battery maintenance

20.3.1 General

The most critical subsystem in a PV-system is the battery. Depending on its maintenance, the useful life of a stationary battery for PV applications can vary from a few years up to ten or even more years. Therefore it is essential that preventive care of the batteries is done by the user and once a year by a specialist.

The following maintenance procedures are valid for lead-acid batteries, the most common in photovoltaic systems. For nickel-cadmium batteries the specific gravity measurements described cannot be used.

20.3.2 Routine battery tests

A routine test procedure needs to be set up before connecting the battery. The user should check his battery bank and look for the following points:

- differences in colour;
- sediment in cell boxes;
- corrosion on cells and connectors;
- cell cracks.

Normally, when the elements are connected for the first time, these points are checked out by the installer and/or manufacturer. If any of these points is observed, the elements should not be connected. The user should recheck these points periodically and contact a specialist, if some of the mentioned signs are observed.

In case of corrosion of connectors it is recommended to clean them immediately. Corrosion of the terminals is indicated by a growing white powder (lead sulphate) on them. Each terminal must be cleaned very well with water and a little brush after the battery has been disconnected from the PV array and the loads. After reconnecting the terminals they are coated with grease or petroleum jelly. Finally the battery is reconnected through the corresponding switch to the PV array and the loads.

The state-of-charge of the battery can be checked on a routine basis by reading its voltage. For a reliable reading, the battery voltage should be measured at the same time of day, usually just after sun down when the array is not charging and when the load is constant from day to day.

This voltage should be recorded in a log book. Action must be taken, if the state-of-charge of the battery is continuously at a low level. Continued use of a partially charged battery will shorten the overall life of the battery.

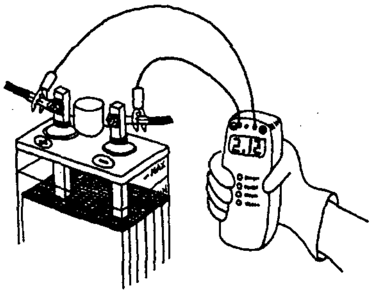
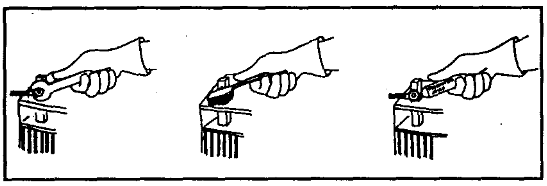


Figure 20.5 Measurement of cell voltages. Note: For lead-acid elements and a temperature of 25 °C, average voltages of 2.12, 2.07, 2.0 and 1.95 V/cell mean 100, 80, 60 and 40% of their rated capacities, respectively.

20.3.3 Monthly battery tests

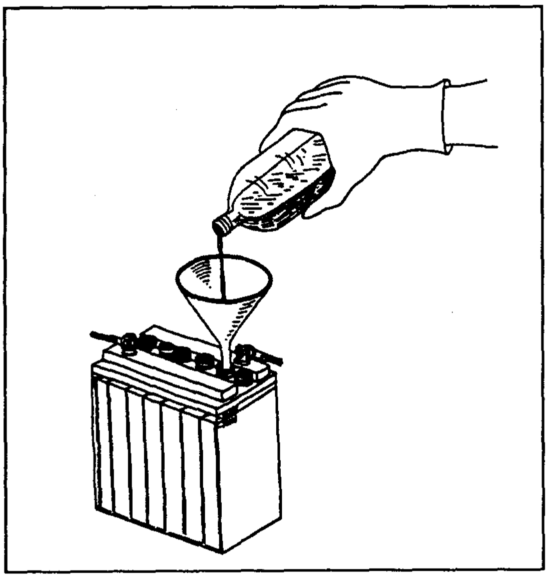
The user and/or a specialist must check the electrolyte level of the battery cells on a monthly basis and, if necessary, refill them using distilled water. Remember to avoid overfilling. Simultaneously it can be observed whether some cells have a lower level than other ones, which could mean an electrolyte leakage.

It is recommended to measure and record the cell voltages with a DC volt meter during the first year of service and to observe whether there are large voltage differences between the cells. This would indicate a defective and/or improperly connected cell.



1) Disconnect the terminals
2) Clean them with a brush
3) Reconnect and fasten the terminals
4) Coat them with grease or petroleum jelly

Figure 20.6 Battery terminals cleaning. Attention: Before cleaning, disconnect the battery from PV array and loads. The use of insulating gloves is always recommended.



1) Use always protective gloves and proper labour wear
2) Use always distilled water
3) Refill slowly.
4) Never overfill.

Figure 20.7 Battery refilling.

20.3.4 Quarterly battery tests

Quarterly tests consist of precise measurement and record of cell voltages, specific gravities and temperatures, which are then used to estimate the working conditions of the battery.

For specific gravity measurements, a hydrometer is used. The hydrometer is inserted into each cell of the battery and measures the specific gravity of the electrolyte within the cells. At 15°C, values of 1.28, 1.25, 1.22 and 1.19 g/cm^3 would roughly mean states-ofcharge of 100, 80, 60 and 40%, respectively. Note that temperature has an effect on the reading.

For batteries with liquid electrolytes it is also recommended to carry out an equalizing charging of the battery. With an equalizing charge each quarterly period, the stratification and sulphate problems will be corrected. The sulphate crystals are broken and the electrolyte circulates in the cells when the electrolyte bubbles during the last steps of charging. After each equalizing charge it is very important to check the electrolyte level and refill with distilled water if necessary.

A typical equalizing charge voltage is 2.4 or 2.5 V/cell at 25°C during a minimum of 3 h and a maximum of 10 h charging. To do so, it is convenient to use an auxiliary energy source such as a backup generator (diesel or gas). It can also be done by connecting the PV array directly to the battery and thus bypassing the charge regulator, which cuts off normally the charging process before bubbling. Obviously, this can be done with the PV array only if there is enough solar radiation. This procedure requires special care and watching during the process.

20.4 Backup generator

Typical backup generators may be fuelled by one of a variety of petroleum based fuels such as gasoline, propane, natural gas, and diesel. Diesel generators are the most common choice for applications where extended operating periods (greater than 4 hours per cycle) are required.

Some general maintenance procedures to be carried out after generator installation are listed below. **Note that these are general recommendations only. Consult the Operator's Manual or equipment supplier for a more complete listing of maintenance requirements.**

Maintenance procedures:

- Check engine oil level daily and/or before start-up.
- Change engine oil and oil filter after 25 hours of operation or at the end of the manufacturers recommended break-in period.
- Thereafter change engine oil and oil filter after every 50 to 150 hours of operation depending on engine type and operating environment (see Operator's Manual).
- Periodically check all fluid levels and add or replace per the manufacturers recommendations.

A properly tuned generator will be able to operate electrical loads to its peak output rating while maintaining voltage and frequency output characteristics to within 5% of specification. Units unable to meet or exceed these specifications are typically in need of a tune-up and/or overhaul of the engine or generator component. This work should be carried out by qualified technicians or manufacturers' representatives.

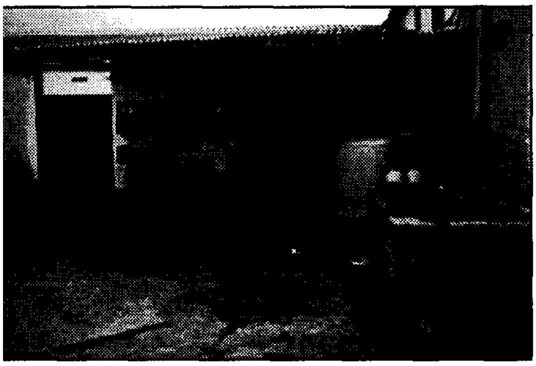


Figure 20.8 30 kVA diesel engine with automatic starting and stopping installed in a milking farm - hybrid PV/diesel powered.

20.5 Power conditioning system maintenance

Maintenance of power conditioning equipment (regulators, inverters and controllers) should not be done by the user. Generally, its solid-state design makes it relatively maintenance-free but also difficult for anyone other than a trained person to repair. A simple visual examination from time to time by the user should show whether the equipment is well performing. From a user point of view it is recommended that the power conditioning equipment of a PV system should show: the instantaneous DC and AC voltages and currents, the total and partial (another counter with reset) amount of Ah generated and consumed and some visual and/or acoustic alarm in case of bad system performance, i.e. battery discharged more than 50% (in case of lead-acid batteries), too high or low battery voltage, frequency out of the required limits, etc.. A check on proper operation of the control and alarm level must be done quarterly.

Figure 20.9 Partial view of a power conditioning system installed.

At present, most inverters include protection against overloads and they disconnect automatically. If the problem was just a temporary overload, a simple reset after disconnecting the offending load will be enough to solve it.

Above all, avoid any short-circuit of the AC output of the inverter during handling. When repairing or cleaning the inverter, disconnect the DC side after switching off the inverter. After a waiting period to allow for discharging of the capacitors (half a minute) disconnecting of the inverter may proceed.

20.6 Other subsystems

Apart from the PV array, the battery bank, the backup generator and the power conditioning equipment, there are other important items in a PV system, which need to be checked regularly, such as grounding, cabling, protection against atmospheric discharges etc.

For grounding a quarterly measurement of its resistance carried out by a specialist is recommended. Required values of grounding resistance have to be lower than 10 ohms. If the measurement obtained is higher than this value, it is recommended to irrigate the ground terminal. In case of very bad grounding values, it may be necessary to dissolve some salt in the irrigation water.

20.7 Safety

Almost all maintenance procedures described in this chapter can be carried out by the user. Although these procedures are easily done, it is very important to follow some safety measures to avoid accidents.

In order to avoid dangerous electrical shocks the user should cover the PV modules with an opaque blanket and disconnect the switch to the PV array from the battery before attempting to work on any circuit of the system. For larger arrays, the output of the array can be short-circuited.

When working with the battery, do not forget to wear safety boots and insulating gloves when you handle the battery bank, as well as to wear appropriate protective clothing to prevent electrical shocks and burning by acid spills. Beware of not shorting the battery terminals with tools and wrist watches. Short-circuits may not cause electric shock but they can cause arcing and burning. Do not smoke near the batteries because it can cause explosions due to the possible high concentration of hydrogen in the battery room. Battery room lighting should use anti-deflagrating lighting equipment.

Chapter 21

Commissioning of Photovoltaic Systems

21.1 Commissioning of PV systems in buildings

After the installation of a PV system has been completed, it is important to go through some kind of acceptance procedure to assure that the installation work has been properly done and that the system is working correctly.

A complete commissioning procedure would have to cover a long list of items including:

- engineering review of system drawings;
- visual inspection of installation;
- mounting procedure (aesthetics, safety etc.);
- initial electrical performance tests on array, batteries, inverter, gensets etc.;
- safety for the user (insulation, grounding, earth fault protection etc.);
- safety for the system (overvoltage protection, fuses etc.);
- control of monitoring system (accuracy of sensors etc.);
- energy meters;
- overall system performance.

Most of the listed items are general subjects that belong to most electrical installations. Therefore, not every item is covered very deeply in this chapter; the electrical performance of the PV system, however, is different from other systems and it is discussed in more detail.

21.2 System configurations

A grid-connected PV system consists of the PV array, a mounting structure, inverter, junction box (one or several boxes containing diodes, fuses, lightning protection etc.) and cables. The utility interface for connecting the inverter to the utility network is also an important part of a grid-connected PV system. Fuses, an AC switch and one or two energy meters are the main parts of the utility interface.

A stand-alone system may have an inverter also but differs in the sense that it also consists of batteries and a charge regulator. In some cases, DC/DC converters are used to power appliances at other voltages than the system voltage.

In a hybrid system, which is a special case of a stand-alone system, a genset and sometimes also a wind generator are parts of the system.

21.3 PV array

Already during the installation of a system it is recommended to check that all modules are connected to the junction box and that the open circuit voltage (V_{OC}) and the short circuit current (I_{SC}) of modules or strings are correct. It is always easier to find and repair a bad cable joint or take care of other failures before the whole system is completed. But even when the V_{OC} and the I_{SC} seem to be right one can find that the values around the operation point are out of the expected limits. A number of cells over even modules in a series string can be shunted. The best way to detect this is to measure the IV-characteristics of the array and subarrays or even of single modules. To do so, a portable IV-tracer is of great help. If such a device is not available, it can be quite easy to design a simple device that at least gives the possibility to measure voltage and current in a point close to the maximum power point.

21.4 Junction boxes and cables

In the junction box the modules are connected to form the DC voltage and current that is to be converted to AC power by the inverter or stored in batteries in the case of a stand-alone system. Depending on the system, one or several boxes can be used. Normally, there is one main box that contains several components like:

- connector terminals;
- blocking diodes;
- fuses;
- overvoltage protection.

A DC circuit breaker is normally placed after the junction box to make it possible to disconnect the PV array from the inverter or from the batteries in case of a stand-alone system. It is important to check that not an AC switch has been used instead of DC. Concerning the cables there are some items that have to be treated:

- type of cable used outdoor (exposure to sun, rain and snow);
- insulation (single, double or inside a tube);
- clamping techniques.

21.5 Grid-connected inverters

One common experience of PV users is that the inverter is the weakest part of the PV system, at least in the case of grid-connected systems. The operation manual is often very poor and does not explain everything. Most problems that occur depend on the inverter. Test procedures for inverters similar to those that exist for modules should be developed.

In order to fully check the inverter some way of measuring active power delivered to the grid is needed. There exist power transducers that can be installed, but one can make relatively accurate measurements by reading the kWh-meter during a stable period with high power and calculating the average AC power delivered to the grid. One can also measure the AC current and calculate a relative good value assuming that the power factor is not too low.

Except for the operation at normal conditions, the inverter behaviour should also be checked at some specific situations:

- The inverter has to restart automatically after a disconnection of the AC net or after switching off the DC power.
- Islanding must be avoided which means that the inverter must immediately shut down its operation if the grid fails.
- Distortion (harmonics) created by the inverter will be very important in a future with a great number of installed systems.

The inverters that are mostly used in stand-alone systems are relative simple ones. A test that can be done is just connecting an AC load with a known power consumption and check that it works without problems.

21.6 Utility interface

The utility interface is the part of a grid-connected system which is needed between the inverter and the grid in order to make the PV system become a part of the utility network. The regulations for grid interaction differ between various countries, but the main parts of this interface consist of an AC switch, fuses and one or two energy meters. The AC switch is the most important component and must be lockable and easily accessible to utility people.

21.7 Charge regulators

There exist a large number of different kinds of charge regulators to be used in stand-alone PV systems. Some are equipped with temperature compensation and with both boost and trickle charge capabilities. However, the basic purpose of the regulator is to prevent the batteries from overcharging or undercharging. The voltage at which charging has to stop (high-voltage charge cut-off) and the one at which the load must be disconnected (low-voltage disconnect) can be checked relatively easily, at least in installations with a low battery capacity. Large errors in these two voltages can shorten battery life considerably. By turning off the loads on a sunny day and measuring the battery voltage, it is possible to check at which point the charging is stopped. To check the low-voltage disconnect, the PV array is disconnected and a high load is applied to discharge the battery. The voltage is measured and the level at which the load is turned off is compared to the value that is given in the operation manual for the regulator.

21.8 Batteries

Batteries are the weak components in stand-alone systems. The life of batteries in most projects is much shorter than expected and the costs to exchange them are high. However, many problems can be avoided by making the installation in a proper way and by following some simple maintenance procedures.

- Avoid using different types of batteries and do not mix new batteries with batteries that already have been used.
- When connecting batteries in parallel, it is important to make the cabling symmetrically, i.e. to use the same total cable lenght for each string. Also the contact resistance has to be considered as the internal resistance is very low for batteries. This will prevent the different strings from being charged in an uneven way.
- Check the water level of each cell.

21.9 Gensets and wind generators

In hybrid systems both gensets and wind generators may be used. These system components are not treated here but should be checked by following the operation manual that is delivered with the equipment.

21.10 Check list for a grid-connected PV system

The design book is dealing mainly with grid-connected systems. However, this check list is to a large extent valid for any type of PV system.

Visual inspection

Compare with design specifications and drawings and check that all parts of the system have been delivered:

- modules (number and type);
- support structure (material of structure, screws etc.);
- inverter (type);
- cabling (dimensions, insulation, clamping etc.);
- connection box(es) (diodes, fuses, overvoltage protection);
- switchgears;
- energy meters;
- monitoring system (data logger, sensors, modem etc.).

In connection to this part there are some other general items that can be mentioned:

- How is the location - shadows from trees, chimneys or other buildings?
- Cables and all other parts of the system should be marked with description signs.
- An operation manual describing all parts of the system and especially the operation of the inverter is a must.
- There must be space for maintenance and of course for normal operation of the system.

Personal safety (owner, operator, utility people and visitors)

The most important part for all kinds of installations is related to the safety of people who will come in contact with the system:

- Safety for the operators - no risk of electrical shocks.
- Safety for other people entering the room where inverter etc. are installed.
- Safety for people who have to enter the roof or facade where the modules are installed.
- Safety for people passing by the building - no risk of falling modules etc.

"Safety for the installation"

Fuses protect electrical installations from too high currents. This is only one part of the system that belongs to the safety of the system.

- fuses on both DC and AC side;
- overvoltage protection;
- grounding of module frames and support structure;
- suppport structure must allow for thermal expansion of modules without breaking the glass;
- in case the modules are integrated in the roof or facade it might be important to know that the surface is watertight and that it can withstand wind and snow load.

Check of operation - electrical performance

- V_{OC} and I_{SC} for each string (or if possible a trace of the IV-curve) calculated to STC and compared to data sheet;
- Power during operation calculated to STC and compared to data sheet;
- Efficiency of inverter, radio interference, harmonics;
- Automatic restart after grid failure.

21.11 An example of a simple function control

The following tests serve as simple function control and should be performed at stable conditions with high irradiance (above 800 W/m2).

Tools needed are:

- a small digital clamp meter for measuring DC current without having to remove any cables;
- a volt meter (digital multimeter);
- some kind of instruments for measuring the irradiance in plane of the array (calibrated Si cell);

Function test

0. Measure the irradiance and keep track of this value when doing the following measurements.

1.Measure V_{OC} and I_{SC} for each string to check that all modules are connected and working. The measured short circuit current value can easily be compared to the value in the data sheet by multiplying the measured value by $1000/G1_{measured'}$

2. Measure V and I during operation and check if the operation point corresponds to the expected maximum power point (MPP).

In the same way as for the short circuit current, the measured power can be compared to the expected power value by using the measured irradiance. A more accurate value can be obtained by also compensating the voltage decrease due to increased cell temperature.

3. Read the energy meter (AC) during one hour of stable operation and calculate the inverter efficiency.

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Appendices

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I Solar Insolation Data

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II System Sizing Worksheets

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III Wire Sizing Tables

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IV Tender Documents

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V Maintenance Logsheets

Alvaro Gonzales-Menendez

VI Trade-Off Considerations

Oyvin Skarstein
Kimmo Peippo

VII Glossary

(several)

Appendix I

Solar Insolation Data

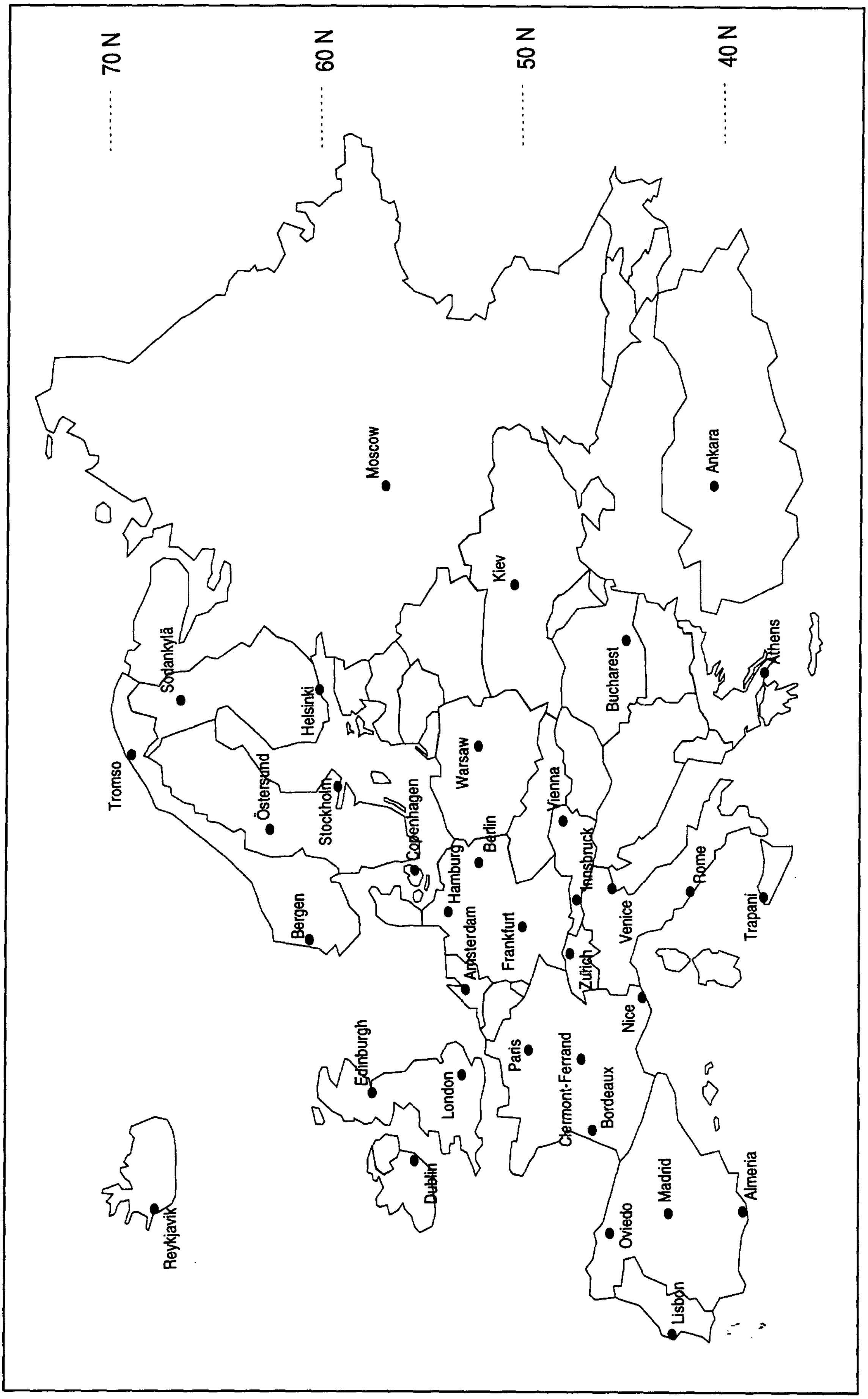
The following tables contain long-term monthly and annual averages of daily solar insolation (in kWh/m^2, day) on horizontal surfaces in selected locations, as well as descriptive temperature data, compiled from various sources. As an indication of the effect of the array inclination and orientation and possible shading, monthly and annual conversion coefficients are computed from horizontal to inclined surfaces for four latitudes: Sodankylä, Finland (67.5°N), Copenhagen, Denmark (55.7°N), Madison, USA (43.1°N) and Phoenix, USA (33.4°N), to be used for estimating the available insolation in accordance with the design procedure (i.e. a figure 0.5 appearing in the table indicates that the corresponding monthly or annual insolation is 50% of value for horizontal level). The coefficients have been calculated using a numerical simulation program PHOTO and the hourly meteorological Test Reference Years of the locations (except for Phoenix, where synthetic data were used). The numerical conversion tables are visualized on annual level by two figures showing the effect of array inclination (13), azimuth, deviation from south (y) and shading of the horizon (v). In the figure depicting the shading effect, the array is due south.

It should be noted, that the conversion coefficients depend, in addition to latitude, on the local climate and are subject to some variations in the calculation models used. Additionally, the nature of the ground cover has an impact on the radiation on inclined surfaces. In the calculations a constant ground reflectance (albedo) of 0.20 was assumed, typical for most natural ground surfaces. Snow cover or other strongly reflective materials may significantly increase the insolation on steeply inclined and vertical surfaces. However, the effect is usually insignificant on annual level. The horizontal shading is given in degrees from the horizontal and assumed uniform over all azimuth angles. In addition to unobstructed horizon (0° shading), two shading angles are given: 20° representing moderate shading and 40° for severe shading. Objects in the vicinity of the array that cast a sharp shadow on part of it may have a more dramatic impact on the array output. This effect is discussed elsewhere in this book.

The insolation given refers to long term averages. However, depending on climate the insolation varies from year to year. The relative variation can be especially pronounced in high latitude locations during the low insolation months. Also, sharp geographical changes may result in markedly different insolation levels for close by locations e.g. in coastal or mountaineous areas. Due to the number of factors affecting the available insolation on the PV-array, primary input for calculations should be local weather data, and the following information is intended as a rough guidelines only. In addition to national meteorological institutes, compiled international insolation data is found in the references.

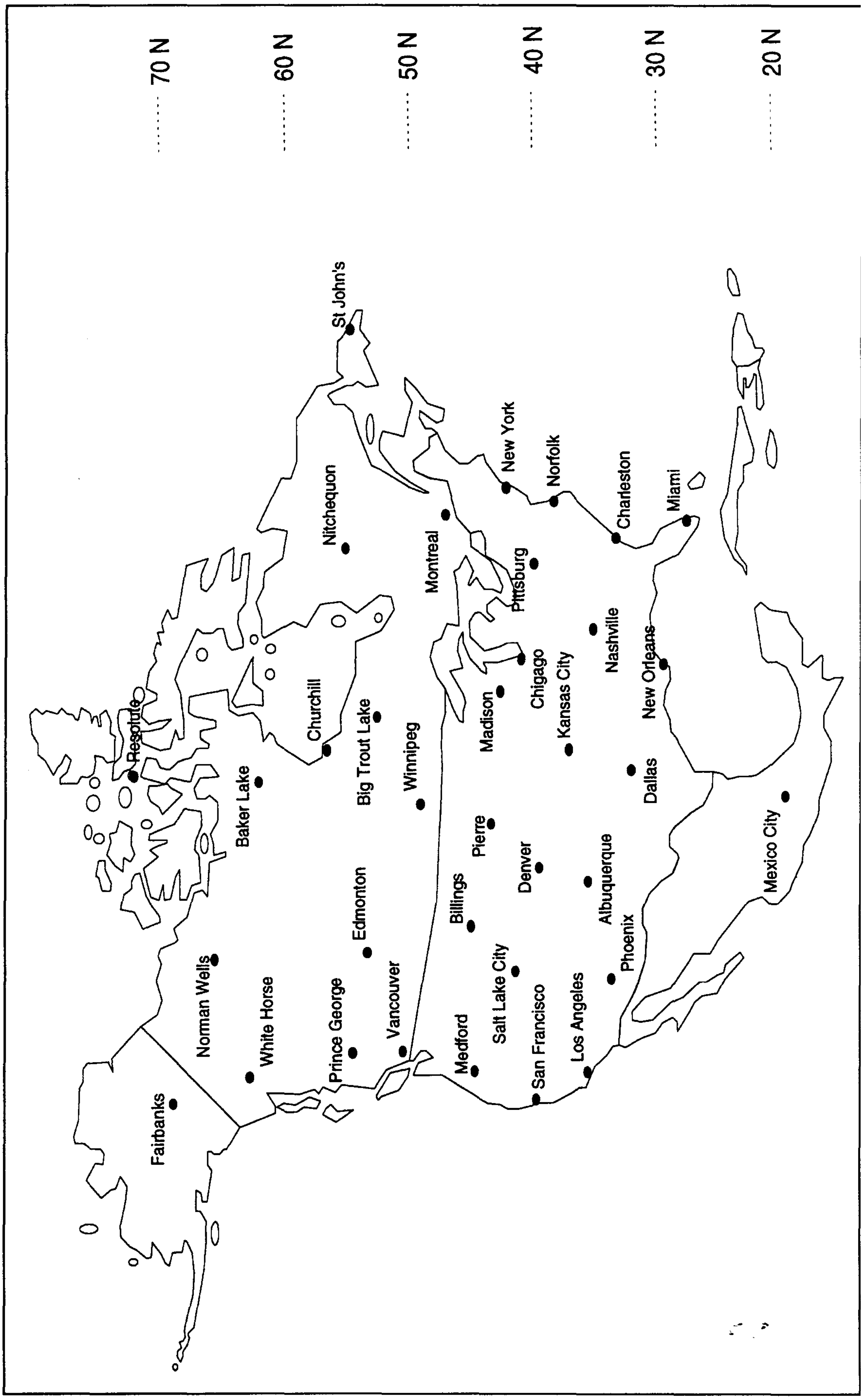
Table I.1: monthly and annual averages of daily insolation (kWh/m², day) for selected locations. The three temperatures indicated are minimum and maximum of monthly averages as well as the annual average. Arranged by continent and decreasing latitude.

Location	latitude(°N)	Insolation (kWh/m²,day)													Temperature (°C)		
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Min	Ave	Max
Europe																	
Tromsø, Norway	69.7	0.0	0.3	1.4	3.1	4.2	4.6	4.5	2.9	1.5	0.5	0.0	0.0	1.9	-4	3	16
Sodankylä, Finland	67.5	0.1	0.5	1.8	3.6	4.9	5.3	5.0	3.3	1.7	0.6	0.1	0.0	2.2	-18	-1	15
Reykjavik, Iceland	64.1	0.1	0.6	1.6	3.1	4.6	4.3	4.7	3.5	1.9	0.8	0.2	0.1	2.1	0	5	11
Östersund, Sweden	63.2	0.2	0.9	2.4	3.9	5.1	5.6	5.2	4.1	2.2	0.9	0.3	0.1	2.6	-8	3	14
Bergen, Norway	60.4	0.2	0.6	1.7	3.4	3.9	5.0	4.8	3.2	1.7	0.8	0.3	0.1	2.2	1	8	15
Helsinki, Finland	60.3	0.3	0.8	2.2	3.4	5.1	6.0	5.2	4.1	2.3	1.0	0.3	0.2	2.6	-10	4	16
Stockholm, Sweden	59.3	0.3	1.0	2.2	3.6	5.2	5.9	5.2	4.1	2.6	1.2	0.5	0.2	2.7	-3	7	18
Edinburgh, The United Kingdom	56.0	0.4	1.1	2.1	3.3	4.0	4.6	4.2	3.5	2.5	1.4	0.7	0.3	2.4	3	9	15
Moscow, Russia	55.8	0.5	0.9	2.6	3.1	4.7	5.4	5.5	4.3	2.3	1.1	0.6	0.4	2.6	-10	4	18
Copenhagen, Denmark	55.7	0.4	1.1	2.3	3.9	5.0	6.1	5.3	4.4	2.8	1.5	0.6	0.3	2.8	-1	8	17
Hamburg, Germany	53.6	0.5	1.1	2.2	3.6	4.7	5.4	4.8	4.3	2.8	1.5	0.7	0.4	2.7	1	9	17
Dublin, Ireland	53.4	0.7	1.5	2.7	4.2	5.2	6.1	5.3	4.4	3.3	1.9	1.0	0.6	3.1	4	10	15
Berlin, Germany	52.5	0.6	1.1	2.4	3.5	4.8	5.4	5.3	4.6	3.0	1.6	0.8	0.5	2.8	-1	9	18
Warsaw, Poland	52.3	0.5	1.0	2.3	3.3	4.6	5.4	5.0	4.6	2.9	1.4	0.6	0.4	2.7	-4	8	19
Amsterdam, The Netherlands	52.1	0.6	1.3	2.2	3.6	4.7	5.2	4.6	4.3	2.9	1.7	0.8	0.5	2.7	2	10	17
London, The United Kingdom	51.5	0.5	1.1	2.1	3.0	4.1	5.0	4.4	3.6	2.7	1.6	0.8	0.5	2.5	4	11	18
Kiev, Ukraine	50.4	0.8	1.5	2.6	3.3	5.6	5.6	5.7	4.8	3.3	2.1	0.7	0.6	3.1	-6	8	20
Frankfurt, Germany	50.0	0.7	1.5	2.6	4.0	5.0	5.3	5.3	4.5	3.4	1.8	0.9	0.6	3.0	0	10	19
Paris, France	48.8	0.8	1.6	2.7	4.0	4.8	5.6	5.6	4.6	3.5	2.1	1.0	0.7	3.1	3	11	19
Vienna, Austria	48.2	0.8	1.4	2.6	4.0	5.1	5.3	5.4	4.5	3.3	2.0	1.0	0.7	3.0	-1	10	20
Zürich, Switzerland	47.4	0.8	1.6	2.7	3.9	5.0	5.5	5.8	4.6	3.6	2.0	1.0	0.7	3.1	-1	9	18
Innsbruck, Austria	47.3	1.3	2.1	3.4	4.5	5.3	5.4	5.4	4.7	4.0	2.6	1.4	1.1	3.4	-2	9	18
Clermont-Ferrand, France	45.7	1.2	1.9	2.9	4.1	4.9	5.6	6.0	4.8	3.9	2.5	1.4	0.9	3.3	3	11	20
Venice, Italy	45.5	1.1	1.7	3.3	4.4	5.1	5.9	6.2	5.5	4.1	2.6	1.4	1.1	3.5	3	14	23
Bordeaux, France	44.8	1.3	2.1	3.5	4.7	5.5	6.1	6.4	5.1	4.1	2.9	1.5	1.0	3.7	5	12	20
Bucharest, Romania	44.5	1.3	2.1	3.5	4.7	6.1	6.6	6.4	5.7	4.3	2.9	1.5	1.1	3.9	-2	11	22
Nice, France	43.6	1.7	2.5	3.9	5.3	6.1	6.8	7.1	5.9	4.6	3.3	2.0	1.6	4.2	10	16	24
Oviedo, Spain	43.1	1.7	2.3	3.1	4.0	4.9	4.8	4.8	4.3	3.8	2.8	2.0	1.4	3.3	8	13	19
Rome, Italy	41.8	1.7	2.5	3.8	5.0	6.0	6.6	6.7	6.2	4.7	3.3	2.0	1.5	4.2	7	16	25
Madrid, Spain	40.4	1.7	2.6	4.2	5.4	6.2	6.7	7.2	6.5	4.8	3.2	2.0	1.8	4.4	5	14	24
Ankara, Turkey	40.0	1.8	2.5	3.9	5.3	6.5	7.5	7.8	7.0	5.5	3.8	2.4	1.5	4.6	0	12	22
Lisbon, Portugal	38.7	2.0	3.0	4.3	5.5	6.7	7.2	7.5	7.0	5.2	3.7	2.5	2.2	4.7	11	17	23
Athens, Greece	38.0	1.8	2.6	3.8	5.1	6.4	6.8	6.9	6.2	4.9	3.4	2.3	1.7	4.3	9	18	28
Trapani, Italy	37.9	2.3	3.0	4.3	5.6	6.7	7.0	7.4	7.0	5.4	3.9	2.7	2.1	4.8	12	18	25
Almeria, Spain	36.8	2.7	3.5	4.3	5.5	6.7	7.2	7.4	6.8	5.3	4.0	2.9	2.5	5.0	12	18	25


70 N
60 N
50 N
40 N
Reykjavik
Tromso
Sodankylä
Bergen
Östersund
Helsinki
Stockholm
Edinburgh
Dublin
Moscow
Copenhagen
Hamburg
Amsterdam
London
Warsaw
Berlin
Frankfurt
Paris
Kiev
Clermont-Ferrand
Vienna
Innsbruck
Zürich
Bordeaux
Venice
Nice
Oviedo
Bucharest
Madrid
Lisbon
Rome
Ankara
Athens
Trapani
Almeria

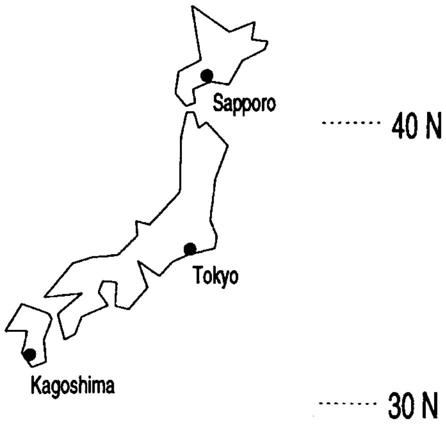
North America

Resolute (Northwest Terr.), Canada	74.7	0.0	0.2	1.5	4.1	6.4	6.9	5.2	3.1	1.4	0.4	0.0	0.0	2.4	-33	-17	4
Norman Wells (Northwest Terr.), Canada	65.3	0.1	0.8	2.3	4.3	5.6	6.4	5.6	4.0	2.3	0.8	0.2	0.0	2.7	-29	-6	16
Fairbanks (Alaska), USA	64.8	0.1	0.7	2.1	3.8	5.1	5.5	4.9	3.5	2.2	0.9	0.2	0.0	2.4	-24	-4	16
Baker Lake (Northwest Terr.), Canada	64.3	0.2	0.9	2.9	4.9	6.2	6.0	5.4	3.8	2.1	1.0	0.3	0.1	2.8	-33	-12	11
White Horse (Yukon), Canada	60.7	0.4	1.1	2.6	4.4	5.4	5.8	5.2	4.2	2.5	1.2	0.4	0.2	2.8	-21	-1	12
Churchill (Manitoba), Canada	58.8	0.8	1.6	3.4	5.2	5.6	6.1	5.7	4.2	2.4	1.2	0.7	0.4	3.1	-28	-7	12
Prince George (Brit. Columbia), Canada	53.9	0.8	1.5	2.8	4.4	5.0	6.0	5.8	4.7	3.1	1.7	0.9	0.5	3.1	-12	3	15
Big Trout Lake (Ontario), Canada	53.8	1.1	2.1	3.6	5.3	5.6	5.4	5.7	4.3	2.7	1.6	0.9	0.8	3.3	-25	-3	16
Edmonton (Alberta), Canada	53.6	1.0	2.0	3.5	4.9	5.8	6.3	6.4	5.0	3.6	2.2	1.2	0.8	3.6	-15	3	17
Nitchequon (Quebec), Canada	53.2	1.0	2.2	3.6	5.2	5.5	5.2	4.7	4.0	2.6	1.5	0.9	0.8	3.1	-23	-4	14
Winnipeg (Manitoba), Canada	49.9	1.5	2.5	3.9	4.9	5.8	6.3	6.4	5.3	3.7	2.3	1.3	1.1	3.7	-19	2	20
Vancouver (Brit. Columbia), Canada	49.3	0.8	1.5	2.8	4.2	5.6	6.1	6.4	5.2	3.7	2.1	1.0	0.6	3.3	3	10	17
St John's (Newfoundland), Canada	47.5	1.2	2.0	2.9	3.8	4.6	5.4	5.5	4.4	3.3	1.9	1.1	0.8	3.1	-4	5	16
Billings (Montana), USA	45.8	1.5	2.4	3.8	4.8	6.0	6.9	7.5	6.4	4.6	3.1	1.8	1.3	4.2	-6	8	22
Montreal (Quebec), Canada	45.5	1.5	2.4	3.5	4.4	5.3	5.6	5.8	4.8	3.7	2.2	1.3	1.1	3.5	-10	6	21
Pierre (South Dakota), USA	44.4	1.7	2.5	3.8	5.1	6.2	6.9	7.2	6.3	4.7	3.3	2.0	1.4	4.3	-9	8	24
Medford (Oregon), USA	42.4	1.3	2.3	3.6	5.2	6.4	7.2	7.8	6.7	5.0	3.1	1.6	1.1	4.3	3	12	22
Chigago (Illinois), USA	41.8	1.6	2.4	3.5	4.6	5.6	6.3	6.1	5.4	4.3	3.1	1.9	1.3	3.8	-4	10	24
New York (New York), USA	40.8	1.6	2.3	3.3	4.3	5.2	5.4	5.3	4.7	3.8	2.8	1.7	1.3	3.5	0	13	25
Salt Lake City (Utah), USA	40.8	2.0	3.1	4.6	6.0	7.4	8.0	8.2	7.1	5.8	4.1	2.5	1.8	5.0	-2	10	25
Pittsburg (Pennsylvania), USA	40.5	1.3	2.0	3.0	4.2	5.0	5.6	5.3	4.8	3.8	2.8	1.6	1.1	3.4	-2	10	22
Denver (Colorado), USA	39.8	2.6	3.6	4.8	5.9	6.7	7.4	7.2	6.4	5.4	4.1	2.8	2.3	4.9	-1	10	23
Kansas City (Missouri), USA	39.3	2.0	2.8	3.8	5.0	5.9	6.6	6.6	5.9	4.6	3.4	2.3	1.8	4.2	-3	10	25
San Francisco (California), USA	37.6	2.2	3.2	4.6	6.1	7.0	7.5	7.5	6.7	5.5	3.9	2.6	2.0	4.9	9	14	18
Norfolk (Virginia), USA	36.9	2.1	2.9	4.0	5.3	6.0	6.3	5.8	5.3	4.4	3.4	2.6	2.0	4.2	5	15	25
Nashville (Tennesee), USA	36.1	1.8	2.6	3.6	4.9	5.8	6.2	6.0	5.5	4.4	3.5	2.2	1.6	4.0	3	15	26
Albuquerque (New Mexico), USA	35.1	3.2	4.2	5.6	7.0	8.0	8.4	7.8	7.2	6.2	4.9	3.6	2.9	5.8	2	13	26
Los Angeles (California), USA	33.9	2.9	3.8	5.1	6.2	6.5	6.7	7.3	6.6	5.3	4.2	3.3	2.7	5.0	13	17	21
Phoenix (Arizona), USA	33.4	3.2	4.3	5.7	7.4	8.4	8.6	7.8	7.2	6.4	5.0	3.6	2.9	5.9	11	19	31
Charleston (South Carolina), USA	32.9	2.3	3.1	4.2	5.5	5.9	5.8	5.7	5.0	4.4	3.8	2.9	2.3	4.2	9	18	27
Dallas (Texas), USA	32.9	2.6	3.4	4.5	5.1	6.0	6.7	6.7	6.2	5.0	4.0	3.0	2.5	4.6	7	19	30
New Orleans (Louisiana), USA	30.0	2.6	3.5	4.5	5.6	6.2	6.3	5.7	5.4	4.4	4.2	3.1	2.5	4.5	12	20	28
Miami (Florida), USA	25.8	3.3	4.1	5.1	5.9	5.8	5.4	5.6	5.1	4.6	4.1	3.5	3.2	4.6	20	24	28
Mexico City, Mexico	19.4	4.6	5.1	5.9	6.1	5.6	5.5	5.1	4.9	4.4	4.6	4.4	4.3	5.0	12	16	19

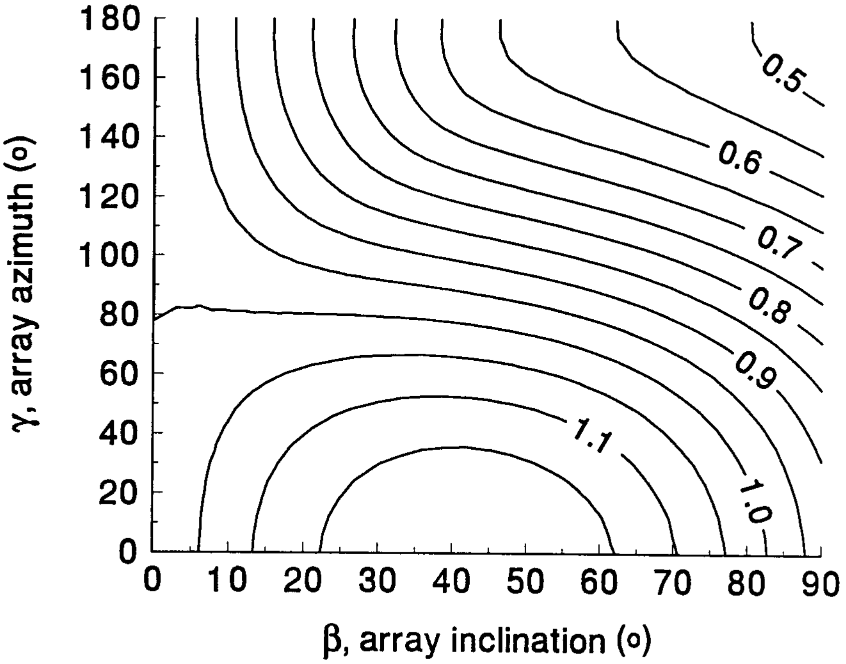

70 N
60 N
50 N
40 N
30 N
20 N
Fairbanks
Norman Wells
White Horse
Resolute
Baker Lake
Prince George
Edmonton
Vancouver
Churchill
Big Trout Lake
Winnipeg
Nitchequon
St John's
Montreal
Medford
Billings
Pierre
Madison
Salt Lake City
San Francisco
Denver
Chigago
Pittsburg
New York
Norfolk
Kansas City
Los Angeles
Albuquerque
Phoenix
Nashville
Charleston
Dallas
New Orleans
Miami
Mexico City

Pacific

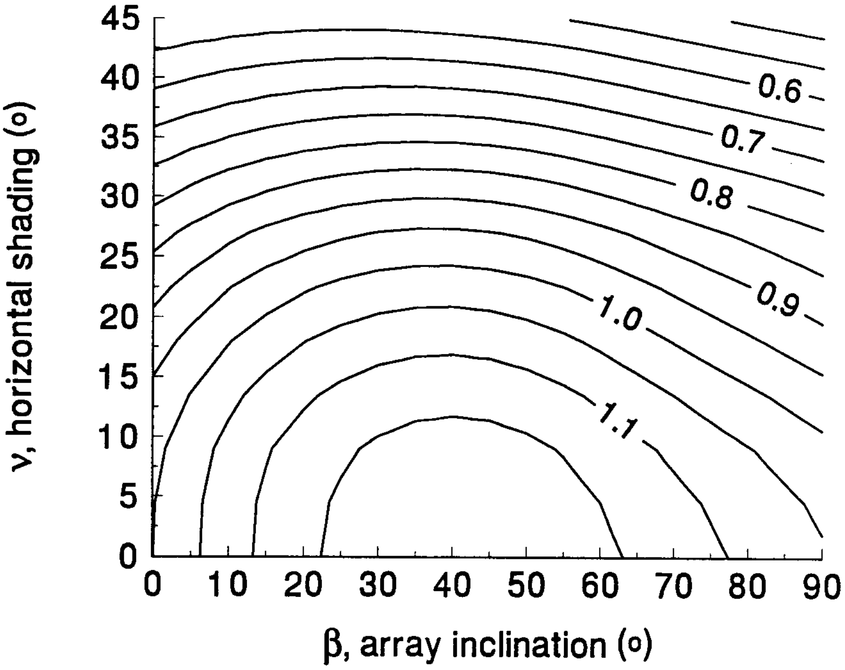
Sapporo, Japan	43.0	1.6	2.3	3.3	4.2	4.7	4.8	4.5	4.1	3.5	2.6	1.7	1.3	3.2	-5	8	22
Tokyo, Japan	35.7	2.2	2.6	3.1	3.6	3.9	3.5	3.8	3.8	2.9	2.3	2.1	1.9	3.0	4	15	26
Kagoshima, Japan	31.6	2.4	2.8	3.6	3.9	4.2	4.1	4.7	5.0	3.9	3.4	2.6	2.3	3.6	7	17	27
Honolulu (Hawaii), USA	21.3	3.3	4.4	5.1	5.7	6.1	6.3	6.3	6.2	5.7	4.9	4.0	3.6	5.2	22	25	27
Darwin, Australia	-12.4	5.1	5.3	5.6	5.1	5.2	5.1	5.3	6.1	6.4	6.5	6.2	5.6	5.6	25	27	29
Alice Springs, Australia	-23.6	7.5	7.2	6.5	5.4	5.4	3.9	4.2	5.3	6.4	6.9	7.2	7.4	6.0	12	21	28
Perth, Australia	-31.9	7.0	6.7	5.4	3.9	2.9	2.5	2.8	3.7	5.0	6.0	6.5	7.2	5.0	13	16	25
Sydney, Australia	-33.8	6.2	5.3	5.1	3.7	3.0	2.5	2.9	3.7	4.6	6.0	6.8	6.4	4.7	12	17	22
Wellington, New Zealand	-41.3	6.2	5.4	4.0	2.8	1.7	1.4	1.5	2.1	3.4	4.8	5.9	6.2	3.8	8	13	17



Sodankylä, Finland 67.5° N

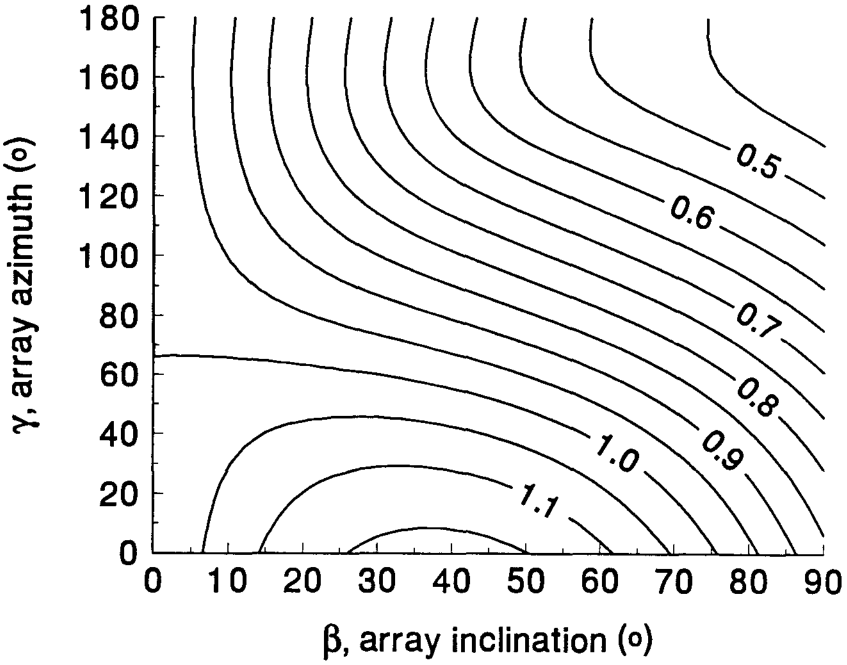


Sodankylä, Finland 67.5 °N

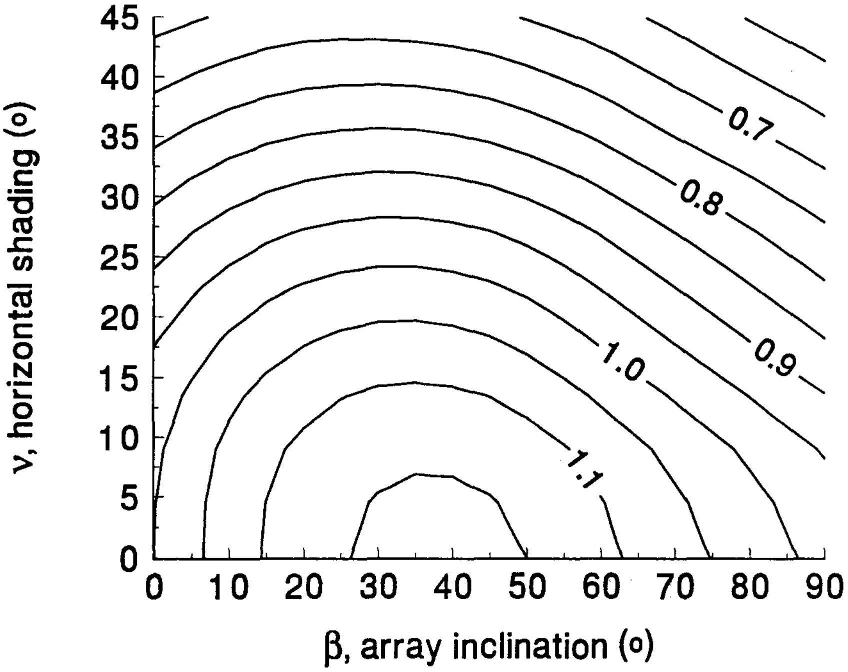


Sodankylä, Finland 67.5°N

β	γ	ν	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
tracking		0	4.0	2.5	2.0	1.5	1.6	1.5	1.7	1.7	2.0	2.2	1.9	0.9	1.7
tracking		20	0.7	0.7	1.0	1.3	1.3	1.2	1.4	1.4	1.2	0.7	0.7	0.9	1.3
tracking		40	0.7	0.7	0.6	0.7	0.7	0.9	0.8	0.6	0.6	0.7	0.7	0.9	0.7
0	0	0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0	0	20	0.9	0.7	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.7	0.9	1.0	0.9
0	0	40	0.9	0.7	0.6	0.7	0.6	0.7	0.6	0.5	0.5	0.7	0.9	1.0	0.6
15	0	0	1.8	1.4	1.3	1.1	1.1	1.0	1.1	1.1	1.2	1.3	1.3	1.0	1.1
15	0	20	0.9	0.7	0.9	1.0	1.0	1.0	1.0	1.1	1.0	0.7	0.9	1.0	1.0
15	0	40	0.9	0.7	0.6	0.7	0.7	0.8	0.7	0.5	0.6	0.7	0.9	1.0	0.7
15	45	0	1.6	1.3	1.2	1.1	1.0	1.0	1.0	1.1	1.1	1.3	1.2	1.0	1.1
15	45	20	0.9	0.7	0.8	1.0	1.0	1.0	1.0	1.0	0.9	0.7	0.9	1.0	1.0
15	45	40	0.9	0.7	0.6	0.7	0.7	0.8	0.7	0.5	0.6	0.7	0.9	1.0	0.7
15	90	0	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
15	90	20	0.9	0.7	0.7	0.9	0.9	0.9	0.9	0.9	0.8	0.7	0.9	1.0	0.9
15	90	40	0.9	0.7	0.6	0.7	0.6	0.7	0.6	0.5	0.5	0.7	0.9	1.0	0.6
15	135	0	0.9	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.9	1.0	0.9
15	135	20	0.9	0.7	0.7	0.8	0.8	0.9	0.8	0.8	0.7	0.7	0.9	1.0	0.8
15	135	40	0.9	0.7	0.6	0.6	0.6	0.7	0.6	0.5	0.5	0.7	0.9	1.0	0.6
15	180	0	0.9	0.7	0.7	0.9	0.9	0.9	0.9	0.8	0.7	0.7	0.9	1.0	0.9
15	180	20	0.9	0.7	0.6	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.9	1.0	0.8
15	180	40	0.9	0.7	0.6	0.6	0.6	0.7	0.6	0.5	0.5	0.7	0.9	1.0	0.6
30	0	0	2.5	1.8	1.5	1.2	1.1	1.0	1.1	1.2	1.4	1.6	1.5	0.9	1.2
30	0	20	0.9	0.7	0.9	1.1	1.1	1.0	1.1	1.2	1.1	0.7	0.9	0.9	1.1
30	0	40	0.9	0.7	0.6	0.7	0.7	0.8	0.7	0.5	0.6	0.7	0.9	0.9	0.7
30	45	0	2.1	1.6	1.3	1.1	1.1	1.0	1.0	1.1	1.3	1.5	1.4	0.9	1.1
30	45	20	0.8	0.7	0.9	1.1	1.0	1.0	1.0	1.0	1.0	0.7	0.9	0.9	1.0
30	45	40	0.8	0.7	0.6	0.7	0.7	0.8	0.7	0.5	0.6	0.7	0.9	0.9	0.7
30	90	0	1.2	1.0	1.0	1.0	1.0	0.9	0.9	0.9	1.0	1.1	1.0	0.9	1.0
30	90	20	0.8	0.7	0.7	0.9	0.9	0.9	0.9	0.8	0.7	0.7	0.9	0.9	0.8
30	90	40	0.8	0.7	0.6	0.6	0.6	0.7	0.6	0.5	0.5	0.7	0.9	0.9	0.6
30	135	0	0.8	0.7	0.7	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.9	0.9	0.8
30	135	20	0.8	0.7	0.6	0.7	0.7	0.7	0.7	0.6	0.6	0.7	0.9	0.9	0.7
30	135	40	0.8	0.7	0.6	0.6	0.5	0.6	0.5	0.5	0.5	0.7	0.9	0.9	0.6
30	180	0	0.8	0.7	0.6	0.7	0.8	0.8	0.8	0.6	0.5	0.7	0.9	0.9	0.7
30	180	20	0.8	0.7	0.6	0.6	0.7	0.7	0.6	0.6	0.5	0.7	0.9	0.9	0.6
30	180	40	0.8	0.7	0.6	0.6	0.5	0.6	0.5	0.5	0.5	0.7	0.9	0.9	0.5
45	0	0	3.1	2.1	1.7	1.2	1.1	1.0	1.1	1.2	1.5	1.9	1.7	0.9	1.2
45	0	20	0.8	0.7	1.0	1.1	1.1	1.0	1.1	1.2	1.1	0.7	0.9	0.9	1.1
45	0	40	0.8	0.7	0.6	0.7	0.7	0.8	0.7	0.5	0.6	0.7	0.9	0.9	0.7
45	45	0	2.5	1.8	1.4	1.1	1.1	1.0	1.0	1.1	1.3	1.7	1.5	0.9	1.1
45	45	20	0.8	0.7	0.9	1.0	1.0	0.9	1.0	1.0	1.0	0.7	0.9	0.9	1.0
45	45	40	0.8	0.7	0.6	0.6	0.7	0.8	0.7	0.5	0.6	0.7	0.9	0.9	0.7
45	90	0	1.2	1.0	1.0	0.9	1.0	0.9	0.9	0.9	1.0	1.1	1.0	0.9	0.9
45	90	20	0.8	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.8	0.9	0.8
45	90	40	0.8	0.7	0.6	0.6	0.6	0.7	0.6	0.5	0.5	0.7	0.8	0.9	0.6
45	135	0	0.8	0.7	0.6	0.7	0.8	0.7	0.7	0.7	0.6	0.7	0.8	0.9	0.7
45	135	20	0.8	0.6	0.5	0.7	0.6	0.6	0.6	0.6	0.5	0.6	0.8	0.9	0.6
45	135	40	0.8	0.6	0.5	0.6	0.5	0.5	0.4	0.4	0.5	0.6	0.8	0.9	0.5
45	180	0	0.8	0.6	0.5	0.6	0.6	0.7	0.6	0.5	0.5	0.6	0.8	0.9	0.6
45	180	20	0.8	0.6	0.5	0.6	0.5	0.6	0.5	0.4	0.5	0.6	0.8	0.9	0.5
45	180	40	0.8	0.6	0.5	0.6	0.4	0.5	0.4	0.4	0.5	0.6	0.8	0.9	0.5
60	0	0	3.6	2.3	1.7	1.2	1.0	0.9	1.0	1.2	1.5	2.0	1.9	0.8	1.2
60	0	20	0.8	0.7	1.0	1.1	1.0	0.9	1.0	1.1	1.1	0.7	0.8	0.8	1.0
60	0	40	0.8	0.7	0.6	0.6	0.6	0.8	0.7	0.5	0.6	0.7	0.8	0.8	0.6
60	45	0	2.7	1.9	1.4	1.1	1.0	0.9	1.0	1.1	1.3	1.7	1.6	0.8	1.1
60	45	20	0.8	0.7	0.9	1.0	0.9	0.9	0.9	1.0	0.9	0.7	0.8	0.8	0.9
60	45	40	0.8	0.7	0.6	0.6	0.6	0.7	0.6	0.5	0.5	0.7	0.8	0.8	0.6
60	90	0	1.2	1.0	0.9	0.9	0.9	0.8	0.9	0.9	0.9	1.0	0.9	0.8	0.9
60	90	20	0.7	0.6	0.6	0.8	0.8	0.7	0.8	0.7	0.6	0.6	0.8	0.8	0.7
60	90	40	0.7	0.6	0.5	0.6	0.5	0.6	0.5	0.5	0.5	0.6	0.8	0.8	0.5
60	135	0	0.7	0.6	0.6	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.7	0.8	0.7
60	135	20	0.7	0.6	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.7	0.8	0.6
60	135	40	0.7	0.6	0.5	0.5	0.4	0.5	0.4	0.4	0.5	0.6	0.7	0.8	0.5
60	180	0	0.7	0.6	0.5	0.6	0.6	0.6	0.6	0.5	0.5	0.6	0.7	0.8	0.6
60	180	20	0.7	0.6	0.5	0.5	0.4	0.5	0.4	0.4	0.5	0.6	0.7	0.8	0.5
60	180	40	0.7	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.5	0.6	0.7	0.8	0.4
75	0	0	3.8	2.4	1.7	1.1	0.9	0.8	0.9	1.1	1.5	2.0	1.9	0.7	1.1
75	0	20	0.7	0.7	0.9	1.0	0.9	0.8	0.9	1.1	1.1	0.7	0.8	0.7	0.9
75	0	40	0.7	0.7	0.6	0.6	0.6	0.7	0.6	0.5	0.5	0.7	0.8	0.7	0.6
75	45	0	2.9	1.8	1.4	1.0	0.9	0.8	0.9	1.0	1.3	1.7	1.6	0.7	1.0
75	45	20	0.7	0.6	0.8	0.9	0.9	0.8	0.8	0.9	0.9	0.6	0.7	0.7	0.8
75	45	40	0.7	0.6	0.5	0.6	0.6	0.7	0.6	0.4	0.5	0.6	0.7	0.7	0.6
75	90	0	1.2	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.9	1.0	0.9	0.7	0.8
75	90	20	0.7	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.7	0.7	0.7
75	90	40	0.7	0.6	0.5	0.5	0.5	0.5	0.4	0.4	0.5	0.6	0.7	0.7	0.5
75	135	0	0.7	0.6	0.5	0.6	0.7	0.6	0.6	0.6	0.5	0.6	0.7	0.7	0.6
75	135	20	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.7	0.7	0.5
75	135	40	0.7	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.5	0.7	0.7	0.4
75	180	0	0.7	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.4	0.5	0.7	0.7	0.5
75	180	20	0.7	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.5	0.7	0.7	0.4
75	180	40	0.7	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.5	0.7	0.7	0.4
90	0	0	3.8	2.3	1.5	0.9	0.8	0.7	0.7	0.9	1.3	1.9	1.8	0.6	0.9
90	0	20	0.7	0.6	0.8	0.9	0.8	0.7	0.7	0.9	1.0	0.6	0.7	0.6	0.8
90	0	40	0.7	0.6	0.5	0.5	0.5	0.6	0.6	0.4	0.5	0.6	0.7	0.6	0.5
90	45	0	2.8	1.7	1.2	0.9	0.8	0.7	0.8	0.9	1.1	1.6	1.5	0.6	0.9
90	45	20	0.6	0.5	0.7	0.8	0.7	0.7	0.7	0.8	0.8	0.6	0.6	0.6	0.7
90	45	40	0.6	0.5	0.5	0.5	0.5	0.6	0.5	0.4	0.4	0.6	0.6	0.6	0.5
90	90	0	1.1	0.8	0.8	0.7	0.8	0.7	0.7	0.7	0.8	0.9	0.8	0.6	0.7
90	90	20	0.6	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.6	0.6	0.6
90	90	40	0.6	0.5	0.4	0.5	0.4	0.5	0.4	0.4	0.4	0.5	0.6	0.6	0.4
90	135	0	0.6	0.5	0.5	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.6	0.6
90	135	20	0.6	0.5	0.4	0.5	0.5	0.5	0.4	0.4	0.4	0.5	0.6	0.6	0.4
90	135	40	0.6	0.5	0.4	0.5	0.4	0.4	0.3	0.4	0.4	0.5	0.6	0.6	0.4
90	180	0	0.6	0.5	0.4	0.5	0.5	0.5	0.5	0.4	0.4	0.5	0.6	0.6	0.5
90	180	20	0.6	0.5	0.4	0.5	0.4	0.4	0.3	0.4	0.4	0.5	0.6	0.6	0.4
90	180	40	0.6	0.5	0.4	0.5	0.4	0.4	0.3	0.4	0.4	0.5	0.6	0.6	0.4



Copenhagen, Denmark 55.7o N

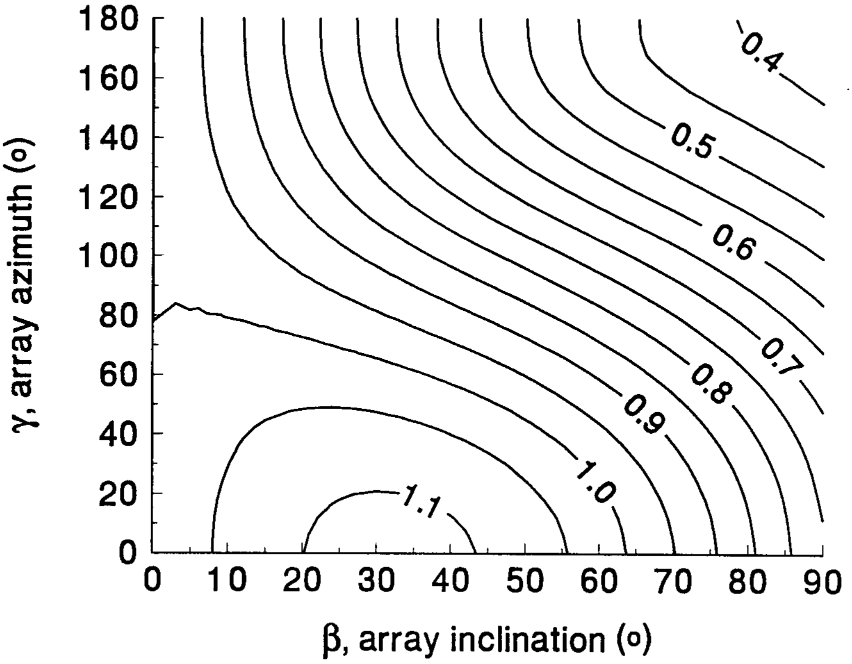


Copenhagen, Denmark 55.7 oN

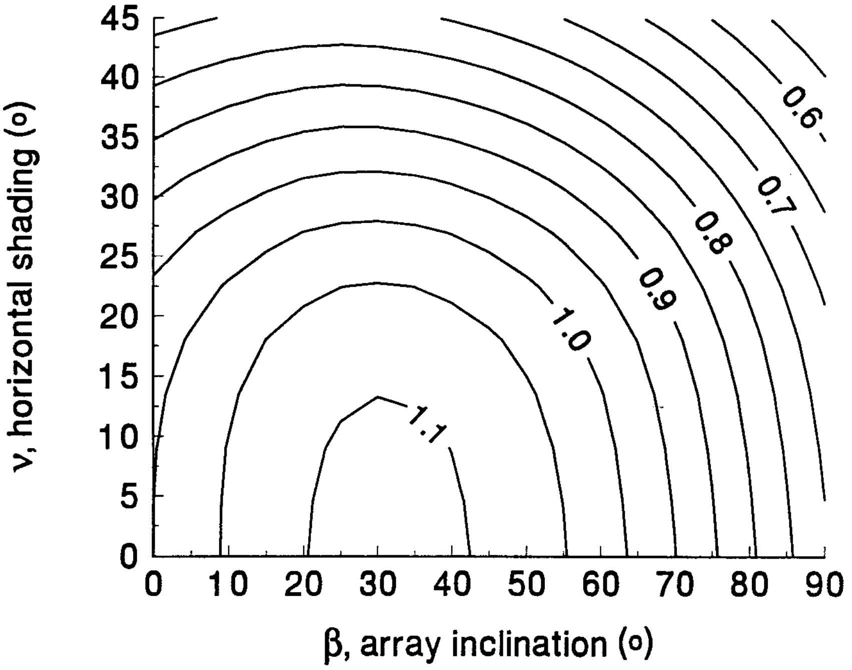
Copenhagen, Denmark 55.7°N

β	γ	ν	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
tracking		0	2.4	2.2	1.7	1.5	1.4	1.4	1.4	1.5	1.6	1.9	2.4	3.4	1.6
tracking		20	0.7	1.3	1.3	1.3	1.2	1.3	1.2	1.3	1.3	1.3	0.6	0.6	1.2
tracking		40	0.7	0.5	0.6	0.8	0.9	0.9	0.9	0.9	0.6	0.6	0.6	0.6	0.8
0	0	0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0	0	20	0.7	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.6	0.6	1.0
0	0	40	0.7	0.5	0.6	0.7	0.8	0.8	0.9	0.8	0.6	0.6	0.6	0.6	0.8
15	0	0	1.4	1.4	1.2	1.1	1.1	1.1	1.1	1.1	1.2	1.3	1.4	1.6	1.1
15	0	20	0.7	1.0	1.1	1.1	1.1	1.0	1.0	1.1	1.1	1.0	0.6	0.6	1.0
15	0	40	0.7	0.5	0.6	0.8	0.9	0.9	0.9	0.9	0.6	0.6	0.6	0.6	0.8
15	45	0	1.2	1.2	1.1	1.1	1.1	1.0	1.0	1.1	1.1	1.2	1.2	1.4	1.1
15	45	20	0.7	0.9	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.0	0.6	0.6	1.0
15	45	40	0.7	0.5	0.6	0.8	0.9	0.9	0.9	0.8	0.6	0.6	0.6	0.6	0.8
15	90	0	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	1.0
15	90	20	0.7	0.8	0.9	0.9	1.0	0.9	1.0	1.0	0.9	0.9	0.6	0.5	0.9
15	90	40	0.7	0.5	0.6	0.7	0.8	0.8	0.9	0.8	0.6	0.6	0.6	0.5	0.8
15	135	0	0.7	0.7	0.8	0.9	0.9	0.9	1.0	0.9	0.9	0.8	0.7	0.6	0.9
15	135	20	0.7	0.6	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.7	0.6	0.5	0.9
15	135	40	0.7	0.5	0.6	0.7	0.8	0.8	0.8	0.7	0.6	0.6	0.6	0.5	0.7
15	180	0	0.7	0.6	0.8	0.9	0.9	1.0	1.0	0.9	0.8	0.7	0.6	0.5	0.9
15	180	20	0.7	0.6	0.8	0.8	0.9	0.9	0.9	0.9	0.8	0.7	0.6	0.5	0.8
15	180	40	0.7	0.5	0.6	0.6	0.8	0.8	0.8	0.7	0.6	0.6	0.6	0.5	0.7
30	0	0	1.8	1.6	1.3	1.2	1.1	1.0	1.1	1.2	1.3	1.5	1.8	2.2	1.2
30	0	20	0.7	1.1	1.2	1.1	1.1	1.0	1.0	1.1	1.2	1.2	0.7	0.6	1.1
30	0	40	0.7	0.6	0.6	0.8	0.9	0.9	0.9	0.9	0.6	0.6	0.7	0.6	0.8
30	45	0	1.4	1.3	1.1	1.1	1.0	1.0	1.0	1.1	1.1	1.3	1.4	1.7	1.1
30	45	20	0.7	1.0	1.1	1.0	1.0	1.0	1.0	1.1	1.1	1.1	0.6	0.6	1.0
30	45	40	0.7	0.5	0.6	0.8	0.9	0.9	0.9	0.9	0.6	0.6	0.6	0.6	0.8
30	90	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
30	90	20	0.7	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.6	0.5	0.9
30	90	40	0.7	0.5	0.6	0.7	0.8	0.8	0.8	0.7	0.6	0.6	0.6	0.5	0.7
30	135	0	0.7	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.7	0.6	0.6	0.5	0.8
30	135	20	0.7	0.5	0.7	0.7	0.8	0.8	0.8	0.8	0.7	0.6	0.6	0.5	0.7
30	135	40	0.7	0.5	0.6	0.6	0.7	0.7	0.7	0.6	0.5	0.5	0.6	0.5	0.6
30	180	0	0.7	0.5	0.6	0.7	0.8	0.9	0.8	0.7	0.6	0.5	0.6	0.5	0.7
30	180	20	0.7	0.5	0.6	0.7	0.8	0.8	0.8	0.7	0.6	0.5	0.6	0.5	0.7
30	180	40	0.7	0.5	0.6	0.6	0.6	0.6	0.7	0.6	0.5	0.5	0.6	0.5	0.6
45	0	0	2.0	1.8	1.3	1.2	1.0	1.0	1.0	1.2	1.4	1.6	2.0	2.7	1.2
45	0	20	0.7	1.2	1.2	1.1	1.0	1.0	1.0	1.1	1.3	1.3	0.7	0.6	1.1
45	0	40	0.7	0.6	0.6	0.8	0.9	0.9	0.9	0.9	0.6	0.6	0.7	0.6	0.8
45	45	0	1.5	1.4	1.1	1.0	1.0	0.9	1.0	1.0	1.1	1.3	1.5	2.0	1.1
45	45	20	0.7	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.1	1.1	0.6	0.6	1.0
45	45	40	0.7	0.5	0.6	0.8	0.8	0.8	0.8	0.8	0.6	0.6	0.6	0.6	0.8
45	90	0	0.8	0.8	0.8	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.9
45	90	20	0.6	0.7	0.8	0.8	0.9	0.8	0.9	0.8	0.8	0.8	0.6	0.5	0.8
45	90	40	0.6	0.5	0.6	0.6	0.7	0.7	0.7	0.7	0.6	0.5	0.6	0.5	0.7
45	135	0	0.6	0.5	0.6	0.6	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.5	0.7
45	135	20	0.6	0.5	0.6	0.6	0.7	0.7	0.7	0.6	0.6	0.5	0.6	0.5	0.6
45	135	40	0.6	0.5	0.6	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.5	0.6
45	180	0	0.6	0.5	0.6	0.5	0.6	0.7	0.7	0.6	0.5	0.5	0.6	0.5	0.6
45	180	20	0.6	0.5	0.6	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.6	0.5	0.6
45	180	40	0.6	0.5	0.6	0.4	0.5	0.5	0.6	0.5	0.5	0.5	0.6	0.5	0.5
60	0	0	2.2	1.9	1.3	1.1	1.0	0.9	0.9	1.1	1.3	1.7	2.2	3.0	1.1
60	0	20	0.7	1.2	1.2	1.1	0.9	0.9	0.9	1.1	1.2	1.3	0.7	0.6	1.0
60	0	40	0.7	0.5	0.6	0.8	0.8	0.8	0.8	0.8	0.6	0.6	0.7	0.6	0.8
60	45	0	1.6	1.4	1.0	1.0	0.9	0.8	0.9	1.0	1.1	1.3	1.6	2.1	1.0
60	45	20	0.6	1.0	1.0	0.9	0.9	0.8	0.9	1.0	1.0	1.1	0.6	0.6	0.9
60	45	40	0.6	0.5	0.6	0.7	0.8	0.8	0.8	0.8	0.6	0.6	0.6	0.6	0.7
60	90	0	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
60	90	20	0.6	0.6	0.7	0.7	0.8	0.7	0.8	0.8	0.7	0.7	0.5	0.5	0.7
60	90	40	0.6	0.4	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.6
60	135	0	0.6	0.4	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.6
60	135	20	0.6	0.4	0.6	0.5	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.6
60	135	40	0.6	0.4	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
60	180	0	0.6	0.4	0.5	0.5	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5
60	180	20	0.6	0.4	0.5	0.4	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.5
60	180	40	0.6	0.4	0.5	0.4	0.4	0.4	0.5	0.4	0.5	0.5	0.5	0.5	0.4
75	0	0	2.2	1.9	1.2	1.0	0.8	0.8	0.8	1.0	1.2	1.6	2.2	3.2	1.0
75	0	20	0.6	1.2	1.1	1.0	0.8	0.8	0.8	0.9	1.1	1.2	0.6	0.6	0.9
75	0	40	0.6	0.5	0.6	0.7	0.7	0.7	0.7	0.8	0.6	0.6	0.6	0.6	0.7
75	45	0	1.5	1.3	0.9	0.9	0.8	0.7	0.8	0.9	1.0	1.2	1.5	2.1	0.9
75	45	20	0.6	1.0	0.9	0.8	0.8	0.7	0.8	0.9	0.9	1.0	0.6	0.5	0.8
75	45	40	0.6	0.5	0.5	0.6	0.7	0.6	0.7	0.7	0.5	0.5	0.6	0.5	0.6
75	90	0	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
75	90	20	0.5	0.5	0.6	0.6	0.7	0.6	0.7	0.7	0.6	0.6	0.5	0.5	0.7
75	90	40	0.5	0.4	0.5	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5
75	135	0	0.5	0.4	0.5	0.5	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.5
75	135	20	0.5	0.4	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.4	0.5
75	135	40	0.5	0.4	0.5	0.4	0.4	0.4	0.5	0.4	0.4	0.5	0.5	0.4	0.4
75	180	0	0.5	0.4	0.5	0.4	0.5	0.5	0.5	0.4	0.4	0.5	0.5	0.4	0.5
75	180	20	0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.4	0.4
75	180	40	0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.4	0.4
90	0	0	2.2	1.8	1.1	0.8	0.7	0.6	0.6	0.8	1.1	1.5	2.1	3.1	0.9
90	0	20	0.6	1.1	1.0	0.8	0.7	0.6	0.6	0.8	1.0	1.1	0.6	0.6	0.8
90	0	40	0.6	0.4	0.5	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.6	0.6	0.6
90	45	0	1.4	1.2	0.8	0.7	0.7	0.6	0.7	0.8	0.9	1.1	1.4	2.0	0.8
90	45	20	0.5	0.9	0.8	0.7	0.7	0.6	0.6	0.7	0.8	0.9	0.5	0.5	0.7
90	45	40	0.5	0.4	0.5	0.6	0.6	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.5
90	90	0	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
90	90	20	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.4	0.4	0.6
90	90	40	0.5	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.5
90	135	0	0.5	0.4	0.5	0.4	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.5
90	135	20	0.5	0.4	0.4	0.4	0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4
90	135	40	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
90	180	0	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
90	180	20	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
90	180	40	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

Madison (Wisconsin), USA 43.1° N



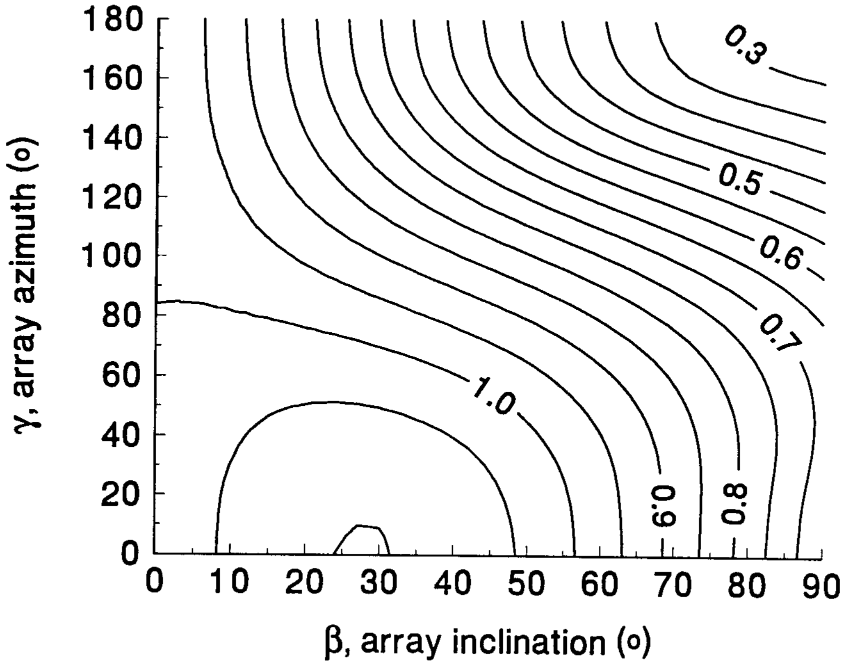
Madison (Wisconsin), USA 43.1 °N



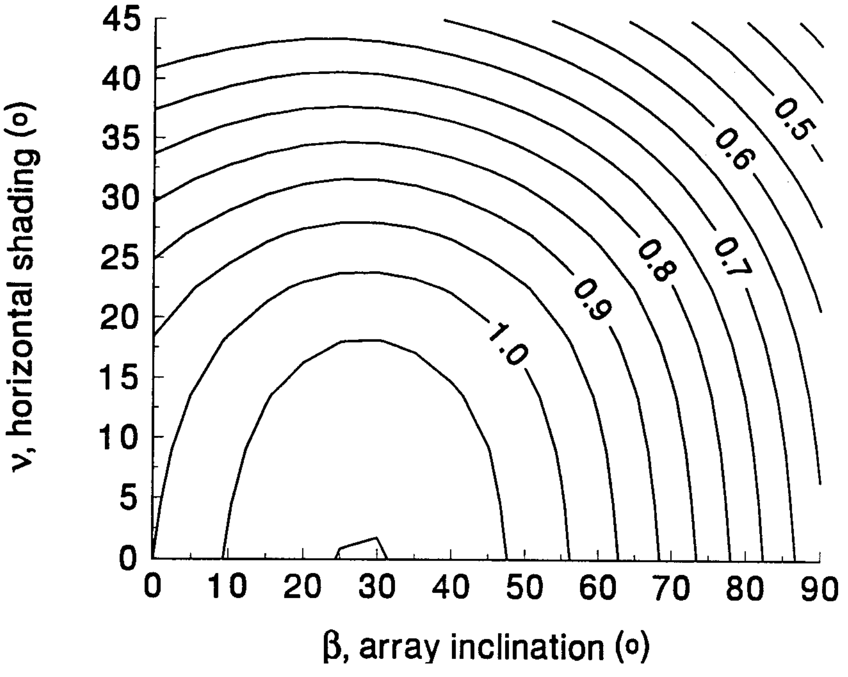
Madison (Wisconsin), USA 43.1°N

β	γ	ν	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
tracking		0	1.8	1.5	1.5	1.3	1.3	1.2	1.2	1.3	1.4	1.5	1.7	1.7	1.4
tracking		20	1.4	1.4	1.3	1.2	1.2	1.2	1.2	1.2	1.3	1.4	1.4	1.5	1.3
tracking		40	0.6	0.6	0.8	1.0	1.0	1.0	1.0	1.0	0.9	0.7	0.6	0.6	0.9
0	0	0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0	0	20	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	1.0
0	0	40	0.6	0.6	0.7	0.9	0.9	0.9	0.9	0.9	0.8	0.6	0.6	0.6	0.8
15	0	0	1.3	1.2	1.1	1.1	1.0	1.0	1.0	1.0	1.1	1.2	1.2	1.3	1.1
15	0	20	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.2	1.1
15	0	40	0.6	0.6	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.6	0.6	0.8
15	45	0	1.2	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.2	1.2	1.0
15	45	20	1.0	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.0
15	45	40	0.6	0.6	0.7	0.9	0.9	0.9	0.9	0.9	0.8	0.6	0.6	0.6	0.8
15	90	0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
15	90	20	0.9	0.9	0.9	1.0	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.9	1.0
15	90	40	0.6	0.6	0.7	0.9	0.9	0.9	0.9	0.8	0.8	0.6	0.6	0.6	0.8
15	135	0	0.8	0.8	0.9	0.9	0.9	1.0	0.9	0.9	0.9	0.9	0.8	0.8	0.9
15	135	20	0.7	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.9
15	135	40	0.5	0.5	0.6	0.8	0.8	0.9	0.9	0.8	0.7	0.6	0.5	0.6	0.7
15	180	0	0.7	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.7	0.7	0.9
15	180	20	0.7	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.7	0.7	0.9
15	180	40	0.5	0.5	0.6	0.8	0.8	0.9	0.8	0.8	0.7	0.6	0.5	0.6	0.7
30	0	0	1.5	1.3	1.2	1.1	1.0	1.0	1.0	1.0	1.2	1.3	1.4	1.5	1.1
30	0	20	1.3	1.2	1.2	1.1	1.0	1.0	1.0	1.0	1.1	1.2	1.3	1.3	1.1
30	0	40	0.6	0.6	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.6	0.7	0.8
30	45	0	1.3	1.2	1.1	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.3	1.3	1.1
30	45	20	1.1	1.1	1.1	1.0	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2	1.0
30	45	40	0.6	0.6	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.6	0.6	0.8
30	90	0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0	0.9	0.9
30	90	20	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
30	90	40	0.5	0.5	0.6	0.8	0.8	0.8	0.8	0.8	0.7	0.6	0.6	0.6	0.7
30	135	0	0.6	0.7	0.7	0.8	0.9	0.9	0.9	0.8	0.8	0.7	0.7	0.6	0.8
30	135	20	0.6	0.7	0.7	0.8	0.8	0.9	0.8	0.8	0.7	0.7	0.6	0.6	0.8
30	135	40	0.5	0.5	0.6	0.7	0.7	0.8	0.8	0.7	0.6	0.5	0.5	0.6	0.7
30	180	0	0.5	0.6	0.6	0.8	0.8	0.9	0.8	0.8	0.7	0.6	0.5	0.6	0.7
30	180	20	0.5	0.6	0.6	0.7	0.8	0.8	0.8	0.7	0.7	0.6	0.5	0.6	0.7
30	180	40	0.5	0.5	0.5	0.7	0.7	0.8	0.7	0.7	0.6	0.5	0.5	0.6	0.6
45	0	0	1.6	1.4	1.2	1.0	0.9	0.9	0.9	1.0	1.1	1.3	1.5	1.6	1.1
45	0	20	1.4	1.3	1.2	1.0	0.9	0.9	0.9	1.0	1.1	1.3	1.3	1.5	1.1
45	0	40	0.6	0.6	0.8	0.9	0.8	0.8	0.9	0.9	0.9	0.7	0.6	0.7	0.8
45	45	0	1.4	1.2	1.1	1.0	0.9	0.9	0.9	0.9	1.1	1.2	1.3	1.4	1.0
45	45	20	1.2	1.1	1.1	1.0	0.9	0.9	0.9	0.9	1.0	1.1	1.2	1.3	1.0
45	45	40	0.6	0.6	0.7	0.9	0.8	0.8	0.8	0.8	0.8	0.6	0.6	0.6	0.8
45	90	0	0.9	0.9	0.8	0.9	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9
45	90	20	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
45	90	40	0.5	0.5	0.6	0.7	0.7	0.8	0.8	0.7	0.7	0.6	0.5	0.6	0.7
45	135	0	0.5	0.6	0.6	0.7	0.7	0.8	0.7	0.7	0.6	0.6	0.6	0.5	0.7
45	135	20	0.5	0.5	0.6	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.5	0.5	0.6
45	135	40	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.6	0.5	0.5	0.5	0.5	0.6
45	180	0	0.5	0.5	0.4	0.6	0.7	0.7	0.7	0.6	0.5	0.5	0.5	0.5	0.6
45	180	20	0.5	0.5	0.4	0.6	0.7	0.7	0.7	0.6	0.5	0.5	0.5	0.5	0.6
45	180	40	0.5	0.5	0.4	0.5	0.6	0.6	0.6	0.5	0.4	0.5	0.5	0.5	0.5
60	0	0	1.7	1.4	1.2	0.9	0.8	0.8	0.8	0.9	1.1	1.3	1.5	1.7	1.0
60	0	20	1.4	1.3	1.1	0.9	0.8	0.8	0.8	0.9	1.1	1.2	1.4	1.5	1.0
60	0	40	0.6	0.6	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.6	0.6	0.7
60	45	0	1.4	1.2	1.0	0.9	0.8	0.8	0.8	0.9	1.0	1.2	1.3	1.4	0.9
60	45	20	1.2	1.1	1.0	0.9	0.8	0.8	0.8	0.8	1.0	1.1	1.2	1.3	0.9
60	45	40	0.6	0.5	0.7	0.8	0.7	0.7	0.7	0.7	0.8	0.6	0.6	0.6	0.7
60	90	0	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.8	0.8
60	90	20	0.7	0.7	0.7	0.8	0.7	0.7	0.7	0.7	0.7	0.8	0.7	0.7	0.7
60	90	40	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.6	0.6	0.5	0.5	0.5	0.6
60	135	0	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.6
60	135	20	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.6
60	135	40	0.5	0.5	0.4	0.5	0.5	0.6	0.5	0.5	0.4	0.4	0.5	0.5	0.5
60	180	0	0.5	0.5	0.4	0.4	0.5	0.6	0.5	0.4	0.4	0.4	0.5	0.5	0.5
60	180	20	0.5	0.5	0.4	0.4	0.5	0.6	0.5	0.4	0.4	0.4	0.5	0.5	0.5
60	180	40	0.5	0.5	0.4	0.4	0.5	0.5	0.5	0.4	0.4	0.4	0.5	0.5	0.4
75	0	0	1.6	1.3	1.1	0.8	0.7	0.6	0.7	0.8	1.0	1.2	1.5	1.6	0.9
75	0	20	1.3	1.2	1.0	0.8	0.7	0.6	0.7	0.8	0.9	1.1	1.3	1.4	0.9
75	0	40	0.6	0.5	0.7	0.7	0.6	0.6	0.6	0.7	0.8	0.6	0.5	0.6	0.7
75	45	0	1.3	1.1	0.9	0.8	0.7	0.7	0.7	0.7	0.9	1.1	1.2	1.3	0.8
75	45	20	1.1	1.0	0.9	0.8	0.7	0.7	0.7	0.7	0.8	1.0	1.1	1.2	0.8
75	45	40	0.5	0.5	0.6	0.7	0.6	0.6	0.6	0.6	0.7	0.6	0.5	0.6	0.6
75	90	0	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.7	0.7
75	90	20	0.6	0.6	0.6	0.7	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.6	0.6
75	90	40	0.5	0.5	0.5	0.6	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5
75	135	0	0.5	0.5	0.4	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5
75	135	20	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.5	0.5
75	135	40	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.5	0.4
75	180	0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4
75	180	20	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4
75	180	40	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4
90	0	0	1.5	1.1	0.9	0.7	0.5	0.5	0.5	0.6	0.8	1.0	1.3	1.5	0.8
90	0	20	1.2	1.0	0.9	0.7	0.5	0.5	0.5	0.6	0.8	1.0	1.2	1.3	0.7
90	0	40	0.5	0.5	0.6	0.6	0.5	0.5	0.5	0.6	0.6	0.5	0.5	0.5	0.5
90	45	0	1.1	0.9	0.8	0.7	0.6	0.5	0.6	0.6	0.7	0.9	1.1	1.2	0.7
90	45	20	1.0	0.8	0.7	0.6	0.6	0.5	0.5	0.6	0.7	0.8	1.0	1.0	0.7
90	45	40	0.5	0.4	0.5	0.6	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.5
90	90	0	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.6
90	90	20	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.5	0.5
90	90	40	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
90	135	0	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
90	135	20	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
90	135	40	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
90	180	0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.4
90	180	20	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.4
90	180	40	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.4

Phoenix (Arizona), USA 33.4° N



Phoenix (Arizona), USA 33.4 °N



Phoenix (Arizona), USA 33.4°N

β	γ	ν	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
tracking		0	2.0	1.8	1.6	1.5	1.5	1.4	1.4	1.5	1.6	1.7	2.0	2.0	1.6
tracking		20	1.6	1.5	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.5	1.5	1.3
tracking		40	0.4	0.7	0.9	1.0	0.9	0.9	0.9	1.0	0.9	0.9	0.5	0.5	0.9
0	0	0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0	0	20	0.9	0.9	1.0	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9
0	0	40	0.3	0.5	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.6	0.3	0.4	0.7
15	0	0	1.3	1.2	1.1	1.0	1.0	1.0	1.0	1.0	1.1	1.2	1.3	1.3	1.1
15	0	20	1.1	1.1	1.1	1.0	1.0	0.9	1.0	1.0	1.0	1.1	1.1	1.1	1.0
15	0	40	0.3	0.6	0.8	0.9	0.8	0.8	0.8	0.9	0.8	0.7	0.4	0.4	0.7
15	45	0	1.2	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.2	1.2	1.1
15	45	20	1.1	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
15	45	40	0.3	0.6	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.4	0.4	0.7
15	90	0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
15	90	20	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.9
15	90	40	0.3	0.5	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.6	0.3	0.4	0.7
15	135	0	0.8	0.8	0.9	0.9	1.0	1.0	1.0	0.9	0.9	0.8	0.8	0.8	0.9
15	135	20	0.7	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.7	0.7	0.9
15	135	40	0.3	0.5	0.6	0.7	0.7	0.7	0.8	0.8	0.7	0.6	0.3	0.3	0.6
15	180	0	0.7	0.7	0.8	0.9	1.0	1.0	1.0	0.9	0.9	0.8	0.7	0.7	0.9
15	180	20	0.6	0.7	0.8	0.8	0.9	0.9	0.9	0.9	0.8	0.7	0.6	0.6	0.8
15	180	40	0.3	0.4	0.6	0.7	0.7	0.7	0.7	0.7	0.6	0.5	0.3	0.3	0.6
30	0	0	1.5	1.4	1.2	1.0	0.9	0.9	0.9	1.0	1.1	1.3	1.5	1.5	1.1
30	0	20	1.3	1.2	1.1	1.0	0.9	0.9	0.9	1.0	1.1	1.2	1.3	1.3	1.0
30	0	40	0.4	0.6	0.8	0.9	0.8	0.7	0.8	0.8	0.8	0.8	0.4	0.4	0.7
30	45	0	1.3	1.2	1.1	1.0	0.9	0.9	0.9	1.0	1.1	1.2	1.3	1.3	1.1
30	45	20	1.2	1.1	1.1	0.9	0.9	0.9	0.9	0.9	1.0	1.1	1.1	1.1	1.0
30	45	40	0.3	0.6	0.8	0.8	0.8	0.7	0.7	0.8	0.8	0.7	0.4	0.4	0.7
30	90	0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	1.0	0.9	0.9	1.0	0.9	0.9
30	90	20	0.8	0.8	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.9
30	90	40	0.3	0.5	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.3	0.4	0.6
30	135	0	0.6	0.6	0.7	0.8	0.9	0.9	0.9	0.9	0.8	0.7	0.6	0.6	0.8
30	135	20	0.5	0.6	0.7	0.7	0.8	0.9	0.8	0.8	0.7	0.6	0.5	0.5	0.7
30	135	40	0.3	0.4	0.5	0.6	0.7	0.7	0.7	0.7	0.6	0.4	0.3	0.3	0.6
30	180	0	0.4	0.5	0.6	0.7	0.9	0.9	0.9	0.8	0.7	0.5	0.4	0.4	0.7
30	180	20	0.4	0.5	0.6	0.7	0.8	0.8	0.8	0.7	0.6	0.5	0.4	0.4	0.7
30	180	40	0.3	0.3	0.5	0.6	0.6	0.7	0.7	0.6	0.5	0.4	0.3	0.3	0.5
45	0	0	1.6	1.4	1.2	1.0	0.8	0.8	0.8	0.9	1.1	1.3	1.6	1.7	1.1
45	0	20	1.4	1.3	1.1	0.9	0.8	0.8	0.8	0.9	1.0	1.2	1.4	1.4	1.0
45	0	40	0.4	0.7	0.8	0.8	0.7	0.7	0.7	0.8	0.8	0.8	0.4	0.4	0.7
45	45	0	1.4	1.3	1.1	1.0	0.9	0.8	0.8	0.9	1.0	1.2	1.4	1.4	1.0
45	45	20	1.2	1.1	1.0	0.9	0.8	0.8	0.8	0.9	1.0	1.1	1.2	1.1	0.9
45	45	40	0.4	0.6	0.8	0.8	0.7	0.6	0.7	0.8	0.8	0.7	0.4	0.4	0.7
45	90	0	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.9
45	90	20	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.8
45	90	40	0.3	0.5	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.5	0.3	0.4	0.6
45	135	0	0.4	0.5	0.6	0.7	0.8	0.8	0.8	0.7	0.6	0.5	0.5	0.4	0.7
45	135	20	0.4	0.4	0.5	0.6	0.7	0.7	0.7	0.7	0.6	0.4	0.4	0.4	0.6
45	135	40	0.3	0.3	0.4	0.5	0.6	0.6	0.6	0.5	0.4	0.3	0.3	0.3	0.5
45	180	0	0.3	0.3	0.4	0.6	0.7	0.8	0.8	0.6	0.4	0.3	0.3	0.3	0.5
45	180	20	0.3	0.3	0.4	0.5	0.7	0.7	0.7	0.6	0.4	0.3	0.3	0.3	0.5
45	180	40	0.3	0.3	0.3	0.4	0.5	0.5	0.5	0.5	0.4	0.3	0.3	0.3	0.4
60	0	0	1.7	1.4	1.1	0.8	0.7	0.6	0.6	0.8	1.0	1.3	1.6	1.7	1.0
60	0	20	1.4	1.3	1.1	0.8	0.7	0.6	0.6	0.8	1.0	1.2	1.4	1.4	0.9
60	0	40	0.4	0.6	0.8	0.7	0.6	0.5	0.6	0.7	0.8	0.8	0.4	0.4	0.6
60	45	0	1.4	1.2	1.0	0.9	0.8	0.7	0.7	0.8	1.0	1.1	1.4	1.4	0.9
60	45	20	1.2	1.1	0.9	0.8	0.7	0.7	0.7	0.8	0.9	1.0	1.1	1.1	0.8
60	45	40	0.4	0.6	0.7	0.7	0.6	0.5	0.6	0.7	0.7	0.7	0.4	0.4	0.6
60	90	0	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9	0.8	0.8
60	90	20	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.7
60	90	40	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.3	0.4	0.5
60	135	0	0.4	0.4	0.5	0.6	0.7	0.7	0.6	0.6	0.5	0.4	0.4	0.4	0.6
60	135	20	0.3	0.4	0.4	0.5	0.6	0.6	0.6	0.5	0.5	0.3	0.3	0.3	0.5
60	135	40	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.4
60	180	0	0.3	0.3	0.2	0.4	0.5	0.6	0.6	0.5	0.2	0.2	0.3	0.3	0.4
60	180	20	0.3	0.3	0.2	0.3	0.5	0.6	0.5	0.4	0.2	0.2	0.3	0.3	0.4
60	180	40	0.3	0.3	0.2	0.3	0.4	0.4	0.4	0.3	0.2	0.2	0.3	0.3	0.3
75	0	0	1.6	1.3	1.0	0.7	0.5	0.4	0.5	0.6	0.9	1.2	1.5	1.7	0.8
75	0	20	1.4	1.2	0.9	0.7	0.5	0.4	0.5	0.6	0.8	1.1	1.3	1.3	0.8
75	0	40	0.4	0.6	0.7	0.6	0.5	0.4	0.5	0.6	0.7	0.7	0.4	0.4	0.5
75	45	0	1.3	1.1	0.9	0.7	0.6	0.6	0.6	0.7	0.9	1.0	1.3	1.3	0.8
75	45	20	1.1	1.0	0.8	0.6	0.6	0.5	0.6	0.7	0.8	0.9	1.1	1.0	0.7
75	45	40	0.3	0.5	0.6	0.6	0.5	0.4	0.4	0.5	0.6	0.6	0.4	0.4	0.5
75	90	0	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.7
75	90	20	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.6
75	90	40	0.3	0.4	0.4	0.5	0.4	0.4	0.4	0.5	0.4	0.4	0.3	0.3	0.4
75	135	0	0.3	0.4	0.4	0.5	0.6	0.6	0.5	0.5	0.4	0.4	0.3	0.4	0.5
75	135	20	0.3	0.3	0.3	0.4	0.5	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.4
75	135	40	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3
75	180	0	0.3	0.3	0.2	0.2	0.3	0.4	0.4	0.3	0.2	0.2	0.3	0.3	0.3
75	180	20	0.3	0.3	0.2	0.2	0.3	0.4	0.3	0.3	0.2	0.2	0.3	0.3	0.3
75	180	40	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.2
90	0	0	1.4	1.1	0.8	0.5	0.3	0.3	0.3	0.4	0.7	1.0	1.4	1.5	0.7
90	0	20	1.2	1.0	0.8	0.5	0.3	0.3	0.3	0.4	0.7	0.9	1.1	1.2	0.6
90	0	40	0.3	0.5	0.6	0.5	0.3	0.3	0.3	0.4	0.5	0.6	0.4	0.4	0.4
90	45	0	1.1	1.0	0.8	0.6	0.5	0.5	0.5	0.6	0.7	0.9	1.1	1.2	0.7
90	45	20	1.0	0.8	0.7	0.5	0.5	0.4	0.4	0.5	0.6	0.7	0.9	0.9	0.6
90	45	40	0.3	0.5	0.5	0.4	0.4	0.3	0.3	0.4	0.5	0.5	0.3	0.4	0.4
90	90	0	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.6
90	90	20	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
90	90	40	0.3	0.3	0.3	0.4	0.4	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.3
90	135	0	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.4	0.3	0.3	0.3	0.4
90	135	20	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3
90	135	40	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.3
90	180	0	0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.3
90	180	20	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.2
90	180	40	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.2

Appendix II

System Sizing Worksheets

WORKSHEET #1: DEFINE SITE CONDITIONS AND SOLAR AVAILABILITY

SYSTEM:

SYSTEM LOCATION:	LATITUDE:	LONGITUDE:
INSOLATION LOCATION:	LATITUDE:	LONGITUDE:

MONTH	Location		Array plane						
	Ambient temperature	Horizontal insolation	*	tilt, azimuth, shadow Factor (appendix I)	=	Insolation			
	°C	$\frac{kWh}{m^2day}$	*	fraction	=	$\frac{kWh}{m^2day}$	*	=	$\frac{kWh}{m^2month}$
January			*		=		*31	=	
February			*		=		*28	=	
March			*		=		*31	=	
April			*		=		*30	=	
May			*		=		*31	=	
June			*		=		*30	=	
July			*		=		*31	=	
August			*		=		*31	=	
September			*		=		*30	=	
October			*		=		*31	=	
November			*		=		*30	=	
December			*		=		*31	=	

S = Annual insolation on PV array [kWh/m^2] = Σ =

WORKSHEET #2: ESTIMATE LOADS

Load Description	AC or DC	AC loads (1) [W]	Inverter efficiency (2) [%]	DC load (3)=(1)/(2) [W]	Duty cycle (4) [h/day]	Duty cycle (5) [day/week]	Daily load (6)= (3)*(4)*(5)/7 [Wh/day]	Nominal voltage (7) [V]	Ah-Load (8)=(6)/(7) [Ah/day]
			MAXIMUM DC LOAD (9) [W]		TOTAL DAILY LOADS (10)=Σ(6) [Wh/day]			TOTAL LOAD (11)=Σ(8) [Ah/day]	

DESIGN LOAD (Total load=(11))		Ah/Day
DESIGN PEAK CURRENT DRAW (Maximum DC load) (Nominal Voltage)		A
ANNUAL LOAD ENERGY (Total daily loads * 0,365)		kWh

WORKSHEET #3: GRID CONNECTED SYSTEM (part I)

Chosen PV array power P_{PV} [kW_P]	/	PV efficiency (table 17.2) η_{PV} [fraction]	=	PV array area A_{PV} [m^2]
	/		=	

Chosen PV Array power P_{PV} [kW_p]	*	Annual insolation on PV array (worksheet #1) S [kWh/m^2]	*	BOS efficiency (see below) η_{BOS} [fraction]	*	K_{PV} factor [fraction]	=	Annual produced PV energy E_{PV} [kWh]
	*		*		*	0.9	=	

Annual produced PV energy E_{PV} [kWh]	/	Annual load energy (worksheet #2) [kWh]	=	PV/load ratio [fraction]	from Figure 17.3	Directly used PV energy [fraction]
	/		=		==>	

Chosen PV Array power P_{PV} [kW_p]	*	Optimum inverter size (from table 17.1) [fraction]	=	Inverter nominal power [kW]
	*		=	

average inverter efficiency [fraction]	*	wiring loss factor (1-loss fraction) [fraction]	=	BOS efficiency η_{BOS} [fraction]
	*		=	

WORKSHEET #3: GRID CONNECTED SYSTEM (part II)

GENERAL INFORMATION

Utility name: ______________________________

Contact address: ______________________________

Phone number: ______________________________

METERING OPTIONS

Single net metering: ____________________ (Y/N)

Size restriction: ____________________ (kW)

Dual metering: ____________________ (Y/N)

Simultaneous buy/sell: ____________________ (Y/N)

Buyback ratio: ____________________

SPECIAL REQUIREMENTS

Outdoor PV disconnect? ____________________ (Y/N)

Price paid for sold PV energy [US-$/kWh]	*	Sold PV energy fraction (1-directly used) [fraction]	*	Annual produced PV energy [kWh]	=	Annual income from sold PV energy [US-$]
	*		*		=	

WORKSHEET #4: SIZE BATTERY BANK

Design load (worksheet #2) [Ah/day]	*	Days of autonomy (see table below) [Days]	/	Max depth of discharge [fraction]	=	Usable battery capacity [Ah]
	*		/		=	

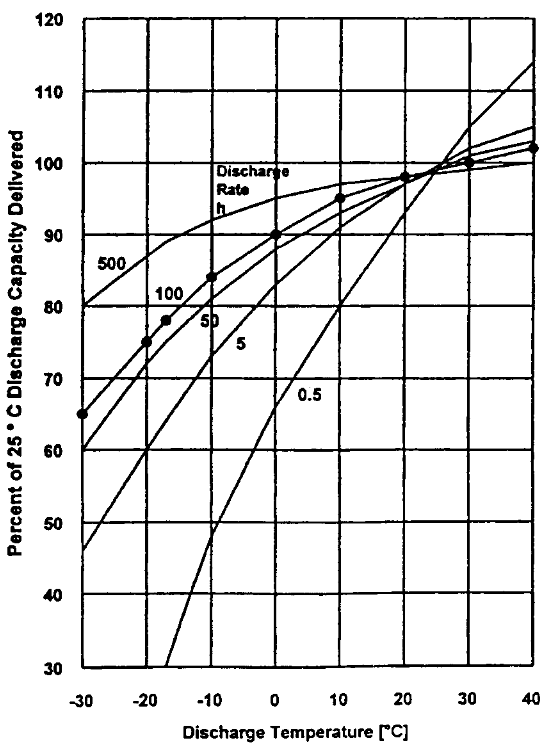
OPERATING TEMP = **[degrees C]**

DISCHARGE RATE = **24 x DAYS OF AUTONOMY**
= [h]

Usable battery capacity [Ah]	/	Usable fraction of capacity available [from graph below]	=	Design battery capacity [Ah]
	/		=	

RECOMMENDED DAYS OF AUTONOMY

Northern Latitude	Summer months 5,6,7,8 (days)	Spring/ autumn months 3,4,9,10 (days)	Winter months 11,12,1,2 (days)
30°	2 - 4	3 - 4	4 - 6
40°	2 - 4	4 - 6	6 - 10
50°	2 - 4	6 - 8	10 - 15
60°	3 - 5	8 - 12	15 - 25
70°	3 - 5	10 - 14	20 - 35



WORKSHEET #5: SIZE ARRAY & COMPONENTS

OPERATING SEASON (Months)	

Design* month daily load [kWh/day]	/	Lowest** insolation on PV array (worksheet #1) [(kWh/m^2)/day]	/	Wiring loss factor (1-loss fraction) [fraction]	/	Charge regulator efficiency [fraction]	/	Battery efficiency [fraction]	=	Design PV array power [kW_p]
	/		/		/		/		=	

Design PV array power [W_p]	*	PV array sizing safety factor (see table below)	=	PV array power [W_p]
	*		=	

PV array power [W_p]	/	Nominal voltage [V]	=	Design array current [A]
	/		=	

Design array current [A]	=	Design power conditioner current [A]***
	=	

PV array power P_{PV} [kW_p]	/	PV module efficiency (from table 17.2) η_{PV} [fraction]	=	PV array area A_{PV} (m^2)
	/		=	

* When load is constant through the year, the chosen design month is the month with lowest radiation. Otherwise the month is chosen so that the mismatch between the monthly load and insolation on PV surface is the largest (worksheets #1 and #2)

** Insolation on array plane ((kWh/m^2)/day) = Peak sun hours [h/day], see definitions

*** If the peak load current is higher than the design array current the power conditioner must be sized on that basis.

PV ARRAY SAFETY FACTOR

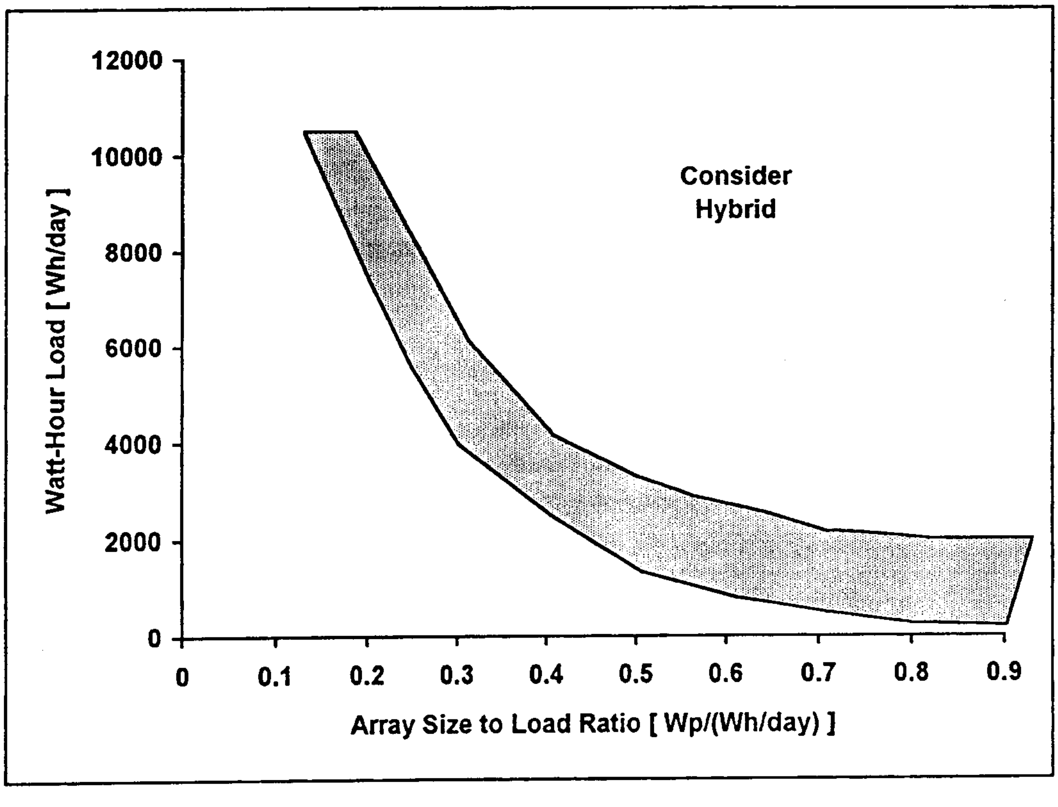
Latitude	Summer [fraction]	Spring/ autumn [fraction]	Winter [fraction]
30°	1.1 - 1.3	1.1 - 1.4	1.2 - 1.6
40°	1.1 - 1.4	1.2 - 1.4	1.3 - 1.7
50°	1.2 - 1.5	1.3 - 1.6	1.4 - 1.8
60°	1.2 - 1.6	1.3 - 1.7	1.4 - 2.0

WORKSHEET #6: CONSIDER HYBRID

Design array power [W_p]	/	Total daily load (worksheet #2) [Wh/day]	=	Array/load ratio [W_p/(Wh/day)]
	/		=	

HYBRID DESIGN (from graph)

YES	NO



WORKSHEET #7: SIZE HYBRID

PV DESIGN PERIOD		Months
LOWEST INSOLATION DURING PV DESIGN PERIOD (from worksheet #1)		kWh/m^2day

Design* month daily load (worksheet #2) [kWh/day]	/	Lowest** insolation on PV array during PV design period (worksheet #1) [$(kWh/m^2)/day$]	/	Wiring loss factor (1-loss fraction) [fraction]	/	Charge regulator efficiency [fraction]	/	Battery efficiency [fraction]	=	PV array power [kW$_p$]
	/		/		/		/		=	

PV array power [W$_p$]	/	Nominal voltage [V]	=	Design array current [A]
	/		=	

Design array current [A]	*	Lowest** insolation on PV array (worksheet #1) [$(kWh/m^2)/day$]	=	PV load contribution [Ah/day]
	*		=	

Design load (worksheet #2) [Ah/day]	*	Days of*** autonomy [days]	/	Maximum depth of discharge [fraction]	/	Usable fraction of battery capacity available (from worksheet #4)	=	Design battery capacity [Ah]
	*		/		/		=	

Design load (worksheet #2) [Ah/day]	/	Battery efficiency [fraction]	/	Rectifier efficiency [fraction]	*	Nominal voltage [V]	=	Design generator load [Wh/day]
	/		/		*		=	

Design generator load [Wh/day]	*	Days of autonomy (see above) [days]	/	Charge time [h]	=	Nominal generator capacity [W]
	*		/		=	

---

[*] Load during PV design period, when usually diesel generator is not designed to operate

[**] Insolation on array plane [$(kWh/m^2)/day$] = Peak sun hours [h/day], see definitions

[**] Recommended days of autonomy is 2 - 4 days for all locations.

Appendix III

Wire Sizing Tables

The following tables give the maximum distance allowed for selected copper wire sizes and currents. The tables are for 12 V, 48 V, and 120 V systems and the voltage drop is limited to 3%. The wire size is in AWG (American Wire Gage) with its equivalent in wire section in square millimeters (mm^2). These tables can be adjusted to reflect a different voltage drop percentage or different wire sections which are not noted in the table by using simple ratios. For example, a 5% table can be calculated by multiplying the values in the table by 5/3, or a 10 mm^2 section can be calculated by dividing any column by its section size and multiplying by 10.

The tables are calculated for one-way distance, taking into account that the circuit has 2 conductors to go from the source of current to the device being powered. For example, if a 48 V array is 10 meters from a 1200 W inverter, the table will show that a No. 12 wire size can be used up to a distance of 10.8 meters.

Note that when sizing the wire, the total current carrying capability (ampacity) of the wire must not be exceeded. Ampacity depends on wire type and temperature. Some ampacity values for copper wire are given below. For other types, please refer to your national electric codes.

AWG	T, TW, UF	RHW,THW, THHN
14	15	15
12	20	20
10	30	30
8	40	50
6	55	65
4	70	85
2	95	115
1/0	125	150
2/0	145	175
3/0	165	200

The following copper wire types are commonly used in PV systems:

UF: (sunlight resistant): used for array wiring and underground burial.

T: commonly called tray cable and used for array wiring, not for burial.
TW/THW: used for interconnecting BOS, must be installed in conduit:
THHN: used as battery cables.

Conductor size for 3 % drop in Voltage											
Voltage:	**12**	**Voltage Drop:**		**3%**							
AWG		14	12	10	8	6	4	2	1/0	2/0	3/0
Section (mm2)		2.08	3.31	5.27	8.3	13.3	21.1	33.6	53.5	67.4	85.6
Amps	**Watts**	Wire Distance from Source of Current to Device (One-Way) - Meters									
1	12	16.9	26.9	42.8	67.5	108.1	171.5	273.1	434.9	547.8	695.8
2	24	8.5	13.5	21.4	33.7	54.1	85.8	136.6	217.4	273.9	347.9
4	48	4.2	6.7	10.7	16.9	27.0	42.9	68.3	108.7	137.0	173.9
6	72	2.8	4.5	7.1	11.2	18.0	28.6	45.5	72.5	91.3	116.0
8	96	2.1	3.4	5.4	8.4	13.5	21.4	34.1	54.4	68.5	87.0
10	120	1.7	2.7	4.3	6.7	10.8	17.2	27.3	43.5	54.8	69.6
15	180	1.1	1.8	2.9	4.5	7.2	11.4	18.2	29.0	36.5	46.4
20	240	-	1.3	2.1	3.4	5.4	8.6	13.7	21.7	27.4	34.8
25	300	-	-	1.7	2.7	4.3	6.9	10.9	17.4	21.9	27.8
30	360	-	-	1.4	2.2	3.6	5.7	9.1	14.5	18.3	23.2
40	480	-	-	-	1.7	2.7	4.3	6.8	10.9	13.7	17.4
50	600	-	-	-	1.3	2.2	3.4	5.5	8.7	11.0	13.9
100	1200	-	-	-	-	-	-	2.7	4.3	5.5	7.0
150	1800	-	-	-	-	-	-	-	2.9	3.7	4.6
200	2400	-	-	-	-	-	-	-	-	2.7	3.5
Voltage:	**24**	**Voltage Drop:**		**3%**							
AWG		14	12	10	8	6	4	2	1/0	2/0	3/0
Section (mm2)		2.08	3.31	5.27	8.3	13.3	21.1	33.6	53.5	67.4	85.6
Amps	**Watts**	Wire Distance from Source of Current to Device (One-Way) - Meters									
1	24	33.8	53.8	85.7	134.9	216.2	343.0	546.2	869.7	1095.7	1391.5
2	48	16.9	26.9	42.8	67.5	108.1	171.5	273.1	434.9	547.8	695.8
4	96	8.5	13.5	21.4	33.7	54.1	85.8	136.6	217.4	273.9	347.9
6	144	5.6	9.0	14.3	22.5	36.0	57.2	91.0	145.0	182.6	231.9
8	192	4.2	6.7	10.7	16.9	27.0	42.9	68.3	108.7	137.0	173.9
10	240	3.4	5.4	8.6	13.5	21.6	34.3	54.6	87.0	109.6	139.2
15	360	2.3	3.6	5.7	9.0	14.4	22.9	36.4	58.0	73.0	92.8
20	480	-	2.7	4.3	6.7	10.8	17.2	27.3	43.5	54.8	69.6
25	600	-	-	3.4	5.4	8.6	13.7	21.8	34.8	43.8	55.7
30	720	-	-	2.9	4.5	7.2	11.4	18.2	29.0	36.5	46.4
40	960	-	-	-	3.4	5.4	8.6	13.7	21.7	27.4	34.8
50	1200	-	-	-	2.7	4.3	6.9	10.9	17.4	21.9	27.8
100	2400	-	-	-	-	-	-	5.5	8.7	11.0	13.9
150	3600	-	-	-	-	-	-	-	5.8	7.3	9.3
200	4800	-	-	-	-	-	-	-	-	5.5	7.0

Conductor size for 3 % drop in Voltage											
Voltage:	48	Voltage Drop:		3%							
AWG		14	12	10	8	6	4	2	1/0	2/0	3/0
Section (mm2)		2.08	3.31	5.27	8.3	13.3	21.1	33.6	53.5	67.4	85.6
Amps	Watts	Wire Distance from Source of Current to Device (One-Way) - Meters									
1	120	67.6	107.6	171.3	269.9	432.4	686.0	1092.4	1739.4	2191.3	2783.1
2	240	33.8	53.8	85.7	134.9	216.2	343.0	546.2	869.7	1095.7	1391.5
4	480	16.9	26.9	42.8	67.5	108.1	171.5	273.1	434.9	547.8	695.8
6	720	11.3	17.9	28.6	45.0	72.1	114.3	182.1	289.9	365.2	463.8
8	960	8.5	13.5	21.4	33.7	54.1	85.8	136.6	217.4	273.9	347.9
10	1200	6.8	10.8	17.1	27.0	43.2	68.6	109.2	173.9	219.1	278.3
15	1800	4.5	7.2	11.4	18.0	28.8	45.7	72.8	116.0	146.1	185.5
20	2400	-	5.4	8.6	13.5	21.6	34.3	54.6	87.0	109.6	139.2
25	3000	-	-	6.9	10.8	17.3	27.4	43.7	69.6	87.7	111.3
30	3600	-	-	5.7	9.0	14.4	22.9	36.4	58.0	73.0	92.8
40	4800	-	-	-	6.7	10.8	17.2	27.3	43.5	54.8	69.6
50	6000	-	-	-	5.4	8.6	13.7	21.8	34.8	43.8	55.7
100	12000	-	-	-	-	-	-	10.9	17.4	21.9	27.8
150	18000	-	-	-	-	-	-	-	11.6	14.6	18.6
200	24000	-	-	-	-	-	-	-	-	11.0	13.9
Voltage:	120	Voltage Drop:		3%							
AWG		14	12	10	8	6	4	2	1/0	2/0	3/0
Section (mm2)		2.08	3.31	5.27	8.3	13.3	21.1	33.6	53.5	67.4	85.6
Amps	Watts	Wire Distance from Source of Current to Device (One-Way) - Meters									
1	120	169.1	269.0	428.4	674.6	1081.0	1715.0	2731.0	4348.5	5478.3	6957.7
2	240	84.5	134.5	214.2	337.3	540.5	857.5	1365.5	2174.3	2739.2	3478.8
4	480	42.3	67.3	107.1	168.7	270.3	428.8	682.8	1087.1	1369.6	1739.4
6	720	28.2	44.8	71.4	112.4	180.2	285.8	455.2	724.8	913.1	1159.6
8	960	21.1	33.6	53.5	84.3	135.1	214.4	341.4	543.6	684.8	869.7
10	1200	16.9	26.9	42.8	67.5	108.1	171.5	273.1	434.9	547.8	695.8
15	1800	11.3	17.9	28.6	45.0	72.1	114.3	182.1	289.9	365.2	463.8
20	2400	-	13.5	21.4	33.7	54.1	85.8	136.6	217.4	273.9	347.9
25	3000	-	-	17.1	27.0	43.2	68.6	109.2	173.9	219.1	278.3
30	3600	-	-	14.3	22.5	36.0	57.2	91.0	145.0	182.6	231.9
40	4800	-	-	-	16.9	27.0	42.9	68.3	108.7	137.0	173.9
50	6000	-	-	-	13.5	21.6	34.3	54.6	87.0	109.6	139.2
100	12000	-	-	-	-	-	-	27.3	43.5	54.8	69.6
150	18000	-	-	-	-	-	-	-	29.0	36.5	46.4
200	24000	-	-	-	-	-	-	-	-	27.4	34.8
Note: 1 meter=		3.281	ft								

Appendix IV

Tender Documents

Tender Document for Solar Modules

1. General

1.1. Product

product's name ________ type: ________
manufacturer/supplier ________
adress ________
telephone/fax ________

1.2. Warranty

general warranty ________ years power warranty ________ years
peak power at purchase ________ Wp and after warranty time ________ Wp

1.3. Power approval (final inspection)

The final inspection is done by measuring power according to the ISPRA-guidelines.

1.4. Documentation

The product offered should be sufficiently documented.
The following are considered to be required:

data sheet
current-voltage-characteristics curve under STC and NOCT
dimensions and weights
information on connection box and laminate composition
efficiency as a function of irradiation, temperature and irradiation angle

2. Specifications

2.1. Electrical data

2.1.1 peak power ________ Wp nominal power under STC: ________ Wp

2.1.2 voltage
max. operation voltage ________ VDC max. open circuit voltage ________ VDC
voltage under STC ________ VDC MPP-voltage ________ VDC

2.1.3 current
MPP-current ________ A short circuit current ________ A

2.1.4 leak current ________ μA

2.1.5 module variation
power max. value ________ Wp min. value ________ Wp
voltage max. value ________ VDC min. value ________ VDC
current max. value ________ A min. value ________ A

2.1.6 efficiency under STC ________ %

2.1.7 temperature dependence
voltage coefficient ________ %/K current coefficient ________ %/K
power coefficient ________ %/K

2.1.5 protecting diodes
bypass diodes included ________ yes/no number: ________
type of bypass diodes ________

2.1.6 connections Description/plan of the electrical connections

2.1.7 classification
are the delivered
modules classified? ______ yes/no number of cl.: ______

2.1.8 material of the cell
monocrystalline, polycrystalline, amorphous or others? ______________

2.2 Mechanical data

2.2.1 dimensions
width, length, depth, weight ______ mm ______ mm ______ mm ______ kg

2.2.2 material choice
colour ______
frame construction ______________

2.2.3 attachement points The modules must have suitable points for attachement

2.2.4 grade of reflection ______

2.2.5 module tests
passed module tests, z. B. ESTI, JPL-Block V
____

2.3. Physical data

2.3.1 vapour diffusion ______ mg/(m*hPa)

2.3.2 heat conductivity ______ W/(m*K)

2.3.3. mechanical strength
admitted forces ______________ ______ N
______________ ______ N
______________ ______ N
hail resistance ______________
fire reference no. ______________

2.3.4 Dilatation
dilatation coefficient ______ /K

2.3.5 corrosion proof
salt water ______________
solvents ______________
other substances ______________

2.3.6. operation temperature
temperature under STC ______ °C

3. Costs

cost per modul ______ valuta
cost per power unit ______ valuta/Wp
transport included ______ yes/no
taxes ______________
payment conditions ______________

Place, date: ______________

Signature: ______________

Tender Document for DC-AC-Inverter

1. General

1.1. Product

product's name ________ technology: ________________

manufacturer/supplier ________________________________

adress ________________________________

telephone/fax ________________________________

1.2. Warranty

warranty time ______ years power warranty ______ years

1.3. Power approval (final inspection)

The final inspection is done by testing efficiency, MPPT-operation and control of several operation stages.

1.4. Documentation

The product offered should be sufficiently documented.
The following are considered to be required:

data sheets
curves of efficiency versus DC-input voltage and power level
list of fulfilled norms and regulations

2. Specifications

2.1. DC-input

2.1.1 power

DC-nominal power ______ W

max. allowed DC-power ______ W min. DC-power for Startup ______ W

2.1.2 voltage

nominal voltage ______ VDC MPT-range ______ VDC-VDC

isolation test voltage ______ VDC open circuit voltage ______ VDC

2.1.3 normal current ______ A

2.1.4 current ripple ______ % peak-peak

2.1.5 terminal ______ mm2-mm2

2.1.6 interferrence suppression under ________________________________

2.2. AC-output

2.2.1 power

nominal power ______ W

2.2.2 voltage

nominal voltage ______ VAC output voltage range ______ VAC-VAC

isolation test voltage ______ VAC

2.2.3 current harmonics ______ %total possible grid impedance ______

mains frequency ______ Hz mains frequency range ______ (+/-) Hz

2.2.4 cos phi under peak power ______

2.2.5 terminal ______ mm2-mm2

2.2.6 overvoltage protection level ________________________________

2.3 Efficiency

at 10% of nominal DC power: ________ %

at 50% of nominal DC power: ________ %

at 100% of nominal DC power: ________ %

no load losses ________ W

stand-by losses ________ W

2.4 Mechanical data

2.4.1 dimensions

width, length, depth mm ______ mm ______ mm

weight ______ kg

2.4.2 cooling

type of cooling ____________________

special cooling necessary? ______________

2.4.3 attachement points inverter must have suitable points for attachement

____

2.5. System data

2.5.1 environmental data
temperature range min. ______ °C max. ______ °C
humidity range min. ______ % max. ______ %
noise production min. ______ dB max. ______ dB

2.5.2 control
operating at ______ VDC shutting down at ______ VDC
reactions to DC-power overload ____________________
reactions to AC-voltage break ____________________
starting up automatically ______ yes/no time to start ______
connectable to PC ______ yes/no type of connection ______
software ____________ operating system ______

2.5.3 operation of several inverters together / master - slave
possibility ______ yes/no control ______

2.5.4 safety measures
overcurrent protection devices ____________________
possibilities for emergency shut down ____________________ yes/no
control of leak current in the pv-field ____________________ yes/no

3. Costs

costs ______ valuta
costs per power unit ______ valuta/Wp
transport included ______ yes/no
taxes ____________________
payment conditions ____________________

Place, date: ____________________

Signature: ____________________

Appendix V

Maintenance Logsheets

In this appendix a collection of logsheets is given to support the systematic maintenance of PV modules, batteries, power conditioning system etc.

It is very important to have each one of the PV modules as well as the elements of the battery bank well identified. Also, the different blocks or cards in the power conditioning or regulator system should be marked clearly.

For the power conditioning subsystem and/or regulator, the most important thing to observe is the good performance of the equipment in reference with the rest of the subsystems: PV modules, battery and loads. For this it is very useful to have volt meters and ampere meters in the DC side as well as in the AC side. To help the specialist in case of failure or bad performance, it is convenient to have the connection schemes of the equipment on hand, in which every electronic card should be well identified. Of course for all cases it is essential to have the schematic of electrical connections of the whole PV system.

W-SYSTEM MAINTENANCE
SHEET No 1

PV Array

DATE OF CHECK:	OK ?	
NAME:	yes	no
1.1 FRONTAL FACE		
* Damage/deterioration or decoloration of the encapsulating material		
* Broken cells		
* Cells decoloured		
* Bubbles		
* Humidity		
1.2 BACK FACE (If it can be surveyed)		
* Damage of connection cabling		
* Bubbles		
* Damage of connection boxes		
(Choose at random 10% of the boxes installed)		
- Corrosion		
- Humidity		
- Tightening/Screws		
1.3 CLEANING OF PV MODULES & OTHERS		
COMMENTS:		

PV-SYSTEM MAINTENANCE
SHEET No 2a

Battery

DATE:

NAME:

ELEMENT NUMBER	DATE	MONTHLY TESTS			
		CORROSION OF TERMINALS AND CONNECTORS [YES/NO]	ELECTROLYTE LEVEL	ELECTROLYTE LEAKAGE [YES/NO]	CELL VOLTAGES [V]

PV-SYSTEM MAINTENANCE
SHEET No 2b

Battery

DATE: NAME:

ELEMENT NUMBER	DATE	QUARTERLY TESTS					
		CELL VOLTAGES [V]	SPECIFIC GRAVITY [g/cm^3]	CELL TEMPERATURES [°C]	EQUALIZING CHARGE [YES/NO]	CLEANING AND RETIGHTENING [YES/NO]	CELL CRACKS [YES/NO]

PV-SYSTEM MAINTENANCE
SHEET No 3

Other System Components

DATE OF CHECK:	OK ?	
NAME:	yes	no
3.1 POWER CONDITIONING		
* Inverter:		
- wiring		
- set points		
* Regulators:		
- wiring		
- set points		
* Controllers:		
- wiring		
- set points		
3.2 BACKUP GENERATOR (see manual)		
* Leakages		
* Oil check		
* Start-up		
3.3. GROUNDING MEASUREMENT [OHMS]		
3.4 LIGHTNING PROTECTION		
COMMENTS:		

Appendix VI

Trade-Off Considerations

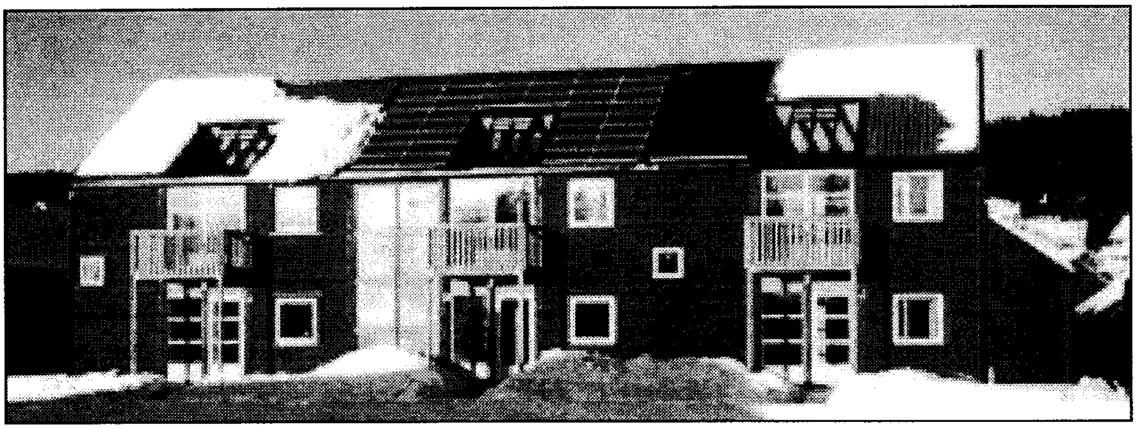


Figure VI .1 The Norwegian Low Energy Dwelling. A three apartment row house with different solutions of the use of solar energy. PV roof in the middle, solar thermal roof panel to the right and other low energy properties (not shown on picture) to the left.

Solar energy is always used in a building in one form or another. i.e. heat gain and daylighting. Extended use of solar energy might also involve photovoltaics and/or solar thermal collectors. Integration of several forms of utilization of solar energy in a building involves considerations of costs, technical performance, legal regulations, safety, environmental aspects and, of course, the architectural aspects. All these considerations must be seen in relation to the needs and wishes of the customer and the designer.

Faced with different proposals of integrating the various uses of solar energy, the decision of choosing between alternatives that must be made by the customer might be a complex task. Decision criteria with respect to the above mentioned aspects are not comparable. Further, the individual priorities may vary strongly from one customer to another, and contradictory preferences may easily occur.

Often, the decision is made in an intuitive way. This may be adequate if the customer either has a good insight into all aspects or he/she has strong preferences leading to obvious choices. In general, however, the choice is not trivial, and a decision making tool is needed by which a multi criterion optimization process is made possible. The decision process is initiated by some conflict, usually caused by the inevitable choice between various, completely different alternatives. The goal is to reduce this conflict by finding the alternative that corresponds in the "best" way to the knowledge and preferences of the decision maker.

The process of decision has several stages: conflict, predecision (rules and criteria), partial decisions (alternatives to be analysed), final decision (comparison and selection), post decision (regret or confidence) and action. All these stages involve elements of uncertainty.

A number of methods can be used in this decision process. Some of these are: Multi Attribute Utility Theory (MAUT), Social Judgement Theory, Compromise Programming, Analytic Hierarchy Process (AHP).

The AHP method, developed by the mathematician Thomas L. Saaty in 1971-75, is very simple and has become popular in multi criterion decision making. Indeed, this method can be used to decide between different alternatives in which the various uses of solar energy are integrated into buildings.

The method implies only pairwise comparisons between aspects and attributes of the projects that are subject to alternative decisions. The process is broken down into levels, where the top level is the ultimate goal: "Choose the best project". Second level is the main aspects to consider, i.e. energy savings, economy, technical issues, architectural features, and environmental considerations. Third level might be the projects themselves between which to choose. Intermediate levels with sub-attributes can be added. Pairwise comparison is then applied between attributes of one level with respect to the aspects of the above level. This way of quantification, people understand intuitively.

A simple example of use of the AHP method is included here. A software package Expert Choice (version 8) was used. Figure VI.1 shows a three apartment building, the Norwegian Low Energy Dwelling, cf. section 14.14. Rather than the actual solution shown in Figure VI.1, one might consider these three sections of the house as three different projects in which the use of solar energy is different (3rd level):

Alt. 1: PV.
  The whole south-facing roof is covered with photovoltaic cell modules,
Alt. 2: THERMAL.
  The whole roof is covered with thermal collectors,
Alt. 3: 50/50.
  PV and Thermal collectors share the surface of the roof.

These three alternatives are specified this way only to visualise the AHP method in a simple way. Note that the alternatives do not correspond to the solar energy installations implemented in the Norwegian Low Energy Dwelling as seen in the figure.

The three example projects defined above (3rd level) are compared using four different criteria (2nd level): economy, technical performance, environmental friendliness and architectural quality.

The pairwise comparison is given as a number 1 through 9 on a fundamental scale which reflects the relative strength of preference and/or feeling, or a real number reflecting the result of some calculation. The number 1 means the two aspects are of equal importance and the number 9 means the first aspect is of extreme importance over the second. Numbers are reciprocals when the comparison is taken the opposite way.

One example: Thermal collectors are strongly favoured over photovoltaic cells with respect to costs, i.e. the number 7 might be assigned to this pair between level 3 and 2. Further, one decision maker might put a rather strong weight on economy compared to architectural beauty, so the number 5 might be relevant to this pair between level 2 and 1.

Without going into detail, the numbers specified by the user in this manner are input to the Expert Choice software. This software then collects the preference numbers in input matrices. Eigenvectors are calculated, normalized and put into new matrices, which are multiplied giving a vector containing the relative (normalized) priority of the projects at the bottom level.

Having done this, the software offers simple procedures for doing 'what-if analyses, or sensitivity calculations.

The result can be displayed graphically as shown in Figure VI.2 below.

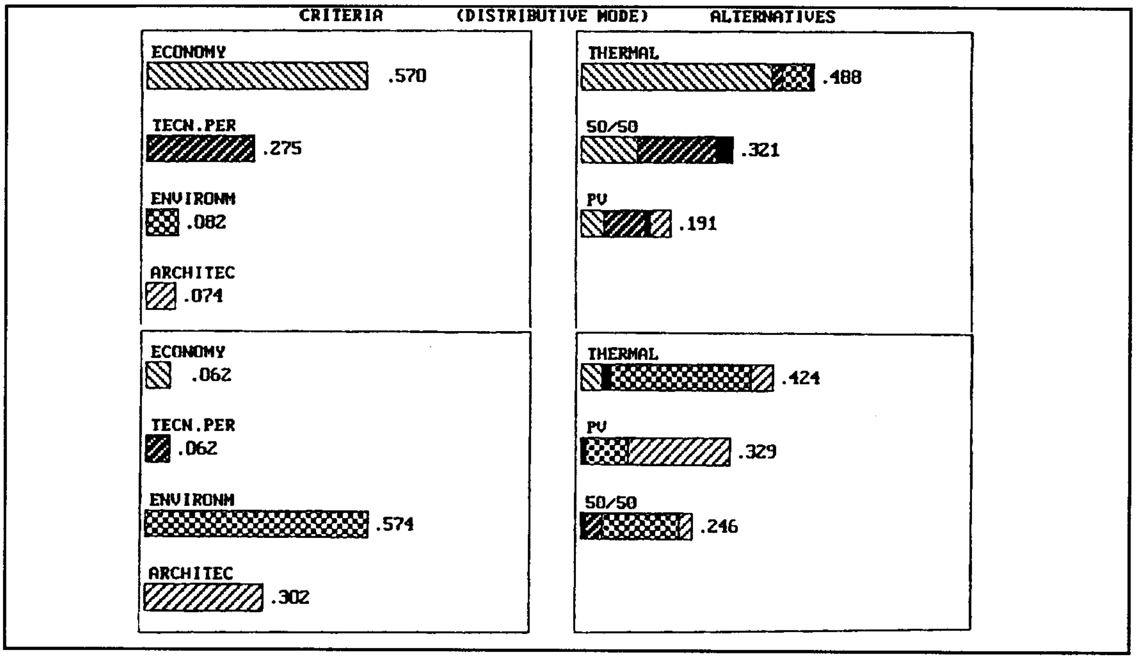


Figure VI.2 Graphical representation of criteria and the decision between alternatives for two different types of decision makers. The upper (left) part shows a decision maker that cares about economy and technical performance much more than environmental and architectural aspects. The right part shows the final decision: Solar thermal is favoured. The lower (left) part shows a somewhat opposite opinion. Environmental and architectural aspects are weighted over economy and performance. This changes the ranking between PV and the 50/50 solution, but it still favours the solar thermal alternative.

The pattern in each of the bars shows the contribution to the final decision from the attributes to the left. This can easily be used interactively to do sensitivity studies (whatif-studies). By changing the weight on the aspects at level 2, the software will immediately show the response to the final decision.

Both these two cases ended up with the solar thermal alternative as the favourable choice. Let us now see in what way the weight of the criteria have to be altered in order to end up with the other two alternatives. This effect is shown in Figure VI.3 below.

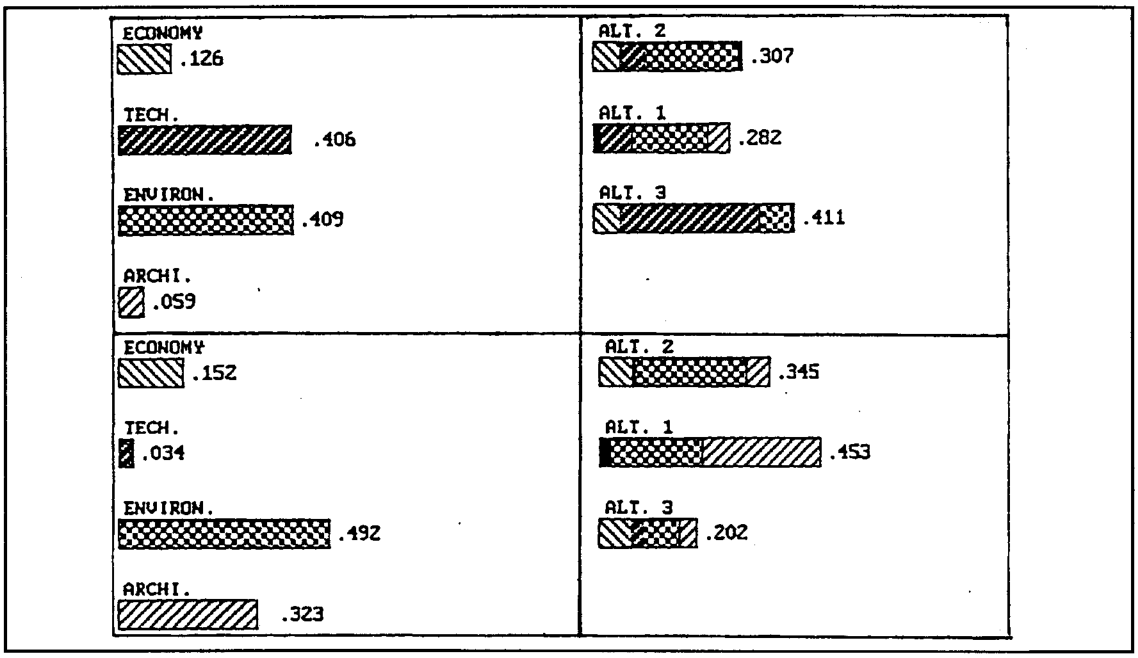


Figure VI.3 Sensitivity analysis showing the necessary changes in the weighting profile of the four criteria at level 2. If technical performance is emphasized along with environmental issues at the expense of the other two (economy and architectural features), it is seen from the upper part of the figure that the favourable choice is the mixed system. However, if the importance of technical performance is strongly reduced, and weight is mainly put on environmental and architectural features, it is seen from the lower part of the figure that the PV alternative is favoured over the other two.

Of course, these results do not hold in general. They are strongly dependent on the underlying technical and economical analysis of the given projects, which results in the preference numbers explained above. This underlying analysis is not shown here. It is, however, emphasizes that detailed studies of costs and technical performance using separate simulation software should give realistic and reliable input to the decision tool. Even the environmental and architectural features of a given set of project alternatives could be given a well defined, although sometimes subjective and qualitative value for the alternatives in question.

From these rather simple examples it is illustrated that the AHP method can virtually any conclusion. This might be held up as a disadvantage of the method. In fact, it should be looked upon as an advantage. The reason is that the method offers a simple way of tracing and documenting the user's preferences.

If the conclusion is unexpected, it can be seen from the different steps in the reasoning, why that particular alternative was ranked on top, and also what kind of changes in preferences are needed to alter the conclusion. If these alterations seem unreasonable in some way to the user, then even quite unexpected, and even unpopular, conclusions must be accepted by the decision maker.

Appendix VII

Glossary

Alternating Current (AC)	Electric current in which the direction of flow is reversed at frequent intervals, usually 100 or 120 times per second (50 or 60 cycles per second or 50/60 Hz).
Amorphous silicon	Silicon in which the atoms are not arranged in an ordered pattern like in crystalline silicon.
Ampere (A)	The unit for the electric current.
Ampere-hour (Ah)	Quantity of electricity or measure of charge. 1 Ah = 3600 C (Coulomb).
Array	See Photovoltaic array.
Atrium	Large, top-lit space rising through several floors in modern buildings.
Autonomous system	A stand-alone photovoltaic system which has no back-up generating source. May or may not in-dude storage batteries.
Awnings	Covering, to screen persons or parts of buildings from the sun or rain.
Back-up generator	Supplementary electricity source to ensure full-time cost-effective electricity supply.
Balance of system	The parts of a photovoltaic system other than the array: switches, controls, meters, power conditioning equipment, supporting structure for the array and storage components, if any.
Batten	Small rectangular piece of timber used to provide fixings for tiles or slates. Cover-slip concealing the joint between two boards, or a strip of timber fixed across two parallel boards to join them together.

Batten seam	Joint in a metal roof formed over a wooden strip or roll.
Battery capacity	Amount of ampere-hours or watt-hours that can be discharged from the battery under specified conditions of discharge (cut-off voltage, current and temperature).
Battery charge regulator	An electrical device used to keep current from running backwards through an array at night or during periods of low sunlight, thereby preventing drainage of the storage battery.
Breastwall	Retaining wall, or parapet which is breast-high.
Building envelope	The outside of a building that contains the interior space, including the roof: the skin or waterproof covering of the structure.
Bypass diode	A bypass diode is connected anti-parallel across a part of the solar cells of a PV module. It protects these solar cells from thermal destruction in case of total or partial shading of individual solar cells whilst other cells are exposed to full light.
Blocking diode	A blocking diode is connected in series to a PV string; it protects its modules from a reverse power flow and thus against the risk of thermal destruction of solar cells.
Cell	See Photovoltaic cell.
Cladding	External face or skin of a building.
Clerestory	Any window, row of windows, or openings in the upper part of a building.
Curtain wall	Non-load-bearing wall placed as a weather-proof membrane round a structure, and usually made of glass or metal.
Cycle life	Amount of discharge-charge cycles that a battery can tolerate under specified conditions before it fails to meet specified criteria as to performance (e.g. capacity decreases to 80% of the nominal capacity).

Direct current (DC)	Electric current in which electrons flow in one direction only. Opposite of alternating current.
DC to DC Converter	????????
Discharge rate	The rate, usually expressed in amperes or time, at which electrical current is taken from the battery.
DOD	100% - SOC (see SOC).
Electrical grid	An integrated system of electricity distribution, usually covering a large area.
Electrolyte	A liquid conductor of electricity.
Energy density	The ratio of the energy available from a battery to its volume (Wh/l) or mass (Wh/kg).
Flashing	Piece of metal led into the joints of brickwork to lap over a gutter, or set along the slates of a roof, to prevent water from penetrating at the junctions. To flash is to make water-tight joints.
Float life	Number of years that a battery can keep its stated capacity when it is kept at float charge (see float charge).
Float charge	Float charge is the voltage required to counteract the self-discharge of the battery at a certain temperature.
Gassing current	Portion of charge current that goes into electrolytical production of hydrogen and oxygen from the electrolytic liquid. This current increases with increasing voltage and temperature.
Gel-type battery	Lead-acid battery in which the electrolyte is composed of a silica gel matrix.
Grid	See electrical grid.
Grid-connected (PV System)	A PV system in which PV arrays act like central "generating plants" supplying power to the grid. Either the PV system is operated by the utility, or (in what is known as a grid-interactive system) individual buildings in the grid are equipped with PV systems that feed into the grid when they generate

	excess power, and draw from the grid at night and in periods of low sunshine.
Grid-interactive (PV system)	See Grid-connected (PV system).
Hybrid PV system	A PV system that includes other sources of electricity generation, such as diesel or wind generator.
Inverter	A PV inverter is a power converter which transforms DC voltage and current of the PV generator into single or multiphase AC voltage and current.
IP	Ingress protection, describes with two figures the protection level against mechanical impact and water penetration.
Junction box	A PV generator junction box is an enclosure where all PV strings are electrically connected and where protection devices can be located, if necessary.
Kilowatt-hour (kWh)	One thousand watts acting over a period of one hour. The kWh is a unit of energy. 1 kWh = 3600 kJ.
Line-commutated inverter	An inverter that is tied into a power grid or line. The commutation of power (Conversion from DC to AC) is controlled by the power line, so that if there is a failure in the power network, the PV system cannot feed power into the line.
Load	Anything in an electrical circuit which, when the circuit is turned on, draws power from that circuit.
Maximum power point	The point on a current-voltage (IV) curve where maximum power is produced. For a typical silicon cell this is at about 0.45 V.
Maximum power point tracker	???????
Module	See photovoltaic module.
Mullion	Slender pier which forms the division between the lights of a window, a screen or an opening.

Mullion/Transom	A popular facade construction often used with curtain wall facades. It consits of vertical beams, mullions, and smaller, horizontal beams, transom.
Multicrystalline silicon	Silicon that has solidified at such a rate that many small crystals (crystallites) were formed. The atoms within a single crystallite are symetrically arranged, whereas the crystallites are jumbled together. "Multi" is used interchangeably with the prefix "poly".
Muntin	Upright piece of timber in a frame, separating panels. cf. mullion.
Ohm	The unit of resistance to the flow of an electric current.
Open-circuit voltage (V_{OC})	The voltage across an illuminated photovoltaic cell or module when there is no current flowing; the V_{OC} is the maximum possible voltage.
Overhang	Projection of a storey or any part of the building beyond a storey below or in front of the naked wall.
Parallel connection	A method of interconnecting two or more electricity-producting, or power-using devices, such that the voltage produced, or required, is not increased, but the current is additive. Opposite of series connection.
Parapet	Low wall to protect any place where there is a drop, as at the edge of a roof, balcony, terrace...
Panel	See Photovoltaic panel.
Peak watts (W_P)	The amount of power a photovoltaic cell or module produces at maximum irradiation conditions.
Photovoltaic (PV) array	An interconnected system of photovoltaic panels that functions as a single electricity-producing unit. The panels are assembled as a discrete structure, with common support or mounting. In smaller systems, an array can consist of a single panel plus support structure or mounting.
Photovoltaic (PV) cell	A photovoltaic cell is the smallest semi-conductor element within a PV module to perform the imme-

	diate conversion of light into electrical energy (DC voltage and current).
Photovoltaic (PV) generator	A PV generator is the total of all PV strings of a PV power supply system, which are electrically interconnected.
Photovoltaic (PV) module	The term "module" is often used interchangeably with the term "panel".
Photovoltaic (PV) panel	A group of modules fastened together and wired in either series or parallel. The term "panel" is often used interchangeably with the term "module".
Photovoltaic (PV) string	A PV string is a series connection of individual modules or equal groups of several paralleled modules.
Photovoltaic (PV) system	A complete set of components for converting sunlight into electricity by the photovoltaic process, including array and balance of system components.
Polycrystalline silicon	See multicrystalline silicon.
Power density	The ratio of the power available from a battery to its mass (W/kg) or volume (W/l).
Power conditioning equipment	Electrical equipment used to convert power from a photovoltaic array into a form suitable for subsequent use. A collective term for inverter, converter, battery charge regulator and blocking diode.
Remote	Here: not connected to a utility grid.
Semiconductor	Any material that has limited capacity for conducting an electric current. Certain semiconductors, such as silicon and gallium arsenide, are well suited to the photovoltaic conversion process.
Series regulator	??????
Series connection	A method of interconnecting devices that generate or use electricity so that the voltage, but not the current, is additive. Opposite of parallel connection.
Shed	Kind of flat roof skylight.

Shelf life	The length of time under specified conditions that a battery can be stored so that it keeps its guaranteed capacity.
Short circuit current (I_{sc})	The current flowing freely from an illuminated photovoltaic cell or module through an external circuit that has no load or resistance; The I_{SC} is the maximum current possible.
Shunt regulator	??????
Skylight	Frame containing glass or translucent/transparent material, set in a roof, fixed or opening.
SOC	State Of Charge, the available capacity remaining in the battery expressed as a percentage of the rated capacity.
Solar cell	Same as photovoltaic cell.
Standard Test Conditions (STC)	Solar irradiation: 1000 W/m2 Cell temperature: 25 °C Spectrum: AM 1.5
Stand-alone (PV system)	An autonomous or hybrid photovoltaic system not connected to a grid. May or may not have storage, but most stand-alone systems require batteries or some other form of storage.
Stand-off mounting	Technique for mounting a PV array on a sloped roof that involves mounting the modules a short distance above the pitched roof and tilting them to the optimum angle.
Structural glazing	A system of retaining glass or other materials to the aluminium members of a curtain wall using silicon sealant. These systems use no mechanical fasteners, and as a result, have no profiles which cast shadows on the glazing surface.
Surge protection	??????
Transom	Horizontal bar dividing a window or opening into two or more lights in height.

Trickle charge	A charge at a low rate, balancing losses through self-discharge to maintain a cell or battery in a fully charged condition.
Truss	Combination of timbers to form a frame, placed at intervals, carrying the purlins. As well as a frame, of timber or metal, the term means a projection from the face of a wall, or a large console.
VAC	Volts AC
VDC	Volts DC
Volt (V)	The unit of voltage which is a measure of the force or "push" given the electrons in an electric circuit. One volt produces one amp of current when acting against a resistance of one ohm.
Watt (W)	The unit of electric power or amount of work (J) done in a unit of time. One amp of current flowing at a potential of one volt produces one watt of power.
Watt-hour (Wh)	A unit of electric energy. One watt-hour is consumed when one watt of power is used for a period of one hour.