A Guide to Designing and Optimizing Small Photovoltaic Systems

by

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Submitted to the Department of
Mechanical Engineering in partial
fulfillment of the Requirements
for the Degree of:

Bachelor of Science

at the

Massachusetts Institute of Technology

June 1997

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ABSTRACT

The design and optimization process for small photovoltaic systems was investigated. Background information on photovoltaic system components was presented along with a methodology for designing and constructing two types of systems. Optimization methods concerning temperature control and irradiance amplification were also presented. A solar powered remote controlled car was constructed according to the design methodology to test the effectiveness of several optimization methods. It was found irradiance modifications were the most effective in improving the performance of a small photovoltaic system. Temperature modifications were not shown to have improved system performance significantly.

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SECTION I: INTRODUCTION

Photovoltaic solar cells are solid-state devices that convert sunlight into electricity. Among the various energy options available today, solar energy is the most abundant and environmentally-benign source available. Because of its modular nature, it can be used in applications ranging in size from powering a small wrist watch to supplying enough electricity for the entire country.

The photovoltaic effect was discovered in 1839 by the French physicist Edmond Becquerel. (Komp, 3) However, it was not put into practical use until the middle of the twentieth century when a long term energy supply was required for space program projects. The first practical solar cell was developed by Bell Laboratories in 1954. (*http://www.nrelgov/research/pv/*) They were first used extensively on satellites because solar power was reliable and cost was not a major issue. As photovoltaic research continued, cell performance improved and costs declined considerably. For example, the cost of electrical energy from photovoltaics was reduced from $50 per watt in 1975 to $5 per watt in 1990 and is expected to be reduced further. (*Bringing Solar Electricity to Earth*, 3)

Throughout the last 50 years, as technology has improved, there have been many initiatives to use solar cells in various applications. However, much of the work has concentrated on relatively large scale projects such as using photovoltaic technology as the primary energy source for a home. Additionally, rural applications of photovoltaic technology are common in areas of the world that lack an electrical infrastructure. These are important applications of photovoltaic technology. However, this thesis seeks to explore small scale applications of photovoltaic technology in common portable products. The focus will be on portable, battery-powered devices such as cameras, flashlights, cellular phones, lap-top computers, toys, power tools, etc.

Since photovoltaic technology is evolving quickly, new applications become cost effective every year as solar products improve and as new products are developed. This thesis will provide a general guide for evaluating and designing photovoltaic systems for small applications. With these guidelines, products can be evaluated repeatedly as technology evolves to discover whether or not photovoltaic technology could be incorporated in a cost effective manner. Additionally, methods for optimizing photovoltaic systems will be explored. Specifically, methods of reducing cell temperature and increasing incident irradiance will be discussed.

In the first section characteristics of photovoltaic technology will be explored. These include operational characteristics, electrical characteristics and an introduction to methods for enhancing performance. The following section will explore energy storage options. This section will focus on the characteristics of four types of rechargeable batteries: lead acid, nickel cadmium, nickel metal hydride and lithium. This section will be followed by a description of overall system integration. This includes the overall methodology needed to construct a photovoltaic system. Next, optimization techniques will be considered in more detail. Calculations involving heat transfer and irradiance amplification will be introduced along with additional comments on tracking devices. The final section describes the evaluation, construction and operating characteristics of a sample application.

SECTION II: PHOTOVOLTAICS

II.1 System Components

This section will describe the basic components of a photovoltaic system. A typical system consists of solar modules, a control device, rechargeable batteries, a load or device and the associated electrical connections.

The solar modules consist of many solar cells connected either in series or parallel depending upon the voltage and current needs of the application. The cells absorb sunlight and convert the solar energy into electrical energy which is then passed to the control unit. The flow of electricity into the rechargeable batteries is controlled by the control device to insure that the battery is not overcharged. Electrical energy stored in the battery can then be used for the intended application. Since the electrical energy produced is direct current (DC), an inverter is occasionally needed to convert the electricity to AC. The entire system is relatively simple. It is free of moving parts so there is little that can wear or break down. Aside from battery disposal, a photovoltaic system is essentially pollution free.

Each component will be described in detail followed by an overall approach for integrating an entire system for a specific application. Since the focus of this thesis is on small systems with a power requirement of 10 W or less, the specific challenges associated with smaller applications will be discussed.

There are many possible variations for a photovoltaic system. These include systems which incorporate a utility grid connection, supplemental generators and AC adaptability. Figure 1 shows several schematics representing these different combinations. However, for our applications, the structures in Figures 1d and 1f will be the standard structures considered in this thesis. The sample application in section 6 uses the system shown in 1d.

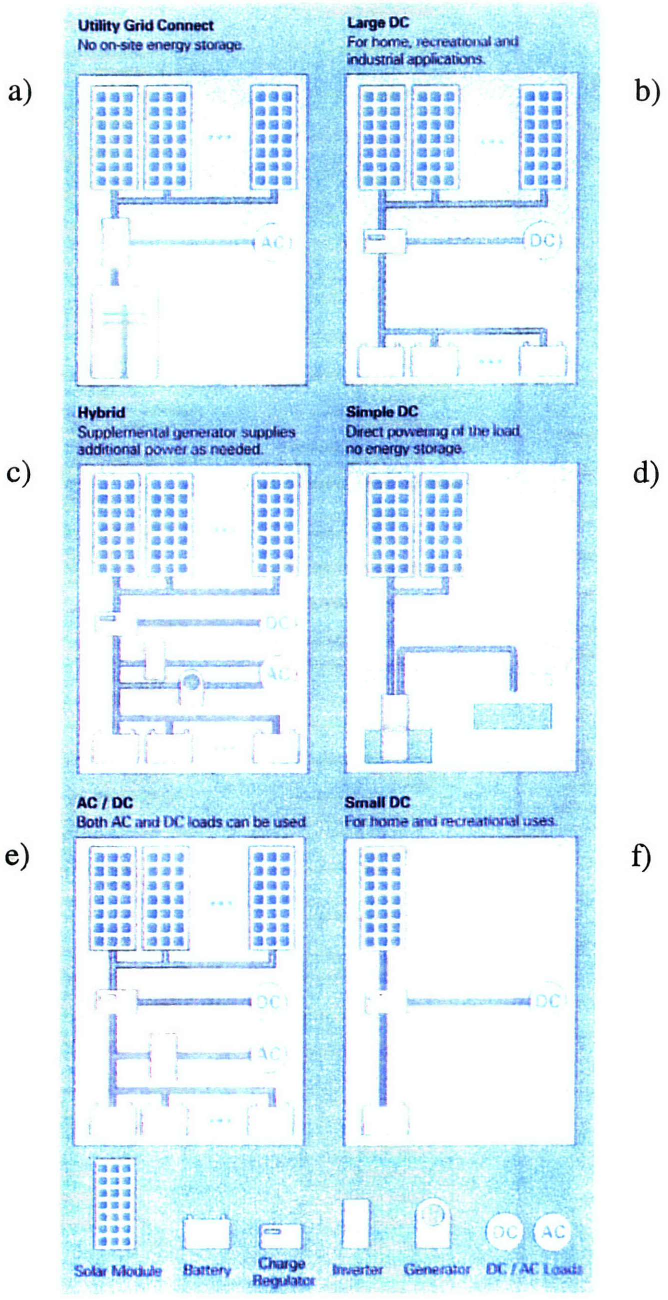


Figure 1: Different photovoltaic system configurations: (a) incorporating a utility grid connection, (b) for large DC applications, (c) incorporating an additional generator, (d) for a simple DC application, (e) able to power AC loads and (f) for small DC applications. (Siemens, 7)

II.2 Photovoltaic Operation

The purpose of this thesis is to examine the *application* of solar power. Therefore, the technical description of how a solar cell operates will be limited. Additional information can be found in appendix A.

There are many different methods for producing photovoltaic cells. One of the first and most widely used methods uses crystalline silicon in ingot form. The ingot is cut into wafers which are then formed into cells. Polycrystalline silicon is also used in this process. A second process involves the direct growth of silicon sheets. These sheets are cut into cell size pieces that are then processed to make cells. This process consumes less silicon then does the ingot based approach.

Thin-film technology is another method used to make solar cells. This films are made by depositing semiconductor materials on a solid substrate such as glass. These semiconductor materials range from amorphous silicon to copper indium telluride. Multi-junction cells can be produced by stacking cells on top of each other. This is done to take advantage of the way different semiconductor materials react to different wavelengths of light. Thin film technology uses less silicon than the previous two methods. (*Bringing Solar Energy to Earth*, 4)

Although solar cells can be made with many different semiconductor materials, most cells currently produced use silicon as the base material. Several layers of silicon are doped with a small quantity of boron and phosphorus. Doping is the process of adding an impurity to a pure semiconductor resulting in a material known as an extrinsic semiconductor. The added boron gives the material a positive or p-type character while the phosphorous added to the other side of the cell establishes a negative or n-type character. The interface between these two layers contains an electric field and is known as a p-n junction. (*http://www.solarex.com/evrythng.html/*)

When photons hit the cell, electrons are released with enough energy to overcome the electric field. These electrons move through the silicon and into an external circuit. This external circuit is connected to the overall photovoltaic system described in the previous section.

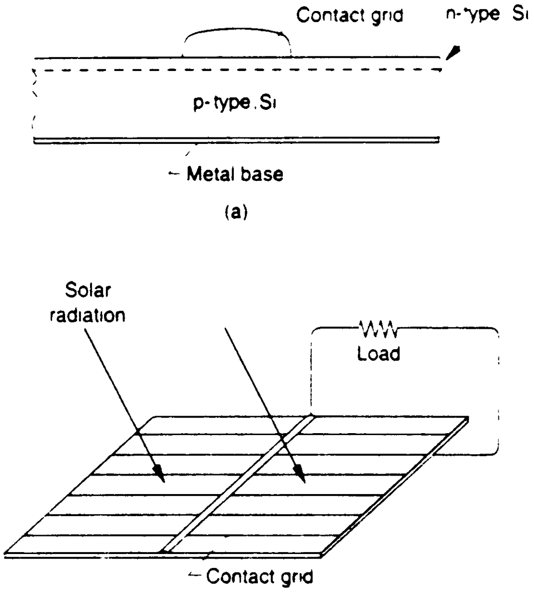


Figure 2: Basic schematic of a silicon solar cell. (Duffie & Beckman, 770)

The individual cells act somewhat like a battery. A voltage is developed across the cell with an accompanying current when the cell is illuminated. A typical cell produces a voltage of 0.46V while the current varies with illumination. The size of the solar cell determines the current output. A typical 4"x 4" cell has a current of 3.2 A at an illumination of 1000 W/m^2. If the desired current is smaller, the cell can be scaled down to achieve lower current values. For example, cutting the 4"x 4" square into two equal pieces would result in two cells with 1.6 A of current each. (*http://members.aol.com/photontek/photon/photon2a.html*)

Cells can be combined in series or parallel to get desired output voltage and current values. The voltages of the solar cells add when connected in series, thereby enabling any voltage - current configuration to be achieved. (within irradiation constraints) A solar module is a combination of individual solar cells. Manufacturers produce modules with different electrical characteristics to meet specific needs. Module power ratings generally range from less than 1W to 250W.

The modular nature of photovoltaic cells is one of the greatest strengths that photovoltaic systems have. Applications ranging from small solar powered watches to power plants capable of supplying electricity to a large city can all use the same technology. For example, a 50 MW power plant is currently being constructed in India. (*http://www.solarex.com*) Although the technology is available for this full range of applications, the associated costs make many applications impractical at this time.

II.3 Cell Performance Characteristics

Photovoltaic modules are rated at a set of conditions known as Standard Test Conditions (STC). Since cell performance varies with temperature and solar intensity, all performance characteristics are measured under these conditions. The standard test conditions require that a cell be tested at a temperature of 25 °C, a irradiation intensity of 1kW/m^2, and a spectral distribution of AM 1.5. Radiation intensity is a measure of the power that the sun supplies per unit area. Spectral distribution refers to the brightness of the different visible colors that make up sunlight. The atmosphere and position of the sun determine this distribution. When the sun is directly over head, the spectrum is called air mass one (AM1). AM1.5 corresponds to the sun being at an angle of 45° above the horizon. (Roberts, 33)

Manufacturers usually list several standard electrical characteristics for photovoltaic modules. These include the open-circuit voltage, short-circuit current, maximum current output, maximum voltage output, maximum power and cell efficiency. Performance curves plotting I-V at different temperatures and occasionally different irradiance levels are also usually included. These are all measured at the standard test conditions.

Most of the electrical characteristics listed above are common attributes often included with battery descriptions. Cell efficiency is defined as the percentage of solar energy received by a module that is actually converted into electricity. The highest efficiency single-junction solar cells are made from crystalline silicon and GaAs. These cells have reached efficiencies of 23% and 25% respectively. For normal solar conditions, the efficiency of polycrystalline silicon made by the growth sheet process can reach 18%. The highest thin-film cell efficiency recorded was 15.8%. Efficiencies of 12-13% are more common in practice with design lifetimes of over 10 years. (Beckman & Duffie, 770) Temperature and irradiance effects will be discussed in more detail in the following section. Figures 4 and 5 illustrate representative IV curves for these effects.

II.4 Factors Affecting Cell Performance

Photovoltaic performance is affected by both internal and external factors. Internal factors include the type of semiconductor material, the purity of the material and the effect of the manufacturing process. External factors include the intensity of the sun and cell temperature Generally, internal factors can only be changed by the manufacturers. Therefore, we can only optimize cell performance by adjusting external factors.

Irradiation directly affects the amount of current produced by solar cells. Figure 4 illustrates an example of this effect on the I-V curve of a representative module. The effect of irradiation varies from product to product. The relationship is not linear; cells approach a maximum current as the irradiation is continually increased. Sun intensity is an important factor largely determined by the geographical area where the application is located. Irradiation can vary extensively in different parts of the country as shown in Figure 3.

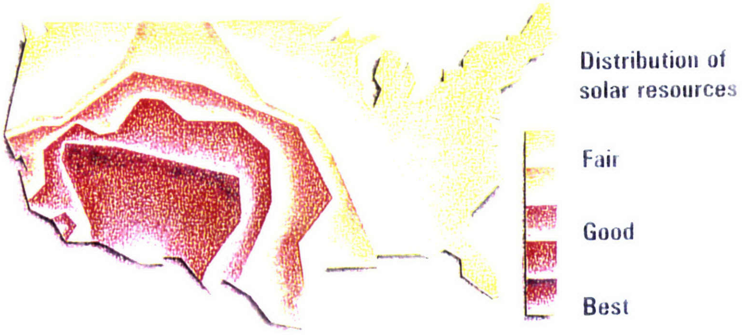


Figure 3: Irradiation variation across the United States. (*Electricity from Sun and Wind*, 3)

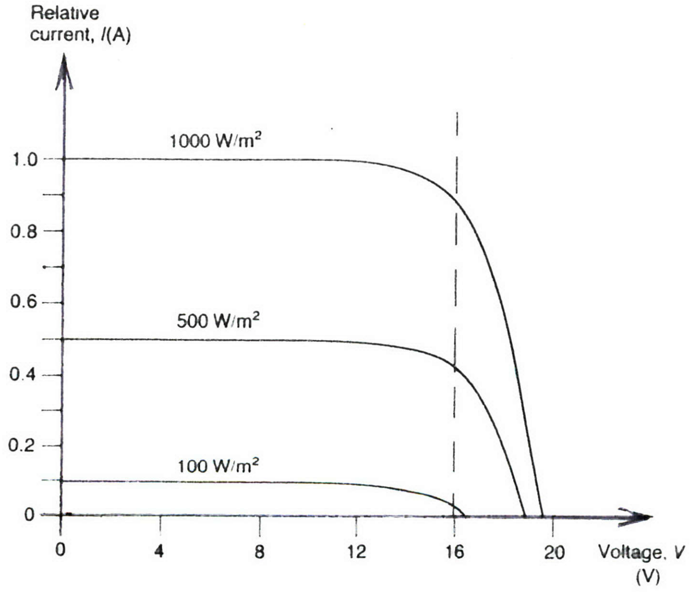


Figure 4: Effect of sunlight intensity on photovoltaic cell performance. (Roberts, 24)

Temperature also affects cell performance and efficiency. The relationship is not intuitive. As the cell gets cooler, it generates more power. The relationship varies for different products. Generally, when the irradiance on a cell is 1 kW/m^2, the cell temperature is about 30 °C higher than the surrounding air. (Komp, 35) To enhance cell performance, it is important to cool the module whenever possible. For small scale applications, this temperature affect is limited. However, there may be applications where the solar module will reach abnormally high temperatures. In this case, an effort to cool the cells may be necessary. Figure 5 illustrates the effect of temperature on the I-V curve of a solar module.

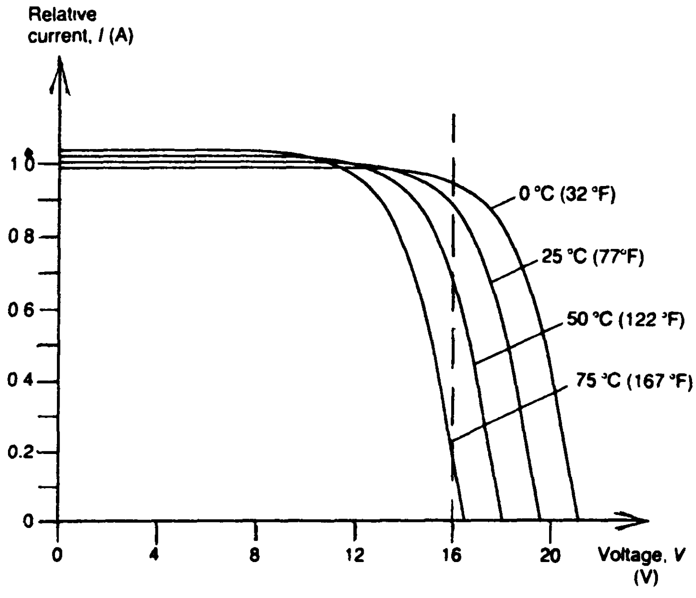


Figure 5: Effect of temperature on photovoltaic cell performance. (Roberts, 26)

II.5 Performance Enhancement

Since irradiation and temperature affect the efficiency and performance of photovoltaic cells, enhancing these properties can enhance the performance of the module. To increase irradiation in a particular site, reflectors, axis tracking devices or anti-reflective coatings may be added to a module.

Reflectors can be positioned around a cell to concentrate solar energy on the module. There are two basic methods for amplifying the sun. The first is by simply using reflectors to redirect more sunlight onto the modules. The second method involves the use of parabolic reflectors to concentrate incoming sunlight on the module. Integrated concentration modules have achieved efficiencies of 30% in laboratory tests. (*http://www.nrel.gov/research/pv/*)

Additionally, axis tracking devices may be employed to follow the sun throughout the day to maintain an optimal angle between the solar module and the sun. These tracking devices can be simply controlled by the movement of a clock for stationary applications. They may also be more complex, using complicated detectors and control systems to move the module. For the applications being considered in this thesis, tracking systems would most likely be impractical. Tracking systems are generally impractical for portable applications. However, some simple design ideas will be explored.

When batteries are used as energy storage devices, a diode is normally connected between the solar modules and the batteries to protect against energy loss. When the solar modules are partially covered, it is possible that the module will draw current out of the batteries. The diode prevents this from happening but draws energy from the system in the process. This loss must be taken into account during system design. If the solar cells directly power the application (i.e., no battery), then a diode is not necessary.

Any attempt at increasing the irradiation on a cell is bound to increase its temperature. As previously mentioned, cells increase electrical production if there temperature is as low as possible. Therefore, performance can be further enhanced by cooling solar modules. Cooling methods include the use of fins, small fans or thermoelectric devices.

Fins may be effective if the temperature is relatively low. They are an inexpensive way to cool solar modules. However, if natural convection were the only method of heat transfer, then the amount of heat removed by the fins would be limited. This will be explained in section 5.

A small fan, as used in electronic equipment, could potentially be an effective way to remove heat. A fan could be used in conjunction with fins to increase cooling. Electronic fans are inexpensive and high heat transfer coefficients can be achieved with strong fans.

Thermoelectric devices are a bit more expensive than fans but have superior cooling properties than fans. A thermoelectric module is a small solid state device that can operate as a heat pump. It operates on the basis of the Peltier effect which exploits the fact that a temperature change can occur between the junction of two different types of conductors when a DC current is introduced. These devices can pump up to 125W of heat or achieve a temperature difference of 70 °F. These devices are small, lightweight, silent and can also provide accurate cooling capabilities. A full technical handbook on thermoelectric devices is available from Melcor Corporation on-line at their web site. (*http://www.melcor.com/*)

These enhancement techniques should be evaluated on a cost-benefit basis. Generally small systems will not need such elaborate enhancing devices. There are, however, instances when several of these options may be practical.

II.6 Costs

The costs of photovoltaic cells have decreased dramatically over the past 20-30 years. As technology improves cell efficiency and manufacturers achieve economies of scale, the price of cells continues to decline. The price of solar modules declined from $50 per watt in 1975 to $5 per watt in 1990. (*Bringing Solar Electricity to Earth*, 3) Additionally, at the utility level the cost of solar energy fell from $2 per kWh in 1975 to 20¢ per kWh in 1990. This is a tremendous decrease. However, fossil fuel based electricity is currently about 6-7¢ per kWh. Therefore, solar technology still needs to come down in cost substantially for solar power to be economically competitive with fossil fuels. In general, large solar modules are less expensive than smaller modules on a $/W basis. A 50 W solar module can cost on the order of $5 per watt while a 1W solar module roughly costs $10 per watt. (*http://www.nrel.gov/research/pv/*)

Most of the current market for photovoltaic cells lies in providing energy for rural areas or in areas where electricity is not readily available. These applications include water pumping, general lighting, remote communications and refrigeration. The cost of extending electric grid lines is such that if a power requirement lies more than a half a kilometer from the electrical line, photovoltaics will be cost effective with the line extension. (*http://www.nrel.gov/research/pv/*) As the cost of photovoltaic technology decreases, more applications will become economically viable.

The key to future cost reductions lies in both increasing the efficiency and in decreasing production cost. Research efforts continue to improve efficiencies but the most substantial cost savings will probably result from increased production. If production is increased substantially, economies of scale will bring down the price of photovoltaics even further. It is important to find the appropriate market opportunities to encourage an increase in current production levels.

Prices of solar modules are expected to decrease steadily over the next few decades. Table 1 illustrates how both efficiency and cost will change for different types of cells. Cost is listed in terms of $/W.

Table 1: Expected efficiency and cost of solar cells. (Solar Today, 29)

Cell Type	1990	1995	2000	2010
Single Crystal Silicon				
Efficiency (%)	10-12	13-14	18	22
Cost ($/W)	5.40	3.50	3.33	2.50
Polycrystal Silicon				
Efficiency (%)	9-11	12-13	16	20
Cost ($/W)	5.00	3.33	2.50	2.20
Sheet Process				
Efficiency (%)	10-12	13-14	17	21
Cost ($/W)	6.00	4.50	3.50	2.50
Amorphous Silicon				
Efficiency (%)	4-6	5-8	10	14
Cost ($/W)	5.00	3.00	2.00	1.50

II.7 Solar Modules Currently Available on the Market

There are several producers which make solar modules to recharge small batteries in consumer products and other miniature photovoltaic systems. There are hundreds of different solar modules available with different power outputs and electrical characteristics. Table 2 lists several different types of solar modules available in 1997. Listed characteristics are at standard testing conditions (STC).

Table 2: Solar modules appropriate for small photovoltaic systems. (Home Power, 113)

Sample	Power (W)	Voltage (V)	Current (A)	Dimensions	Cost ($/W)
1	8.0	5.0	1.6	2" x 4"	5.50
2	16.0	5.0	3.2	4" x 4"	5.00
3	65.0	16.3	4.0	20" x 40"	4.90
4	75.0	17.0	4.4	20" x 47"	4.86
5	120.0	16.9	7.1	26" x 58"	4.75

SECTION III: ENERGY STORAGE OPTIONS AND SPECIFICATIONS

After electricity is generated through the photovoltaic cells, a method is generally used to store the energy. Energy storage methods can be as varied as batteries, capacitors, flywheels, or pressurized storage vessels. Our objective is to design for small self-contained systems with low energy requirements that already use some type of battery power. As a result, we will use secondary or rechargeable batteries to replace primary batteries. First, a brief description of four of the most common types of rechargeable batteries will be given. This will be followed by a list of guidelines for battery selection. The tradeoffs between different battery types will be examined on the basis of these guidelines.

Since the focus of this work is on small photovoltaic systems, the battery size will be limited to a capacity of about 10A h. Solar modules are not generally economical for high powered applications such as those involving large motors.

III.1 Battery Characteristics

There are a standard set of performance criterion when deciding upon a battery. These include battery capacity, cycle depth, cell life, operating voltage, charging efficiency, self-discharging rate and operating current range. Most of these are self-explanatory. However, there are some important things to consider about these characteristics.

Battery capacity is the total charge able to be stored in a battery. This is normally measured in Amp-hours (Ah) or mili-Amp-hours (mAh). Although battery capacity measures the total charge, it does not measure the total available charge. Lead-acid batteries can not be cycled down too far, otherwise the batteries will become permanently damaged. As a result, the usable capacity is often used in calculations. The usable capacity is the amount of charge that can be safely used without damaging the battery.

Cycle depth is another important concept. It refers to the amount of energy that is removed from the battery after each cycle. Deep cycling occurs when 50% or more of the battery's capacity is removed in one cycle. In general, the deeper that a battery is cycled, the shorter is the cell life of the battery. Figure 6 illustrates the connection between cycle life and cycle depth for a lead acid battery. NiCd batteries can be safely discharged completely without any harmful effects. The problem with cycling depth occurs primarily with lead acid batteries.

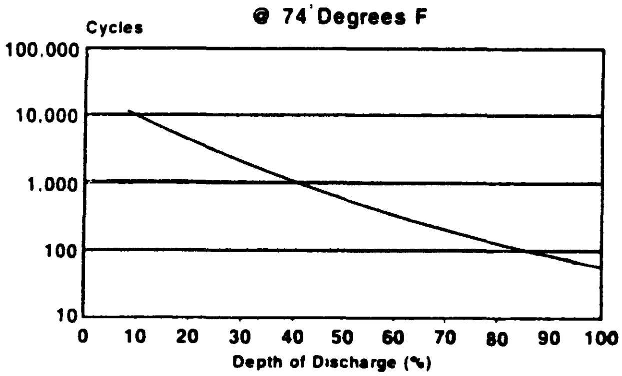


Figure 6: Cycle life vs. depth of discharge for a lead acid battery. (Optima Batteries)

A battery has a natural lifetime that is considered to be the time it takes for the fully charged capacity to be reduced to 80% of its original value. This cell life is a function of both time and cycling. If a battery's life is primarily reduced by the aging process, then its cell life is called its standby life. Cell life varies greatly depending upon battery type and usage. (Roberts, 44)

The self discharging rate is the rate at which the battery slowly lose charge over time. Depending upon factors such as temperature and storage time, different batteries have different self-discharging characteristics. NiCd and NiMH batteries generally have very low self-discharge rates under moderate temperatures. However, as temperature increases, self-discharge increases rapidly. Figure 7 illustrates the connection between temperature and the self-discharge rate.

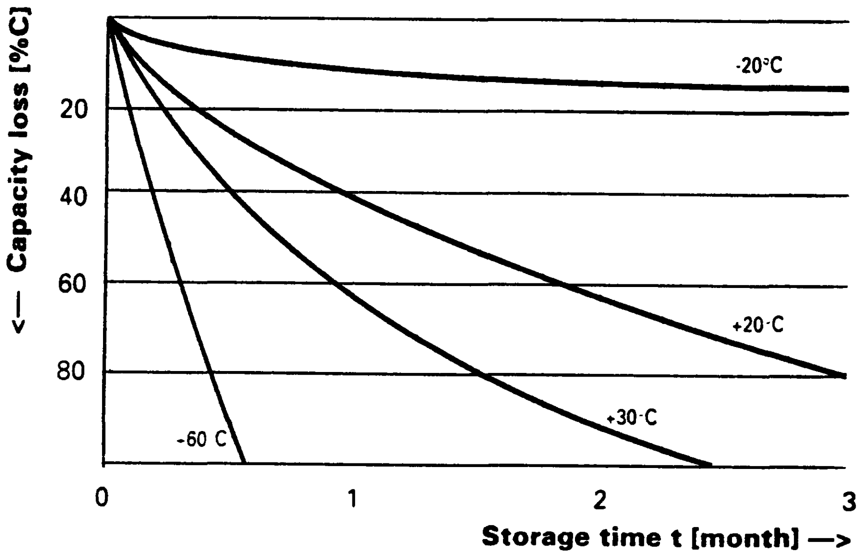


Figure 7: Self-discharge of NiMH batteries at different temperatures.

Additionally, there are a series of voltage and current characteristics which are generally given for batteries. The open current voltage (V_{oc}) is the voltage measured across the battery terminals when there is no current. The operating voltage is the voltage at which the load is drawing current from the battery. The short circuit current (I_{sh}) is the maximum current measured by shorting the battery with an ammeter. Similarly, the operating current is the current which the load draws. The characteristics are all represented on an I-V curve which measures the performance of a battery across a different range of operating currents and voltages. Figure 8 illustrates the construction of an I-V curve for a battery. The two extremes, V_{oc} and I_{sh}, are on their respective axis and the operating values fall at different points on the curve.

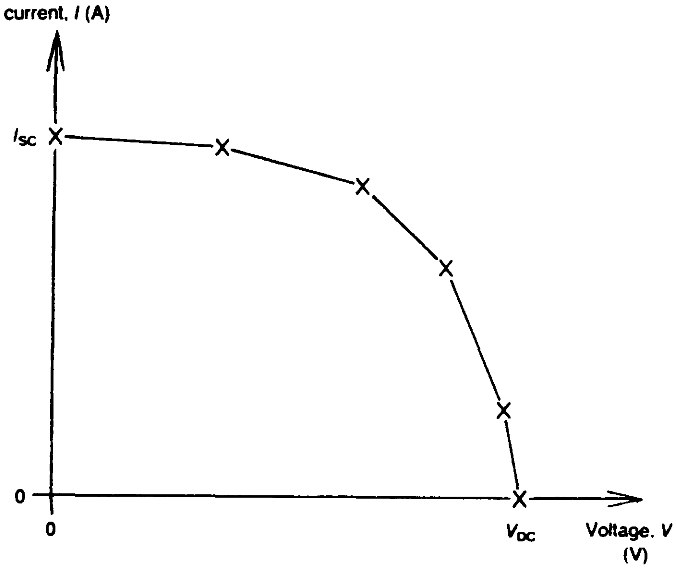


Figure 8: Construction of a typical I-V performance curve for a battery. (Roberts, 22)

III.2 Rechargeable Batteries

Several different rechargeable batteries will be considered. These include lead-acid, nickel-cadmium (NiCd), nickel metal-hydride (NiMH) and lithium (Li). The most common rechargeable battery type used in small applications is the nickel-cadmium battery. However, nickel-metal hydride and lithium are also used extensively in small specialized applications. Lead-acids are commonly used for bigger systems and are seldom used in small applications. The process by which batteries store energy will not be discussed. Information on this topic can be found in the additional information section in appendix A.

III.2.1 Lead-Acid Batteries

Lead-acid batteries are the most common type of battery used to store energy in medium to large photovoltaic systems. Each individual lead acid battery cell is 2V and therefore lead-acid batteries are generally available in 2V, 6V, 8V, 12V and in 24V. They are not available in standard portable battery sizes (i.e. AA). Generally, lead acid capacities range from 1 Ah to 150 Ah. Typical applications include automobiles, golf carts and forklift trucks.

Special care must also be given to the problem of sulphation. Sulphation is the formation of large grains of lead sulphate on the cells of the battery. These large grains, once formed, no longer contribute to the charging process. As a result, the batteries capacity is permanently reduced. This problem, particular to lead-acid batteries, occurs when the battery is left discharged for a long period of time or is continually under-charged. It can also occur if the battery is continually used in temperatures above 45 °C. (Compton, 56)

The best way to avoid the sulphation problem is to keep the batteries charged at all times. This can be a significant problem for deep-cycling applications where the solar cells can not charge up the batteries fast enough. This effect should be addressed and compensated for when using lead-acids in a photovoltaic system. Additionally, maintaining lower temperatures is also important. Lead-acid batteries operate best at temperatures below 40 °C. However, very low temperatures can also lead to problems. These will be discussed in the following section.

The voltage output of lead acid batteries does not stay constant through the capacity. As the battery's energy level decreases, the voltage also decreases slightly. As a result, lead-acid batteries can not be used in applications which require a constant voltage.

III.2.2 Nickel-Cadmium Batteries

Nickel-cadmium (NiCd) batteries are the most common type of rechargeable battery used for small applications. NiCds are rugged and long lived. They have excellent low temperature characteristics and can be completely discharged for long periods of time without any harmful effects. They are more expensive than lead-acid batteries but are less expensive than either NiMH or Li batteries. They are generally practical for smaller applications because they are light, durable and come in standard primary battery sizes (i.e. AA, C, D etc.)

NiCds have several additional advantages. They produce a steady voltage, have a very low discharge rate and require very little maintenance. Typical energy densities range from between 20-30 Wh/kg. They are typically charged at a rate of C/10 with C being the rated capacity of the battery. Although NiCds can safely be completely discharged, deep cycling does reduce the life of the battery. Some NiCd batteries actually change their electrical characteristics depending upon their cycling behavior. This phenomenon is known as the memory effect. If a NiCd battery is continuously cycled to the same level for a large number of cycles, then on a subsequent discharge of the battery, it will not give more capacity than the amount of the routine cycling regimen. As a result, it is important to periodically fully discharge NiCd batteries to eliminate this effect. (Crompton, 19-11) One additional disadvantage of NiCd batteries is their environmental effect. Cadmium is a toxic substance that can severely pollute the environment. As a result, NiCd disposal results in a potential environmental hazard.

III.2.3 Nickel Metal Hydride Batteries

Nickel metal hydride batteries are not as common as NiCd batteries mainly due to their higher cost. However, they outperform NiCd batteries in a number of ways. They have a longer cycle life and also require minimal maintenance. They have a specific energy of between 44 and 77 Wh/kg, which is higher than NiCds making NiMH the lighter battery. Capacity is also superior. Figure 9 illustrates the difference between the discharge characteristics of each type of battery. Although both NiCds and NiMHs have roughly the same discharge voltage, NiMH has almost double the capacity for the same size battery. Additionally, cell pressure can be used to determine the state of charge in NiMHs whereas NiCds are difficult to monitor because of their unchanging output voltage. NiMHs are also more environmentally benign than NiCds.

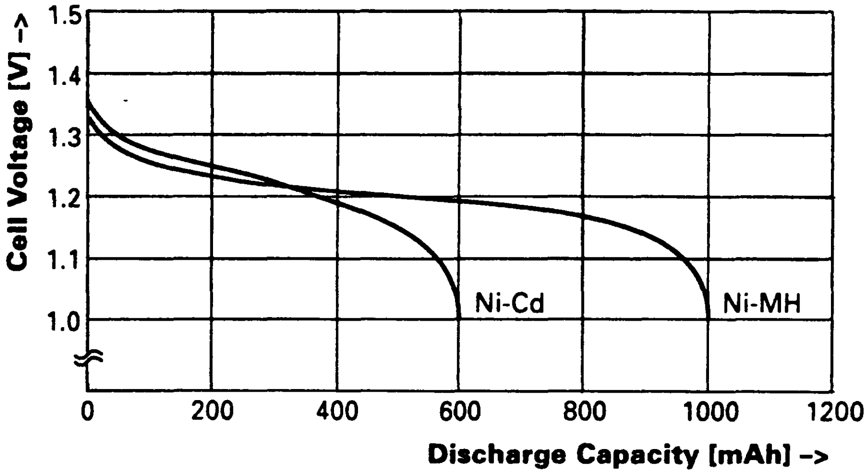


Figure 9: Discharge voltage and capacity of NiMH and NiCd cells.

There are a few disadvantages. As mentioned earlier, NiMH are more expensive than NiCds. The difference in price is illustrated in the cost section. However, if the longer life of NiMH is considered, the effective cost is more comparable. In addition to the cost problem, the hydrogen pressure within the battery contributes to a higher self-discharge rate. (Crompton, 4-15 - 4-18)

III.2.4 Lithium Batteries

Lithium batteries are considerably more expensive than the other three types of batteries. They do, however, have some distinct advantages over other rechargeables . First, they have the highest energy density of any of the batteries considered. Some lithium batteries can provide an impressive 125Wh/kg which is four times better than NiCd. (*http://batteryeng.com/*) This makes them the best choice for light weight applications.

Lithium batteries also allow for high discharge currents and voltages; capable of supplying 2 A of continuous current at a typical cell voltage of 3.5 V. Because of the non-aqueous nature of the electrolytes in lithium batteries, they perform very well in cold temperatures. Additionally, energy leakage is limited. After a year of storage, they will still be charged to 85% of their capacity. (Some lithium batteries claim 80% of capacity after 10 years) (*http://www.batteryeng.com/*) Like Ni-MH and NiCd batteries, lithium batteries have a flat discharge curve yet they lack the memory affect found in many NiCd batteries. They can be found in standard sizes ranging from AA to DD. Containing no heavy metals, they are more environmentally benign than the other three battery types considered.

Lithium battery applications are somewhat limited because of their high cost. They are currently used in small, portable high-tech devices where weight is critical and product cost is generally high. Product using lithium batteries include cellular phones, PCN phones, palm held computers, camcorders, note and sub notebook computers and PC backup power supply.

III.3 Temperature Effects

Battery performance is distinctly affected by temperature. Very high or very low temperatures can be detrimental to the performance of a battery. Generally, for a lead acid battery, higher temperatures lead to a higher battery capacity. However, as mentioned earlier, higher temperatures also increase sulphation rates, self-discharge rates and reduce cycle life. High temperatures dramatically increase self-discharge rates in NiCds.

Although high temperatures can have negative effects on battery performance, excessively low temperatures can also cause severe problems. If a lead-acid is operated at temperatures below 0 °C, the electrolyte in the battery may freeze. This disables the battery and causes severe permanent damage. If the battery is completely charged, the acid is in its full-strength state and will only freeze at -50 °C. However, as the battery discharges, the acid becomes more dilute and the freezing temperature increases.

Temperature also affects the performance of nickel-cadmium batteries. It is recommended that nickel-cadmium batteries not be operated above 45 °C. At this temperature, plates within the battery may touch as the separator degrades due the temperature. This internally short-circuits the battery and causes irreversible damage. Also, high temperatures can cause the battery to dry out as the seal on the battery degrades from increased pressure caused by the high temperature. There are no capacity improvements associated with higher temperatures. (Crompton, 30-12)

On the other hand, low temperatures can also cause problems. If the battery is operated below -25 °C, the electrolyte will freeze. This disables the battery but does not cause permanent damage. Therefore, it is recommended that nickel-cadmium batteries be used between -25 °C and 45 °C. Figure 10 illustrates the effect low temperatures have on NiCd performance.

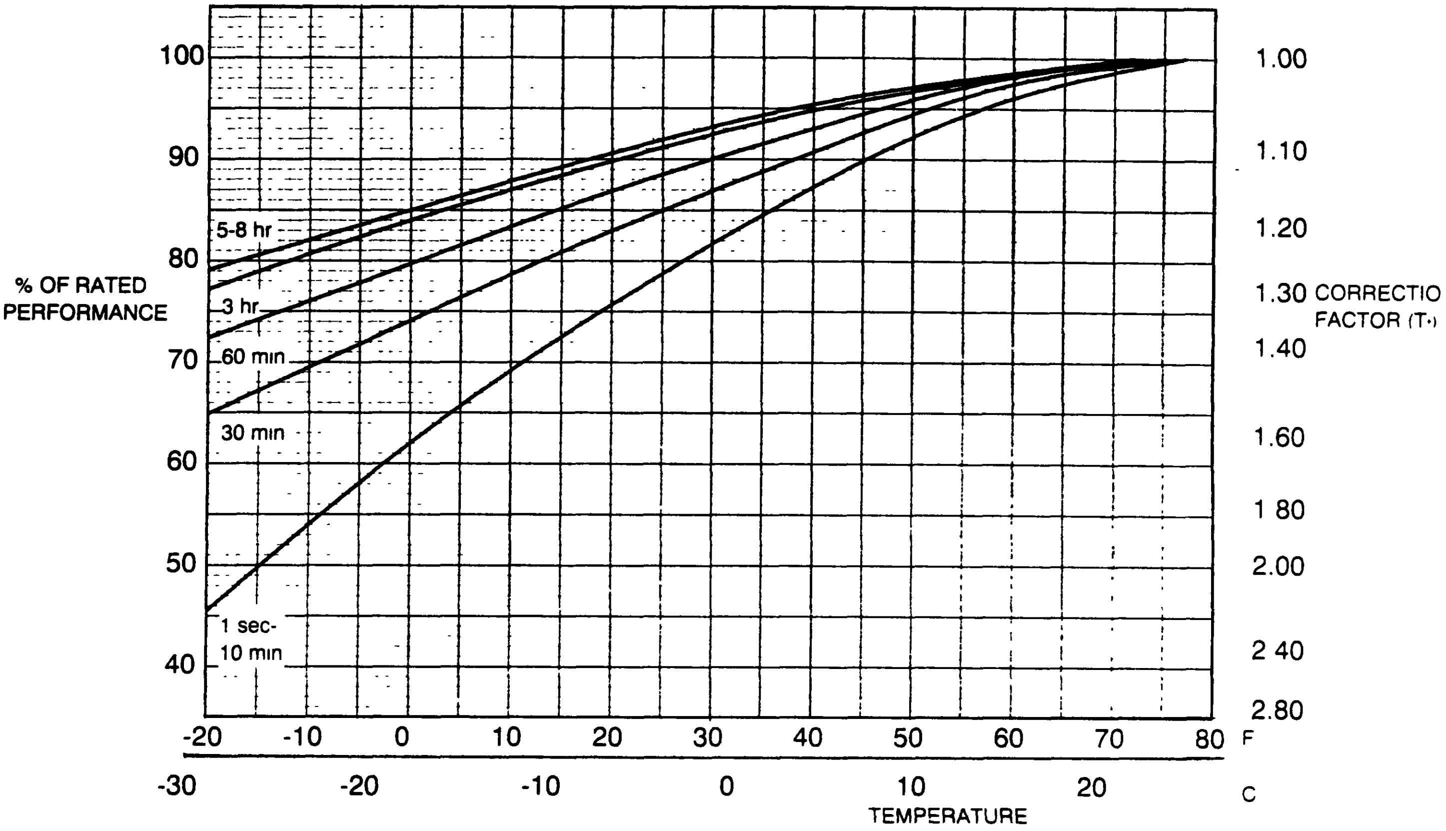


Figure 10: Temperature correction factors for NiCds. (Alcad, Inc. catalog)

Lithium batteries are well-known for their ability to perform over a wide temperature range, -54 to 71 °C, giving a higher discharge rate at low temperatures than is possible with other types of batteries. Figure 11 depicts the discharge profile of lithium batteries at extremely low temperatures. It is important to note that the discharge curve is very flat over a relatively wide temperature range. (Crompton, 30-9)

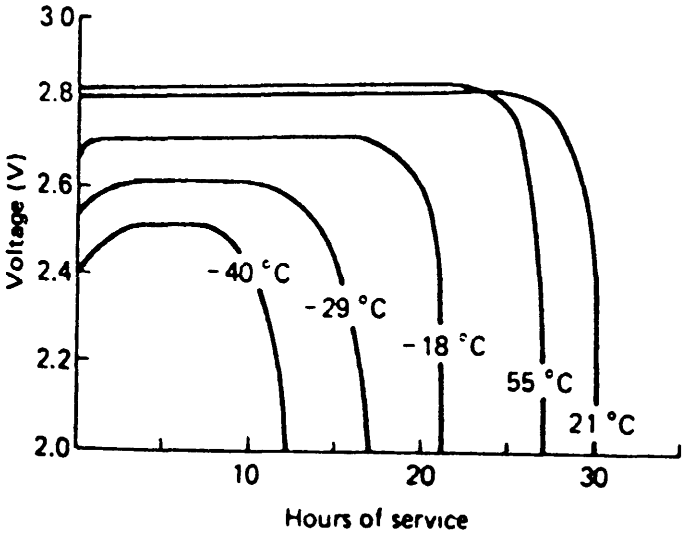


Figure 11: Lithium discharge characteristics at various temperatures. (Crompton, 30-9)

III.4 Safety & Environmental Concerns

There are several areas where the use of batteries can be dangerous if used improperly. One such danger is the possibility of short-circuiting the battery. This is a severe fire hazard. To protect against this danger, it is essential that fuses are included in the battery connections. This is often accomplished through the control system in PV systems.

Additionally, the polarity of the battery must be checked carefully upon constructing a photovoltaic system. If the polarity is reversed, some appliances will not work, some will actually be damaged and the batteries will not charge.

Lead-acid batteries also have important ventilation considerations. During the charging process, hydrogen is released and must be removed from the battery. Vented lead-acid batteries release this gas to the environment. As a result, it is important to keep these batteries in a well-ventilated area. Otherwise, the hydrogen could build up and create a potentially explosive danger.

The acid within a lead-acid battery is also a source of danger. It is important that vented lead-acid batteries are not tipped resulting in severe acid burns. This is an additional reason that using lead-acids in portable devices is impractical. As mentioned earlier, NiCds contain cadmium which is extremely hazardous to the environment.

III.5 Costs

Costs vary depending upon battery type, capacity and other features. In general, among the batteries discussed above, lead acids are the most inexpensive. However, because of their size and weight, they are often not practical for portable applications. Table 3 illustrates the prices of a variety of lead-acid batteries.

Table 3: Representative lead-acid battery prices. (Keystone Battery, 4/97)

Voltage (V)	Capacity (Ah)	Price	Price/Ah
12	32	$32.00	$1.00/Ah
12	60	$65.00	$1.00/Ah
12	120	$120.00	$1.00/Ah

Nickel-cadmium batteries are generally more practical for portable photovoltaic applications but are more expensive than lead-acids. They come in a wider variety of small sizes and are currently used in many applications ranging from camcorders to cellular phones. Table 4 illustrates representative prices of nickel-cadmium batteries available today.

Table 4: Representative nickel-cadmium prices. (You-Can-Do-It Electronics, 4/97)

Size	Voltage (V)	Capacity (mAh)	Price	Price/Ah
AA	1.2	1200	$3.50	$2.92/Ah
C	1.2	2000	$8.90	$4.45/Ah
D	1.2	4000	$9.90	$2.48/Ah

As mentioned in the previous section, NiMH batteries have several distinct advantages over NiCds. However, they are significantly more expensive. Table 5 lists some typical NiMH prices.

Table 5: Representative nickel-metal hydride battery prices. (Dantona Industries, 4/97)

Size	Voltage (V)	Capacity (mAh)	Price	Price/Ah
A	1.2	1800	$9.68	$5.37/Ah
4/3 A	1.2	2500	$12.25	$4.90/Ah
C	1.2	2500	$11.40	$4.56/Ah

Lithium batteries have an astounding energy density, making them extremely light batteries. However, they are more expensive. Table 6 lists some common lithium battery prices.

Table 6: Representative lithium battery prices. (Dantona Industries, 4/97)

Size	Voltage (V)	Capacity (mAh)	Price	Price/Ah
	3.6	850	$11.00	$12.94/Ah
	3.6	1900	$12.00	$6.32/Ah
	6.0	1700	$24.90	$14.65/Ah

SECTION IV: DESIGN METHODOLOGY

Figure 1 illustrates six different photovoltaic system configurations. The majority of these configurations (i.e. hybrid system) are beyond the scope of this thesis. In this section, we will consider two configurations: a simple DC system where the solar cells directly power the load (Figure 1d) and a small DC system which includes a battery for energy storage (Figure 1f). This design methodology is intended to be used with small applications that are already battery powered. The goal here is not to build a solar powered product from the ground up but instead to convert an existing product into one using a photovoltaic system for energy. As a result, the design process is relatively simple and straightforward.

In the first section, we will consider the design of the directly powered system. This will be followed by the second section where the photovoltaic system with energy storage is discussed. Finally, the last section concerns any necessary refinements that may be needed.

IV.1 Direct Drive System Design

Converting a battery powered product into one that is directly powered by solar energy is not a difficult process. However, before constructing the system it is best to thoroughly evaluate the needs of the product.

Using solar energy to directly drive a load introduces several limitations to the performance of the product. First, in order to operate at all, the product has to be completely exposed to sunlight at all times. If there is a shadow cast anywhere on the module, the system will not operate at all. Therefore, the practicality of this approach is very limited to products which will constantly be exposed to sunlight. The product would also be completely useless on very overcast or rainy days. Whereas a system with an energy storage element could comfortably work in any of these conditions. Therefore, any application where a reliable energy source is crucial (such as for some type of emergency lighting) would be out of the question for this approach.

Additionally, directly driving a load requires substantially more current than a system which simply recharges batteries. For example, if four NiCd batteries, each with a capacity of 1200 mAh, are used to power a motor which draws up to 2.5 A then the charging current needed would be about 120mA (using the C/10 method for NiCds).

On the other hand, the directly driven system would need to generate the full 2.5 A. Since current is directly related to solar cell size, the module needed in the direct drive case would be about 20 times the area of the cell configuration needed to recharge the battery. This brings up the next limitation of direct drive systems. Direct drive systems often require an enormous area to place the solar cells in order to generate the necessary current. Therefore, the application would also need to have a large, free area that would both be directed at the sun and not receive a great deal of wear and tear.

If, after these considerations, it is decided to go ahead and implement this system, the first step is to evaluate the electrical characteristics of the system. The voltage is very straight forward. Examine the current battery pack to find out what voltage the product operates at. This is simply the sum of all of the individual voltages of the cells (i.e. 4 NiCds x 1.2V = 4.8V). Test this assumption by attaching a voltmeter in parallel to the load. To find the necessary current, attach an ammeter in series with the load. Use the product in a manner which draws the maximum current (i.e. hold the blades of a small fan and put it on the high setting). Next, examine the body of the product and estimate the total available area where a solar module could safely be attached.

Knowing the electrical characteristics of the product, it is simple to construct the appropriate module. Each individual solar cell is approximately 4" x 4" and produces about 0.5V. A full size cell also produces 3.2A under standard conditions. Take the required voltage needed for the application and divide this number by 0.5. The result is the number solar cells that are needed to be connected in series to achieve the desired voltage. Next, divide the needed current by 3.2. This will give the percentage of the area that is needed on each cell. For example, if the desired current was 0.8 A, then the percentage would be 25%. Therefore, each cell would have to be cut to 25% of their original size. Most small applications do not require currents higher than 3.2 A. However, if this is the case, then the cells can connected in parallel and series to achieve the needed electrical characteristic.

To calculate the total area needed for the solar module, multiply the total number of cells times the percentage times 16 in^2. If this area can fit on the product than the approach is feasible and the system can be constructed. If the needed cell area is too big than reconsider the parameters and see if adjustments can be made. If not, than the approach is not viable. This will often be the case for systems which draw a lot of current.

If the system is feasible, solder the individual solar cells in series using a flux-like solder. Encapsulate the cells in a modular format and simply attach the appropriate leads to the old battery connections. Mount the solar module and the product is now directly solar powered. Modifications will be discussed in the last section of this chapter.

IV.2 Design of a Photovoltaic System with Energy Storage

There is a little more involved in designing a system which incorporates and energy storage device. Some of the additional concerns are battery selection and control systems. Aside from these additional considerations, the process is very similar to that of a direct drive system.

Some of the advantages of photovoltaic systems with energy storage were discussed above. Realistically, it is the best practical way to use photovoltaics as a form of energy because of their sporadic nature. With ample energy storage, a device may be used in any location provided that it is adequately charged in the sun at some later time. Additionally, the solar cells are generally much less obtrusive. However, since the battery charging process is somewhat limited by the speed at which a battery can accept charge, it may take many hours (6-10) to obtain enough energy to run the product for a half hour or so, performance is severely limited. This is a substantial limitation. If the conditions are right, the direct drive system could be used continuously. These are the basic tradeoffs between the two systems. However, an energy storage element is almost always needed for a practical photovoltaic application.

The first step in constructing a system with an energy storage element is to actually select the energy storage element itself. This is chosen first because the size and type of solar cells are completely dependent upon the charging characteristics of the batteries.

Examine the batteries currently used in the product. If they are primary batteries than the best approach is to obtain rechargeable batteries which are the same cell size (i.e. AA, D etc.) or that have the same voltage and as big if not bigger capacity. If the existing batteries are primary, than the battery configuration will have to be changed to accommodate both the charging and discharging. However, this is a minor change. Simply connect the cells in series independent of the product. One of the two resulting leads will be connected to the load while the other will lead to the solar cells.

The next question is to decide what kind of rechargeable batteries to use. Although there are many different rechargeable batteries out on the market, the most practical and available are the ones discussed in section 3 namely lead-acid, NiCd, NiMH and lithium. Lead acid batteries are generally used in medium to large, non-portable applications. They can almost be immediately eliminated for every small product considered. They were included in this thesis because they are by far the most commonly used energy storage element in most average size photovoltaic systems and deserve being discussed. However, for the niche of products being considered here, lead acids are usually not a viable option.

This leaves NiCd, NiMH and lithium as the remaining options. The best approach to take from this point is to consider NiCds the default rechargeable battery unless their is a reason to use the other two. NiCds are the most common and least expensive portable battery type available. NiMH or lithiums should be chosen over NiCds for the following reasons:

Chose NiMH if:

- Long term, maintenance free storage is particularly important to the application.
- The memory effect of NiCds would prove problematic.
- If the battery size is fixed and a larger capacity is needed than that provided by the NiCd
- If weight is a slight consideration. Not severe enough to warrant lithium batteries but enough so that it would justify the added cost of the NiMH batteries

Chose Lithium if:

- Weight is a critical issue. Lithium's impressive energy density allows it to provide the same amount of energy for 1/5 of the weight of NiCds
- A high current is needed for a long period of time. Each lithium cell can deliver 2 A for an extended period of time
- The batteries are going to be stored for a long period of time and maintaining capacity is important. Lithium batteries maintain their capacity even if they are stored for years.
- It is a cold weather application. Lithiums perform particularly well at low temperatures
- Money is not an issue. Lithium batteries are superior to the other rechargeables mentioned but they are more expensive.

Once the type of battery has been selected, it is important to pick a specific model and determine what the charging characteristics are. These characteristics dictate the type of solar module that will be needed. Although the battery might operate at certain voltage, it is most likely charged at a different voltage. The current is particularly important. For NiCds, it is recommended that they be charged at 1/10th of their capacity.

They could take in more current but increasing the charging current may shorten the batteries life. Charging characteristics for different batteries are readily available from the manufacturers.

Knowing the charging characteristics, we can now determine what size solar module is needed. Follow the same procedure outlined above for direct drive system. First, add 0.5V to account for the loss due to the diode. The reasons for including a diode will be discussed shortly. Divide this charging voltage by 0.5 to determine the number of cells. Then divide the charging current by 3.2 to determine how small the cells need to be cut down. Again, make sure that there is adequate room on the product to accommodate the cells. Then, solder the cells in series, encapsulate them and connect them to the battery and load as shown in figure 12.

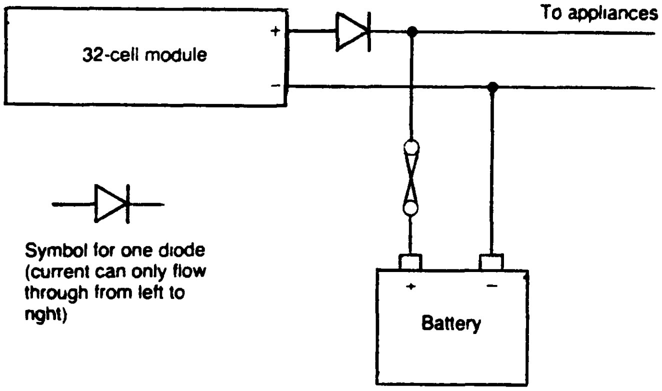


Figure 12: Photovoltaic system with energy storage. (Roberts, 89)

Using an energy storage device adds the challenge of controlling the incoming charge. It is essential to include a diode within the circuit as shown in figure 12. A diode prevents dark current leakage which occurs when the solar cells are completely or partially covered. Without a diode, energy actually leaks out of the battery when the cells are covered. Also, adding a fuse near one of the battery terminals should always be done to prevent short circuit damage. This could be a potential fire hazard.

In addition to adding a simple diode or fuse, some type of control unit is also necessary to monitor the charge and prevent over-charging or over-draining of the battery; both of which can damage most batteries. Control devices range from very simple devices (adding a diode is an example of a control unit) to very complex control systems. Since complex control units are beyond the scope of this thesis, simple solutions to the control challenge will be discussed.

To prevent against over-discharge (not a problem for NiCd but important for lead-acids), a low-voltage disconnect unit can be used. It disconnects the load when it finds that the battery has very low charge. This is mainly used for lead-acid batteries because only lead-acids have lower voltage at a state of low charge. Other types of batteries maintain the same voltage and then suddenly drop off when the charge runs out. (Roberts, 88) A similar type of control system could be used with NiMH where the internal pressure is monitored.

To protect against over-charge, an over-voltage shunt can be used to prevent the voltage across the battery terminals from going above a certain value. Again, this is particularly useful with lead-acid batteries. In general, control systems are most necessary for lead acid batteries. For simple systems, control units are generally not necessary.

SECTION V: PERFORMANCE ENHANCEMENT

There are several modifications that can be made to photovoltaic systems to enhance performance. These fall into two main categories: reducing temperature and increasing irradiation. First, the temperature related modifications will be considered. This section will explore the calculations involved with cell heating, fin design, convection options (i.e. fans) and conduction options (i.e. thermoelectric devices). Next, the irradiation options will be considered. These include calculations involving surface coatings and different types of reflectors. Axis tracking will also be mentioned briefly.

V.1 Temperature Related Modification

Reducing cell temperature improves the performance of the solar module. Figure 5 illustrates the effect that temperature has on the I-V performance curve of a solar module. Before considering the cooling options, it is important to understand how the solar cell is heated in the first place.

As in any heating case, all three modes of heat transfer may be working at the same time. However, the effect of one or two types usually dominates the process, neglecting the effects of the other modes. In the case of cell heating, thermal radiation is the primary mode of heat transfer.

Heating by thermal radiation is governed by the following equation:

$$\dot{Q}_{21} = A_1 h_r (T_2 - T_1) \tag{1}$$

where $\dot{Q}_{21}$ is the heat flow rate from surface 2 to surface 1 measured in Watts. We will take object 1 to be the solar module and object 2 to be the source of energy. A_1 is the exposed area of surface 1 measured in m^2. T_2 and T_1 are the respective temperatures of surfaces 2 and 1 measured in degrees Kelvin. h_r is the radiation heat transfer coefficient measured in W/m^2K. h_r is given by:

$$h_r = 4\varepsilon_1 \sigma T m^2 \qquad \textbf{(2)}$$

where ε_1 is the emittance of object 1 and is dependent upon color and surface finish. σ is the Stefan-Boltzmann constant with a constant value of 5.67×10^{-8} W/m^2K^4. T_m is the mean temperature of T_1 and T_2 which is also measured in degrees Kelvin. (Mills, 16)

Therefore, we can see that heating by thermal radiation is very dependent upon surface temperature. Consequently, as the temperature of the cell is reduced, it requires more and more energy to continue the cooling process since thermal radiation increases exponentially as a result of the increase in ΔT. Any attempts at reducing the *heating effect* of radiation (such as lowering the emittance), will result in less irradiation which will decrease the solar module's output. This is the basic tradeoff we need to address when optimizing solar systems. The best way to minimize T_1 is to employ an effective cooling system.

V.1.2 Natural Convection

If the solar module is not modified, its only method of self cooling is natural or buoyant convection. This method of heat transfer occurs because of the buoyancy force caused by the heated air. Since the density of the heated air is less than the cooler air surrounding it, the warm air rises causing a gentle flow of warm air away from the object.

Heat transfer rates for natural convection are generally modest. For a solar module, we can model the process of natural convection as that of a heated horizontal plate facing up. In this case, Nusselt number is given by:

$$\overline{Nu}_L = 0.54 Ra_L^{(1/4)} \tag{3}$$

where L is the shorter side of a rectangular plate and Ra_L is the Rayleigh number for a rectangle with shorter side L. The Rayleigh number categorizes the transition from laminar to turbulence within the boundary layer and is given by: (Mills, 263)

$$Ra_L = \beta \Delta T g \frac{L^3}{\upsilon \alpha} \tag{4}$$

where β is the volumetric coefficient of expansion. For an ideal gas, $\beta = 1/T$ where T is measured in degrees Kelvin. ΔT is the temperature difference between the surface of the object and the surrounding area (T_∞ - T_l), g is the acceleration of gravity (9.81 m/s^2). L is the length of the short side of the rectangular module measured in m. α

is the thermal diffusivity of air measured in m^2/s. ν is the kinematic viscosity measured in m^2/s and equal to μ/ρ. (Mills, 259)

After calculating the appropriate Nusselt number, the heat transfer coefficient for natural convection can be found by

$$\overline{h}_c = (k / L)\overline{Nu}_L \tag{5}$$

where k is the thermal conductivity of the object measured in W/mk. (Mills, 221)

Heat transfer due to convection is given by

$$\dot{Q} = A_1\overline{h}_c(T_2 - T_1) \tag{6}$$

Natural convection is dependent upon the natural properties of the object. Unless these are altered, trying to increase natural convection appears to be futile. One parameter which can be changed without drastically altering the system is the surface area A_1. Here, fins can be used to increase heat transfer away from the solar modules. The calculations for natural convection should be used to establish a baseline from which to evaluate the other heat transfer methods.

V.1.3 Fins

To increase the convective heat transfer coefficient, the exposed area of the solar cells could be increased by incorporating fins. This is assuming that the bottom of the cells will be connected to fins. Attaching fins to the top would not be practical because they would interfere with solar module performance.

The improvement in convective heat transfer can not be found by simply increasing the A_l term in equation 6. The heat transfer characteristics change depending upon the fin characteristics. For a single fin, the dissipated heat can be found by:

$$\dot{Q} = \frac{h_c \mathrm{P}}{\beta}(T_B - T_\infty)\tanh \beta L \tag{7}$$

where h_c is the convective heat transfer coefficient (it can either be calculated for natural convection or for forced convection) measured in $\mathrm{W/m^2K}$. P is the perimeter of the fin. T_B is the temperature at the base of the fin (equal to the temperature at the solar cell surface) measured in degrees Kelvin. L is the length of the fin in meters. (Mills, 75) β is a fin parameter given by

$$\beta^2 = \frac{h_c \mathrm{P}}{k A_c} \tag{8}$$

where A_c is the cross-sectional area of the fin. (Mills, 73) A rough approximation of a series of fins can be made simply by adding the individual effects of each independent fin.

Material selection is an important consideration in fin design. It is best to minimize β by selecting a material with a very high thermal conductivity (k). Materials such as aluminum and copper have high thermal conductivities making them good fin materials.

To fully optimize a fin design, it is important to consider the topic in more detail. For our purposes, we want to just introduce fins and provide a background to understand how heat is transferred via fins. More detailed information concerning the design of a fin system can be found in Mills, pp. 70-95.

V.1.4 Forced Convection

As discussed earlier, natural convection is the heat transfer method acting to cool heated solar cells if there are not any additional system modifications. However, the convective heat transfer coefficient can be increased substantially if forced convection is employed as a heat transfer method. Forced convection is the process of forcing air or any other fluid over a surface using a fan or blower to cool the surface more quickly.

To calculate the effect of a fan on a solar cell, we can model the solar module as a flat plate. It is important to discern whether or not the flow produced by the fan is turbulent or laminar. This can be determined by examining the Reynold's number of the flow across the leading edge of the solar module. The Reynold's number can be calculated as follows

$$\mathrm{Re}_L = \frac{u_\infty L}{\upsilon} \qquad \textbf{(9)}$$

where u_∞ is the free-stream velocity of the fluid, L is the length of the module parallel to the flow and ν is the kinematic viscosity of the fluid. (Mills, 246) For our purposes, we can assume that the fluid is always air. Values of Re_L above 5 x 10^5 indicate turbulent flow while a Re_L below this value indicates a laminar flow.

For laminar flow, the Nusselt number can be calculated by

$$\overline{Nu} = 0.664\,\mathrm{Re}\,L^{1/2}\,\mathrm{Pr}^{1/3} \qquad ; \; Pr > 0.5 \tag{10}$$

where Pr is the Prandtl number which is equal to ν/α. In general, gases have Pr ~ 1 so this Nusselt number case is sufficient for our analysis of laminar boundary layers. (Mills, 247)

For the turbulent case ($Re_L > 5$ x 10^5), the Nusselt number is given by

$$\overline{Nu} = 0.664\,\mathrm{Re}_{tr}^{\,1/2}\,\mathrm{Pr}^{1/3} + 0.036\,\mathrm{Re}_L^{0.8}\,\mathrm{Pr}^{0.43}\left[1 - \left(\frac{\mathrm{Re}_{tr}}{\mathrm{Re}_L}\right)^{0.8}\right] \tag{11}$$

where Re_{tr} is the Reynold's number at the transition point from a laminar to a turbulent boundary layer.

The heat transfer coefficient can now be calculated using equation 5. With this new h_c, the heat transferred using a fan can be calculated using equation 6 or 7 depending upon whether or not fins are being used. The heat transfer coefficient for forced convection is typically much higher than that for natural convection. Typical forced convection heat transfer coefficients for forced air range from 10-200 W/m^{2}K and for forced water range from 50-10,000 W/m^{2}K. On the other hand, natural convection heta transfer coefficients typically range from 3-25 W/m^{2}K. The resulting difference in heat transfer is can be very substantial. (Mills, 22)

V.1.5 Conduction

Conduction is used in the fin method to conduct heat away from the surface into the fin. At this point the fins themselves are convectively cooled. There are several additional ways to use conduction to cool the solar cells. These include establishing a heat sink and using thermoelectric devices.

If the solar cells were mounted on a surface maintained at a lower temperature, then the cells would expel heat to this surface via conduction. This type of heat sink could be established using cooled water (perhaps flowing through pipes), or any material with a large heat capacity and with a favorable coefficient of thermal conductivity. Conduction is governed by:

$$\dot{Q} = \frac{kA}{L}(T_1 - T_2) \tag{11}$$

where A is the cross-sectional area of the material and L is the thickness of the conducting material. (Mills, 11) Since the constraints of the system often dictate the dimensions, lowering the temperature of the second surface (heat sink) is the most effective way of increasing heat transfer.

Another conduction method for cooling solar cells is the use of thermoelectric devices. A thermoelectric device pumps heat away from a surface. It requires a voltage input and as a result may use more energy than it creates by improving cell performance.

Since there are not any simple calculations for sizing thermoelectric devices, the best procedure for considering these devices is to consult the company catalog. Melcor corporation maintains an on-line catalog which has all of the characteristics of their products. After estimating the desired solar module temperature and the surrounding air temperature, it is easy to select a device that would be appropriate for the application. The improvement in performance due to the incorporation of this device can also be estimated. If the solar cell manufacturer includes a characteristic I-V curve representing the effect of temperature on cell performance, than knowing the temperature difference (with and without the device), the improvement can be estimated.

VI.2 Irradiation Related Modification

In a similar way that temperature improves cell performance, increasing irradiation also increases photovoltaic performance. Since current output is directly related to irradiance, increases in light intensity serve to increase the current proportionally. Three different irradiance related modifications will be considered in this section. First, the effect of module surface conditions will be discussed. This will be followed by an examination of the use of solar concentrators and a brief section on tracking devices.

VI.2.1 Module Surface Modifications

One way to increase the incident irradiance on the solar cells is to optimize the surface properties of the solar module. Maximizing the transmittance of solar radiation increases the radiation incident on the cells.

The transmittance of the module surface depends upon several parameters. One parameter that determines the transmittance is the extinction coefficient (*K*). This coefficient is a proportionality which is a material property which remains constant over the solar spectrum. *K* is normally lower for materials that have superior absorptive properties. The transmittance of a material surface is given by:

$$\tau = e^{\left(\frac{-KL}{\cos\theta}\right)} \tag{12}$$

where *K* is the extinction coefficient, *L* is the thickness of the material and θ is the incident angle of the radiation. The incident angle of radiation is the angle that a beam of light approaches the solar module. It is measured from a line perpendicular to the surface of the module. (Duffie & Beckman, 221)

Transmittance can be maximized by minimizing either *K* or *L*. Therfore materials with a low extinction coefficient increase the amount of radiation that a solar cell receives. Additionally, keeping θ as close to 0 as possible also increases transmittance. This is intuitive enough and provides one of the basic motivations to using tracking systems.

One additional surface modification that can help increase irradiance is the process of etching. Etching involves coating the surface of the module with a film of low refractive index. This is typically used on camera and binocular lenses. The solar reflectance of glass is typically 8%. Etching can bring this value to below 1% which significantly increases transmittance and as a result incident irradiance. (Duffie & Beckman, 234)

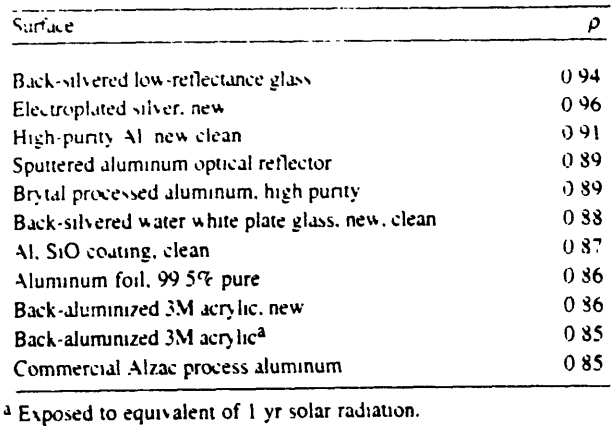
VI.2.2 Solar Concentrators

In addition to modifying the surface of a module, solar concentrators can also be used to increase incident radiation. Solar concentrator refers to any device which directs radiation onto a receiver (solar module). There are a myriad of different geometric configurations for concentrators. Analysis of these devices is specific to the particular configuration. However, there are some concepts that can be applied to all concentrators. Equation 13 illustrates the relation between S (absorbed radiation) and several reflector parameters.

$$S = I\rho(\gamma\tau\alpha)K_{\gamma\tau\alpha} \qquad \textbf{(13)}$$

where I is the irradiance incident on the reflector, $K_{\gamma\tau\alpha}$ is an incident angle modifier and $\gamma\tau\alpha$ are all functions of both the incident angle and the geometry of the system. (Duffie &Beckman, 341)

Most of the parameters in equation 13 are geometry specific but the specular reflectance is reflector specific. It is a material property that can be considered when deciding upon the material with wich to construct the reflector. It can be seen that an increase in ρ leads to an increase in S. Typical values for ρ are shown in figure 13.



Surface	ρ
Back-silvered low-reflectance glass	0.94
Electroplated silver, new	0.96
High-purity Al, new, clean	0.91
Sputtered aluminum optical reflector	0.89
Brytal processed aluminum, high purity	0.89
Back-silvered water white plate glass, new, clean	0.88
Al, SiO coating, clean	0.87
Aluminum foil, 99.5% pure	0.86
Back-aluminized 3M acrylic, new	0.86
Back-aluminized 3M acrylic[a]	0.85
Commercial Alzac process aluminum	0.85

[a] Exposed to equivalent of 1 yr solar radiation.

Figure 13: Specular reflectance values for selected materials. (Duffie & Beckman, 212)

Since reflectors require irradiation to be coming at a specific angle (since the reflectors can only be set up in one way) in order to work properly, tracking devices are often required to keep the sun in the right position relative to the system throughout the day. Standard reflectors need tracking systems which will be discussed in the next section.

There is one particular type of reflector that allows a little leeway with regards to the position of the sun. These reflectors are made in a way that they may be used seasonally or even annually without any tracking requirements. This can be accomplished with parabolic shaped reflectors. Compound parabolic concentrators (CPCs) Each side of the CPC is a parabola and if light hits the reflector within a certain angle range, the light will be reflected to the solar cells. Figure 14 illustrates the cross-section of one side of a CPC.

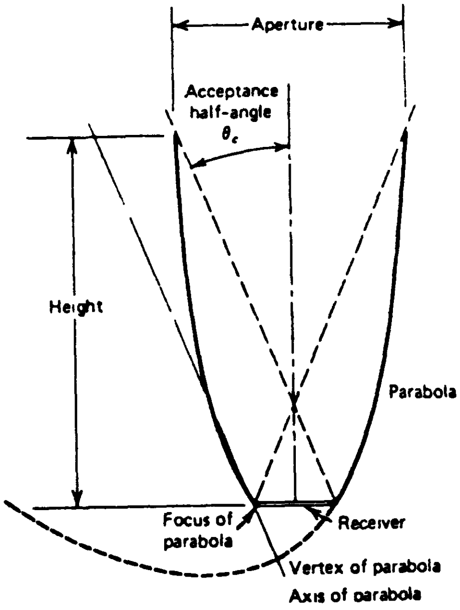


Figure 14: Compound parabolic concentrator diagram. (Duffie & Beckman, 346)

Although there is a degree of flexibility with respect to incoming sunlight, the focus point of a CPC must be carefully aligned to the solar module to insure that the reflected light goes to the appropriate place. Although they increase irradiance, CPCs or any metallic reflectors can be used to transport heat away from the solar cells. If the reflectors are connected to the cells, they act like fins. These effective fins can help to lower cell temperature.

VI.2.3 Tracking Devices

Tracking devices track the movement of the sun throughout the day to maximize the incident irradiance on the solar cells. Normally, these systems are mainly used to minimize the incident angle θ. There are several ways to measure the angle of incidence at different times of the day accurately. Detailed calculations can be found in Duffie & Beckman, pp. 21-24.

In addition, these systems are often necessary for solar concentrating systems. Since most reflector systems are very sensitive to the location of the sun, tracking devices are needed to keep the sun at the correct angle so that the reflectors are in a position to work well.

Tracking systems vary in complexity. Some simply use the motion of a clock to track the sun throughout the day. While others use complicated tracking and feedback systems to maintain the solar module in an ideal position. If the modules are stationary, than positioning can be calculated in a straightforward manner as described in Duffie & Beckman.

On the other hand, if the system is mobile, then the tracking system increases in complexity. The system must have a way of identifying where the sun is at all times. Its response time must be fast enough to be able to keep up with the motions of the system. One way to do this would be to position individual test cells at different locations around the system. Each of the cells would be identical and the currents of all of the test cells could be continuously compared to determine the best position of the solar cells relative to the sun. The solar module could then be moved into this orientation. This would require that the module was independent of the test cells and that there be a feedback system responsive enough to keep up with the system's movements. Alternatively, if there is some type of solar sensor which can find the sun's position, then the control system can be built around this sensor. Any tracking system for a portable system would have to incorporate the solar detection characteristics described above.

VI. SAMPLE DESIGN PROJECT INCORPORATING METHODOLOGY

The methodology described in section 4 was used to design and develop a small photovoltaic system for a remote controlled toy vehicle. The first step in this process was to decide which product to convert to solar powere by evaluating the feasibility of applying photovoltaic technology to several different applications. Determining feasibility was particularly important in this case because it was decided to use the direct drive photovoltaic system for this project. As a result, many products did not have enough space to accommodate the solar cells. The reasons for using a direct drive system will be discussed in the first section along with an evaluation of the different products considered.

Following the product evaluation, a description of the procedure used in the design and construction of the remote controlled car is included. This is followed by information regarding the performance of the system under various conditions and how well it performed compared with its predicted performance.

Several of the optimization methods described in section 5 were used to improve the performance of the car. A testing station consisting of 4 halogen lights was constructed to establish a consistent irradiance source. With this testing station, the performance of the system with different optimization techniques was evaluated. Finally, recommendations for future work were presented.

VI.1 Application Selection

It was decided to use a direct drive photovoltaic system for two main reasons. First, by using a direct drive system, much higher currents are involved than would have otherwise in a system with energy storage. This was important because higher currents allow us to detect minor differences in performance due to optimizing methods that may have been too subtle to detect at lower currents. The second reason that this type of system was used was because improvements in cell performance could be visually seen in improvements in product performance. If their had been an energy storage system, a decrease or increase in cell output would go visually unnoticed.

It was important to be able to directly observe modification effects in performance because the sample project was included was as a potential project for a solar engineering class. It was conceived that the final project would be set up in a contest type of format. With this in mind, students could modify a directly driven car using the suggestions in section 5. Then they could race them under controlled conditions to determine who optimized their car in the best manner. A competition of this sort with cars powered with systems with energy storage would not be able to distinguish the differences made by the performance enhancement features. In reality, a remote controlled solar car should have a battery if it were being made for production. However, for our purposes, the direct drive system was the most appropriate.

After considering the list of possible applications located in Appendix B, ten applications were selected to evaluate thoroughly. These products were examined to determine whether or not photovoltaic technology could be realistically applied. These products were chosen based upon the following criteria: they were interesting, they had low power requirements, they spend a significant amount of time outdoors, and each product had substantial area where solar modules could be installed without hampering the performance of the product. The products chosen were:

- Remote controlled car
- Remote controlled boat
- Walkman with cassette
- Walkman with a CD player
- Radar detector
- Outdoor refrigerated cooler
- Walkway lights
- Bug Zapper
- Christmas lights
- Garage mounted trickle charger for battery powered lawnmower

Each of the products listed above was evaluated in the manner described in section 4. The results indicate that the remote controlled car would be the best product to use a photovoltaic system. It was chosen for several reasons. First, the analysis indicates that new batteries and solar modules of the appropriate size could easily be integrated into the product. Additionally, building this product is a practical task. For example, the garage mounted trickle charger would be interesting but the scale of this product is too big and building it would not be practical. As mentioned earlier, this product also provides an opportunity to stage a competition. And finally, it incorporated a motor and had a significant range of motion. This type of product lends itself well to a mechanical engineering project. (Whereas a radar detector would not since it does not move and has more electrical engineering characteristics than mechanical ones)

VI.2 Application Evaluation

The remote controlled car that was chosen to be modified was made by Nikko and it was selected for several reasons. First, it included a NiCd battery back that powered the motor with a potential of 4.8 V. This was relatively low compared to other remote controlled cars that ran on 7.2 and 9.6 V. This low voltage reduced the number of solar cells needed which is particularly important for a direct drive system. Additionally, although it ran on a low potential, the car had a lot of free space (free area ~ 96 in^2) which would allow it to support many solar cells..

In following with the general evaluation procedure in section 4, the first step in examining this product is to assume that the voltage supplied by the batteries was the voltage that the motor required. As a result, after dividing 4.8 by 0.5, it was found that approximately 10 solar cells were needed. In order to find the current required by the motor, an ammeter was connected in series between the batteries and the car. The wheels were slowly forced to stop to find the maximum current drawn by the motor. The maximum current was found to be approximately 1.5 A. After dividing 1.5 by 3.2, it was found that each cell would need to be cut in half (from 4" x 4" to 2" x 4") to provide the appropriate current. Therefore, the total area needed for these solar cells was estimated to be 80 in^2. This would effectively cover the entire car but could be successfully implemented.

VI.3 Implementation Procedure

After contacting several vendors, a company was found which was willing to donate the solar modules for free. They did not have modules to meet my exact specifications. However, the company did have two 6 cell modules that were rated at 1.6 A. Although they were to produce 60 V when connected in series, they were adequate for this application.

The modules were connected in series and then soldered to the battery connections. All connections were soldered and then sealed with shrink tubing. The two modules, which consisted of solar cells epoxied to foam board with a plastic cover, were mounted on top of the car using long bolts. Figure 15 illustrates what the assembly between the solar modules and the car looked like.

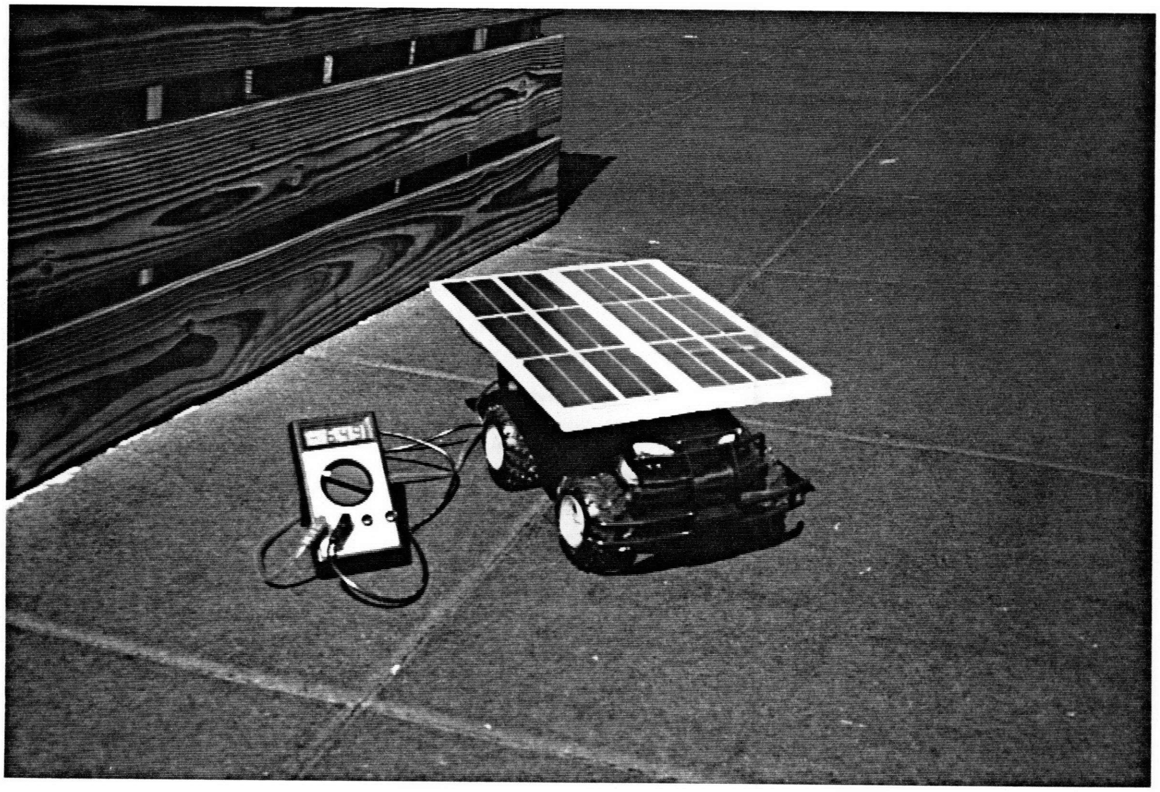


Figure 15: Assembled remote controlled solar car.

Since a constant source of light was needed in order to accurately test the effect of different modifications, a test table was constructed. It consisted of four 300W halogen lights in parallel, connected to the underside of a small test table. Solar cells can be powered indoors by using either halogen light or mercury vapor light. 8" lag screws were screwed up into each leg to give the table vertical adjustability. A picture of the testing apparatus is shown in figure 16.

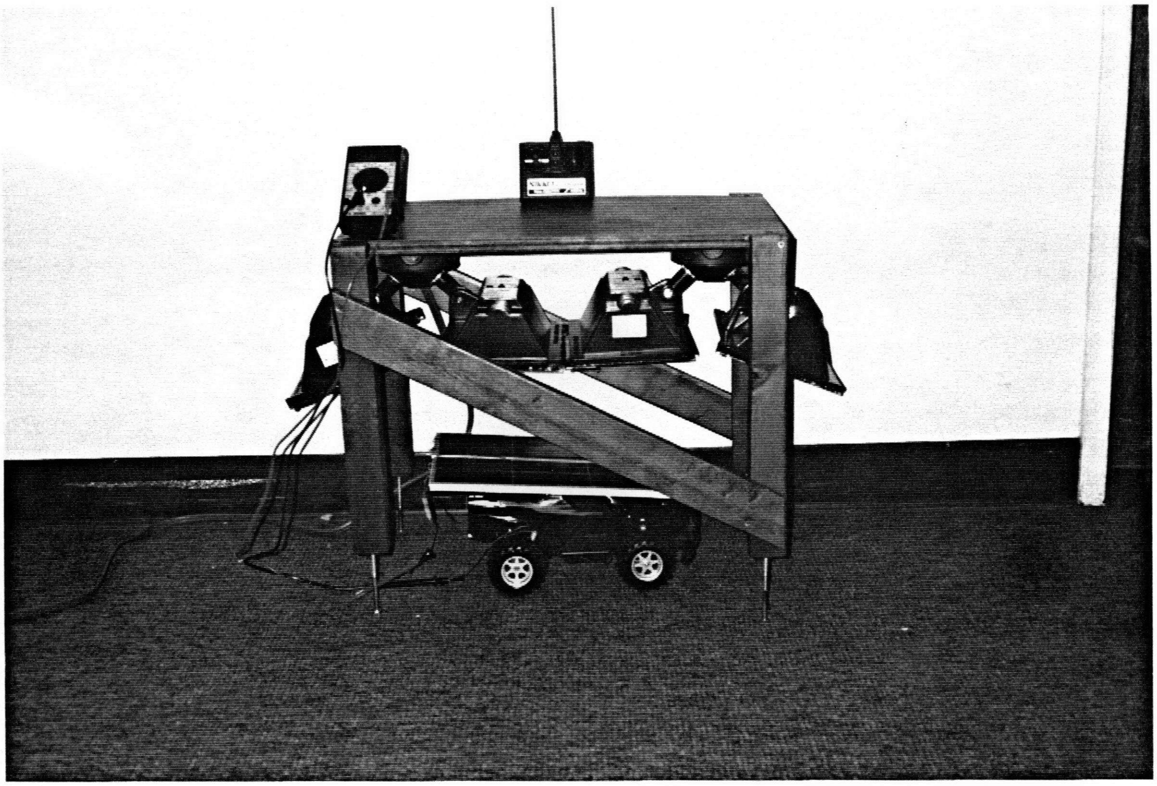


Figure 16: Halogen testing apparatus.

VI. 4 Performance

The car was taken outside a number of times when the weather was appropriate. It performed well going forward and reverse in a straight line. However, it had some trouble turning. At first, it was thought that this could be attributed to the excess weight of the cells. However, upon further investigation, it was found that the additional current needed to turn the front wheels was not originally accounted for during the evaluation process. The car needed about 1.5 A to accelerate smoothly and another 300

- 400 mA to be able to turn as well. Therefore, the car needed close to 2 A to match the performance it had under battery power.

The electrical characteristics of the solar cells were both a little above and below expectation. The open circuit voltage (V_{oc}) was measured outside to be about 6.5 V, 0.5V higher than expected. While the short circuit current (I_{sh}) was measured to be about 1.25 A which is 350 mA short of the expected value of 1.6 A. This shortfall in the current level may have been a major factor in the car's outdoor performance. The low current was most likely due to the fact that there was not $1000 W/m^2$ of irradiance available outside. Assuming standard test conditions was a mistake. An adjustment for irradiance should have been made. Refer to the charts in Appendix C to get a rough idea of the different irradiance levels in different parts of the world at various times of the year.

VI.5 Modifications Effects

One of the primary reasons for building the car was to test some of the performance enhancement methods of section 5. Several temperature and irradiation methods were tested to determine which type was most effective in improving system performance.

VI.5.1 Temperature Adjustments

There were some limitations concerning what could and could not be tested. The effect of natural convection was simply reflected in the baseline electrical characteristics of the car. This was accomplished by simply placing the car under the testing apparatus and measuring the electrical characteristics as shown in figure 17.

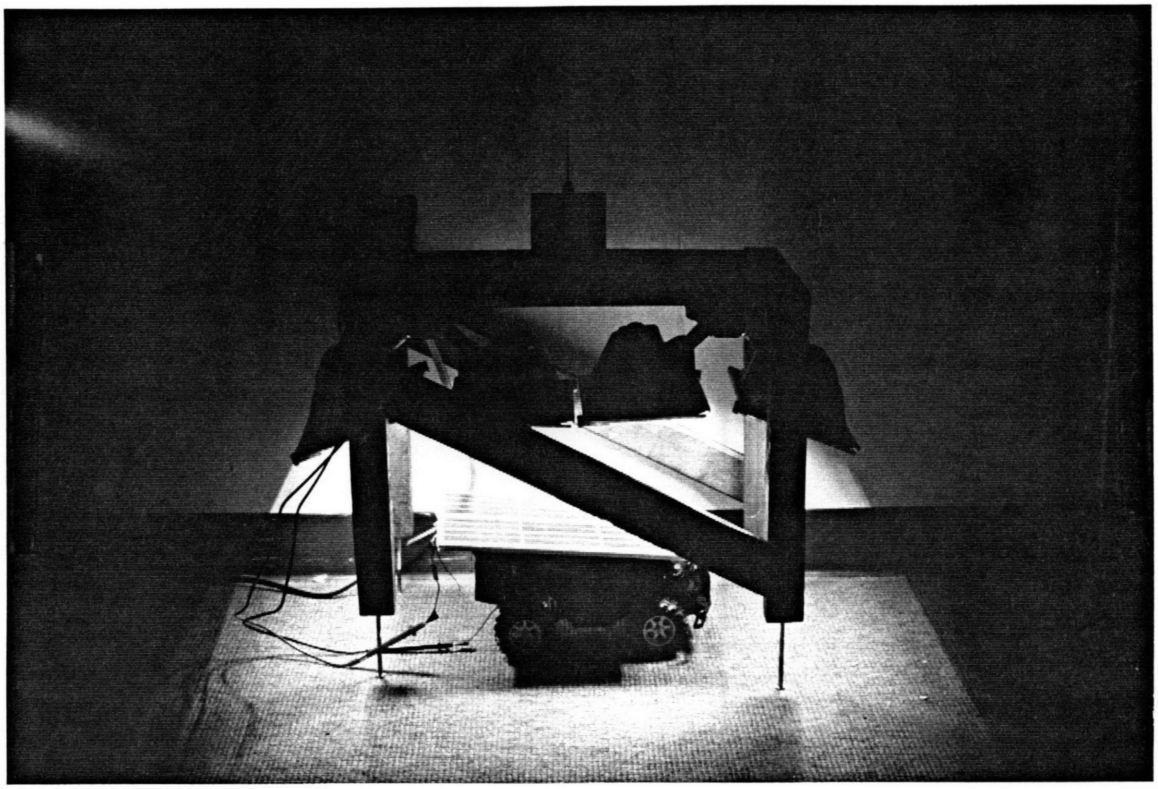


Figure 17: Halogen Testing apparatus in use.

The electrical characteristics measured were V_{oc}, I_{sh}, V_{op} and I_{op}; where I_{op} and V_{op} were the operating current and voltage. Under the baseline conditions, these parameters were measured in 20 second intervals for one minute. Measuring incrementally was done to account for the heating effect of the halogen lights. The results are listed in Appendix D.

The effect of adding fins (both under natural and forced convection conditions) could not readily be determined. The solar modules arrived pre-assembled from the manufacturer. As a result, the cells were already epoxied to foam mounting board. It would not be possible to remove these cells without damaging them in some way. To be effective, fins would have to be attached to the cells themselves because the foam board acts as an insulator and therefore does not conduct heat. A future recommendation would be to mount the cells on an aluminum wafer board. Because of aluminum's high thermal conductivity, this type of wafer board would be an quick and easy way to add a simple and effective fin system.

Forced convection was also examined but the limitations of the equipment again prevented a thorough examination of this effect. The testing apparatus (with its 1200 W of halogen lighting) generated intense heat. As a result, extremely powerful fans would be needed to effectively remove the heat added by the lights. Unfortunately, the most powerful fan at a local retailer was the only fan obtainable due to resource constraints. It did not have enough power to remove all of the heat generated by the testing apparatus quickly enough.

The car was placed under the testing apparatus with all components initially at room temperature. The variable speed fan was placed in front of the car to simulate the forced convection effect. Three different flow rates were used. The electrical characteristics were measured at 20 second intervals for one minute. The experimental setup is shown in figure 18.

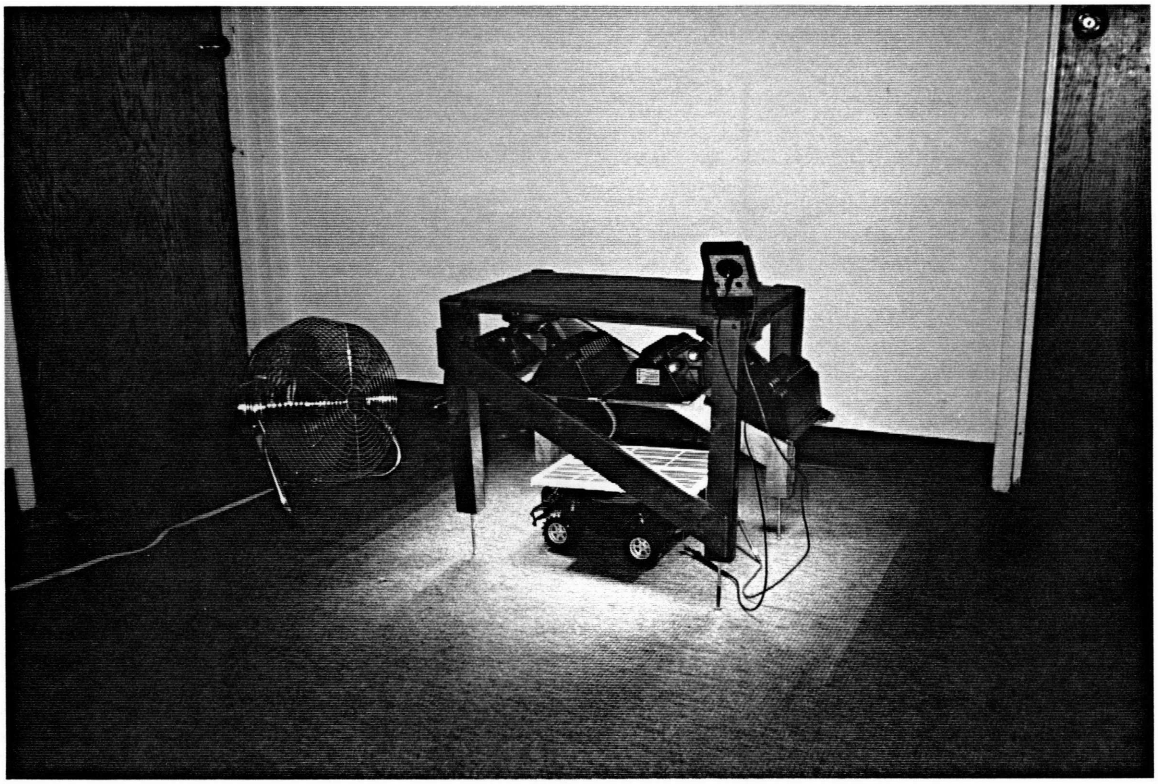


Figure 18: Forced convection experimental set up.

The fan did not seem to affect the electrical characteristics of the system in a significant way. At first, the cells were initially cooler than room temperature due to the fan. However, when the lights were turned on, the cells quickly heated up and exhibited much of the same characteristics as they did at the baseline conditions. The fan did seem to keep the V_{oc} above the baseline value within the testing time. However, this difference would probably be eliminated shortly after one minute as the cells continue to get hotter.

The problem was the intense power of the testing apparatus. It is important to interpret these results carefully. Even under intense heat (the state of the cells after one minute under the lamps), the open circuit voltage never dropped below 6.25 V. This was still well above the operating voltage of 4.11 V. At the same time that heat drive down the voltage (and shifts the I-V curve to the left), it also raises the current slightly. This is a positive effect. (Refer to figure 5 for a graphical demonstration of the heating effect) Therefore, as long as the voltage drop of the solar cells is large enough to withstand a small drop in voltage due to heat without affecting the performance of the load, cooling small systems may not be necessary.

Since outdoor radiation will not heat the cells as drastically as they were heated under the testing apparatus (and there will likely be a breeze or flow of air to help cool the cells), it can be concluded that the negative effects of heat are not significant for small systems operating in normal conditions as long as the voltage across the cells is high enough. This guideline (to account for heating losses) should be added to the design methodology. The test results are listed in Appendix D.

An effective conduction system could not be set up for the system, again because the cells were mounted on foam which acted as an insulator. Since a heat sink could not be attached to the top of the solar modules (this would impede performance), it was not possible to set up a conduction cooling system. Alternatively, the cells were initially cooled down to 0 °C by icing down the modules before being tested under the apparatus. The results of the icing process on cell performance can be found in Appendix D.

The icing process gave the cells a low initial temperature. This resulted in a dramatic increase in initial open circuit voltage. Its initial value was 7.30 V, a full 0.5 V above the baseline value. The current was at a lower value (almost 0.1 A lower). This temperature result serves to reinforce the conclusions drawn from the convection results. Even with the temperature of the cells at 0 °C (which would be very difficult to maintain by a simple cooling method on a small photovoltaic system) only served to boost the voltage by 0.5 V which does nothing for the performance of the car. It seems that the temperature effect only matters if it *lowers* the voltage to a level which impedes the performance of the car (i.e. low enough that the operating voltage does not fall on the flat part of the I-V curve). Raising the voltage any higher than the initial level (already assumed to be well above the operating value) will not help performance and is in fact an unnecessary measure. The icing results can be found in Appendix D.

VI.5.2 Irradiation Adjustments

There were several irradiation adjustments mentioned in section 5. These included module surface modification, adding reflectors and using tracking devices. Changing the module surface was not practical because the cover was epoxied on. Also, the materials and equipment necessary to develop an effective cover were not available. Experimentally attempting to use this modification method was beyond the scope of this thesis.

Similarly, incorporating a tracking device was not technically feasible. The control systems and equipment needed were beyond the available resources. The tracking system option was included because it is a common modification in practice today used to increase irradiance. Also, it would be a feasible option for a small photovoltaic system if the resources were available.

The only method that could be experimentally tested was the practice of adding concentrating devices - specifically reflectors. Two different types of reflectors were added. The first type, shown in figure 19, consisted of two rounded metallic reflectors. These were meant to simulate the compound parabolic concentrator (CPC) mentioned in section 5.

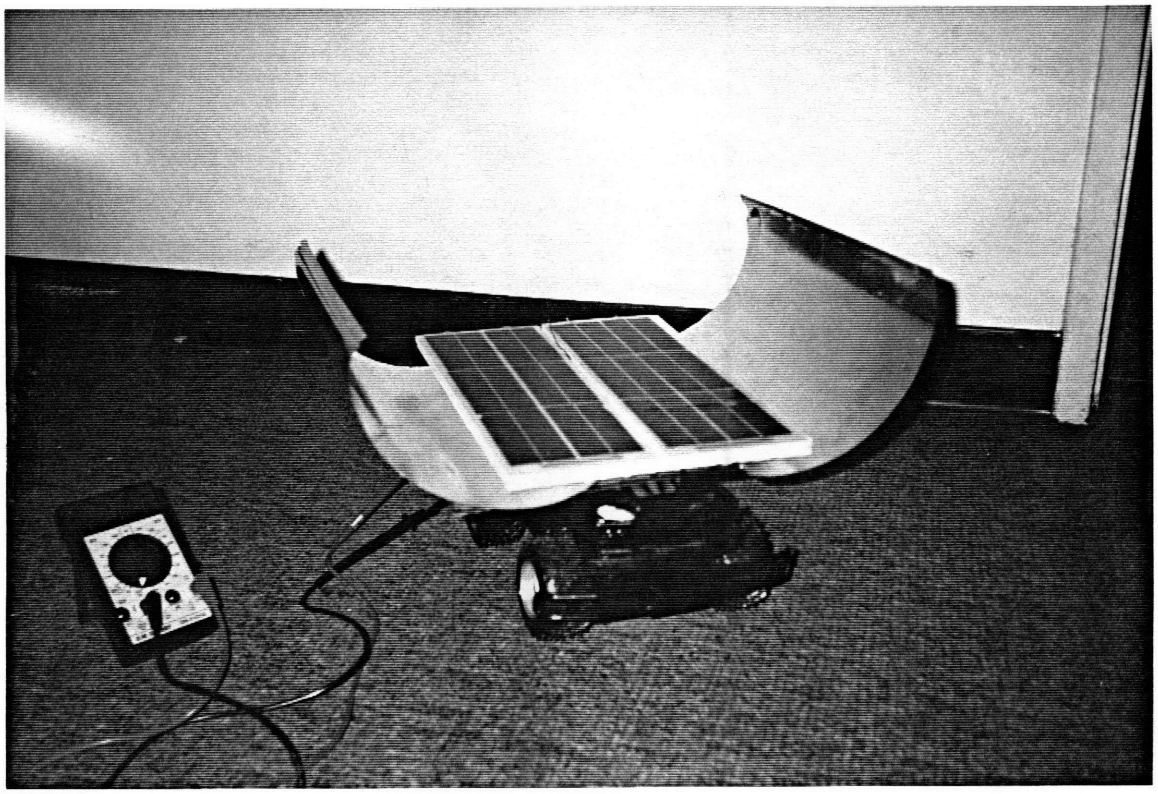


Figure 19: Car with simulated CPC reflectors.

This simulation has several problems. First, it was difficult to shape the reflectors into a perfect parabolic shape with a predictable focal point. Instead, a roughly rounded shape was used. A second, more significant problem was that in order for reflectors to be effective, it is necessary that the amplified light reaches *every cell equally* because the performance of the module is limited by the weakest cell. Therefore, if the entire module is illuminated with greatly amplified light while one cell is completely covered, the output of the module will be close to zero if the cells are connected in series. Therefore, a reflector system is only effective if it reaches every cell. Since this simulated CPC system could not be focused perfectly, its ability to improve module performance was limited.

The other type of reflector tested used was a simple, flat, white reflector positioned at an angle of about 45° on either side of the modules. Figure 20 depicts this configuration.

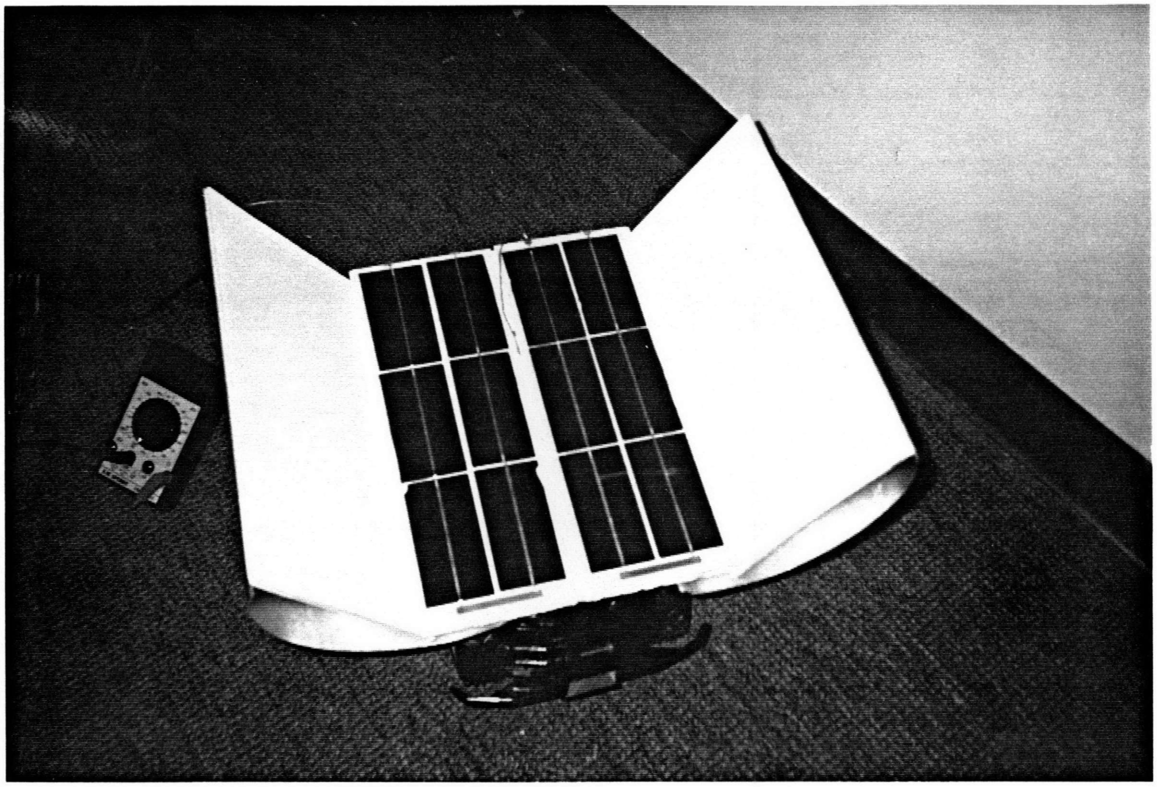


Figure 20: Car with a simple white reflector configuration.

Both configuration were tested under the using the same test methods previously described. The results are displayed in Appendix D.

These irradiation modifications raised the current levels by an appreciable amount despite the fact that they were not installed perfectly. The voltage levels remained unaffected by the reflectors, indicating that they did not contribute to any significant heating effect. Both of the observed electrical effects were expected as seen in the I-V curves shown in figure 4. The white reflectors increased the current by more than the CPC reflectors.. This was most likely due to the fact that white surfaces reflect light better than metallic surfaces. Although the reflectors were not positioned perfectly, they still increased the current significantly (see results in Appendix D) without decreasing the voltage. A current increase will directly impact performance by increasing the torque of the motor. Therefore, it seems that modifications aimed at increasing irradiation are very worthwhile.

Values of V_{oc}, I_{sh}, and I_{op} were plotted for all of the modifications. V_{op} was not plotted because it remained constant for all of the different methods. This is due to the fact that the motor required a voltage drop of approximately 4.11 V for every current load. Figures 21, 22 and 23 illustrate the plots of V_{oc}, I_{sh} and V_{op} respectively.

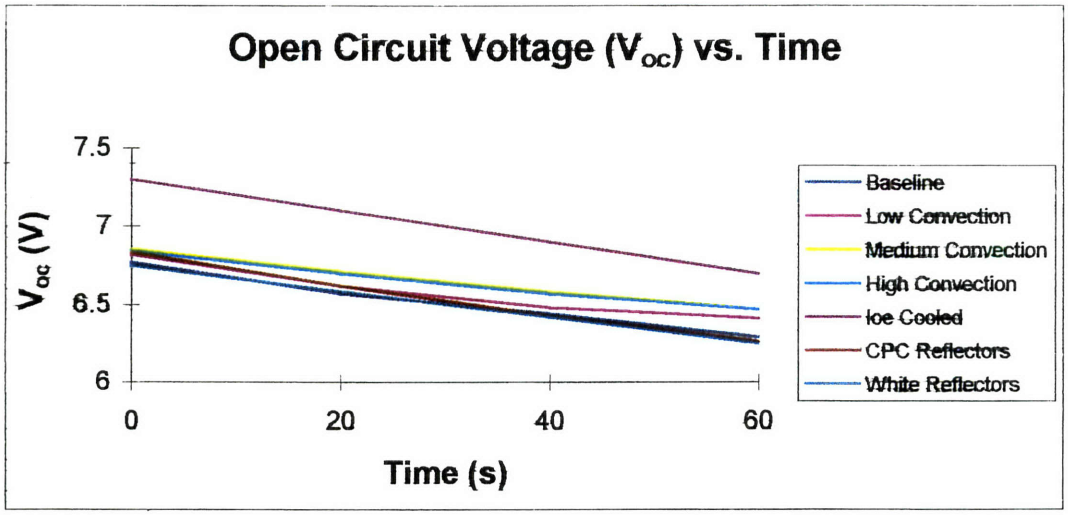


Figure 21: Modification effects on the open circuit voltage.

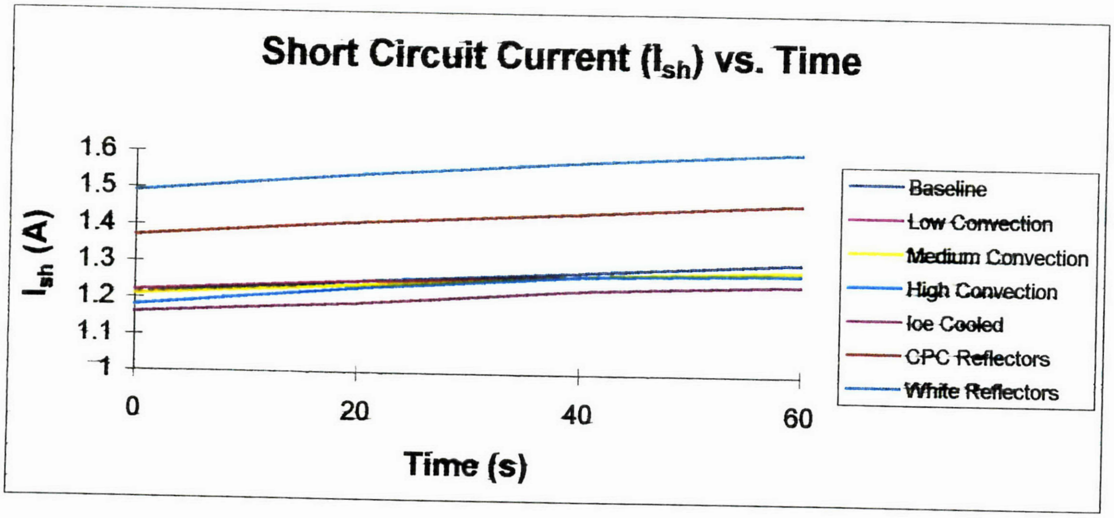


Figure 22: Modification effects on the short circuit current.

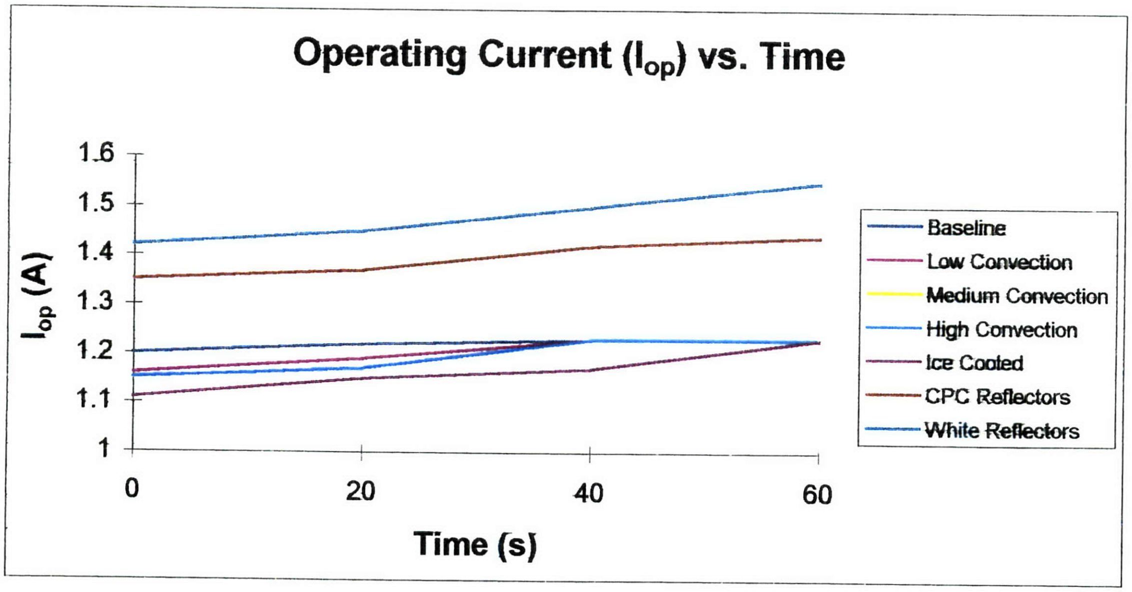


Figure 23: Modification effects on the operating current.

The graphs show that certain modifications stood out in one area or another. In the V_{oc} graph, it can be seen that the icing method increased voltage substantially. In the I_{sh} and I_{op} graphs, it can be seen that the reflectors had a big impact.

VI.6 Final Comments and Recommendations

Overall, it appeared that aside from a miscalculation, the design methodology worked well when designing the solar car. Also, although the experimental methods used to evaluate the modification effects were somewhat limited, they did serve to demonstrate that attempts at amplifying irradiation seem to have more of a direct impact on performance than do attempts at lowering cell temperature.

It is recommended that irradiation modifications be implemented in small photovoltaic systems. The negative affects of increased temperature on solar cells does not seem to pose a problem from small photovoltaic systems in normal circumstances. For future investigations, specific irradiation methods should be explored in more detail to understand which method is the most effective for which application. I would also recommend that photovoltaic systems with an energy storage element be explored in more detail since they are by far the most ubiquitous systems in use.

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http://www.melcor.com/ - Melcor Corporation - manufacturer of thermoelectric devices.

http://www.solarex.com/ - *Solarex Corporation* - largest manufacturer of solar cells in the world

http://www.powerexpress.com/ - *1-800-Batteries* - battery supplier specializing in NiCd, NiMH and Lithium batteries and related products

http://members.aol.com/photontek/photon/photon2a.html/ - *Photon Technologies* - a producer of mini-solar panels for small products

http://www.nrel.gov/research/pv/ - National Renewable Energy Laboratory
http://batteryeng.com/ - *Battery Engineering Inc.* - Manufacturer of standard and custom lithium batteries

Appendix A: Additional Information

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http://www.eren.doe.gov/ - U.S. Department of Energy - Energy Efficiency and Renewable Energy Network (EREN)

http://solstice.crest.org/ - Center for Renewable Energy and Sustainable Technology

http://www.ncdc.noaa.gov/ - National Climactic Data Center - Provides on-line data about climactic conditions worldwide

http://isesnt.ises.org:8888/solarinforvs.nsf - International Solar Engineering Society - Information on renewable technologies

http://www.pvpower.com/ - PV Power resource site

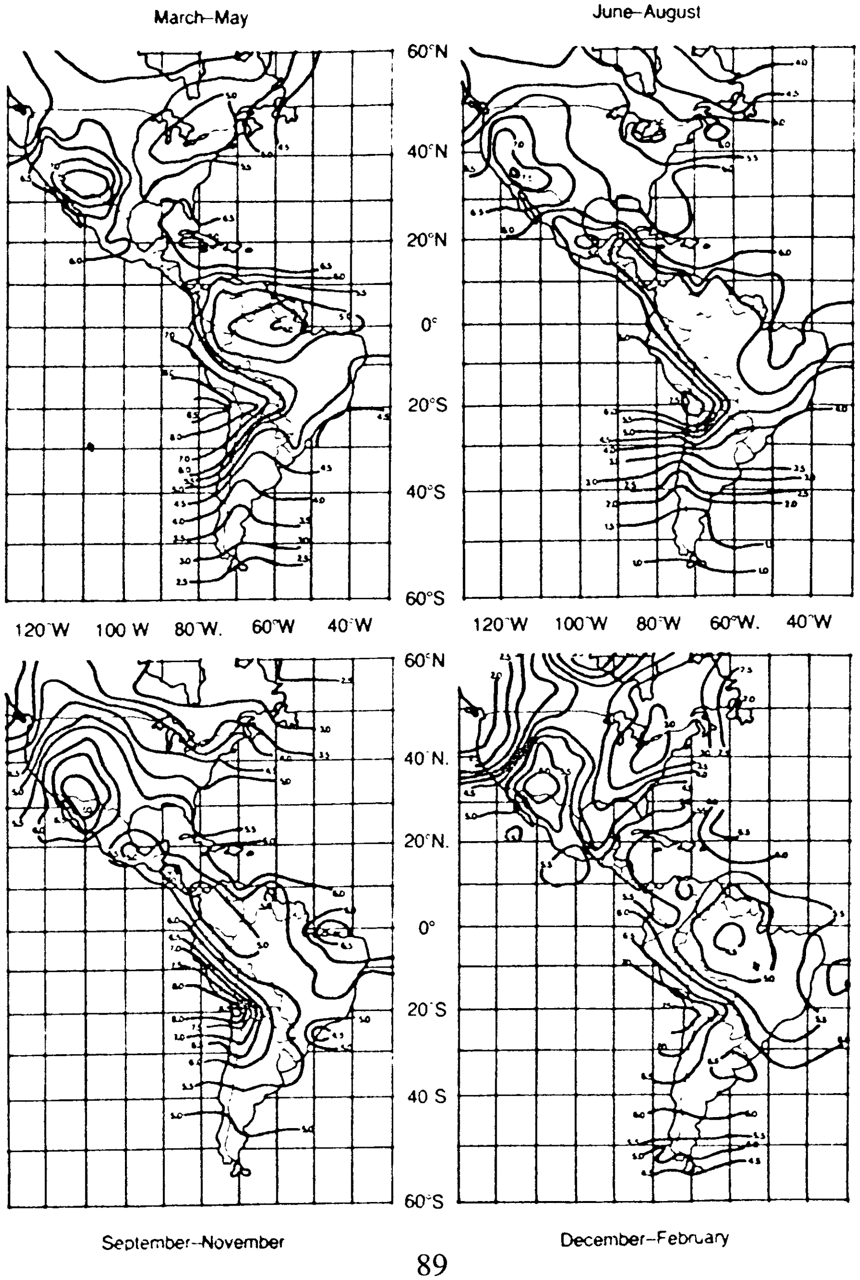
http://www.yessolar.com/ - *Yessolar, Inc.* - Producer of small solar-powered products

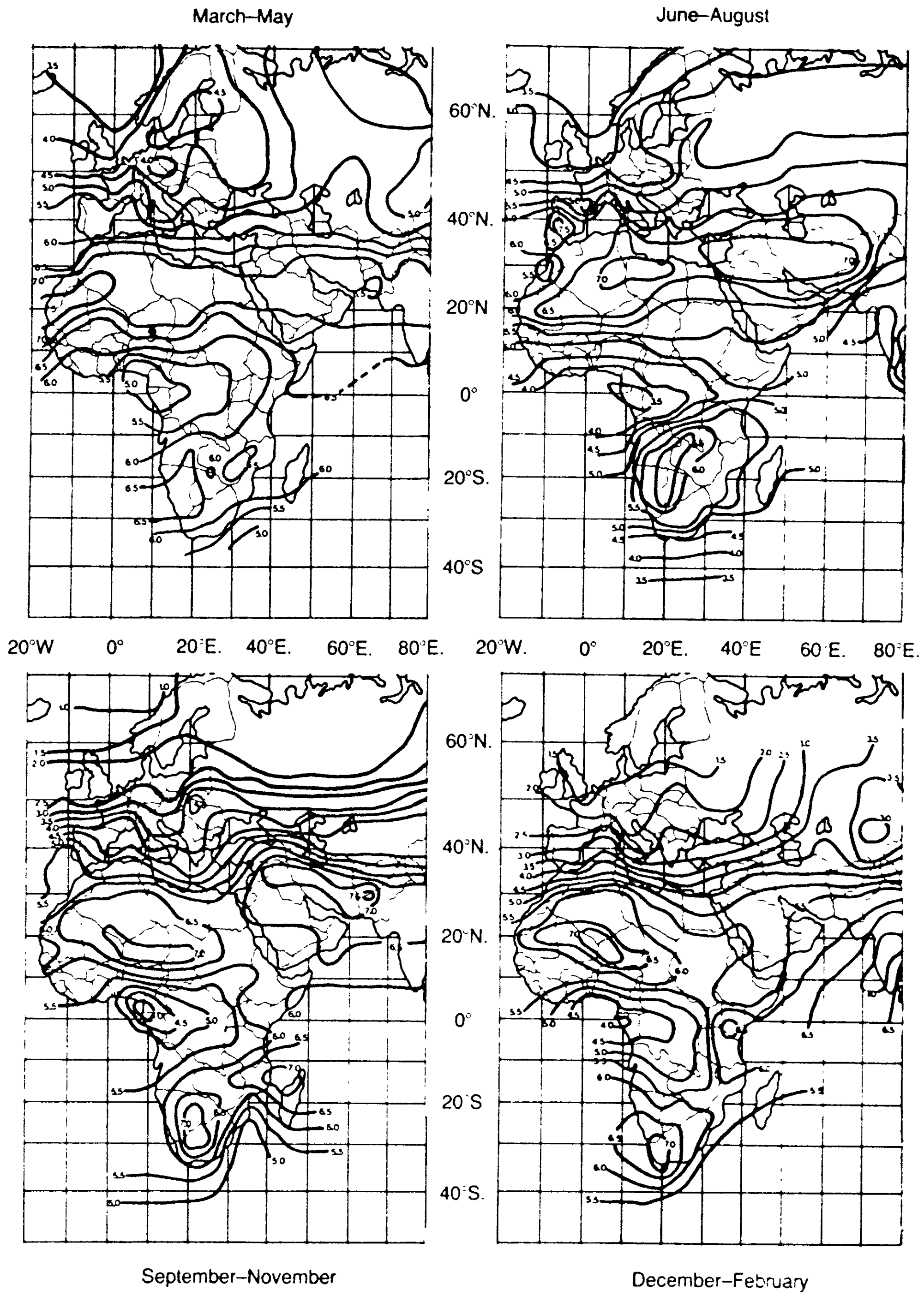
Appendix B: Small Photovoltaic Applications

Large Battery Maintenance (trickle charging)
Two way Radio
Security Intrusion Detection
Lawn Mower (shed mounted battery trickle charger)
Cellular Phones
Recharging for lights, Speedometer, Radio etc. for Bicycles
Hand-Held Radios
Portable Microwave
Remote Cordless Phone
Security Microwave Sensors
Security Intrusion Detection
Remote Camera
Traffic Control Lights
Bug Killer
Automatic Window Shading Skylights
Security/Lawn Lights
Electric Screw Driver
Flashlight
Drill
Fan (inside automobile)
Gate Opener
Construction
Soldering Iron Etc.
Outdoor Refrigeration (Cooler)
Window Mounted Fans, Sunroof Mounted
Notebook Computer
Radar Detector
Trunk Mounted to Keep Emergency Supplies Charged (Flashlight, Transmitters, etc.)
Backpack Battery Charging
Lantern
Water Purifier
Christmas Lights
General Battery Charger
Exterior Clock
Portable CD Players
Portable Tape Recorder
Portable TV
Camera
Video Camera
Emergency Air Pump
Radio Controlled Cars
Radio Controlled Boats
Radio Controlled Planes and Helicopters

Appendix C: Average Daily Insolation Maps

The following maps illustrate the average daily insolation for most countries in the world for four different periods per year. The numbers represent the peak hours per day. On average, this is the number of total hours per day that this region receives the STC irradiance described in section 2. This standard irradiance is 1000 W/m^2. The average number of hours is particularly useful for systems with an energy storage device. For direct drive systems, an average daily irradiance may be more useful. A rough estimate can be made by taking the average number of hours and multiply this value by 1/10th the STC irradiance which gives us 100 W/m^2. The usefulness of this approximation is limited when considering direct drive systems because irradiance varies throughout the day. (Roberts, 175-177)



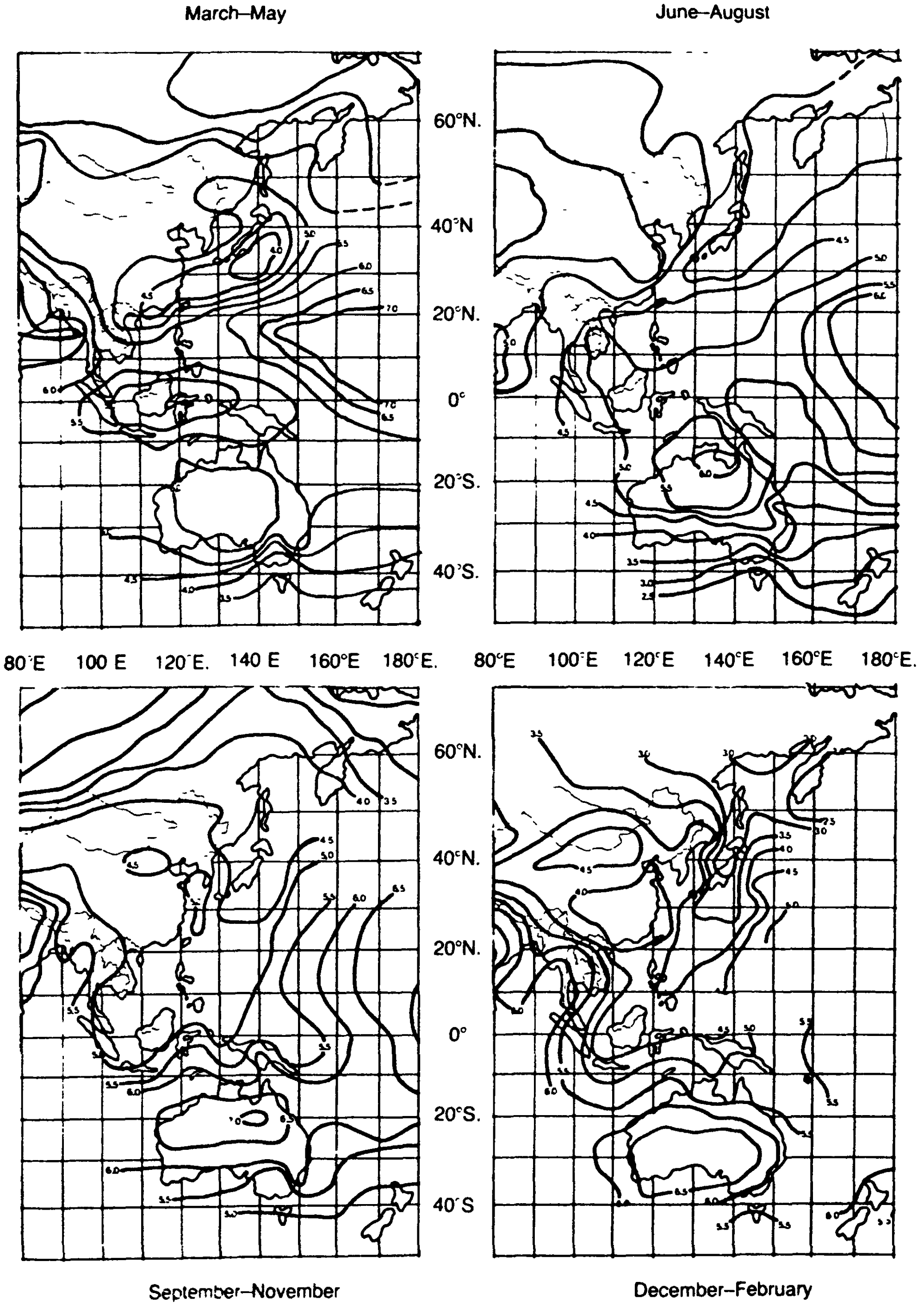


March–May

June–August

September–November

December–February


March–May
June–August
60°N.
40°N
20°N.
0°
20°S.
40°S.
80°E
100 E
120°E.
140 E
160°E
180°E.
80°E
100°E
120°E
140°E
160°E
180°E.
60°N.
40°N.
20°N.
0°
20°S.
40°S
September–November
December–February

Appendix D: Experimental Results

The experimental results for the modification effects tested in section 6 are listed below. A discussion of the results can be found in section 6.

BASELINE

	0 s	**20 s**	**40 s**	**60 s**
V_{oc} (V)	6.77	6.57	6.44	6.29
I_{sh} (A)	1.21	1.25	1.28	1.31
V_{op} (V)	4.11	4.11	4.11	4.11
I_{op} (A)	1.20	1.22	1.23	1.23

FORCED CONVECTION.

Low Flow Rate

	0 s	**20 s**	**40 s**	**60 s**
V_{oc} (V)	6.82	6.62	6.48	6.41
I_{sh} (A)	1.22	1.25	1.27	1.29
V_{op} (V)	4.11	4.11	4.11	4.11
I_{op}(A)	1.16	1.19	1.23	1.23

Medium Flow Rate

	0 s	**20 s**	**40 s**	**60 s**
V_{oc} (V)	6.85	6.71	6.58	6.47
I_{sh} (A)	1.21	1.24	1.27	1.29
V_{op} (V)	4.11	4.11	4.11	4.11
I_{op}(A)	1.15	1.17	1.23	1.23

High Flow Rate

	0 s	**20 s**	**40 s**	**60 s**
V_{oc} (V)	6.84	6.70	6.57	6.47
I_{sh} (A)	1.18	1.23	1.27	1.28
V_{op} (V)	4.11	4.11	4.11	4.11
I_{op}(A)	1.15	1.17	1.23	1.23

ICE COOLED

	0 s	**20 s**	**40 s**	**60 s**
V_{oc} (V)	7.35	7.10	6.90	6.70
I_{sh} (A)	1.16	1.19	1.23	1.25
V_{op} (V)	4.11	4.11	4.11	4.11
I_{op} (A)	1.11	1.15	1.17	1.23

CPC SIMULATED REFLECTORS

	0 s	**20 s**	**40 s**	**60 s**
V_{oc} (V)	6.83	6.62	6.43	6.26
I_{sh} (A)	1.37	1.41	1.44	1.47
V_{op} (V)	4.11	4.11	4.11	4.11
I_{op} (A)	1.34	1.36	1.41	1.43

WHITE REFLECTORS

	0 s	**20 s**	**40 s**	**60 s**
V_{oc} (V)	6.75	6.58	6.42	6.25
I_{sh} (A)	4.11	4.11	4.11	4.11
V_{op} (V)	1.49	1.54	1.58	1.61
I_{op} (A)	1.42	1.45	1.50	1.55