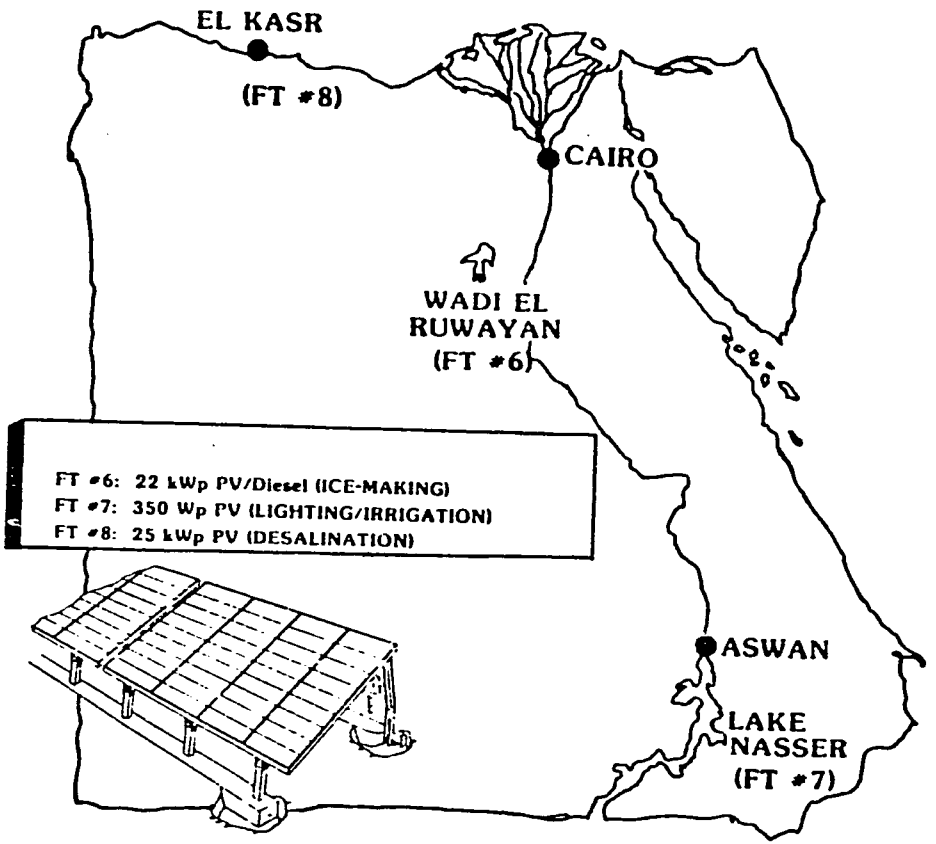
PN-ABA-411
ISN 57183

2.

EGYPTIAN RENEWABLE ENERGY FIELD TESTING PROJECT

INTRODUCTION TO PHOTOVOLTAIC SYSTEM APPLICATIONS

Egypt Renewable Energy Field Tests



Prepared for:

[redacted]

Prepared by:

MERIDIAN CORPORATION
Falls Church, Virginia USA

13 May 85
PN-ABA-411

BRIEFING AGENDA

- PV SYSTEMS-A DEFNITION
- PV SYSTEM COMPONENTS
- SYSTEM APPLICATIONS
- ELEMENTS OF PV SYSTEM CONCEPTUAL DESIGN
- CONSIDERATIONS FOR SYSTEM INSTALLATION, OPERATION, REPAIR, AND MAINTENANCE

PV ENERGY SYSTEM DEFINITION

A PHOTOVOLTAIC ENERGY SYSTEM CONSISTS OF THE COMPONENTS NECESSARY TO CONVERT SUNLIGHT INTO A USEFUL END PRODUCT (DC OR AC ELECTRICITY, POTABLE WATER (PUMPED, PURIFIED, DESALINATED), LIGHTING, REFRIGERATION, COMMUNICATIONS, GROUND GRAIN, ETC.)

THIS BROAD DEFINITION IS REQUIRED BECAUSE:

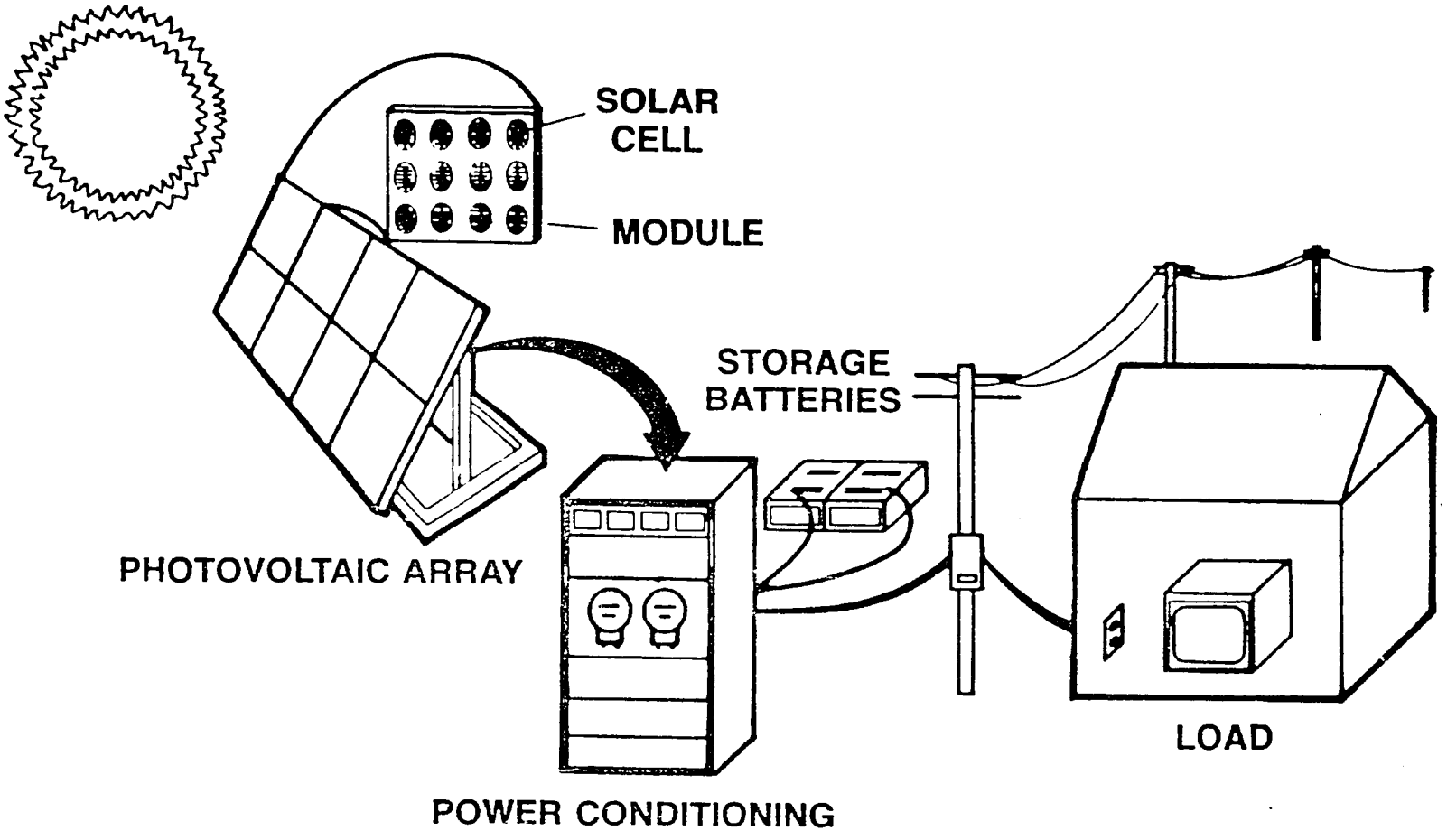
1) MANY END USE DEVICES ARE SPECIFICALLY DESIGNED FOR PV POWER, AND

2) MODULES, BATTERIES, CONTROLLERS, INVERTERS AND DIESEL OR WIND EQUIPMENT (HYBRID SYSTEMS) ARE DESIGNED TO OPERATE AS A "SYSTEM" MATCHING SOLAR RESOURCE WITH LOAD CHARACTERISTICS

PV SYSTEM COMPONENTS

- PHOTOVOLTAIC CELL
- MODULE, PANEL, (STRING), SUBARRAY, ARRAY
- REGULATOR/CONTROLLER
- STORAGE: BATTERY, PRODUCT
- BACK-UP: DIESEL, WIND, GRID
- POWER CONDITIONING-INVERTER, REGULATOR
- END USE DEVICES
- WIRING, JUNCTIONS, SWITCHES, GROUNDING EQUPMENT, MOUNTING HARDWARE, ETC.

PHOTOVOLTAIC SYSTEM



PHOTOVOLTAIC ENERGY SYSTEMS MATCH RESOURCE TO LOADS BY:

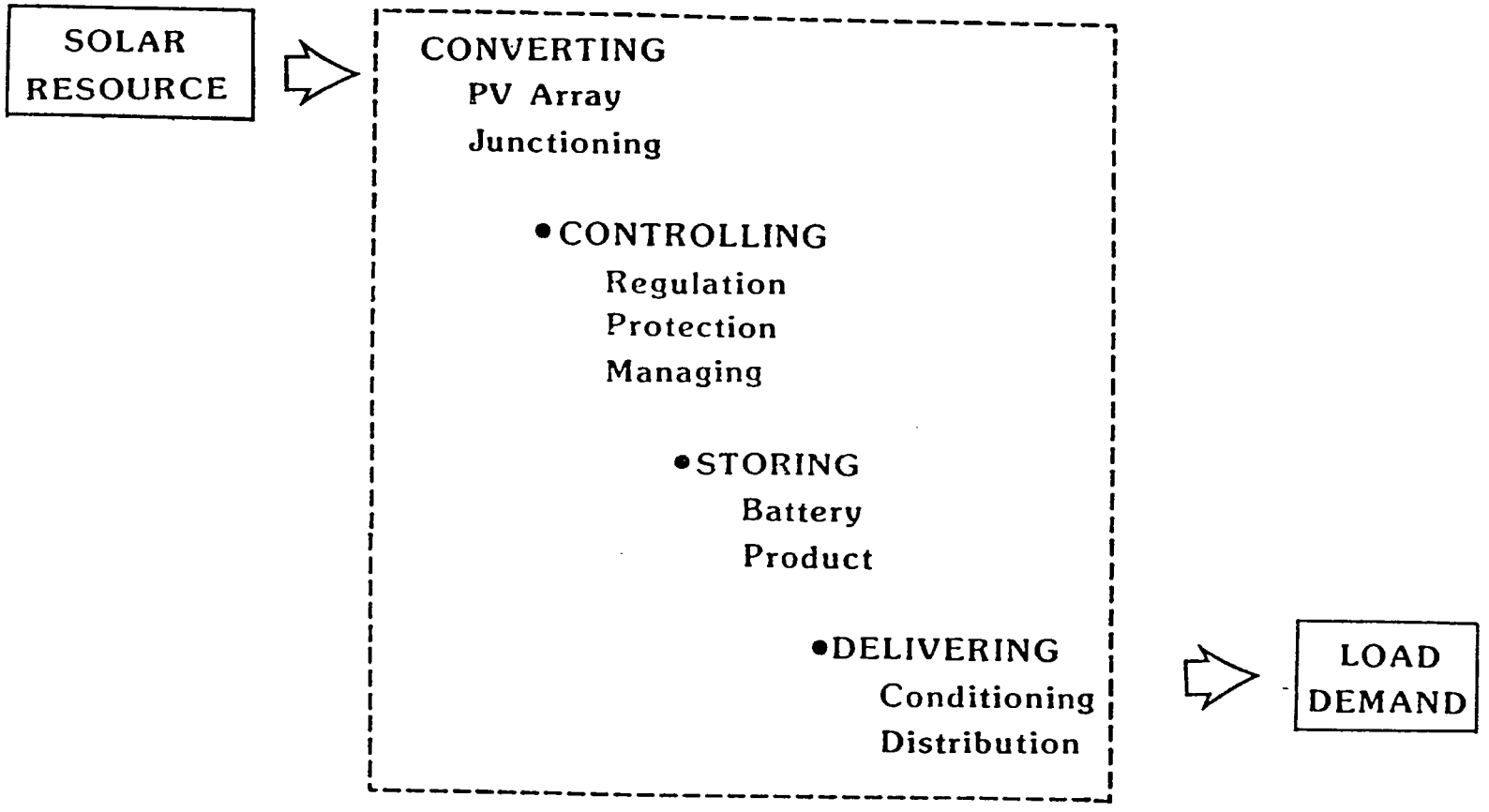


Figure 5. PV System Components

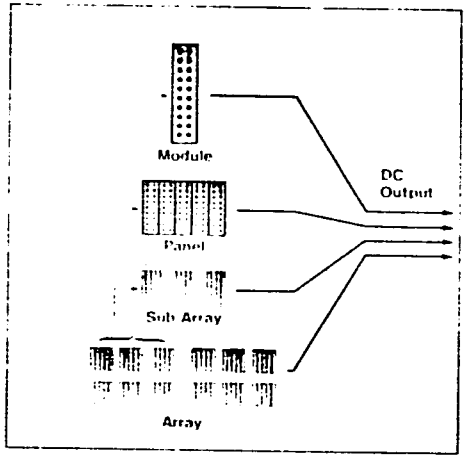


Figure 6. PV System Components

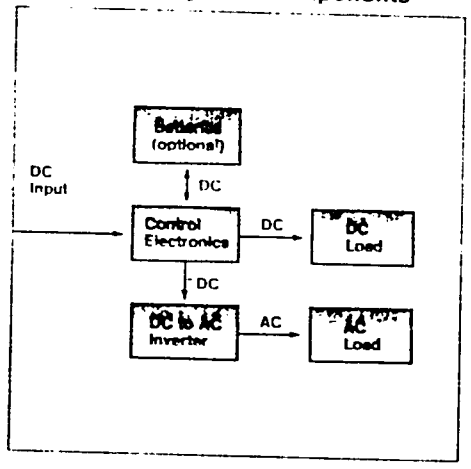
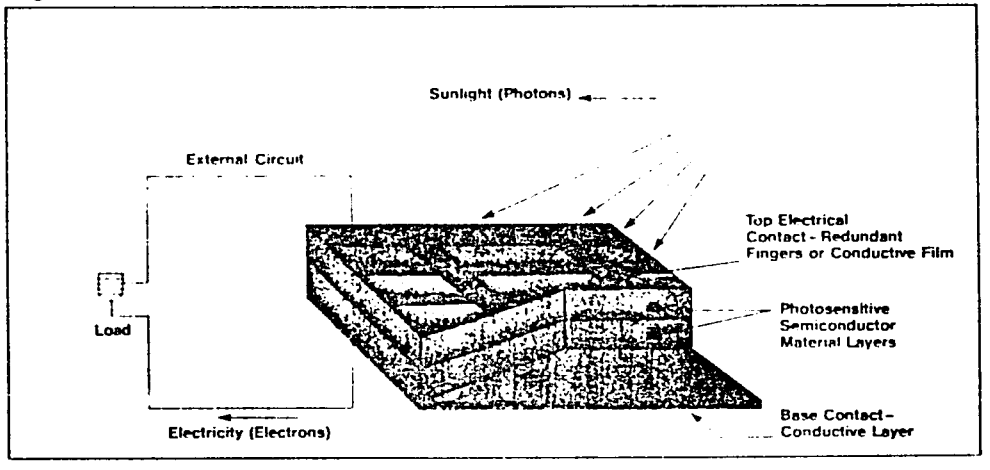


Figure 4. Basic Solar Cell Construction

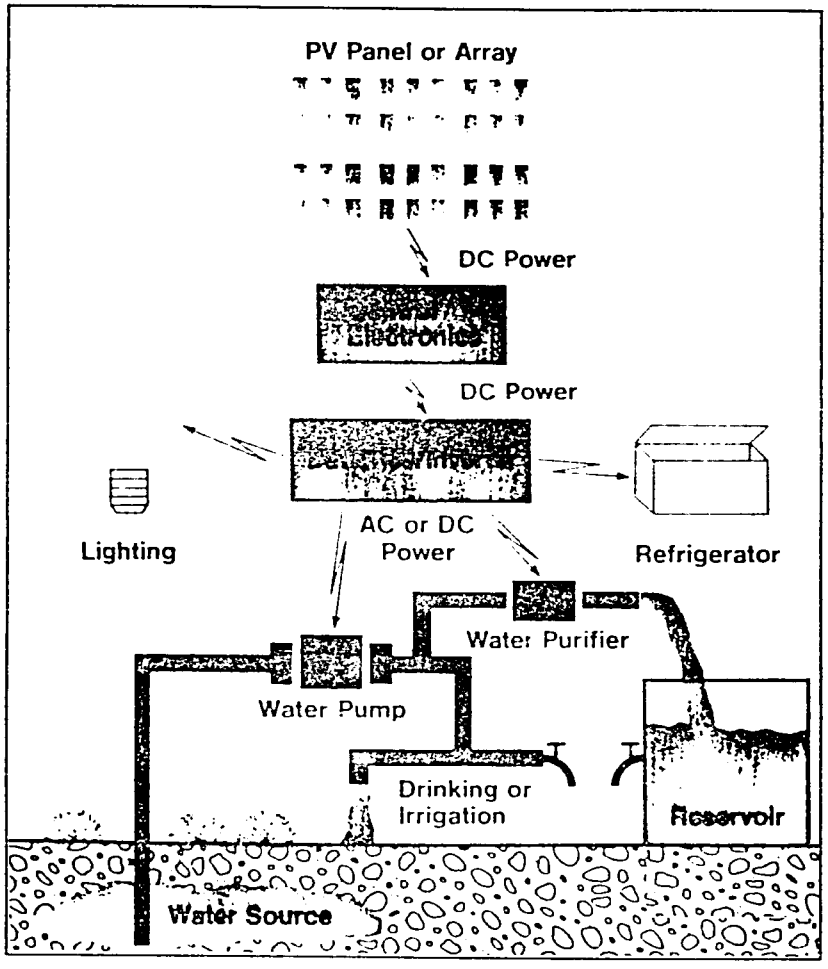


SLIDES

- SINGLE CRYSTALLINE MODULE
- SEMI-CRYSTALLINE MODULE
- ARRAY, MODULE, STRING, PANEL (20 kW KUMAKA, GUYANA)
- ARRAY (3 kW SAND CREEK, GUYANA)
- CONTROLLER
- BATTERIES
- INVERTERS
- LIGHTS (FLUORESCENT)
- LIGHTS (LPSV)
- REFRIGERATOR/FREEZER
- RADIO
- STERILIZER
- PUMP

PV SYSTEM APPLICATIONS

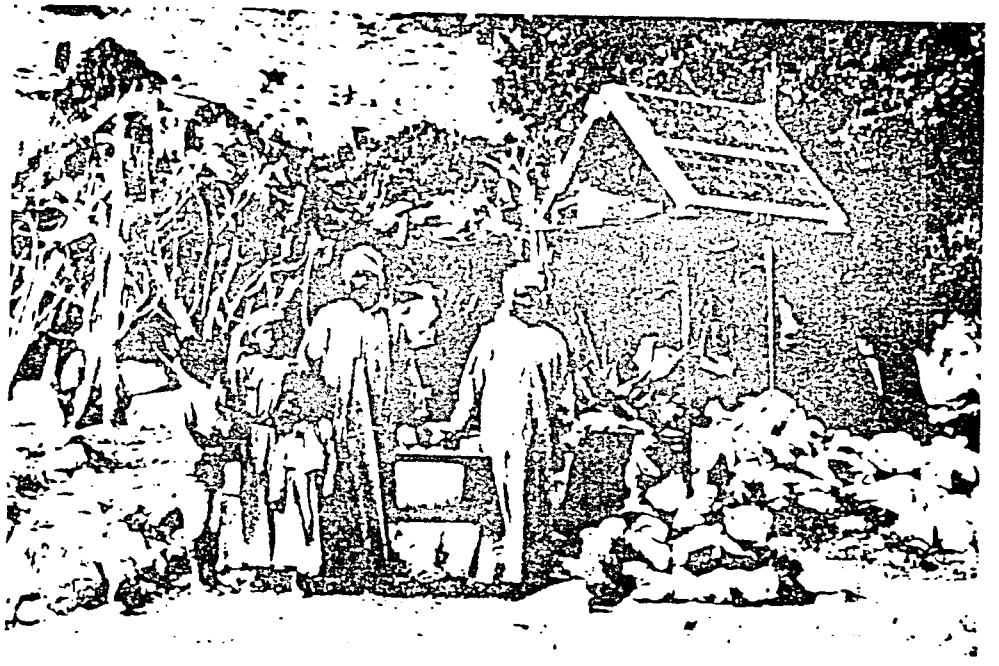
- EXAMPLES-



TYPICAL RURAL ELECTRIFICATION SYSTEM

Since 1981, a 68 W$_p$ Educational TV system has provided training and entertainment for the 35 inhabitants of a rural village in Oman

5.



A separate 1.5 kW_p system installed at Hammam Biadha Sud in 1983 pumps up to 750 m^3 (198,000 gal.) monthly from a 1.5 m (50 ft.) well to irrigate one hectare of fruit trees.

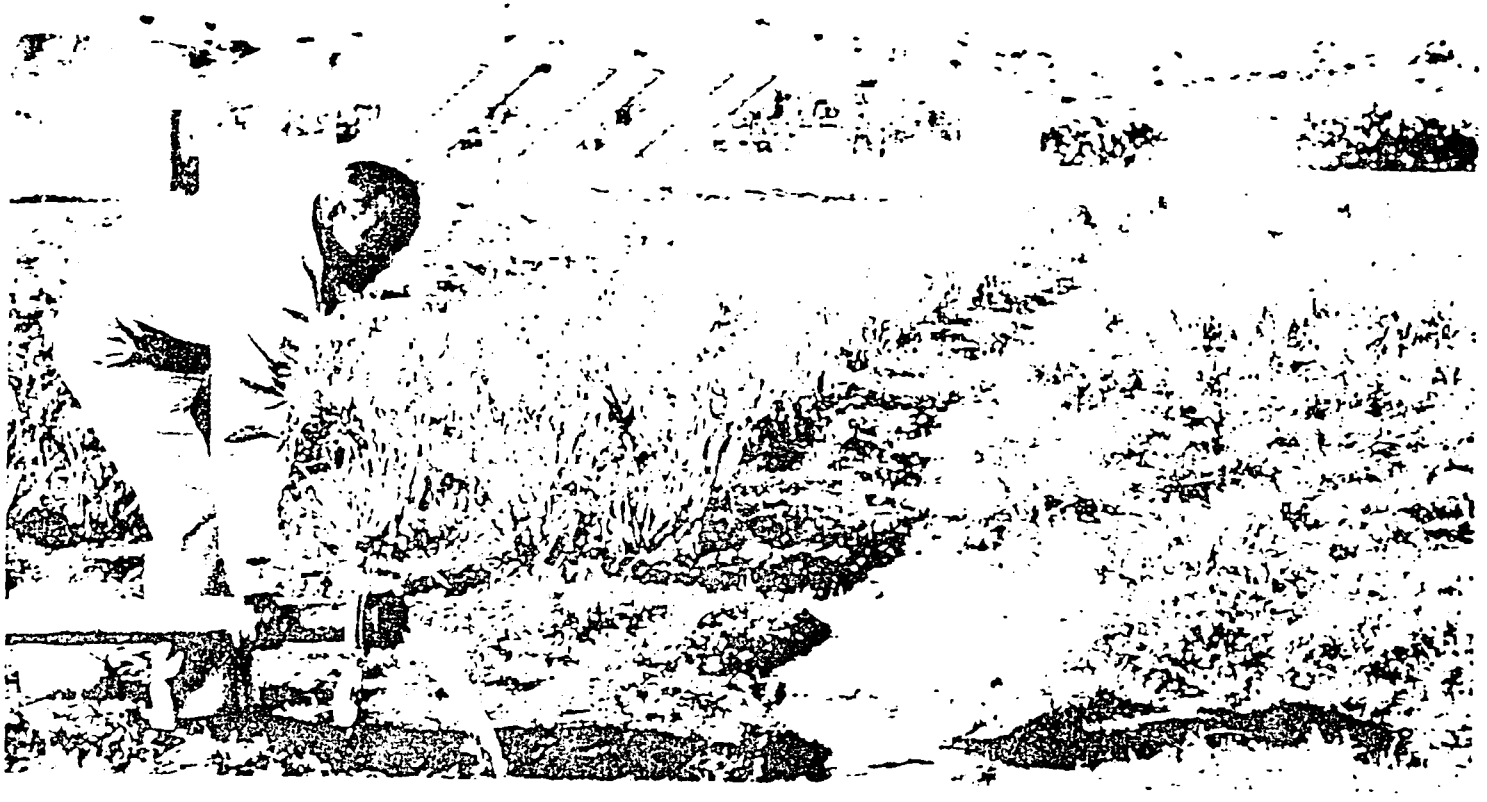
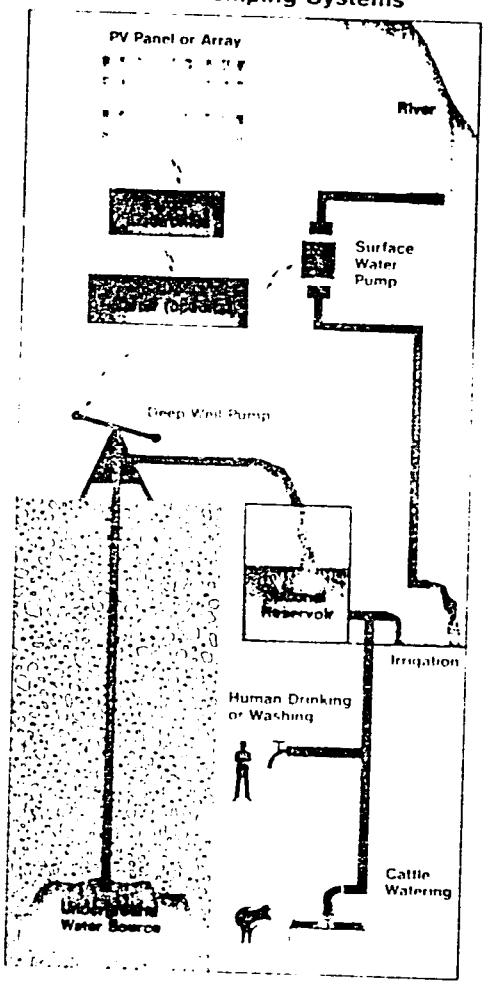
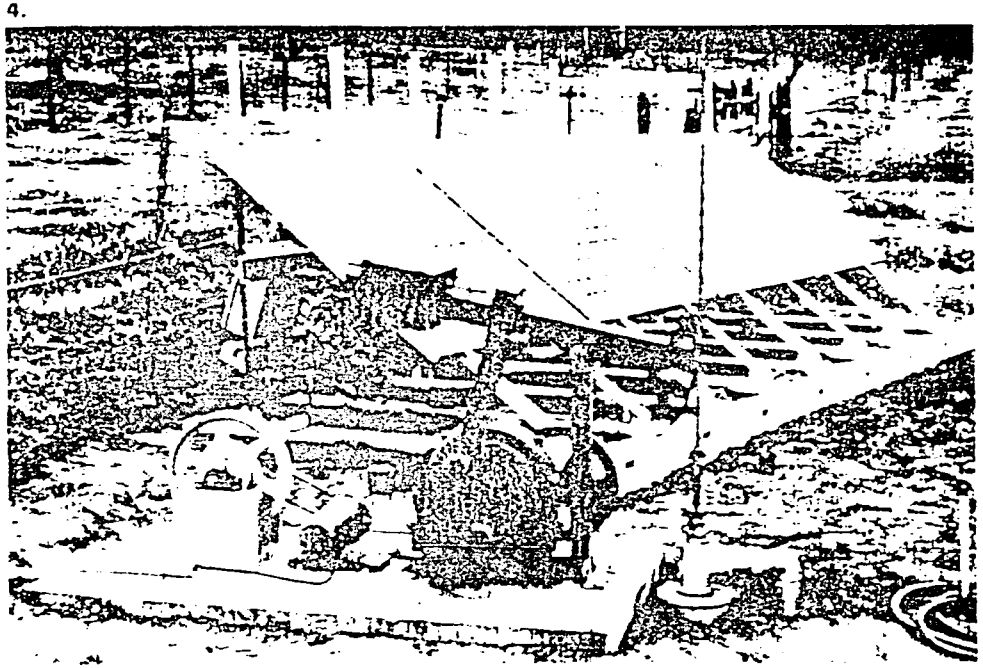


Figure 10.
Typical Water Pumping Systems

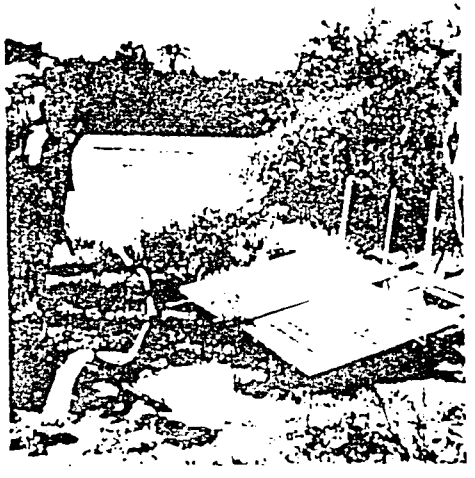


4.



4.

In California, a 600 W_p system pumps up to 5.7 m^3 (1500 gal.) daily from a 45 m (150 ft.) well to supply drinking water for an Indian community (1981)

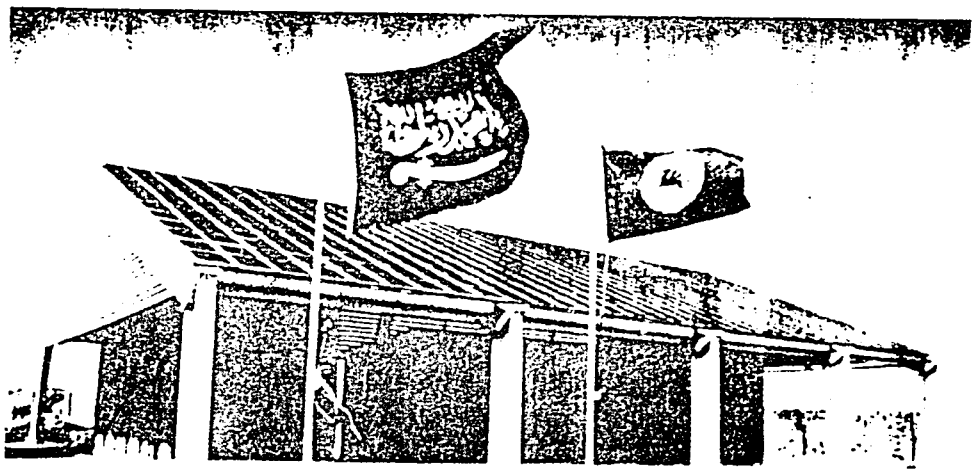


3.

A portable 300 W_p surface water pumping system has been in use in Basaisa Village, Egypt since 1979 to provide up to 45 m^3 (12,000 gal.) daily for irrigating farms around the village.

An 8 kW_p desalination system provides up to 2.3 m^3 (600 gal.) of fresh water daily for the city of Jeddah, Saudi Arabia. Sea water with 43 000 parts per million (ppm) salt is converted to fresh water with less than 100 ppm salt. (1981)

1.



SLIDES

MEDICAL SYSTEMS - Africa, South America

ELEMENTS OF CONCEPTUAL DESIGN

1. LOAD EVALUATION

2. RESOURCE EVALUATION

3. STORAGE REQUIREMENT
   - ENERGY OR PRODUCT SUPPLY RELIABILITY
   - BATTERY
   - BACKUP SYSTEM (DIESEL)

4. DETERMINE WORST MONTH RESOURCE AND LOAD MATCH (LOW RESOURCE, HIGHEST LOAD)

5. ARRAY SIZING

6. BATTERY SIZING

7. BOS SIZING
   - CONTROLS
   - INSTRUMENTATION
   - WIRING
   - SWITCHES

8. END USE DEVICES

Energy and Power

Energy

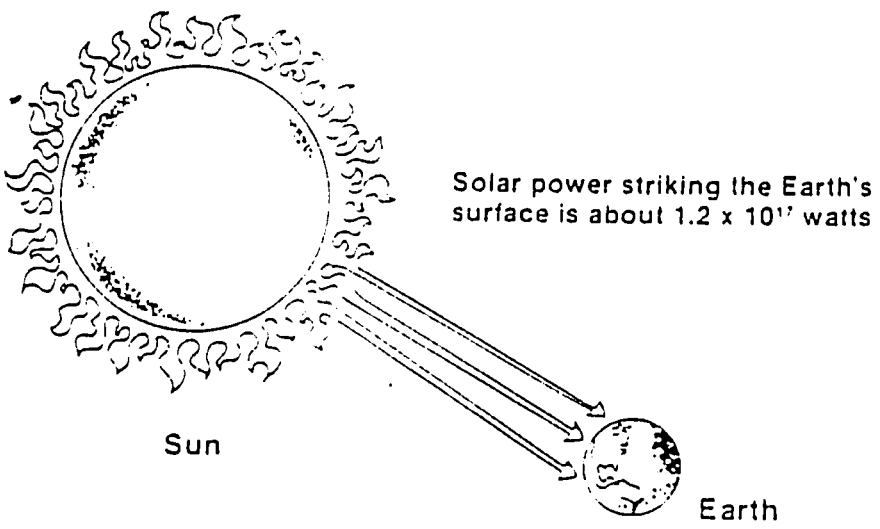
- Capacity for doing work
- Symbol: E
- Units: kWh

Power

- Rate of doing work
- Symbol: P
- Units: kW, or watts

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

Solar power reaching earth



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1. LOAD EVALUATION

- o WHAT IS THE PRESENT ENERGY LOAD?
- o HOW IS THIS LOAD BEING SUPPLIED?
- o WHAT WILL BE THE EFFECT OF SUBSTITUTING PV FOR HUMAN OR ANIMAL LABOR OR PETROLEUM ENERGY?
- o EVALUATE LOAD CHARACTER
  - PUMPING - WATER DEPTH, WELL (SOURCE) YIELD (PEAK AND AVERAGE), QUALITY, DISTANCE FROM POINT OF USE, EXISTENCE OF STORAGE TANK, AMOUNT REQUIRED PER HOUR, DAY, MONTH. CRITICAL SUPPLY PERIODS AND AMOUNTS.
  - LIGHTING - INTENSITY, USE (HOURS/DAY), AVAILABILITY OF SPARE BULBS/BALLASTS, DESIGN OF LIGHT (PORTABLE, FIXED).
  - DESALINATION - WATER QUALITY, AMBIENT TEMPERATURE, HUMIDITY.
  - REFRIGERATION - AMBIENT TEMPERATURE, FREQUENCY OF ACCESS, REGRIGERATED PRODUCTS (TEMP. CHANGE, AMOUNT, FREQUENCY)
  - RURAL ELECTRIFICATION - LOCAL VOLTAGE LEVEL(S); FREQUENCY, END USE DEVICES.
  - AGRICULTURAL - QUALITY OF GRAIN, AMOUNT, IRRIGATION METHODS, ETC.

- ESTIMATE AVERAGE AND PEAK LOADS BY HOUR, DAY, AND MONTH IN WATTS AND WATT-HOURS
- DETERMINE LOAD PROFILE

2. RESOURCE EVALUATION

- SUNSHINE METERS, PYRANOMETERS, HELIOPYRANOMETERS
- SITE-SPECIFIC DATA IS BEST FOR PROPER SIZING
- INSOLATION INSTRUMENTATION SHOULD REPLICATE ARRAY AND ENVIRONMENT (TILT ANGLE, SAND, HEIGHT ABOVE GROUND)
- COMPUTER MODELS OF ARRAY OUTPUT AT VARIOUS TILT ANGLES ARE GENERALLY INACCURATE ($\pm$ 10%)
- 4-7 KWH/M^2/DAY ACROSS EGYPT

3. STORAGE REQUIREMENTS

- o RELIABILITY OF LOAD
- o NUMBER OF DAYS OF "NO SUN"
- o TYPES OF STORAGE
  - PRODUCT (WATER, GRAIN, COLD, ETC.)
  - BATTERY (DEEP CYCLE, SHALLOW CYCLE)
  - BACKUP (DIESEL)

4. "WORST" MONTH

- o DESIGN TO MEET LOAD 100% - USE "WORST MONTH"
- o DESIGN FOR AVERAGES - PROGRESSIVE DISCHARGE/CHARGE

5. ARRAY SIZING

- o ARRAY ORIENTATION
  - SUN ALTITUDE (± 23.5° FROM EQUATOR)
  - MONTHLY AVERAGES SOLAR DECLINATION
- o CELL TEMPERATURE EFFECTS ON PERFORMANCE
  - VOLTAGE IS INVERSELY PROPORTIONAL TO TEMPERATURE (2.4 mV/°C/CELL, 25°C REF.)
  - CURRENT IS PROPORTIONAL TO TEMPERATURE (25MA/°C/cm^2, 25°C REF.)
- o PROTECTION FROM "KNEE OF THE I-V CURVE"

6. BATTERY SIZING

- o DAYS OF STORAGE
- o DEPTH OF DISCHARGE
- o TEMPERATURE

Irradiance, or Radiant-flux density

- Radiant power per unit area
- Symbol: H
- Units: kW/m^2, or watts/m^2, or mw/cm^2
- Measurement: Pyranometer (e.g., Eppley PSP)
  Reference (solar) cells
- Peak value: 1 kW/m^2 (1000 watts/m^2, 100 mw/cm^2)
- Nominal value: 0.8 kW/m^2 (800 watts/m^2, 80 mw/cm^2)

Solar constant

The irradiance on a surface normal to the sun's rays immediately outside the earth's atmosphere (AM0).

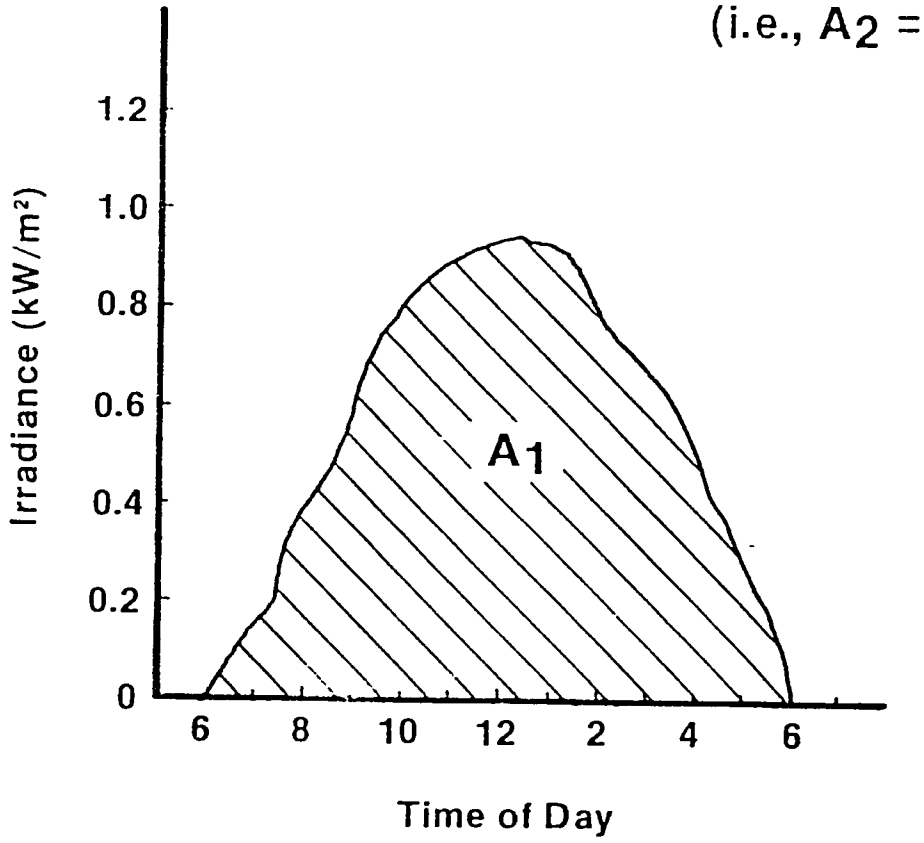
Solar constant = 1.353 kW/m^2 (428 $Btu/hr \cdot ft^2$)

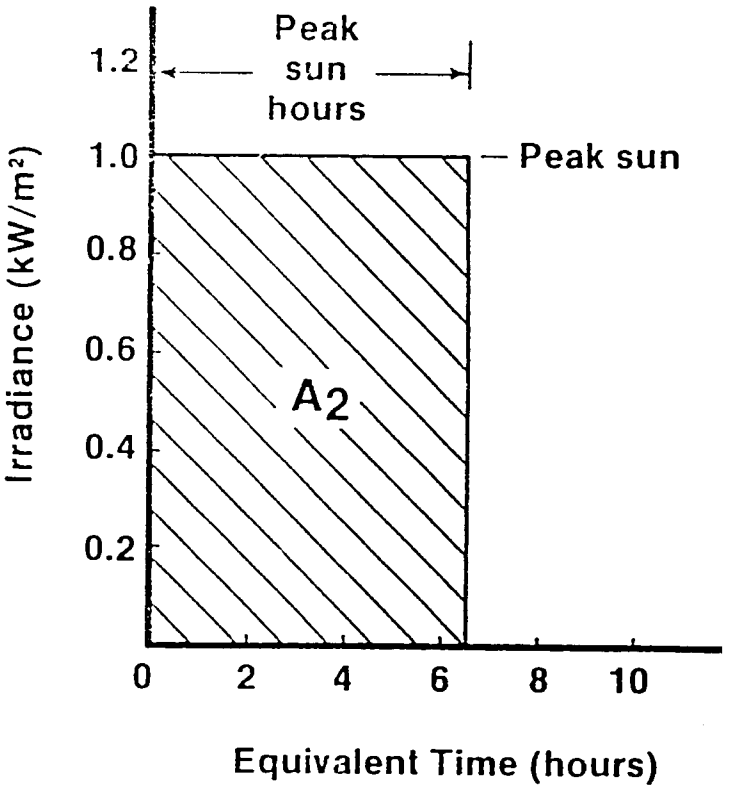
Insolation

- Radiant energy per unit area
- Irradiance summed over time
- Units: kWh/m^2

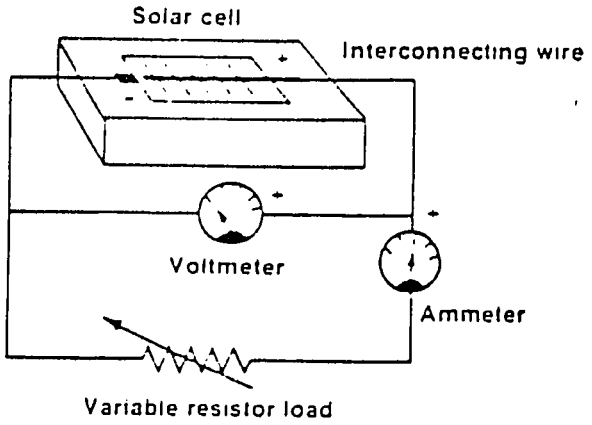
Peak sun hours

The number of peak sun hours per day at a given location is the equivalent time (in hours) at peak sun condition (i.e., 1 kW/m²) that yields the same total insolation (i.e., $A_2 = A_1$).



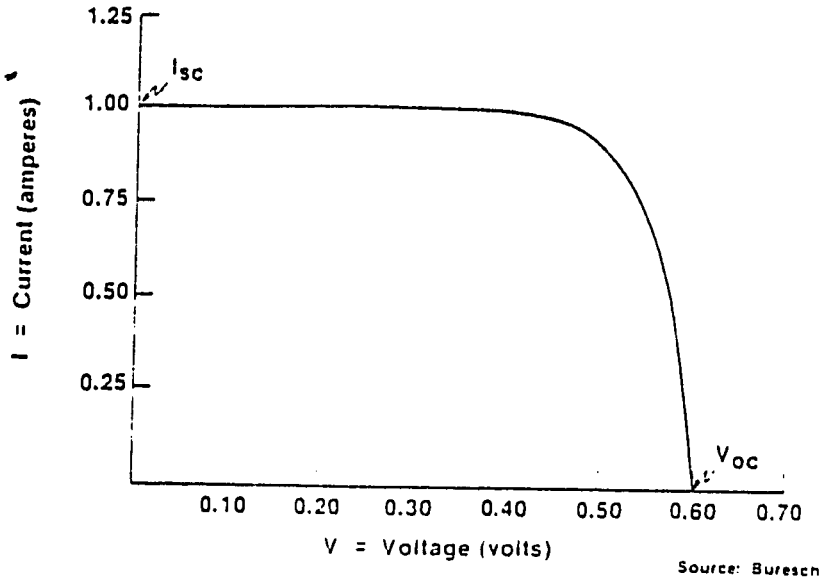


Setup for testing solar cell response



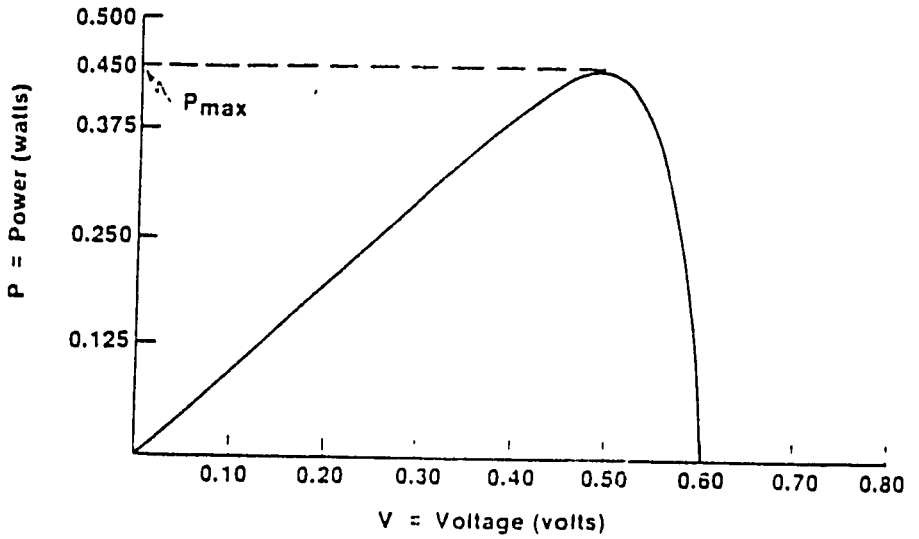
Source: Buresch

Current-Voltage (I-V) characteristic for a solar cell



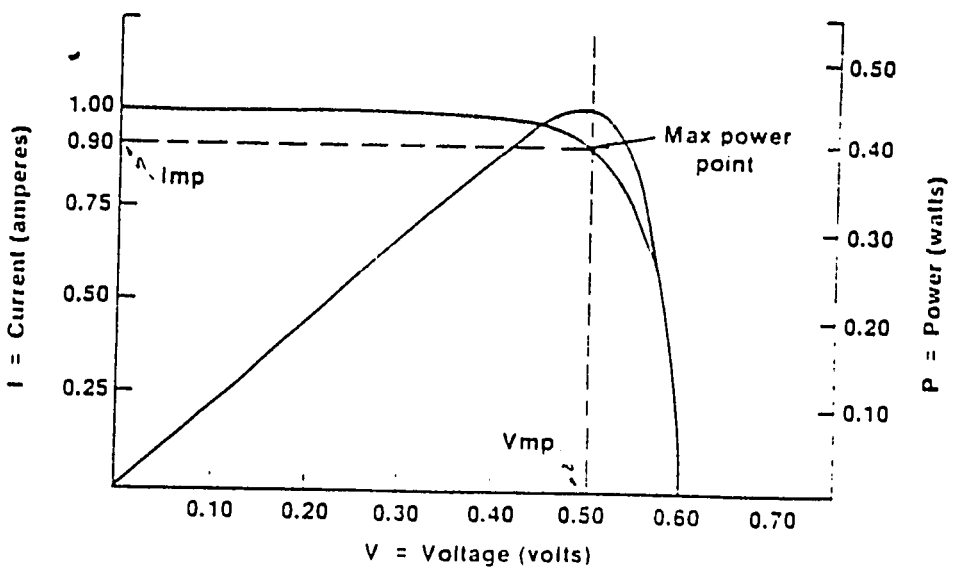
Source: Buresch

Power versus voltage for a solar cell



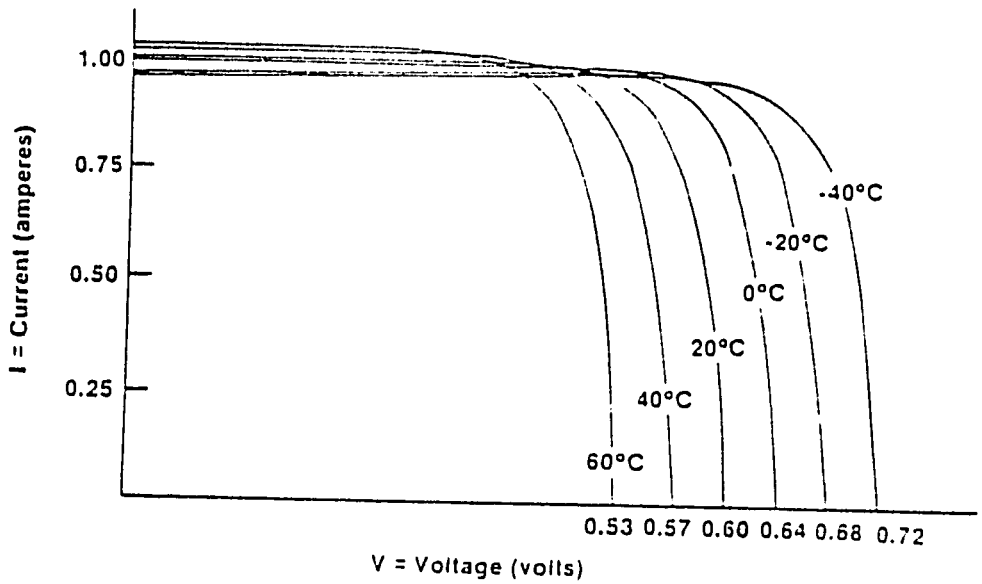
Source: Buresch

Maximum power point for a solar cell



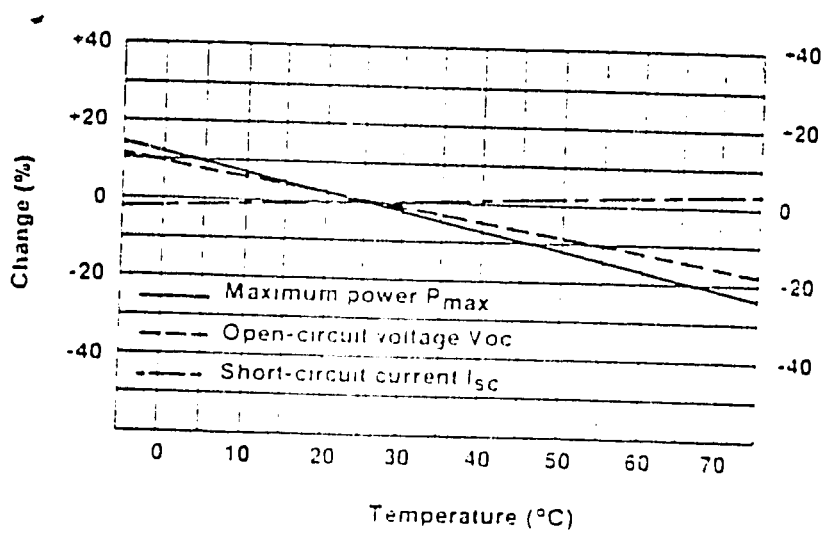
Source: Buresch

Effect of temperature on cell response



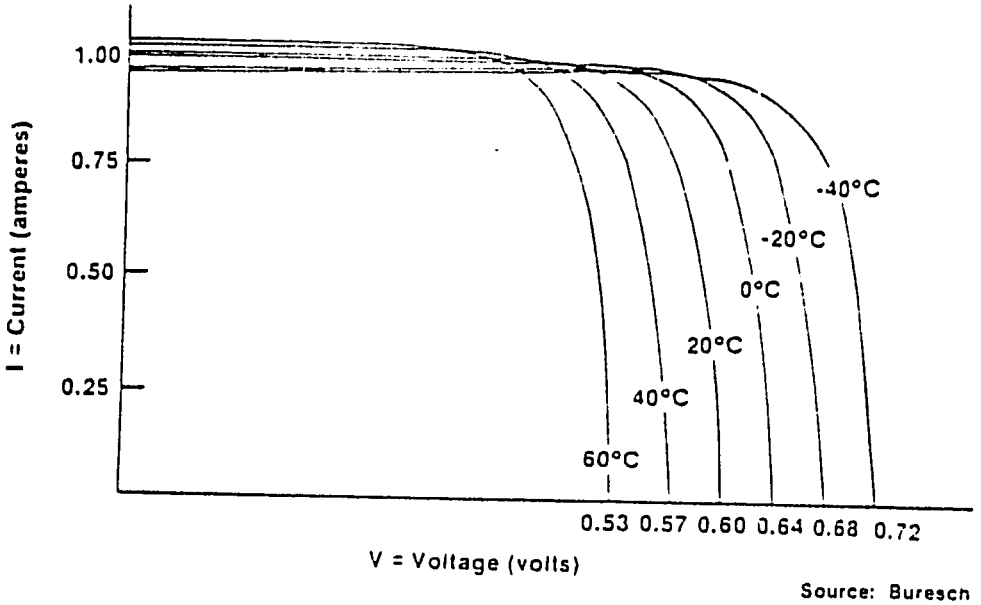
Source: Buresch

Effect of temperature on cell voltage, current and power



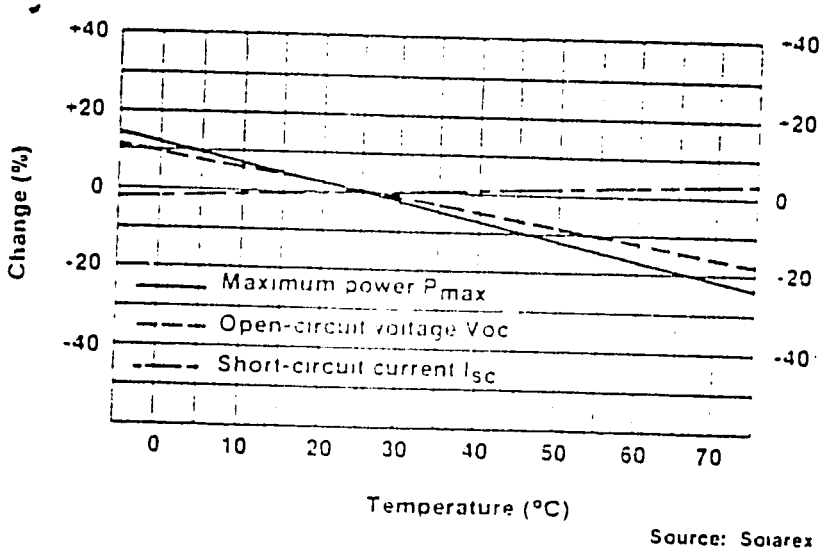
Source: Solarex

Effect of temperature on cell response



Source: Buresch

Effect of temperature on cell voltage, current and power



Source: Solarex

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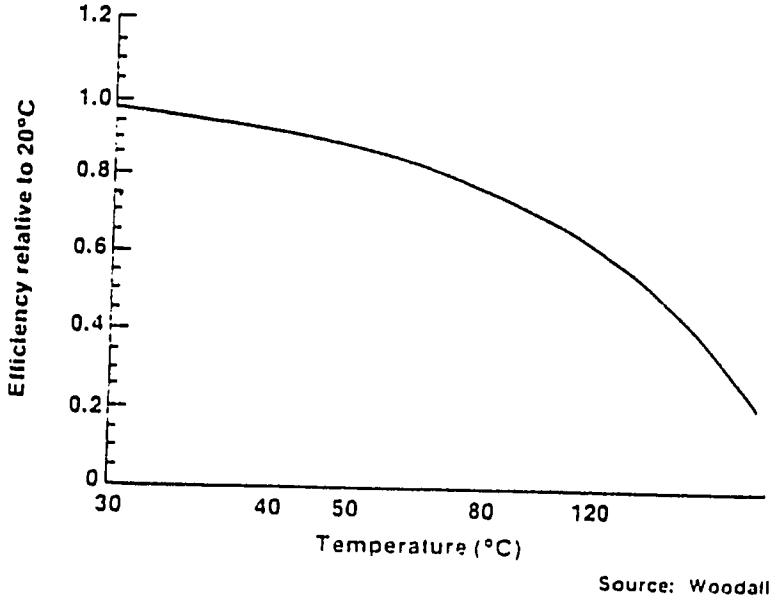
Nominal Operating Cell Temperature (NOCT)

The array temperature when:

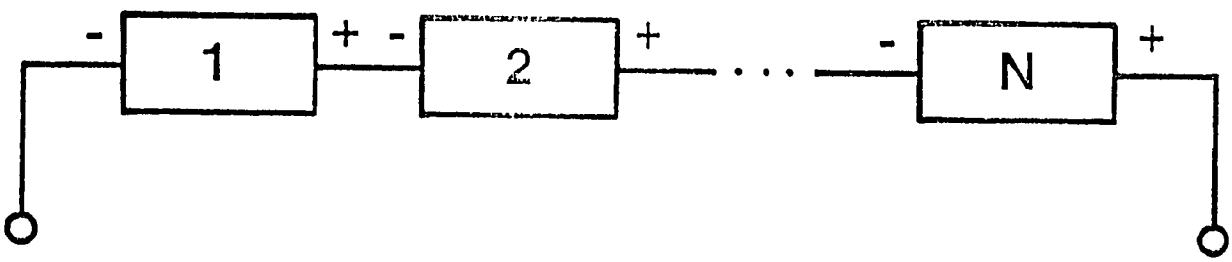
- Irradiance on array plane = 800 watts/m²
- Ambient air temperature = 20°C
- Array is electrically open-circuit
- Wind-speed = 1.0 m/sec (approximately)

Effect of temperature on solar cell efficiency



Source: Woodall

Any number of photovoltaic devices connected in series



Voltage

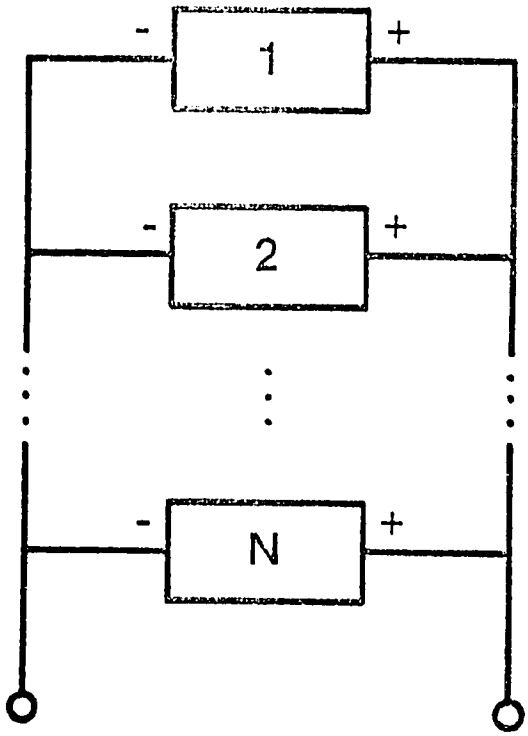
$$V = V_1 + V_2 + \ldots + V_N$$

Current

$I = I_1 = I_2 = \ldots = I_N$ Similar devices

$I \approx I_{MIN}$ Dissimilar devices

Any number of photovoltaic devices connected in parallel



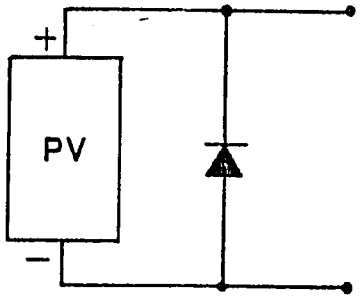
Voltage

$V = V_1 = V_2 = V_N$	Similar devices
$V \approx \frac{1}{N}(V_1 + V_2 + \ldots + V_N)$	Dissimilar devices

Current

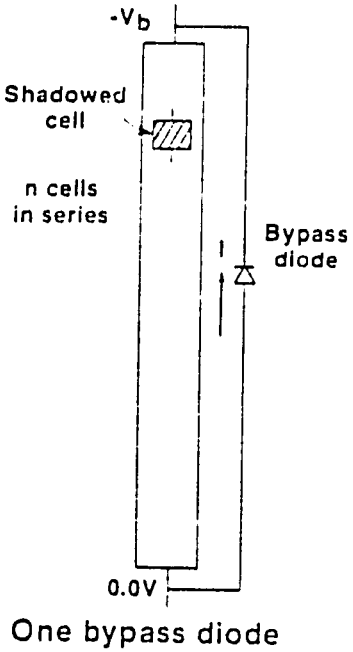
$$I = I_1 + I_2 + \ldots + I_N$$

Bypass diode

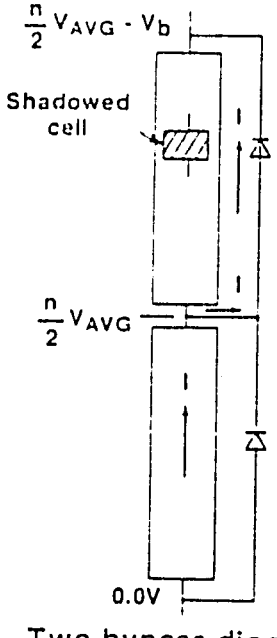


A bypass (or shunt) diode allows current to bypass the module (or group of cells) in the event of an open-circuit condition or failure.

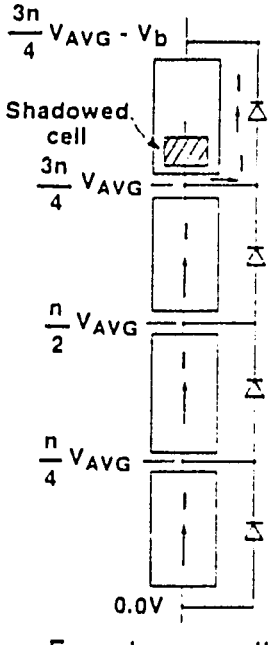
Effect on performance by the addition of bypass diodes for one-cell shadowing



One bypass diode

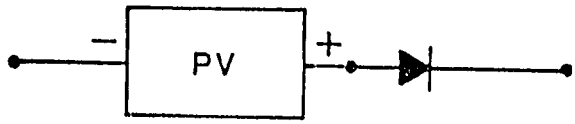


Two bypass diodes



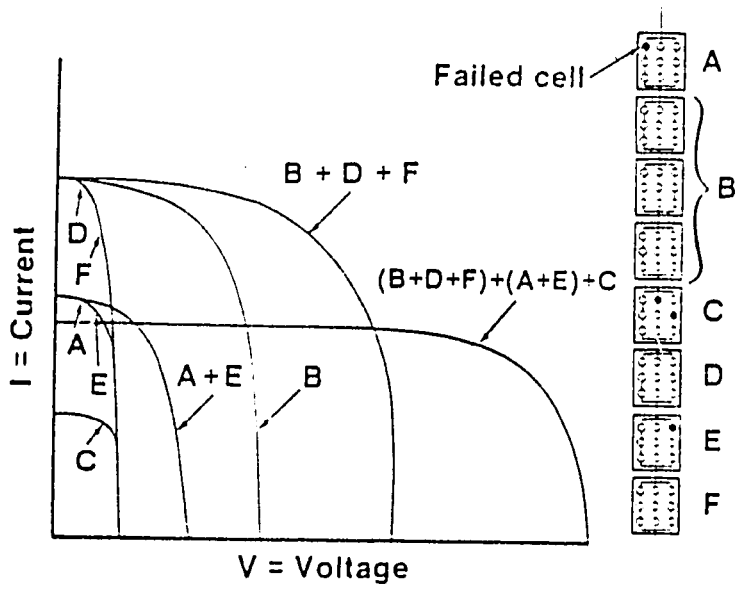
Four bypass diodes

Blocking diode



A blocking (or series) diode prevents reverse flow of current into the module(s).

Simulation of cumulative I-V curve for a branch circuit containing failed and unfailed elements



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Array peak rating conditions

- Irradiance = 1000 watts/m² = One sun
- Air mass = 1.5
- Cell temperature = 25°C

Array nominal rating conditions

- Irradiance = 1000 watts/m² = One sun
- Air mass = 1.5
- Cell temperature = NOCT

Nominal Operating Cell Temperature (NOCT)

The array temperature when:

- Irradiance on array plane = 800 watts/m²
- Ambient air temperature = 20°C
- Array is electrically open-circuit
- Wind-speed = 1.0 m/sec (approximately)

PHOTOVOLTAIC BATTERY REQUIREMENTS

1. Low self-discharge rate
2. High depth of discharge
3. Capability of great number of charge/discharge cycles
4. High temperature adaptability
5. Low water loss
6. Low internal resistance
7. Suited for low charge/discharge rates
8. Capable of withstanding overcharging
9. Adaptable to freezing temperatures

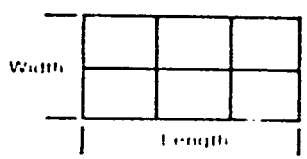
	Approximate Cost/kWh ($)	Cycle Life	Depth of Discharge	Normal Self-Discharge
Lead-Antimony (car)	70	150-250	10%	7-50%/month
Lead-Acid (Photovoltaic)	80	1,000-2,000	10-30%	3-4%/month
Pure Lead (Photovoltaic)	140	1,000-3,000	30-50%	2%/month
Lead Calcium (Photovoltaic)	200	2,000-6,000	20-70%	1%/month
Nickel Cadmium	300-1,000	3,000-10,000		5%/month

SPECIFICATIONS — TYPE QP BATTERIES

DEEP DAILY DISCHARGE BATTERIES

Cell Type	AH Capacity @ 77°F (25°C)					Overall Dimensions						Weight Including Tray	
	to 1.70 VPC	to 1.75 VPC				Length		Width		Height			
	6 Hr.	8 Hr.	12 Hr.	16 Hr.	24 Hr.	in.	mm.	in.	mm.	in.	mm.	lbs.	kgs.
QP75- 5	150	154	165	170	176	1.89	48	6.19	157	22.75	578	33	15
QP75- 7	225	231	249	255	264	2.64	67	6.19	157	22.75	578	46	21
QP75- 9	300	308	330	340	352	3.39	86	6.19	157	22.75	578	58	26
QP75-11	375	385	412	425	440	4.14	105	6.19	157	22.75	578	71	32
QP75-13	450	462	495	510	528	4.89	124	6.19	157	22.75	578	84	38
QP75-15	525	539	577	595	616	5.68	144	6.25	159	22.75	578	96	43
QP75-17	600	616	660	680	704	6.43	163	6.25	159	22.75	578	109	49
QP75-19	675	693	742	765	792	7.18	182	6.25	159	22.75	578	122	55
QP75-21	750	770	825	850	880	7.93	201	6.25	159	22.75	578	134	61
QP75-23	825	847	907	935	968	8.68	220	6.25	159	22.75	578	147	67
QP75-25	900	924	990	1020	1056	9.47	240	6.25	159	22.75	578	160	73
QP110-19	990	1012	1089	1134	1197	7.18	182	6.25	159	29.88	759	178	81
QP110-21	1100	1125	1210	1260	1330	7.93	201	6.25	159	29.88	759	196	89
QP110-23	1210	1237	1331	1386	1463	8.68	220	6.25	159	29.88	759	215	97
QP110-25	1320	1350	1452	1512	1596	9.47	240	6.25	159	29.88	759	233	106

Recommended end of charge voltage — 2.60 to 2.65 volts per cell @ 77°F (25°C)
Specific gravity @ 77°F (25°C) — full charge — 1.290
Recommended start of charge current — up to 20 to 25 amperes per 100 AH rated 6 Hr. capacity



* Cells are mounted in multi-cell trays In order to determine trayed battery weight and dimensions do the following

Trayed Battery Weight Multiply number of cells in a tray by the cell weight
Example

6 cell QP75-11

Weight Calculation = 6 cells × 32KG = 192KG

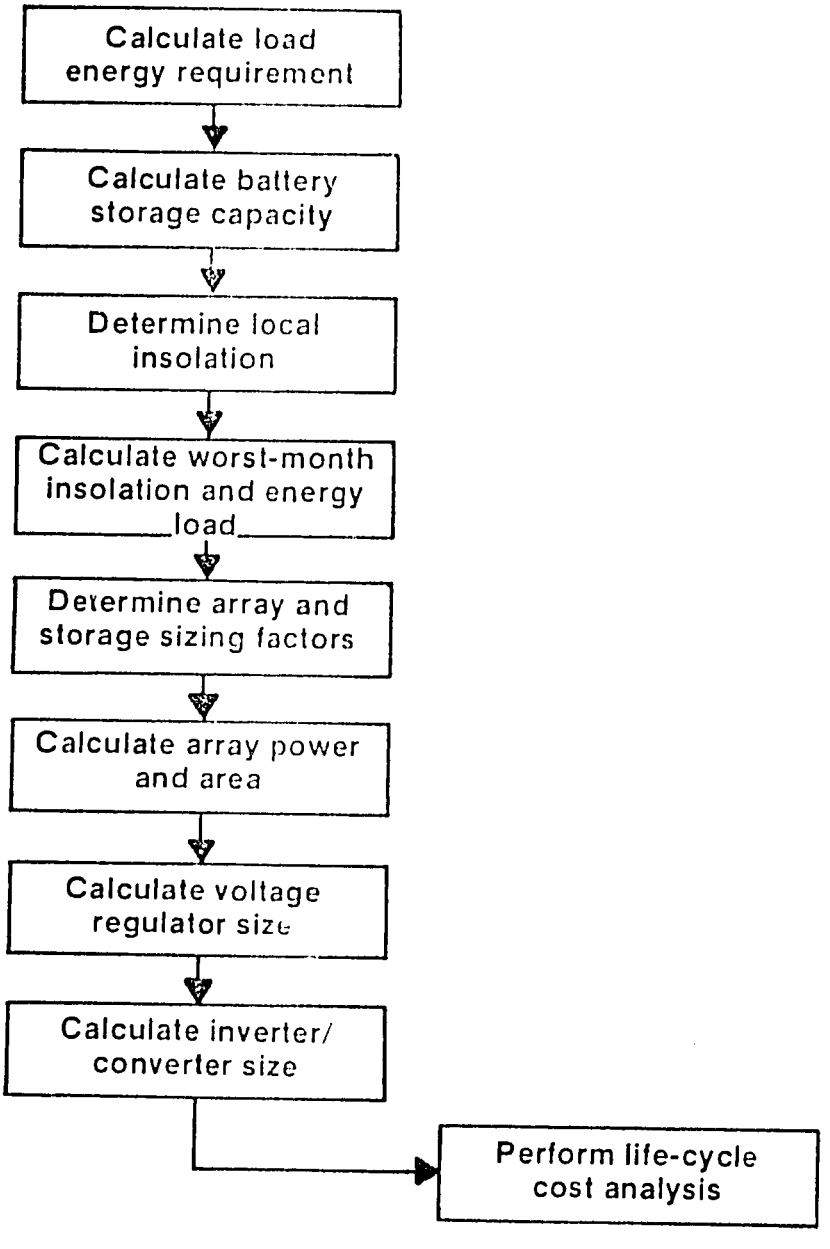
Trayed Battery Dimensions Multiply cell dimensions by tray configuration
Example

2x3 Tray Configuration for QP75-23 (6 cell tray)

Width = 2 × 159MM = 318MM

Length = 3 × 220MM = 660MM

Sizing a remote, stand-alone PV system



SIZING OF STAND-ALONE PHOTOVOLTAIC SYSTEMS

Worksheet

APPLICATION _____

LOCATION _____ LATITUDE _____

A. LOADS

A1 Inverter efficiency (decimal) _____

A2 Battery bus voltage _____ volts

Component	(A3) Rated Wattage	(A4) Adjustment Factor 1.0 for dc (A1) for ac	(A5) Adjusted Wattage (A3/A4)	(A6) Hours Per Day Used	Energy Per Day (A5xA6)
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____

A7 Total energy demand per day ======= watt-hours

A8 Total amp-hour demand per day (A7/A2) _____ amp-hours

B. BATTERY SIZING DESIGN MONTH _____ DESIGN TEMPERATURE _____

B1 Days of storage desired/required _____ days

B2 Desired depth-of-discharge limit (decimal) _____

B3 Required usable capacity (A8xB1) _____ amp-hours

B4 Amp-hour capacity of selected battery* _____ amp-hours

B5 Useful battery capacity (B4xB2) _____ amp-hours

B6 Number of batteries in parallel (B3/B5) _____

B7 Number of batteries in series (A2/battery voltage) _____

B8 Total number of batteries (B6xB7) _____

* Use amp-hour capacity at a rate of discharge corresponding to the total storage period, B1.

C. PV ARRAY SIZING OPTIMUM TILT _____

C1 Total energy demand per day (A7) _____ watt-hours

C2 Battery round-trip efficiency (0.80-0.85) _____

C3 Required array output per day (C1/C2) _____ watt-hours

C4 Selected PV module max power voltage x 0.9 _____ volts

C5	Selected PV module power output at 1000 watts/m^2 and NOCT	_____	watts
C6	Peak sun hours at optimum tilt	_____	hours
C7	Energy output per module per day (C5xC6)	_____	watt-hours
C8	Operating temperature derating factor, DF (0.80 for hot climates and critical applications; 0.95 for moderate climates and non-critical applications) (DFxC7)	_____	watt-hours
C9	Number of modules required to meet energy requirements (C3/C8)	_____	modules
C10	Number of modules required per string (A2/C4) rounded to next higher integer	_____	modules
C11	Number of strings in parallel (C9/C10) rounded to next higher integer	_____	strings
C12	Number of modules to be purchased (C10xC11)	_____	modules

D. BOS REQUIREMENTS

1. A voltage regulator is recommended unless array output current (at 1000 w/m^2 conditions), less any continuous load current, is less than of the selected battery bank capacity (at the 8-hour discharge e).

2. Wiring should be adequate to ensure that losses are less than 1% of the energy produced.

3. In low voltage (i.e., less than 50 volts) systems, germanium or Schottky blocking diodes are preferred over silicon diodes.

4. Fuses, switches, and other components should be selected to satisfy both voltage and current requirements.

5. All battery series branches should contain fuses.

6. Fused disconnects are strongly recommended to isolate the battery bank from the rest of the system.

CONSIDERATIONS FOR SYSTEM INSTALLATION, OPERATION, REPAIR, AND MAINTENANCE

INSTALLATION

- o SITE TRANSPORT AND COMMUNICATION'S
- o NEAREST LOCATION OF WATER, CONCRETE (SAND AND GRAVEL) AND POWER
- o LOCAL CONSTRUCTION MATERIALS AVAILABILITY
  - MECHANICAL FASTENERS, TOOLS (HAND AND POWER), FENCING
  - ELECTRICAL EQUIPMENT
  - WOOD, REBAR, SCREEN, ROPE, ECT.
- o SHIPPING WEIGHT OF LARGEST PACKAGE (MANUAL UNLOADING AND TRANSFER, INVERTED CONTAINERS, "DROP DAMAGE", ETC.)
- o CONSTRUCTION DETAILS OF ALL ON SITE STRUCTURES
- o DETAILED SITE LAYOUTS AND TOPOGRAPHIC LAND FEATURES
- o LOCAL/COUNTRY SPECIFIC BUILDING CODES (MECHANICAL AND ELECTRICAL)
- o BATTERY EQUALIZING CHARGE TIME
- o "LIVING WITH THE SYSTEM"

OPERATION

- o EMERGENCY SHUTDOWN/SUBSEQUENT START UP PROCEDURES
- o SIMPLICITY OF OPERATION
- o INSPECTION ROUTINES
- o MANUAL CLARITY AND THOROUGHNESS
  - COUNTRY LANGUAGE
  - LEVEL OF DETAIL
- o INSTRUMENTATION

REPAIR

- o MANAGEMENT OF TECHNICAL SUPPORT
- o PROCUREMENT OF SPARE DARTS
- o STOCK OF SPARES (COST, DISTANCE, AVAILABILITY-TECHNOLOGY LIFE)
- o USE OF SPARES (ABILITY AND RESPONSE TIME)
- o COMMUNICATIONS LINK: SITE TO SUPPORT
- o EQUIPMENT TO BE COMPATABLE WITH EXISTING EQUIPMENT INFRASTRUCTURE TO THE EXTENT POSSIBLE

- CLEANING ARRAY

- BATTERY INSPECTION/EVALUATION

- LOAD MAINTENANCE (LOAD SPECIFIC)

  - PUMPS-BEARINGS, CLEANLINESS
  - DESALINATION-FILTERS
  - R/F-DEFROST, CLEANING
  - LIGHTING-CLEANING
  - GRINDING-MILL MAINTENANCE

INSTRUMENTATION

- IDENTIFY PURPOSE AND END USE OF DATA

- MINIMIZE AND ELIMINATE INSTRUMENTATION REQUIRED (OR PERCEIVED TO BE REQUIRED) FOR OPERATION

  - VOLTMETER
  - RUN-TIME METER
  - HYDROMETER

- SIMPLIFY INSTRUMENTATION REQUIRED FOR EVALUATION

  - USE TESTED PROVED EQUIPMENT
  - SOLID STATE OR MANUAL DATA AQUISITION

- CONSIDER "COMMERCIALLY VIABLE" AS SEPARATE FROM "DEVELOPMENT/TEST" SYSTEMS

SLIDES

DESIGN CRITIQUES OF EXISTING SYSTEMS, COMPONENT FAILURES
FIELD EXPERIENCE WITH INSTALLATION AND START UP OF SYSTEMS

APPLICATIONS OF PHOTOVOLTAICS

SYSTEMS, COMPONENTS, SIZING, DESIGN

by

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STEVEN J. STRONG

Steven Strong founded Solar Design Associates, Inc. in 1974 after serving as an engineering consultant on the Alaskan Pipeline. Convinced there was an easier and less-costly way to deliver comfort to the consumer than "going to the ends of the earth" to extract the last drop of fossil fuel, he drew on a background in both architecture and engineering to design a new kind of building which he calls "the energy-producing organisim" that produces enough energy to satisfy its own requirements.

He designed The Carlisle House, the country's first full-size PV-powered residence and was Chairman of the first national conference on the application of photovoltaics held in March 1983 at MIT. Mr. Strong has consulted to many of the leading companies in the PV industry and has taught architecture and renewable energy systems engineering at the Boston Architectural Center. His book on photovoltaic applications will soon be published by Rodale Press.

SOLAR DESIGN ASSOCIATES

Solar Design Associates is an architectural and engineering firm specializing in energy-conscious building design and renewable energy systems engineering. This year, the photovoltaic-powered, all-solar home the firm designed for Boston Edison Company to represent housing in the year 2000 is the feature of the 26-week national PBS television series "The All-New This Old House". The firm provides full design services as well as consulting for residential, commercial and institutional clients with a focus on the integration of energy systems and architecture.

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Applications of Photovoltaics

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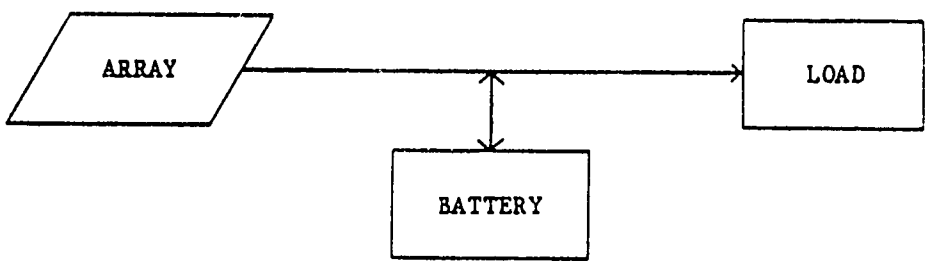
SECTION 3. SYSTEM TYPES

The following block diagrams show the connections between components in various types of basic PV systems. The diagrams are given in order of system complexity.

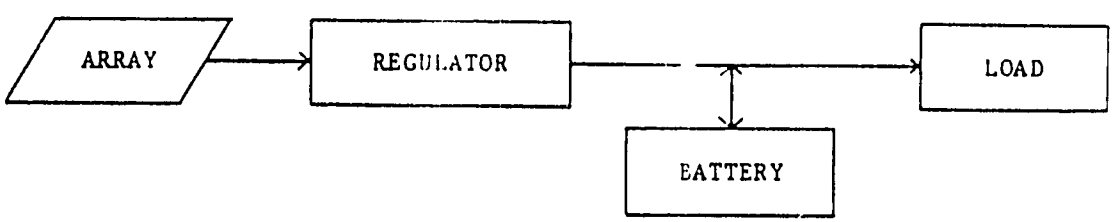
Most basic DC stand-alone system: Array connected directly to load

Example: water pumping, DC variable speed, variable voltage motor, with no electrical storage. In this case, water may be stored in a tank so that it is available at all times (called "pumped water storage"). The system is simple, reliable, requires negligible maintenance and is ideal for shallow-well irrigation systems. (For deep well systems, because of the large motor, batteries are needed often to supply the high-motor starting current.)



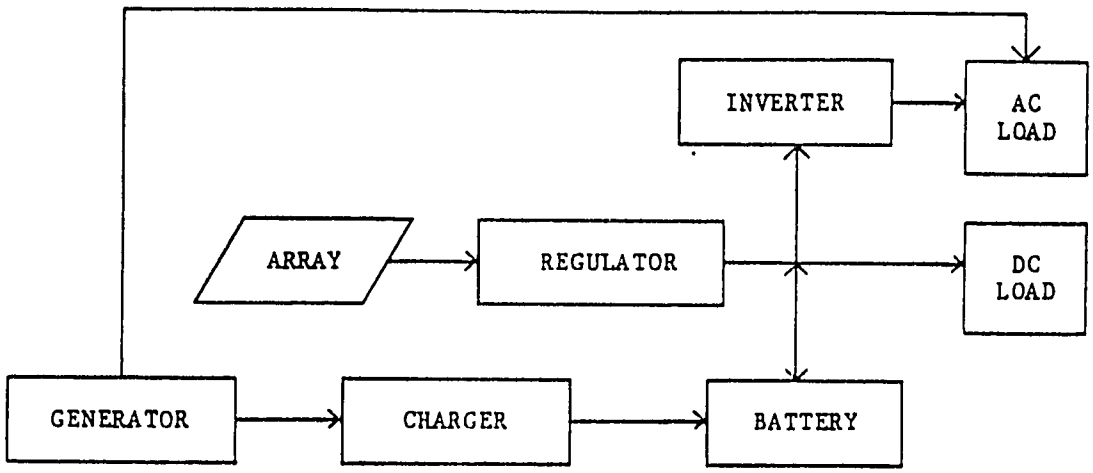
Very basic DC stand-alone system: Array connected to load with storage

Example: attended home lighting system, DC lights. No regulator is used. It is assumed that a daily check of the battery condition will be made to determine when the modules should be disconnected (battery is overcharged) or when the load should be reduced (battery is discharged).



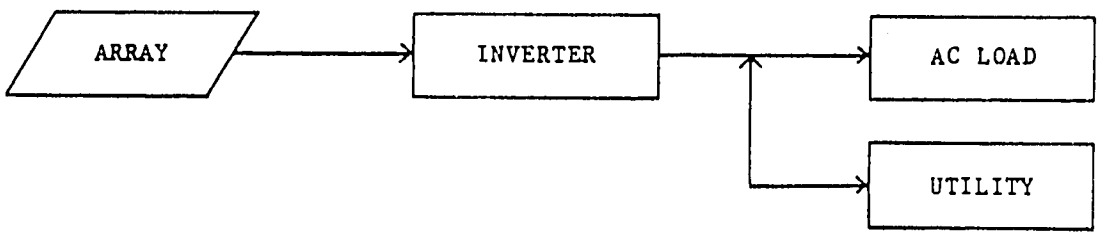
Basic DC stand-alone system: Array connected to load and batteries via a voltage regulator

Example: remote communications system. A regulator is used to automatically control the state of charge of the battery. For unattended systems using battery storage a regulator should always be used.



AC/DC stand-alone system with regulator, storage, inverter, backup generator and battery charger

Example: residential off-grid (no utility-connection). An inverter is used here to change a portion of the DC electricity into AC. WHen the PV array output is low, the generator charges the battery and also delivers AC directly to the AC loads during its operation. While the generator is running, DC loads are served with generator output via the battery charger.



Utility-interactive PV system

Example: residential utility inter-tie. The utility supplies power whenever the array cannot fully meet the load. When the array produces more electricity than the load requires, the excess is fed back into the utility line. The utility must buy this power from the system owner (by mandate of Federal law, PURPA).

SECTION 4. BATTERIES

Since photovoltaic cells only produce electricity during the daytime, it is often necessary to store that energy for use at night or during times when the sunlight isn't strong enough to power the load of a stand-alone PV system.

The most reliable form of electrical energy storage available today is the battery. It is available as either a primary battery or a secondary battery. Primary batteries cannot be recharged whereas secondary batteries can be repeatedly discharged and recharged. Discharging and recharging is called cycling. Not too many years ago, primary batteries were used in most of the off-shore warning light system. Now, more and more, these primary batteries are being replaced by photovoltaics and secondary batteries.

Secondary batteries are manufactured from a wide variety of materials and methods. The more commonly available types are lead-acid and alkaline (includes nicads). In the past, the high cost of nicad batteries has precluded their use in PV systems. Today, in locations where extreme weather conditions prevail, (very cold and very hot) nicads may compete favorably in life cycle costing. For most locations in the US the less expensive lead-acid is most commonly used in photovoltaic systems. As such, this section will deal with lead-acid batteries.

4.1. Types of Lead-Acid Batteries

Lead acid batteries are designed for a wide variety of applications ranging from:

* Emergency standby power
* Electric vehicle power
* Automotive starting and lighting
* Deep and shallow-cycle solar.

Emergency standby batteries are designed for short periods of operation (less than 1 hour of discharge time) with a high current output. They are generally maintained at a "float" voltage with occasional "equalizing" voltage applied (more on these terms later).

Electric vehicle batteries (motive power batteries) are usually discharged over a 6 to 8 hour period and recharged at a constant rate right after being discharged.

Starting and lighting batteries, otherwise called car batteries, are used for a very short while, (6 to 10 seconds) with a high-current output and recharged right away. In a PV system, their internal losses must be calculated and added to the system's load requirements to externalize the load.

Shallow-cycle batteries can be discharged to between 10% and 20% of their capacity (in Ah) on a daily basis. For example, a 100 Ah shallow-cycle battery will deliver 10 to 20 Ah on a daily basis (provided it's also recharged daily). Repeated deep-discharges, on the order of 50 to 80% of rated capacity, will very seriously shorten the life of the battery.

Deep-cycle batteries are designed to allow between a 60 to 80% daily discharge. They are often used when the storage requirement of the system is for 1 to 5 "no sun" days.

4.2. Battery Construction

The family of batteries known as lead-acid batteries is typically constructed of lead or lead-alloy plates immersed in a sulphuric acid/water solution. The plates are either positive or negative. A cell is a group of positive and negative plates with a single positive output terminal, or lead, and a single negative output terminal. The nominal voltage of a cell is 2 volts. A twelve-volt battery then has 6 cells which are connected in series. (Remember, series connections increase the voltage while parallel connections increase current). The plate materials and construction determine battery life as well as operation, efficiency and cost.

Lead-acid batteries are constructed with several different types of plates depending on the application. Examples are:

* Lead-lead oxide
* Lead-antimony
* Lead-calcium
* Lead-calcium/antimony hybrid

The pure lead (lead-lead oxide) battery typically has a very long life (25 years or more) with high current rate discharge capability. The positive plate contains about 2% antimony (Plante cell). Historically the battery has been used in standby power applications, however, it is beginning to be used in photovoltaic systems.

Lead-antimony batteries have 4% to 12% antimony concentration in the positive plate. It is designed for deep discharge capability and has good cycling ability. Unfortunately, lead-antimony batteries have relatively high self-discharge rates, which get progressively greater with age. Also, upon charging, there is a good deal of water vapor produced (gassing) which must be replaced by frequent maintenance (every 3 months is average).

Since ampere hour efficiency of a battery is adversely affected by the amount of gassing during the charging cycle and by self discharge rate, the ampere hour efficiency of a lead-antimony battery is not as high as that for a battery that does not contain antimony.

The lead-calcium battery is characterized by a low self discharge rate (1% to 4% per month at 25°C) and low gassing during charging. Like the lead-antimony battery it has good cycling capability but is limited in the number of deep discharges it can withstand. It is only used in shallow discharge applications. The lead-calcium battery requires lower maintenance and in some cases has been designed as a sealed "maintenance free" battery (never needing the addition of water).

The lead-antimony-calcium hybrid battery combines the favorable characteristics of both the lead-antimony and the lead-calcium batteries. It has a long cycle life (up to 3500 and more) and allows deep discharge without requiring as much maintenance as the comparable lead-antimony battery. It is also one of the most expensive batteries available.

4.3. Factors Affecting Battery Performance

All batteries work by storing electrical energy in the form of chemical energy. Charging a battery means putting electricity into it which causes a chemical reaction to take place. When a load is connected to a battery, this chemical reaction goes in the opposite direction with the result being electricity being delivered by the battery.

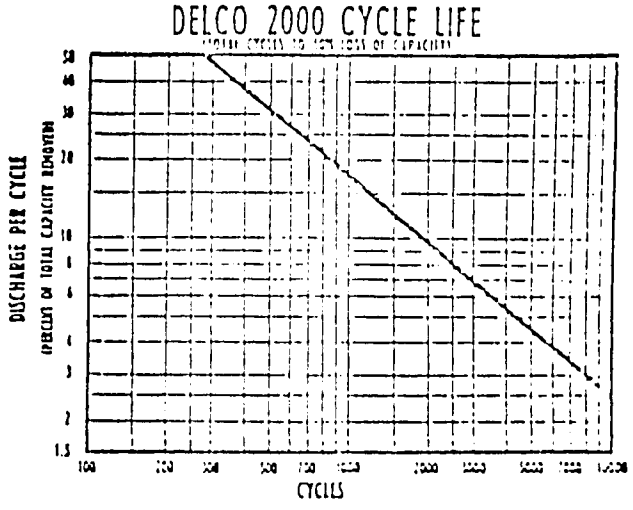
There is no known energy conversion process that is 100% efficient (i.e., has no inherent internal losses). Batteries are no exception. The efficiency of a battery is defined as the ratio of the electrical energy

delivered by the battery to the electrical energy consumed by the battery. The overall energy conversion efficiency (or cycling efficiency) of most lead-acid batteries ranges between 80% and 85%.

There are many factors which affect battery efficiency and their influence on storage capacity varies from battery to battery. Some are internal to the design and condition of the battery such, as plate type and battery age while others are external, such as operating temperature and charging procedure. Some of the more important factors affecting battery efficiency are:

* Daily Depth of Discharge
* Charge and discharge rates
* Charging procedure
* Self-discharge rate
* Time spent discharged
* Temperature of operation
* Battery age and history
* Electrolyte specific gravity

Daily depth-of-discharge Shallow-cycle batteries can only withstand a daily depth-of-discharge (DOD) of 10% to 20% of their capacity, whereas most deep cycle batteries can withstand up to 80% depth-of-discharge on a daily basis. The actual DOD will have a strong influence on the storage capacity and life of a battery as shown in Graph 4.1. If manufacturer's guidelines are not followed and the battery's recommended DOD is exceeded, significant loss of storage capacity and service life can result.



Graph 4.1
Battery Life (cycles) vs: Daily Depth of Discharge for the Delco 2000

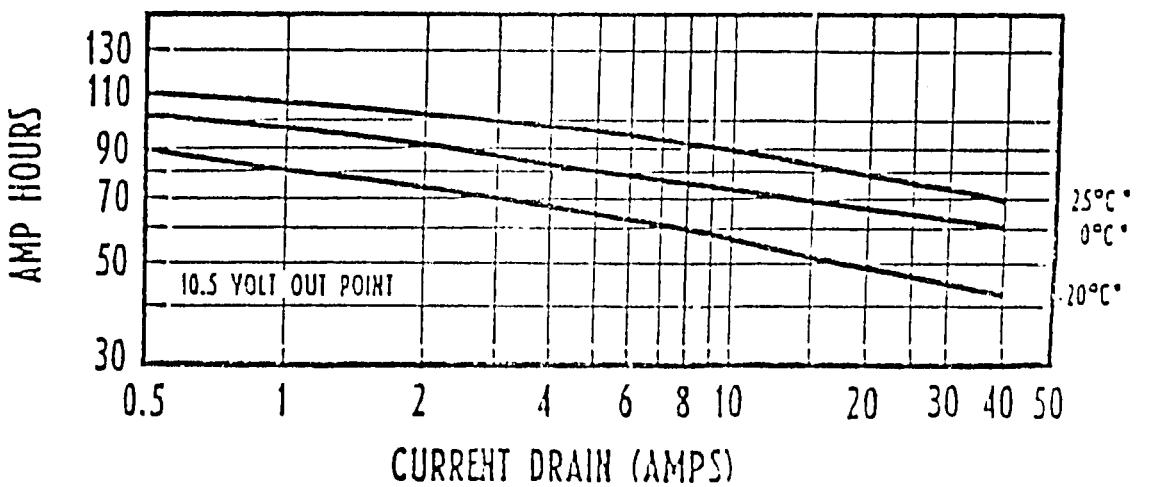
As an example, a Delco 2000 discharged 10% per day will last for nearly 5 years, however, if discharged 20% per day it will only last a little more than 2 years.

Charging Procedure If a battery is maintained at its float voltage (13.8 V for the Delco 2000 at 25°C) and never charged above this voltage two problems can occur. First, the electrolyte may stratify. This means that

the acid will be concentrated in the bottom of the battery with the water at the top. Stratification of the electrolyte results in poor performance of the battery and makes the battery more susceptible to freezing and permanent internal damage. Second, in a system where several batteries are connected in series, it is possible that a single battery may lose its capacity before the rest. This will cause poor performance of the entire battery bank.

In order to minimize these problems it is a good idea to provide an occasional "equalizing charge" to the batteries. This means raising the battery voltage above the float voltage. Under normal charging conditions, the charging rate (the current going into the battery) is lowered once the float voltage is reached so that excess "bubbling" of the electrolyte does not occur. This last step in charging a battery is frequently called a finishing charge or trickle charge. When an equalizing charge is applied, a controlled amount of bubbling of the electrolyte is purposely introduced to de-stratify the solution and also bring up any weak cells to full potential. This process is recommended about once a month but varies with service.

Charge and Discharge rates The chemical conversion of energy which produces electricity in a lead-acid storage battery has an optimal rate of conversion vs: time. Most batteries are designed to provide a reasonable latitude in the charge discharge rate (the rate of current flowing into or out of a battery vs: time expressed in Amps per Hour). If these design rates are exceeded, the energy conversion efficiency will be adversely affected and the battery's internal losses will increase resulting in less net electrical energy delivered. A battery will deliver its maximum output when discharged at or below the manufacturer's recommended discharge rate. The converse is also true. A battery will accept its fullest charge when recharged at or below the manufacturer's charging rate. Graph 4.2 presents manufacturer's data on Amp-hour capacity as a function of both temperature and rate of discharge for the Delco 2000.



Graph 4.2
Amp-Hour Capacity as a Function of Temperature
and Discharge Rate for the Delco 2000

Self Discharge Rate All batteries continually lose some of their stored energy because of internal reactions, even if they are not being discharged by the load. This is called "self discharge", usually expressed in terms of Ah lost per month or per cent capacity lost per month. It increases

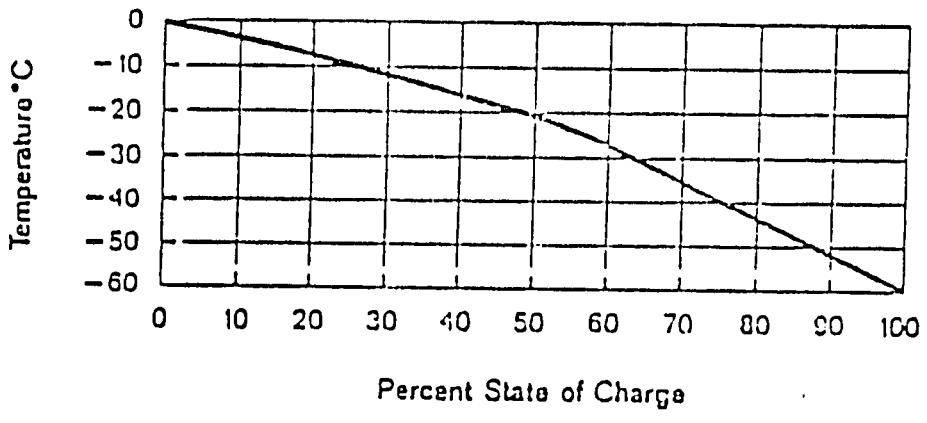
with battery temperature and age. (Self discharge of the batteries causes your flashlight to never work when it's needed.)

In the extreme case of a lead-antimony battery near the end of its life and in a hot climate, the self discharge rate can get as high as 40% to 50% of its capacity. This means the PV array will not only have to supply the battery with the normal charging current but will, in addition, have to supply an equal amount just to keep the battery from self discharging. Unless the array were sized to deliver this extra energy the net effect on the system would be a reduction in the energy available for the load.

Time Spent Discharged A battery that has been discharged should be recharged as soon as possible. Prolonged periods of low state-of-charge result in severe shortening of battery life. If a battery is left in a low state of charge for a long period of time (varies with battery type), the battery will either not regain full capacity or may not even be able to be recharged at all.

Temperature of Operation Although a battery operates more efficiently as its temperature increases (over the standard rating at 77°F), it should ideally be kept at or near this point because, as temperature increases above 77°F, the battery's service life is shortened. A battery should also not be subjected to very low operating temperatures. This results in inefficient operation and could possibly freeze the electrolyte. Freezing becomes even more likely when the battery is subjected to low temperatures in a discharged state (because the proportion of water to acid in the electrolyte increases).

For example, the Delco 2000 has a 105 Ah capacity (at a 1 A current drain) at 25°C (77°F) but only a 95 Ah capacity at 0°C. It is recommended that the Delco 2000 be operated between -5°C and 35°C. The relative loss of capacity of a shallow-discharge Exide battery is somewhat less (at 0°C it maintains 92% of its rated capacity). Graph 4.3 shows the correlation between freezing point and battery state-of-charge.



Graph 4.3
Freezing Point vs: State-of-Charge

As an example, a battery will not freeze at -20°C (-4°F) if it is above 50% state of charge, however, if at 20% state of charge and the temperature is -10°C (14°F) you can count on having to buy a new battery.

Battery Age and Past History All batteries gradually loose their ability to store energy over their service life. A battery's useful service life is considered over when the battery storage capacity in ampere-hours is reduced to 80% of its initial rating. As a result, in order to ensure that a battery will continue to satisfy a system's specific load requirement over its full useful life, the nominal capacity (rated for the new battery) should be divided by 0.80 to account for the loss in capacity. For exam-

ple, if a 425 Ah battery is required then the nominal capacity of the battery to be used should be 425 Ah/0.80 or approximately 530 Ah.

If used batteries are employed, do not expect the performance of the battery to equal that of a similar, but new battery. Just a few deep discharges on a shallow-discharge battery can significantly shorten the life and the capacity of the battery. Addition of anything other than clear distilled water to a battery in the past will cause problems (short life, low capacity) in the future. Battery additives that claim to improve battery performance or increase capacity are to be avoided. Using used batteries is not recommended unless past operation and maintenance are well known and the application is considered non-critical.

Electrolyte Specific Gravity The specific gravity of a battery cell electrolyte is an indicator of the state of charge of the cell. During cell operation the electrolyte (water and sulphuric acid solution) changes in composition. At full charge the specific gravity is high (1.250 - 1.300) and the acid concentration is high (40% at a specifc gravity of 1.300). As the state of charge falls so does the concentration of the acid (acid gets used up and water is formed). Most lead-acid batteries are considered to be completely discharged if the specific gravity is 1.100.

Specific gravity is measured with a battery cell hydrometer. This instrument should be cleaned with pure water after each use and should never be used to test different types of batteries (i.e., don't use the same hydrometer to test a lead-antimony battery as a lead-calcium battery). The actual specific gravity of the electrolyte in a new fully charged battery is a part of the battery design and varies with manufacturer. Although specific gravity of "maintenance free" cells cannot be measured, some manufacturers have built a state of charge indicator into the battery.

Specific gravity readings are affected by temperature. As a result, in order to obtain an accurate value, you must first measure the temperature of the electrolyte then record the specific gravity reading and adjust it to the corrected value. The adjustment most often used is to add 0.001 to the reading for every 3°F above 77°F, subtract 0.001 for every 3°F below 77°F.

As an example, the temperature of a particular battery cell's electrolyte is found to be 88 °F, The specific gravity reading on a hydrometer is 1.240. Determine the corrected specific gravity.

$$\text{Corrected Reading} = 1.240 + (88 - 77)\,\frac{(0.001)}{3} = 1.244$$

4.4. Battery Selection Criteria

The choice of battery for any photovoltaic system depends on many factors. Among the more important considerations are:

* Climate at site and number of expected "no sun" days
* Site accessibility
* Size and type of system
* Required system reliability
* Battery physical characteristics and warranty
* Required maintenance
* Availability of backup power source
* Initial purchase price and life-cycle cost

As discussed previously, batteries can be classified as either deep or shallow-discharge. Generally deep-discharge batteries are used when less than five days' of storage are required. For longer storage periods, shallow-discharge batteries are more often used. Although a deep-discharge battery may be used in a shallow-discharge application, it is likely to develop a stratified electrolyte condition unless the electrolyte can be periodically mixed. Mixing can be accomplished by either a mechanical device or by a short period of overcharging (equalizing charge).

Where the system is located is very significant in battery selection. If the site is far away and unattended, or, in the extreme case, inaccessible, (such as space power systems), it is very important to have a low maintenance or maintenance free battery. High-maintenance batteries such as lead-antimony batteries are to be used only if proper precautions are taken and the site is accessible so that routine maintenance can be easily performed.

Batteries are heavy and large batteries are very heavy (up to 350 pounds per cell and more). As a result, proper handling equipment must be available on site if large batteries are used. For this reason, very remote systems located in hard-to-access places will often be better served with a large number of small batteries as opposed to a few large batteries because of logistical requirements of transporting and handling large heavy units.

The smaller the system the more likely the owner is willing to replace his battery every three to five years. The large industrial system owner will usually look for a longer battery system lifetime.

Although most battery manufacturers agree that any number of parallel connections in a battery bank will not reduce reliability, a large number of connections may increase installation cost. Some manufacturers have stated that a large number of series-connected batteries can reduce reliability, however, experience with up to 120 series-connected batteries has shown no reliability problems to date due to wiring. Proper hardware and installation proceedures are most important.

When systems are installed in remote areas and/or accurate local climatic data is not available, a conservative value for "no-sun days" should be selected due to variability in local climate from year to year. The increase in the size of battery storage bank resulting from designing around a conservative number of no-sun day is considered desireable, particularly in critical systems such as communications.

When a backup power supply is available, such as a diesel generator, it is possible to select a short "no sun" day period without sacrificing system reliability. The advantages of a backup generator are most apparent in systems that would otherwise have a long (15 days or more) "no sun" period. For example, if a mountain-top system requires 20 days of storage, use of a reliable backup generator would allow you to shorten the period to 3 to 5 days. (Note: most generators must be used periodically to ensure their starting when necessary - this is called exercising.)

With batteries, as with most other things, you "get what you pay for". If initial low cost of a system is a prime consideration, it may be best to use less costly but shorter life batteries. On the other hand, if life-cycle costs are considered, it may be more economical to use a longer life battery (which, of course, costs more). Table 4.1 compares several batteries' initial and life cycle costs.

Other considerations are manufacturer's experience, design capability and commitment. Does he make a specially designed photovoltaic battery or is he trying to sell a car battery with a new label? How is the product warranteed? What accessories are available? How are terminal connections made? The PV systems designer should consult and be fully-familiar with the battery manufacturer's design criteria, specifications and recommended operating and maintenance procedures before specifying any battery.

Table 4.1
Comparison of Various Storage Batteries

MANUFACTURER	MODEL	LIST PRICE ($)	SHALLOW/ DEEP CYCLE	NOMINAL AH* (AH)	NOMINAL V (V)	DDOD (%)	LIFE (CYCLES)	LIFE (YEARS)	# SETS OVER 20 YR PV LIFETIME	TOTAL kWh DELIVERED (KWH)	$/kWh
Exide Charge Retaining	3-DD-3	93	S	95	6	15	1625	4.5	4	139	0.67
						20	1500	4.1	5	171	0.54
	DD-5	51	S	190	2	15	1625	4.5	4	93	0.55
						20	1500	4.1	5	114	0.45
	DHB-5	185	S	480	2	15	1675	4.5	4	234	0.79
						20	1500	4.1	5	288	0.64
Exide Tubular Modular	6E95-5	702	S	192	12	15	4100	10**	2	1417	0.50
						20	3900	10**	2	1797	0.39
	6E120-9	1092	S	538	12	15	4100	10**	2	3970	0.28
						20	3900	10**	2	5036	0.21
	6E120-21	1116	S	1346	6	15	4100	10**	2	4967	0.22
						20	3900	10**	2	6299	0.18
Exide Tubular Stationary	EI-5	181	S	372	2	20	3500	10	2	521	0.35
	EI-13	343	S	1116	2	20	3500	10	2	1562	0.22
	10-S-17	620	S	1809	2	20	3500	10	2	2533	0.24
Delco-Remy Photovoltaic	2000	110***	S	105	12	10	1800	4.9	4	227	0.48
						15	1250	3.4	6	236	0.47
						20	850	2.3	8	214	0.51
Globe Solar Reserve Gel Cell	SRC-125G	181	S	125	6	10	2000	5.5	4	150	1.21
	SRC-250G	100	S	250	2	10	2000	5.5	4	100	1.00
	SRC-375G	150	S	375	2	10	2000	5.5	4	150	1.00
Globe	G 12 800 18	100	S	80	12	20	1500†	4	5	288	0.35
			D	80	12	80	550	<1	MANY	240	0.42
Surrette	CH 175	112	D	175	6	80	1400	3.8	5	2520	0.13
	25 29	755	D	490	6	80	1400	3.8	5	3293	0.23
	25 33	1158	D	564	8	80	1400	3.8	5	5053	0.23
Exide Tubular Modular	195 5	117	D	180	2	80	1800	4.9	4	518	0.23
	1120 9	182	D	360	2	80	1800	4.9	4	1037	0.18
	1120-21	372	D	1250	2	80	1800	4.9	4	3600	0.10

* Taken at 5 day rate for shallow, 72 hr. rate for deep (when data was available from mfg).
** Limited by mfg.
*** Mfg. doesn't set list price. Value approximate.
† Approx. life, obtained through conversation with mfg.

4.5. Battery Sizing

When sizing a PV system to meet a given load, efficiencies (energy output divided by energy input) of all components must be determined. However, when the ampere-hour (Ah) method is used to size a battery bank, the energy efficiency of the battery is not considered in the battery sizing calculation. The battery's internal losses are, instead, considered as an another addition to the system's total load during the PV array sizing and, must be calculated so that the PV array size and output can be increased to insure that enough net power is available after all internal system's losses are considered to satisfy the system's load.

When sizing the battery bank then, we consider the Ah efficiency (called "coulombic" efficiency) to be close to 100% (when the batteries are new) such that Ah OUT = Ah IN. Of course, this is not the same as saying that the energy efficiency is 100%.

What actually happens during the charge-discharge cycle is that a battery is charged by putting in a certain number of Ah at an input voltage (e.g., 13 - 15 V for a 12 V battery) and delivering the same number of Ah out at an output voltage that is lower than the input voltage (e.g., 12 V). Hence, a battery's energy efficiency can be calculated as its average voltage output divided by the average input voltage. This is called the battery's "voltaic" efficiency and is most often what people are refering to when they speak generally in terms of battery efficiency when storage batteries are incorporated in a PV system.

The first step in determining the size of the battery required is to calculate the daily load, L, in terms of ampere hours (Ah) and the system voltage, V (explained later in System Sizing). The load will determine the battery capacity (Ah); the system voltage will determine the number of cells to be connected in series. In determining L, be sure to include all non-negligible power consuming devices (such as inverters).

Next, you must decide on the number of "no sun" days (N). The number is based on experience with the local weather conditions and the required reliability of the system. In a few cases, local codes specify the storage requirement. As an example, Table 4.2 presents no-sun data for Tucson, Arizona and can be used to determine the number of "no sun" days for a PV system in a region (such as Phoenix) that is known to have very clear skies almost every day.

REQUIRED RELIABILITY	APPLICATION	NO-SUN DAYS
Medium 90-95%	Lighting Water pump/with storage Appliances	3
High 95-98%	Cathodic protection at remote site	5
Very High* (Better than 98%)*	Communications at "inaccessible" sites	8

* It is unrealistic to consider a system that is 100% reliable.

TABLE 4.2
System Reliability and No-Sun Days in Tucson, AZ.

For areas of less daily sun, such as in Massachusetts, the required amount of storage is two to three times as high. PV system engineers have developed computer sizing programs which utilize a statistical reliability analysis to determine the optimum number of days of storage for a given

required system reliability.

To calculate the total usable battery capacity (TUC) required for a PV storage system, multiply the load, L, by the number of days of storage, N:

$$TUC = (L)(N)$$

It is important to remember that TUC <u>does</u> <u>NOT</u> equal the nominal rating of the battery capacity as specified by the manufacturer.

Once the TUC has been determined, the required rated battery capacity, C, (as stated by the battery manufacturer) should be calculated. The calculation procedure differs according to manufacturer depending on what parameters the manufacturer considers to be important. Most often the parameters are:

* Daily depth-of-discharge
* Maximum allowable discharge
* Rate of charge and discharge
* Operation temperature
* Rated capacity of battery near end of its life

If we use the Delco 2000 for an example, the manufacturer recommends the following procedure:

1. Determine N, the number of "no sun" days.
2. Determine the actual battery capacity as a function of ambient temperature and discharge rate. Call this "C".
3. In order to avoid discharging the battery more than its maximum allowable depth-of-discharge, MDOD, (50% for the Delco 2000) even at the end of the "no sun" day period, multiply C by the DOD to get the usable rated capacity.
4. In the case of the Delco 2000, the number of batteries required in parallel is equal to TUC divided by the product of C and MDOD, obtained in step 3.
5. Determine the number of batteries needed IN PARALLEL

   $$Bp = \frac{TUC}{.5*C} = \frac{2\ TUC}{C}$$

   If the Bp calculated is not a whole number, always round up.
6. To find the number of batteries in series, divide the system voltage, V, by 12 (the nominal voltage of the Delco 2000).

   Batteries needed IN SERIES

   $$Bs = V/12$$

   If the Bs calculated is not a whole number, the Delco 2000 should NOT be used.
7. The total number of batteries needed in the product of the two.

4.5.1. Battery Sizing Example

The following basic sizing example for a simple, stand-alone PV system will serve to illustrate this battery sizing process.

System Design Parameters:

* System load, L, = 42.4 Ah per day
* System voltage, V, = 48 volts DC
* Location is Fish Creek, Arizona
* Operation is not critical, but important

Since the load requires a medium to high reliability, four no-sun days are chosen.

Determine Battery Capacity, C

It is assumed that the battery will be used mostly during the day and will be kept near 70°F during the winter months. If 42.4 amp hours are being drawn during 8 hours the average discharge rate is 42.4/8 = 5.3 A. According to the manufacturer's data presented in Graph 4.2 for the Delco 2000, the capacity of the battery is approximately 96 Ah.

Find the required number of batteries in parallel,

$$Bp = \frac{(2)LN}{C}$$

$$Bp = \frac{2(42.4)}{96}\frac{(4)}{}$$

$$Bp = 3.53 \text{ rounded up to 4 batteries}$$

Now let's calculate the daily depth-of-discharge and see if it is within the manufacturer's recommended limits. Since we have a total Amp-hour capacity of 4 x 96 = 384 Ah and we are withdrawing 42.4 Ah each day, the daily depth-of-discharge is 42.4/384 = 11%. This falls within the allowable range of daily depth-of-discharge as recommended by Delco which is 15% or less. As a result the battery bank will have a life of about 1700 cycles (nearly 5 years). Cycle life for the Delco 2000 is found using Graph 4.1.

Find the required number of batteries in series:

$$Bs = \frac{V}{12} = \frac{48}{12} = 4$$

Therefore the total number of batteries required is equal to sixteen. Four in series to deliver the required voltage and four in parallel to provide the required Amp-hours of current.

If it had been decided that only two days' of storage were needed, then Bp would be found initially to be:

$$Bp = \frac{2(42.2)(2)}{96} = 1.7 \text{ rounded up to 2 batteries in parallel}$$

Hence, a total capacity of 2 x 96 = 192 Ah. Since we are taking out 42.4 Ah each day, the daily depth-of-discharge = 42.4/192 = 22%. In this case we have passed the manufacturer's recommended allowable 15% daily depth-of-discharge and consequently have shortened battery life to about 700 cycles (less than 2 years). Since such a short battery life is probably not acceptable, either the number of batteries should be increased or a battery that allows a deeper daily discharge should be specified.

Table 4.2, on the following page, is a comparison between some of the various batteries currently used in PV systems. The LIST PRICE is that which is offered by the manufacturer on a retail basis for small

quantities. Some of the batteries are listed more than once to show how the daily depth-of-discharge affects battery life and, ultimately, system cost. Performance characteristics were all obtained from manufacturers' literature and are not to be considered as measured performance values. Total kWh delivered is equal to:

TkWh = (DDOD) (VNOM) (# Cycles) (Ah Rating)

Then, cost per kWh of electricity delivered from storage calculated as LIST PRICE/TkWh.

In determining what battery to use in a system it is also important to add the cost of freight, handling and labor to the cost of replacing the battery when it reaches the end of its life. As an example, we see in the table that the Delco 2000 is an inexpensive battery but must be replaced every 2 years if discharged 20% per day. On the other hand, the Exide Tubular Modular battery will last 10 years at a 20% daily depth-of-discharge. The life-cycle cost of the Exide may be considerably less than that of the Delco. This could be especially true if the storage bank was installed in a very remote location where transportation costs for more frequent replacement could be significant.

SECTION 5. VOLTAGE REGULATORS

5.1. Function of the Voltage Regualtor

The purpose of a voltage regulator in a stand-alone PV power system with batteries is to control the state of charge of the batteries. This prevents the batteries from overcharging or undercharging. It is also possible to minimize overcharging without a voltage regulator by a combination of careful PV module selection and system design however this practice is dependent on a variety of variable factors and is not generally recommended.

5.2. Types of Voltage Regulators

There are various types of regulators, each of which uses a different technique to regulate the batteries. The following types of regulators are described in this section:

* Series
* Shunt
* Sequential (array shedding)
* Ampere-hour integrating.

Series Regulator The series regulator, shown in Figure 5.1, incorporates a series charging relay in line with the PV array. In the morning as the sun rises, the regulator senses the rise in array voltage and closes the charging relay (appx. 140 mA draw) thereby connecting the array directly to the batteries. This is the first of the two-step charging sequence. As the battery voltage increases to a preset level (high voltage level termination point), indicative of a 90 to 95% state of charge, (approximately 14.5 to 15V on a 12V system depending on manufacturer and system parameters), the relay opens (no current draw). This stops the full array output from going into the battery (prevents overcharging).

At this point the regulator is in the float charge mode where a bypass transistor (i.e., the transistor is in parallel with the charging relay contacts) allows up to 3 amps of array current to go into the battery. The float charge will help maintain the batteries at a high state of charge. The battery will continue at a high state of charge as long as the array output exceeds the load. When the load needs more energy than the array can deliver the battery must supply the extra. This will cause the battery

voltage to drop. When the voltage falls to the "full charge resumption point" the charging relay will close, once again allowing full array output to go into the battery.

At night, the charging relay opens (this prevents wasting the energy the relay needs to stay closed) when it senses that the array voltage has dropped to a low voltage, typically 4 to 5 volts on a 12 volt system. On cloudy days, short cycling of the charging relay is prevented by using a time delay and by choosing a threshold voltage which is below the voltage level of the PV array voltage for "typical cloudy periods". Typical relays have a cycle life of 500,000 cycles. On a daily basis of two cycles per day, a relay would last close to 700 years.

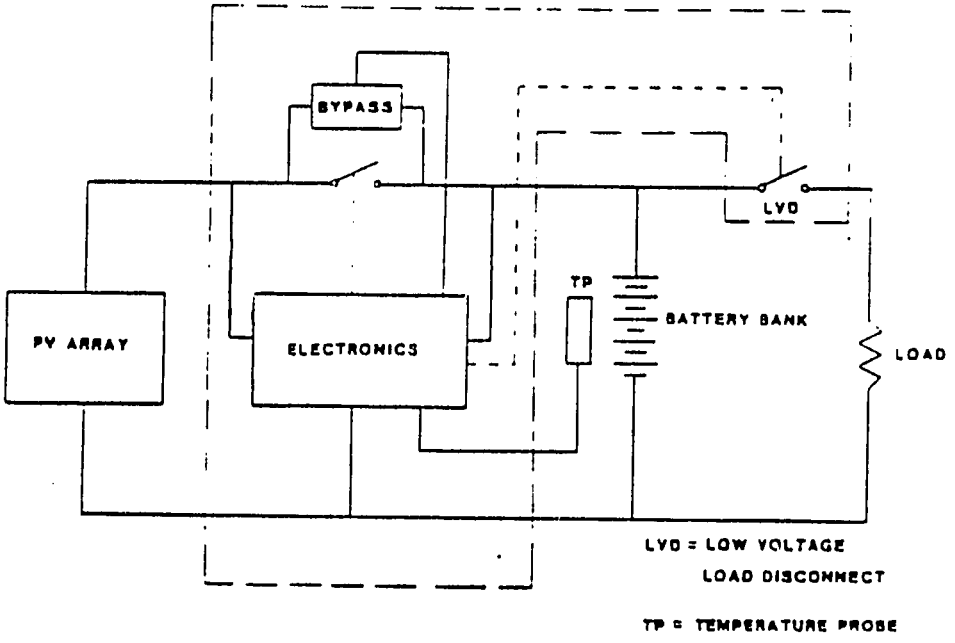


Figure 5.1
Series Regulator Block Diagram

Shunt Regulator The Shunt Regulator shown in Figure 5.2 is a solid-state voltage regulator that prevents overcharging of the battery through the use of a solid state device (e.g., transistor), by shorting out the array. The shorting of the array occurs when the regulator senses a high battery voltage (high voltage level termination point). At this point the regulator goes into a pulsating trickle charge mode whereby the shunt transistor opens and closes at varying rates, every 30 seconds on the average, depending on the array current. The slow switching of the transistor is purposely chosen to eliminate the possibility of a noise injection interference which is particularly important in communication systems.

This type of regulator incorporates a blocking diode (series regulators do not). The purpose of the blocking diode is to prevent the battery from discharging through the array at night. Without the diode the battery would slowly discharge (at a 20 mA rate). The disadvantage of using a blocking diode is power dissipation, typically 1/2 watt per amp for a silicon diode and 1/4 watt per amp for a Schottky diode. Schottky diodes are 2 to 3 times more expensive and have lower current ratings than silicon diodes. The diode can become quite hot and, therefore, must be mounted on a heat sink. The shunt transistor also must be mounted on a heat sink. Because of these heat sinks, shunt regulators are usually bulkier than series regulators. They also tend to cost more than comparable series regulators due to higher component and overhead costs. The need for and

use of blocking diodes is discussed further in the section on blocking and bypass diodes which follows.

A shunt regulator typically has a current rating between 6 A and 20 A. In systems that use an array that produces greater current than a single regulator will carry, several regulators may be used (they are connected in parallel). One manufacturer's method for increasing current handling capability is with the addition of slave units. The slave units are controlled by a master control board. Each slave is capable of handling the same amount of current as the master unit typically 12 amps in a 12 volt system.

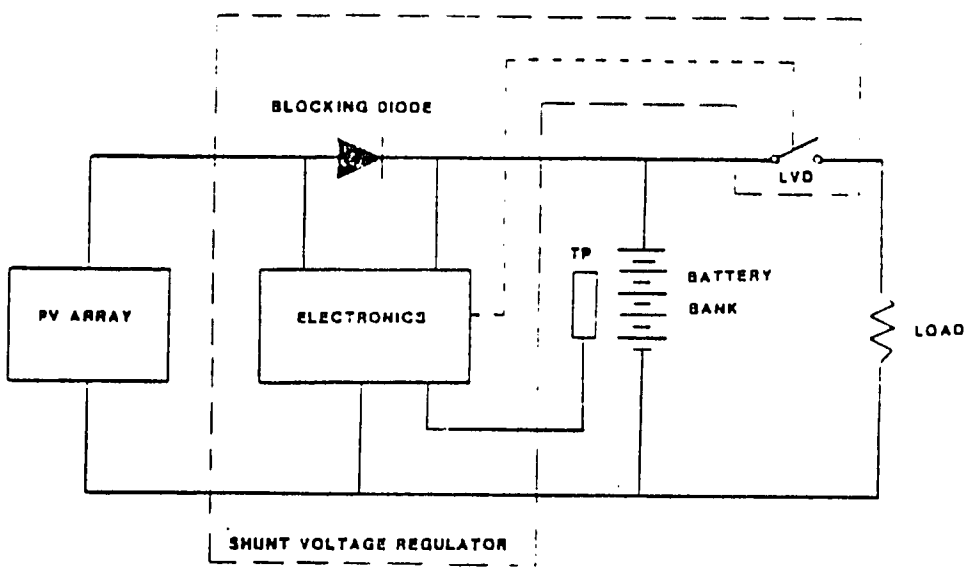


Figure 5.2
Shunt Regulator Block Diagram

Sequential (Array Shedding) Regulator The Sequential Regulator, shown in Figure 5.3, is used on large arrays (e.g., in the kW region). The PV array is divided into subarrays where each subarray is controlled independently. As the battery state of charge increases, the subarrays are disconnected one at a time, thereby diminishing the amount of charge going to the battery. The reverse is also true, the subarrays come back onto the system as the battery state of charge decreases. This regulator is typically made up of multiple series type regulators.

One advantage of the sequential regulator is failure tolerance. If one of the series regulators that make up the system regulation fails, then only a portion of the total array charging current is lost.

Ampere-Hour Integrating Regulator The Ampere-Hour Integrating Regulator, shown in Figure 5.4, is very accurate in controlling the amount of charge entering and leaving a battery bank because it measures the number of amp hours entering and leaving the battery bank. Voltage sensing regulators (series, shunt and sequential) only measure the two battery charge/discharge limits. The state of charge versus voltage of a battery bank can vary depending upon the charging or discharging current (e.g. overcharging or undercharging could occur especially with an old battery). The ampere-hour integrator can more accurately limit the battery depth-of-discharge (DOD).

For example, given a battery that is not to be discharged more than 50% per day, the amp-hour integrating regulator can be programmed to disconnect the

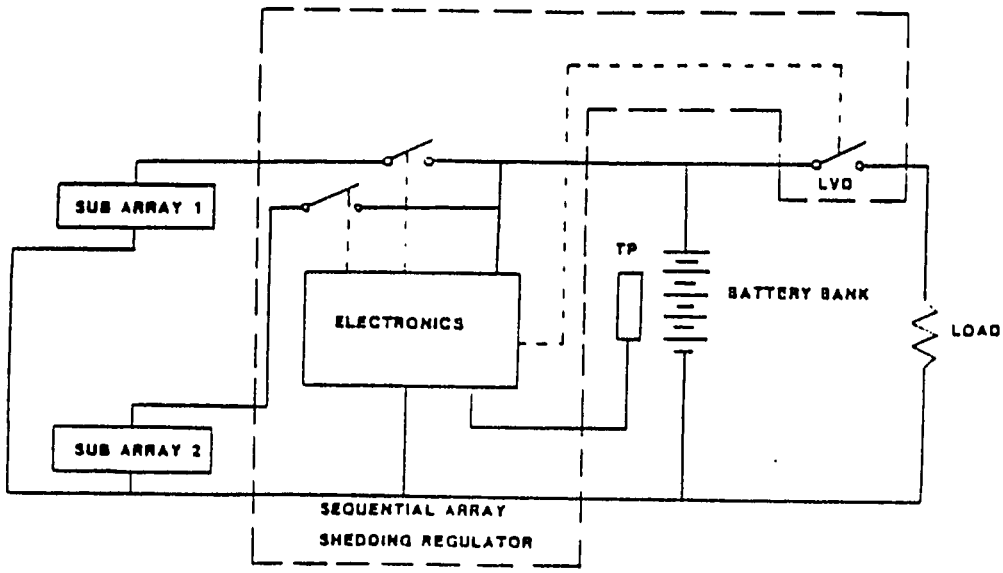


Figure 5.3
Sequential Regulator Block Diagram

load at exactly the 50% capacity point. When full capacity is restored the regulator will either shunt the array (disconnect it), or, if the load is off, turn on the load which will use up the excess array output. Of course, this is only done if the system load is discretionary such as some water-pumping applications. The PV array output could also be connected to an additional load. Exactly what is done with the "excess" array output is up to the system designer and will vary with each application

The amp-hour integrating regulator is primarily used in high current systems because its parasitic losses are larger than those of series or shunt regulators. Due to the added electronic components and memory storage inherent in this type of regulator it is perhaps somewhat less reliable than other regulator types.

5.3. Optional Features For Voltage Regulators

There are various features which may be incorporated into each of the voltage regulators described above. The ones discussed here are:

* Low voltage load disconnect
* Timers
* Battery temperature compensation
* Alarms and tran-sient protection

Low Voltage Load Disconnect This device disconnects the load at a preset battery voltage level called the load disconnect threshold (11 to 12 volts for a 12 volt system). This protects the battery bank from being discharged too deeply. The load is reconnected after the battery voltage rises to a higher level called the load reconnect threshold (between 13 V and 13.6 V for a 12 V system). This hysteresis prevents rapid ON/OFF cycling of the load (often called hunting).

Both mechanical and solid state relays can be used to disconnect the load, however, the solid state relay has inherent limitations that cause most manufacturers to use the mechanical relay. (Solid-state relays consume

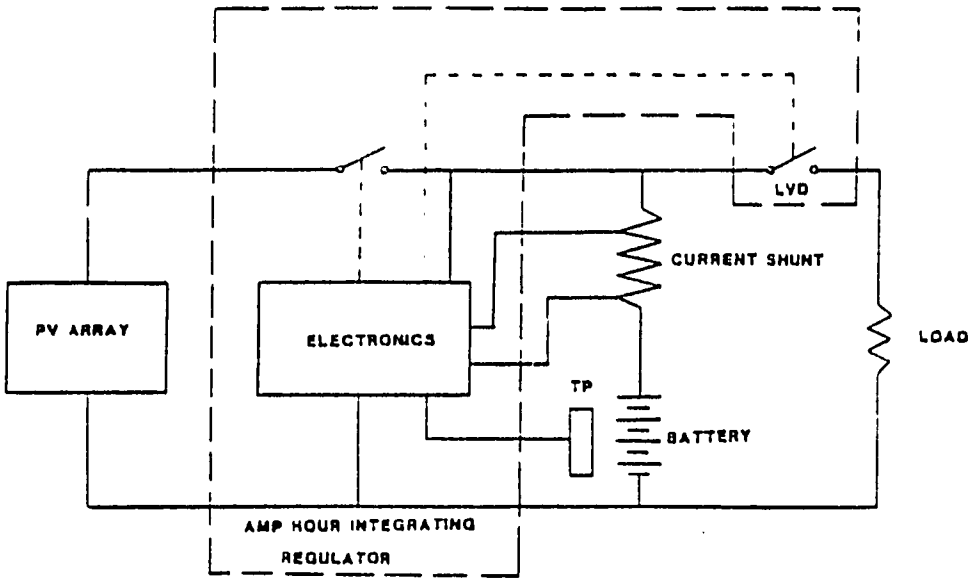


Figure 5.4
Ampere-Hour Integrating Regulator Block Diagram

more power than mechanical relays and are limited to 5 amps at 60 Vdc or 1 amp at 200 Vdc.)

Timers Timers are used to turn the load on and off at specific times of the day or night. The most common application of a timer is for street lighting. In street lighting systems, a controller turns on the light at dusk (seen as a low array voltage). After a specified amount of time, the timer turns the light off. If dawn (seen by the controller as a rise in the PV array voltage) comes before the time is up, the timer automatically resets and the light is turned off.

Temperature Compensation Regulators with battery temperature compensation automatically adjust the high voltage charge termination point. This maximizes the charge entering the battery bank with respect to the battery's temperature. This compensation is on the order of -5mV/°C per battery cell for lead-acid batteries. The temperature sensing device can be located either inside the regulator (the regulator must then be put close to the battery bank) or outside (the regulator can have a remote battery temperature probe). A remote probe will allow placement of the regulator outside the battery enclosure.

Alarms Alarm circuitry is used to signify a condition of unusually high or low battery voltage. When this condition occurs a switch is turned on that activates an alarm signal. The signal may be a light, an audible alarm or a radio wave. Alarms are frequently used in remote, critical systems.

Transient Protection Transient protection is standard on most regulators, and is critical because high voltage surges can be very destructive to the electronics in the voltage regulator. A high voltage surge can result from a nearby lightning strike or from a load that causes a rapid on/off current flow (e.g., DC motor brushes, DC contactors or DC to AC inverters when the switching frequency of the inverter interferes with the electronic logic of the voltage regulator). Lightning surges transmitted through the PV array can also damage the load if care is not taken to limit these surges to a safe level. The most common form of transient protection is a metal oxide varistor (MOV). Others include zener diodes, transorbs, and gas-discharge surge arrestors.

5.4. Selecting a Voltage Regulator

There are many parameters to consider when specifying a voltage regulator. Some of the more important ones are:

* Reliability
* Power handling capability
* Cost
* Low voltage load disconnect
* Parasitic losses
* Totally solid-state
* Size and ease of installation

The type of PV system will determine which of these concerns are most important. A general overview of the concerns follows.

Reliability Some systems need to be more reliable than others (e.g. communication repeaters need to be more reliable than street lighting or residential applications). Desired system reliability is a function of the system's importance to the user and maintenance cost, which includes travel cost to repair the system.

Power handling capability This is predetermined by the array and load size. It is necessary to choose a regulator which can match or surpass the power handling requirements of the array and load.

Cost The cost of a regulator is dependent on the size of the array and load. Other items which affect cost are enclosures, metering and regulator type.

Low Voltage Load Disconnect This is a very useful feature as it accomplishes two things. First it extends the battery life by not allowing the battery to drop below its rated capacity and second, it decreases the likelihood of damage to the load in cases where the load has a minimum input voltage requirement.

Parasitic losses The parasitic (internal) loss of any system component (in this case, the regulator) must be considered as an additional load on the system. In small systems (100 W or less) the parasitic loss may be a considerable portion of the total system's design load. In order to avoid having to increase the array/battery size, it is best to select a regulator that causes a negligible parasitic load.

Totally solid-state Complete solid state componentry is sometimes necessary where there is danger of explosion such as in a gaseous environment of a poorly vented battery box, or a corrosive atmosphere, such as coastal areas or off-shore oil platforms, which could corrode mechanical relay contacts or circuit board contacts.

Size The importance of the size of the regulator depends on its intended location in the PV system (such as when the regulator must be placed in the battery enclosure) and its final destination. The size of the regulator also affects both the installation and transportation costs.

Ease of Installation The easier it is to connect a regulator into a system, the less time and money spent. This is especially true if periodic replacement is necessary. Positive things to look for, depending on the system, are a crimp type terminal block (i.e., no lugs necessary), good installation instructions and solid construction.

Table 5.1
Comparison of Various Voltage Regulators

VOLTAGE REGULATORS

Function	With Low Voltage Load Cutoff				Without Low Voltage Load Cutoff		
	Photocomm SBM45S5/SBMH15S5M	Specialty Concepts SCI Charger	Tri Solar BCR	Rho-Sigma RS 602	Photocomm SS,SRM	Specialty Conns. ASC	Specialty Conns. ASC
SYSTEM VOLTAGE	12,24,36,48,96,120	12,(24),120 max.	12,24,36,48	12,(24)	12,(24)	12,(24)	12,(24)
ARRAY CURRENT (MAX)	SBM45S5-6A ea. SBMH45S5M-12A ea.	30A @ 12V 20A @ 24V	25A	10A	6,12,(6),(12)A	2,6,(4)A	2,6,(4)A
LOAD CUR. (MAX) (RESISTIVE)	5A @ 24V max.	30A @12V 20A @ 24V	15A @ 24V max.	10A	-	-	-
TYPE OF CONTROL	Shunt w/Blocking Diode	Series Relay No Blocking Diode	Shunt w/Blocking Diode	Series Relay No Blocking Diode	Shunt w/Blocking Diode	Shunt w/Blocking Diode	Series Trans. No Blocking Diode
LOW VOLT. LOAD DISCONNECT PT.	Optional 12,24,36,48,96,120	11V,(22V)	Optional 10.7,21.4,M4,42.8V	10.5-12.5V (21-25V)	-	-	-
LOW VOLT. LOAD RECONNECT POINT	13.24,39,52,104,130V	13V,(26V)	11.7,23.4,M4,46.8V	13V,(26V)	-	-	-
HIGH VOLTAGE TRICKLE CHG. PT	14.4,28.8,43.2,57.6 115.2,144	14.1V,(28.2V)	14.4,28.8,43.2,57.6V	14.5,(29V)	[illegible],(28.8)V	14.1,(28.2)V	14.1,(28.2)V
TRICKLE CHARGE CURRENT (MAX)	Array Current	3A,(1A)	Array Current	2A	-	Array Current	Array Current
TEMPERATURE COMPENSATION	Remote ±2%	Remote	Remote	Remote	Local ±2%	-	-
QUIESCENT CUR. DRAIN	5.7mA @ 12V	10 mA	8,6.5,6,6 mA	25 mA	11 mA	5 mA,(7mA)	10 mA,(12 mA)
WORST CASE CUR. DRAIN	50 mA @ 15V	180 mA	7.5-65 mA	75 mA	11 mA	5 mA,(7 mA)	10 mA,(12 mA)
INDICATOR LED's	-	Low Voltage Disconnect	-	Charge Status Low Volt. Discon.	-	-	-
METERS	-	Optional Separate	-	-	-	-	-
FUSES	-	Standard	-	-	[illegible]	-	-
OPERATING TEMP. RANGE	-40°C to 55°C	0 to 50°C	-25°C to 60°C	0 to 70°C	[illegible]50°C	-20°C to 50°C	-20°C to 50°C
ENCLOSURE	None (P.C. Board)	Vented Box	Weatherproof Box	Rain-tight	[illegible]ated	Encapsulated	Encapsulated
SIZE, IN. (cm)	SBM45SMH-SM45SRSM-	8x5.5x3(20x14x7.6)	8x9x3.5(15x23x9)	5x9.5x3(13x24x7.6)	5x8x1(7.6x20x2.5)	4.7x2x0.9(12x5x2.3)	4.7x2x0.9(12x5x2.3)
WEIGHT	1 lb. (0.45kg)	2 lbs. (0.9kg)	2.5 lbs. (1.3 kg)	3.5 lbs. (1.6kg)	1.1 lbs. (0.6kg)	4 oz. (0.1kg)	4 oz. (0.1kg)
WARRANTY	5 yrs	1 yr	1 yr	3 yrs		1 yr	1 yr
EASE OF HOOK UP	Poor	Very Good	Good	Fair	Very Good	Very Good	Very Good
COMMENTS							

5.5. Blocking and Bypass Diodes

As it was mentioned previously, a device called a blocking diode also helps to manage the flow of electricity between the array and the batteries. At night, or at times when the PV array is generating a voltage which is less than the battery voltage, electricity stored in the batteries can and will flow back out into the array and be dissipated as heat. If allowed to occur, this reverse flow would drain down the batteries and could also cause possible damage to the array.

Blocking diodes are included in the PV array wiring to prevent this reverse current flow and they operate like an electrical version of a one-way check valve in a hydronic piping system. Blocking diodes simply do what their name implies: allow the current to flow only in one direction. In this case into the batteries from the array. They are installed in series with the main "string" connections from the array to the inverter input in a utility-interactive system and to the battery bank in a stand-alone system. They are often located in a "string combiner box" which combines the positive and negative feeders from the PV array strings in parallel to provide a single pair of positive and negative DC output feeders from the array.

Another small but important device in a PV system is the bypass diode. The purpose of bypass diodes is to provide an alternate path for electricity which would otherwise have been impeded by a shaded or failed cell or string of cells within a PV module so that the failure of a single module will not seriously affect the entire array.

If one module in a series array string becomes shaded (or damaged) so that the module does not produce electricity, it will limit the current flow in all of the other modules in the series string (much like the old series strings of Christmas tree bulbs - when one failed, they all went out). A bypass diode provides an alternate path for the flow of current produced by the remaining modules in the string.

Typically, one bypass diode is placed in parallel with each module in a series array string, with the diode's anode on the module's negative terminal and the diode's cathode on the module's positive terminal. Most commercially-available PV modules include bypass diodes as a standard, built-in feature from the factory.

With a bypass diode in place, the string current will remain (to the first order) essentially unchanged when one PV module in a large series string of modules is shaded; the string voltage will decrease by an amount equal to the normal operating voltage rating of the module plus the forward voltage drop of the diode which is typically around .7 volts.

Bypass diodes are important items to include in a PV array. In early PV systems which didn't have bypass diodes, many PV modules were destroyed when an entire string's worth of current was "dropped" across a single inoperative cell which, because of shadowing or damage, became an electrical resistor rather than a current producer. The resultant heat from the dissipated current created a "hot spot" condition which, over time, led to module delamination and failure. Always make certain that each PV module in a series array string is protected by its own bypass diode and make every effort to install the PV array in an area where it will not be shadowed.

SECTION 6. INVERTERS

Electrical current comes in two basic types: direct current, (DC) and alternating current, (AC). In a direct-current system, the polarity and electrical pressure (voltage) remain constant whereas, with alternating current, polarity and voltage are constantly reversing. One example of an AC power source is a rotating generator of the type used by utility companies. During the development of the public electric utility industry, the practicality of alternating current which could much more easily be stepped up to high voltage and transmitted across substantial distances than direct current was demonstrated. This led to the universal adoption of alternating current as the medium for utility grids and, consequently, was the type of power source the vast majority of electrical equipment was designed to function with.

Direct current, of course, did not disappear from the scene. There are DC appliances ranging from fluorescent fixtures to motors, refrigerators, electronics and communications equipment designed for use in marine, aircraft and recreational vehicle applications (among others). Sources of DC power include batteries, the DC generators used with many small wind and hydroelectric systems, and, of course, photovoltaics.

A photovoltaic array, regardless of its size or sophistication, is capable of generating only DC electricity. Fortunately, there are many applications for which direct current is perfectly suitable. When AC power is required from a PV system the task of converting the PV system's DC output to AC electricity can be accomplished easily and efficiently through the use of a piece of equipment called the <u>inverter</u>.

Inverters are nothing new. They have been around as long as there has been a need for converting DC into AC electricity. Early models were of the rotary type with internal moving parts, where the source of DC electricity was used to power a DC motor which was connected to an AC alternator which produced AC electricity for the load. Rotary inverters are still manufactured, largely for use in marine and aircraft electrical systems. The inverters employed in alternative home power systems are, almost without exception, of the transistorized, solid-state type. Solid-state inverters are preferred for their high efficiency, ease of maintenance and infrequency of repair.

Generally speaking, inverters designed for use in PV sysems may be divided into two categories: <u>static</u>, or "stand-alone" and <u>line-tie</u> or "utility-interactive". The first of these is capable of functioning independently as part of a home electrical generating system unconnected to the public utility grid. It is activated solely by the incoming DC power from the photovoltaic array (or batteries, or wind turbine, or hydroelectric generator). Line-tied inverters, on the other hand, are compatible only with a utility-interactive home power system that is tied into the central utility grid.

In both stand-alone and utility-interactive residential photovoltaic systems, the inverter's function is not only to change DC into AC electricity. It also must perform the task of "conditioning" the array output, so that it can efficiently operate the various components of the load (appliances, lighting, motors, etc.) and, in the case of utility-interactive inverters, integrate smoothly with the current, voltage, and frequency characteristics of the utility-generated power present on the distribution line.

In addition, the inverter is expected to provide a stable voltage output, a steady AC frequency and a waveform which departs as little as possible from the basic sinusoidal wave shape of a 60-cycle sine-wave (50 cycles in Europe and many other foreign countries). Inverter conversion efficiency is also a very important consideration. Internal losses in a DC-to-AC inverter can consume between 5 to as much as 40% (or more at low power levels) of the system's DC output power.

In stand-alone applications, sizing of the inverter is critical. The unit must be sized large enough to handle motor-starting surge inrush currents and the resultant peak minute/second loads if two pieces of equipment happen to start up at the same time. However, care must be taken to avoid oversizing the unit because it will not deliver its peak efficiency when operated at only a portion of its rated capacity.

Utility-interactive inverters are not bound by the surge-capability requirements of stand-alone units, (because the utility will satisfy any load surge requirements) but sizing is very important nonetheless. The inverter must be carefully chosen to match both the PV array output and the utility interface parameters. Although an isolated PV system is unlikely to cause much difficulty, a sizable aggregate of badly-designed or poorly-functioning inverters could cause harmful variations in line voltage and frequency on the distribution line beyond the utility's acceptable limits.

The utility-interactive inverter differs from stand-alone units in that it can function only when tied to the utility grid. In effect, it provides the interface between the photovoltiac array and the utility, and makes possible the "sell-back" of power provided for under the Public Utilities Regulatory Policy Act (PURPA) of 1978. It is worth noting that, in many line-tied PV systems, much if not most of the PV array output will be sold to the utility rather than used directly on-site because of the difference between the time of peak array output and peak load requirements that often exists. Because of this situation, the utility rate structure should be examined and factored in to the system planning for a utility-interactive PV installation.

Important parameters that should be considered when choosing an inverter are:

* Efficiency (ratio of output AC power to input DC power)
* Operating loss at less than full output
* Tare loss (energy used by the inverter in standby mode)
* Waveform harmonics and distortion (how close the output wave is to a true sine wave)
* Power factor (how close the current and voltage waveform are being syncronized - the ideal power factor is 1.0 or unity)
* Surge capability (used to start motors)
* physical characteristics
* cost and reliability

6.1. Utility-Interactive Inverters

From the outside, a utility-interactive PV installation looks much the same as a stand-alone. However there are fundamental differences in the internal relationship of the components, particularly with regard to the function of the inverter. In short, a utility-interactive system is not just a stand-alone system without batteries.

DC electrcity generated within the modules of the array flows through lightning protection and source combining equipment directly to the inverter, which along with its filters and controls is referred to as the <u>power conditioner</u> in a utility-interactive system. At the power conditioner, the raw DC output of the array is inverted to AC electricity of the quality required for load consumption and grid interface. At this point, depending upon the level of output and the fluctuating demand of the house loads, the AC power from the power conditioner flows either to the loads, or -- during

times of excess output -- to both the loads and the utility grid.

The PV side of the system, however, cannot operate with complete independence from the utility -- that is, with presently-designed equipment, the utility requires that the PV system immediately disconnect from the grid whenever the grid fails to eliminate any possibility of PV-generated power being fed out onto a "downed" line and endangering service personnel.

The only exceptions to this technical dictum are if you install a second inverter capable of stand-alone operation or, one of the new, semi-experimental, bi-modal, self-commutated inverters capable of either line-tie or stand-alone operation. These new inverters are not likely to be easily accepted by the utilities, though, unless it can be proven to their satisfaction that they will not send current out onto the lines when the grid is down.

Since there can be no PV contribution at night, and since an inverter kept in operation by incoming grid current but doing no work can represent a parasitic load in and of itself, most utility-interactive systems incorporate an automatic "night-mode" sensing circuit, which deactivates the inverter during periods when PV generated-power is inadequate.

Much is asked of a utility-interactive inverter, both by the system itself and, by the utility to whose grid it will feed power. Some of these requirements will vary with the size of the installation, while others are implicit in the nature of the demands placed upon dispersed power producers and will apply in all cases. These latter requisites are by now assumed to be fundamental by all manufacturers of quality utility-interactive inverters, and should not have to be individually specified by the PV system designer. Nevertheless, it's a good idea to have at least a general familiarity with what this piece of equipment is supposed to do, and why.

6.1.1. Selecting a Utility-interactive Inverter

There are many different factors which affect the cost and performance of a utility-interactive inverter. **Size and efficiency** are two important variables. The utility-interactive inverter has to be sized large enough to handle the PV array output power including the higher-than-normal **source surges** generated during certain weather conditions which produce up to 1.4 times the normal solar insolation intensity (1400 Watts per M^2) on the array by magnification from cloud and snow reflections. All quality utility-interactive inverters are designed to handle these occasional periods of increased array output. If this is not clear from the manufacturer's literature, you should inquire as to the capabilities of a particular unit before you purchase it. Load surges such as those from motor-starting inrush currents are not an important issue in utility-interactive systems, since the utility grid itself covers the home's peak requirements. Of course, this is not true in stand-alone PV systems.

Most utility-interactive inverters achieve their maximum operating efficiency at or near full power rating. Since the solar insolation intensity and the angle of incidence on the array as well as temperature and other operating parameters are constantly changing, the utility-interactive inverter operates at its full power rating only a small portion of the time. It is, therefore, very important to choose an inverter with a high <u>average</u> efficiency or a (nearly) flat efficiency curve. Most inverter manufacturers publish the output efficiency of their units as a function of the percentage of rated power from 1/8 power to full load and many provide this information in graphic form as well. If this information isn't easily understood from the manufacturer's literature, inquire about it. An increase of a percent or two in average inverter efficiency can mean thousands of kilowatt hours of increased output over the life of your PV system.

Max-power Tracking As for the variations in PV array output characteristics, many of today's more sophisticated inverters are able to perform

maximum power point tracking. This is the ability of an inverter to find and operate at the array voltage that maximizes the output power of the PV array at any given instance, under any set of conditions. Throughout each day, the output power of the array, measured as a product of current (amps) and voltage, is constantly shifting. Changes in insolation intensity affect current, and changes in temperature affect voltage.

Most high-quality inverters have an electronic control circuit that enables it to determine the voltage that offers the optimum power level on a fluctuating and continuing basis, thus enabling the system to make the most of prevailing circumstances. This is loosely analogous to the automatic exposure setting in a camera, where either aperture or speed are automatically adjusted according to the monitoring of light conditions to give the best exposure.

Inverter efficiency and maximum-power-point-tracking are of direct concern to the owner of a utility-interactive PV system. However, there are a variety of other factors which are of principal concern to utility companies that the owner or designer of a line-tie PV system must be aware of. These factors are those which have a potential effect upon the quality of the power in their grids and consequently upon policies governing the acceptability of utility-intertie arrangements.

Up until now, most of these concerns have remained academic, since there are hardly enough PV, wind, or other alternate generating facilities interacting with the grid to cause any real problems. However, as dispersed power generation becomes more widespread and the sources of power signals more numerous and diffuse, each of these influences on signal quality will grow in importance. Thus, inverter manufacturers, PV system designers, consumers, and the utilities themselves are wise to address these concerns at an early stage of the technology's development.

The critical issues include:

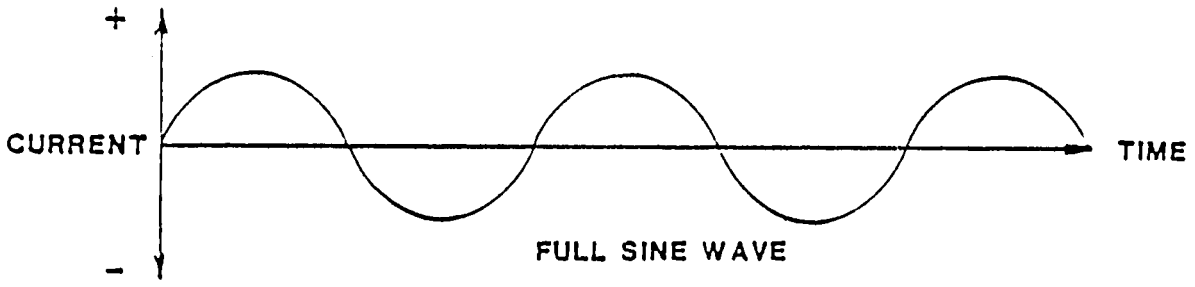
* Power factor or reactive power
* Wave shape and harmonics
* Voltage stability
* Frequency stability
* Electromagnetic interference (EMI and RFI)
* Safe operation

Power Factor is a qualitative measure of the in-phase relationship between the voltage wave form and the current wave form which, together, make up the AC signal in the utility grid. The ideal power factor is represented by the value 1.0, also called the "unity" power factor. Departures from unity power factor are indicated as fractions of that optimal number. A low power factor results when these wave forms are out of phase and is indicative of the amount of reactive or "parasitic" power in the signal being sent through the lines.

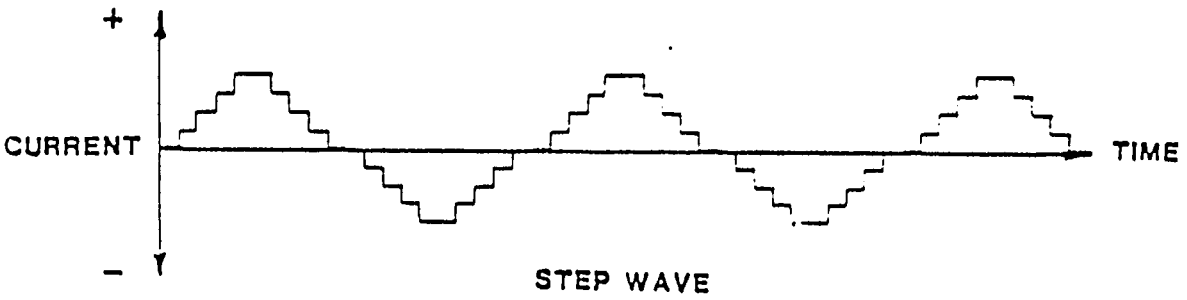
Inductive electric motors, such as those found in refrigerators, freezers, other large household appliances and industrial equipment, can bring down the power factor across the grid. Utility-interactive inverters, too, can have a negative effect on power factor; some of the earlier and less satisfactory models put out a signal with a power factor rating of as low as .3. The products currently being sold, however, often have a power factor rating exceeding .95 and are capable of meeting the utilities' requirements which are now applied as a general rule even though it will be a matter of many years before enough utility-interactive inverters are present on the nation's grids to significantly affect overall signal quality.

Wave Shape We are more accustomed to thinking of sound and radio transmissions in terms of waves rather than electrical currents. The term wave shape as used here means the shape of the waves which comprise the AC signal in a power line. The ideal wave shape for AC household current is the sine wave. The method by which inverters transform DC into AC varies with inverter quality and manufacturer. As a result, the shape of the AC wave output also varies from a basic square wave to a near-perfect sine wave. Some equipment and appliances operate more efficiently on a true sine wave inverter than on a square wave inverter. The closer the inverter output is to a sine wave the more expensive it is likely to be. A square-wave inverter may be adequate for some loads, however, sensitive electronics such as most televisions will operate correctly only on a sine wave.

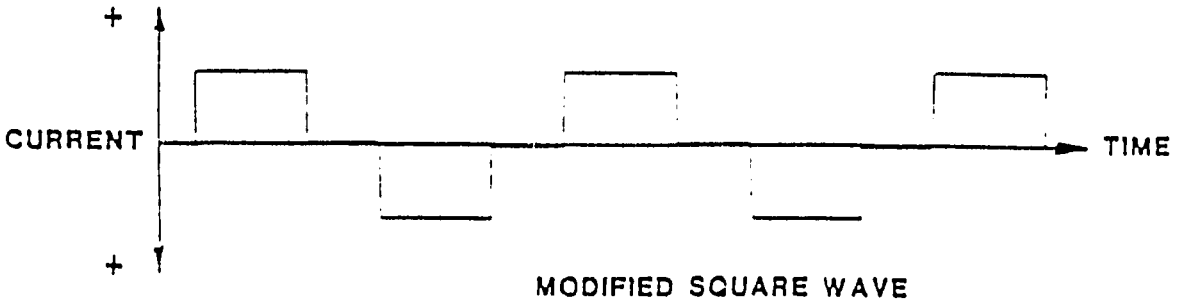
For the operation of synchronous and induction motors as well as the smooth interface with the utility grid, the sine wave is vastly preferable to the square wave put out by less-sophisticated inverters, although the step wave is a somewhat less-discordant compromise which can mesh with reasonable efficiency into the sinusoidal main current. Advanced thyristors and silicon switching transistors have made it possible for today's inverters to produce a very close approximation to a sine wave, acceptable to the utilities and harmless to household induction motors. The figures below illustrate the wave shapes commonly available from present inverters.



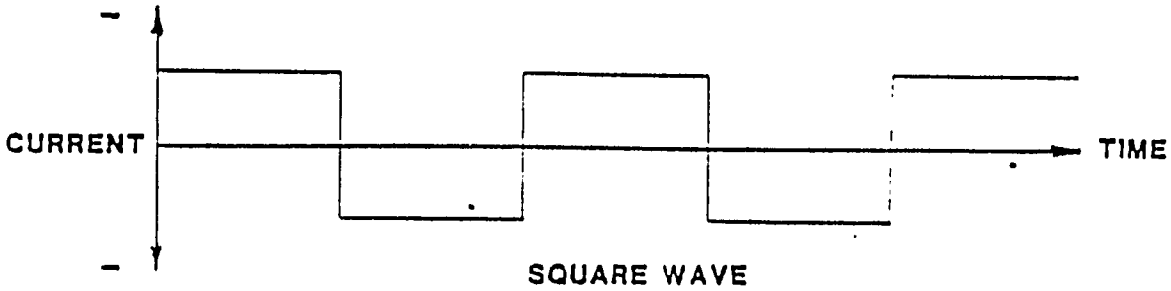
FULL SINE WAVE



STEP WAVE



MODIFIED SQUARE WAVE



Harmonics are closely related to wave shape. The harmonic content of either the voltage or current waveform is a measurement of the secondary signals and other interference present which, when taken in total with the primary sine wave signal, either adds to or subtracts from the primary signal resulting in a distorted wave form. If this harmonic distortion goes beyond 20 or 30 percent, an appreciable increase in the operating temperatures of induction motors becomes apparent. (This is why a square-wave signal is unacceptable, since by its very nature it represents distortion of greater than 40 percent.) The better synchronous inverters on the market are very low in current harmonic distortion, generally below 5 percent. In fact, developments in inverter technology have of late been charted in terms of months rather than years, and the very best contemporary designs are actually capable of producing a "cleaner" AC signal than that which normally prevails on the utility grid itself.

Voltage Stability Voltage harmonic distortion is the result of harmonic current from the inverter acting on the utility voltage. It is very unlikely that this problem will occur with residential PV systems especially if the inverter's current harmonic distortion is kept below 5%. Voltage regulation in a utility-interactive PV system will nearly always be determined by the utility's generation source. This is because the utility's source is so many times larger than the residential PV array's output that the utility-interactive inverter has no choice but to work at the utility-supplied voltage (or not work at all). All utility-interactive inverters must be capable of operating within the normal operating range or "window" of utility-supplied voltage which is required by the American National Standards Institute to be between 216 and 254 volts for a typical 240 VAC service.

Frequency Stability The frequency of an AC power signal is the measurement of the number of cycles it makes in one second. The unit of measurement is in cycles per second and is known as Hertz, abbreviated Hz. Frequency stability of the AC cycle is important because all synchronous motors respond and lock into the frequency of the power supply on which they are drawing, and any departure from the proper cycle can cause erratic operation of equipment such as clocks and phonograph turntables. In a utility-interactive PV system, deviations from the appropriate 60 Hz frequency are very seldom a problem because the inverter itself is synchronized with the grid. This is, of course, not the case in stand-alone PV systems where the inverter must generate and control the frequency of its AC output.

Electromagnetic-interference EMI is the phenomenon responsible for the crackle in radio or TV reception which sometimes occurs and is carried over the lines when another nearby appliance is switched on. Higher frequency EMI called radio frequency interference (RFI) is actually transmitted from the offending equipment through the air much like radio and TV signals. Line-tied (and stand-alone) inverters can themselves be a source of both high and low frequency EMI, not only in the homes where they are installed but at other sites close by. This problem has been recognized for some time and manufacturers of quality inverters have equipped their devices with filters capable of screening out this unwanted interference. Such

modifications detract slightly from efficiency and increase costs, but help assure that the inverters will not be a source of either utility consternation or neighborhood annoyance.

Safety Now as to that matter of safety. When there is a blackout on any portion of the power grid, the utility must be able to rely on the assumption that the lines are completely dead before sending repair personnel out to work on them. If there are no dispersed small power producers along the grid, the utility has no problem in making this assumption. But if there is just one line-tied independent electricity producer continuing to feed power into the "down" utility lines, the consequences could be disastrous for a lineman working on repairs -- particularly if the PV system output were to pass through a transformer and be stepped up to 4,000 volts.

If all utility-interactive PV systems were to fall completely silent upon grid failure, the problem would solve itself. But with the parallel connection of capacitors as a means of correcting the power factor of line-tie inverters, the door is left open for the possibility of continued operation (called run-on). When the utility signal is taken away, the output of some of the less sophisticated units can, under certain circumstances, become a square wave rather than a sinewave, and continue to deliver both voltage and current capable of entering the power lines.

It is also theoretically possible if two or more utility-interactive inverters are feeding power into the same utility distribution feeder that the units would continue to operate using each other's output for commutation in the event of a utility outage. For a more detailed discussion of this phenomenon and some of the solutions being developed, see the DOE report Loss of Line Shutdown for a Line-Commutated Utility - Interactive Inverter by E.E. Landsman.

Assuring the near-instantaneous (within milliseconds) shutdown of line-tied inverters in the event of a utility-power outage has been a priority of both PV-involved utility companies and inverter manufacturers alike. This is not only due to the obvious safety concerns already mentioned but, in addition, and of more immediate concern is the non-interference with the utility fault clearing process which occurs immediately after a line fault is detected. For these reasons, all utility-interactive inverters should shutdown within milliseconds of a utility-power failure and remain off the line until normal voltage and frequency have been restored to the line by the utility and remain stable for at least several seconds.

This concern naturally extends to work being done on the class of new dual-mode inverters being designed to be capable of either stand-alone or utility-interactive operation. Photovoltaic system owners and designers should be aware of the utilities' requirements in this crucial area, and must be certain they are met in their choice of inverters.

6.2. Stand-alone Inverters

We should begin the discussion on stand-alone inverters by briefly considering the general parameters of size and type of the load which determine the choice between supplying alternating or direct current to the system's loads.

AC or DC? When and where can we use direct DC current and when should we use AC? Given the low overall wattage demand and the varied assortment of DC equipment and appliances available; telecommunications repeater equipment, a micro-irrigation water pumping installation, and a small homestead or remote vacation retreat can all get along quite nicely using only DC to satisfy system loads.

With a larger load more representative of the electrical demands of everyday living, such as an average house, one invariably runs into certain inconveniences and limitations that make a DC-only system design strategy unworkable. Even after energy conservation is employed and non-electric-

specific loads are satisfied with alternative fuels, the average person will find it rather difficult to live without the benefits of AC power without a significant adjustment in lifestyle.

To begin with, not all of the AC-powered appliances we take for granted have DC-powered counterparts. An even more serious problem is the fact that most of those DC appliances available operate at 12 volts. This will cause little problem if the overall load is going to be kept small (less than 300 watts) but can create problems with wiring if the load is to be much more than that. If the system's voltage is chosen to be low, then loads had better be light as well, because low voltages, transported at the higher amperages required to satisfy substantial loads, are inefficient and require wiring which is much heavier, more expensive, and harder to install.

Wire is rated and sold according to gauges; the smaller the wire, the higher the gauge number. Each wire gauge has a maximum power carrying capacity which is determined by the amperage (not voltage) above which overheating and voltage drops can occur. When designing a PV system with moderate-to-heavy loads, good system design dictates that amperage should be kept low and, thus, voltage should be high (remember watts = volts x amps), to take advantage of lighter, less-expensive wire. In addition, all other system's power-handling components such as disconnect switches, circuit breakers, contactors and fuses can be sized smaller in a higher-voltage system, reducing cost (and maintenance requirements).

To summarize then, a PV system should be specified to deliver only 12-volt DC when the loads are very small and fixed (unlikely to grow). In moderate-to-high demand systems, the DC side of the system should be at least 24 volts and preferablly 48 or even 120 volts. And, except under special circumstances such as dedicated direct-coupled DC water pumps, AC should be incorporated to service all loads with high-power (>1kW) requirements. In some systems, it can be desireable and practical to have both AC and DC distribution where AC is supplied to the loads that require it and DC is delivered to low-power dedicated (fixed) loads such as lighting in a residence.

Input Voltage There are stand-alone inverters that will take almost any DC voltage and boost it to standard line current. Inverter efficiency is inversely proportional to the amount of "stepping up" required from the DC input voltage to deliver AC line current. For example, if all other factors are equal, a 120 VDC inverter will deliver 120/240 AC at a higher conversion efficiency than say a 12 or 24 volt model. In order to obtain the maximum conversion efficiency from the inverter, its DC input voltage should be specified as high as possible.

Specifying a high-DC operating voltage will serve to reduce line losses on the input (system) side of the inverter and eliminate the need for the more-expensive, high-current-handling switchgear. As an example, a 5 kW inverter obtaining its DC input from a 120-volt battery bank will draw less than 42 amps at full load. If this same inverter is serviced from a 48-volt battery bank the required current draw is over 100 amps. If 24-volts is used, the figure is twice that.

Power Capacity In broadest terms, stand-alone inverters can be divided into three general categories based on their output power capacity. The first, which need concern us here only in an auxiliary capacity, comprises the so-called "superlight" inverters with outputs between 25 and 150 watts. These are primarily designed for use with an individual appliance on a periodic basis, and are turned on and off along with that appliance. They are a useful option for PV users who have comfortably come to terms with DC for all but one or two functions.

The second group consists of medium-duty inverters, ranging in capacity roughly from 500 to 1000 or 1500 watts. Like the "superlight" inverters, these are generally used in larger and stand-alone systems to run specific

appliances at or slightly below their wattage rating; or, they may serve two or more small loads. When we move into this class of inverter, we begin to find automatic on-demand switching among some of the more sophisticated models.

Finally, there are the big heavy-duty inverters, which put out power at 120/240v AC and are equipped to handle sizable surges. For any total residential load demand exceeding 1,500w/day (1.5 kWh), a heavy-duty inverter is the hardware of choice. But the big inverters can also benefit from on-demand switching and/or manual override, since the large appliance loads for which they are designed are often not in continuous operation.

In fact, an argument could be made for a two-inverter system, in which the heavy-duty unit is employed only with compatibly heavy loads, and a small-to-medium size inverter handles small appliances. The object is to avoid operating any inverter for too long at too low a percentage of capacity, unless the entire system is large and complex enough to warrant steady service from a big inverter. In such instances, the PV array will probably be powerful enough to account for unavoidable idling losses. (Another reason one might wish to have a "spare" or auxiliary inverter would be to power one or two small loads which require a high-quality 60 hz sine wave.)

6.2.1. Selecting a Stand-alone Inverter

The freedom from the utility-interconnection requirements of fidelity to utility-generated waveshape and power factor make the internal electronic logic and power conversion circuitry of a stand-alone inverter different from that of a utility-interactive unit. However, many of the same basic output requirements are common to the two inverter types. Those factors that are most important to the PV system designer selecting a stand-alone inverter include:

* Efficiency
* Load-demand switching
* Power and signal quality
* Surge-handling capability

Efficiency All inverters expend a certain amount of electricity on their own operation, independent of the current which they supply to the load. This small percentage of system output is variously referred to as "parasitic," "internal," or "tare" losses. The most efficiently-functioning inverter is one which is fully or nearly fully loaded, since at such times its tare loss is a much smaller percentage of overall output than would be true if the device were supplying AC power only to a few light loads. And when the inverter is idling -- when it is functioning with no load at all -- it is at its least efficient.

The full-load efficiency of a stand-alone will depend on its design and can range between 60% for a small 12 Vdc unit such as that available from Radio Shack, to 95% for a well-designed, high-quality unit. At an efficiency of 90%, a 3-kW nominal inverter will require 3,333 watts of input power to deliver its full-rated 3 kW of power output. As the load is decreased (for example, to 1 kW) the conversion efficiency of the unit falls - perhaps to as low as 40%.

PV system engineers must always keep in mind that compensation for an inefficient inverter can only be made by enlarging the PV array and batteries, or by scaling down loads. The first option is expensive, and the second, inconvenient. Just a few percent increase or decrease in inverter efficiency can account for many thousands of kilowatt hours over the life of the PV system. Even when the load is not operating the inverter will continue to consume energy (unless shut down). This is called the idling loss.

Load-demand Switching One way of minimizing internal inverter losses is to equip the machine with an automatic load-sensing "load-demand" switch, which causes it to activate and start converting DC to AC only when there is an immediate load demand. Many modern stand-alone inverters are so equipped, and respond to a minimum threshhold starting current -- that is, the demand placed upon the inverter by switching on a load must reach a prescribed minimum level — usually about 50 watts. Through voluntary load management, the system user can cluster certain small loads to meet the threshhold.

This enables the inverter to automatically switch itself on and off when there is a load, eliminating the losses associated with idling. This is an especially important feature on a small inverter, which by its nature is likely to be used only for brief periods of the day and consequently might expend a lot of electricity idling. Of course, if the use of an appliance or piece of machinery can be planned, the manual inverter off-on switch will work just as well -- <u>if</u> it is turned off following each use.

A disadvantage of automatic switching is the starting threshhold (usually about 50w) to which we referred earlier. Some small appliances demand so little current that they are not, by themselves, capable of reaching the demand threshhold and calling the machine into service. The answer to this problem is to either use a manual override switch, or group small loads together -- e.g., make coffee and listen to the radio while you are shaving.

Power and Signal Quality Many of the same power and signal quality requirements imposed by utility interface in a line-tie system are shared by the loads likely to be connected to a stand-alone PV system. For instance, excessive harmonic distortion can cause induction motors to overheat, and a voltage variation in excess of 10% above or below 120 volts can burn such motors out. Some appliances, most notably record turntables, tape recorders, and other devices with synchronous induction motors, require a constant 60 hz frequency in the power signals which they use.

So, don't look for too much leeway in signal integrity just because a system happens to be free from utility connections. Our first inverter requirement is a clean, low-distortion signal with good voltage regulation.

Surge-handling Capability The next characteristic which we should demand of a stand-alone inverter is the ability to handle <u>surges</u> adequately, in accordance with load demands. Surging, as was mentioned, is the phenomenon associated with the start-up of certain appliances, and is the major contributing factor to high peak minute and second loads. Certain loads, such as motors, demand a high in-rush current to start. For example, a shaded-pole motor rated at one horsepower will normally require between 1000 W to 1500 W of power to operate (depending on motor efficiency) but may require up to 4 kW of in-rush current just to start.

In a utility-interactive PV system, there is always insurance against heavy-surge, high momentary peak situations in the form of the utility grid itself. When you are on your own, though, handling peaks and surges becomes a matter of having an appropriately powerful inverter <u>and</u> a working load management plan. In larger systems or critical-reliability applications, this is accomplished by using a microprocessor-based load management device. In PV residences, it can be accomplished by practicing simple discretion in the simultaneous operation of household equipment.

The surge capabilities of different inverters are rated by their manufacturers in comparison with the <u>maximum continuous load</u> which they are capable of handling, and in terms of the size (in horsepower) of the induction motors which they are capable of starting one at a time. Typical comparative ratings might look like this: for inverter A, a maximum continuous load of 2,500 watts, a surge capacity of 10,000w, and ability to start a 1 hp motor; for inverter B, a maximum continuous load of 1,500,

surge of 6,000w, and .5 hp motor starting capacity; for inverter C, respective figures of 5,000w continuous; 20,000w surge, and 2 hp motor start. Ratings such as these are changing as rapidly as inverter technology, and relative prices should be expected to reflect both versatility in surge capacity and overall efficiency.

The inverter is a very important piece of equipment in both stand-alone and utility-interactive PV systems. It should be a high-quality piece of equipment and must be carefully selected to suit the needs of the particular system. The PV system designer should be intimately familiar with the manufacturer's design and performance specifications as well as the installation and operation procedures for every unit being considered.

A comparison of several inverters of both types follows.

UILITY-INTERACTIVE INVERTERS

	Gemini	Abacus	DECC	Am. Power
Size	4kW	4kW	4kW	4kW
Overall Efficiency	85%	90%	90-95%	94%
Current Waveform	Poor	Excellent	Excellent	Excellent
Power Factor	Poor	1.0	1.0**	1.0
Max-power tracking	Optional	Yes	Yes	Yes
Transformer Isolation	Optional	Yes	Yes	Yes
EMI and RFI	Poor	Fair	Good	Excellent
Reliability	Good	Fair	Good	Excellent
Retail Cost ($+/-)	6,000	9,000	8,000	5,000

** Can be made to be leading

STAND-ALONE INVERTERS

	Abacus	Best	Nova
Size	2kW	2kW	2.5kW
Input Voltage	28	28	24
Overall Efficiency	75%	82%	90%
Waveform Harmonics	4% THD (Good)	20% THD (Poor)	5% THD (Good)
Surge Capacity	150%	500%	200%
Voltage Regulation	2%	5%	1%
Frequency Stability	.05% (Good)	.04% (Good)	.15% (Fair)
Retail Cost ($+/-)	4,000	2,200	3,200

SECTION 7. THE SOLAR RESOURCE

This section will explain how the output of a solar module is affected by the change in the module's orientation and the time of year. The output of a module is directly proportional to the amount of light that falls on its surface. As seasons change, so does the amount of available sunlight. As the position of a module changes so does the amount of energy that it can capture relative to the energy that is available.

7.1. Availability of Sunlight

An important factor in determining the total average daily solar energy falling on the earth's surface for a given month of the year is the number of hours of daylight. This is strictly a matter of the geometry of motion of the earth spinning about its axis once each day and traveling about the sun over the course of a year. Table 7.1 shows the number of hours from sunrise to sunset on a horizontal surface for the 2nd of every other month and as a function of latitude in the northern hemisphere. Also listed are the bands of latitude considered.

LATITUDE AND LOCATIONS

	20°-30° Tampa, Houston Mexico City	30°-40° Phoenix Atlanta	40°-50° Boston, Omaha Bucrest	50°-60° London, Berlin Juneau
January	10.6	10.0	9.1	7.8
March	12.0	12.0	12.0	12.0
May	13.5	14.0	14.8	16.0
July	13.5	14.0	14.8	16.0
September	12.0	12.0	12.0	12.0
November	10.5	9.9	8.9	7.5

TABLE 7.1
Daylight Hours as Function of Latitude and Month of Year

For any given latitude, the peculiarities of climate and weather at the specific site determine the amount of solar energy that reaches the earth's surface. Phoenix, Arizona and Charleston, South Carolina are at roughly the same latitude and so see the same number of hours of sunshine on a clear day but Phoenix receives approximately 30% more solar energy over the course of the year. This is because of the generally clearer atmosphere and fewer clouds in Phoenix (most of us call this "good weather"). Climate conditions differ dramatically from the Southeast to the Southwest.

Because of this variation, statistical estimates of average daily solar energy levels, obtained from records taken at, or near, a site, must be relied on in the design of photovoltaic solar energy systems. Listed below are sources for weather data for the United States and international locations.

United States Locations

Knapp, Stoffel, and Whitaker. Insolation Data Manual. SERI/SP-755-789. Oct., 1980

Bues, Anderson, et al. Availability of Direct, Total, and Diffuse Solar Radiation to Fixed and Tracking Collectors in the USA. Sandia Laboratories. Aug., 1977.

On the Nature and Distribution of Solar Energy. U.S. DOE. March, 1978. Doc. HCP/T252-01.

International Locations

Solar Radiation Input Data. University of Wisconsin. 1966.

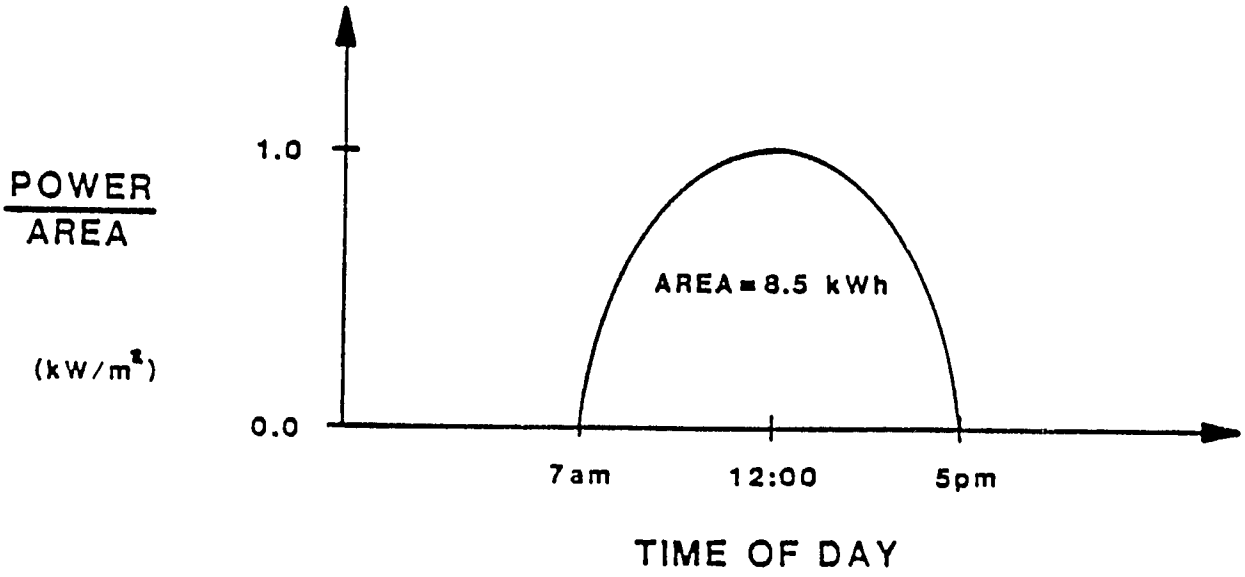


Figure 7.2
POWER VS TIME
(For actual power on a surface that tracks the sun in Phoenix in January - atmosphere present)

examples is the product of the power and the amount of time during which that power prevails. Thus, in our atmosphere-less Phoenix in January, the total energy would be:

Total E = 1.35 kW/m2 * 10 hours = 13.5 kilowatt-hours/meter squared.

In the real world case, (with the atmosphere present), in order to find the total energy, we must compute the area under the curve in Figure 7.2. Our clear January day with an atmosphere in Phoenix shows a total of 8.5 kilowatt-hours/meter squared. Note the reduction due to the presence of the atmosphere.

If we did not track the sun over the course of the day, positioning the square meter such that it was perpendicular to the sun's rays at every instant, but instead left the one-meter square surface lying flat on the ground (assumed horizontal), then the measurements change again. With the sun's rays striking the surface now on the ground, less power will strike each square meter at any hour of the day except when the sun is directly overhead. In other words, to intercept the same power as would an area perpendicular to the sun's rays requires a larger area on the ground than one square meter as demonstrated in Figure 7.3.

Early in the morning and late in the afternoon we expect little insolation on a horizontal surface for the following reasons:

1. The large portion of the sun's rays will be reflected off

2. The effective power per unit area is reduced by not having the surface perpendicular to the sun's rays

3. The sun's rays must travel through the atmosphere at an angle the makes the "thickness" of the atmosphere greater; more sunlight is absorbed in the atmosphere. At solar noon, on the other hand, we expect to get the greatest amount

7.2. Measuring the Sun's Power and Energy

Imagine there were no atmosphere at all. If you were to measure the power from the sun striking a one meter square flat surface held perpendicular to the sun's rays at every instant over the course of a January day in Phoenix, Figure 7.1 below shows what your record of measurements would look like. (Keeping the surface perpendicular to the sun's rays throughout the day, as the sun moves, is called "two axis tracking of the sun".)

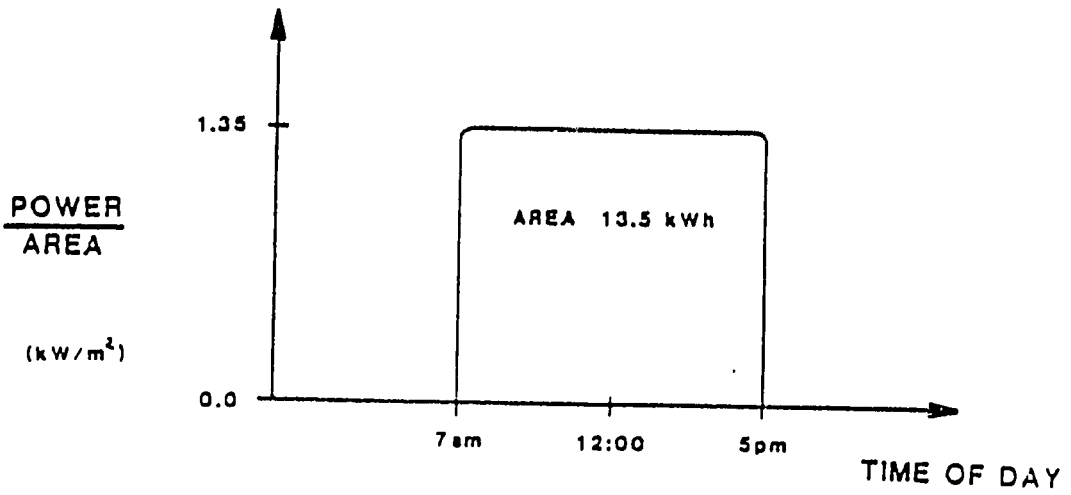


Figure 7.1
POWER VS TIME
(Theoretical power on a surface that tracks the sun in Phoenix, in January with no atmosphere present)

The solar insolation, the power impinging on the one meter square surface, measured in kilowatts per square meter, would not vary from sunrise to sunset. It would remain at its value observed in space, in near earth orbit, of 1.35 kilowatts per meter squared (1.35 kW/m2). (Since the earth traces an elliptical orbit about the sun, this value varies somewhat from season to season. We also neglect in this theoretical argument the fact that the full sun will not appear at the instant of sunrise nor disappear instantaneously at sunset).

Now consider the actual situation with an atmosphere present. Assume, though, that it is a crisp clear day and we again track the sun. Figure 7.2 shows our new real-time measurements of solar power as it varies over the course of the day. Note that at solar noon*, instead of 1.35 kW/m2, we see only 1.0 kW/m2. That shows the attenuating effect of the atmosphere (i.e., when light from the sun passes through our atmosphere, some of it - approximately 30% at noontime - is absorbed by the atmosphere). Because the sun's rays have more atmosphere to travel through near sunrise and sunset, the attenuation is more severe during early morning and late afternoon.

The peak value of solar insolation is very near to 1.0 kilowatt per meter squared and occurs at solar noon. This is the nominal power of the sun impinging on a surface perpendicular to its rays at solar noon on a clear day over a wide range of latitudes. It has become a universal reference and we define:

FULL SUN power = 1.0 Kilowatts per meter squared, often called ONE SUN.

The total energy delivered to the one square meter area in the above

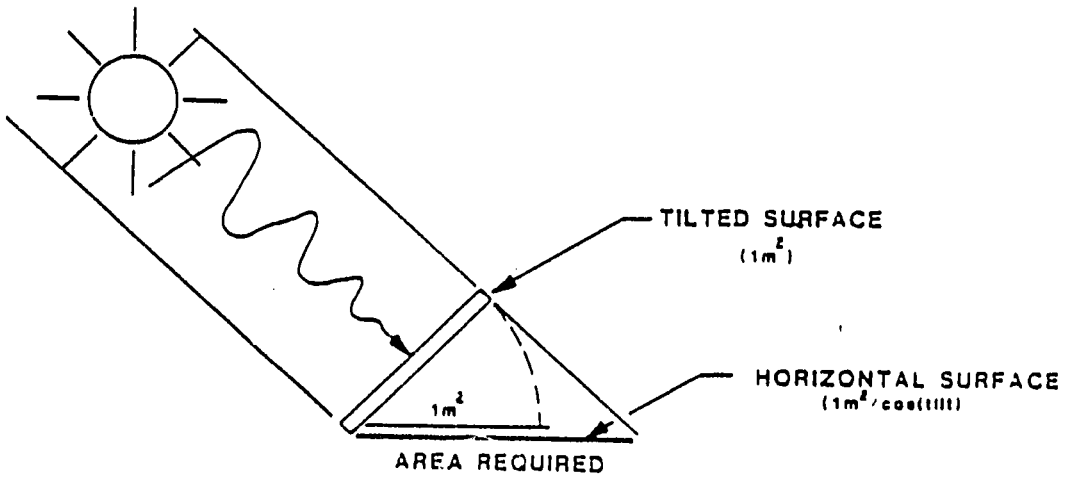


Figure 7.3
Comparison between area required to capture equivalent solar energy as a function of surface tilt

Figure 7.4 shows the record of solar insolation falling on a horizontal surface again in Phoenix on a clear day in January. The difference between this and the previous figure is due to the fixing of our one meter square surface to the ground.

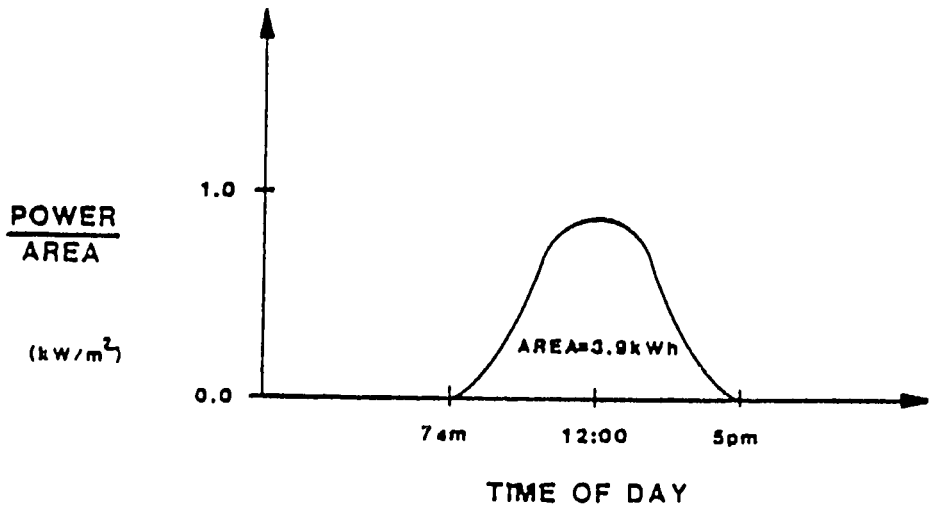


Figure 7.4
Power vs time for power on a horizontal surface in Phoenix in January

7.3. Equivalent Hours of Full Sun

Energy is the product of power and time of duration, e.g. kW * hours = kilowatt-hours. In figure 7.4, the energy striking the one square meter of horizontal area over the hour 11:00 am to 12:00 noon is approximately 0.9 kilowatt-hours. From 7:00 am to 8:00 am it is approximately 0.15 kilowatt-hours. The total energy impinging on a square meter of horizontal surface is given by the total area under the curve. This figures out to be 3.9 kilowatt-hours. Note that this is less than that obtained if one tracks the sun.

If the sun shone at FULL SUN intensity of one kilowatt per meter squared, then 3.9 hours of FULL SUN insolation would produce the same result. We

can speak as well then of "EQUIVALENT HOURS OF FULL SUN" as of a total amount of solar energy impinging on one square meter over the course of a day. The area below the curve shown in Figure 7.5 equals the area below the curve in Figure 7.4. The energy received in each case is the same, however, in Figure 7.5, the power level is constant at 1 kW/m^2 and lasts for only 3.9 hours. When EQUIVALENT HOURS OF FULL SUN is used as a measure of energy, it is understood that the hours are at the intensity of full sun at 1 kW/m^2.

Note that because full sun power is the nominal maximum insolation possible on the earth's surface, the number of equivalent hours of full sun is always much less than the number of hours from sunrise to sunset. For example in Phoenix in January, the number of hours of daylight is 10 hours while the number of equivalent hours of full sun on a horizontal surface, or the total energy impinging on one square meter of horizontal surface, is 3.9 equivalent full sun hours.

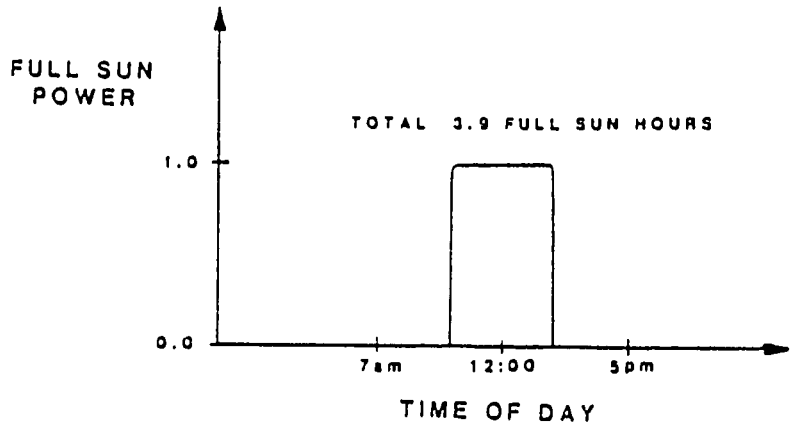


Figure 7.5
Equivalent full sun power vs time on a horizontal surface in Phoenix in January

Not every day is a clear day, even in Phoenix. Because of weather, haze, smog, overcast, rain, etc., the average daily solar energy impinging upon a surface - the average number of equivalent hours of full sun - will be less than the clear day value in any month. Again, for the month of January in Phoenix, the <u>average</u> daily value on a horizontal surface is

$$\text{Full sun hours} = 3.5 \text{ kWh/m}^2$$

7.4. Effects of Array Orientation

So far we have discussed two ways to position the PV module; either using two-axis tracking of the sun or at a fixed tilt equal to the horizontal. It is clear that tracking gives a greater array output, however, the additional output rarely justifies the complexity and expense inherent in tracking systems. Indeed, the majority of the PV systems in use today utilize an array at a fixed tilt angle as depicted in Figure 7.6. As we shall see later, the output of a PV module is strongly dependent on the tilt angle selected.

In addition to tilting the PV module at the most optimum tilt, we must also position it in the best direction. For all locations in the United States, the module should face (true solar) south. Variations from true south will reduce total array output. The farther north the installation is, the more important is true-south orientation.

The sun's daily path changes throughout the year. The angle between the

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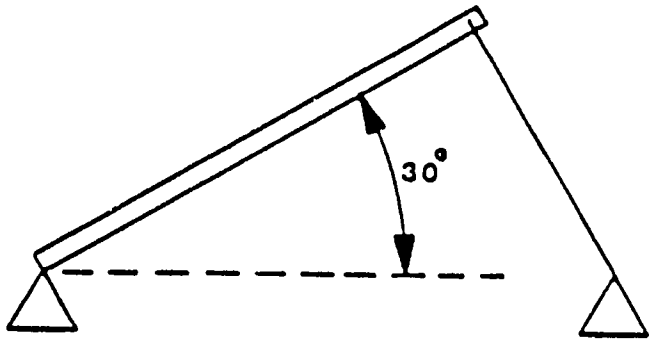

Figure 7.6
Side View of a Module Mounted at a Fixed Tilt of 30°

horizontal and a line from our location on earth through the center of the sun, called the sun altitude, varies by over 46° between the summer and winter solstice. Figures 7.7 and 7.8 show the relative positions of the sun in winter and in summer at noon.

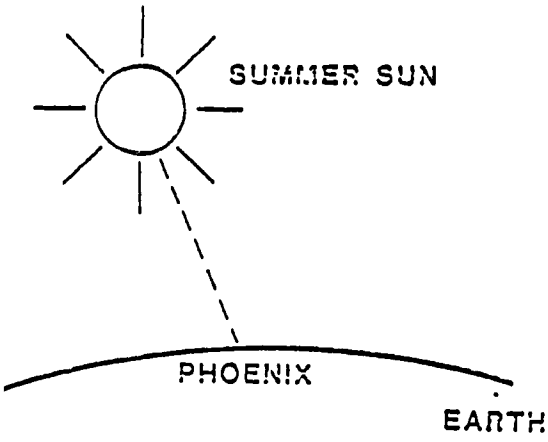

Figure 7.7
Summer position of the sun

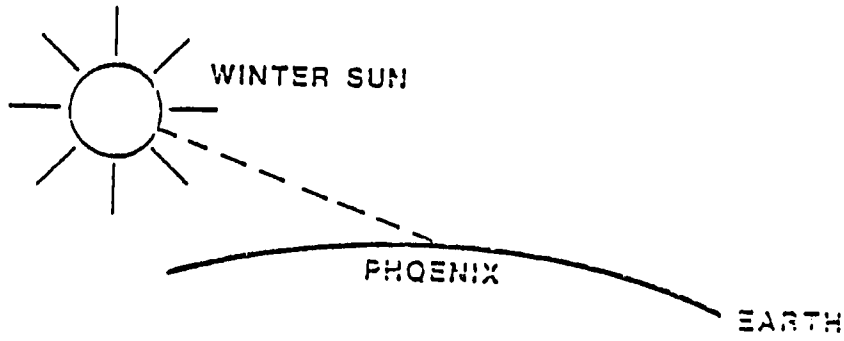

Figure 7.8
Winter position of the sun

The actual change in the sun's altitude angle for any given site is from 90° - latitude angle + declination where the declination varies from -23.45 (December 21) to +23.45 (June 21). Since a module will produce the greatest energy when it is positioned perpendicular to the sun, the best tilt to put a module at is the latitude angle - declination. The declination changes every day so to get the absolute most energy it would be best to change the tilt of the array every day. Unfortunately, tilt changing often brings up more problems for the system user than it is worth. As a result, it is recommended that the tilt be changed a minimum number of times throughout the year. In fact, in systems that are designed to power a constant load throughout the year there is no benefit gained by changing the tilt away from the optimum for winter sun. In terms of system's cost

and complexity, it is generally best to consider a fixed tilt throughout the year.

For a load that remains constant throughout the year, we set the tilt angle equal to the latitude +15° (e.g., 45° to 50° for Phoenix). This is because we want to get the greatest output possible from the module even when there is the least amount of sun. (In the winter there is less sun so we tilt the module above the latitude to take advantage of the fact that the sun is at a low altitude angle.) As we saw before, the best tilt for a module in Phoenix ranges from 10° (33.5° - 23.5°) to 57° (33.5° + 23.5°) but these angles are the extreme values and are seen only one day in the year. Hence, it turns out that the optimum "winter tilt" is about 15° greater than the latitude. Even though this is about 30° away from the best "summer tilt", the extra light available from the sun during the summer makes up for the non-optimum setting. The result is a fairly steady module output throughout the year as shown below in Figure 7.9.

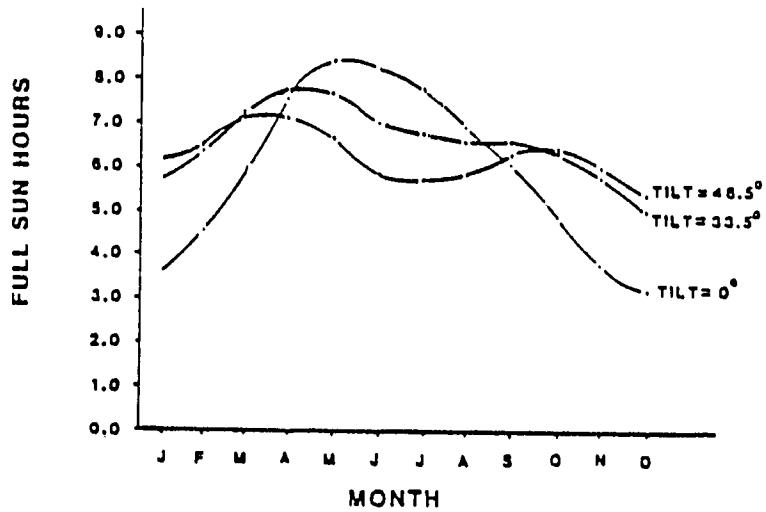

Figure 7.9
Monthly daily average full sun hours vs month on a surface at various tilts from the horizontal

The following tables show, for three locations, the energy available (in full sun hours) on a 1 m^2 surface at various tilts: horizontal, latitude - 15°, latitude and latitude + 15°.

TABLE 7.2 LOCATION: PHOENIX, ARIZONA

MONTH	ENERGY AVAILABLE (FULL SUN HOURS)			
	Horizontal	Lat-15°	Latitude	Lat+15°
Jan	3.6	5.0	5.8	6.2
Feb	4.5	5.7	6.3	6.5
Mar	6.0	6.9	7.2	7.1
Apr	7.5	7.8	7.7	7.1
May	8.4	8.2	7.6	6.6
Jun	8.1	7.7	7.0	5.9
Jul	7.7	7.4	6.8	5.8
Aug	6.9	6.9	6.6	5.9
Sep	6.1	6.6	6.7	6.3
Oct	4.9	5.8	6.3	6.4
Nov	3.8	5.0	5.7	6.0
Dec	3.1	4.3	5.0	5.4
YEAR TOTAL:	70.6	77.3	78.7	75.2
AVG	5.9	6.4	6.6	6.3

TABLE 7.3 LOCATION: BOSTON, MASSACHUSETTS

MONTH	ENERGY AVAILABLE (FULL SUN HOURS)			
	Horizontal	lat-15°	latitude	lat+15°
Jan	1.8	2.7	3.1	3.2
Feb	2.5	3.3	3.6	3.6
Mar	3.8	4.5	4.6	4.5
Apr	4.5	4.8	4.6	4.2
May	5.6	5.5	5.2	4.6
Jun	5.9	5.7	5.2	4.5
Jul	5.7	5.5	5.1	4.5
Aug	5.2	5.3	5.0	4.5
Sep	4.2	4.7	4.7	4.4
Oct	2.8	3.5	3.6	3.6
Nov	1.8	2.5	2.7	2.7
Dec	1.6	2.5	2.8	3.0
YEAR TOTAL:	45.4	50.5	50.2	47.3
AVG	3.8	4.2	4.2	3.9

TABLE 7.4 LOCATION: ALBUQUERQUE, NEW MEXICO

MONTH	ENERGY AVAILABLE (FULL SUN HOURS)			
	Horizontal	lat-15°	latitude	lat+15°
Jan	3.6	5.0	6.1	6.7
Feb	4.5	5.9	6.5	6.8
Mar	5.9	6.9	7.2	7.1
Apr	7.3	7.7	7.5	6.9
May	8.3	8.1	7.5	6.6
Jun	8.6	8.2	7.4	6.2
Jul	8.1	7.8	7.1	6.1
Aug	7.6	7.7	7.3	6.6
Sep	6.2	6.8	6.9	6.5
Oct	5.1	6.3	6.8	6.9
Nov	3.8	5.2	5.9	6.3
Dec	3.2	4.7	5.6	6.1
YEAR TOTAL:	72.2	80.5	81.8	78.8
AVG	6.0	6.7	6.8	6.6

From the data in these tables it can be seen that the optimum tilt angle, for the worst case month, at any site is always latitude + 15°. Very often the designer also considers other factors for evaluating the optimum array orientation. Examples would be micro-climatic affects specific to the site such as early-morning fog or predominant afternoon cloudiness. Note that a tilt equal to the latitude will give the maximum total energy output for the year. "Worst case month" signifies that the system will put out at least that month's potential throughout the year. The tilt angle that gives the best in the winter (latitude + 15°), will, of course, reduce the potential summer output.

Section 8. SYSTEM SIZING

Sizing the elements of a photovoltaic system means determining the number of photovoltaic modules and the amount of energy storage capacity (if storage is used) that are needed to insure that the user of the system has electrical power available when desired - with an acceptable reliability.

Most methods of sizing the stand-alone system treat the photovoltaic array and the battery storage bank independently. The array size, defined by the number of modules employed and rated at its peak power condition, is determined by requiring the average daily array output to match the average daily load for the worst case month of the year. A safety factor is introduced to account for degradation in array output due to dirt accumula-

tion, line losses, and general uncertainties about "average" outputs and inputs.

The amount of storage capacity is usually fixed by estimating the number of "no-sun days", the number of consecutive days during which overcast conditions prevail, liable to be experienced at the site. If a high degree of system reliability is demanded, the usable daily battery capacity, measured in ampere-hours, is fixed by the anticipated maximum daily load, again measured in ampere-hours. The number of no-sun days times the maximum daily load gives the required total usable battery capacity.

8.1. Sizing in terms of Ampere-Hours

Batteries had been used to provide power at remote sites long before anyone developed a photovoltaic module to keep a battery charged. Those designers experienced in the application of batteries in telecommunications, navigation, etc., still regard the battery as the central element in a photovoltaic system and size the PV system in terms of "ampere-hours".

Every battery is rated at a certain number of ampere-hours of which only a certain percentage are actually usable. A battery's usable ampere-hour capacity is determined by the manufacturer's recommended depth-of-discharge (DOD) and can be considerably less than its rated capacity. The battery can provide a current in amperes equal to its usable ampere-hour capacity for one full hour, or a current of one-half its usable capacity for two hours, or etc..., before running out of charge. (Actually the battery does not run out of charge but, if the recommended usable capacity is frequently exceeded, then irreparable damage is liable to be done to the battery and its life may be shortened). For more detail on battery system dynamics, refer to the previous section on batteries.

This simplified example of a very basic stand-alone system will be used to illustrate the fundamental principles of the ampere-hour method of PV system sizing. A PV system is required to power a light for a remote cabin in eastern Massachusetts during the late summer and early fall (August, September and October).

Assume:

1. A 20 watt fluorescent lamp with DC ballast will be used. Power requirements are 1.8 amps at 12 volts DC.

2. Four hours of light per day are required (average usage 7 days per week).

3. Availability of power for the load, which consists of only the light, is not considered critical.

Step 1. Determine the Load

Determine the average daily load (DL) by multiplying the average hours (h) of daily usage by the load current (IL).

$$DL = H * IL = (4 \text{ hours/day}) * (1.8 \text{ amperes})$$
$$DL = 7.2 \text{ ampere-hours/day} = 7.2 \text{ Ah/day}$$

Step 2. Determine the number of days storage.

The amount of storage required will depend on:

1) The availability of backup power (e.g. engine generator).

2) Nature of the load (essential vs non-essential).

3) Size of the load (including duty cycle).

If a backup source of energy is available, such as an engine generator set, then only a fraction of the anticipated maximum number of no-sun days need be covered by battery storage. With a backup power source available, two or three days of storage are typically adequate for the New England region.

If backup power is not available, then values from the table below should be used:

RECOMMENDED NO-SUN DAYS FOR BATTERY STORAGE
IN NEW ENGLAND

Reliability Required	Number Days Storage
Low	3 - 4
Medium	8
High	12

The 12-days' storage requirement for high reliability reflects the maximum number of anticipated no-sun days for the New England region. For the example considered, assume a low level of reliability is required and thus select 3 days' of battery storage.

Step 3. Determine the Usable Storage Capacity Required.

The usable battery capacity required (Total Usable Capacity or TUC) is determined by multiplying the load (Ah/d) determined in Step 1 by the number of days' storage determined in Step 2.

$$TUC = (7.2\ Ah/d) * (3\ days) = 21.6\ Ah.$$

Step 4. Select an appropriate battery.

Proceed as described in the section on batteries. To determine the required rated battery capacity, the TUC must be divided by the maximum allowed daily depth-of-discharge (DOD) for the battery chosen. Since the load is relatively small, a shallow-cycle battery will probably be sufficient even though only 3 days of storage are required. The majority of shallow-cycle batteries available are recommended to be discharged by no more than 25% and many have a lower recommended daily depth-of-discharge. Using the 25% DOD, we get the required <u>rated</u> battery capacity, C, as follows: $C = TUC/0.25 = 86.4\ Ah$.

The Delco 2000 has a 105 ampere-hour capacity rating at standard conditions and hence would be a suitable choice for this application. Availability and cost (low) are other factors to be considered. The Delco 2000 scores well in both categories. Another possible candidate for this application would be a standard 12-volt automobile battery. While it is not generally recommended to use car batteries for photovoltaic storage, a 75 to 100 ampere-hour car battery would satisfy this small, non-critical requirement and no other battery is so readily available at such a low cost.

Step 5. Determine the equivalent hours of full sunlight at the site.

From Table 6.3 we get the number of equivalent hours of full sun on a surface tilted at an angle equal to the latitude for Boston during the months of August, September, and October. Note that these are the number of equivalent hours of full sun, or what is the same, the total average daily solar energy in kilowatt-hours per meter squared falling on a south-facing surface set at a tilt angle equal to the latitude of the site.

August = 5 Hours
September = 4.7 Hours
October = 3.6 Hours

Remembering that this is a non-critical system we can size according to the average number of full sun hours, which is 4.4 hours. Had this been a critical application we would have sized for the worst case condition of 3.6 full-sun hours (and also provided for more battery storage capacity.)

Step 6. Determine the required array size.

The array charges the battery on sunny days when the array output exceeds the load. When the sun is not out, on a cloudy day and certainly at night, the load exceeds the array output and drains the battery. The array must then be sized to insure that, over the long run, the balance is positive; the battery is more likely to be charged than discharged. Set the average daily array output equal to the average daily load, including all the internal system losses in the wire runs and through the electronics.

The average daily output of a PV array, in ampere-hours, is the product of the number of full sun hours times the peak-power current of one of the PV modules in the array times the number of PV modules in parallel. Or:

$$\text{ARRAY OUTPUT} = (I_p) * (\text{FULL SUN HOURS}) * (\text{\# MODULES IN PARALLEL})$$

where I_p = the peak power current of the module when the solar insolation is 1 kw/m^2.

Figure 8.10 shows the IV curve of the Ra30 module from Mobil Solar Energy Corporation. Several curves are given to show the dependence of the module output current on insolation intensity. For the case shown, the peak-power current is 2.0 amperes (at the full sun condition). This module is designed to charge a 12-volt battery. Figure 8.11 gives similar information for the 48-volt Ra180 Mobil Solar module.

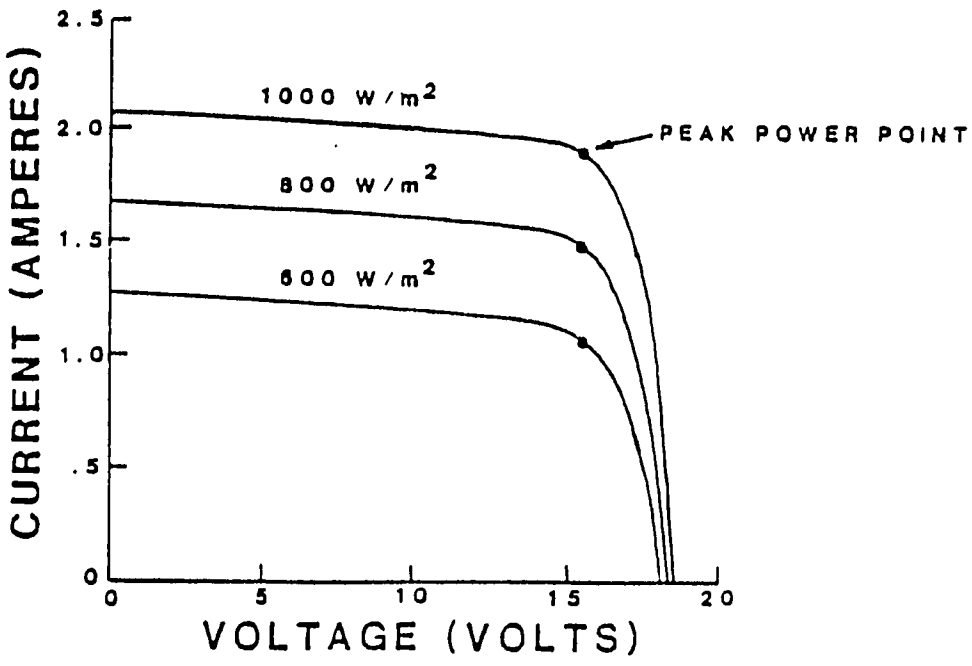

Figure 8.1
Mobil Solar Ra30 IV curve as a function of insolation intensity

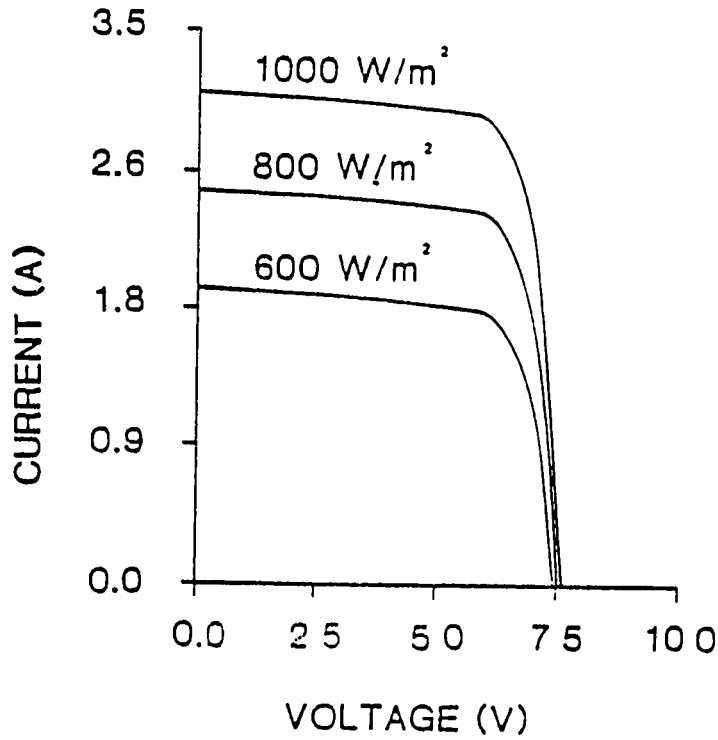

Figure 8.2
Mobil Solar Ral80 IV curve as a function of insolation intensity

Then the daily ampere-hour output of one module will be the daily number of equivalent hours of full sun times the peak power current:

Ah out = 4.4 hours * 2.0 amperes
Ah out = 8.8 ampere-hours.

Step 7. Select the number and type of modules.

The average daily load was determined to be 7.2 Ah in Step 1. Thus a single module having the I-V characteristics shown in Figure 8.10 will do the job and then some.

8.2. A Second Example of Amp-Hour Sizing

Now let's examine a less basic and more realistic example of design by the ampere-hour method which elaborates on the fundamental principals presented in the first example to include temperature correction for module output and loss of battery storage capacity over time. For this second example, we'll consider the sizing of a photovoltaic powered refrigerator for a village in the Southwest US.

Step 1. Determine the Load.

Data from the refrigerator manufacturer on the power consumed by the refrigerator is given in the following form:

The compressor consumes 6 amperes at 12 volts whenever it is called upon to do its job. The compressor duty cycle, defined in terms of the percentage of hours of the day during which it is on, is a function of the average ambient temperature. The higher the temperature, the more the compressor is required to do work.

More specifically:

REFRIGERATOR COMPRESSOR DUTY CYCLE

% ON TIME	AVG. AMBIENT TEMP. °C
10.	LESS THAN 15
20.	15. - 18.
30.	19. - 22.
40.	23. - 26.
50.	27. - 30.
60.	31. - 34.
70.	35. - 38.
80.	39. - 42.
90.	43. - 46.

Assume that, in order to keep the winter load to a minimum, the refrigerator is kept in an unheated area that is always at the outside ambient temperature. Clearly the average daily load will vary throughout the year. In the summer months when the ambient temperature reaches its maximum value the average daily ampere-hour load will also reach its maximum. To determine the month during which that occurs requires knowing the ambient temperature data at the site.

Given that the site is within 200 miles of Phoenix, we will use solar energy and ambient temperature data for Phoenix to size the system. Consulting the appropriate reference materials, we find that the maximum average daily ambient temperature occurs in the month of July and is 32 degrees C. From the Table above we conclude that the compressor will be on and drawing 6.0 amps for 60% of the hours of the day. The average daily load in July will then be:

Load = 0.60 * 24 hours * 6.0 amps
= 86.4 ampere-hours.

Similar calculations can be done for all other months of the year given the average daily ambient temperature for each month. The results of this set of calculations are displayed in Table 8.1 below:

TABLE 8.1
LOAD, TEMPERATURE, & EQUIVALENT FULL-SUN HOURS DATA FOR PHOENIX

MONTH	AMBIENT TEMP degrees C	LOAD ampere-hours	EQUIVALENT FULL-SUN HOURS on horiz	tilt=lat.
January	12.	14.4	3.6	5.7
February	15.	28.8	4.5	6.3
March	19.	43.2	6.0	7.1
April	21.	43.2	7.5	7.7
May	24.	57.6	8.4	7.6
June	29.	72.0	8.1	7.0
July	32.	86.4	7.7	6.8
August	31.	86.4	6.9	6.6
September	30.	72.0	6.1	6.6
October	23.	57.6	4.9	6.2
November	17.	28.8	3.8	5.6
December	12.	14.4	3.1	4.9

The equivalent number of full sun hours both on a horizontal surface and on a south-facing surface tilted up an angle equal to the latitude of Phoenix (= 33.3°) are also shown.

Step 2. Determine the number of days' storage required.

To size the storage we assume that a moderate degree of reliability is

required. Here again we must not only take into account the variation of the daily load throughout the year, but also should take advantage of a corresponding variation in anticipated "no-sun" days. These are given below.

Maximum Number of No-Sun Days - Phoenix

Month		No-Sun Days	Load x No-Sun Days
January	- February	6.	173. amp-hrs
March	- April	4.	173.
May	- June	2.	144.
July	- August	3.	259.
September	- October	3.	216.
November	- December	5.	144.

The LOAD x NO-SUN DAYS column is the product of the daily average load and the number of no-sun days. Note that the greatest value is 259 Ah which corresponds to a storage capacity of three no-sun days during the July-August period.

Step 3. Determine the Usable Storage Capacity Required.

The total usable battery capacity required (TUC) is given in the above table. Three days of July and August load require

TUC = 259. ampere-hours.

Step 4. Select an appropriate battery.

Again we refer to the previous section on batteries. In this case, let us assume that we are interested in using a long-life battery in the system. Since we require only three days storage we select a deep-discharge battery. The maximum manufacturer's recommended depth-of-discharge (DOD) for most deep-cycle batteries is 80% of rated capacity which gives a required battery capacity, C, of 259 Ah/0.80, or, 324 Ah.

In this example, we will also account for the loss in storage capacity over the lifetime of the battery. If we are considering using an Exide E series battery, the end of useful service life is specified by the manufacturer as being at the 80% capacity level. We therefore divide our C of 324 Ah by 0.80 to get 405 Ah. This is the battery ampere-hour rating, as rated by the manufacturer, that we will require. According to Table 4.2 the Exide E120-9 has only 360 Ah. This is less capacity than what we have calculated but will probably suffice since the number of "no-sun" days chosen is somewhat conservative for the site and, the system's availibility is considered non-critical.

The life of the deep-cycle battery specified is given by the manufacturer in terms of the number of discharges to 20% capacity left. Since we have already built three days storage into the design, we can expect that the 80% discharge will only occur <u>in the worst case</u> every 3 days. Hence, the 1800 allowed cycles should result in a battery life of nearly 15 years which is excellent.

Step 5. Determine the equivalent hours of full sunlight at the site.

Using data obtained from Table 8.1, the table displayed under Step 1 shows both the number of full-sun days by month for 1) an area tilted up at an angle equal to the latitude of the site, and 2) an area lying horizontal.

Step 6. Determine the required array size.

July and August show the largest average daily load (86.4 ampere-hours). Of the two, August has fewer full sun-hours and so becomes the determining month. Since the greater number of full sun hours (6.9) falls on a horizontal surface during this month in Phoenix, it appears that the array

should be placed flat. Unfortunately, this leaves the array subject to significant accumulation and buildup of dirt and dust (when flat, the rain water will not help to wash off the array). As a result, the array should not be tilted less than 15°. Let us look at the data in Table 7.1 to see how many full sun hours fall on a surface tilted at the latitude -15° (18.5°) in Phoenix in August. We find that we still get 6.9 hours in August and so we continue the sizing using 6.9 full sun hours.

Step 6a. Determine the effect of temperature on module output.

We remember from the previous section on PV modules that, as the temperature of a PV cell rises, the voltage it produces lowers by a small amount (-0.5% per °C rise in cell temperature over a base of 25°C). It is important to realize that when a module is exposed to sunlight it will get hotter than the surrounding air. We assume 25°C above ambient as a base value at an insolation level of 0.8 kW/m². The average daytime ambient temperature for the month of August averages 31°C. Thus, we estimate the normal operating cell temperature (NOCT) for this site of 25°C + 31°C = 56°C.

With this high a cell temperature, it is necessary to check the current voltage characteristics of the module to verify the ampere output within the 12 volt operating range. The I-V curve for the Mobil Solar Ra30 module as it varies with temperature is shown in Figure 8.12 below. The reference insolation level is the full-sun condition of 1.0 kW/m².

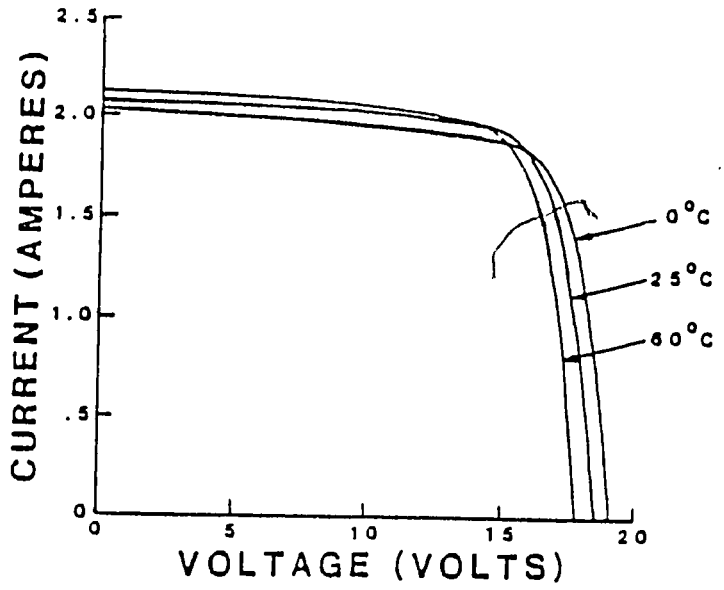

Figure 8.3
Mobil Solar Ra30 module IV curve as a function of cell temperature

From the plot at 60°C cell temperature, the current output of the module in the twelve-volt-battery operating range is a small amount less than at the reference condition. The ampere-hour output of one module will then be:

Ah out = 2.0 x 6.9 full sun hours = 13.8 ampere-hours.

But the shape of the module IV curve at 60°C in the operating range is different. So much so that we have lost the margin of safety usually inherent in taking the maximum-power current as the factor of proportionality between amp-hours out and kW hours in.

To correct for this we introduce a 15% safety margin and "derate" the module output accordingly.

$$\text{Ah out} = 13.8 \times 0.85 = 11.7 \text{ ampere-hours}$$

The 15% safety margin is derived from a "rule of thumb" calculation. The module peak power decreases at a rate of 0.5%/°C rise in temperature. For a 30°C temperature rise the peak power loss is 0.15 volts which we make the safety margin (15%).

Step 7. Select the number and type of modules.

We have already chosen to use a Ra30 module for this example. To meet the average daily load in August we will need:

86.4 (load Ah)/11.7 (Ah output per module) = 7.4 modules (or, rounding up, 8 modules)

8.3. Sizing in Terms of KWH

Sometimes batteries, or any other form of energy storage, are not needed in a photovoltaic system. This is the case with all utility-interactive systems as well as some stand-alone systems. Pumping water to irrigate a field is one example of a stand-alone system which may not require battery storage. When the sun shines, power from the PV array drives the pump and the water flows. When the sun is not out, the pump is off. If water is not required at a particular time and only a total daily volume need be delivered, then storage, of electrical energy from the photovoltaic array or, of water itself, is not necessary.

Consider the following design problem: Water is required in the amount of 1000 cubic feet per day during the month of July at a farm in the vicinity of Phoenix. The water is to be pumped up from a 50 foot well. No battery storage is required. The 48-volt DC motor driving the pump will be directly coupled to the photovoltaic array. The task is to size the array. For the sake of simplicity, in this example we will ignore any detailed specification of the type of motor-pump combination that might do the job. Instead we assume such hardware is available and that the combination has an overall efficiency of 50%.

Step 1. Determine the Average Daily Load.

The amount of work done in lifting 1000 cubic feet up 50 feet, given that water weighs 62.4 pounds per cubic foot, is

$$\text{Work Done} = \text{Energy Expanded} = (62.4)\times(1000)\times(50)$$
$$= 3.12 \times 10^6 \text{ foot-pounds.}$$

From the conversion table in the appendix, we find the work to be equal to

$$3.12 \times 10^6 / 2.66 \times 10^6 = 1.17 \text{ kilowatt-hours.}$$

If the motor-pump combination is 50% efficient, then the load seen by the PV array will be double that amount.

$$\text{Average Daily Load} = 2.34 \text{ kilowatt-hours.}$$

Step 2. Size the array.

A photovoltaic module, and hence a photovoltaic array, is rated according to its MAXIMUM POWER. The maximum power is the power the module will produce at certain reference conditions on 1) Module temperature and 2) Solar insolation intensity. For example, the Mobil Solar Ra30 module, whose current voltage characteristics are shown in Figure 8.10, has a maximum power of 30 watts at a cell temperature of 25°C and a solar insolation intensity of 1.0 kW/m². The voltage and current at the maximum

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power point are: V=14.9 volts at I=2.0 amps. The product of these two is the power at the rated conditions.

As in the second example, the effect of temperature on the PV array must be accounted for. The above-quoted maximum-power values were for a cell temperature of 25°C. But in July, in Phoenix, the array will run at a temperature of about 25 to 30°C above the 30°C ambient temperature. Hence:

normal operating cell temperature (NOCT) = 60°C.

Since, as stated above, the maximum power decreases by 5% for every 10°C temperature rise above the rated conditions (at 25°C), we expect to see a maximum-power output of a Ra30 module under these operating conditions of:

30 x 0.85 = 25.5 watts

However, temperature is not the only loss factor. Assume that, in order to obtain optimum system performance we include a maximum-power-point tracker to extract the maximum power out of the PV array. This device will also have some inefficiencies, not much, but enough to require taking into account. Assume the max-power tracker is 95% efficient. We are then at:

0.95 x 25.5 = 24.2 watts

Finally, the maximum power point does not quite vary proportionally to insolation. This means we cannot use the concept of equivalent hours of full sun without a further correction. We subtract another 5% off the rated output to account for this effect.

We thus expect to get out of each Ra30:

0.95 x 24.2 = 23.0 watt-hours

for every full-sun hour of energy impinging on the array.

Assuming that we mount the PV array in a horizontal position which, in practice, we would not do, we find that the table in the Second Example shows 7.7 full sun hours on a horizontal surface in July, in Phoenix. Thus, each Mobil Solar Ra30 module will produce an average daily output of:

7.7 h * 23.0 W = 177 Wh = 0.177 kWh

To meet the load will then require 2.34 kWh (daily load)/0.177 kWh (module output/day) = 14 Ra30 modules. We now must determine how to arrange these modules in a series/parallel network to deliver the required power at the desired bus voltage.

The modules chosen have a 12-volt nominal output. To deliver 48 volts to the load will require four 12-volt modules in series. When we divide the total number of modules required, which is 14, by the number of modules required to make up a 48-volt series string, we find that 14/4=3.5 which results in a "theoretically-ideal" PV array configured in 3.5 parallel strings of 4 series modules each. Since we obviously can not specify fractions of modules, we must increase (round up) the number of modules in parallel to the next whole number which results in a specified PV array configuration of 4 parallel strings of 4 series modules each.

This sizing procedure has resulted in an oversizing of the system over the "theoretical ideal" by two additional modules which is a 14% increase over the mathematical requirement. This is good in that it adds an additional margin of capacity to the system and, its undesirable in that it increases the system cost.

However, its a fact of life. Four 12-volt modules are required in series to deliver 48 volts to the load. Thus, the string of four series modules becomes, (after the modules themselves), the basic building block of the PV

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array for this system (and all other 48-volt systems). The PV system designer can specify the array size only in increments of full series strings. The only other option open to the designer would be to use PV modules whose internal cell configuration was wired to deliver 48-volts.

48-volt modules do exist, (such as the Mobil Solar Ral80). However, the vast majority of PV modules available on the market today have a rated output of 12 volts nominal and, most small systems (less than 1 kWp) will be designed around modules of this voltage.

This basic principle of array design sizing in minimum increments of one full series string is applicable to all systems design methods. Sizing in terms of full-string increments can be a real limitation especially when specifying PV arrays in higher voltage applications such as utility-interactive residential systems which often require DC input voltage to the inverter of 220-240 volts resulting in series array strings of 18 to 20 12-volt modules each. If the designer were using 40-watt, 12-volt modules in such a system, he would have the option of sizing in even increments of a 20-module string, resulting in array sizing options of 800-watt increments with nothing in between.

8.4. Sample Design Problems and Solutions

Design Problem #1: A simple 12-volt DC system for a mountain cabin

Given: Maximum stay in winter 3 days (long weekends)
Maximum stay in summer 3 weeks (vacation)
Elevation: 3000′
Solar Insolation yearly average of 4.0 hrs at 50° tilt
Latitude = 40°

Loads	Amperage	Summer hours	Winter hours
1 - 40 W Fluorescents	3 A	2	6
2 - 20 W Fluorescents	3.4 A	2	4
9" Color TV	2.0 A	3	8

Assume: We will leave the PV array at a 50° tilt all year to increase winter output and accept the resulting reduction in summer output. We find that we will have 4.5 hours peak output in the summer and 3.5 hours peak output in the winter.

Step one: Calculate winter load in Amp-hours

Lights: 40 W, 3 x 6 = 18.0 AH
2 - 20 W, 3.4 x 4 = 13.6 AH
TV, 2 x 8 = 16.0 AH
47.6 AH per day of usage

However there are only 3 days out of 7 usage or 3.7 x 47.6 or 20.4 AH average per day usage in the winter.

Assuming an overall battery efficiency of 80% we need 20.4/.8 or 25.5 AH per (average) day of charging.

Assuming 3.5 hours of peak sun, this will require:

$$\frac{25.5 \text{ amps/day}}{3.5 \text{ hours of full sun/day}} = \text{a total of 7.29 Amps}$$

of output from the array per average day. If we use the Mobil Solar Ra-30 which delivers an output of 2.0 amps under full sun, we have:

$$\frac{7.29 \text{ Ap total}}{2.0 \text{ Ap/module}} = 3.64 \text{ modules.}$$

We can not specify a fraction of a module so we'll "round up" to provide a margin of additional capacity to account for long periods of poor winter weather conditions, and use four Ra-30's to satisfy the winter load in this application.

Step two: Calculate summer load in Amp-hours

Lights:	40W	3 A x 2 hr.	= 6.0 AH	
	2-20W	3.4A x 2	= 6.4 AH	
	TV set	2.0 x 3	= 6.0 AH	
			18.4 AH per day of usage	

We will assume continuous daily in the summertime usage and therefore use 18.4 AH per day. With battery efficiency of 80% we need 18.4/.8 = 23 AH per day. At 4.5 hrs per day of average peak sunlight we need 23/4.5 or: 5.11 amps per (average) day of output from the PV modules or:

$$\frac{5.11 \text{ amps/day}}{2.0 \text{ amps/day/module}} = 2.56 \text{ Ra-30 modules.}$$

From these basic calculations, it can be seen that the winter design condition dominates and four Ra-30 modules are recommended for the system.

Sample Design Problem #2: Sizing a PV system to power a water pump

Given: A family of 4, with a remote PV powered house, and a small garden plot (supplimental watering only needed during summer). They wish to add another PV system to power their well pump. Their well is 4" in diameter and 200' deep. Depth to water 100' maximum. Maximum draw down = 5' at 10 gpm. Family already owns an AC submersible pump which they would like to use. It is 25% efficient and delivers 10 gpm. There is a 150 gallon pressurized storage tank. There are 5.0 peak hours of sunlight annually for location at a tilt of 45°.

Determine: PV system size required to satisfy pumping requirements.

Assume: 150 gal. per day per person (600 gal. total/day) and that pressure tank has been set to cycle between 25 and 50 psi which allows a delta storage of 60 gallon.

Determine: HP needed by pump and daily pumping time. First calculate total dynamic head. Total dynamic head equals:

100' depth + 5' draw down + assume 5' friction loss +

$$\frac{40\text{psi average pressure}}{.43 \text{ psi/ft of head}} = 110' + \frac{40'}{.43} = 203 \text{ ft. of total head}$$

Next, calculate the water Hp required.

$$\text{Water Hp} = \frac{(\text{head}) \times \text{GPM}}{3960} = \frac{203 \times 10}{3960} = .51$$

Assuming 25% efficiency (pump and AC motor combined), the pump's actual electrical load will be:

$$\text{HP} = \frac{.51}{.25} = 2.05 \text{ HP or } 2.05 \text{ HP} \times 746 \text{ watts/HP} = 1.53 \text{ kW load}$$

This 1.53 kW load on the inverter is the average load and does not account for the inrush current required to start the pump. If we assume an inverter efficiency of 90%, the load demand from the inverter to the system when

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the pump is running is:

$$\frac{1.53\ KW}{.9} = 1.7\ kW$$

If we assume an average battery efficiency of 80% and assume further that 65% of the energy to run the inverter for pumping comes from the batteries (because the pump runs at night and during bad weather) and 35% comes directly from the array (when pumping coincides with sunshine), we have an actual load on the array when the pump is running of:

$$\frac{1.7\ kW}{.8} \times .65 + 1.7\ kW \times .35 = 1.97\ kW$$

Next, we calculate the required running time per day:

Time of running is $\frac{600\ gal\ per\ day}{10\ gal\ per\ min.}$ or 60 min., (1 hr per day)

This translates into an array output requirement of approximately 2 kWh per (average) day. The pressure tank holds about 60 gal (usable) and the pump will run an average of about 10 times per day.

To complete the sizing in terms of Amp hours, we will assume a 5 KW power inverter and 48-volts DC for the PV array, battery bank and inverter input. This would require:

$$\frac{2000\ watt\ hours/day}{48\ volts} = 41.6\ Amp\ hours/day$$

When we divide the (average) daily Amp Hour requirement (at 48 volts) of 41.6 by the daily average number of full sun hours for the site, we obtain an output requirement from the array of:

$$\frac{41.6\ A\text{-}hr}{5.0\ hr\ of\ sun} = 8.33\ Ap\ from\ array$$

$$\frac{8.33\ Ap\ needed}{2.0\ Ap/module} = 4.1\ modules\ or\ 4\ modules\ in\ parallel.$$

Since this is a 48-volt system, a total of 16 12-volt Mobil Solar Ra-30 modules will be required. Four in series to deliver the required 48 volts and four in parallel to produce the daily Amp-hours of current required.

Note: If a high efficiency DC powered pump is used, the power requirements can be cut almost in half with an equivalent savings in modules.

Battery capacity needed:

Again, the winter design conditions dominate. Assume we have cloudy weather for three days of usage and the battery is not to be discharged below 50% of capacity:

3 days at 47.6 AH = 142.8

$$\frac{142.8}{.5} = 285.6$$

Therefore 300 AH capacity (at 48 volts) is required. If prolonged cloudy weather is common 400 or 500 AH capacity would be an even better choice.

TYPICAL LOAD RATINGS

APPLIANCE	POWER (W)	CURRENT 12 V	CURRENT 115 V	HOURS USED PER MONTH	TOT kWh/MONTH
Air conditioner	1566	130	13.7	74	116
Electric blanket	177	14.5	1.5	73	13
Blender	350	29.2	3.0	1.5	0.5
Broiler	1436	120	12.5	6	8.5
Clothes dryer	4856		42	18	86
Dryer (gas)	325	27	2.8	18	6
Coffee pot	894	75	7.8	10	9
Dishwasher	1200	100	10.4	25	30
Drill	250	20.8	2.2	2	0.5
Attic fan	370	30.8	3.2	65	24
Freezer (15 ft^3)	340	28.4	3	290	100
Frost free	440	36.6	3.8	330	145
Frying pan	1196	99.6	10.4	12	15
Garbage disposal	445	36	3.9	6	3
Baseboard heat	10000		87	160	1600
Iron	1088	90.5	9.5	11	12
light bult 75 W	75	6.25	0.65	120	9
1/8 HP motor	250	20.8	2.2	64	16
Turntable	60	5	0.52	50	3
Refrigerator/ freezer	326	27.2	2.8	290	95
Frostless	615	51.3	5.4	250	152
B&W TV	35	3	0.3	110	3.9
Color TV	85	7	0.7	125	10.6
Toaster	1146	95.5	10	2.6	3
Vacuum	630	52.5	5.5	6.4	4
Washing Mach.	512	42.5	4.5	17.6	9
Water Heater	4474		39	89	400
Water pump	460	38.3	4	44	20

TEMPERATURE COEFFICIENTS:

SHORT CIRCUIT CURRENT	+.1%/°C
OPEN CIRCUIT VOLTAGE	-.4%/°C
PEAK POWER	-.5%/°C

OPERATING CELL TEMPERATURE

$\Delta T = 26^{o}C$ @ 800 W/M^2

$= 32^{o}C$ @ 1000 W/M^2

LIGHT INTENSITY EFFECTS

I_{sc} LINEAR WITH LIGHT INTENSITY

P_p NOT LINEAR WITH LIGHT INTENSITY

ENVIRONMENTAL TESTING

TEST	CYCLES	CONDITIONS
THERMAL CYCLE	200	$-40^{o}C$ TO $90^{o}C$
HUMIDITY/FREEZING	10	$85^{o}C/85\%$ RH TO $-40^{o}C$
MECH. LOADING	10,000	± 50 LB/FT^2
TWIST TEST	-	1.2^{o} OUT OF FLAT
HAIL IMPACT	-	1" DIA. ICE BALL @ 52 MPH
SALT FOG		7 DAYS 5% SALT/$35^{o}C$
U.S.C.G. PIT TEST	2,000	1) $50^{o}C$ SALT WATER 5PSI 5X 2) $5^{o}C$ SALT WATER 5PSI 1X
ACCELERATED U.V.	-	8X CONCENTRATION + WATER SPRAY
REAL TIME EXPOSURE	-	

(MODULE FAILURE IS $> 5\% \Delta P_p$)

SOLAR CONVERSION FACTORS

1 sun = 1 KW per m^2 = 1 mw per cm^2 = 92.9 watts/$ft.^2$
1 m^2 = 10.764 $ft.^2$
1 Langley = 3.689 BTU/$ft.^2$
1 BTU/$ft.^2$ = .2711 Langley
1 Langley = 1.08 Watts/$ft.^2$/day

To Convert Langleys to Equivalent Peak Sun Hours (h_p) per day:

Langleys x .01166 = h_p

To Convert BTU/$ft.^2$ to Equivalent Peak Sun Hours (h_p) per day:

BTU/$ft.^2$ x .003161 = h_p

To Convert Kilowatt-hours/m^2/day to Equivalent Peak Sun Hours (h_p) per day:

KWh/m^2/day x 1 Sun/KW/m^2 = 1 Sun-hrs/day = h_p
(KWh/m^2/day is same as h_p)

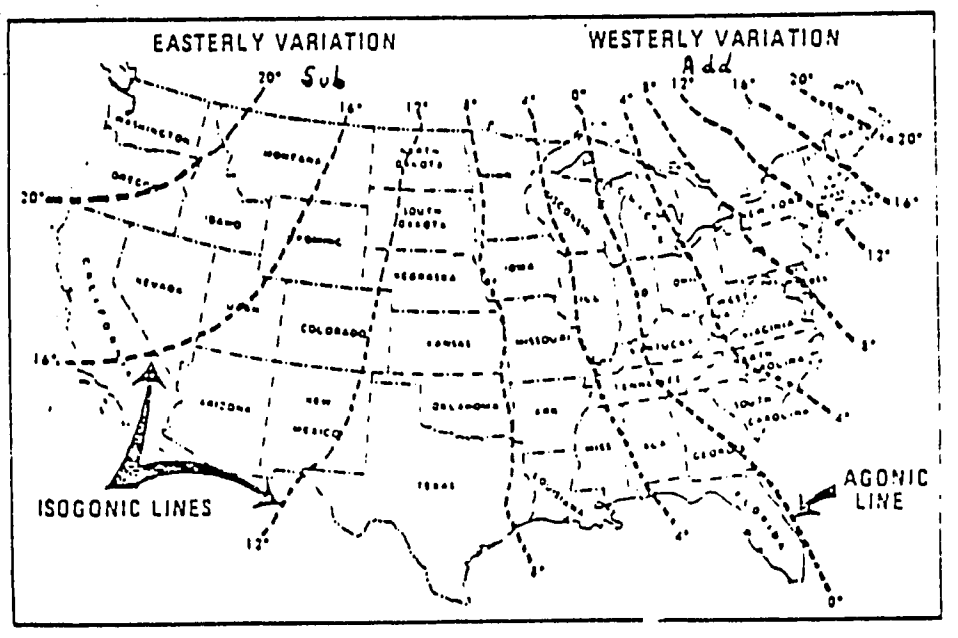

Fig. 7-7. Magnetic Agonic and Isogonic Lines

"Rules of Thumb", Formulae & conversion factors

Preferred System Voltage

1. System Wattage:	12 VDC	24 VDC	48 VDC	120 VDC
	< 500 Wp	500 to 1K Wp	1K to 2.5K Wp	2.5K Wp up

2. Use approximately 100 Amp-hour of battery capacity for every 2.5 Amps of peak module current from the PV array.

3. In arid areas water usage varies widely from 40 acre-feet per year for Alfalfa to 2 acre-feet per year for Jojoba starting and 1 acre-foot once it is established.

Conversion Factors

Acre-feet to gallons multiply by 3.259×10^5

Barrels (oil) to gallons (oil) multiply by 42

Acres to square feet multiply by 43,560

Acres to square meters multiply by 4,047

Gallons to liters multiply by 3.785

BTU/hr ÷ 12,000 = Tons of Air Conditioning

Tons A/C x 12,000 = BTU

1 gal. of water = 8.32 pounds

1 BTU = Heat to raise one pound of water 1° F

BTU x 3.931×10^{-4} = horsepower - hrs.

BTU x 2.928×10^{-4} = Kilowatt - hrs.

Gallons x .1337 = cu. ft.

Horsepower x .7457 = Kilowatts

Horsepower x 745.7 = Watts

Watt - hours x 1.341×10^{-3} = horsepower - hrs.

Panel and Structure Loading

Pounds per sq. ft. loading = $0.00256(V^2)$

V in (MPH)

eg. 100 MPH = 25.6 PSF loading

Note: for non perpendicular loading, multiply by the sine of the angle of incidence

- 460°F = absolute zero in degrees Fahrenheit
- 273°C = absolute zero in degrees centigrade

CONVERSION FACTORS

To convert from	To	Multiply by
Length		
centimeters (cm)	inches	0.394
feet (ft)	centimeters	30.5
inches (in)	centimeters	2.54
kilometers (km)	miles	0.621
meters (m)	feet	3.28
meters (m)	yards	1.094
miles (mi)	kilometers	1.609
millimeters (mm)	inches	0.0394
yards (yd)	meters	0.914
Area		
acres	hectares	0.405
acres	sq. meters	4047
hectares (ha)	acres	2.47
sq. centimeters (cm^2)	sq. inches	0.155
sq. feet (ft^2)	sq. meters	0.0929
sq. inches (in^2)	sq. centimeters	6.45
sq. kilometers (km^2)	sq. miles	0.386
sq. meters (m^2)	sq. yards	1.196
sq. meters (m^2)	sq. feet	10.76
sq. yards (yd^2)	sq. meters	0.836
Volume		
cubic centimeters (cm^3)	cubic inches	0.0610
cubic feet (ft^3)	cubic meters	0.0283
cubic inches (in^3)	cubic centimeters	16.39
cubic meters (m^3)	cubic feet	35.3
cubic meters (m^3)	cubic yards	1.308
cubic yards (yd^3)	cubic meters	0.765
gallons (gal)	liters	3.79
liters (l)	quarts, U.S.	1.057
milliliters (ml)	ounces	0.0338
quarts, U.S. (qt)	liters	0.946
Mass		
grams (g)	ounces, avdp.	0.0353
kilograms (kg)	pounds	2.205
ounces avdp (oz)	grams	28.3
pounds (lb)	kilograms	0.454
tons (long)	pounds	2240
tons (long)	kilograms	1016
tons (metric)	pounds	2205
tons (metric)	kilograms	1000
tons (short)	pounds	2000
tons (short)	kilograms	907
Pressure		
atmosphere	bars	1.013
atmosphere	grams/sq.cm	1033
atmosphere	pounds/sq.in	14.7
pounds/sq.in (psi)	grams/sq.cm	70.3
Force		
dynes	newtons	0.00001
newtons (N)	pounds	0.225
pounds (lb)	newtons	4.45
Energy		
British thermal units (Btu)	calories	252
calories (cal)	Btu	0.00397
ergs	joules	1×10^{-7}
foot-pounds (ft-lb)	calories	0.324
foot-pounds (ft-lb)	joules	1.36
joules (J)	Btu	9.48×10^{-4}
joules (J)	calories	0.239
kilowatt-hours (kWh)	Btu	3410
kilowatt-hours (kWh)	foot-pounds	2.66×10^{6}
Power		
horsepower (hp)	Btu/min	42.4
horsepower (hp)	horsepower (metric)	1.014
horsepower (hp)	kilowatts	0.746
kilowatts (kW)	horsepower	1.341
watts (W)	Btu/hour	3.41
watts (W)	joules/sec	1

SI UNIT PREFIXES

Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	u
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

TEMPERATURE CONVERSION

°C	°F	°C	°F	°C	°F
−50	−58	40	104	120	248
−40	−40	45	113	130	266
−30	−22	50	122	140	284
−25	−13	55	131	150	302
−20	−4	60	140	160	320
−15	5	65	149	170	338
−10	14	70	158	180	356
−5	23	75	167	190	374
0	32	80	176	200	392
5	41	85	185	225	437
10	50	90	194	250	482
15	59	95	203	275	527
20	68	100	212	300	572
25	77	105	221	325	617
30	86	110	230	350	662
35	95	115	239	400	752

HEAT AND SOLAR FLUX

$kW \cdot m^{-2}$	$mW \cdot cm^{-2}$	$cal \cdot sec^{-1} \cdot cm^{-2}$	$Btu \cdot h^{-1}\ ft^{-2}$
1	100	0.0239	317.3
0.01	1	2.39^{-4}	3.173
41.83	4.183^{3}	1	1.327^{4}
3.15^{-4}	3.15^{-2}	7.53^{-5}	1

POWER

hp	kW	$ft \cdot lb \cdot s^{-1}$	$Btu \cdot h^{-1}$	$cal \cdot s^{-1}$	$MeV \cdot s^{-1}$
1	0.7457	550	2,547	178.2	4.65^{15}
1.341	1	737.6	3,415	239	6.24^{15}
1.818^{-3}	1.356^{-3}	1	4.63	0.324	8.46^{12}
2.546	1.899	1,400	6,480	453.9	1.18^{16}
3.93^{-4}	2.93^{-4}	0.216	1	0.070	1.82^{12}
5.61^{-3}	4.18^{-3}	3.088	14.29	1	2.61^{13}
2.15^{-16}	1.60^{-16}	1.118^{-13}	5.47^{-13}	3.83^{-14}	1

ENERGY

$kW \cdot h$	Btu	$ft \cdot lb$	cal	MeV	erg
1	3413	2.66^{6}	8.60^{5}	2.24^{19}	3.6^{13}
5.27^{-4}	1.8	1,400.6	453.6	1.18^{16}	1.9^{10}
2.93^{-4}	1	778.1	252	6.58^{15}	1.06^{10}
3.77^{7}	1.29^{-3}	1	0.324	8.46^{12}	1.36^{7}
1.16^{-6}	3.97^{-3}	3.087	1	2.61^{13}	4.19^{7}
4.46^{-20}	1.52^{-16}	1.18^{-13}	3.83^{-14}	1	1.60^{-6}
2.78^{-14}	9.48^{-11}	7.38^{-8}	2.39^{-8}	6.23^{5}	1

Note: Exponents indicate powers of 10.