

A REVIEW OF INTERNATIONAL AND LOCAL DEVELOPMENTS IN
PHOTOVOLTAIC TECHNOLOGY AND ECONOMICS FOR DEVELOPING AREAS

by

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at the University of Cape Town in partial fulfillment
for the Degree of Master of Science in Engineering

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DECLARATION

I, David John Sinclair, declare that this thesis is my own original work and is being submitted in partial fulfillment for the degree of Master of Science in Engineering. It has not been submitted before in this or any other form for any degree or examination at any University.

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...10th day of...May....1989

ABSTRACT

The experiences with photovoltaic systems in developing areas in the Third World, generally, and in South Africa, in particular, are assessed with respect to technical and economic performance. Literature on international developments in photovoltaic technology and markets and on applications in the Third World is reviewed. The results of photovoltaic demonstration projects in South Africa are discussed and implications are drawn in terms of improved system design methodologies. The costs of local photovoltaic applications are compared with petrol and diesel generators. Finally, recommendations are made for further research in areas relevant to systems applications in South Africa.

TABLE OF CONTENTS

ABSTRACT.....(iv)

1. INTRODUCTION

1.1 Objectives.....1

1.2 Background Rationale.....1

1.3 Key questions.....3

1.4 Outline of the report3

2. INTERNATIONAL DEVELOPMENTS IN PHOTOVOLTAIC TECHNOLOGY AND ECONOMICS

2.1 Introduction.....5

2.2 History of the development of photovoltaic technology....7

2.3 Production technologies.....14

2.3.1 Silicon refining.....14

2.3.2 Cell production.....16

2.3.2.1 Single-crystal Silicon cells.....17

2.3.2.2 Polycrystalline cells.....22

2.3.2.3 Thin films.....27

2.3.2.4 Cascade cells.....34

2.3.2.5 Concentrator systems.....37

2.3.2.6 Summary of solar cell types38

2.3.3 Fabrication of cells and modules.....41

2.3.3.1 Processing wafers into solar cells.....42

2.3.3.2 Wafer preparation.....43

2.4 Discussion of cell efficiencies.....47

2.4.1 Summary of efficiencies.....52

2.4.2 Small and large area efficiency.....53

2.4.3 Conclusion.....54

2.5	Photovoltaic module production.....	55
2.5.1	Total production.....	55
2.5.2	Production by technology.....	56
2.5.3	Output of photovoltaics according to country.....	59
2.5.4	Production by company.....	61
2.5.5	Summary of major trends (1980-1987).....	65
2.6	Photovoltaic economics.....	66
2.6.1	Historical trends.....	66
2.6.2	Future trends.....	70
2.6.3	South African PV prices.....	71
2.6.4	Cost versus efficiency.....	73
2.6.5	Cost comparisons with alternatives.....	73
2.7	Future prospects.....	75
3.	<u>PHOTOVOLTAIC APPLICATIONS IN THE THIRD WORLD</u>	
3.1	Introduction.....	79
3.2	Technical review.....	80
3.2.1	Water pumping.....	80
3.2.1.1	Technical considerations.....	81
3.2.1.2	Field experience.....	82
3.2.1.3	Survey reports.....	83
3.2.2	Communications.....	86
3.2.2.1	Technical considerations.....	87
3.2.2.2	Field experience.....	88
3.2.2.3	Survey reports	88
3.2.3	Vaccine refrigeration.....	90
3.2.3.1	Technical considerations.....	90
3.2.3.2	Field experience.....	91
3.2.3.4	Survey reports.....	92
3.2.4	Lighting and home power.....	94
3.2.4.1	Technical considerations.....	95
3.2.4.2	Field experience.....	96
3.2.4.3	Survey reports.....	96
3.2.5	Multi-use systems.....	98
3.2.5.1	Technical considerations.....	99
3.2.5.2	Field experience.....	101
3.2.5.3	Survey reports.....	102

3.3	Financial analysis.....	103
3.3.1	Common base case assumption.....	104
3.3.2	Water pumps.....	108
3.3.3	Communications.....	110
3.3.4	Vaccine refrigeration.....	112
3.3.5	Lighting and home power.....	114
3.3.6	Multi-use systems.....	116
3.3.7	Summary of sensitivity analysis.....	119
3.4	Institutional factors.....	121
3.4.1	Key institutional issues.....	121
3.5	Summary.....	123
3.5.1	General conclusions.....	123
3.5.2	Conclusions specific to each application.....	124
3.5.2.1	Water pumping.....	124
3.5.2.2	Communications.....	124
3.5.2.3	Vaccine refrigeration	125
3.5.2.4	Lighting and home power.....	125
3.5.2.5	Multi use systems.....	126
3.5.3	Recommendations.....	127

4. TECHNICAL AND INSTITUTIONAL ASPECTS OF PHOTOVOLTAIC APPLICATIONS IN DEVELOPING AREAS IN SOUTHERN AFRICA

4.1	Introduction.....	128
4.2	First world PV applications	128
4.3	Third world PV applications.....	130
4.4	PV demonstration projects in developing areas in South Africa.....	131
4.4.1	Home power.....	132
4.4.1.1	Uitsig.....	132
4.4.1.2	Omdraaisvlei.....	135
4.4.1.3	Uitsig and Omdraaisvlei assessed.....	136
4.4.2	The Bophuthatswanan "Edutel" project.....	137
4.4.3	Health Care / Vaccine Refrigeration.....	144
4.4.4	The Sondela water pumping project.....	146
4.4.4.1	Comparative financial analysis.....	147
4.4.4.2	Institutional factors.....	149

4.5	Discussion	151
4.5.1	Technical issues.....	151
4.5.2	Institutional issues.....	160
4.5.3	Financing.....	162
4.6	Conclusions.....	163
5.	<u>THE ECONOMICS OF PHOTOVOLTAIC APPLICATIONS IN</u> <u>DEVELOPING AREAS OF SOUTHERN AFRICA</u>	
5.1	Introduction.....	164
5.2	Costing methodology.....	165
5.2.1	Comparative methods.....	165
5.2.2	Life cycle cost analysis.....	167
5.2.3	General assumptions.....	171
5.3	PV electricity costs	172
5.3.1	Key variables.....	172
5.3.1.1	PV system size.....	174
5.3.2	PV system cost comparison with size.....	176
5.3.3	PV System costs versus module price.....	177
5.3.4	PV system costs versus solar radiation.....	178
5.3.5	PV System costs versus discount rate.....	179
5.3.6	PV System costs versus battery type.....	181
5.4	Costs of conventional alternatives.....	181
5.4.1	Key factors affecting costs.....	182
5.4.2	Paraffin lamps.....	183
5.4.2.1	Photovoltaic system and paraffin lamp compared.	183
5.4.3	Petrol generators.....	185
5.4.3.1	Petrol genset system assumptions.....	185
5.4.3.2	Petrol genset costs.....	186
5.4.4	Diesel generators.....	189
5.5	Cost comparison of PV to alternatives.....	192

6. RECOMMENDATIONS AND CONCLUSIONS

6.1 Introduction.....195
6.2 Developing country applications.....196
6.3 Southern African applications.....198
 6.3.1 Technical issues..... 199
 6.3.2 Institutional/Social issues.....202
 6.3.3 Economics of Southern African PV applications....202
6.4 Recommendations.....204
 6.4.1 PV system design.....204
 6.4.2 Batteries.....205
 6.4.3 Regulators.....205
 6.4.4 PV Modules.....205
 6.4.5 Solar radiation data.....205
 6.4.6 Hybrid systems..... 206
 6.4.7 Institutional finance..... 206
6.5 Conclusion..... 206

APPENDICES

A.1 PV sizing methodology.....209

B.1 Mean total monthly/annual radiation - kWh/m²/ month....221

C.1 PV system costs.....222
 C.1.1 Small system..... (0,0366 kWh/day).....222
 C.1.2 Medium home system.(0,366 kWh/day)229
 C.1.3 Large home system..(37,5 kWh/day).....231
 C.1.4 Community center...(400 kWh/day).....233

D.1 Paraffin lamp and Petrol Generator Costs.....235
 D.1.1 Paraffin lamp life cycle costs.....235
 D.1.2 Petrol genset annualized electricity cost.....236

E.1 Brochures from firms offering PV systems.....243

REFERENCES AND BIBLIOGRAPHY.....251

CHAPTER ONE

INTRODUCTION

1.1 OBJECTIVES

The overall aim of this report is to assess the technical and economic performance of photovoltaic systems in the Third World generally and in South Africa in particular.

Photovoltaics are semi-conductor devices which convert sunlight directly into electricity. There have been significant technological and economic advances in recent years and photovoltaic systems are beginning to be used effectively for remote area power supply applications. One of the largest potential markets for photovoltaics is in developing areas which do not have established electricity grid systems.

1.2 BACKGROUND RATIONALE

The energy needs of vast numbers of the population of rural areas of Southern Africa (and elsewhere in the Third World) are met by the use of fuels such as wood, charcoal, coal, paraffin and candles. Small electrical requirements are often met by batteries. Surveys undertaken have shown clearly that the people concerned would prefer to have the use of grid electricity, perceiving it as a convenient, clean, effective and smoke free source of power (Eberhard, 1986a).

The provision of grid electricity to remote areas is often cited as being too expensive an undertaking. Although Eskom (the electricity generating authority in S.A.) has the policy of extending the national grid to such areas the possibility of completing this task in the present climate of financial restraint is remote. Nevertheless the demand for electricity exists at all levels, ranging from individual homes to whole communities. The question arises as to how such a requirement may be economically satisfied.

The use of petrol and diesel gensets in remote areas is, at present, a common method of overcoming the lack of a grid supply. These units have the advantage of being available in a range of power outputs, of being transportable (at least in the smaller sizes) and of using fuels which are normally obtainable. They suffer the disadvantages of being noisy, producing unpleasant fumes, requiring specialised maintenance which is often difficult to arrange in remote areas and, as will be shown later in this report, of providing electricity at a cost which can often be higher than anticipated.

Photovoltaics, by contrast, are largely maintenance free and are ideally suited for small decentralised remote area power supply. Costs have fallen dramatically in recent years and new generation technologies are resulting in much improved efficiencies. Photovoltaics have begun to be used extensively in the Third World, and it is important that this experience be monitored and its relevance for South Africa assessed.

In addition, the Energy Research Institute of the University of Cape Town has been monitoring the performance of four PV applications - one for water pumping, another for powering lights and audio-visual equipment at a rural school and two for providing minimum electrical requirements for low income housing. There has been need to assess this experience as a whole and to relate it to current and future applications.

1.3 KEY QUESTIONS

Specific questions to be addressed in this report are:

- (i) What has been the general assessment of the technical and economic performance of PV systems in Third World areas?
- (ii) How successful are current photovoltaic applications in developing areas in South Africa in terms of meeting specified loads in a cost-effective and reliable manner?
- (iii) What are the implications of international advances in PV technology, economics and applications for the potential of photovoltaics in South Africa?
- (iv) Based on international and local experience, what further areas of photovoltaic systems related research needs to be undertaken locally?

1.4 OUTLINE OF THE REPORT

Any assessment of the potential of photovoltaics requires an understanding of international developments in photovoltaic technology and economics. Chapter Two provides a history of developments in photovoltaic technology. Various types of photovoltaic cells are described and improvements in cell efficiencies are discussed. An overview of the international PV market is presented in terms of production volumes, cost trends and likely future prospects

The main focus of this report is photovoltaic applications in developing areas. In recent years there have been a number of studies of photovoltaic projects in the Third World which have included detailed technical and economic performance data. These are summarized in Chapter Three. Four main applications are examined: water pumping; telecommunications; vaccine refrigeration; and lighting and home power. In each case the technical and institutional lessons from field experience are noted and a financial evaluation is undertaken which compares photovoltaics with conventionally used alternatives such as diesel power.

Photovoltaics (PV) are also beginning to find application in South Africa, Chapter four describes the particular uses of PV systems in the South African context. The E.R.I. demonstration projects are discussed: Uitsig and Omdraaisvlei for home power; the Edutel project in Bophutatswana for educational aids; the Sondela project for water pumping, and in addition, the Ciskei project for vaccine storage. The technical and social experience from these projects is assessed.

Chapter Five investigates the economics of PV applications in the Southern African context. The various methods of costing are presented with a full description of the favoured method chosen for this report viz. Life Cycle Costing (LCC). The costing of a wide range of PV systems is then presented with appropriate sensitivity analysis undertaken. Costs of conventional alternatives are assessed in the appropriate power ranges. Finally, a chart is obtained which shows the most economic choice for different load ranges.

Chapter Six concludes the above by drawing together the information assessed and presents recommendations and conclusions appropriate to the use of PV systems in remote and rural areas of Southern Africa.

CHAPTER TWO

INTERNATIONAL DEVELOPMENTS IN PHOTOVOLTAIC TECHNOLOGY
AND ECONOMICS

2.1 INTRODUCTION

The viability and potential of photovoltaics for power production is largely dependent on the extent to which the cost of the fabrication of cells will continue to fall. There have been significant technological advances in photovoltaics over the past decade which have resulted in significant cost reductions. This chapter outlines the major developments in photovoltaic technology and production and looks at likely future trends.

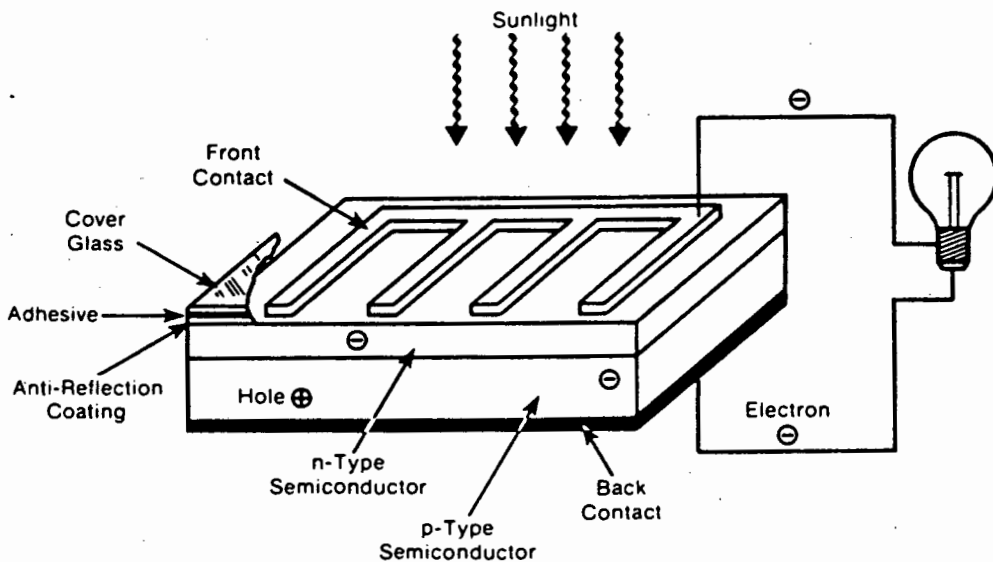


Figure 2.1 Schematic of a solar cell.

Source: SERI, 1985, p2

Photovoltaics or solar cells are devices which convert the

energy of sunlight directly into electricity. Many types are available, and are described later in this chapter, but they all work on the same principle: a photon of light reaches an electron in a semi-conductor material and gives it energy. The electron, under the impetus of this extra energy, is freed from its bound state in the valence band of the molecule and moves into the conduction band. The effect is to create a supply of free electrons together with what are known as 'electron holes'. A junction formed between dissimilarly doped semiconductor layers sets up a potential barrier in the cell, creating a voltage which induces an electric current. The electricity is collected and transported by metallic contacts placed in a grid-like fashion in the surface of the cell.

Silicon is the most widely used cell material, although several other substances are in use and are being experimented with. The photovoltaic industry is in constant search for new and better materials, some of those used so far being: Gallium Arsenide, Cadmium Sulphide, Copper Sulphide, Indium Phosphide, Cadmium Telluride and Copper Indium Diselenide; but all of the latter materials are more expensive than silicon. The cells are fabricated into modules and then combined into 'arrays' of varying sizes.

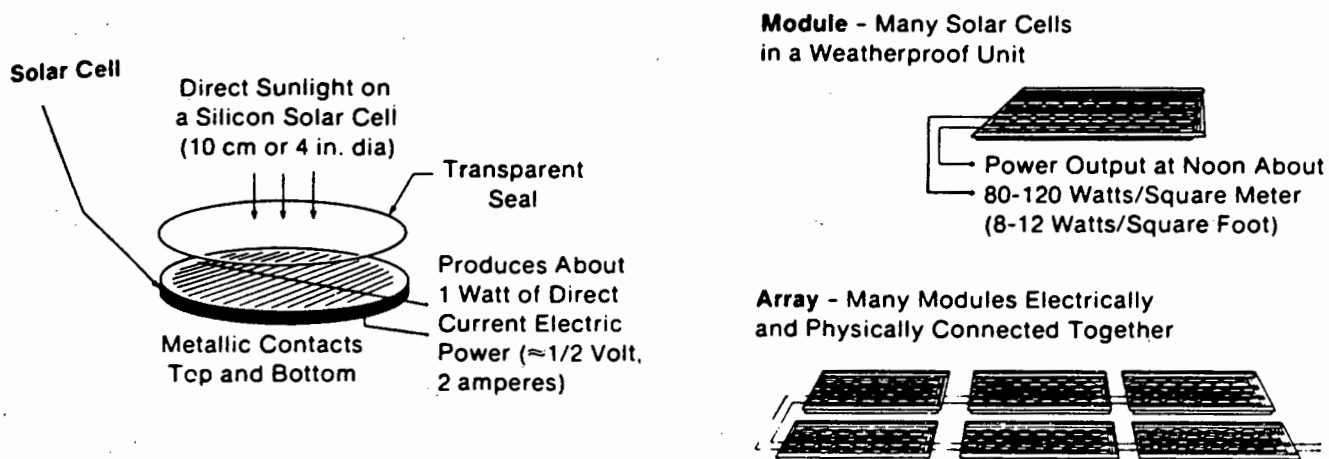


Figure 2.2 Solar cell, module and array.

Source: SERI, 1985, p3

Modules are typically rated in peak power expressed in peak watts (W_p). Peak power is, loosely speaking, the amount of power produced by the module at noon on a clear day with the collector faced directly towards the sun. More precisely, it is the amount of power produced at standard test conditions (STC): viz. cell temperature of 25°C and a solar radiation intensity of 1000 W/m^2 .

The photovoltaic array is erected in a suitable position and inclination so as to catch as much of the solar radiation as is possible, and then converts this sunlight directly to electricity. The efficiency of this operation has been one of the main concerns of engineers since photovoltaics became feasible alternatives for power production.

Rapid technological advances have resulted in new manufacturing techniques, improved efficiencies and falling costs so that photovoltaics are increasingly becoming cost effective with other electricity producing technologies and hold great promise for widespread application in the years ahead.

2.2 HISTORY OF THE DEVELOPMENT OF PHOTOVOLTAIC TECHNOLOGY

The photovoltaic effect was first observed in 1839. At this time a nineteen year old French Physicist, Edmund Becquerel, happened to note that a voltage was produced when one of two metal electrodes in a conducting solution was illuminated. Nothing was made of this effect until the 1870's when in 1873 Willoughby Smith discovered photoconductivity in selenium. This led to a number of discoveries finally resulting in the observation by Adams and Day in 1876 of the photovoltaic effect in a solid state selenium structure, triumphantly reported to the Royal Society in June of that year.

By the 1880's the first selenium photovoltaic cells were being made and producing efficiencies of between 1-2%. These cells were quickly adopted by the emerging photographic industry as they were (and are) particularly suited to visible light changes. They are still used for photometric devices and light meters in cameras, to this day.

These early inventors may well have thought they had a viable competitor to the Dynamo for the production of electricity. However, as it turned out, the high cost and low theoretical efficiency of the selenium cell precluded its use for power applications. Little, at this stage, was understood of the basic physics involved. Significant advances in cell technology had to wait until the concepts of quantum mechanics were demonstrated and hence the theoretical foundations for the present understanding of photovoltaics established

Together with this theoretical advance came the Czochralski method of producing wafers of silicon. The technique led, in 1941, to the development of a single-crystal silicon photovoltaic 'device' at Bell laboratories. Nevertheless, significant improvements in efficiency still eluded researchers until Bell Telephone Laboratories, in their search for better rectifiers, found that adding impurities to silicon improved its electrical efficiency. When the silicon rectifier was exposed to light, a surprisingly strong current was generated.

The method of impurity diffusion had been stumbled upon and as a consequence the efficiency of the cells began to increase dramatically. By 1954 6% had been obtained. By 1958 further improvements had been achieved and the Hoffman Electronics Corporation reported 14% efficiency. Also in 1958 the Bell Telephone company tested a photovoltaic array on a telephone pole in Georgia to power a repeater amplifier, and reported that it worked well for over a year, although it could not compete with other conventional systems when it came to costing.

And there things may have rested but for the launching of Sputnik in October 1957, when the United States became embroiled in a space race with the Soviet Union. By March 1958 the satellite, Vanguard 1, carried on board a small photovoltaic array, which provided power for more than six years. The success of this array meant that future developments of the system would continue under the auspices of NASA. And until the mid 1970's the market for photovoltaics was for space projects. Advances were made in the areas of efficiency, reliability and costs. But terrestrial applications were limited, in large part due to the inability of photovoltaics systems to compete financially with conventional power sources. Hence from a terrestrial point of view PV systems were relegated to the position of supplying electricity for small power applications, usually in remote areas where the cost of extending the power line or installing a diesel generating set would have been prohibitive.

The Japanese began their preliminary research in the early sixties. By 1973 some 720 photovoltaic systems had been installed with a total array output of 13 kilowatts. Half of these were installed in lighthouses with the remainder finding land applications. "The Sunshine Project" was instituted in 1974 and involved considerable R&D in solar energy technology. By 1985 a 1 megawatt plant, built by the New Energy Development Organization, was in operation. Emphasis was given to the consumer market, with development focussing on the applications for watches and calculators, which are now commonplace, using amorphous silicon cells in place of batteries.

In the Soviet Union photovoltaics were found to be especially advantageous in the remote, semi-arid South Eastern areas of that country. From the late sixties, a variety of systems have been installed ranging in size from 1 to 500 watts. Use includes irrigation pumps, water gates, communications equipment and lights on buoys.

Early research in the U.S.A. and the U.S.S.R. to determine the optimum material for solar cells progressed along different lines. The U.S. favoured n-type silicon whilst the Russians favoured p-type, because it was cheaper in the U.S.S.R. and because it contrasted with the scientific work in the U.S.A. However the discovery of the Van Allen belts and the realization that cells made from p-type silicon were more resistant to the effects of radiation, caused the U.S.A. to turn, after 1960, to cells produced by diffusion of n-layers into p-type silicon.

Between 1961 and 1971 no major progress was reported in solar cell technology but in 1972 a 30% increase in efficiency was achieved in state-of-the-art space cells by critical examination of the existing theories, by increasing the cell's blue response, by decreasing the internal resistance of the cell (to about 0,05 ohms) and by improving the charge carrier collection process.

The energy crisis of the 1970's, with the oil embargo on the U.S.A., spurred congress to initiate programs to develop alternative forms of energy. The U.S. Department of Energy was formed out of a growing awareness of the limitations in fossil fuel resources. Legislation was enacted giving clear aims and goals for photovoltaic systems and various other alternative technologies. Although the final costs set by this legislation per peak watt of photovoltaic power have not been met as yet, there is no doubt as to the very real advances that have occurred since then in photovoltaic technology. Efficiencies achieved in the laboratory have recently exceeded those which were thought previously to be theoretically possible.

During the mid-seventies much effort and research was applied to lowering fabrication costs so as to allow solar cells to become competitive for terrestrial applications. The main thrust of this effort went into growing larger silicon crystals and improving cutting techniques. By 1977 it was apparent that this approach had also to be combined with producing cells of higher efficiency. It was found, for instance, that larger cells exhibited lower efficiency than smaller cells. Research in the field of concentrating systems did not produce sufficient trade-off potential at that time, though this technology has shown greater potential since. The newer materials in use in the 1980's, particularly amorphous silicon and gallium arsenide, combined with newer technologies such as thin film and stacked cells, offer a good possibility for cost reduction in the future to enable solar cells to compete with conventional forms of electricity production.

The largest solar plant now in operation is at Carrisa Plains in California. Built in less than a year, it provides 6,4 megawatts of peak power to the electricity grid (Amaro, 1986, p41.5).

U.S. Federal spending on PV research reached a peak in 1980 of 150 million dollars after which funding for all alternative forms of energy waned as oil became plentiful and cheap again. By 1987 federal money available for photovoltaics had fallen to 40,4 million dollars.

The tail-off of U.S. government spending on photovoltaic R&D as instanced above, is a trend followed by some countries only. Many, as illustrated below in table 2.1, have begun to increase their spending.

As Hamakawa points out (1987, p81) the thrust of the worlds effort has been to increase the efficiency to above 15%, to reduce module cost to below 50\$ per square meter and to ensure durability for 30 year periods for outdoor installations.

COUNTRY	YEAR				
	1980	1983	1984	1985	1986
Australia	1,08	-	2,10	-	
Austria	0,83	0,15	0,21	0,62	
Belgium	0,37	1,42	1,64	2,23	1,59
Canada	0,86	2,60	3,92	3,29	1,15
Denmark	0,04	0,00	0,00	0,00	
Germany	38,12	39,95	20,76	18,10	27,62
Greece	0,47	0,00	1,04	1,35	3,57
Ireland	0,07	0,00	0,00	0,01	
Italy	6,74	9,23	38,99	6,04	8,08
Japan	10,08	27,60	33,52	35,19	44,32
Netherlands	3,02	0,00	0,00	0,00	1,92
New Zealand	0,00	0,00	0,00	0,00	
Norway	0,00	0,00	0,00	0,00	
Portugal	0,00	0,08	0,42		
Spain	0,91	0,23	0,00	0,00	1,37
Sweden	0,50	0,65	0,53	0,51	0,63
Switzerland	0,71	0,71	0,85	0,73	1,33
Turkey	0,00	0,02	0,05	0,05	0,06
UK	0,60	0,30	0,80	0,00	
U.S.A.	131,50	58,00	50,70	56,90	40,70
TOTAL	195,89	168,38	125,15	148,94	160,34

Table 2.1 Expenditure on Photovoltaics R&D by country.
Expressed in millions of dollars for the year listed.

Source: Energy Policies and Programs of IEA Countries from country submissions

Progress has been steady towards these goals and costs have fallen with increased production as is illustrated below:

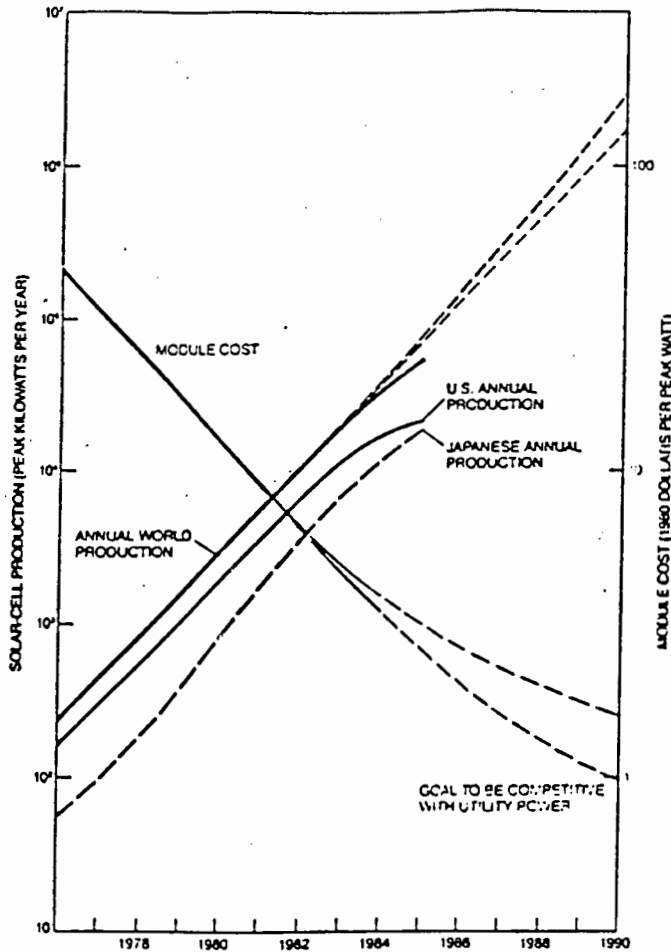


Figure 2.3 Solar cell: Cost versus Time

Source: Hamakawa, 1987, p82

It is tacitly accepted by the major researchers that the first large markets will be for remote applications in developing countries (SERI, 1985, p10). Future prospects are promising, the key issue being economics. The major requirement for large scale power production is that the cost per kilowatt-hour of PV generated power must be cost-effective to conventional generated power utilizing coal, uranium, gas or hydro. At the moment this is not so.

2.3 PRODUCTION TECHNOLOGIES

The efficiencies and costs of photovoltaic systems are dependent on the materials and manufacturing processes employed. Generally, the production of photovoltaics includes the following steps (Seippel, 1983, p35):

- (i) Refining of the raw material, usually Silica,
- (ii) Growing of polycrystalline or crystalline silicon,
- (iii) Developing of silicon sheets or wafers,
- (iv) Processing of wafers into solar cells,
- (v) Connecting the solar cells into modules,
- (vi) Encapsulation,
- (vii) Structuring of the array, and
- (viii) Engineering the complete photovoltaic system.

2.3.1 Silicon refining

Nearly all commercial photovoltaic cells are made from silicon. It is interesting, then, to discuss first the production of silicon itself, for it is the cost of obtaining pure silicon which is at the root of the economics of cell production. Available on the earth in the form of silica (SiO_2) it is a most abundant material. Indeed it is estimated that some 60% of the earth's crust is composed of silica. The usual starting point is not ordinary sand, which would be convenient except that it contains too many impurities to eliminate, but quartzite. This is mined in the normal way and is composed of 90% or more of silica. As many of the impurities as is possible have to be eliminated from the material, in order to maximise the efficiency of the solar cell.

The first step in refinement is the production of metallurgical-grade silicon (MG) which is around 98% pure. This is achieved through the direct reduction of silicon dioxide with carbon in an arc furnace (known as carbothermic reduction). The costs of this process are relatively low (\$1/kg Si) and energy consumption is also low (about 11 kWh/kg Si), but impurities are still too high for acceptable solar grade silicon (SG). Research is being undertaken continuously to reduce the cost of SG silicon. A recent report focuses on an advanced carbothermic reduction process which would produce SG silicon suitable for use in high efficiency cells (up to 13,4%) at a cost of 10\$ per kilogram (Aulich et al, 1986, p157-158 and p162).

At present most solar cells are produced from semi-conductor or electronic grade (EG) silicon at a cost of around \$45/kg. The most established technique is the Siemens process which produces trichlorosilane. This gas is then decomposed into silicon of 99,999999% purity. The processing cost is fairly high since a large amount of electrical power (150-200 kWh/kg of Si) is consumed in the reduction of trichlorosilane (Shimomura, 1986). There are various modifications of this process and these rely on the reduction of Si-H-Cl compounds.

Another method of purification is the Union Carbide process. This technique prepares near pure silicon from metallurgical-grade silicon by pyrolysis. The above purity is two orders of magnitude greater than is required for PV cells, though it is a necessary requirement for the semiconductor industry. Researchers have been attempting to find a way of producing low cost PV grade silicon and one potential technique has been reported that provides silicon of purity 99,9999% at a cost of \$6,50/kg (SERI, 1984c, p26).

2.3.2 Cell production

Photovoltaic module types are classified according to their production technology: single crystalline cells made from single crystalline silicon (or sometimes gallium arsenide) ingots; polycrystalline cells from polycrystalline silicon bricks; single-crystal or polycrystalline ribbon or sheet cells; and single or multi-junction modules made by thin-film deposition techniques using not only amorphous silicon, but also polycrystalline compounds. A further category of cells are the concentrating types which can use single crystal silicon or gallium arsenide cells or a variety of materials in high efficiency cascade cells.

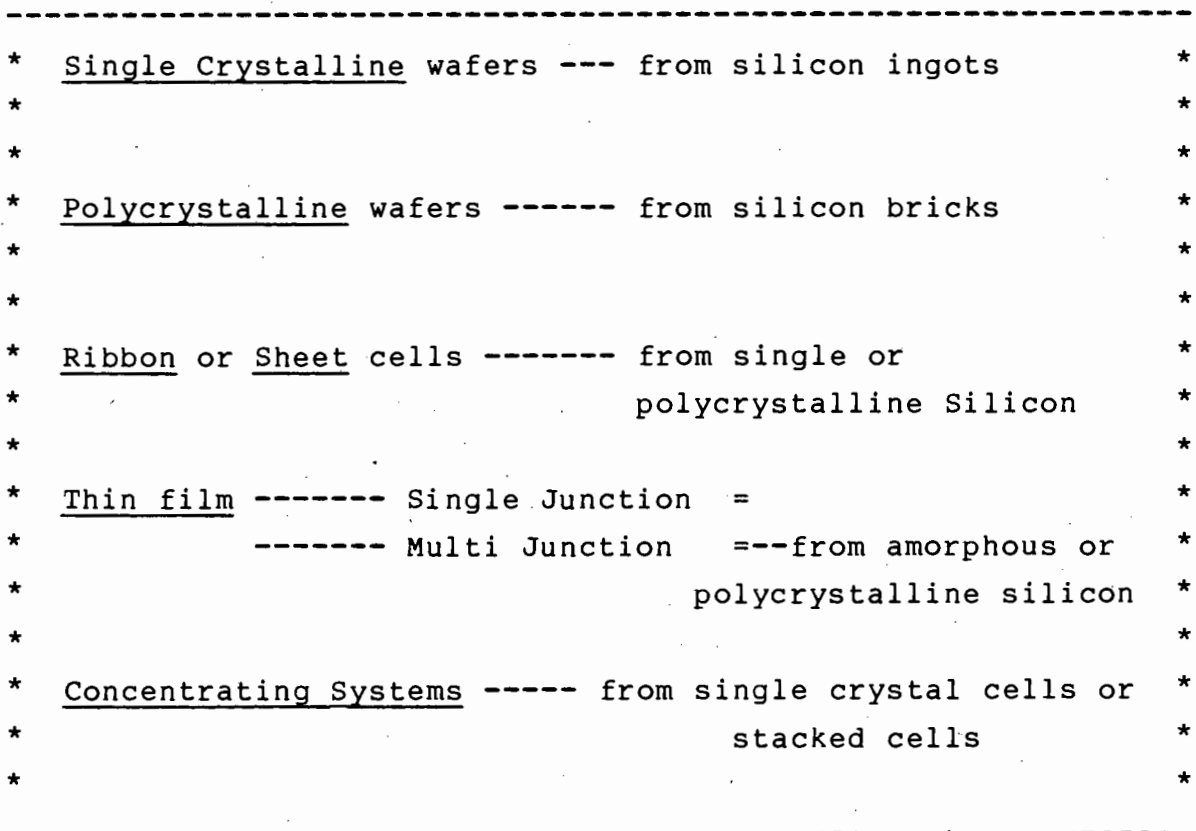


Figure 2.4 Types of Solar cells

2.3.2.1 Single-crystal Silicon cells:

Purified silicon is usually polycrystalline, i.e. the grains are packed randomly with defined boundaries. To transform this material into single-cell silicon, which has superior electrical properties, it is necessary to melt the purified silicon and then to allow it to cool slowly under carefully prescribed conditions. Further, as the single cell grows, dopants are added to aid the flow of electrons. Dopants are usually boron for the p-type base and phosphorus for the n-type collector layer.

The Czochralski (CZ) Process

Approximately three-quarters of single crystal cells are made using this technique which consists of pulling molten silicon from a rotating cylinder at a prescribed rate to allow proper cooling. The schematic (fig.2.5) gives an overall picture.

The process is initiated by allowing a 'seed' of single crystal silicon to touch the surface of the molten silicon held in the kiln. This seed is raised pulling with it crystallized silicon at a rate of about 10 cm per hour. The effect of the seed is to generate single crystal silicon in the rising cylindrical cooling mass. This is termed "crystal growing".

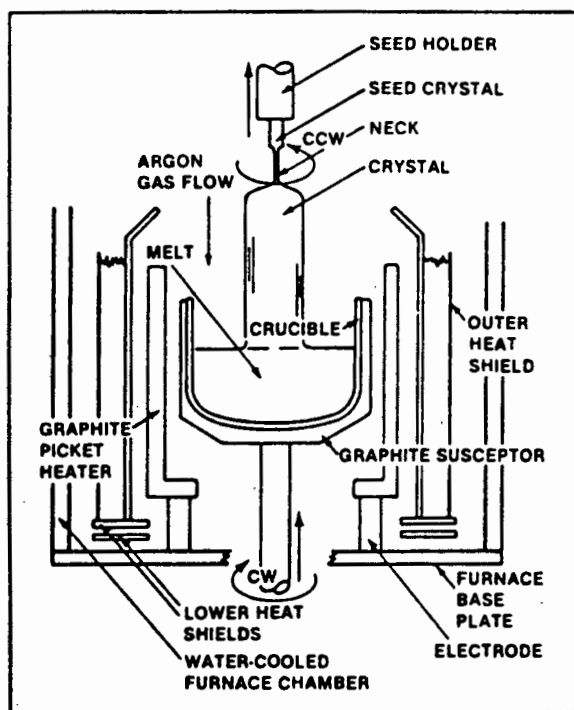


Figure 2.5 Schematic of the CZ process.

Source: Seippel, 1983, p46

The final result is a cylindrical ingot some 100-125 mm in diameter and a length which depends on the size of the furnace and, hence, the volume of the melt. After cooling the ingot is ready for cutting and fabricating into the thin disc wafer of the typical cell. The successful transfer of the Boron dopant from the melt to the crystal is one of the key essential requirements of the process. It is also one of the advantages of the CZ process in that the 'wanted' impurity Boron is not segregated as are other impurities still remaining in the melt, but is able to jump the 'freezing barrier'. In other words the CZ process itself also acts as a further chapter in the refining story, and the ability to pass through the barrier is the particular behavioural characteristic of Boron which makes it such a suitable choice.

The disadvantage of the process is that the crucible, made of SiO_2 , can give up some oxygen atoms to the melt, and these can then have deleterious effects on the final cell efficiency.

Float Zone (FZ) Technique

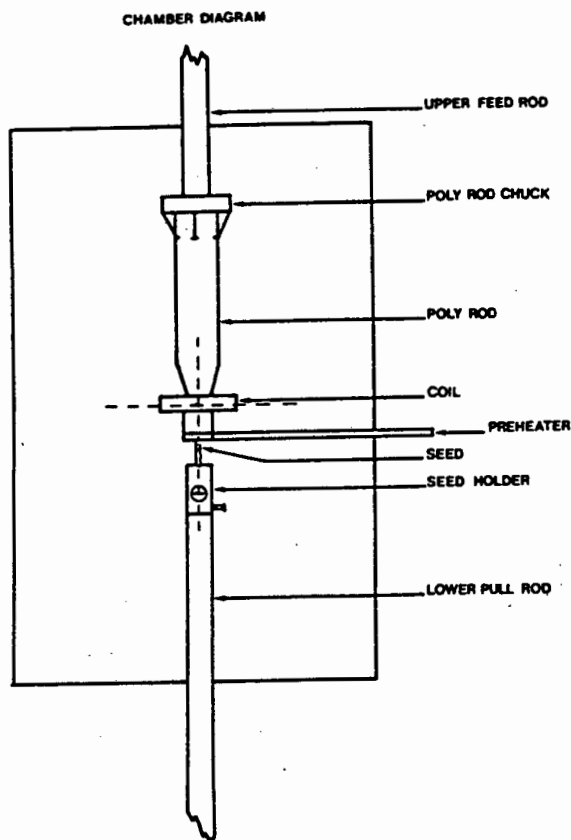


Figure 2.6 Schematic of the Float Zone process.

Source: Seippel, 1983, p56

This is an alternative method to the CZ. It is faster but costs more. It has applications in the rectifier and thyristor fields but until now limited use for PV application. Essentially the seed and a poly-crystalline rod, surrounded by an RF heating coil, are carefully brought into contact as shown diagrammatically in figure 2.6. The controlled movement of the rod and the seed through the coil produces crystal growth. The molten zone is around 20mm in length. The finished ingot is almost identical in shape to the CZ method product, but is normally smaller in diameter.

One advantage of this system is that less oxygen is absorbed by the silicon since it is not in contact with the container. Resultant oxygen count for CZ is about 30-35 ppm whereas for FZ it is 0,3-0,35ppm. CZ crystals are generally less expensive to produce on account of the larger diameter of the final CZ ingot.

Recent research into concentrator systems has necessitated the use of dimensions and purity which cannot be met by the CZ process and emphasis is now being made on reducing the cost of the float zone technique, which is capable of producing the required specifications (Moore, 1987, p9).

Advances in Single-crystal Silicon Solar Cells

Once the silicon has been produced as above, the ingots have to be sliced into wafers for polishing and etching. This process is highly wasteful of the material, largely due to the thickness of the saws themselves. In fact some 50% of silicon is wasted during the sawing operation. Hence newer fabrication processes attempt to reduce expense by forming the molten silicon directly into usable thin wafers, thus eliminating the costly and wasteful sawing.

It is to be noted that the following methods do not, strictly, produce single crystal silicon as previously discussed. They result in a large grain crystal which has the same electrical properties as single grain and is, consequently, usually categorised under the general name of 'single crystal'.

Edge-Defined Film-Fed Growth (EFG)

In this method the molten silicon is drawn upwards, by capillary action, through a die. The shape of which produces a thin sheet of single crystal silicon of some 25-100 micrometers thickness.

Problems associated with this process are:

- (a) The die has to be of highly refined material which will not contaminate the silicon.
- (b) The technique does not prevent impurities entering the ribbon from the melt.
- (c) As a consequence of the above, highly pure (and more expensive) silicon is required.
- (d) Continued use tends to erode the die.
- (e) Because of the impurities the final crystal structure is not as good as the CZ process and lower efficiencies result.

Mobil, in the U.S.A., have invested large sums in this technology which is now bearing fruit with improved production rates.

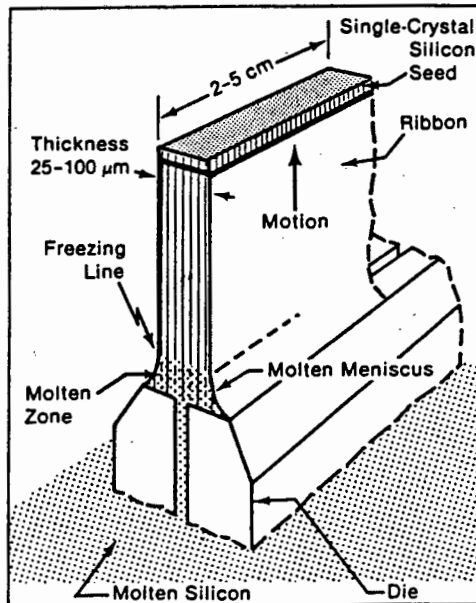


Figure 2.7 Edge-defined film-fed production of single crystal silicon (EFG).

Source: SERI, 1984a, p51

Dendritic Web Growth

Twin single-crystal dendritic seeds (i.e. in the shape of two parallel wires) are allowed to touch the melt and then are slowly withdrawn. The effect is to produce a film of single crystal silicon between the parallel dendrites, due to the surface tension of the material.

The silicon is then wound directly around a take up reel and is some 0,0127cm thick (Rose and Arnold, 1986, p52). The main advantage of this process is the high silicon utilization. By comparison the CZ process uses as much as four times the quantity of silicon. A second plus is that no surface preparation is necessary prior to processing thus eliminating the costly etching and lapping inherent in the CZ technique. Westinghouse have been largely responsible for the continued development of this technology.

Ribbon to Ribbon (RTR) Growth

This is a variation of the FZ method. Instead of using cylindrical ingots it is applied to ribbons of polycrystalline feed. High defects result if the speed of 7cm/minute are exceeded but cells of some 13%-14% efficiency are considered as typical (SERI, 1984a, p53). Once again it is the elimination of waste and costly processing which makes this a potentially viable proposition.

2.3.2.2 Polycrystalline Cells:

Polycrystalline cells use less refined silicon feedstock. Fabrication techniques are simpler and thus less expensive.

Polycrystalline silicon physically differs from single-crystal silicon in that it is made up of many grains of single crystal silicon. The formation of the grains are random, with this type of crystal being the start of the various processes already mentioned. Grain boundaries cause problems as they

impede the way in which light generated charges behave. Hence a cell made from this type of material will be less efficient than one made from a single crystal. However the trade-off comes with the cheaper manufacturing process. Polycrystalline cells promise significant longterm reliability with decreased use of raw material and sheet fabrication costs.

The essential aspect of the production techniques used is to produce relatively uncontaminated material with a reasonable grain structure. Wide columnar grains, a centimeter in size, can be formed by 'directional solidification'; that is by allowing the silicon to cool in one direction and so to propagate a uniform crystal structure through the melt. The major objectives are similar to the previous methods:

- (1) To design the equipment so that the correct size and shape is satisfactorily produced.
- (2) To reduce contamination from equipment and the atmosphere to a minimum.
- (3) To prevent the contaminants already in the melt from reaching the web.

Fabrication methods

Casting

A vat of molten silicon is allowed to solidify resulting in an ingot. It is a cheap process requiring relatively little energy and fewer labour skills than other processes. The casting has then to be sawn into wafers which causes high material losses and results in cost increases. A further problem is dislocations and impurities caused by exposure to carbon in the furnaces.

Ribbon growth

The earlier methods, i.e. dendritic growth, EFG, and RTR, have been briefly described and are applicable to polycrystalline formation. A further development is termed 'Edge-supported pulling'.

This practice is similar to that of dendritic web growth. But in this case two graphite filaments are pulled up from the melt, previously seeded. The web formed can result in uniform grains with useful efficiencies.

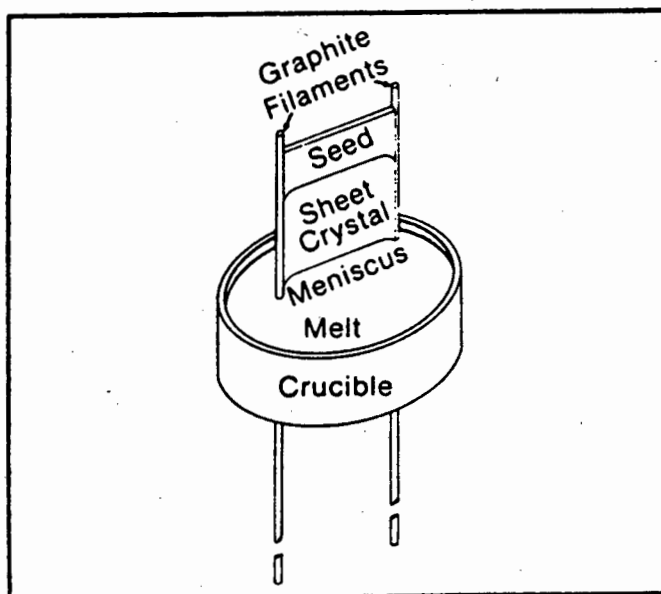


Figure 2.8 Edge-supported pulling (ESP).

Source: SERI, 1985, p77

Sheet growth

In addition to ribbon growth, polycrystalline silicon can be grown as sheets on supporting substrates:

(i) Silicon-on-Ceramic (SOC)

(a) Dip-coating

If a piece of carbon coated ceramic is slowly withdrawn from a bath of molten silicon, a polycrystalline layer of silicon will be deposited upon the ceramic, which is carefully designed to act as the substrate of the cell. The grains produced can be 4-5 millimeters in diameter and a layer of 100 micrometers is formed at a rate of 5-6 cm/minute. Efficiencies of 10% and more have been produced, but contamination with aluminium is a problem and dislocations in the atomic structure persist.

(b) Silicon coating by inverted meniscus (SCIM)

This is a later variation whereby the substrate is drawn over a meniscus of molten silicon at an angle around 25 degrees. The advantages are less contamination and a continuous process suitable for large area coverage.

(ii) Silicon-on-silicon

The ceramic material is unwieldy and the base electrical contacts difficult to fit. Hence the use of silicon directly as a substrate. Several methods have been tried, including vapour deposition of pure silicon on a base of low grade silicon. At the moment the effect of impurities in the substrate have not been overcome, and so the economy of the method is not proved.

(iii) Silicon on other substrates

Research is taking place to examine the deposition of the silicon on inexpensive materials such as steel or glass. Problems are encountered, as above, with impurities affecting the conduction layer. Efficiencies have yet to become competitive in this area, although improvements continue to be reported (Barnett and Culik, 1987, p220).

Further research into the production of polycrystalline silicon includes, Low-Angle Silicon Sheet (LASS), ultra-high-speed quenching and electrochemical techniques.

Linear rates over 55cm/min have been reported, with ribbons 33m long being produced. Efficiencies of 10% have been attained. Newer techniques include the innovative use of a carbon fibre web to aid the drawing process with resultant increased speeds of production. (Falckenberg et al, 1986 p165-169)

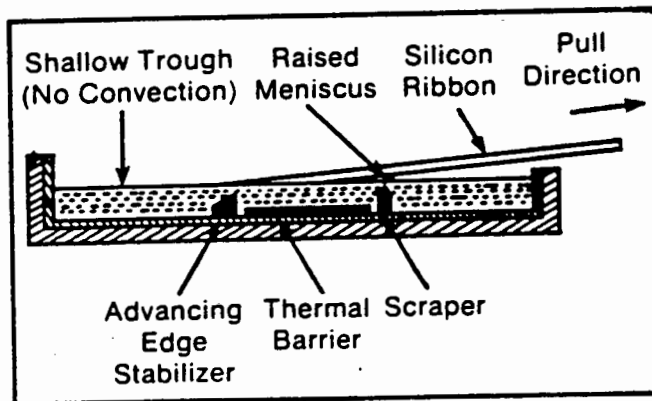


Figure 2.9 Low-angle silicon sheet growth LASS.

Source: SERI, 1985, p30

It has been found that adding hydrogen results in absorption in the grain boundaries and results in an increase in efficiency. The process is termed 'passivation'.

By and large it is accepted that the cost of polycrystalline cells is less than for single crystal, also the speed of production is faster. Despite their lower efficiency these cells are considered viable alternatives on account of the economic implications.

2.3.2.3 Thin films:

There are three main methods which are being developed for the deposition of these thin layers: glow discharge; sputtering; and chemical vapour deposition. These techniques apply to materials such as Amorphous Silicon, Gallium Arsenide, Copper-Indium-Diselenide, and Cadmium Telluride.

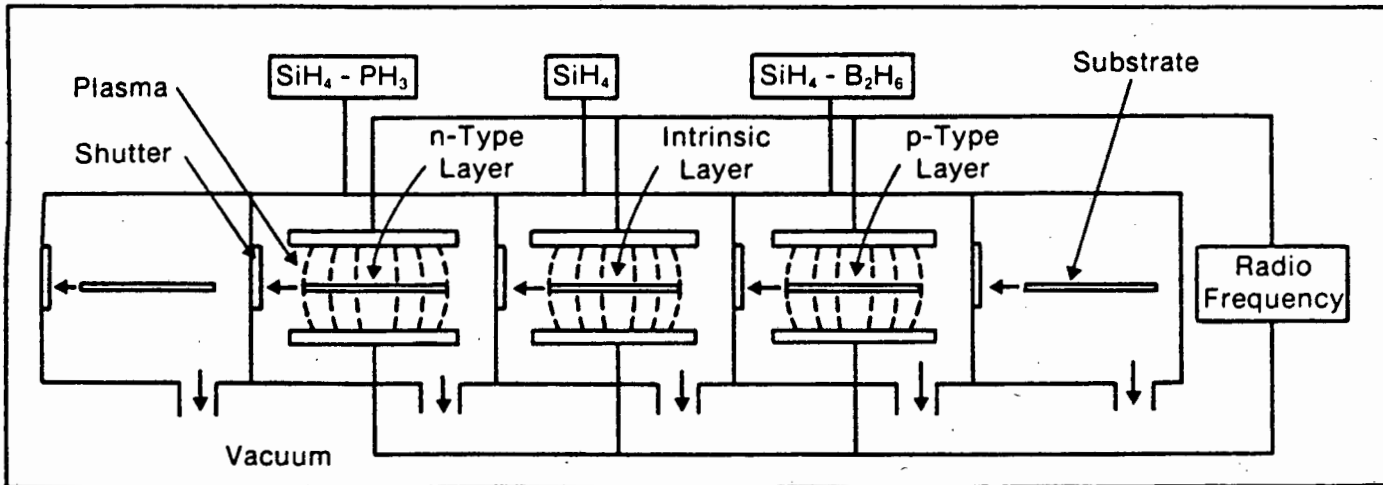


Figure 2.10 Radio-frequency glow discharge.

Source: SERI, 1982, p16

(i) Radio frequency, alternating current glow discharge

This method has proved popular and has been used to produce the most efficient cells. Basically, it consists of passing a stream of silane and hydrogen between electrodes which reverse polarity at high frequency. The result is to decompose the silane and to deposit a-Si onto a substrate which is, itself, moved between the electrodes. A sequential series of electrodes is set up to apply the two dopants and the various layers. Production of large area cells of high dependability in recent years has opened up many market possibilities (Falckenberg et al 1986, p36).

(ii) Chemical Vapour Deposition Techniques (CVD)

In this process gases, such as disilane, thermally decompose in such a manner as to deposit solids onto a suitably placed substrate. The technique has some advantages over the above glow-discharge method in that it should result in more uniformly deposited material. A disadvantage is that the method may not effectively passify the film and hence further passivation processes are necessary. It is reported that both IBM and Chronar are experimenting with this technique.

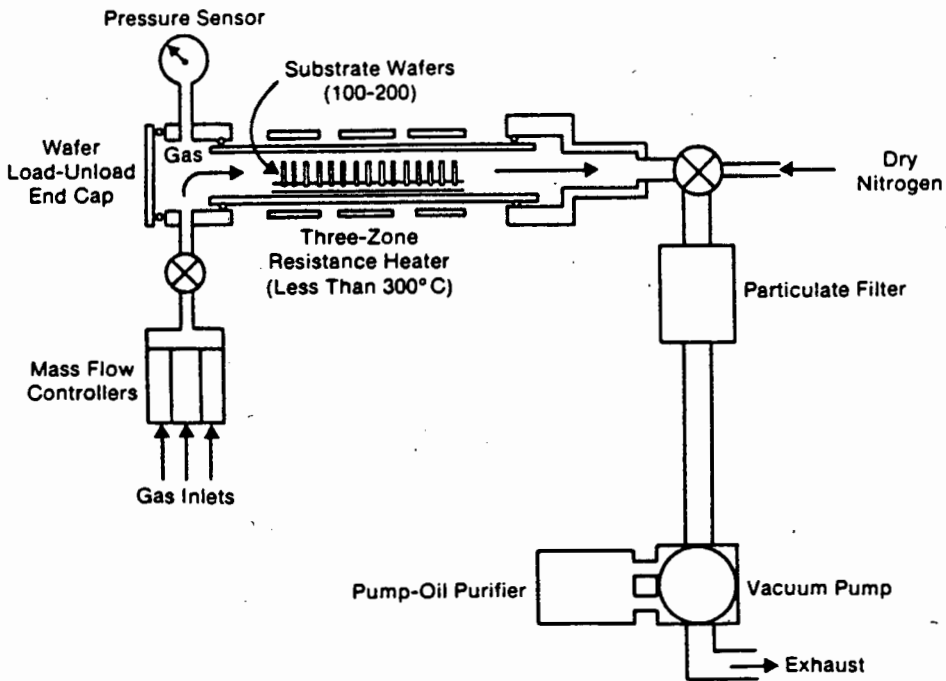


Figure 2.11 The Chemical Vapour Deposition process.

Source: SERI, 1984c, p6

(iii) Sputtering

Another alternative to the glow discharge sequence is to bombard crystalline silicon with a stream of high energy argon ions. The effect is to bounce silicon ions off towards a suitably placed substrate. SERI (1984b, p7) noted that Exxon was having some success with this technique.

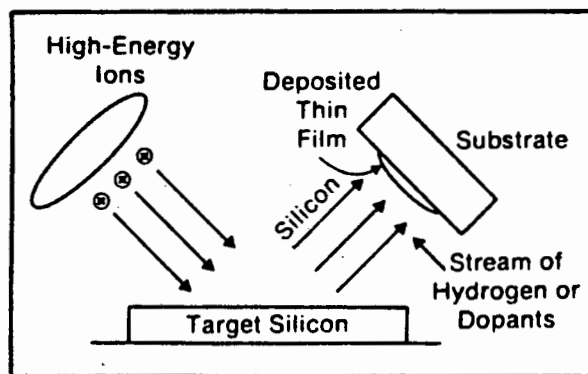


Figure 2.12 Sputtering.

Source: SERI, 1984a, p95

Types of thin film

(i) Amorphous Silicon (a-Si)

The most commonly used material for thin film solar cells is amorphous silicon. First made in 1974 by the RCA corporation, this technology now has a substantial share of the PV market, held mainly in consumer products. The basic advantage is that a-Si has the ability to absorb light some two orders of magnitude better than crystalline silicon.

It may, then, be made into thin films of some 0,5 micrometers as against the typical thickness of 100-300 micrometers required for ordinary silicon to capture the same quantity of light. The consequent saving in material results in considerable cost reductions. Research efficiencies of greater than 10% for a-Si films are now common due to intensive development over the past few years.

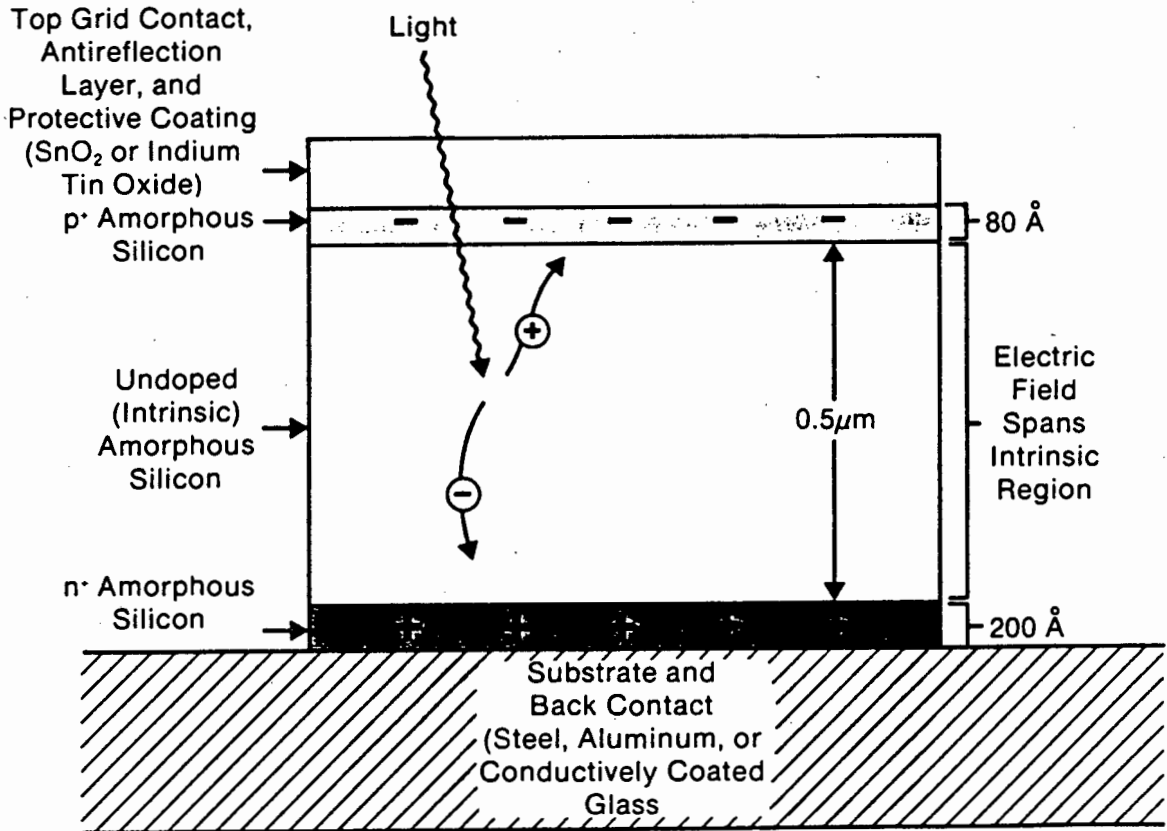


Figure 2.13 A typical p-i-n Amorphous silicon cell.

Source: SERI, 1982, p15

Silicon atoms tend to join together in a tetrahedral structure which produces a regular lattice in crystalline silicon. In amorphous silicon this lattice does not form. Instead each tetrahedron of four atoms does not line up with similar tetrahedrons but are twisted in orientation with respect to one another. The result is that amorphous silicon is dense and disordered, with chains and clusters ending in dangling bonds. These bonds tend to 'trap' electrons and thus prevent free movement. In this state a-Si is not efficient for use in

a solar cell. However it was found that if hydrogen (and lately, fluorine) is allowed to link with these ends then the efficiency is markedly improved as the flow of electrons is not impeded to the same extent.

Hydrogenated amorphous silicon (a-Si:H) is doped with boron and phosphorous in a similar way to crystalline silicon, with similar results, i.e., the production of p-type and n-type zones. Another characteristic of a-Si is that its bandgap energy is about 1,75 eV which is higher than polycrystalline or single crystal cells.

Figure 2.13 shows how the cell is formed, and clearly demonstrates the sizes involved. A human hair, by comparison, is around 80 micrometers thick. Most of the light which hits the top layer passes through into the i-layer and generates hole pairs. The p-type and n-type layers have the effect of inducing a field across the intrinsic layer which is instrumental in creating the necessary flow of electrons.

In summation, a-Si has the following main advantages:

- (a) high optical absorption and large photoconductivity for the solar spectrum;
- (b) a greater light absorption efficiency than single crystal silicon, with the consequence that a thickness of only one micrometer is needed to absorb 90% of the usable solar energy;
- (c) significant cost savings through material savings with thin films;
- (d) it may be deposited in the vapour phase onto any substrate material;

- (e) the above process requires relatively low temperatures (200-300°C);
- (f) the substrates can be low-cost and innovative shapes;
- (g) low balance of system costs can be achieved through the hybridisation of units such as solar tiles; and
- (h) they are comparatively easier to mass produce, for instance the interconnection of cells can be made simultaneously with the process of a-Si deposition.

(ii) Alloys of a-Si

The invention of the amorphous silicon carbide cell in 1980 saw a turning point in thin-film solar cell development. This cell gives control over valency bands with variations in doping, and control of energy gaps by varying the degree of carbon content. This is leading to a range of cells which are being tailored to fit the layers of a stacked cell. Amongst materials used in this manner are amorphous silicon-germanium, microcrystalline silicon, and amorphous silicon-nitride (Hamakawa, 1986 p33).

(iii) Gallium Arsenide (GaAs)

GaAs has a direct band gap of 1,4 eV, making it potentially able to produce the highest photovoltaic efficiency. Further, it degrades slowly with increasing temperature and hence is useful for concentrator systems.

(iv) Copper Indium diselenide (CuInSe₂)

In 1981 an efficiency of 10% was achieved by a team at Boeing Aerospace using this material and by 1986 this had been raised to 11,9%. The fabrication of CuInSe₂ cells in quantity has been slow until the recent discovery of low cost methods. Arco Solar is presently producing commercial modules. This

company has also recently reported an efficiency of 14,2% for a cascade cell using Copper Indium Selenide as the bottom cell. Zweibell (1986, p38) reports that this material has emerged as one of the most promising new thin-film substances, and whilst the U.S. now dominates this technology, the Japanese are making serious efforts to catch up.

(v) Cadmium Telluride (CdTe)

Pioneered by Eastman Kodak, these cells are now exhibiting efficiencies of over 10%, with the multitude of technologies available for the production of this material considered the technology's strength. Despite the problem of the successful application of contacts, it is reported that recent advances by Matsushita have placed these cells in close competition with a-Si and CuInSe₂ for the thin film market.

Both CuInSe₂ and CdTe are being funded by the Federal program in the U.S., partly, as Krantz (1986, pl260) points out, as a 'hedge against amorphous silicon.'

Fabrication Techniques

The flexibility of design of these thin films is one of their most advantageous features. They are marketed on different substrates such as glass which, for example, may be formed directly to the shape of a building tile, on stainless steel and produced in a continuous roll, on a polymer and presented as a 'stick-on' roll (Hamakawa, 1986, p32). It is estimated that as the technology of thin-film cells develops, so this design will play an ever more important role in the photovoltaic industry.

2.3.2.4 Cascade cells:

These cells are also known as 'stacked' or 'multi-junction' cells. They consist of several layers of thin films deposited or stacked one above the other. They rely on the principle that different materials absorb different parts of the solar spectrum more efficiently. Briefly, light from the sun which reaches the first cell, chosen so as to have the largest band gap, is partially absorbed. Those photons not held by this layer will be transmitted to the next layer, and so on. The final result is that by careful use of appropriate band gaps, a much higher percentage of the incident light will be absorbed by this design.

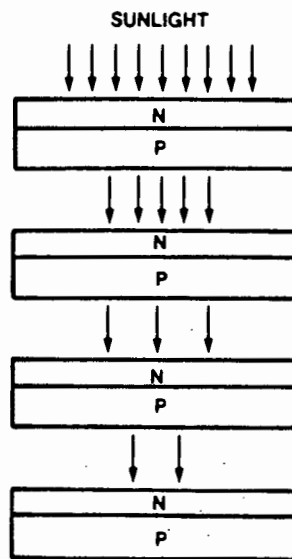


Figure 2.14 Principle of a Cascade or Stacked cell.

Source: Seippel, 1983, p144

Cascade cells consist of several different materials necessitated by the requirement for different band gaps. For instance, a-Si absorbs light with energy above 1,75 eV and CuInSe₂ absorbs light above 1,0 eV. Hence a CuInSe₂ cell arranged below an a-Si film will absorb photons with energies between 1,0 and 1,75 eV. However the light reaching the lower cell would be less than the full spectrum due to the cell on

top. The result is that the CuInSe_2 thin film works at lower than its normal efficiency. Nevertheless the combined efficiency of the cell is greater than either thin film produces on its own. This increased efficiency easily compensates for the additional costs of production.

If the cells are well matched the efficiency of the combination is about the efficiency of the top cell plus 50% of the efficiency of the bottom cell. Fabrication temperatures are all similar (about 200°C to 250°C) and are low enough to avoid inducing interdiffusion damage to the various layers.

The cell illustrated below attained the highest efficiency recorded by any thin film tested by SERI in 1985.

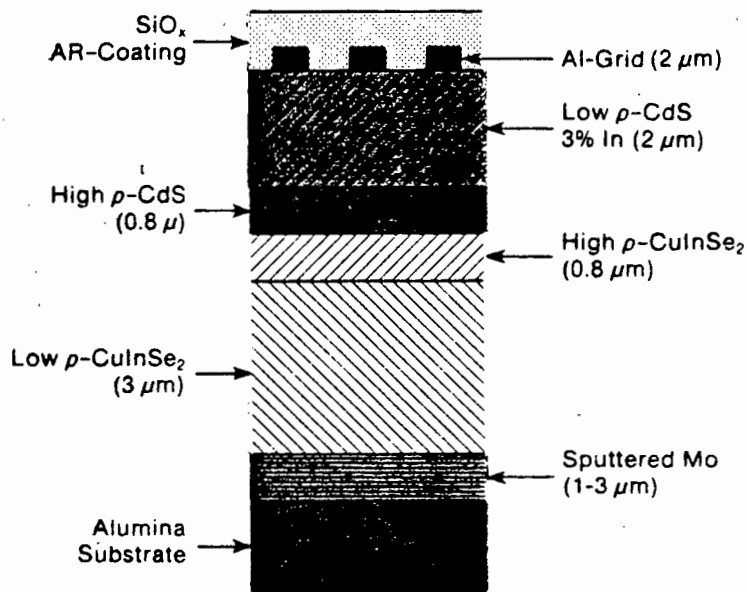


Figure 2.15 A CdS/CuInSe₂ cascade cell. 10,3% Efficiency.

Source: SERI, 1986, p7

Some flat plate cascade cells are shown in table 2.2. The cells are categorized as:

"High" = high efficiency with high cost

"Low" = low efficiency but low cost

For example, the "high/Low" strategy means using a high cost, high efficiency cell on the surface and then backing this up with an inexpensive bottom cell.

The CLEFT technique is a potentially economic method of producing single crystal GaAs film upon single crystal GaAs substrate. A carbon interlayer allows later cleavage of the film from the substrate, which may then be reused (Zweibel, 1986, p45).

Top Cell	Bottom Cell	Category: top cell/ bottom cell	Comments
a-Si	CuInSe ₂	Low/Low	13,1% Efficiency. Work by Arco Solar.
a-Si	a-Si:Ge	Low/Low	12,7% Efficient, work by Energy Conversion Devices.
CdTe(Mn,Mg Zn)	CuInSe ₂	Low/Low	CdTe alloys in early research stage.
Te(Mn,Mg Zn)	CdHgTe	Low/Low	CdHgTe in early research stage but promising.
HgZnTe	HgZnTe	Low/Low	Experimental.
CuGaSe	CuInSe ₂	Low/Low	CuGaSe ₂ in early research stage.
a-Si	CdHgTe	Low/Low	CdHgTe in early research stage but promising.
GaAs(P,Al)	CuInSe ₂	High/Low	GaAs alloys in early (CLEFT) research stage.
GaAs(P,Al)	CdHgTe ₂	High/Low	GaAs and CdHgTe in early (Cleft) research stage but promising.
GaAs(P,Al) (CLEFT)	Crystalline Silicon	High/High	GaAs alloys in early research stage.

Table 2.2 Flat-plate Cascade cell combinations.

Source: Zweibel, 1986, p46

2.3.2.5 Concentrator Systems:

Most solar cells improve their efficiency when subjected to concentrated sunlight. A 20% efficient cell could, for example, improve its performance to achieve 25% efficiency when exposed to 500 'suns'. Lenses and reflectors are used in this technology to focus or 'concentrate' the light received from the sun upon specially designed highly efficient solar cells.

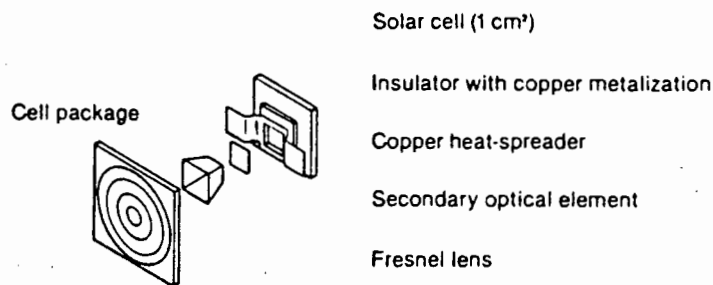


Figure 2.16: Concentrator system.

Source: Moore, 1987, p10

A limiting factor is that concentrators require direct not diffuse sunlight and thus are restricted to clear desert type climates. It is interesting, in this regard, to note that the Americans have been leading in the development of this technology as there is much potential in the dry South-West of the U.S.A. In Japan, on the other hand, where diffuse radiation is typically 50% of global radiation, development work has focussed on flat plate technology.

Concentrating systems are more complex and hence are more appropriate to somewhat larger installations (e.g. 100 kW plus). For example, concentrating systems have to track the sun and the cell has to be kept cool as marked deterioration occurs with increase of temperature.

Their greatest potential lies with the production of power for grid systems; this is instanced by EPRI devoting a significant portion of their budget in 1986 to the development of the advanced cells required for this technology. EPRI reports the development of what is called a 'point contact' cell. In Stanford, under laboratory conditions, recent work has led to an efficiency of 28,2% at 110 suns concentration. It is expected that once economic manufacturing techniques can be established that these cells, in conjunction with concentrating technology, will be able to produce electricity for the target cost of 6-8c/kWh in the 1990's (Moore, 1987, p8).

Researchers from the Jet Propulsion Laboratory argue that PV is on the brink of becoming cost effective for peak power applications at 12-20c/kWh (Callaghan, 1987, p741). It is envisaged that utility scale applications will use concentrating systems which have higher annual capacity factors. More importantly they are projected to have lower costs per peak watt because of higher efficiencies and lower balance of system costs per unit area of cell (mirrors and tracking supports are cheaper than cells).

This market is potentially huge, particularly for peaking power applications in the South-West of the U.S.A. where the potential market to the year 2000 is estimated at 1 GW (DeMeo, 1987, p780). Thus, many in the U.S.A. believe that the future of PV lies in high-efficiency concentrating cells for grid-connected applications.

2.3.2.6 Summary of solar cell types

The detailed discussion of different cell types above may seem confusing, dealing as it does with the wide range available. It is useful, then, to summarize the areas of development into the main technological generations that have occurred:

(1) Single Crystal Ingots.

Silicon is the usual material produced in this manner though other substances such as Gallium Arsenide are used. The methodology is well established with a high proportion of marketed cells being produced by this technology.

(2) Polycrystalline Silicon blocks.

These are a cheaper substitute for the higher efficiency single crystal cells. Although the inherent nature of the material prevents the cell attaining the efficiencies common to the single crystal variety, the cost saving involved can make this material a viable alternative. Polycrystalline silicon is also the starting point for the production of single crystal silicon by several of the processes described

(3) Sheet or Ribbon Silicon.

The expensive and wasteful sawing process necessary to produce the wafers from ingots or blocks can be bypassed by a number of different processes to directly produce usable thin wafers of both single and polycrystalline silicon.

(4) Thin Films.

The advent of this technology whereby a thin film, measured in micro-meters, is deposited upon a substrate, has provided a means of lowering the cost of solar cells. The main material in use is amorphous silicon though much research and development is being carried out to explore alternatives. An offshoot of this is the method of depositing several layers of material to produce the stacked or multijunction cell. A considerable number of materials and combinations are in use and are being developed.

(5) Concentrator Systems.

Special lenses or reflectors are used to concentrate sunlight upon the cell. Efficiencies can be high and, despite the additional cost of concentrators, this technology may well have the greatest potential for the supply of power to a grid.

Research and development are ongoing processes in this comparatively young industry. The twin aims of improving efficiency and lowering costs are the main motivations. It is likely that new discoveries will be made in production techniques and new materials. At the end of the day the cost of PV cells compared with the price of electricity produced by conventional means will be the main yardstick upon which the industry will be judged.

The following diagram sums up the main types of photovoltaic cells:

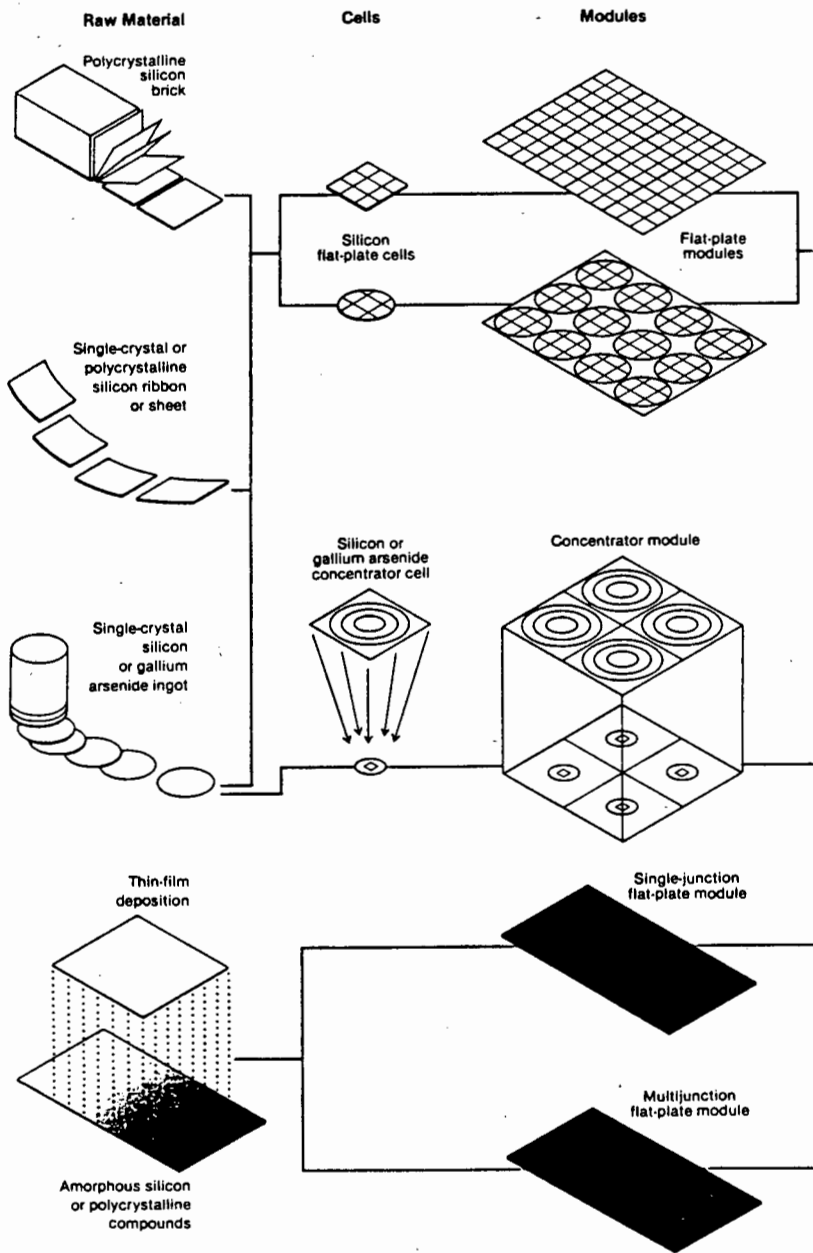


Figure 2.17 Photovoltaic types.

Source: Moore, 1985, p8

2.3.3 Fabrication of cells and modules

The above sections have described the initial phases in the growth and fabrication of PV cells. A series of further processes are required before the finished cell can be connected into a module.

TYPICAL \$0.70/WATT SEQUENCE*

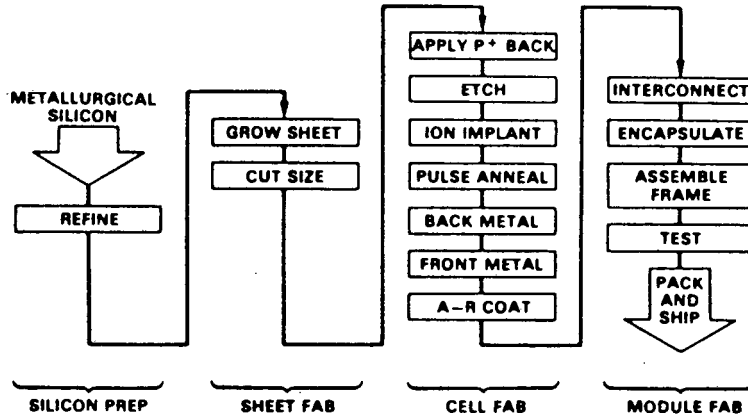


Figure 2.19 Fabrication process using sheets.

Source: Seippel, 1983, p107. Courtesy the Jet Propulsion Laboratory

2.3.3.2 Wafer preparation:

The wafer is lapped, polished, etched, cleaned and is as free of dislocations and anomalies as is possible. Contamination is a problem which is overcome by stringent quality control at each stage in the process. The contamination of the working area is measured by the presence of dirt particles in the air. Suitable clean clothing has to be worn by personnel and the equipment kept rigorously clean. These requirements contribute to the overall cost of production.

Untreated silicon reflects around 30% of incident light. Hence it is advantageous to coat the surface with a material, called an 'antireflective coating' which will cut down this loss. For instance, a single layer of silicon oxide will reduce the reflected light to 10% and a double layer to below 3%.

2.3.3.1 Processing wafers into solar cells:

Once the silicon has been prepared by any of the methods discussed, the backing of the cell has to be formed, and the various layers of the cell constructed. A typical single crystal cell will be composed of:

- (a) The base plate, which also usually acts as the metal contact.
- (b) The base of p-type silicon, about 500 micrometers thick and
- (c) The collector layer of n-type silicon, which is around one micrometer thick.
- (d) Top terminals.
- (e) An anti-reflective coating and/or a textured surface.
- (f) An outer cover of glass, with a layer of adhesive.

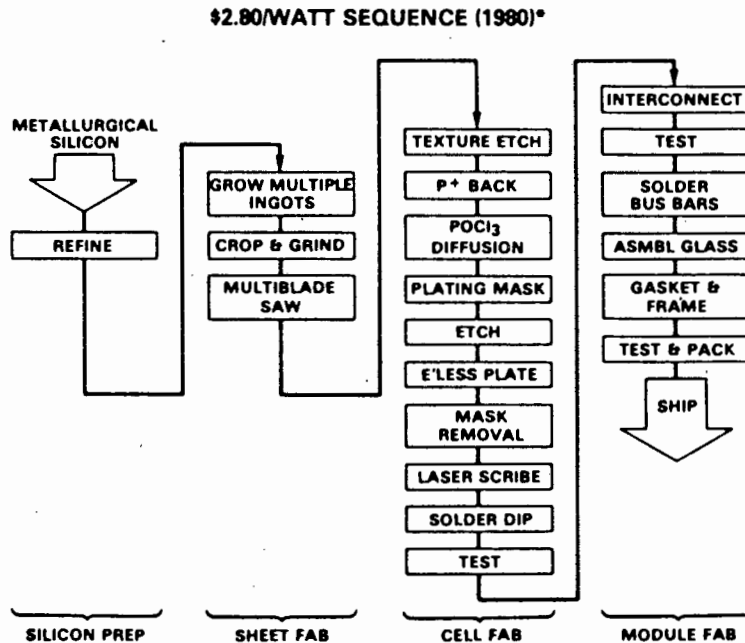


Figure 2.18 Fabrication process using wafers.

Source: Seippel, 1983, p106. Courtesy the Jet Propulsion Laboratory.

Another method is to 'texture' the surface so that incident light which is reflected is partly recaptured into the cell. These techniques have been important in obtaining the very high efficiencies which have been reported in recent years by, for example, Professor Martin Green at the University of New South Wales. One of these cells is shown below:

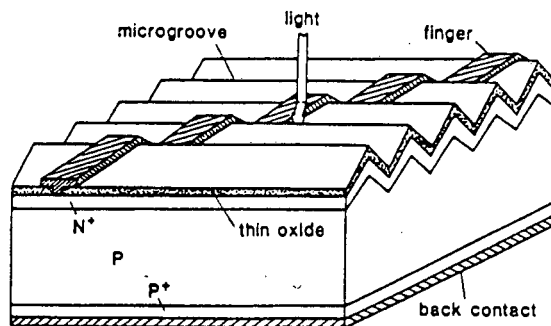


Figure 2.20 The Micro-grooved passivated emitter solar cell.
Source: Green, 1987, p153

The P-N junction

In 1983 there were three main methods in use for doping the silicon to the desired impurity level. Diffusion, epitaxy and ion implantation. As Seippel (1983) points out there are 'certainly others under test and study' (p112).

Essentially, Phosphorous (which produces n-type silicon) or Boron (which produces p-type silicon) is introduced to the material. These methods all require the highest degree of accuracy and control to enable the exact level of doping to occur, and consequently, the appropriate electrical characteristic to emerge.

Metallization

The electrical contacts have to be connected to the top and sometimes the bottom of the cell as well (if the substrate itself does not act in this capacity). The base contact is usually a sheet of metal, which is not complicated to insert into the production sequence. The surface or top contact requires careful design and manufacture. The contact has to produce as little shadowing as is possible and at the same time fulfill its function of collecting the current over the whole area of the surface. This is accomplished by directly depositing metal, usually by vacuum deposition techniques, onto the surface in the form of fine webs or other suitable lattice configuration.

The metal deposited has to:

- (a) Be of low resistance.
- (b) Be strong enough to bond with external leads.
- (c) Be non-corrosive.
- (d) Be a good conductor.
- (e) Adhere to the junction and be able to contour easily.
- (f) Be economic.

Aluminium generally fits these requirements.

Many of the high efficiency research results have been obtained with expensive photolithographic definition of vacuum evaporated top contact metallization.

These techniques are probably not economic for mass production cells. Martin Green has recently developed a new and cheaper cell which uses laser grooved buried contacts, while maintaining high efficiencies of around 20%. This cell is shown below:

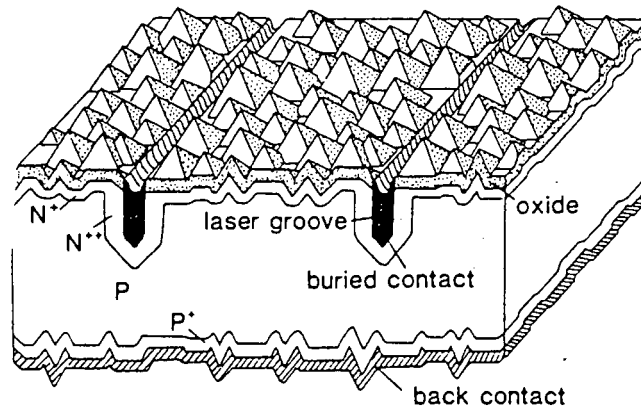


Figure 2.21 Laser grooved, buried contact solar cell.

Source: Green, 1987, p155

Another approach, which attempts to bypass the problem of shading altogether, is the back-contact or point-contact cell and some dramatic results in terms of high efficiencies have been obtained at Stanford, under the leadership of Professor Swanson.

Encapsulation

The glass or plastic envelope which surrounds a PV module is required to be efficient in transmitting light as well as providing a stable outer skin to hold all the module components in place. This surrounding envelope has to resist weathering, inhibit all forms of corrosion, attach firmly to module parts and be suitable for use in a wide variety of applications. Ethylene vinyl acetate (EVA) has been the industry standard for this purpose. Improvements are reported to this product, including a fibreglass-based back surface material which enables the module to be resistant to 'severe fire exposure' (SERI, 1986, p18).

The above can only be a brief introduction to some of the complexities involved in module fabrication. Authors point out that advances are made in production techniques on a continuous and on-going basis, as the goal of cost competitiveness with utility electricity is sought. In 1986, it was reported, for instance, that an innovative technique was in use by Westinghouse for cutting the number of steps required to form the cell. This process uses liquid dopants to form simultaneously both front and back junctions. The method, once implemented, is estimated to reduce the cost of junction forming by at least one-third. (SERI, 1986, p15)

2.4 DISCUSSION OF CELL EFFICIENCIES

Radiation from the sun strikes the atmosphere of the earth at a rate estimated to be $1,3 \text{ kW/m}^2$. Part of this energy is reflected, part is absorbed by the atmosphere itself, and the remainder reaches the surface. This amount is about 1 kW/m^2 at noon.

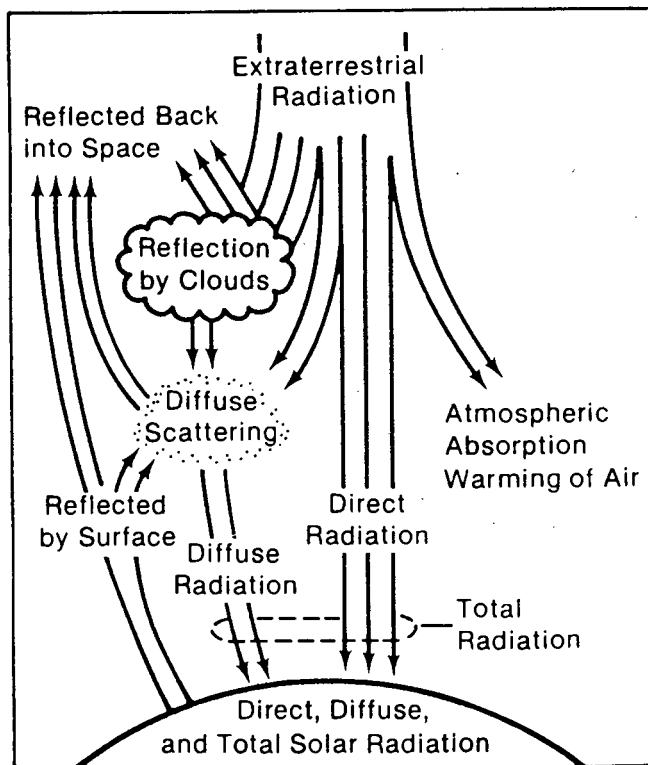


Figure 2.22 The effect of the atmosphere upon extraterrestrial radiation.

Source: Seri, 1984a, p6

The efficiency of a solar cell is, then, the proportion of the available radiation from the sun which the cell converts into electricity. Of this amount of 1000 watts, the silicon cell is sensitive to approximately 44%, though this differs with different types of cells.

The way in which the incident wavelength can be absorbed depends upon the ability of the photon to knock an electron out of its defined position. The energy required to 'promote' an electron from its bound state into the conduction band is known as the 'band gap'. Silicon has a band gap of 1,12 electron volts which corresponds to a wavelength of 1,1 microns. Since over half the energy arriving from the sun has a wavelength longer than 1,1 microns, (these photons cannot play a part in producing electricity in a silicon cell), it can be seen where the theoretical upper level of efficiency is established. Of the energy reaching an electron, a substantial amount is converted to heat, further reducing the actual or resultant efficiency.

The newer cascade type cells, especially adapted for differing wavelengths can use more of the incident radiation. Concentrator units, by their nature, receive more in the first place. The work of Fan at M.I.T. produced the following diagram.

This has application when two materials are being considered as layers in a cascade cell. It shows that the highest efficiencies will occur when the bottom cell has bandgaps between 0,9 eV and around 1,1 eV and the top cell has bandgaps in the region between 1,55 eV and 1,85 eV.

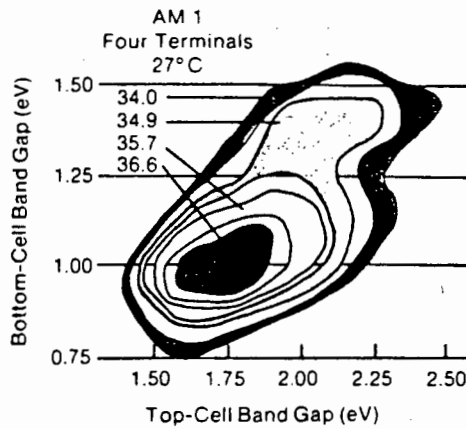


Figure 2.23 Efficiency of cascade four terminal cells.
Source: Zweibel (1986, p42) after Fan.

The Sankey diagram below, as applied to a silicon cell shows how the radiation reaching the cell is distributed.

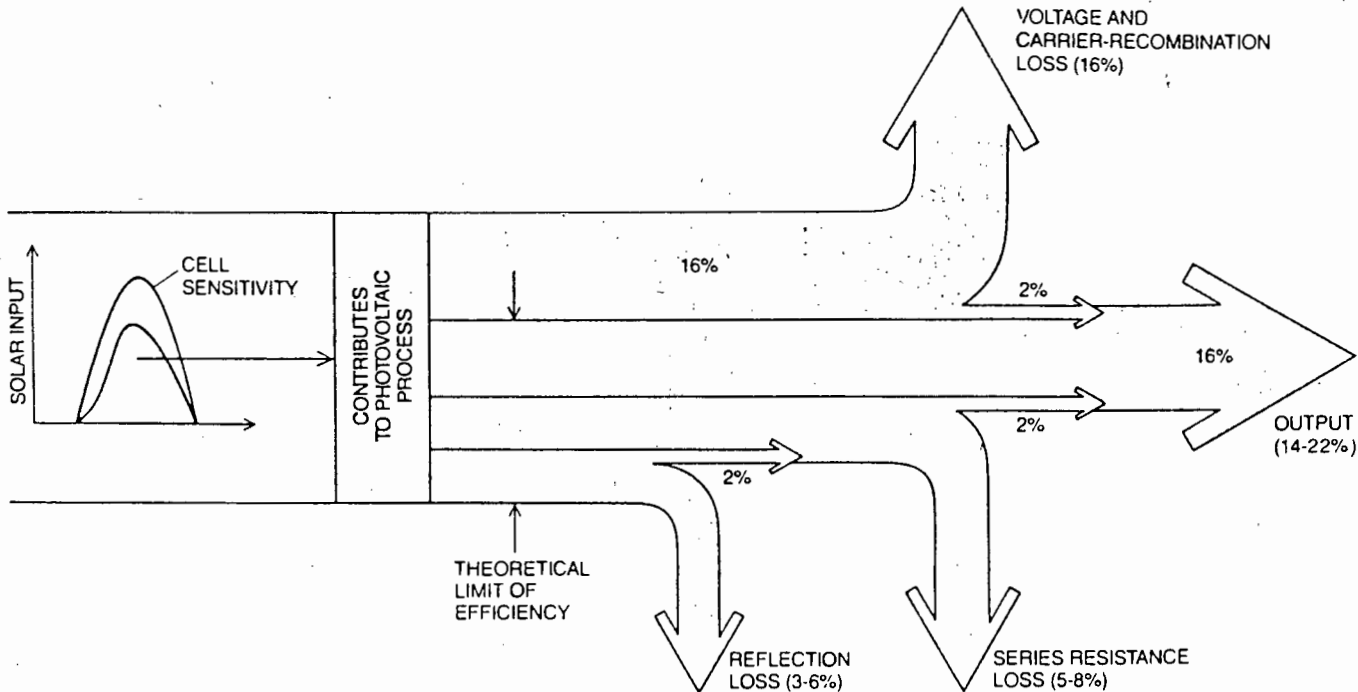


Figure 2.24 Energy flow in a Crystalline-silicon solar cell.
Source: Hamakawa, 1987, p80

Some 16% is lost to the processes within the cell, leaving a theoretical limit of efficiency of approximately 28%. Hamakawa notes that the small arrows labeled 2% are losses which can be recovered from a well designed unit, thus implying a practical limit for the efficiency of a silicon cell to be 22%, although recent publications suggest that these figures may be exceeded.

The efficiency for six different semiconductors is shown in the next figure. The maximum theoretical efficiencies, as a function of band gap energies, are illustrated by points on the curve. Silicon would be around 27%, corresponding to the Sankey diagram earlier. GaAs and CdTe show the highest availability. The various other points plotted show the highest reported efficiencies obtained by each of the semiconductors when used in the form designated. It can be seen that only single crystal solar cells made from silicon and GaAs demonstrate efficiencies close to the theoretical predictions.

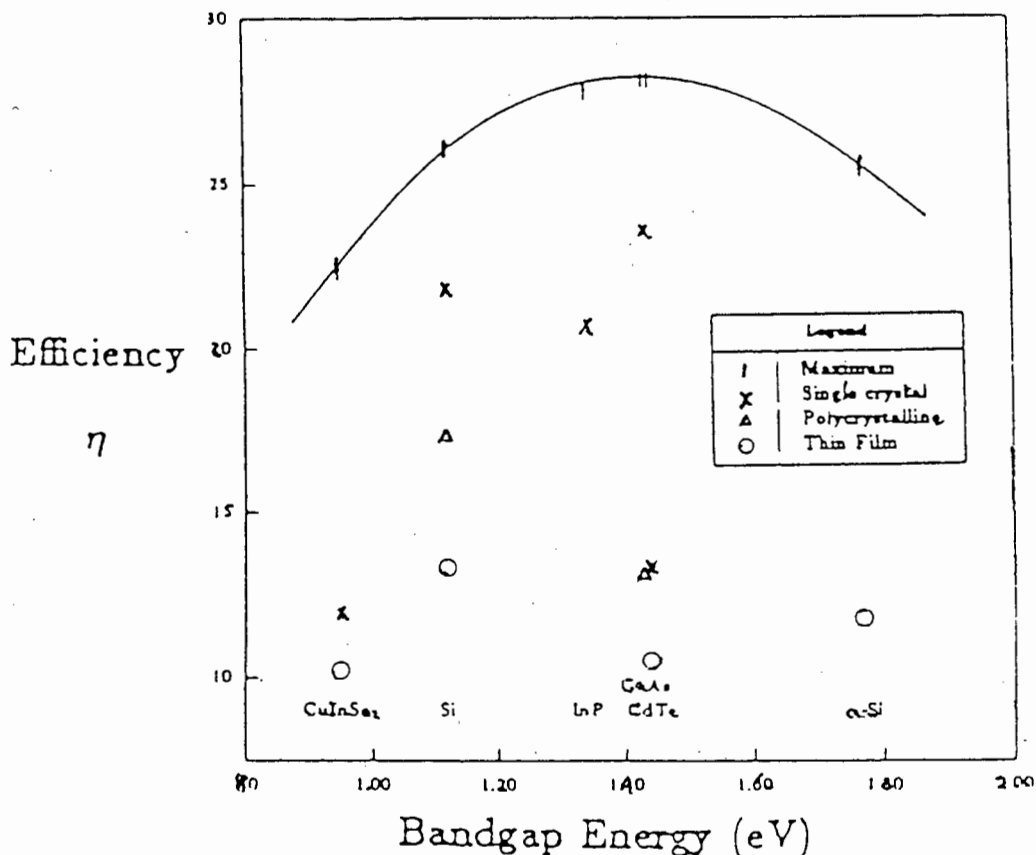


Figure 2.25 Efficiency versus Bandgap Energy as a function of crystallinity.

Source: Barnett and Culik, 1987, p220

The efficiency also depends on the position of the module. 'Air mass 1' (AM1), on the surface of the earth, gives different results to 'air mass zero' (AM0), in outer space.

This is illustrated by the following combined curves:

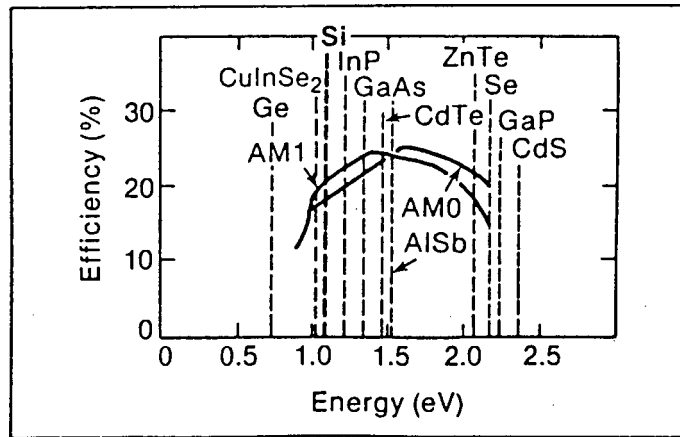


Figure 2.26 Maximum Theoretical Efficiency versus Band Gap.

Source: SERI, 1984a, p27

Another factor which has to be taken into account is the temperature sensitivity of the PV cell. Materials differ in their individual reaction to increases in temperature although it can be generally stated that the efficiency does fall as temperature increases. Hence a remark regarding efficiency should, ideally, state the exact temperature being considered.

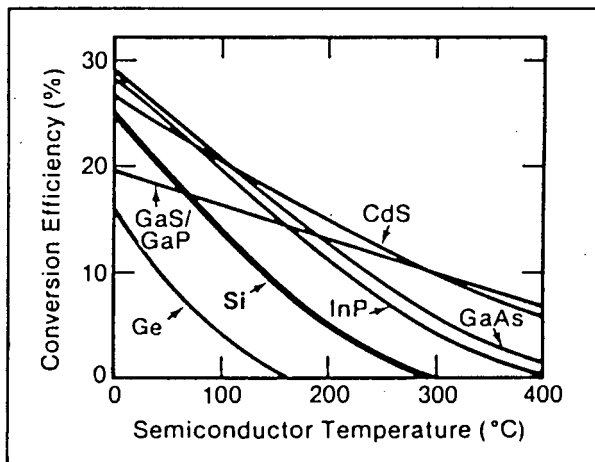


Figure 2.27 Solar cell Efficiency versus Temperature.

Source: Seri, 1984a, p33

2.4.1 Summary of efficiencies

The search for greater efficiency is persistent, with advances, innovation and new materials being reported continuously. The table below lists a selection of reported efficiencies for a variety of cells which have been broadly classified into five main categories.

Cell Classification	Max. Eff. Theoretical	Laboratory Efficiency	Commercial Efficiency
Single Crystal Si.	28% ₁	20,8% ₁₁	15,2% ₁₂ (50 cm ²) 18,9% ₁₃ (47 cm ²)
Point Contact		22,2% ₁₁	
Polycrystalline		15,3% ₁₄ (100 cm ²)	8%-10%
Cast brick			(mass production) ₃
Ribbon Crystalline Si		19,1% (4cm ²) ₆	
Gallium-arsenide		16,6% ₁₁	
Thin film: a) a-Si		23,7% (0,5cm ²) ₉	
		12%(1cm ²) ₈	6%-7% (wide area, mass prod.) ₃
	b) CuInSe ₂	11,0% ₆ 11,9% ₇ 12,5% ₁₀	3,6cm ²
	c) CdTe	9%-11% ₆ 12,8% (1cm ²) ₇	5% (0,5 m ²) ₇
	d) a-SiC/a-Si	11,7% ₃	
Cascade:		36,6% ₇	
	a) CaS/CuInSe ₂	10,3% ₂	
	b) GaAsP/GaAs	15% ₂	
	c) AlGaAs/Si	17,2% ₉	
	d) a-Si/polycrystall	13,3% ₃	
	e) a-Si/CuInSe ₂	13,1% ₁₀	65cm ²
Concentrator: GaAs		26,1% ₁₅ (750 suns)	16,9% (in field, 1000 suns) ₄
	AlGaAs	26% (753 suns) ₄	
Single crystal Si		28,2% (110 suns) ₅	

Table 2.3 Cell Efficiency

Sources:

Suffix	Name	Date	Pages
1	HAMAKAWA, Y.	1987	p79, p80
2	SERI	1986	p3, p7, p9
3	HAMAKAWA, Y.	1986	p33, p32, p33
4	MOORE, T	1985	p13, p14
5	MOORE, T	1987	p8
6	SERI	1984c	p13, p15, p21
7	ZWEIBEL, K	1986	p38, p39, p42
8	KRANTZ, A.D.	1986	p1260
9	INT. SOLAR ENERGY REPORT	1986	p44
10	STRATEGIES UNLIMITED	1987	p45
11	EBERHARD, A.	1987	p8
12	PRINCE, M.B.	1987	p7
13	ARVIZU, D.E.	1987	p131
14	SHIRASAWA et al,	1987	p97
15	GEE et al,	1987	p133

2.4.2 Small and large area efficiency

By 1977 it had become apparent that making larger and larger solar cells was not going to lead to greater economy as larger cells tend to exhibit lower efficiencies than smaller ones. The main reason for this drop off of efficiency with size is seen as material defects which are a significant factor in larger area cells but which can be easily eliminated by rejecting faulty or small output cells from a production batch of small area cells.

Nevertheless efficiencies based upon laboratory conditions using a small area cell have then to be translated to field conditions using a module of much greater area. This also gives rise to problems of maintaining uniformity of thickness, resistance, and the maintenance of a good interface.

As an example it took Spire in the U.S.A. some two years to move from the laboratory situation where a 19% efficiency cell of 0,5 cm by 0,5 cm was demonstrated to production runs of several hundred cells of area 10 cm by 10 cm having an efficiency of 17,5% (See reference 9 above).

Further losses arise when the cells are connected into modules due to electrical connection resistances and further, when the modules are fabricated into arrays. It is to be noted that the DC current finally produced is usually converted to AC current with further losses occurring in the inverter.

2.4.3 Conclusion

At a recent international PV meeting, the 3rd International Photovoltaic Science and Engineering Conference (Tokyo, 3-6 Nov 1987) it was reported by researchers that steady improvements continue to be made in efficiencies of cells. Whilst the efficiency of amorphous silicon cells appears to be limited to around 12%-14%, advances in thin film multi-junction cells are more hopeful. There is still no consensus at present as to which material is likely to be the most economic overall. In 1987 a resurgence of interest appears to have occurred in crystalline silicon with Professor Martin Green, of the University of New South Wales, having produced 19% efficient cells from the standard Czochralski process (47 cm²). Laboratory results have been even higher.

The upper limits of efficiency have been revised and it is now thought that single crystalline cell efficiencies of 25% at one sun and 30% for concentrating systems are achievable in the next few years. The rapid increases of efficiency that have occurred during the last decade bode well for the continuation of this trend. The use of computer models has enabled the fundamental physics of the cell process to be thoroughly explored. Increases of efficiency will parallel more economic production techniques and the possibility exists that the aim to make photovoltaic cells a viable and economic alternative to fossil fuel will be met.

2.5 PHOTOVOLTAIC MODULE PRODUCTION

2.5.1 Total production

Before 1980 very few terrestrial uses for photovoltaics were in operation. This was largely due to the cost involved which limited applications to space. In 1980 only 3 MW were produced, but by 1986 this had risen to 27 MW. Indications are for a steady increase of production with estimates for the 1990's being in the 120 MW range.

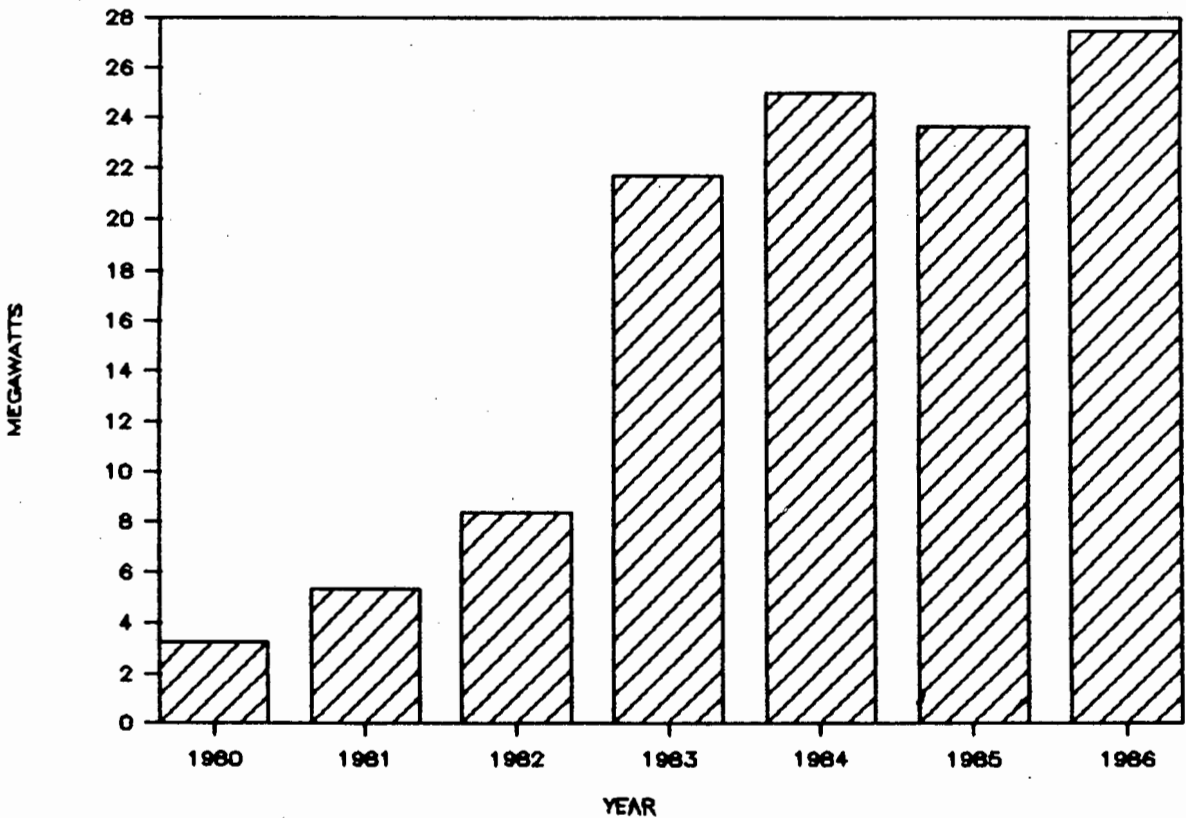


Figure 2.28: World Photovoltaic Shipments.

Source: Watts and Smith 1986 p2.2

Estimates for PV shipments come from a report from Battelle (Watts et al, 1986), from Strategies Unlimited (1987) and from Photovoltaic Energy Systems Inc. in Virginia (Maycock, 1985). It is to be noted that estimates vary and these differences are ascribed to differences in accounting for the power output of modules.

The range of these estimates (MW) is shown for the period 1983-1987

	1983	1984	1985	1986	1987
	----	----	----	----	----
Batelle.	20,8	21,6	20,5		
Strategies Unlimited.	14,5	17,4	18,7	21,0	
Photovoltaic Energy Systems.	21,7	25,0	23,7	27,3	28,6

Table 2.4 World Photovoltaic Power Output Estimates (MW).

2.5.2 Production by Technology

World production of photovoltaics can also be described in terms of the five main technologies, ie. single-crystal, polycrystalline, amorphous silicon, concentrators, and ribbon.

<u>Technology</u>	1980	1981	1982	1983	1984	1985	1986
	----	----	----	----	----	----	----
Single-crystal	1,9	2,5	4,5	9,9	9,6	9,9	11,1
Semicrystalline	1,0	1,3	2,1	3,2	4,5	4,5	5,5
Amorphous Sil.	0,3	0,6	0,8	3,0	4,3	5,8	8,0
Concentrators	0,0	0,9	0,9	4,6	3,1	0,1	0,1
Ribbon etc.	0,1	0,1	0,1	0,1	0,1	0,2	0,3
	----	----	----	----	----	----	----
	3,3	5,4	8,4	20,8	21,6	20,5	25,0

Table 2.5 Distribution of PV Shipments by Technology. (MW).

Source: Watts et al, 1986, p3.1

* mid-year estimate

Despite strong challenges the production of single crystal technology is stable, at about 10 MW since 1983. This reflects its continued use and strength in a number of market sectors. Semicrystalline cells reflect a growing interest as their efficiency improves and the manufacturing technology is established. Watts (1986, p3.1) points out that these two types have captured two thirds of the market due to their outstanding reliability and continued efficiency improvements. The report goes on to suggest that these set "the standard for other developing technologies to match".

Amorphous silicon has found a market in areas not competed for by the above technologies. To date, no serious penetration of the power module market has taken place by thin film technologies. However, research is taking place along such lines and modules larger than 5 W_p are appearing on the market. It is estimated that the share of the power module market supplied by amorphous silicon will increase in the late eighties. Applications in a variety of other areas (e.g. auto-mobile air conditioning) assure a continued use for this adaptable and innovative technology.

Despite "brilliant technical achievements" in the field of concentrating systems, (Watts 1986, p3.3), the market share has dwindled as shown in table 2.5 above. This is attributed to the loss of various tax shelter and government purchases which enabled this fledgling technology to develop and expand. Also, small photovoltaic buyers apparently consider the systems to be complicated compared to flat plate techniques, which have also been subject to greater federal assistance

Ribbon and sheet technologies have not made significant inroads upon the market, although they have maintained their 1-2% share. It is reported that several companies are involved (Westinghouse, Mobil Solar, and Solarvolt) with future expansion in this area.

In future years much will depend on innovations which could enable a newer technology to challenge the established and proven systems being produced by CZ techniques. The outstanding efficiency, reliability, and costs of these products will have to be matched by a-Si, before serious penetration can be envisaged.

The production by technology is clearly illustrated by the following bar chart:

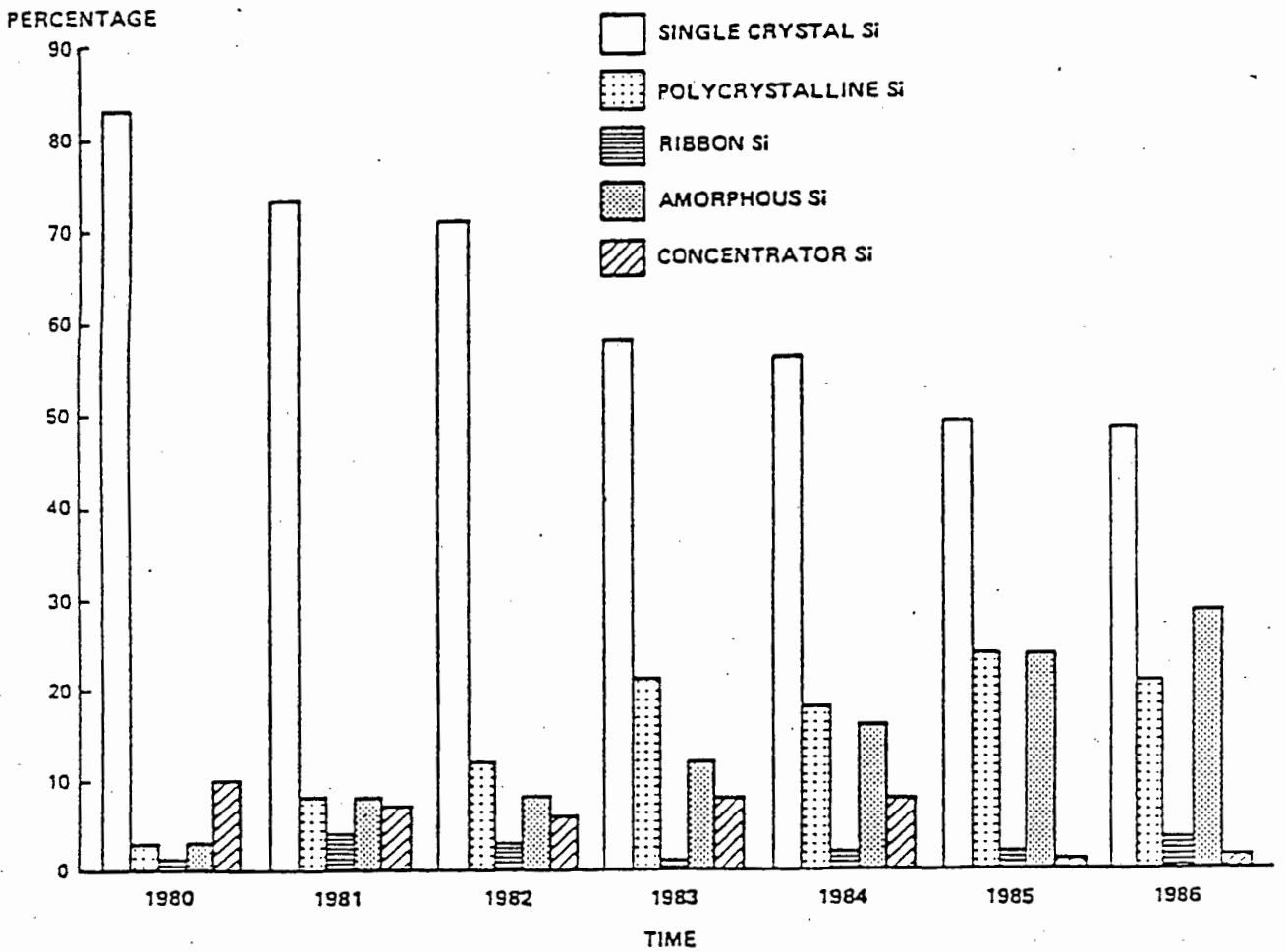


Figure 2.29 Photovoltaic Production by Technology.
Source: "Strategies Unlimited", 1987, p41

2.5.3 Output of Photovoltaics according to country

Production output was dominated by the U.S. for some years until the Japanese caught up with the technology. Thereafter the influence of thin film applications in the consumer market (mainly in the area of watches and calculators) has enabled Japan to lead the U.S.

Development, research and output in the U.S. have been affected by the efforts of the U.S. government to stimulate interest in various renewable forms of energy of which photovoltaics played an important role. In 1983 some 70% (8,5 MW) of U.S. shipments were either directly bought by the government or were heavily subsidized. This amount dropped to about 5,5 MW in 1984 and to around 1,5 MW in 1985, and is expected to decrease further as tax credits have been further reduced.

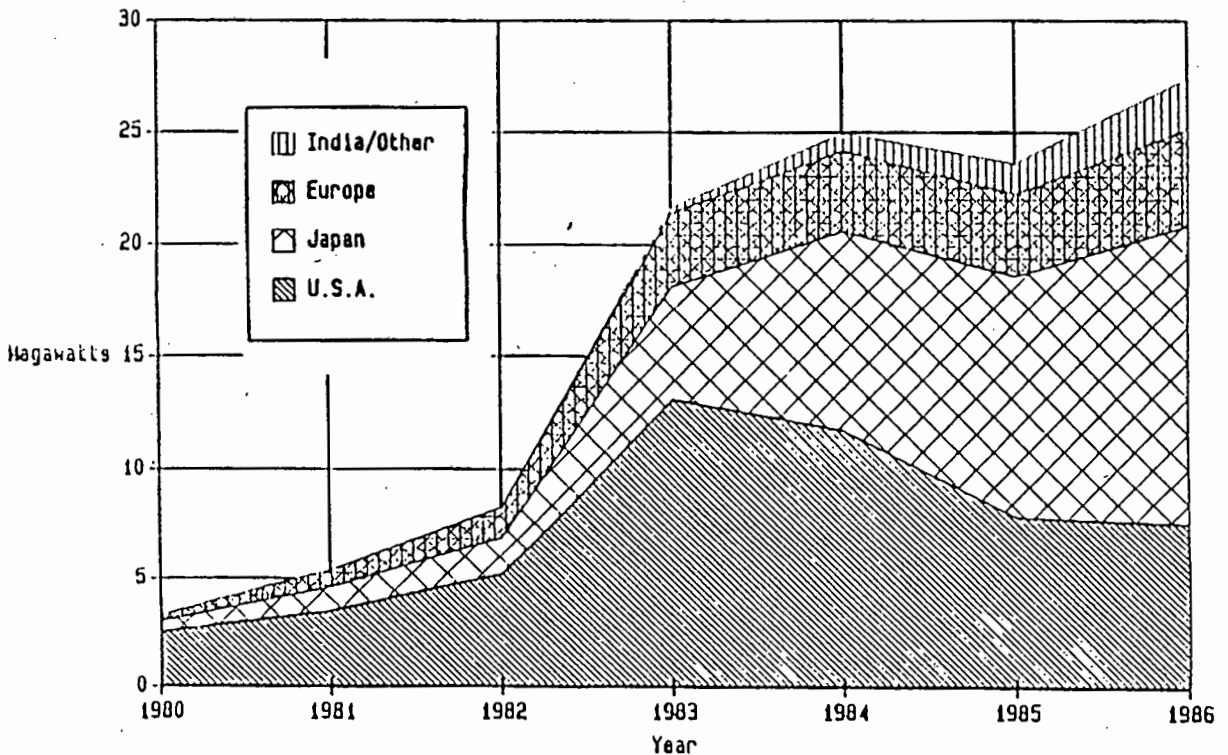


Figure 2.30 World Photovoltaic Shipments by Country.

Source: Photovoltaic Energy Systems, Inc.

(cited by Sissine, 1987, p15)

Considering percentages, the following above charts illustrate this loss of dominance of the U.S. and the rise of the Japanese. Also it is to be noted that Europe has managed to maintain its percentage and that 'other' countries are gradually increasing their share of the market.

The following charts illustrate these differing market shares for 1985:

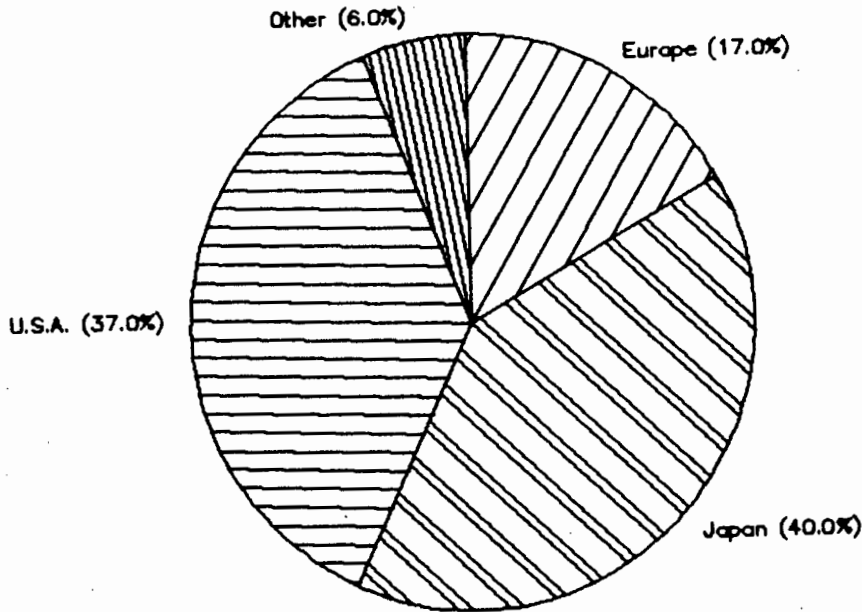


Figure 2.31 World Market Share for 1985. All Modules.
Source: Watts et al, 1986, p2.7

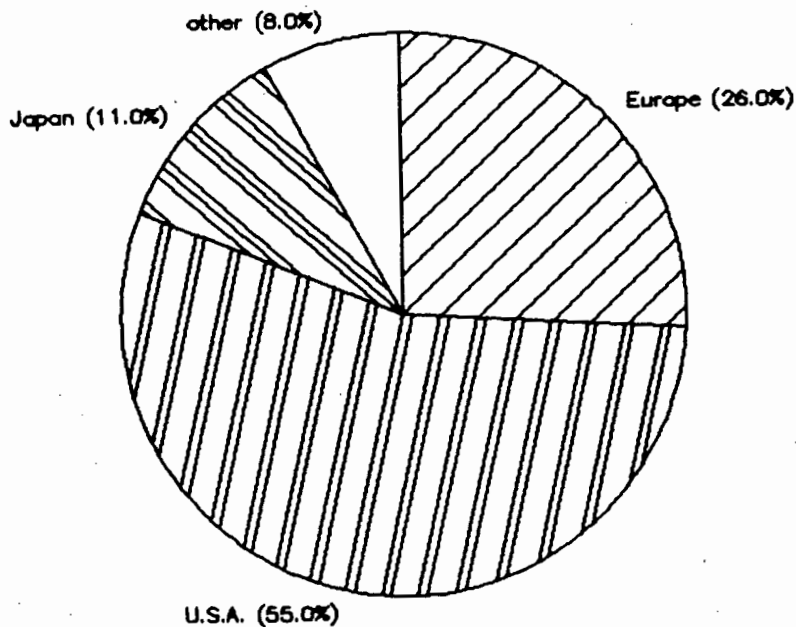


Figure 2.32 World Market Share for 1985. Power Modules only.
Source: Watts et al, 1986, p2.4

2.5.4 Production by Company

The technological interests of companies worldwide is summed up by Stategies Unlimited:

TECHNOLOGY		COMPANY
GENERATION	TYPE	
FIRST	<ul style="list-style-type: none"> • CZ Silicon 	<ul style="list-style-type: none"> • Arco Solar, Siemens, Sharp, Solec, Etc.
SECOND	<ul style="list-style-type: none"> • Polycrystalline Cast-Block Silicon 	<ul style="list-style-type: none"> • AEG Telefunken (Wacker), Kyocera, Photowatt, Pragma, Solarex, Solavolt • R&D. Only: Hamco, STC, Energy Material Corp., Spire, Crystal Systems Company
THIRD	<ul style="list-style-type: none"> • Dendritic Web • EFG Ribbon • ESP/ESR • ICC/Raft • RAD • RTR • SCS • S-Web 	<ul style="list-style-type: none"> • Westinghouse • Mobil Solar • A.D. Little • Heliotronic (Wacker) • Photowatt/CGE • Solavolt • Hoxan • Siemens
FOURTH	<ul style="list-style-type: none"> • Amorphous Silicon • CdS/Cu₂S • CdS/CdTe • CdS/CuInSe₂ • GaAs 	<ul style="list-style-type: none"> • AEG, Arco Solar, Chronar, Fuji Electric, Kanegafuchi, Komatsu, Kyocera, MBB, Mitsubishi, Sanyo Electric, Sharp, Siemens, Solarex, Solems, Sovonics, Spire, Teijin, 3M (partial) • Nukem • SOHIO, Matsushita, BP Solar, Photon Energy • Boeing, Arco Solar • ASEC, Chevron, Mitsubishi, Spectrolab, Spire, Varian

Figure 2.33 Company Support by Technology Options.

Source: Johnson, 1986, p2

Individual country shipments are listed in reports by Photovoltaic Energy Systems.

These are grouped into four main sections:

- (a) UNITED STATES
- (b) JAPAN
- (c) EUROPE
- (d) REST OF THE WORLD

(a) UNITED STATES

	1983		1984		1985		1986	
	MW	Module	MW	Module	MW	Module	MW	Module
Arco Solar	6,0	Single	5,5	Single	4,9	4,7 Single 0,2 a-Si	4,5	4,2 single 0,3 amorphous
United Energy	4,5	Conc.	3,0	Conc.	-	-	-	-
Solarex	1,3	Poly	2,1	1,5 Poly 0,5 Singl 0,1 a-Si	2,2	1,9 Poly 0,2 Single 0,1 a-Si	1,6	1,5 Single 0,1 amorphous
Solarvolt	0,1	Single	0,3	Poly	0,1	a-Si	0,3	Poly
Chronar					0,5	Poly	0,3	single
Sovonics					0,2	a-Si	0,1	consumer amorphous
Solar Power	0,4	Single	Terminated				-	-
Photowatt	0,3	Single	Terminated				-	-
Solec, Int'l	0,3	Single	0,4	Single	0,4	Single	0,3	Single
Solenergy	0,05	Single	0,1	Single	Terminated		-	-
Motorala	0,1	Single	0,3	Poly	-		-	-
Mobil Solar	0,07	Ribbon	0,08	Ribbon	0,1	Ribbon	0,12	Ribbon
United Energy	4,5	Concen.	3,0	Conc.	-		-	
Other Companies	0,05	0,03 Single 0,02 Conc.	0,2	0,1 singl 0,1 Conc.	0,15	0,05 Single 0,05 Conc 0,05 Ribbon	0,25	0,15 amorphous 0,15 concentrator 0,05 ribbon
TOTAL	13,07	MW	11,68	MW	8,55	MW	7,47	MW

(b) JAPAN

	1983		1984		1985		1986	
	MW	Module	MW	Module	MW	Module	MW	Module
Sanyo	2,0	a-Si	3,5	3,2 a-Si c 0,3 a-Si t	3,9	3,3 a-Si c 0,6 a-Si t	4,6	3,9 a-Si cons. 0,7 Terres
Fuji	0,8	a-Si	2,5	a-Si	2,8	2,6 a-Si c 0,2 a-Si t	2,5	a-Si cons.
Kyocera	0,4	Poly	0,65	0,6 Poly 0,05 a-Si	0,7	0,4 Poly 0,2 Single 0,1 a-Si c	0,85	0,8 Poly 0,05 a-Si cons.
Sharp	0,8	Single	0,5	Single	0,9	Single	1,0	single
ECD/Sharp	0,3	a-Si	0,4	a-Si	0,5	a-Si c	0,8	a-Si cons.
Hoxan	0,1	Single	0,3	Poly	0,5	Single	1,25	1,2 single
Kaneka	--		0,3	a-Si on steel	0,2	a-Si c	1,0	a-Si cons.
Nippon Elec.	0,15	Single	0,2	Single	0,3	Single	0,3	single
Hitachi	0,07	Single	0,15	Single	0,2	Single	0,2	Single
Komatsu	0,2	Single	0,1	Single	0,1	Single	0,1	Single
Mitsubishi	--		0,1	Single	0,2	Single	0,2	Single
Taiyo Yuden	--		--		0,15	a-Si c	0,3	a-Si cons.
Other	0,2		0,2	0,1 Single 0,1 a-Si	0,3	0,1 Single 0,2 a-Si c	0,3	0,15 Single 0,15 a-Si cons.
TOTAL	5,02 MW		8,9 MW		10,75 MW		13,4 MW	

c=consumer

t=terrestrial

(c) EUROPE

	1983		1984		1985		1986	
	MW	Module	MW	Module	MW	Module	MW	Module
AEG, Germany	0,95	Poly	0,75	Poly	0,8	Poly	0,6	Poly
Photowatt, France	0,6	Single	0,5	Single	1,0	Poly	1,0	Poly
Photon, France	0,4	Poly	0,3	Poly	0		0	
Pragma, Italy	0,25	Single	0,2	Single	0,5	0,3 Single	0,4	0,2 Single
			0,2	Poly		0,2 Poly		0,2 Poly
Ansaldo, Italy	0,25	Single	0,4	Single	0,3	Single	0,3	Single
Helios, Italy	0,35	Single	0,3	Single	0,2	Single	0,3	Single
Zontec, Belgium			0,25	Poly	0,1	Poly	0	
BP Solar Syst, U.K./Aust.	0,1	Single	0,2	Single	0,1	Single	1,0	Single
Isophoton, Spain	0,1	Single	0,15	Single	0,1	Single	0,15	Single
Siemens, Germany	0,15	Single	0,15	Single	0,1	Single	0,25	Single
Other	0,1	0,05 Single	0,10	0,05 single	0,1	0,05 Single	0,3	0,1 Single
		0,05 Poly		0,05 Poly		0,05 Poly		0,1 Poly
								0,1 a-Si
TOTAL	3,25	MW	3,6	MW	3,7	MW	4,3	MW

(d) REST OF THE WORLD

	1983		1984		1985		1986	
	MW	Module	MW	Module	MW	Module	MW	Module
Cel, India	0,1	Single	0,2	single	0,6	Single	1,0	Single
Heliodynamica, Brazil	0,07	Single	0,2	Single	0,2	Single	0,04	Single
Silonex, Canada	0,01	Single	0,1	Single	0,1	Single	0,15	Single
Bharat, India	0,01	Single	0,1	Single	0,2	Single	0,31	Single
Solarpac, Canada							0,02	Single
Other	0,08	Single	0,1	Single	0,2	Single	0,3	Single
TOTAL	0,31	MW	0,8	MW	1,4	MW	2,3	MW

Table 2.6 Output by company.

Source: Maycock, 1986.

2.5.5 Summary of Major Trends (1980-1987)

The output of photovoltaic cells has shown a dramatic increase over the last seven years. In 1980 only 3,3 MW were shipped and graphs shown illustrate the rapid rise which took place to around 20 MW by 1983. Total output has not maintained the same rate since this initial impetus. During this period the U.S. began to decrease its funding of alternative energy programs with the result that manufacturing companies were compelled to alter their programs accordingly, some companies leaving the industry altogether.

In the early days the United States dominated the scene, and still has a dominant hold on the power module market, though they will find strong competition for this position from Japan during the coming decade. The advent of amorphous silicon and its multitude of consumer applications changed the overall perspective. The Japanese concentrated on this technology and achieved the major share of the market.

The trend in standard technology has been to confirm the reliability and efficiency of single and polycrystalline silicon cells. Companies can now guarantee life spans of at least ten years for their power modules with expectations of twenty years or longer. More recent developments have been the sheet and thin film technologies which, so far, have not significantly altered the overall picture. Much research is being carried out to explore ways to achieve the same reliability and efficiency for thin film modules as is attained for single and polycrystalline cells.

It is also interesting to note that Europe has maintained its share of markets since 1983 and that a photovoltaic industry is evolving in the 'rest of the world'.

2.6 PHOTOVOLTAIC ECONOMICS

Photovoltaic costs comprise the cost of the module and the cost of the remainder of the materials and land required to produce a complete system. These are termed 'balance of system costs', (BOS) and account for some 30% of the total, although the proportion varies considerably depending on the size of the system and whether energy storage is included (SERI, 1986, p18).

The cost of the module is normally expressed in dollars per peak watt ($\$/W_p$), though some sources use a cost per square meter ($\$/m^2$). The cost of a system is usually expressed as dollars per watt ($\$/W$) produced, with comparisons also made in cents per kilowatt-hour (c/kWh). In the following discussion it will be shown that this cost is the essence of photovoltaic economics; the long term aim being to make photovoltaic systems cheaper than fossil fuel electricity.

2.6.1 Historical trends

The costs of photovoltaics have dropped since serious development work began in the 1970's. And although new generation technologies are maintaining this trend, progress has not quite kept up with earlier projections. The cost per peak watt was forecast to decrease significantly over the last decade. This is demonstrated by the next graph which represents a U.S. Department of Energy projection in 1980.

The current low cost of oil and resultant reduction in research funding has had the effect of slowing down the development of cells and has consequently reduced the rate of cost savings which seemed reasonable in the early 1980's.

Curve C estimated costs for thin film with the comment that if mass production became feasible by mid 1984 then the curve would move to position B. The ideal of 50c/W_p has not been realized to date.

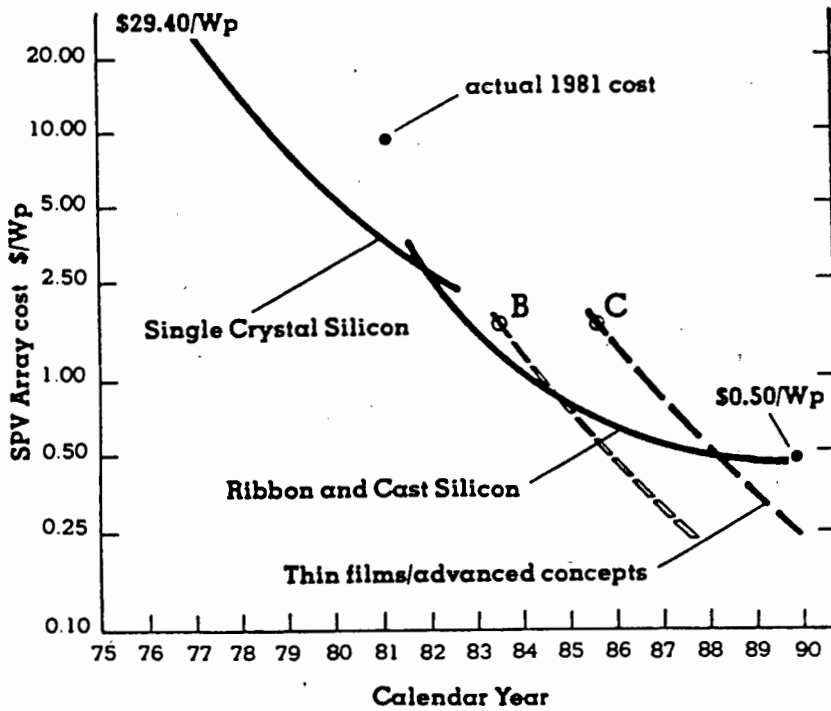


Figure 2.33 Projected PV prices (1980 U.S. dollars).
Source: Kiss (1982) p63. From U.S. Dept. of Energy

Actual PV costs and prices are collated below from the given sources and though the cell materials are often 'not specified', it can be assumed that silicon crystal flat plate cells are referred to, particularly when power applications are in question.

The distinction is not often drawn, by the sources listed, between production and selling costs. Equally it is sometimes not apparent whether some prices apply to the cell, module or system. Also, sources seldom differentiate between the year referred to and the time of writing dollar value.

Hoffman (1985, p9) points out that the cost of photovoltaic modules is further obscured by the common practice of manufactures being 'typically reticent' regarding the price to produce the cells and the cost in the marketplace. He adds that it is widely assumed that production costs are higher than sale prices as manufacturers are striving for a market share rather than profits. It is considered that profits will occur when demand increases and economies of scale are attained. This may have some bearing on the values quoted.

Nevertheless, the following table shows clearly the downward trend exhibited by photovoltaics.

Cell material	Date	Module Price in \$/W _p	Source
Not specified	1958	2000	Hoffman (1985, p9)
Not specified	1959	1000	Kiss (1982 p63)
Not specified	Early 70'	500	SERI (1985, p3)
Not specified	Early 70's	50-60	Hoffman (1985, p9)
Not specified	1974	50	Hamakawa (1986, p31)
Not specified	1975	25-90	Ferber et al (1979 p2)
Not specified	1979	10	Kiss (1982 p63)
Polycryst. Si	1979	12,7	Wald (1982 p8) From DOE.
Not specified	1980	10	Hoffman (1985, p9)
Not specified	1983	7-10	SERI (1985, p60)
Not specified	Feb 1985	10	SERI (1985, p3)
CZ Si	1985	4-6	Hamakawa (1986 p31)
a-Si	1985	3-5	Hamakawa (1986 p31)
Concentrator	1986	4	Krantz (1986 p1260)
All modules	1986	4-8	Hamakawa (1986 p30)
Single and polycrystalline	1987	3.50-3.75 cost 5.50 selling price 4.50-5.50 large orders	Maycock, cited in ISEI report April 1987, p120.
Ribbon-cell	1987	4.50 cost 7,50 selling	ibid
Concentrator	1987	3,00 cost 5,00 selling	ibid
Amorphous Si	1987	3,00 cost 5,00 selling	ibid

Table 2.7 Prices for PV modules.

Source: as quoted in table.

Expressed in graphical form from 1974, it is seen how the prices have fallen sharply from then and have steadily reduced since.

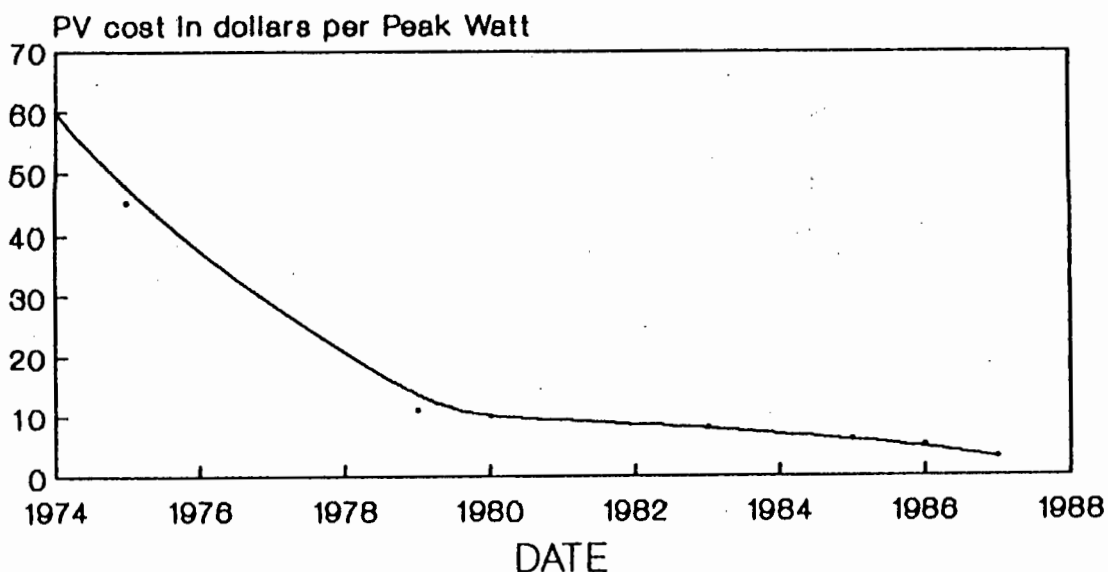


Figure 2.34 Photovoltaic Module Cost against Time.

Source: Table 2.7

2.6.2 Future Trends

Estimates for future prices are of importance and are collated in the table below:

Cell material	Module Price		Projected year
	Cost	Selling	
Single crystal	\$2,40	\$4,00	1990
	\$2,10	\$3,50	1995
Polycrystal	\$2,10	\$3,50	1990
	\$1,80	\$3,00	1995
Ribbon Cell	\$3,00	\$5,00	1990
	\$2,10	\$3,50	1995
Concentrator	\$1,80	\$3,00	1990
	\$1,20	\$2,00	1995
Amorphous Si	\$1,50	\$2,50	1990
	\$1,20	\$2,00	1995

Table 2.8 Estimation of PV costs in the future.

Source: Maycock, cited in ISEIR April 1987, p120

Maycock, cited further in the ISEI report, says that if a concentrator cell costing $10-20c/W_p$ can be manufactured then the price of a concentrator module will fall to below $\$1/W_p$. He states that this forecast will become reality after the year 2000. Estimations of production potential depend on a number of factors such as the price of oil. Maycock points out that if the present price of oil is maintained ($\$15-20$) then the likelihood of the above estimates leading to large scale installed PV power is 'very low'. However, he goes on to say that world PV markets are going to be very large indeed if the 1990 and 1995 estimates hold. PV will be able to compete directly with '10 million small diesel or gasoline generators now used for daily power.'

2.6.3 South African PV prices

The above cost reduction in dollar prices are not so apparent in Rand terms as the value of the Rand has fallen over the last few years. Considering the values expressed in table 2.8 and listing the Rand equivalent, quoted for August of the year concerned, shows this clearly in the following table. Quoted prices of local suppliers are also indicated, where available.

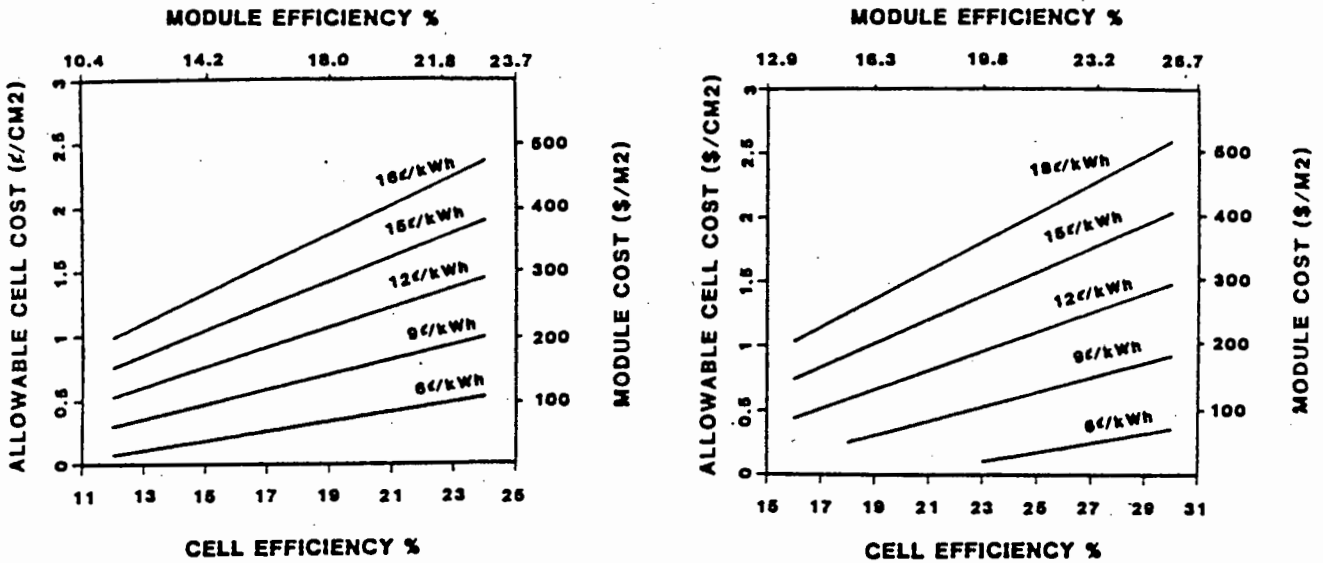
Date	Module price \$/Wp	Module price in Rand Equivalent Rate \$/R	Rand cost	Local Supplier list price. R/Wp
1959	1000			
early 70's	500	1,41	R354,61	
early 70's	50-60	1,41	R35,46-R42,55	
1974	50	1,45	R34,48	
1975	25-90	1,4	R17,85-R64,30	
1977		1,15		
1979	12,7	1,21	R10,49	
1980	10	1,31	R7,63	
1981		1,056		
1982		0,86		13,61 (36 Wp)
1983	7-10	0,89	R7,86-11,24	11,11 (35 Wp)
1984		0,625		11,33 (30 Wp)
1985	4	0,45	R8,89	15,64 (Average)
1986	4-8	0,38	R10,53-R21,05	22,14 (35 Wp)
1987	5 (average)	0,47	R10,64	19,40 (40 Wp)

Table 2.9 Comparison of Dollar to Rand Costs.

Source: Table 2.8 Local suppliers and Standard Bank
International Division

2.6.4 Cost versus Efficiency

The price to which photovoltaics will have to fall to be fully economic with alternatives is also linked with improvements in the efficiency of PV power production. This is shown clearly in the graphs following for flat plate and concentrating systems.



(a) Fixed Flat Plate

(b) Concentrator

Figure 2.35 Fixed plate and concentrator cell cost versus peak performance for various system levelized energy costs.

Source: Arvizu, 1987, p130

2.6.5 Cost comparisons with alternatives

Ultimately the potential of photovoltaics is determined by the cost of electricity production compared to competing electricity generating technologies. Currently photovoltaics are competitive in many remote area power supply situations where it is unrealistic to extend the national grid. Here the main alternative is diesel generation, which is both costly and has high maintenance requirements.

As the costs of photovoltaics fall, more and more applications closer to the national electricity grid will become competitive and some optimists even forecast that photovoltaics will be able to compete with fossil and nuclear power stations by the turn of the century.

The comparisons with other forms of energy on an installed capacity basis is illustrated by the next chart:

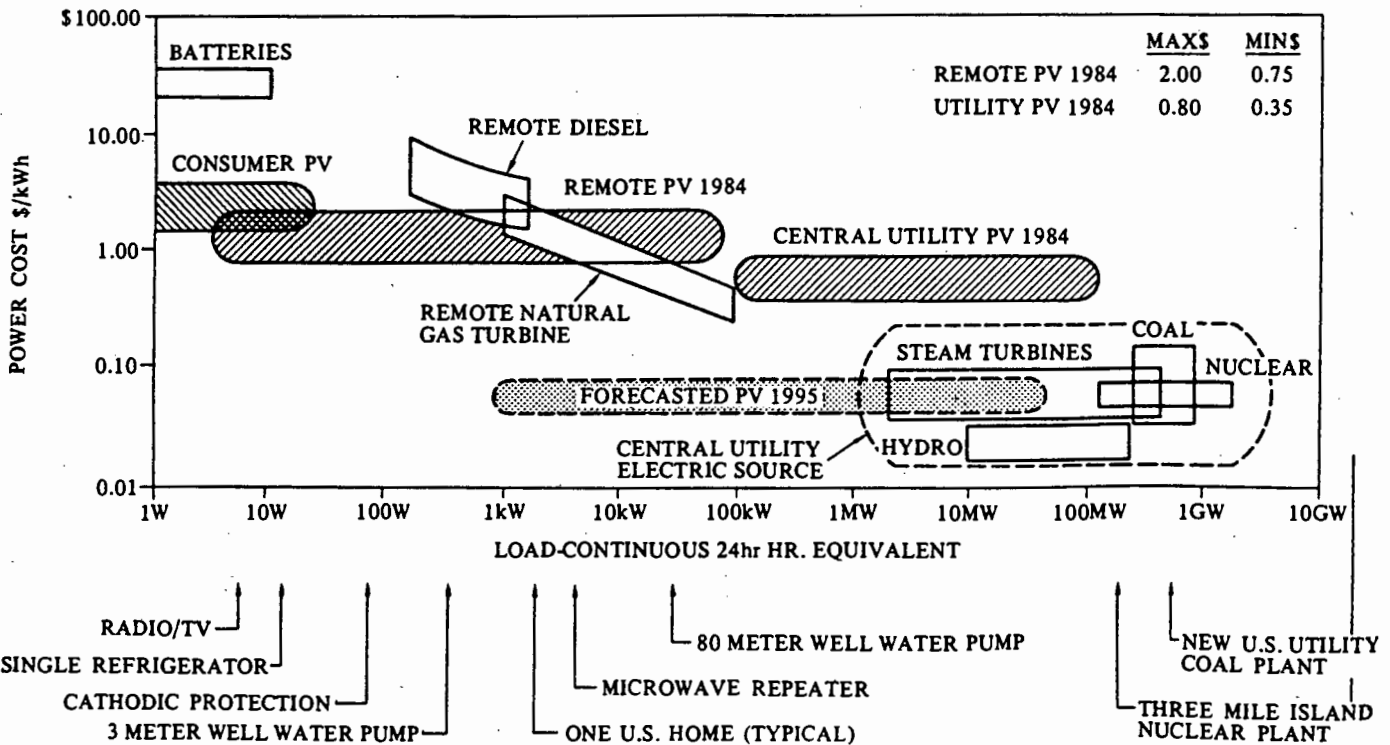


Figure 2.36 Economic Domains

Source: Hamakawa, 1986, p34

2.7 FUTURE PROSPECTS

The following goals have been set by the U.S. Department of Energy for photovoltaics:

Systems	Flat Plate Systems	Concentrator
Module Efficiency	13%-17%	23%-29%
Module Costs	\$40-\$75/m ²	\$90-\$160/m ₂
Balance-of-System		
Area related	\$50/m ²	\$100/m ²
Power related	\$150/kW	\$150/kW
System Life-expectancy	30 years	30 years
PV electricity costs	6,5c/kWh	6,5c/kWh

Table 2.10 Long-Term (late 1990's) Technical Goals
(1982 dollars).

Source: SERI, 1986, p3

The cost of 6,5c/kWh would make PV systems highly competitive with conventional fuel systems. The U.S. government has set intermediate goals too. For instance, the 1988 aim is 12% efficiency for a-Si small area cells (1 cm²) and 8% efficiency for submodules of 1000cm². SERI notes that the efficiency achieved in 1985 of 10% for small area cells and 7% under outdoor conditions was an increase of 15% on the achievements of 1984 (SERI, 1986, p5).

Systems	Flat Plate Systems	Concentrator
Module Efficiency	15%-20%	25%-30%
Module Costs	\$45-\$80/m ²	\$60-\$100/m ₂
Balance-of-System		
Area related	\$50-\$100/m ²	\$125/m ²
Power related	\$150/kW	\$150/kW
System Life-expectancy	30 years	30 years
PV electricity costs	6,0 c/kWh	6,0 c/kWh

Table 2.11 Long-Term (year 2000) Technical Goals
(1986 Dollars).

Source: Document DOE/ch10093-7 (cited by Prince, 1987, p3)

It is noteworthy that the goals were revised and by May 1987 in updated Five year Research Plan (figure 2.11) was issued which increased efficiency expectations and reduced expected costs.

It is assumed that the rate at which improvements are made will continue and the goals called for above will be met, not only in obtaining increases in efficiency but also in achieving the important life expectancy of 30 years.

If these aims can be met then the advent of sufficient, pollution free, power from the sun will become a reality. The following graph shows clearly how the cost of PV power has fallen over the last decade and that the trend is expected to continue and to be well below the utility power costs in the 1990's.

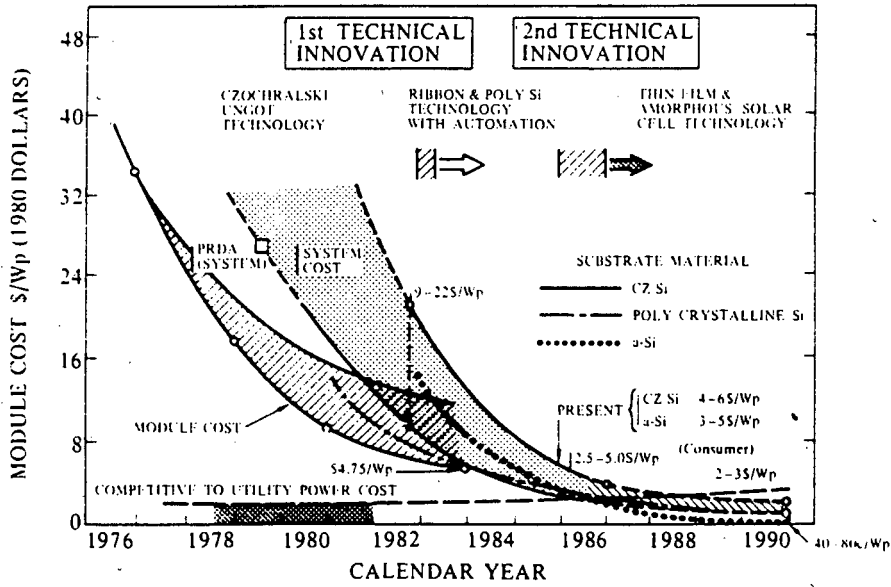


Figure 2.37 PV Module cost versus Time.

Source: Hamakawa, 1986, p31

The market volume into the future is estimated by Strategies Unlimited to continue to grow impressively:

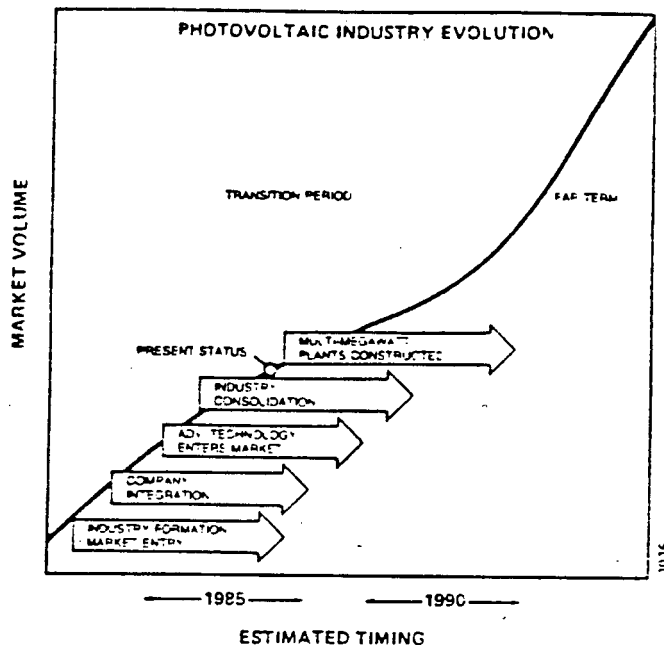


Figure 2.38 PV Industry Evolution

Source: Johnson (Strategies Unlimited), 1986, p2

The trends in company participation is noted by Johnson as interesting. In both the U.S. and Europe, four major oil companies are now amongst the leading photovoltaic manufacturers. Germany is an exception with AEG and Siemens predominating and in Japan, production is in the hands of electronics manufacturers.

Krantz (1986, p1259) points out that at the start of the five year research program in the U.S. it was thought that the Czochralski method, with possible improvements in technique, would be sufficient to meet the goals outlined previously. Current thinking, he says, rules against this concept as U.S. manufacturers gradually switch their emphasis to advanced technologies.

Recently this appears to have altered. Strategies Unlimited, in their 1987 report point out that a continuing interest in developing lower cost, relatively higher efficiency cells using single crystal and polycrystalline materials is emerging. Both Westinghouse and Mobil Solar have announced expansions of their ribbon production facilities.

It is not too speculative to comment that the rate of discovery has been so rapid over the last decade that with or without a '3rd Technical Innovation' the world will be able to enjoy a truly changed outlook on photovoltaic power by the turn of the century. Looking even further ahead Frost and Sullivan estimate that by the year 2010 some 131 000 megawatts of solar power electrical generating equipment will be installed worldwide of which some 88% will be supplied by photovoltaic systems (Stoiaken, 1984, p6).

CHAPTER 3

PHOTOVOLTAIC APPLICATIONS IN THE THIRD WORLD

3.1 INTRODUCTION

paraffin Photovoltaic applications can be categorized according to three broad types of systems:

(i) Stand alone systems

These systems are not connected to the grid. Applications include navigational aids, communications, vaccine refrigeration, cathodic protection, central village power, lighting, home power and water pumping.

(ii) Grid-connected systems

Here, power generated from the array is fed into the electricity grid system. Applications range from small residential systems to multi-megawatt generation plants.

(iii) Consumer products

Applications include watches, calculators, toys, trickle chargers, vehicle air conditioning etc.

Because of the absence of extensive electrical grids in developing countries it is generally stand alone PV systems which are of most interest.

Over the last decade significant progress has been made in the installation of photovoltaic powered projects in developing countries.

PV power systems have proved to be an appropriate technical solution for rural and remote applications, resolving fuel supply uncertainties and maintenance problems. They offer the advantages of high reliability, low maintenance, short construction periods, modularity and environmental acceptability.

This chapter is a review of these projects, with particular emphasis on the technical, financial and institutional factors involved in each of the main areas, viz.:

- (1) water pumping;
- (2) communications;
- (3) vaccine refrigeration;
- (4) lighting and home power systems; and
- (5) multi-use systems.

In each of these sections, discussion will include a summary of field experience, current technical and cost data, including data for competitive technologies, and a financial analysis comparing life cycle costs of PV and conventional powered systems.

This chapter will draw quite substantially upon Eskenazi et al (1986), a study which was sponsored jointly by the US Department of Energy and the US Bureau for Science and Technology, and which reviewed some 2700 projects in 45 countries.

3.2 TECHNICAL REVIEW

3.2.1 Water Pumping

The majority of the rural populations in underdeveloped countries live in sunny areas with relatively shallow water resources. Their need for water for both human and animal consumption and for irrigation can be largely met by the use

of photovoltaic-powered water pumping systems. In the past, the principal power sources have been diesel generators, human labour and animals. PV systems can meet the need without requiring any fuel or the extensive maintenance common to diesel generating sets. Further, the release of labour to pursue more productive activities is a welcome bonus, as is the avoidance of the "milk and meat loss" accompanying the use of farm animals as power sources.

3.2.1.1 Technical considerations:

The simplest arrangement consists of a PV array and a motor/pump set.

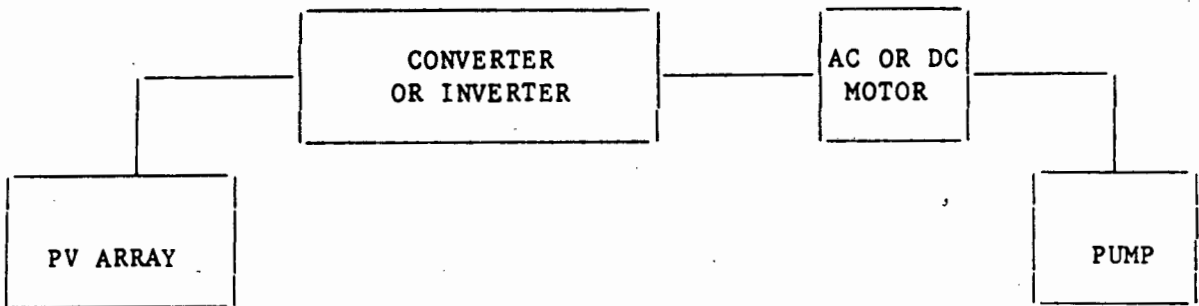


Figure 3.1 Configuration of a PV-Powered Pumping system.

Source: Eskenazi et al, 1986, p3-4

If a DC motor/pump set is used, power conditioning is eliminated though a DC-DC converter can increase efficiency. An AC unit would require an inverter but has the advantage of having a brushless motor. Battery storage is not common with this application; storage of water, itself, being a more economic proposition. However, some battery storage may be used for early morning motor start-ups when insolation is still low.

Centrifugal pumps are most efficient at flow rates greater than 25m³ per day and lifts of up to 50 meters. Positive displacement pumps, both rotary and reciprocating, are good for low flow applications with lifts from about 15 to 300 meters.

Systems may be broadly classified as:

- (1) Submerged pump and motor. The centrifugal pump may be single or multi-staged.
- (2) Submerged pump with a surface-mounted motor. Centrifugal or positive displacement pumps are in use.
- (3) Floating pump and motor using a centrifugal pump.
- (4) Surface mounted pump with a self-priming tank, taking advantage of the better self-priming characteristics of positive displacement pumps.

3.2.1.2 Field experience:

The experience of actual projects has identified factors common to successful systems.

- (1) The reliability and good performance of the subsystems.

Failure of components has been ascribed to lack of quality control of equipment and/or installation; further, insufficient well yield can cause the motor to burn out.

More overload and protection equipment is suggested with greater emphasis on carefully matching the system to the particular well.

- (2) The availability of accurate solar and water resource data.

Array sizing is a direct function of accurate and credible solar data. It is a key factor since inaccuracy can result in underpowered or overpowered systems causing failure to meet water requirements or the installation of a too costly system.

(3) The involvement of end-users.

Experience has shown that feelings of ownership and responsibility are the key to successful enterprises. The more the local community can be involved with the installation and running of the project the more likely will the community strive for the success of the system. User expectation is another key factor which necessitates careful handling. "The use of pumped water for irrigation or village water supply is a sociopolitical issue for any installation." (Eskenazi et al, 1986, p3-15)

* (4) The presence of the necessary infrastructure to provide technical back up and spare parts.

PV systems experience the same infrastructure problems as other remote power technologies, but due to their reliability and low maintenance characteristics, are liable to be more dependable than conventional systems.

3.2.1.3 Survey reports:

Some comments drawn at random from a survey carried out of water pumping projects around the world are listed below:

(i) Mali

More than 80 systems have been installed in Mali. The choice of PV was found to be necessary because of the unavailability of other types of fuel. Most performance difficulties have come from the pumps and electronics, consequently the training of engineers in PV system technology is considered essential, with emphasis on trouble shooting, repair, and maintenance requirements.

Users perceive problems with ancillary equipment, such as storage tanks, to be failures of the PV system and hence greater emphasis is recommended to be placed on full system design (Eskenazi et al, 1986, pB-4).

(ii) Egypt

The Desert Development Project has been successfully powered since 1981 by 10 kWp and 3 kWp PV arrays. These power an HQ building, an AC submersible pump and a DC motor driving a deep well pump. Apart from pump vibrations, there have been no problems. It is noted that the 88,8 kWh of battery storage must be attended to with unfailing regularity (Assabghy and Derrick, 1985; Lesnick, 1985).

(iii) Botswana

The study was based on more than 3 years of actual field experience, and compared a 6 kW Diesel with a PV system. It concluded that there was no significant mechanical obstacles involved with installing PV systems, cost being the significant factor. Further, the well recovery rates were often lower than the yields with the result that wells would dry out. Peak yields were considered to be a significant limiting factor in PV application.

A "continuous discounting" life-cycle cost analysis, based on a 2% discount rate and a 20 year life, showed that photovoltaics are economically competitive with diesel engine systems at the present time. The range of economic competitiveness was found to be higher than any previous quoted work and was considered in part due to the use of existing pumps and infrastructure in the design.

(Danley, 1984).

(iv) India

Diesel and biogas systems were rejected in favour of a photovoltaic system. The problems which arose were of a bureaucratic and administrative nature. By consensus, a solar water management committee came into being for the distribution of water. It has managed to satisfy contradictory needs after much debate. It was concluded that such systems can only be implemented with the full cooperation of everybody concerned (Amado and Blamont, 1983).

(v) UNDP pump test

The 1980-1983 pump test programme of the UNDP, and the World Bank, undertaken by Sir William Halcrow and Partners, showed that PV systems are cost competitive with diesel pumps when:

- (a) Irrigation water requirements were not more than 150 m³/day with the minimum monthly average solar radiation greater than 15 MJ/m²/day.
- (b) Daily water requirements are less than 250 m³/day and where the average solar radiation is greater than 10 MJ/m²/day. (UNDP Project GLO/80/003, 1983).

3.2.2 Communications

Traditionally, communication systems have been powered by grid electricity, stand alone generators or primary batteries. Because of problems involving fuel, spare parts, poor quality power and high costs, the expansion of telecommunication networks and the implementation of small systems in the third world, has been severely restricted.

Equipment Type	Typical application
VHF/UHF Microwave repeaters repeaters	High capacity radio for TV and Phones.
Radiophones VHF/UHF	Single channel radio with PABX interface.
Cablephones	PV powers subscriber unit in mountains.
HF Radio	Inexpensive low quality rural radio.
TV Translators	Redirect TV broadcasts into valley areas.
Fibre optic Cable System	Data Transmission.
Mobile Radio VHF/UHF	Personal, vehicle or cellular radio.

Table 3.1 Typical Telecommunication Applications.

Source: Eskenazi et al, 1986, p4-1

PV-powered communication systems, on the other hand, have a proven commercial record throughout the world. In communication systems reliability is critical due to the difficulty and cost involved in frequenting the site and/or the intangible cost of not having a communications link. This reliability requirement is ably met by photovoltaics. Some 10 000 new PV systems are being installed per year, with typical applications listed above.

3.2.2.1 Technical considerations:

The simplest arrangement consists of the array, battery storage and power conditioning, though more complex systems can include remote telemetry, allowing for control and monitoring from a distance. Some systems are hybrids combining PV with diesel, battery or wind technologies.

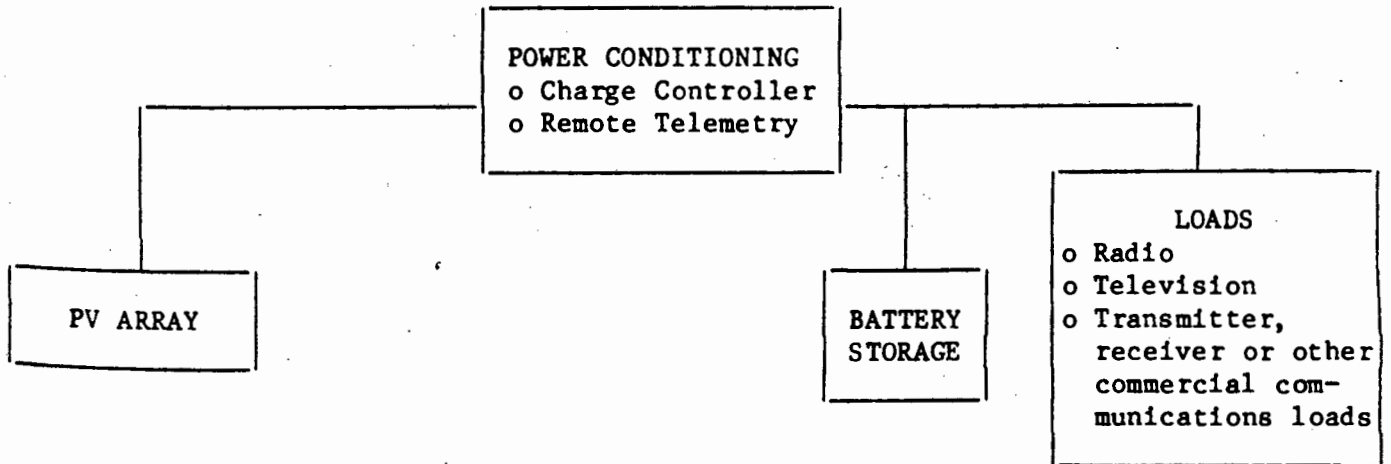


Figure 3.2 Basic PV Powered Communications System.

Source: Eskenazi et al, 1986, p4-3

Sealed batteries are usually used for remote communications systems to eliminate the periodic addition of water and to increase safety. It is to be noted, in the use of diesel generators, that the smallest 'off the shelf' unit is 3kW. For smaller systems this mismatching has resulted in high maintenance and operating costs. By comparison photovoltaics are designed to match the required load, whatever the size.

Further, diesel and gasoline engines require a constant supply of fuel and spare parts. The cost of these items is highly site specific and often dependent upon prevailing socio-political considerations. ✖ Failure of supplies often leads to deep discharging of the batteries and hence shortened life. Again, photovoltaic systems bypass these problems and, in addition, can include built-in protection measures against overdischarge. ✖

3.2.2.2 Field Experience:

Key factors for successful implementation of communication projects are identified as:

(1) Charge controller reliability

These components represent a small percentage of the overall cost but potentially a high cost maintenance item on failure. Early generation controllers experienced difficulty due to environmental conditions, but the latest types have overcome such problems. Purchasers of successful systems have been willing to pay a higher price for reliable, field proven equipment.

(2) Radio Equipment Durability

The durability of load equipment is no different to conventional powered systems, for successful implementation of a communications project strong attention has to be given to the selection of appropriate field proven equipment.

(3) Battery Life

These items are a major cost of any PV system. For remote telecommunications the reliability of the battery is of paramount importance. Careful selection of the best unit is advised, with a preference for low maintenance, sealed and deep discharge units, being shown by companies.

3.2.2.3 Survey reports:

Some comments drawn at random from surveys carried out of various Communication systems are listed below.

Papua New Guinea

In 1976 a PV repeater station was commissioned on Mount Namsbamati. It consisted of nine 26 W modules together with rechargeable nickel cadmium batteries. The microwave repeater is a vital link in the Trans-PNG International Telecommunications Network. The system has functioned well with zero maintenance requirement. Many more PV-Powered stations have been commissioned since 1978 (Suarez, 1978).

Niger

More than 1000 PV-powered Television sets have been installed in rural sites. PV technology was chosen because of its compatibility with rural village conditions of isolation and difficult roads. It has proved totally effective and the system is continually being expanded (Chevillard, 1985a).

Guyana

Health Care Communication Systems. The importance of two way radio communication for medical purposes is well recognized. Power supplies are a persistent technical problem which are overcome by the installation of PV systems. The medical radio system performed well over distances of 200 km in Guyana although more problems were experienced in the hillier terrain of Kenya. Field testing does not indicate any problems with the PV system, but it is pointed out that none have been in use long enough for definite evaluation (Slominski, 1983).

Australia

Although not a developing country, the extensive experience of Telecom Australia with PV powered repeaters is relevant. They have had no system failures after 10 years of continuous use. PV systems have proven economic as well as reliable for systems up to 300 W continuous. For greater loads, hybrid systems of PV with Wind or Diesel are planned (Moon, 1985).

3.2.3 Vaccine Refrigeration

Refrigeration is a vital component of health care in the developing world. It is needed for storing vaccines and freezing ice packs in hospitals and health centers. Vaccines have to be transported over great distances to reach people in remote areas. Several months may be involved in this process. Refrigerators are identified as the final link in this 'cold chain'.

Generally there is no electricity in these rural areas where the health centers are located. Fuel and power supplies can be erratic. Refrigeration has been usually supplied by paraffin or bottled gas refrigerators. Some six to eight hundred PV powered refrigerators have been installed world wide. The better performance, lower operating costs, better reliability and longer working life of these units is being demonstrated.

3.2.3.1 Technical considerations:

A wide range of refrigerator sizes are available and whilst the WHO states that only about 4 liters of packed vaccine are needed per month in villages with approximately 150 births per month, there are other medical supplies that need storage. Thus, the optimum size is under debate.

Further, the system should be able to freeze ice packs which are essential for the transportation of vaccine to the field. This specification places a significant load on the system.

The reliability of PV powered refrigeration systems has improved with increased field experience. The effectiveness of the refrigerator can be expressed in terms of the percentage of time the system is operational.

Earlier PV systems had an availability of 80 to 85% whereas recent installations have improved to 95-99%. This is a particularly sensitive issue for vaccine refrigeration where not operating within technical specifications can result in total vaccine loss.

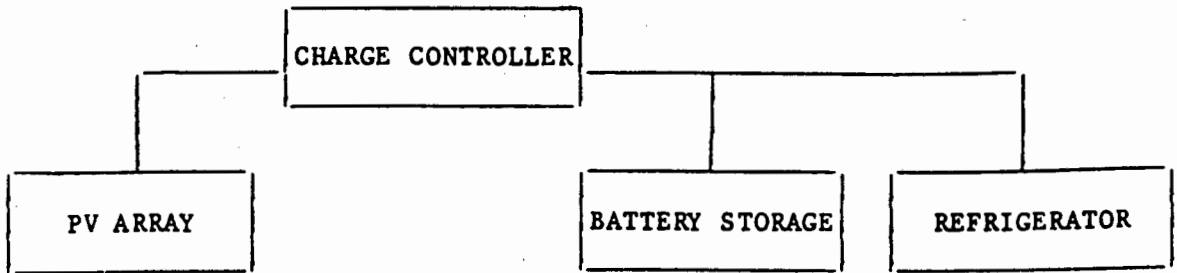


Figure 3.3 Schematic of a PV powered Refrigeration system.

Source: Eskenazi et al, 1986, p5-4

Conventional powered systems have not been able to meet the high reliability standard demanded. The logistical problems of maintaining a continuous fuel supply are so great that for most of the units purchased for use in outlying areas continuous operation has proved impossible. To add to this difficulty, the lack of spare parts and maintenance problems necessitated by the poor quality of local paraffin have further hampered efficient operation.

3.2.3.2 Field experience:

Key factors that have emerged as essential to successful implementation are:

- (1) Accurate array and battery sizing

Successful systems have generally been implemented by suppliers with previous experience, who have then been able to avoid costly systems resulting from overdesign or poor performance due to underdesign.

TECHNICAL
DISADVANTAGE
Underdesign has been one of the main factors causing refrigerators to experience operating temperatures outside the prescribed range.

(2) User training and support

Successful operations have been those which have provided effective training for the user, not only in terms of use of the refrigerator (incorrect use has usually meant the user placing large amounts of warm material into the refrigerator) but also in terms of maintenance and trouble shooting. Adequate manuals, documentation and spare parts are not always provided by suppliers.

(3) Coordination with end use organization.

An important element of successful systems has been co-operation between the supplier and the host country. Identification of appropriate organizations and implementation agencies is seen as the key. Some projects have failed to meet their objectives because the responsible agencies in the field were not familiar with the end use.

3.2.3.4 Survey reports:

Some comments drawn at random from surveys carried out of various PV powered refrigeration systems are listed below.

NASA-Lewis survey

PV powered refrigerators were installed at 28 sites in 23 countries around the world from 1981-1983. There have been no known PV power system problems, although system defects include defective components such as voltage regulators.

Refrigerator misuse occurs by incorrect setting of the thermostat and by the placing of excessive amounts of warm food into the refrigerator. The refrigerators, themselves, have been relatively problem free with no compressor problems (Hein, 1982; Ratajczak, 1985).

WHO field trials

Twenty field trials were initiated in different areas of the world ranging from Ghana to the South Pacific Islands. The result of these trials was to endorse four refrigerator models for vaccine storage. Technical problems in the field included improper sizing of the array/battery and instrumentation failures. It was noted that energy consumption in the field did not match that anticipated from laboratory tests (Dierof et al, 1985).

Gambia

An analysis of an actual immunization program carried out in the Republic of Gambia estimated the cost per dose for paraffin refrigerators to range from \$0,62 to \$1,19 whereas the more reliable PV powered units cost \$0,53 to \$1,14. However, it is pointed out that the benefit consists of improved cost-effectiveness rather than reduced costs, since many more vaccinations will occur for a given quantity of vaccine using the PV system. This analysis, based on field experience of 28 systems, assumes that the solar vaccine refrigerator will be 90-100% reliable, compared with paraffin being only 85% reliable (UNDP/World Bank, 1985).

3.2.4 Lighting and Home Power

Photovoltaic power for area lighting and home power systems is emerging as a significant technology in the developing world. In the past, the demand for lighting in rural areas has been met by using paraffin, candles or primary batteries. These sources are expensive and of poor quality. For example, a 20 W fluorescent tube supplies some eight times the light given out by an average paraffin lamp.

In these areas lighting is used for street and security lighting purposes as well as the normal evening activities of cooking, reading, simple work and social activities. Photovoltaic systems supply these needs as well as being able to produce power for radios, televisions, refrigerators and/or water pumps. It is this versatility which makes PV systems so attractive.

PV powered lighting and home power systems have proved to be technically reliable with many users finding such systems to be cost competitive with the current predominant technology of paraffin fueled lamps.

3.2.4.1 Technical considerations:

A lighting system consists of three parts. The PV module; the light, which is usually of the gas vapour type; and the ballast, which controls the current flow into the lamp. For home use a typical one or two module system would operate two to four fluorescent lights (ten to forty watts each). This type of system is often combined with other user options such as refrigerators, radios, televisions, fans, etc.

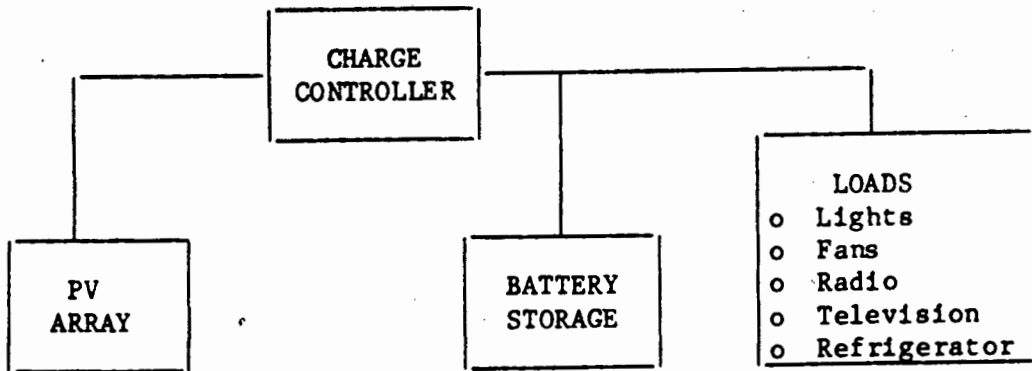


Figure 3.4 Configuration of a Home Power System.

Source: Eskenazi et al, 1986, p6-3

In rural areas paraffin lamps have the versatility of use both within and without a building. This has been addressed by developing a rechargeable nickel-cadmium powered fluorescent lamp, which fulfills this purpose admirably. The problems of fuel and maintenance are significant for a paraffin based technology. The lamps require constant attention and spare parts. By comparison, the PV system is easy to use, is clean and non-polluting and not dependent upon a chain of fuel suppliers.

3.2.4.2 Field experience:

By examination of past projects certain factors emerge as being critical to the successful implementation of PV schemes.

(1) The reliability of the Charge Controller

In early systems the controller was the weak link. Nowadays the increased protection given by manufactures to this item to protect it from environmental hazards has solved this initial reliability problem. Also, effective back up of spares has considerably increased overall performance of PV schemes.

(2) Available spare parts and distribution systems

As with any technology, the essence of a successful system is the backup of spares and maintenance. Adequate supplies of spare lamps and ballasts are necessary and the wherewithal to reach remote areas with these products.

(3) Customer financing policy

Several governments have instituted policies to enable PV systems to be successfully introduced. In 1980, PV-powered lighting was determined to be cost competitive with paraffin in Papua New Guinea.

3.2.4.3 Survey reports:

Papua New Guinea

A survey over a 5 year period determined the cost and performance of PV systems in comparison to paraffin lamps. In this period paraffin lamps would cost 817 Kina whereas the initial expenditure on a PV system was 655 Kina.

Costing was not considered the only criteria as the lighting produced by the PV system was not only far superior but was available instantly. An estimated potential of 17,5 MW for PV lighting kits exists if the government encourages loan institutions (Kinnell 1982).

Zimbabwe

A 1983 report by PTA Consulting services of Harare addressed the economic viability of PV systems for water pumping and lighting. Portability of lamps were stressed as important design parameters.

PV systems compared favourably with candles, gas or paraffin. When compared to a petrol generator, the PV system showed a payback of less than two years (PTA Consulting Services, 1983).

Mali, for school lighting

In November 1980 a PV system was installed in a classroom. The competing alternative was gas lamps. Despite good performance and minimal maintenance, the initial costs were felt to be too high. The introduction of such systems requires lower costing and/or a substantial increase in the rural education budget of Mali (Chevillard, 1985b).

United Arab Emirate, for traffic lighting

21 PV-powered street lights and a high mast roundabout light were installed in Dubai in 1983. Large differences in illumination were found to exist in commercial fluorescent tubes. The local population were pleasantly surprised by the illumination delivered by the 20 W lights, enabling newspapers to be read in the roadway some 18 feet below the light. It was noted that high efficiency, high powered DC ballasts are considered essential for optimization (Ellis, 1984).

French Polynesia, home powered systems

More than 1000 home power systems have been installed to provide lighting, television and fans. The program was subsidized by several agencies and developed from studies that it would be more cost effective to introduce PV than to extend a grid. Photovoltaic systems were found to be justified when the user is more than 200 meters from the grid. The South Pacific Commission was encouraged by these results and is proposing such rural electrification throughout the South Pacific (Jourde, 1985).

3.2.5 Multi-use systems

A large number of villages situated in remote locations in the developing world are not electrified. Photovoltaic powered multi-use systems are an elegant solution to this problem.

The concept of multi-use covers mini-utility systems and load centers. A mini-utility will have a central PV powered source which serves a whole community, (as against the home systems discussed in 3.2.4). A load center consists of a PV powered source making available electricity to a number of different applications. Schools, medical centers and agricultural centers are examples.

3.2.5.1 Technical considerations:

The distinction between a mini-utility and a load center is illustrated by the following Table:

Characteristic	Multi-use System Type	
	Load Center	Mini-Utility
Array size	< 5 kW	>5kW (up to 30 kW)
Type of power outlet	AC or DC	AC
Power Conditioning	Charge controller (with load shedding capabilities) Inverter (if AC loads)	Charge Controller Inverter (with load shedding capabilities) Metering
Power Distribution System	Only within one facility	Throughout entire village Metering
Infrastructure	Supply of spare parts System repair	Supply of spare parts System repair Billing system Power management

Table 3.2 Comparison between Multi-use systems.

Source: Eskenazi et al, 1986, p7-2

Typical configurations are shown in the following diagrams:

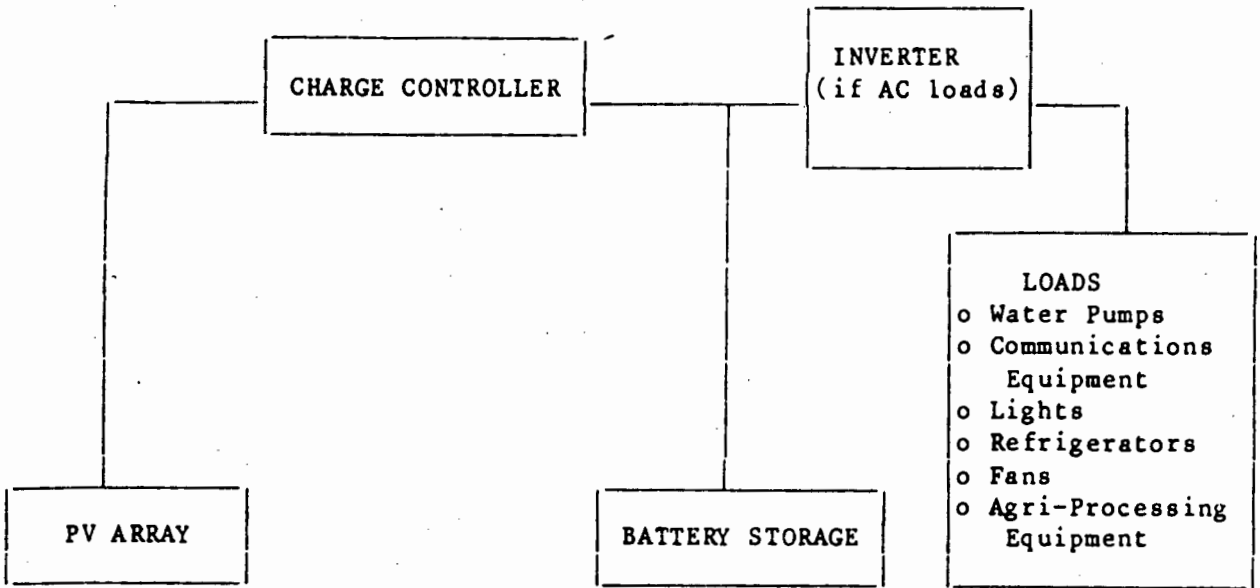


Figure 3.5 Schematic of a PV-powered Load Center System.

(A) Centralized Loads.

Source: Eskenazi et al, 1986, p7-3

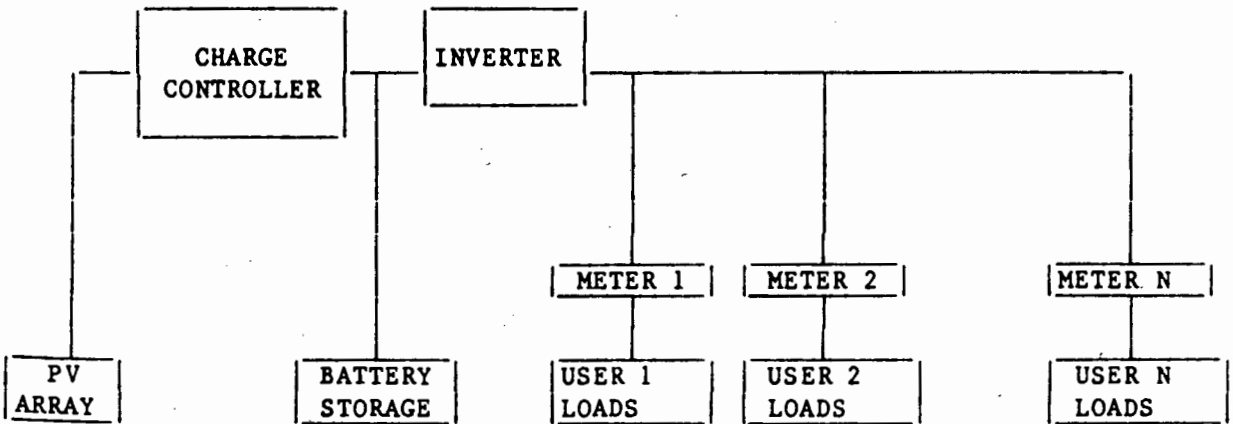


Figure 3.6 Schematic of a PV-powered Load center System.

(B) Decentralized loads.

Source: Eskenazi et al, 1986, p7-3

Mini-utilities are traditionally AC, since AC is more efficiently distributed. Load centers should be DC whenever possible, bypassing the need for an inverter.

3.2.5.2 Field experience:

Key factors for successful implementation are:

(1) Reliability and Complexity of Power Conditioning Equipment..

Charge controllers and inverters have caused problems due to lack of quality control at factory level. It has been recommended that the manufacturers institute 'burn-in' testing. Further, low power inverters are identified as a weak link in the multi-use system (both in terms of reliability and efficiency losses). Hence the use of DC systems is recommended where possible.

(2) Infrastructure for System Management.

Effective management is identified as the most important factor affecting the success of a multi-use system. A sense of 'ownership' has to be developed in the community, with resultant commitment to the success of the project. The critical nature of this necessity becomes more apparent with increasing size and complexity.

(3) Rural Electrification Policy.

The decision to procure one centralized system as opposed to many dispersed systems is a key policy issue. The way in which individual governments approach this issue and coordinate with funding organizations is germane to the successful implementation of schemes.

3.2.5.3 Survey reports:

Tunisia

NASA-Lewis Research Center installed a 29 kW system to serve the public and private sectors of a village of 120 people in 1983. Additionally, a 1,4 kW system was installed to provide power for a farmhouse and two similar systems installed to provide drip irrigation. Users are billed for specific consumption. Instrumentation was kept to a minimum. Numerous problems with the 1 kW inverter for the farm system were experienced resulting in extensive time required for repairs. Apart from some initial problems with some of the array wiring, due to incorrect specifications, no problems were reported with the PV system (Bifano, 1984).

Gabon and the Marshall Islands

NASA-Lewis installed an 8 kWp Village electrification scheme in the Marshall Islands and 17 community systems in the Gabon. These were operational in 1984 and 1985 respectively. Both PV village electrification projects have had 100% availability, however the failure rate of the integral inverters in the fluorescent lights was found to be proportional to outside storage time in the moist tropical climate before installation. Those installed in fixtures directly had no failures (Kaszeta and Ratajczak, 1985).

Egypt

A 200 Wp system was installed in 1980 to power a community center. In 1981, a 300 Wp system was added for irrigation. Modules were provided by CEL, an Indian manufacturer. BOS costs are less in India than the USA due to low labour costs.

This project has generated tremendous enthusiasm, attracting people from neighbouring villages. The villagers manage security, operation and maintenance on a cooperative basis. It is felt that PV systems have proven to be technically feasible in India.

Senegal

Niaga Wolof, a village of 1500 people, was provided in 1983 with a PV hybrid for lights, water pump and refrigerators. No problems with the PV portion of the system have been experienced. The system confirms "the reliability of photovoltaic solar energy". It was also noted that a full time operator was not necessary, as periodic inspections would suffice. Users of the system are billed according to an established tariff structure (Ministry for Scientific and Technical Research, Republic of Senegal, 1984).

Burkina Fasso

NASA-Lewis installed a 1,8 kWp array to power a water pump and grain mill in the remote village of Tangaye. The system has had over 90% performance reliability in the first four years. The complexity of the original controller was replaced by a simple packaged control module. A local cooperative was formed and has been a major contributing factor to the success of the PV project. The village, which was dispersed, is now centralized around the service points of water pumping and grain milling (Martz et al, 1985).

3.3 FINANCIAL ANALYSIS

Eskenazi et al (1986) have reviewed the cost of PV powered systems in developing countries and have compared them with the most likely conventional alternative systems. The following is a summary of their results. Each of the five areas, water pumping, communications, vaccine refrigeration, lighting, home power and multi-use, are discussed.

The financial parameters used are consistent with development bank loans, as opposed to those for commercial loans. In each area conceptual designs are developed to meet 'base case' load requirements. The systems are then compared using a 20 year life cycle analysis.

3.3.1 Common base case assumption

(a) Financial

Parameter	Assumption
Debt service	100% of system initial capital CIF cost CIF cost is capitalized 20 year term 10% per year (compounded at the end of the year)
Salvage Value	Included
Installation Costs	Not included
Operating Labour	Not included
Diesel Fuel cost	\$0,50 per liter
paraffin Fuel cost	\$0,70 per liter
General inflation	5% per year
Nominal discount and Interest rate	10%

Table 3.3 Base case Financial assumptions.

Source: Eskenazi et al, 1986, p8-3

(b) Technical

The range of PV applications in developing countries is clearly quite varied. As a basis for a comparative analysis the following applications are specified as being typical.

Application	Specification
Water Pumping	<ul style="list-style-type: none">* Village drinking water system* 50 m³/day annual average water demand* 25 meter head
Communications	<ul style="list-style-type: none">* Microwave repeater use.* 7,2 kWh/day, with constant, continuous load.
Vaccine Refrigeration	<ul style="list-style-type: none">* Vaccine Storage and refrigeration* Two particular types:<ul style="list-style-type: none">(a) Small, 24 Liter. (b) Large, (68-80 Liter)
Lighting and Home Power	<ul style="list-style-type: none">* Small, One light* Medium, Two lights* Large, Two lights and a radio
Multi-use	<ul style="list-style-type: none">* 10 kWh/day annual average electricity demand over a period of 12 to 15 hours

Table 3.4 Load specifications for base-case analysis.

Source: Eskenazi et al, 1986, pl-7

Specification	System Type		
	PV	Diesel	Paraffin
Component life (years)			
-Array	20	NA	NA
-Genset	NA	6	NA
-Power conditioning	10	10	NA
-Batteries	5	5	2*
-Loads	5	5	10 refrig. 3 lights
Major Maintenance			
-engine overhal	NA	every 3 years	NA

* Batteries used in conventional home power systems.

Table 3.5 Common base case Technical Assumptions.

Source: Eskenazi et al, 1986, p8-5

The availability of power/load systems is defined as the percentage of time the system operates within technical specifications.

Application	Availability	
	PV	Conventional
Pumping ¹	95	95
Communications ²	99,9	99,9 (2 diesels at 97,5)
Refrigeration ¹	95	50*
Home power	NA	
Multi-use ²	97,5	97,5

1. Availability of power/load systems. .

2. Availability of power system.

* Includes unavailability of fuel.

NA Not applicable (i.e., system specific availability not determined but assumed to be equal).

Table 3.6 System Availability.

Source: Eskenazi et al, 1986, p8-6

The above assumptions result in a conservative assessment of PV financial viability, because:

- (1) Labour costs associated with operation, maintenance and repair are not included.
- (2) The supply of spare parts and fuel is assumed to be uninterrupted.
- (3) No price reductions are assumed for system components.
- (4) No system design costs are included.

- (5) Macroeconomic considerations such as shadow pricing and tax revenues are not addressed.
- (6) The implication of tax benefits to the system owner is not established.
- (7) Most costs are based on the purchase of one system.
- (8) A 20 year PV array life is assumed.

3.3.2 Water pumps

Comparison is made between PV powered water pumping systems and diesel powered systems for rural water supply. The result shows that PV powered systems are the least cost option at demands of up to 25m³/day at a head of 25 meters, even under unfavourable financial assumptions. When the conditions are more favourable, PV powered systems are competitive up to 550m³/day.

Twenty year life cycle costs

Using Base Case parameters the final Net Present Value (NPV) was estimated as:

PV System	\$31 166
Diesel Genset	\$38 021

Sensitivity Analyses

Parameter	Variation	PV cost advantage, for demands of:
Discount and Interest Rate	5%	Up to 112 m ³ /day
	10%	Up to 70 m ³ /day
	20%	Up to 40 m ³ /day
Fuel Cost	\$0.25	Up to 57 m ³ /day
	\$0,50	Up to 70 m ³ /day
	\$0,75	Up to 90 m ³ /day
Diesel Lifetime	3 years	Up to 115 m ³ /day
	6 years	Up to 71 m ³ /day
	9 years	Up to 54 m ³ /day
Insolation	4 kWh/m ² -day	Up to 50 m ³ /day
	6 kWh/m ² -day	Up to 70 m ³ /day
	8 kWh/m ² -day	Up to 90 m ³ /day

Table 3.7 Water Pump Sensitivity Analysis.
Source: Eskenazi et al, 1986, p9-13 to p9-20

The best and worst cases are summarized in the following figure:

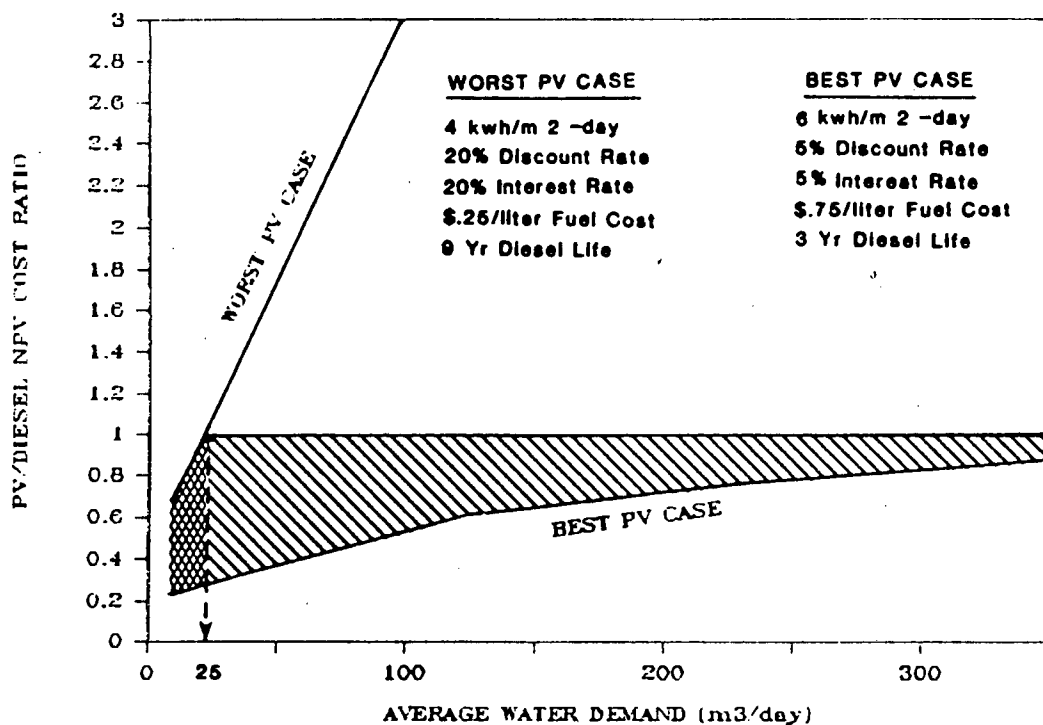


Figure 3.7 Sensitivity of Water Pumping Costs to Best and Worst Conditions.

Source: Eskenazi et al, 1986, p9-2

3.3.3 Communications

Comparison is made between PV and diesel powered microwave repeater systems. The conclusion is that PV powered systems are the least cost option for daily energy demands of up to 5 kWh under least favourable financial conditions and up to 24 kWh when the financial parameters are more favourable.

Twenty year life cycle costs

With the same parameters (refer to table 3.4) the NPV is:

PV	\$59 230
Diesel Genset	\$86 259

Thus for communication loads less than 7,2 kWh/day (300 watts continuous) PV systems are more cost effective.

Sensitivity Analyses

Parameter	Variation	PV cost advantage, for demands of:
Discount and Interest Rate	5%	Up to 13,4 kWh/day
	10%	Up to 11,0 kWh/day
	20%	Up to 7,8 kWh/day
Fuel Cost	\$0.25	Up to 7,9 kWh/day
	\$0,50	Up to 10,9 kWh/day
	\$0,75	Up to 13,8 kWh/day
Diesel Lifetime	3 years	Up to 14,2 kWh/day
	6 years	Up to 11 kWh/day
	9 years	Up to 9,6 kWh/day.
Insolation	4 kWh/m ² -day	Up to 10,8 kWh/day
	6 kWh/m ² -day	Up to 11,8 kWh/day
	8 kWh/m ² -day	Up to 12,6 kWh/day

Table 3.8 Communications Sensitivity Analysis.

Source: Eskenazi et al, 1986, p10-11 to p10-16

The best and worst cases are shown in the following figure:

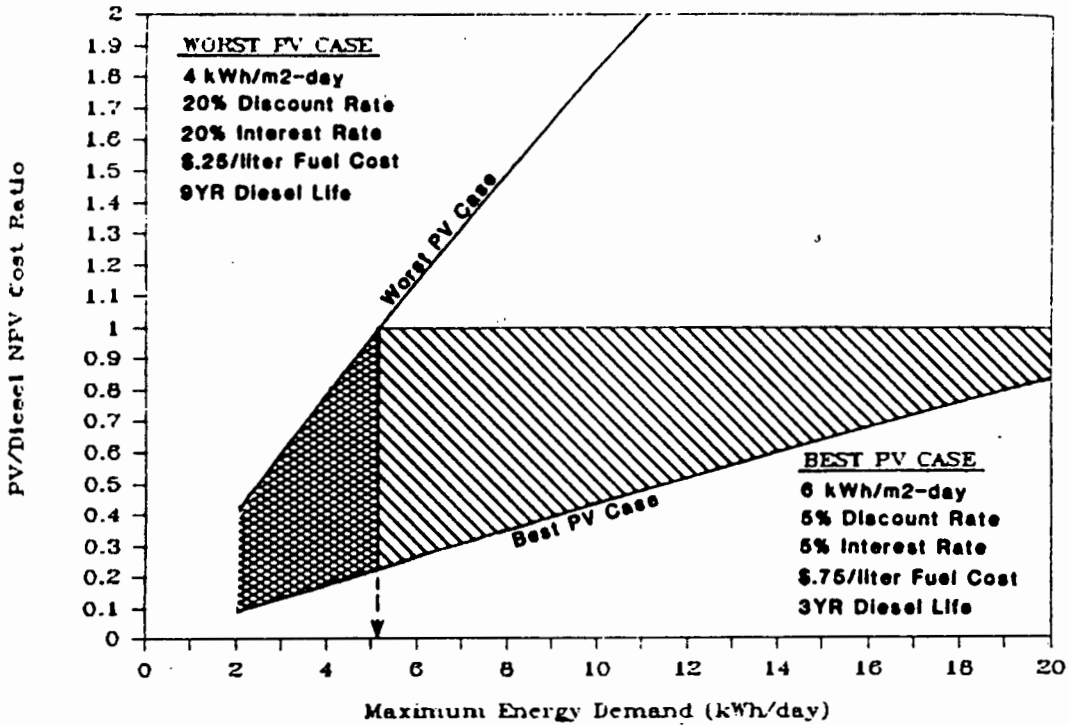


Figure 3.8 Sensitivity of Communications Costs to Best and Worst Conditions.

Source: Eskenazi et al, 1986, p10-2

3.3.4 Vaccine Refrigeration

PV powered vaccine refrigeration was compared to paraffin fueled refrigerators. No clearcut conclusions were drawn as to the viability of PV powered vaccine refrigeration. The most critical assumptions used relate to the problem of vaccine wastage. The unquantifiable cost of lost vaccines in terms of the human cost of not having the vaccine when needed is not dealt with. If it were possible to quantify this loss then it would most likely sway specific analyses in favour of PV powered vaccine refrigeration .

Twenty year Life Cycle Costs

With base case parameters the NPV costs were:

Small unit: PV...\$8 252 Large unit: PV...\$10 757
 Paraffin ...\$9 406 Paraffin ...\$10 569

Sensitivity Analysis

Parameter	Variation	PV Cost Effectiveness:	
		Large System	Small System
Discount and Interest Rate	5%	YES	YES
	10%	YES	YES
	20%	NO	NO
Fuel Cost	\$0,50	YES	YES
	\$0,70	YES	YES
	\$1,00	YES	YES
Litres of vaccine per year.	25	YES	YES
	50	YES	YES
	75	NO ? YES	YES
	100	NO	NO
Paraffin System availability	20%	YES	YES
	50%	YES	YES
	80%	NO	YES

Table 3.9 Sensitivity Analysis of Vaccine Refrigeration Systems.

Source: Eskenazi et al, 1986, p11-14 to p11-19

The best and worst cases are summarized in the following figure:

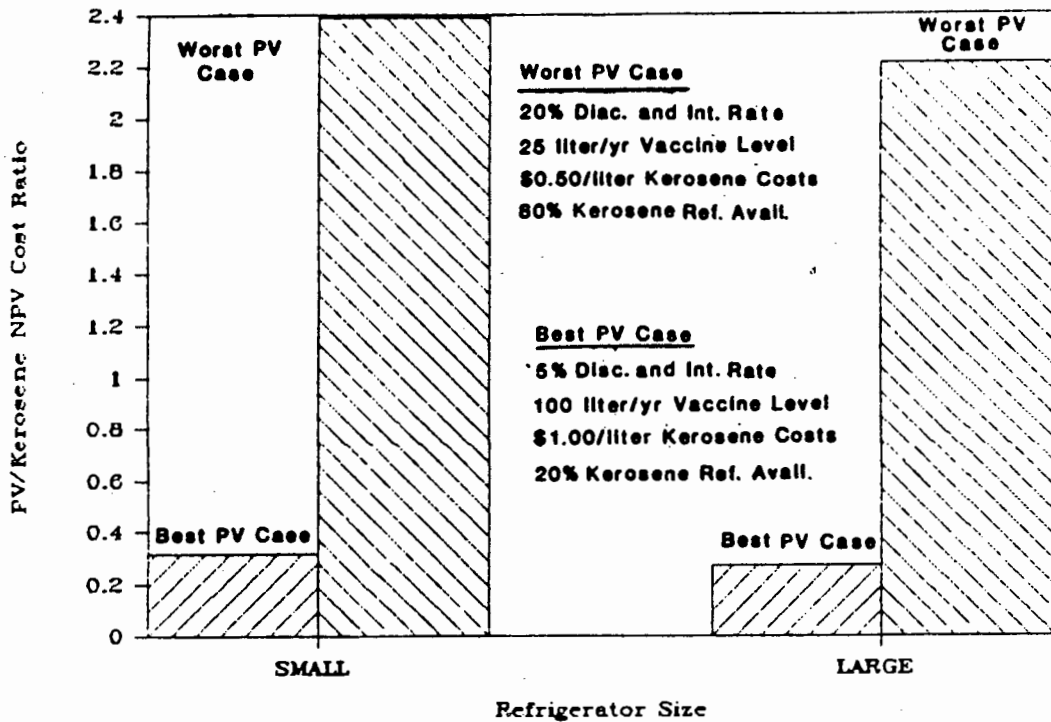


Figure 3.9 Sensitivity of Refrigeration Costs to Best and Worst Conditions.

Source: Eskenazi et al, 1986, p11-2

3.3.5 Lighting and Home Power

Comparison is made between PV and conventional systems (paraffin lamps and batteries) for home power. The conclusion made was that photovoltaic systems are the least cost option for small systems under all scenarios.

For medium and large size, PV systems are the least cost option also, with the exception of when worst conditions of PV liability are considered, i.e.

- Discount and Interest rates between 10% and 20%
- Insulations of $< 4 \text{ kWh/m}^2$, and
- Paraffin cost of $< \$0,50/\text{liter}$.

Twenty year Life Cycle Costs

Using the base case assumptions the NPV costs were :

System	small	medium	large
PV	1 002	1 796	2 674
Conventional	1 797	2 447	3 087

Table 3.10 Lighting and Home Power Life Cycle Costs.

Source: Eskenazi et al, 1986, p12-10

Sensitivity Analysis

The following table shows the extreme conditions beyond which conventional systems will have a cost advantage. These conditions vary with size of system, although it is to be noted that any single assumption will lead to conventional system cost effectiveness.

Parameter	Small	Medium	Large
Discount and Interest rate	27%	17,7%	13,5%
Paraffin cost (\$/liter)	0,15	**	0,48
Insolation (kWh/m ² -day)	1,6	2,5	3,3

Table 3.11 Assumptions necessary for Conventional Home Power System Cost-Effectiveness.

Source: Eskenazi et al, 1986, p 12-17

** NPV cost ratio leveled out before conventional systems showed financial attractiveness.

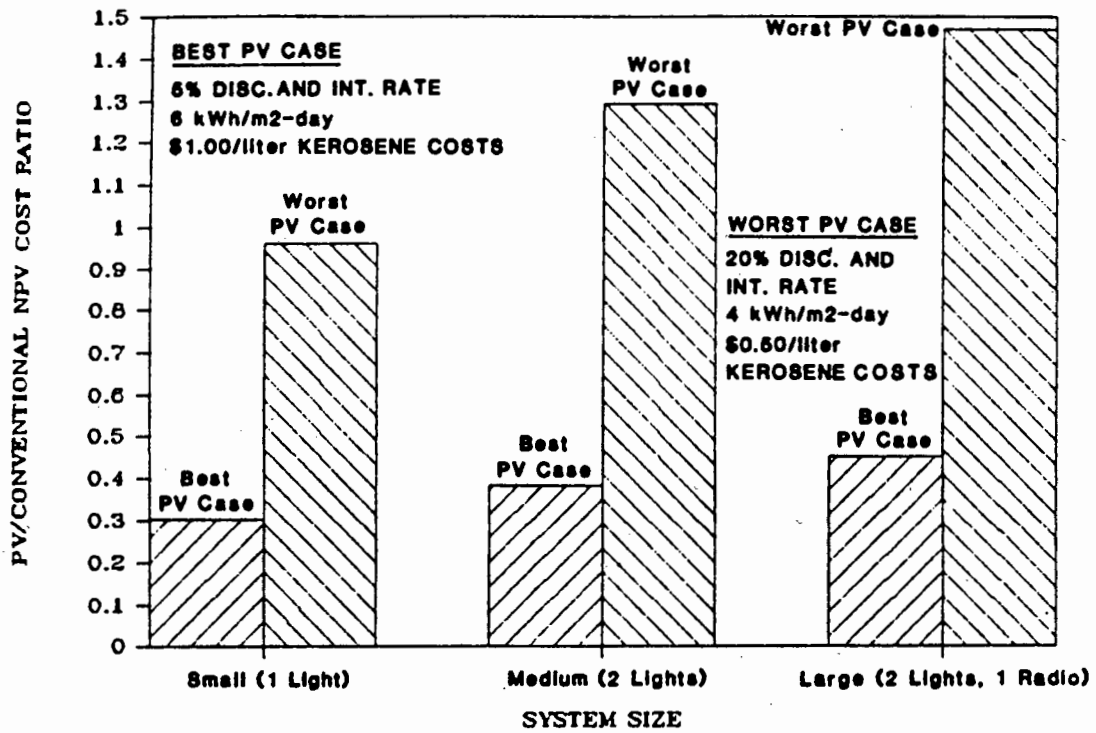


Figure 3.10 Sensitivity of Lighting and Home Power Costs to Best and Worst Conditions.

Source: Eskenazi et al, 1986, p12-2

3.3.6 Multi-use systems

Comparison is made between PV and Diesel powered systems designed for multi-use. The analysis shows that under unfavourable financial parameters, PV systems are cost effective for energy demands up to 2 kWh. For more favourable financial conditions, PV systems are cost effective up to 16 kWh/day.

Twenty year life cycle costs

The base case 20 year life cycle cost analysis project NPV costs of :

PV \$67 715
Diesel \$41 486

The crossover between PV and Diesel costs occurs at 6,2 kWh/day.

Sensitivity Analysis

Parameter	Variation	PV Cost Effectiveness:
Discount and Interest Rate	5%	up to demands of 8 kWh/day
	10%	up to demands of 6,2 kWh/day
	20%	up to demands of 4 kWh/day
Fuel Cost	\$0.25	up to demands of 4.6 kWh/day
	\$0,50	up to demands of 6,2 kWh/day
	\$1,00	up to demands of 7,8 kWh/day
Diesel Lifetime (years)	3	up to demands of 8 kWh/day
	6	up to demands of 6,2 kWh/day
	9	up to demands of 5,5 kWh/day
Insolation (kWh/m ² -day)	4,0	up to demands of 5,4 kWh/day
	5,0	up to demands of 6,2 kWh/day
	6,0	up to demands of 6,8 kWh/day

Table 3.12 Sensitivity Analysis of Multi-use Systems.

Source: Eskenazi et al, 1986, p13-9 to p13-14

The best and worst cases are summarized in the following figure:

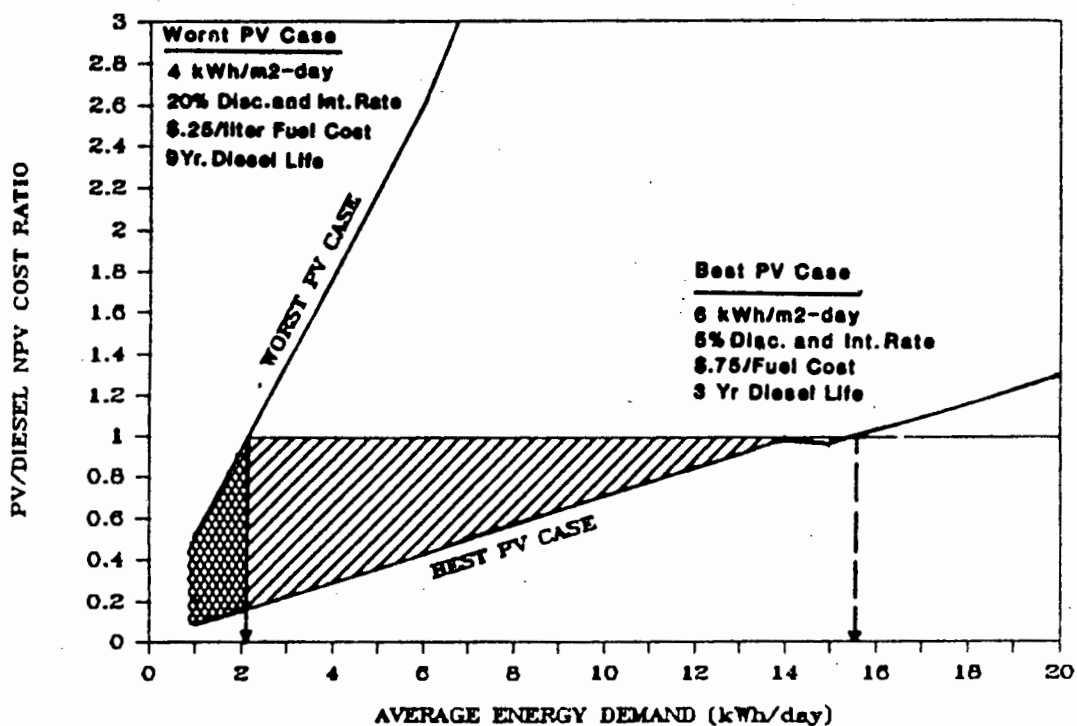


Figure 3.11 Sensitivity of Multi-Use Systems Costs to Best and Worst Conditions.

Source: Eskenazi et al, 1986, p13-2

3.3.7 Summary of Sensitivity Analysis

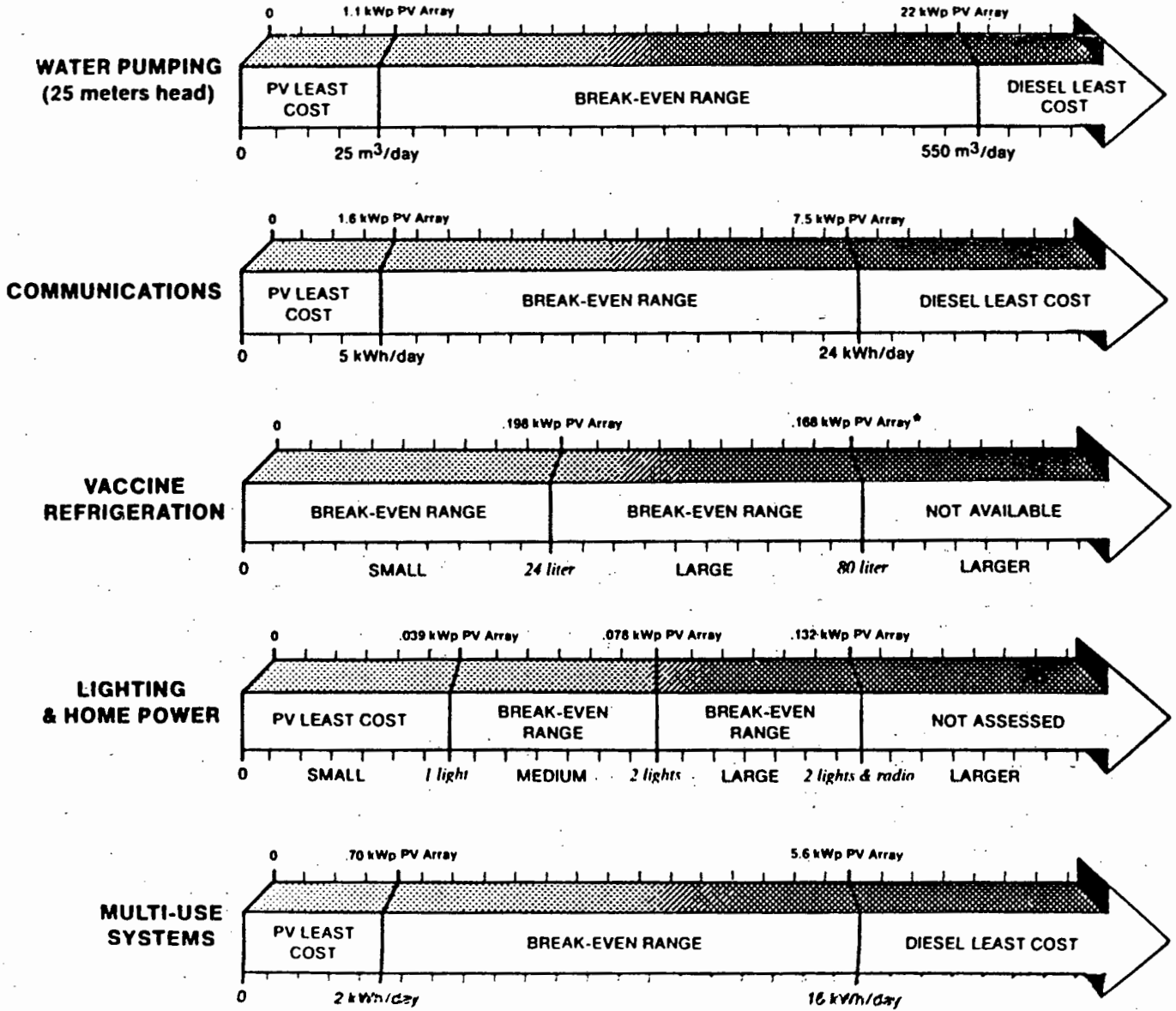


Figure 3.12 PV Financial Viability Limits.

Source: Eskenazi et al, 1986, p15-3

These diagrams sum up the effect of the variables considered in sensitivity analyses. The viability ranges have been obtained by simultaneously varying the parameters from the extremes of their respective ranges, viz:

Parameter	Variation
(1) Discount and Interest rate	5% to 10%
(2) Fuel cost	
- Diesel	\$0,25 to \$0,75/liter
- Paraffin	\$0,50 to \$1,00/liter
(3) Diesel Lifetime	3 to 9 years
(4) Insolation	4 to 6 kWh/m ² -day
(5) Paraffin Refrigerator operating viability	20% to 80%
(6) Vaccine requirements	25 to 100 liters/year

Table 3.13 Parameter ranges.

Source: Eskenazi et al, 1986, p15-2

"PV Least Cost" implies the load range in which PV systems are the least cost option even under the PV worst case scenario. Similarly, "Diesel Least Cost" refers to the range where Diesel Gensets are the least cost option even when the PV best case scenario applies. "Break Even Range" indicates the load range where either PV or the alternative system could be the least cost option, dependant upon the parameters.

The main conclusion to be drawn from these diagrams is that PV systems are viable propositions at loads greater than previously thought. The reasons why this change has occurred are not only due to the recent improvements in the cost and performance of PV systems and the assumption of development agency financing but also to a careful analysis of the performance of the alternative systems involved.

3.4 INSTITUTIONAL FACTORS

There are a number of issues which affect the implementation of PV schemes which do not fall under the category of technical or financial. These are broadly classified as institutional. Many of these issues are not quantifiable but need to be examined to ensure successful implementation of schemes.

3.4.1 Key Institutional Issues

(1) Need for decision-maker/user training

Four areas are identified:

(a) Operation and maintenance (O&M).

Minimal requirements exist for training in general system O&M. A suitable technical skills base exists in most countries to manage the day by day O&M requirements and should be utilized.

(b) Repair

The inability of local manpower to repair equipment is a major problem. Increased attention to in-depth training of personnel in electronic and end-use equipment is identified as of major importance.

(c) System specification and application

For the wide-spread success of PV systems in developing countries local personnel have to become proficient in a variety of skills such as: resource and load assessments; writing system specifications; system installation etc.

(d) System management

Assistance is also required for the training of personnel at all management levels. This management can provide the supervision necessary for the planning and implementation of PV projects at local level and also provide the expertise required at national and local energy committee levels.

(2) Availability of spare parts

Although PV systems require less support than conventional systems, responsive technical backup with appropriate spare parts is an essential factor for successful longterm operation. Spare parts are often not budgeted for in the project, resulting in unnecessary system failures.

(3) Availability of financing

Suitable financing is a significant factor in the widespread dissemination of PV systems. Despite the proven long term advantages of these systems, the initial capital cost may often predominate in choices made by government agencies, donor agencies and private firms. This occurs despite the fact that conventional systems have substantial operation, maintenance, repair and replacement costs that often are not listed in procurement budgets.

(4) Involvement of local manufacturers

Developing countries often require that local firms become more involved in the manufacture of the systems. This has ranged from local production of batteries to the manufacture of PV cells in more technologically advanced societies.

(5) Insufficient resource data

Credible data on insolation levels are essential for accurate system sizing. This data does not currently exist for LDC's.

3.5 SUMMARY

PV powered systems have been well accepted by users, based on their reliability, independence from fuel, and minimum maintenance requirements. The limitations to implementing PV systems in developing countries are institutional support and the lack of long term financing.

3.5.1 General conclusions

(1) Technical

PV arrays have proved to be exceptionally reliable under all conditions. This is not so regarding the rest of the equipment which must be carefully chosen from field proven components to ensure system success.

(2) Financial

All five PV applications are cost effective at low power loads, when 20 year life cycle costing is used. Further, PV systems are also financially attractive when conventional systems operate inefficiently. These conclusions are born out by case studies of programs in operation.

(3) Institutional

Institutional support has been the overall weak link for successful implementation. PV technology is a new, innovative technology and does not, as yet, possess the established infrastructure common to conventional systems. Even so, PV systems fair better when institutional support is lacking for both methods, due to their lower operation, maintenance and repair requirements.

3.5.2 Conclusions specific to each application

3.5.2.1 Water Pumping:

PV systems are the least cost option at loads more than twice those previously claimed. This is true even under PV worst case scenarios. The cutoff of 25 m³/day, at a head of 25 m (625 m⁴/day) is more than twice the quantity established by the UNDP/World Bank study completed in 1983.

For water demands of 25m³/day to 550m³/day, under a head of 25 meters, the cost effectiveness of PV systems is dependent upon case specific parameters; the most sensitive of which are discount and interest rates and diesel genset lifetime.

The viability of PV water pumping systems is also a function of the institutional and technical factors previously discussed. Successful systems have implemented the recommendations involving selection of equipment; proper use of solar and well yield data; and effective training of personnel.

3.5.2.2 Communications:

PV systems have proved competitive for many typical applications, as evidenced by the recent growth in commercial systems. Compared with diesel powered units they are the least cost option up to 5 kWh/day of continuous load. Between 5 and 24 kWh/day the case specific parameters affect the issue; the most sensitive being diesel fuel cost and diesel genset lifetime.

Reliability of PV systems depends on the careful selection of equipment; in particular, the use of field proven components tested under the correct climatic conditions.

3.5.2.3 Vaccine Refrigeration:

PV powered refrigerators do not evince a clear cut range for financial viability, at this time. For both small and large systems the comparison with paraffin refrigerators is always in the break even range and dependent on case specific parameters. In the PV system the governing factors are those of recurring capital costs and debt servicing. For the paraffin system the most important is vaccine wastage.

PV powered refrigerators have demonstrated reliable performance in many developing countries. Operating availability has proven to be significantly higher than paraffin units. Vital factors in successful systems are credible solar resource data; refrigerator power consumption data under field conditions; effective user training; and complete coordination with end user organizations.

3.5.2.4 Lighting and Home Power:

PV systems are more attractive in the small system range for all scenarios. In the medium and large ranges, PV systems may be financially more attractive dependent on specific parameters. The major factor for PV systems being debt servicing and for the conventional power system, fuel costs.

The most important factors affecting successful implementation are the selection of field proven, reliable charge controllers and the availability and distribution of spare parts for all the equipment. Shorter loan terms, it is suggested, would still show PV system attractiveness (as has occurred in French Polynesia with consequent increased growth).

3.5.2.5 Multi Use Systems:

PV systems are shown to be the least cost option for power requirements up to 2 kWh/day. For the range up to 16 kWh/day, the most sensitive parameters are the discount rate and diesel fuel cost.

PV systems have been successfully installed, but the reliability of power conditioning equipment has to be investigated. The record of small stand alone inverters is poor and has caused designers to turn to DC systems. However, DC is not an option for mini utilities. A local infrastructure for managing power is essential for successful application and the general decision making between mini utilities and load centers is a major rural electrification policy issue which should be taken in conjunction with local communities and government officials.

3.5.3 Recommendations

Eskenazi et al (1986) make the following recommendations. These are based on factors present in successful systems and notably absent from unsuccessful systems.

TECHNICAL	FINANCIAL	INSTITUTIONAL
Select field proven components	Evaluate viability using life cycle costing	Establish field service capability
-Tested under local conditions		-management of technical support and spare parts.
Obtain and properly use design data	Utilize financial mechanisms for developing countries	Provide training at all levels
-Load, solar and weather data	-Development agencies and banks	-Operation and maintenance. -Fault detection -Repair
Provide user orientated with product engineering		Coordinate activities end users
-Design components for simple user interface		-Local ownership and responsibility
-Anticipate operating errors		-Early involvement of users

Table 3.13 Recommendations.

Source: Eskenazi et al, 1986, p15-10

CHAPTER FOUR

TECHNICAL AND INSTITUTIONAL ASPECTS OF PHOTOVOLTAIC APPLICATIONS IN DEVELOPING AREAS IN SOUTHERN AFRICA

4.1 INTRODUCTION

PV systems are being increasingly used in South Africa where markets for small off grid applications are expanding. The kind of applications that PV systems are used for are discussed below. Broadly speaking these may be divided into two categories; First world and Third world, although a degree of overlapping is inevitable since the two 'worlds' are inextricably linked.

4.2 FIRST WORLD PV APPLICATIONS

In areas remote from the national grid PV, systems are being recognized as a viable alternative for the production of electricity.

The major application in Southern Africa is in the field of telecommunications. PV electricity is used to supply power to remote telephone exchanges and telephones, to fibre optic repeaters, and to microwave repeater sites. In many of these cases the remote, inaccessible nature of the sites means that the stand-alone generators originally used to produce electricity were very expensive and difficult to fuel and maintain and so hindered the expansion of telecommunication networks. The use of PV systems provides for the economic expansion of these networks into regions where no other technology would be practical.

A main military application in this field is the MARNET (Military Area Radio Network) system. The reliability and durability of the installed units has proved to be highly satisfactory.

Another area of use is in the field of telemetry and data-logging. As with other communication equipment, the power requirement is not high. PV power is the only reasonable way of providing energy in this range. For similar reasons, automatic weather stations are now being converted to PV's countrywide.

Whilst the above may be considered major applications, photovoltaics are used increasingly in a number of other fields; typical of which are for the supply of electricity on farms in direct competition to diesel gensets; as a preferred option in National Parks where aesthetic considerations also play a part; and for security lighting, buoys, marine craft, highways (emergency telephones) etc.

There is also a leisure market which includes such items as PV battery charging, car ventilation and PV powered Hi-Fi sets. PV powered television and radios are possibilities for future market penetration.

With the continued fall in module prices, PV's will find increasing applications in areas other than those remote from the national grid.

4.3 THIRD WORLD PV APPLICATIONS

In developing areas it is envisaged that the needs of communities remote from the national grid can be met by the use of systems in the following main categories:

- Water Pumping
 - Drinking water
 - Irrigation
- Communications
 - Remote telephones
 - Remote radios for clinics
- Health Care
 - Vaccine Refrigeration
 - Emergency Lighting
 - Communications
- Home Power
 - Lighting
 - Recreation
 - Home based small industries
- Community Use
 - Street and safety lighting
 - Power Tools
 - Agricultural needs
 - Community Center
 - Lighting
 - Educational needs (e.g. television)
- Leisure use
 - Consumer products
 - Watches/toys
 - PV powered Hi Fi sets
 - PV powered TV sets
 - PV powered Radios

International experience with the use of PV systems in developing areas in some of these categories has been summarized previously in Chapter Three. This chapter will focus on the particular needs and problems associated with Southern African conditions.

It is worthy of mention, at this point, that it has been estimated that some 21 million people representing roughly 3 million homes in Southern Africa are without the benefit of grid electricity and hence are the largest unexplored market of potential users of PV systems.

Research has shown overwhelmingly that the perceptions of the people living in developing areas are clearly in favour of the use of electricity for basic and recreational purposes. This assessment also includes the understanding that the result of such availability of electricity would upgrade the quality of life of all concerned and hence help stimulate economic growth.

Although the declared policy of Eskom is to provide electricity for the whole of South Africa, it is apparent that the extension of the national grid to all areas is probably not achievable in the short term (a cost of approximately Nine Billion Rand is involved). It is further noted that Eskom, themselves, are considering the leasing of PV systems to farmers in remote areas as a competitive and viable alternative to grid extension.

4.4 PV DEMONSTRATION PROJECTS IN DEVELOPING AREAS IN SOUTH AFRICA

The easiest way to review the experience of PV use in developing areas in South Africa is to look at the demonstration projects which have been monitored by the Energy Research Institute of the University of Cape Town. These installations are typical of many of those now being undertaken in South Africa.

PV applications for home power, rural educational television and water pumping were designed, procured and installed by the E.R.I. Their performance was closely monitored with remote automatic data logging of all key system parameters. Data was stored in E-prom chips, which were posted to the E.R.I. for downloading onto micro-computers. Detailed analysis was undertaken on the technical and economic performance of these systems, and relevant social parameters relating to usage patterns were also studied.

4.4.1 Home Power

Many low income households which do not have access to grid electricity, use batteries or petrol generators to power lights and, typically, television and hi-fi sets. PV systems are becoming a viable alternative.

Two demonstration systems were installed by the E.R.I. One at Uitsig in the Western Cape, which lies within the winter rainfall area, and the second at Omdraaisvlei in the Northern Cape. Full details of these projects may be found in Muller (1988).

4.4.1.1 Uitsig:

Uitsig is a sub-economic township near Elsie's River on the Cape Flats. It is located some 18 km east of Cape Town (Lat: 34°S and Long: 18°E). It was originally started as a transit settlement but, in some cases, families have been living there for as long as 10 years.

None of the houses in Uitsig are electrified and the Regional Services Council has stated that there is no possibility of this occurring in the near future. The houses consist of four rooms with an outside toilet and tap. Total floor area is 36 sq.m. The particular house chosen is orientated East-West, and has an A-frame roof.

One 11 W fluorescent Comlite light was provided for each room as well as a 15 W socket for the living room which could be used for a portable TV set or a music center. The loading for summer was estimated to be 148 Wh/day and for winter 236 Wh/day.

A small photovoltaic system was designed to provide for these estimated loads. This consisted of:

- (a) Two ARCO M75 PV panels rated at 47 Wp each.
- (b) One Solar Sciences 10A 12V DC Voltage regulator, with boost/float charging and undervoltage load shedding.
- (c) One 90 amp-hour Raylite Leisure Pack Battery.

The sizing of the panel was based on the "worst" month of the year. That is, the month which has the lowest ratio of solar radiation received to the projected load requirement. In this case June was the worst month receiving an average of 14 MJ/m² on a 54⁰ tilted surface.

The optimum angle of tilt varies over the year but providing for such variation would be an expensive option to install and maintain. It is usual, in simplified designs, to compromise by installing the modules either at the angle of tilt which maximizes total annual radiation, or, if there are large seasonal variations, at the optimum angle for the "worst" month.

Using this radiation data for June the PV module output was calculated as 94 Wp with a battery storage requirement of 114 Ah. The Voltage regulator provided both under and over-charging protection. When the battery voltage drops below 11,5 Volts the load is disconnected from the system and stays disconnected until the battery voltage rises to 12,1 Volts. During the "boost" mode of charging the maximum voltage cut-off was set at 14,5 Volts. In the "float" mode the battery voltage is maintained at 13,8 Volts.

The average power drawn during 1987 from the unit was some 20% more than the design estimate. The initial design was based on average radiation readings recorded during the preceding years from D.F. Malan Airport, some 10 km from Uitsig. Whilst the month of June 1987 was reasonably matched the remaining winter months showed a considerably lower incident radiation than the design data (Muller, 1988 p116).

This underscores a major problem when designing PV systems. Accurate load and radiation data should be available for the particular site being considered otherwise the installed system can be either over or under sized with resultant distortion of electricity generation costs.

In spite of actual usage being higher than the design load, and solar radiation being lower than expected, the system has worked satisfactorily. Loss of power was experienced briefly three times during the monitoring period of a year when the load shedding function in the regulator came into operation in order to protect the battery from being discharged too deeply.

Whilst the PV panels have operated without any failures, problems have been experienced with all the other components of the system. Lights have had to be replaced due to failed ballasts, the regulator shorted and burned out and had to be replaced and the battery could no longer hold charge after 14 months of operation and had to be replaced. The electrolytic levels of the battery had not been maintained. It is thus likely that the life of the battery could have been extended, but probably not significantly, as SLI type batteries are not designed for repetitive deep cycling.

This experience has highlighted the fact that while PV modules are known to be reliable, balance of system components are often sub-standard and inappropriate selection or specification of batteries, regulators and appliances can lead to regular failures. As many of these are specialist components, users experience some difficulty in locating suitable replacements.

The experience at Uitsig was that without close back-up support from the E.R.I. the system would have remained out of operation after the first component failure.

4.4.1.2 Omdraaisvlei:

Omdraaisvlei is a farm situated in the Upper Karoo in the Prieska farming district, 73 km from Britstown (Lat: 30⁰S and Long: 23⁰E). The altitude is some 1100 metres above sea level.

The system was installed in a labourer's house which consists of 3 bedrooms, a living room, a kitchen, a store room, and an open verandah. The roof is constructed of corrugated iron sheets with the North facing surface at an angle of 32 degrees. None of the cottages on the farm are connected to the national grid.

Four 20-Watt lights and two 11-Watt lights were installed together with a socket in the living room for a portable black and white TV set. Two of the 20 Watt lights were placed in the living room, one in the large bedroom, and one in the kitchen. The smaller lights were arranged as bedside lights in the two other bedrooms.

Based on the general energy usage observed before the system was installed, an estimation was made of expected patterns of use with PV power. After consultation it was considered that each light would be used for 3 hours per day and that the TV would average out at 4 hours per day. A total loading of 366 Wh/day was thus estimated.

The specifications for the design were :

- (a) Two M.Setek MSP-103 41 Wp Solar Cell Modules.
- (b) One 98 Amp-hour Sabat Battery.
- (c) One Arco Solar Battery Protector rated at 20 amps.

In this instance the design "worst" month radiation was based on data recorded at Bloemfontein and found to be 21,7 MJ/m² in May. The actual measurements recorded on the farm were some 2,5% higher. The optimum angle was calculated to be 35 degrees in this case.

Using radiation data from Bloemfontein for May the PV module output was calculated as 91 Wp with a battery storage requirement of 95 Ah. The voltage regulator provided both under and over-charging protection, as with Uitsig, and provided a boost charge efficiency of 99,5%.

The average power drawn by the family was measured at only 115 Wh/day. This low amount is attributed to the conservation habits of the family, who were used to dealing sparingly with available sources of energy (ibid, p120).

4.4.1.3 Uitsig and Omdraaisvlei Assessed:

For both of these home power installations actual power drawn was very different to projected design loads, even though a careful assessment of power needs was undertaken. As load pattern usage directly affects system efficiencies and the unit electricity costs, it is important to match loads and system capacities closely. The experience of these two home

power systems highlights the difficulty of designing flexible, but efficient systems for remote area power applications. The problem of low capacity factors and their impact upon unit generation costs is a problem not unique to petrol or diesel generators, but applies also to stand-alone PV systems.

The PV system at Omdraaisvlei experienced what appears to be a failure after one years operation, and has remained out of service for a considerable period of time due to the inability of local residents (including the farmer) to diagnose the fault and the difficult logistics of procuring either skilled technicians or replacement parts in a very remote area.

Reliable balance of system components are thus critical in remote areas. Without them, PV systems cannot be regarded as maintenance free.

It has been interesting to note that a number of companies have entered the local market and are now offering a variety of systems suitable for the production of home power. Most companies offer packaged systems and it is hoped that this will ensure greater reliability and better matching of system components. A selection of brochures in this area are shown in Appendix E.1.

4.4.2 The Bophuthatswanan "Edutel" project

In recent years attention has focussed on the educational advantages of the use of video films. For this purpose an effective supply of electricity is essential. One of the largest PV projects in the region has been the provision of PV powered educational television/video to all the secondary schools in Bophuthatswana.

Over 350 middle and high schools have been supplied with television and video facilities since 1985 under a programme called "Edutel" originally initiated in 1984.

As only 20% of the schools supplied are connected to the national grid, an alternative supply of electricity was sort. Photovoltaic power was chosen and installed as the viable alternative for the remaining 80% of these schools. The E.R.I. undertook to monitor one such unit at a demonstration site in the Transvaal.

The equipment installed in the schools is made up of two PV modules, mounted in the school grounds, which are connected to a cabinet inside the school, housing a colour television, a videocassette recorder and appropriate battery storage.

Equipment Summary

- (a) Two Photowatt PW-p 801 polycrystalline modules each rated at 80 Wp.
- (b) Four 12V Delco 2000 Solar Batteries, each of 105 amp-hour capacity (giving a total of approximately 5 kWh).
- (c) One energy management unit.
- (d) One 56 cm French television, model T47C; specially designed to run off of a low voltage DC supply and to consume 38-40 Watts.
- (e) One JVC Video-recorder, model HR 2650, designed to run from a DC supply and to consume 8-9 Watts.

Design Load

The system was designed to provide some 450 Wh/day. This amount allows for the television to be run for approximately ten hours each day with the VCR also able to be used for some five hours per day.

At the demonstration site in the Transvaal the system was monitored over several months. Analysis of the data obtained showed that the PV system installed was well able to support the operation of the television and VCR (Cowan 1989a, p11-5). However, the monitoring of the system raised a number of important issues regarding improved design procedures and methodologies.

Availability

Mathematical modelling of expected system performance was undertaken using statistical probabilities derived from hourly insolation records from the South African Weather Bureau's weather station at Pretoria-Forum. The model predicted that the loss of power probability would average less than 0,001 over a typical ten year period. This prediction meant that the Edutel system could expect only 3 days of non-use, caused by insufficient solar radiation, in a ten year period.

System sizing

Cowan (1989a, p11.6) reported that the power of the array was well sized for achieving the above loss of power probability. However, it can be argued that such a high level of availability is unnecessary in school applications. Acceptance of a level of 0,01 probability, which means an average of 3 days a year of non-availability, would be acceptable in such a non-critical use as educational television. The effect on the design would have been a saving of 8% on the size of the array.

The battery storage capacity is 5 kWh, reduced to an available 3,5 kWh by the charge controller settings, thus preventing deep discharging of the battery bank and so prolonging the expected lifetime. The mathematical model predicted that this capacity could have been reduced by half but, it should be noted, such fine tuning may affect battery life.

Whilst any savings achieved may be of economic significance, the uncertainties involved in loss of power probability sizing methodologies, combined with the doubts regarding the accuracy of solar radiation data and the actual performance characteristics of the modules mean that optimum settings are difficult to achieve with any degree of confidence.

Some doubt was expressed as to the validity of the solar radiation data upon which the French company based its design specifications.

Array performance characteristics and manufacturer's advice

The original sizing information supplied by Photowatt SA specified two monocrystalline modules with a rated peak power of 164 Wp (± 12,5%). Analysis indicated that it would not only have been greatly oversized but would also have been poorly matched to the load characteristics as the optimum power voltage would have been larger than the system take off voltage.

In the event, polycrystalline modules were actually installed. Cowan determined that their rated capacity under standard test conditions was only 135 Wp (± 10%). However, this reduced rating proved to be well matched for the design load.

Cowan (1989a p11.7) makes the following observations:

- (1) Photovoltaic array peak power ratings may not provide an adequate indication of expected array power in onsite conditions.
- (2) Information about module performance in varying spectral conditions could be a useful as an aid to critical sizing of arrays, and

- (3) It may be advisable to test individual modules in representative local daylight conditions, both as a measure of how applicable manufacturers power ratings are and also as a test of variation between and within production batches.

Reliability

Maintenance reports of the supplier company, covering the Bophuthatswana school equipment, do not record any failure of the PV equipment other than lightning induced damage. This appears to have occurred rarely, with fewer than 2% of the systems affected. The extra cost of lightning protection was not considered to be justified.

A crucial advantage of the particular choice for the television receiver/monitor was the modular nature of the circuitry involved. Because of the ease of replacement of a defective unit, the company were able to employ relatively inexperienced maintenance personnel to travel around the schools servicing the equipment. Defective circuit boards could then be returned to a central workshop for repair. In this way, an excellent maintenance and back-up service was provided.

Cowan (1989a, p11.8) reported that the equipment installed was robust and 'resilient to inexperienced users'. However a number of other problems have been experienced such as theft and stoning, emphasising the need for care being taken to blend in the technology with local social conditions.

Utilisation

The extent of usage within the schools is the key indicator of the broad acceptance of the technology. Whilst such levels are difficult to establish, the suppliers estimated that after four months some 30% of the schools were making use of the equipment and after six months some 80% were involved.

The levels of use directly affect the overall economics. The system was initially sized for a ten hour daily usage, consequently under-usage by the schools means that the initial sizing was too high and a larger system was installed than was necessary.

The following figure shows clearly how the utilization level affects unit energy costs:

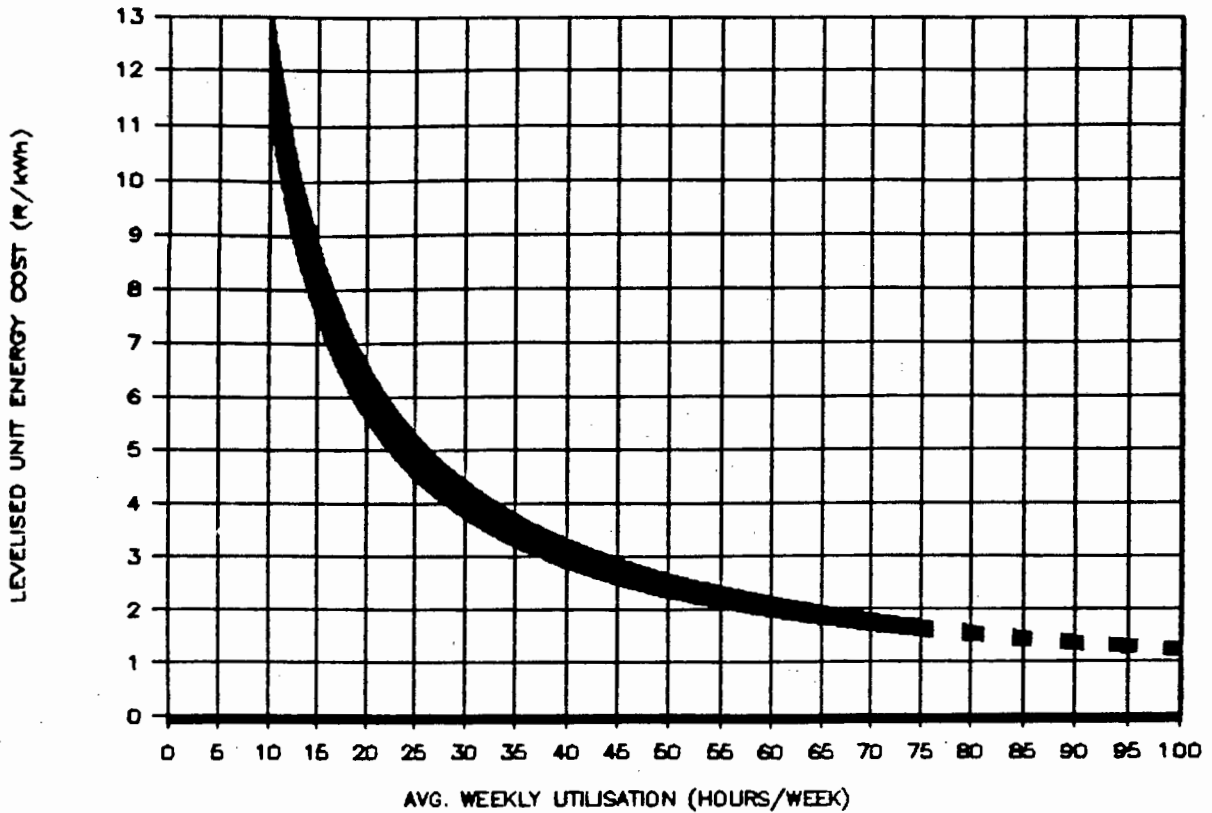


Figure 4.1 Estimated levelised unit energy costs as a function of utilisation levels.

Source: Cowan, 1989a, p11.15

A utilisation level of 4 hours per day, or 20 hours a week will produce a cost of some R6/kWh. This figure appears high. However, it is not only this bare cost which has to be assessed but also the service provided. Taking into account the full life cycle costs of the project, the effective weekly cost of having a reliable educational television facility available is R5-R6 irrespective of utilisation level.

General comments

In the light of the aforementioned experience, certain factors should be taken into account before adopting a particular photovoltaic system design.

- (1) Accurate prediction of load demand is identified as the single most important factor in the successful economic sizing of a stand alone system.

Whilst this may be easily accomplished when the load is a dedicated unit, the problem is more complex when the loading is a variable, as experienced by typical educational applications

- (2) Utilization levels should not be initially overestimated. The modular nature of PV technology allows for expansion when demand begins to exceed initial sizing estimates.
- (3) Educational T.V. is considered a non-critical application. The acceptable number of days of non-availability per year should be keenly assessed with overall system sizes, and hence costs, in mind.

Cowan (1989a, p11.16) sums up by stating that small photovoltaic systems are viable if:

- (1) the value of the application is high and the electricity consumption is low;
- (2) the load demand is reasonably steady and predictable;
- (3) low maintenance and running costs and high reliability are priorities; or
- (4) cheaper, practical alternatives are not at hand.

4.4.3 Health Care/Vaccine Refrigeration

In 1986 the E.R.I. undertook a brief review of PV powered vaccine refrigeration units installed at clinics in the Ciskei.

PV powered refrigerators have proved their worth in comparison to their paraffin powered conventional alternatives under actual use in many developing areas of the world. However, attention has to be paid to the parameters discussed in Chapter 3. If sufficient emphasis is not placed on correct sizing, training and support infra-structure then problems can be experienced as instanced by the following experience.

The installation of solar powered refrigerators in 1986 was part of larger project also involving recreational and educational equipment to be supplied to the Ciskei Government under a package of development projects.

Twenty two clinics in rural areas were supplied with solar powered refrigerators by Qualitron, a subsidiary of an Israeli firm, Degem.

Specifications

Solar Panels

Two or four PV panels (dependent on fitters assessment) of size 40 Wp and fitted magnetic North (inclination not specified and varied from site to site).

Refrigerator

One Katz International Corporation Refrigerator BP160, of capacity 160 liter. The rating was not on the machine but stated as 80W by the fitter.

Charge Regulators

None fitted at the time of the report though units were promised.

Battery

One 100 amp-hour unit (Fitters estimation).

The refrigerators have not met the expectation of the nurses, as they do not maintain a low enough temperature. Those tested appeared to reach a minimum of 10⁰C only, and in some cases much higher temperatures, when a specification of 4-8⁰C was necessary. This has been a disappointment to the staff of the clinics who now have a poor attitude to solar power in general.

In one clinic, for instance, the refrigerator worked for a day and never thereafter. In another, it worked for two weeks, stopped for a month and then resumed suddenly.

Apart from the technical inadequacies of the design and the lack of effective maintenance and aftersales service it is also apparent that the social needs and wishes of the community were not assessed properly. As an example, the essential need of the clinics for lights in the maternity wards was disregarded whilst security lights at the local Tribal Authority were kept blazing all night.

The little, if any, attention paid to the above had the end result that the systems installed were rejected by the staff of the clinics. It is reported that large quantities of vaccine had to be destroyed, that the use of PV systems were forbidden for this purpose and that the clinics have returned to the use of gas run refrigerators.

This project highlights the importance of a proper assessment of social needs and priorities before installing systems and also of properly engineered systems. In the above case, batteries and panels were undersized, and regulators omitted. Such poorly designed projects can be disastrous to the reputation of PV.

4.4.4 The Sondela Water Pumping Project

A common application for stand alone PV systems is the provision of water for drinking purposes and/or for irrigation.

The Sondela community is situated in KwaZulu some 40 km South of Pietermaritzburg. The garden of some 1,4 Hectare stands on a gentle slope close to the banks of the Umsunduze River. Forty-six households have plots in the garden.

The garden represents a major opportunity for the women to earn money. The buying of the pump, with the commitment to pay back the loan involved, represents the importance of the pump to the group and the realization of its long term benefits.

Before the purchase of the PV powered pump, the women faced the long and tedious job of collecting water directly from the river. The time saved by the pump has resulted in more work being done in the garden with resulting higher food yields and hence incomes. It has also had the beneficial effect of releasing the women to enable other money earning industries, such as basket weaving, to expand.

It is to be noted that the water used is less than the pump capacity and hence there is now a real possibility of expanding the garden.

Although the community was not involved with the technological choices made with regard, for instance, as to whether to use diesel powered or PV powered pumps the involvement with and use of the final system is unmistakable, the financial commitment of the women concerned being a major indicator.

System specifications

The irrigation needs were assessed as 27 m³/day during the summer months and at 17 m³/day during the winter months. A head of 13 metres was specified. This flow requires a maximum power output of 1902 Wh/day (in the summer months) and is met by a PV system incorporating a 656 Wp array.

Equipment installed

One Mono progressive cavity pump.
One 90 V, DC motor, rated at 1 HP.
One DC/DC converter rated at 1 kW.
16 modules each rated at 41 Wp.

The high starting torque of the motor made the use of a converter essential to the system.

4.4.4.1 Comparative financial analysis:

Gosnell (1989) undertook a comparative analysis of the economics of PV and diesel water pumping. He looked at three rates of flow and examined the unit costs using two different PV systems, one with a subsystem pumping efficiency of 30% and the other 40%, and compared the results with two diesel pumping cases, one based on operating conditions normally encountered in remote developing areas and the other based on best possible operating and cost assumptions.

His results are summarized in the following table:

Unit cost of Pumped water in South Africa in 1986

Power Source	Unit Cost of Pumped water at a 30 m head.		
	5 m ³ /day	10 m ³ /day	30 m ³ /day
40 % Eff. PV	1,81	1,56	1,39
30 % Eff. PV	2,14	1,85	1,64
Diesel "Best Case"	2,57	1,80	1,29
Diesel "Normal"	6,16	4,32	3,10

Table 4.1 South African pumped water costs.

Source: Gosnell, 1989, p10.13

These figures show that using a "normal" diesel driven pump is some 2 to 3,5 times more expensive than using a PV system for the full range of volumes considered, even if the less efficient PV case is considered. However, the "Best Case" diesel, i.e. one maintained to the manufacturers specifications, and run at the most economic loading, compares more favourably with PV, but at higher pumping loads only.

Other factors identified by Gosnell (1989, p10.14) as significantly affecting cost comparisons are:

- (1) The remoteness of the site,
- (2) The insolation levels and,
- (3) The technical knowledge of the users.

It should be remembered that diesel systems in South Africa do not usually receive the type of attention required to become "best case" scenarios. For all practical purposes it may be concluded that PV pumped water is more cost effective.

Further, diesel costs are likely to rise in the future, whereas PV prices are going to fall. Hence PV system costs are likely to undercut even best case diesel costs at the volumes and heads considered.

The above makes the assumption that the initial cost of the PV system can be spread over the projected lifetime (20 years). Few developing communities can afford the initial expenditure; the Sondela PV system cost R22 000, for instance (Gosnell, 1989, p10.14). Hence there is a need, if PV pumps are to become viable in the developing areas of South Africa, for the type of financial organization which will provide high risk capital to such communities. Gosnell points out that there is some security in that modules can be reclaimed by the financing company on a pro rata basis, if the debt is unpaid. This is similar in concept to the ideas which are discussed in section 4.5.3 under 'creative financing'.

4.4.4.2 Institutional Factors:

Photovoltaic modules rarely fail. However, a number of other factors can cause the system to malfunction. The Sondela project provides a rather unfortunate example of the things which can go wrong in a photovoltaic project. All of the following hazards were encountered and are listed with possible solutions below:

Hazard	Possible Safeguards
Flooding. (the complete system was washed away by freak floods)	Care should be taken to establish the high water mark caused by any previous floods before finally siting the project.
Lightning	The cost of lightning protection has to be assessed against the possibility of a strike occurring. The conductor itself can reduce reliability by attracting a strike. Providing surge protection on the equipment might be an economic compromise.
Vandalism	It would be difficult to completely protect (Stoning of the modules) modules from stones without unduly reducing the efficiency from shadows caused by grills. Education of the local community, especially the school children, as to the value of the project might be a better approach to the problem.
Theft (Eight panels taken)	At some cost the surrounding fences could be electrified. What can be done to prevent theft in remote and isolated regions is debatable. At present, modules cannot be easily secured without the welding of brackets to the structure, etc.

Insurance of PV systems could, presumably, be incorporated into loan agreements. Whilst institutions supplying such equipment would be able to afford the rates charged, it is not clear whether individuals or communities would be able to do so.

Vandalism and theft could possibly be alleviated by careful attention to the needs and values within the community and incorporation of leading figures from the community into the planning and implementation stages.

Such concepts were discussed and identified as factors essential to successful implementation in chapter three. The experiences above highlight the importance of benefiting from the accrued experience of previous projects.

A novel solution has been suggested by a group working in Lesotho. Vandalism and theft by members of a community might be restrained by involving the local 'medicine man' or 'witch doctor'. If properly handled, the site could become an area sacred to the people concerned and so protected from interference.

4.5 DISCUSSION

4.5.1 Technical issues

A number of technical issues have been highlighted as being germane to the success of a stand alone PV installation.

(1) Load Estimation and utilisation levels

All of the projects, previously discussed in this chapter, demonstrate the difficulty of accurately estimating load requirements. Accurate load estimates are vital for effective PV designs. Underestimation of loads can lead to system failures or reduced battery lifetimes.

Over estimation of loads will result in underutilisation of the PV system and, as was graphically illustrated in the Edutel project in Bophuthatswana, this can lead to unnecessarily high capital expenditure and very high effective electricity generating costs.

Another factor which will lead to low system utilisation is if there are large seasonable variations in solar radiation. PV systems invariably have to be designed to cope with worst month conditions which may result in large overcapacity in summer and hence low utilisation levels. It has been suggested that in these conditions, PV cannot be cost effective.

Two strategies might be employed to improve the matching of PV system capacity to load estimates. Firstly, close consultation with prospective users will lead to more accurate load estimates. Secondly, a conservative design approach may be adopted. PV systems are essentially modular in nature and so the system may be designed for the minimum expected load and modules may be added subsequently if demand increases.

(2) AC or DC Loads

The use of AC or DC outputs is dependent on a number of factors. For example, it is suggested that 12V DC equipment is optimal for installations where the maximum demand is not greater than 1 kW and the power requirement per day does not exceed 3 kWh (Paul, 1981 cited by Morris, 1988 p187).

Transmission losses are high for low voltage DC loads and hence widely dispersed demands should either be served by AC or a higher voltage DC considered with small dedicated DC/DC converters.

DC appliances are usually more efficient than their AC counterparts but are more expensive and not, normally, so easily obtainable. Hence the decision concerning an AC or DC output is taken with regard to the particular constraints both economic and technical existing for the design under consideration.

(3) Batteries

Because of the intermittent nature of solar energy, the energy storage component plays a vital role in PV systems. The correct sizing and selection of the batteries is an essential part of the design since they represent a significant proportion of the initial costs (20%) and also of the running costs over the system lifetime (up to 50%), (Morris, 1988 p184).

At present it is very difficult to optimise rationally the economic selection of batteries for PV applications. The three main types of batteries most often used in PV systems (i.e. SLI, traction, and stand-by batteries) all have quite different lifetimes for different operating conditions and also vary greatly in initial cost. So, although SLI batteries are not designed for deep and regular discharges, and will suffer reduced lifetimes in PV applications, their use may be economically justified as replacement costs may be cheaper than the initial cost of a more suitable PV battery with a longer lifetime.

Very little reliable or appropriate technical performance information is available from battery manufacturers in this country. For example, a designer requires expected battery cycle life for different depths and rates of discharge. This information has not been available for any of the batteries used in the demonstration projects discussed above even after visits to local factories. Information on discharge voltages, and depth of discharge for different discharge rates was not even available for some of the batteries used and it was not

possible to provide control settings for the voltage regulators with any certainty for over voltage and, particularly, undervoltage battery protection. Another area where there has been no information is on charge and discharge efficiency for typical applications. All of this information is vital for effective design of PV systems.

(4) Voltage Regulators

The cost of replacement batteries can significantly affect the economics of PV systems. Voltage regulators are essential to extend battery life by controlling charge and discharge regimes within desirable limits.

The quality of locally manufactured regulators varies substantially, not only in terms of efficiencies, but also reliability, with failures being encountered in the demonstration projects.

Experience would indicate that there is room for improvement in the development of locally manufactured regulators which are low cost, are reliable, and perform the essential functions of over and under voltage protection. This is particularly the case for small systems which are typically rated at 12 Volts and 10 Amps.

Very few regulators incorporate maximum power point tracking. Lower cost chips and other electronic components may make this an economic proposition. Maximum power point tracking (or similar DC/DC converters) are essential in water pumping applications where PV modules are coupled directly to DC motors.

(5) Inverters

As with other PV system components, the correct sizing of inverters is essential. If over sized the efficiency can suffer. The efficiency drops to typically 60% when inverters are used at 50% capacity and there have been reports of inverters operating as low as 45% efficient (Morris, 1988, p185).

It is thus essential in sizing such a system (i.e. one requiring AC outputs) to establish typical load requirements before specifying the inverter. The efficiency problem can be mitigated by the use of multistage or multiple dedicated inverters; although the problem of inductive loads which require considerably oversized inverters to cope with the start up current spikes, is difficult to overcome. The exception being large systems having a large number of loads with different start up patterns.

(6) PV Modules

Whilst PV modules have been consistently reliable in all the projects considered above a number of issues have been raised by Cowan (1989b) from his experience with the Edutel project.

(i) PV specifications:

How reliable are manufacturers specifications for the performance of photovoltaic modules? The unexplained change of power rating of the module chosen by the company, followed by the inability of the company to supply specifications for the actual modules used in the Edutel system is a case in point. Further, the tolerance stated for the performance ($\pm 12,5\%$) introduces a wide margin at a critical stage of sizing.

The question of manufacturers specifications established under controlled conditions, as against a field environment, also needs to be assessed. Questions such as whether derating of modules should occur for change in angles of incidence and direct irradiation and changes in spectral variation, also need to be considered.

(ii) Peak power:

The peak power rating generally quoted by manufacturers for a module's performance can only be an indication of the characteristics of the array generating capacity. Apart from the margins of uncertainty involved in manufacturers specifications themselves there is also the question of the shape of the output characteristics of the array (fill factors) and the necessity to match such characteristics with the load requirements.

(iii) Tilt-radiance response:

The angle of the incident light upon the module is related to the quantity of energy reaching the cell. The impact upon performance of non-tracking modules needs to be assessed. Coulson (cited by Cowan, 1989b) pointed out that at an angle of incidence of 60 degrees bare silicon solar cells exhibit a drop to 85% relative response. It would be helpful for effective design procedures if manufacturers would supply specifications for the tilt-radiance response of their modules.

(iv) Spectral response of photovoltaic modules:

As mentioned earlier in this chapter, spectral response of modules needs to be assessed. This is particularly important when weather station records are used for predicting insolation figures and when substantial spectral variations are experienced in critical months. As above, it is pointed out that it would be helpful if manufacturers would also supply such information instead of only supplying the response of the module under standard conditions.

(7) System Efficiencies

Most of the demonstration projects considered above recorded system efficiencies well below typically quoted module efficiencies of 12-14%. The reduction in performance efficiencies is not primarily the result of efficiency losses associated with the use of ancillary equipment. The efficiency of regulators under normal charging conditions was found to be 95-99%. Battery charge and discharge efficiencies were also relatively high at 85-90%.

Overall system efficiencies are affected primarily by reduced PV module efficiencies as a result of variations from maximum power operating points. It will be remembered that the output of PV cells may be characterized as a series of current-voltage (IV) curves which are dependent on solar radiation and temperature levels. Maximum power and hence optimal module efficiencies are obtained at the knee of the curve where the product of current and voltage are at a maximum. However, the actual operating point on the IV curve is determined by the apparent impedance which the module "sees", i.e. the load line determined by the type of load connected to the PV module. If this load is not well matched to the maximum power point of the PV module then reduced efficiencies will result.

In most cases which have been considered above, PV panels have been connected via controllers to storage batteries and hence variations in load use do not directly affect PV performance except in the important situation of low load utilisation when batteries are fully charged. In this case, regulators or controllers will force the panels to operate at increased voltages and reduced current output levels which result, necessarily, in very low efficiencies. (Controllers might also dump power, resulting in low overall system efficiencies.)

In general, the charging voltage range of batteries is reasonably closely matched to the maximum power output characteristics of PV modules, although the mismatch of battery and PV module type may result in power and efficiency losses of up to 12% (Cowan, 1989b), and there may then be an economic case for the use of maximum power point controllers.

Cowan (1989b) has broadly divided the variety of interacting elements affecting system efficiencies of stand-alone PV systems with battery storage into circumstantial, probabilistic and design factors. Circumstantial factors deal mainly with areas such as the variation in utilization patterns; whilst probabilistic factors cover issues such as the variation in insolation levels experienced. Design factors are concerned primarily with the degree of mismatch between array output characteristics and load input characteristics. Other design factors include system size, array/battery balance, choice of components and component efficiencies.

Whilst circumstances relating to utilization are important (these have already been discussed) design factors are critical, not only with regard to the appropriate matching of system components, but also in relation to adequate and accurate sizing to guarantee long term reliability and to efficiently match demand requirements.

(8) Solar insolation data

The correct insolation data for a particular site enables the array size to be finely tuned to the load requirement. Without accurate data the array can be sized significantly larger than is required with consequent increase in costs and lowering of overall efficiency. As Muller (1988, p169) points out, it is "no good striving for a few percent increase in cell efficiency when radiation data may be as much as 20% out."

A current project at the E.R.I. is processing all available radiation data and a solar radiation handbook for designers will be published. Most solar radiation data is available only in the form of daily or monthly averages. For accurate design purposes long term variations in solar radiation must be known. The loss-of-power probability design methods, discussed below, attempt to incorporate these issues.

Another area of concern centers on methods for converting horizontal radiation data (supplied from weather recording stations) to values which can be expected on tilted surfaces (most solar applications are angled to the sun).

As much as 12% difference in insolation predictions were obtained by Cowan (1989b) by using different tilt-plane calculation methods and the different extractions of data from the same weather station. He argues that this percentage difference may not be significant in view of the unpredictability of specific climatic conditions from year to year but points out that such a variation is an initial embarrassment if the aim is to ensure critical and evaluable sizing techniques.

(9) Design methodologies

Much of the analysis of the performance of the PV demonstration projects considered above points to the need for improved sizing methodologies. Not only does one need to ensure that design loads are reliably met, but also that systems are not unnecessarily oversized with concomitant under utilization and exorbitant electricity generating costs.

Few of the systems were accurately designed to match loads, some relied on suspect solar radiation data and all relied on arbitrary design approaches which give no indication of the long term probability of failure in relation to weather variations.

In some cases, arbitrary levels of autonomy, expressed in terms of days of battery storage, were specified. In other cases, design methodologies based on dubious assumptions regarding loss of power probabilities were used.

This experience points to the need for the development of design methodologies, based on local long term radiation data, which are able to predict accurately loss of power probabilities. Such a design tool is particularly appropriate for applications in developing areas where cost considerations are critical and higher probabilities of power loss may be acceptable.

4.5.2 Institutional Issues

A variety of institutional and social factors influence the viability and effectiveness of PV applications, as has been noted earlier under each specific project.

Further points to be considered, which may not have been mentioned previously, fall under two general headings:

Quality of life issues

The experience of the Omdraaisvlei and Uitsig demonstration projects has shown the dramatic impact that photovoltaic systems can have on peoples lives. Not only have PV's resulted in savings as compared to previously used systems but improved lighting and the introduction of TV have resulted in changed lifestyles. The community at Omdraaisvlei, for instance, were able to read, write or knit without the strain imposed by poor illumination and were considering the possibility of starting on a small home industry. The community at Sondela were able to use their time saved in manual irrigation to expand their home industries. Educational TV for school children has value which cannot be quantified.

Spares/maintenance

A factor which is essential to the successful implementation of a PV installation in a rural situation is the availability of spares. Experience has shown that balance of system components can fail and that these are not readily available in remote and/or rural areas.

A major third world worry is that once the installation of equipment has taken place, the technicians will disappear and hence the maintenance and replacement of the equipment will become impossible. Careful steps should be taken to ensure that spares and effective maintenance are available and that the people concerned are made well aware of this availability. The initial schemes should amply demonstrate the effectiveness of the back-up services available.

As has been noted previously, an excellent example of this is the Bophuthatswanan "Edutel" project. Components which have the highest probability of failure have been designed into removable cards and trays which a small trained maintenance crew are easily able to replace and send to a central workshop for repair. This maintenance system has resulted in a very high level of availability.

4.5.3 Financing

As has been mentioned, the relatively high initial cost of PV systems means that some financial assistance is essential if the general dissemination of the technology is to be successful throughout developing areas. However, financial institutions are often unlikely to back low income rural units.

Holmes (1987, p3957) identifies the need for another type of loan approach which he calls 'creative financing' and adds that such a scheme should be an integral part of the overall social package presented. This type of package would have to satisfy both parties concerned, that is both the seller and the buyer. Holmes reports that his company is able to arrange such satisfactory financing by installing the equipment ordered on a 'pay as you go' basis.

For example, a contract might be made for the supply and installation of:

Four PV modules; twelve lights and one inverter.

If the customer has only a small deposit available and can only pay a moderate amount per month then the installation can be carried out in several phases.

- (1) Initially one module with some lights and possibly the inverter are installed.
- (2) As and when further payments are made, additional work is performed.

Holmes has experienced success with this method of 'creative financing' with extensive PV sales in homeland areas. One might add that the modular nature of the PV systems make them an ideal subject for such schemes.

4.6 CONCLUSIONS

This chapter has highlighted some of the problems encountered with PV installations in South Africa. Through detailed monitoring of the PV demonstration projects, key problems have been identified and possible solutions suggested. The experience of these systems has also pointed to those factors which are critical to the successful implementation of PV technology.

This review of technical and institutional factors together with the economic review in the next chapter will allow recommendations for further research to be made in the final chapter.

CHAPTER 5

THE ECONOMICS OF PHOTOVOLTAIC APPLICATIONS IN
DEVELOPING AREAS OF SOUTHERN AFRICA

5.1 INTRODUCTION

This chapter discusses the financial viability of photovoltaic systems for different applications in developing areas in Southern Africa. The main uses considered are in areas some distance from the national electricity grid and cover such applications as home and community electrical requirements. A range of system sizes are examined in each of these applications.

The final cost used for comparison is expressed in cents per kilowatt hour (c/kWh).

Comparative costs of photovoltaic and competing power systems will vary according to the nature as well as the size of the installation. For example, the cost of photovoltaic power for water pumping will be lower than home power applications, as battery storage is generally absent in the former but is essential for the latter.

The size of installation is also significant. PV systems are modular and hence the cost of PV power per kilowatt hour does not alter significantly with the size of the system; the same is not true for competing power systems which are generally size sensitive. An example of this would be the cost of a diesel generating system to produce loads of less than 3 kW say, compared with a larger system producing 30 kW. In the former case PV produced electricity is generally competitive but for higher power requirements PV systems are not yet cost effective.

The objective of this chapter is to develop a chart which compares the costs of a wide range of PV system sizes and applications with standard competing technologies.

5.2 COSTING METHODOLOGY

The choice of which technology is cost effective for a particular application centers not only on the initial capital cost but also involves an analysis of long term economic considerations, such as the operating and maintenance costs of competing technologies together with the impact of inflation and discount rates on the value and cost of expenditures.

The calculation of realistic costs is further complicated by the multitude of parameters and constraints which cannot easily be financially quantified. It is not easy, for instance, to include in a financial costing the benefits of the clean, noiseless, and pollution free aspects of photovoltaic technology.

5.2.1 Comparative Methods

There are three main methods which are used to assess the economic potential of different technologies:

(i) The payback period

The length of time is calculated which is necessary to pay back the initial investment in terms of the benefits accumulated by the use of the new installation. This method has the disadvantage that the benefits accruing are very often unquantifiable. For example, the benefit of vaccine availability or a fresh water supply are not easy to assess in financial terms.

(ii) The rate of return

The discount rate is calculated at which the technology costs equal the benefits accruing over the lifetime of the system. As with the previous method, this involves the financial quantification of benefits. However, this method of assessment does provide a figure which is independent of estimations of discount and inflation rates over the system lifetime.

(iii) Life Cycle costs

This method calculates the present value of all the costs involved with the system over the estimated lifetime. It will include all future costs such as replacement of parts and costs of fuel and maintenance over the projected period. This method gives a costing which is comparable for each technology since the benefits are assumed to be equal for each system.

The method requires four main assumptions:

- (a) the discount rate;
- (b) the escalation rate;
- (c) the technology lifetime; and
- (d) the technology operating and maintenance costs.

Problems associated with this method are the estimations involved in not only forecasting the discount and escalation rates over a period of 20 or 30 years into the future but also the problems of estimating the lifetimes and maintenance costs of the technologies used. Whilst manufacturers provide some guidance in these areas, field experience should also be considered.

5.2.2 Life Cycle Cost Analysis

The life cycle cost methodology is widely used elsewhere for comparative analysis of competing technologies and is the preferred method for this report.

The life cycle cost of the photovoltaic system is compared to the life cycle cost of the alternative power system to establish cost competitiveness in a given application. These costs are calculated from the initial cost of the system installed at the project site, and the present value of all the recurrent costs. The sum of current and recurrent expenditure represents the amount of money required to completely cover all costs, over the operating lifetime of the system.

Initial costs (IC)

These are the capital costs incurred when a system is installed. The cost would cover the array (or alternatives such as a diesel or petrol run generators), a converter or inverter, voltage regulator and batteries. Also usually included are the area balance of system costs to cover the cost of land, any structures, wiring, connectors, etc. It is usual to assume that the indirect costs, which include engineering, management and contingency fees and the installation costs, which include site preparation, testing and checkout, are each a fixed percentage of the equipment capital cost. For the purpose of this analysis, the cost of land and indirect costs such as design and installation have been ignored.

Replacement costs

The present value of replacement costs (RPV) is calculated as follows:

$$RPV = \sum_{j=1}^{nrep} BR \times \left(\frac{1 + esc_b}{1 + dr} \right)^{j \times k}$$

- Where
- j = Counter for number of replacements (1,nrep).
 - k = Component lifetime (years).
 - j*k = Constrained to be strictly less than photovoltaic system lifetime or lifetime used in LCC analysis.
 - BR = Single time replacement cost of unit considered, in base year Rands.
 - esc_b = Real (above inflation) annual escalation rate for the equipment under consideration.
 - dr = Real discount rate (cost of money to system owner, typically defined as 10% (real) for government applications.

Although the anticipated lifetime of a photovoltaic array is, in excess of 20 years, this period is used as a conservative estimate in this analysis. Components used are thus costed over an equivalent period. For instance, dependent on usage, the lifetime of a petrol generator could be as low as two years with the result that some 9 replacements would be made in a 20 year system comparison. Batteries will also need to be replaced several times during the lifetime of the PV system.

The scrap value of replacements is ignored in these calculations. The real escalation rate is assumed to be zero and the real discount rate taken as 4% in the base case analyses which follow.

Operation and maintenance costs

The present value of the operating and maintenance costs of the system over its lifetime are calculated as follows:

$$OMPV = OM \times \left(\frac{1 + esc_{om}}{dr - esc_{om}} \right) \times \left[1 - \left(\frac{1 + esc_{om}}{1 + dr} \right)^N \right], \text{ if } dr \neq esc_{om}$$

or $OMPV = OM * N$ if $dr = esc_{om}$

Where $OMPV$ = Present value of operation and maintenance costs.

OM = Annual operation and maintenance costs in base year rands.

esc_{om} = Real (above inflation rate) annual escalation rate for operation and maintenance activities (fraction), typically zero.

dr = real discount rate (fraction).

N = System lifetime.

Regular operation and maintenance costs can be estimated on an annual cost basis. They cover not only array or generator, battery and inverter maintenance but also upkeep of the grounds and the cost of site visits. As before, these amounts may be estimated as a fixed percentage of the initial capital cost of the equipment.

Life cycle Costs. (LCC)

These costs are equal to the sum of the initial costs and the present day value of the expenditures incurred during the lifetime of the system, i.e.

$$LCC = IC + RPV + OMPV.$$

Levelized annual cost

Further to the life cycle costing above it is useful to consider the levelized annual cost in cents per kilowatt hour as a means of comparison between energy alternatives offering the same service.

The levelized annual cost in cents/kWh (A) is calculated from :

$$A = LCC \cdot i / [1 - (1+i)^{-n}] \cdot 100 / K$$

where

LCC = present value of the life cycle costs in Rands.

n = number of interest periods taken over the expected life.

i = interest rate per period.

K = The total power produced per year in kWh.

This formulae can be adapted to compare pumping systems so as to obtain a levelized annual cost in cents/m⁴. In which case 'K' is defined by:

K = The yearly total of the volume pumped multiplied by the head. Measured in m⁴ units.

In this study, these calculations were combined with a standard PV sizing methodology (outlined in appendix A) and incorporated into a Lotus 123 spread sheet to enable rapid calculation of life cycle costs and levelized energy costs for a number of different cases, examples of which are given in Appendix C.

5.2.3 General assumptions

The following key parameters were used in base case analysis for both PV systems and the alternatives, where applicable.

(1) Array cost	R20/Wp
(2) System lifetime	20 years
(3) Real Discount Rate	4%
(4) Real Escalation Rate	zero
(5) BOS costs	zero
(excluding batteries and controllers)	
(6) PV O&M costs	1% of initial costs
(7) Insolation	6 kWh/m ² -day
(8) Efficiencies	
Module	12%
Battery	85%
Voltage Regulator	95%
Inverter Efficiency	75%
(9) Module Operating Temperature	55 ⁰ C
(10) Module temp. Coefficient	-0,005/ ⁰ C
(11) Inverter Cost	1,00 R/W

Sensitivity analyses were undertaken by varying the following parameters:

- (1) Module cost 3, 5, 10, 15 Rands per peak Watt
- (2) Discount Rate 2%, 10%, 15%
- (3) Insolation 3, 4, 5 kWh/m²-day
- (4) Battery Choice:
 - (i) Automotive (SLI):
 2 year life. Cost of 132,00 R/kWh.
 Depth of discharge 40%
 - (ii) Traction:
 7 year life. Cost of 283,30 R/kWh.
 Depth of discharge 50%
 - (iii) PV special:
 10 year life. Cost of 430,50 R/kWh.
 Depth of discharge 60%

Also, variation of fuel costs were considered for the petrol and diesel alternatives :

(5) Fuel price escalation rate: From -5% to +5%

The choice of these variables is discussed further below

5.3 PV ELECTRICITY COSTS

PV costs are sensitive in varying degrees to certain key parameters which are examined below. This section discusses the effect on costs of each variable and will show that the cost of PV generated electricity is relatively insensitive to the system size due to the modular nature of PV construction. This is a major advantage of the use of PV systems as it means that expansion can easily and economically be undertaken as electricity needs increase.

5.3.1 Key variables

The final costs of a PV system will differ significantly according to the assumptions used. The identification of the key parameters and the establishing of their range is an essential part of the costing methodology.

(a) Module Cost:

It is evident that every effort is being made to reduce this cost to a price which will be competitive with conventional fossil fuel alternatives by the late 1990's. At present 20 R/Wp is a reasonable present day price on which to base sensitivity analysis with a price of 3 R/Wp being a long term aim. However, 10 R/Wp is a best short term prediction which is assumed to be the best case achievable within a reasonable time period.

(b) Insolation levels:

The range of insolation considered, that is from 3 kWh/m²/day to 6 kWh/m²/day, is within the limits of sunshine experienced under normal Southern African conditions.

A copy of a standard meteorological chart showing yearly sunshine averages is shown in Appendix B.

(c) Escalation and Discount rates:

The prediction of these values over the 20 year proposed lifetime is subject to some discussion. The rates estimated are within the range of accepted banking practice and consequently provide a reasonable basis for this analysis. Real escalation rates are used; i.e. 5% escalation implies an increase of 5% over and above the rate of inflation.

(d) Battery Type and Cost:

Batteries have a limited lifetime and thus a number of replacements have to be made during the life of the PV system. It is assumed that the costs of batteries escalate at the rate of inflation, i.e. a zero real escalation rate.

Batteries play a significant role in the overall costs of PV power production with the final annualized costs being sensitive to the types of cells considered. Whilst special PV batteries are currently being designed and tested, their cost is presently prohibitive. Use is therefore made of three types of commercially available cells.

(i) Automotive (SLI)

Ordinary automotive batteries used for 'Starting, Lighting and Ignition' are not generally suitable for PV applications due to their characteristics and short life (2-3 years). However, they are cheap to buy and install, and are used in this costing to compare the smallest PV system discussed to its conventional alternative, a paraffin lamp.

(ii) Traction

Currently used in such applications as forklift trucks and milk floats these batteries have suitable characteristics for PV use being designed for deeper discharge than SLI batteries. Manufacturers claim a life of some 10 years for this type of cell but a more conservative estimate is used in this costing of 7 years.

(iii) PV special

These are tubular cell batteries designed for low maintenance and the ability to withstand multiple deep cycled discharges. Current applications would be where uninterruptable power supplies are a requirement and for use as backup units for emergency supplies. They are the most expensive of the three options but have the longest accepted lifetime (10 years).

5.3.1.1 PV system size:

This study examines the calculated costs of PV systems over a wide range of system sizes applicable to developing areas ranging from a single light application of a few watts to a 400 kW power requirement for a community center.

Four sets of detailed designs of typical applications have been undertaken in order to establish the range of likely costs, as well as that of currently used alternatives.

- (a) A small system application, designed to compare with paraffin lamp use. Output: 0,044 kWh/day.

A small PV unit is designed to provide minimum lighting only (one 11W fluorescent light used for 4 hours per day) for an average rural home. This system is compared to the usual alternative means of providing such light, i.e. a paraffin lamp.

- (2) A medium sized application designed to compare with a small petrol genset. Output: 0,366 kWh/day and 4 kWh/day.

A television set and several lights are supplied by a PV system for this medium sized home with comparison made between the PV unit and a petrol generator.

- (3) A large home case designed to compare with a diesel genset. Output: 37,5 kWh/day.

This power rate would be typical of a large home unit running a variety of loads ranging from totally domestic needs to some small machinery for agricultural and/or farming requirements.

- (4) Community power systems, designed to compare with diesel gensets. Output ranging to 400 kWh/day.

Details of the costing of the above designs are shown in Appendix C.

5.3.2 PV system cost comparison with size

Application	Load kWh/day	Cost c/kWh	BOS costs	Electrical Supply	Battery type
Small light	0,044	319	47%	DC	SLI
Medium Home	0,366	157,73	21%	DC	Traction
Medium Home	4,00	159,00	18%	DC	PV Special
Large home	37,5	147,61	17,9%	DC	PV Special
Com.Center	100,00	147,62	17,9%	DC	PV Special
Com.Center	200,00	147,62	18,0%	DC	PV Special
Medium Home	0,366	215,14	34%	AC	Traction
Medium Home	4,00	177,55	20%	AC	PV Special
Large home	37,5	174,91	18,7%	AC	PV Special
Com.Center	100,00	174,74	18,5%	AC	PV Special
Com.Center	200,00	174,66	18,5%	AC	PV Special
Com.center	300,00	174,65	18,5%	AC	PV Special
Com.center	400,00	174,65	18,5%	AC	PV Special

Table 5.1 Comparison of generation costs.

The modular nature of PV systems leads one to expect constant costs, measured in c/kWh, regardless of any size change. However, this does not take into account variations in the proportion played by such factors as the balance of system costs. In smaller systems, the proportionate cost of batteries and regulators is higher. To illustrate this point Table 5.1 lists the percentage part played by such costs over the range of sizes considered.

If the electrical output is AC as against DC then an inverter has to be supplied. If inductive loads are also used then the instantaneous starting current requirements will be greater than non-inductive AC loads.

Variation in load demand patterns can also result in high peak demands. Thus these loads will necessitate a larger inverter resulting in marginally increased costs. These costs are represented in figure 5.1. Results obtained by other researchers using different assumptions are also shown.

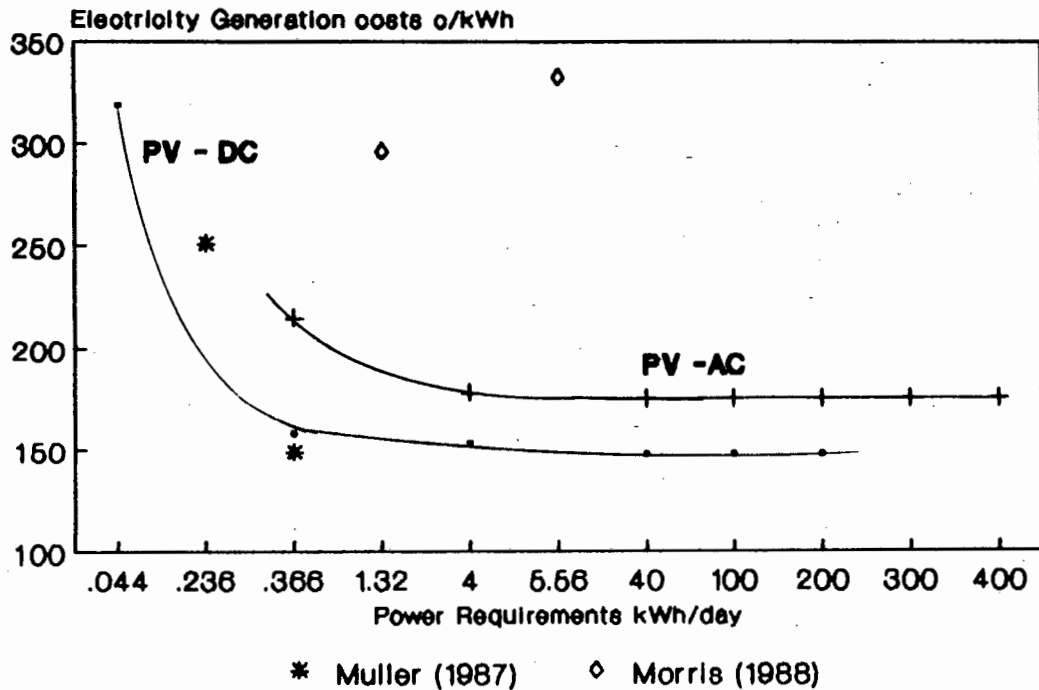


Figure 5.1 Generation Costs (c/kWh) versus Power Requirement (kWh/day).

5.3.3 PV System Costs versus Module price

The cost parameter with the greatest potential to vary is the module price. The world price for PV modules has fallen dramatically over the last ten years, as has been shown graphically in chapter three.

Thus it is useful to examine directly the effect of changing module costs upon the unit cost of generated power. The following graph uses a daily load requirement of 37,5 kWh/day and shows costs as module prices vary from R3/Wp to R20/Wp:

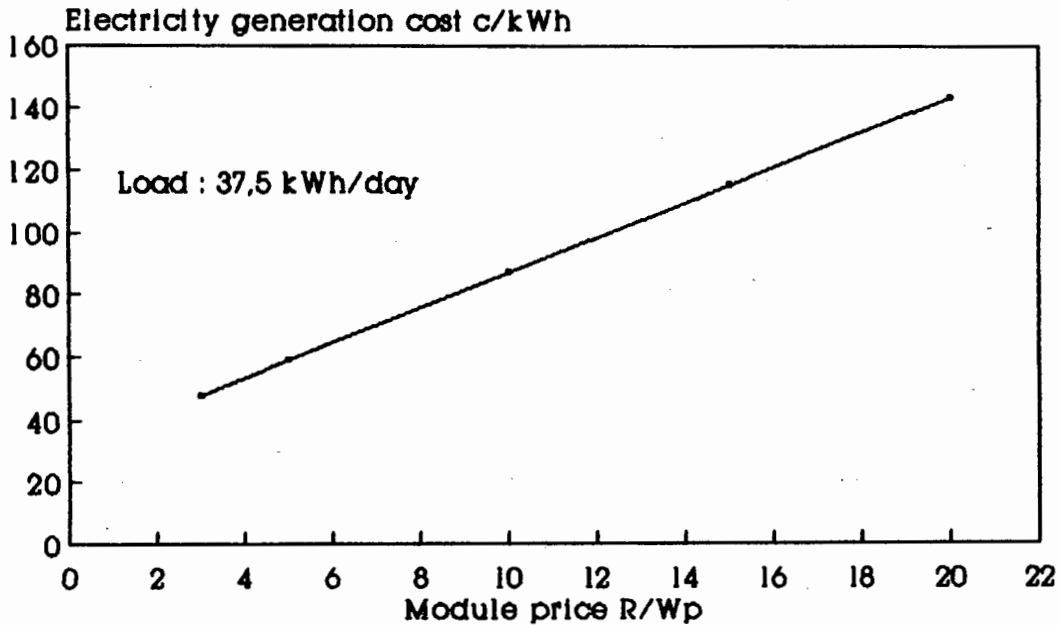


Figure 5.2 Electrical Generation costs versus Module price.

5.3.4 PV system costs versus Solar Radiation

Perhaps the most critical design parameter for PV systems is solar radiation. In regions of low insolation, more modules have to be provided to supply the same output as in regions of high insolation, with resulting increases in cost.

Diurnal and seasonal variation of radiation further complicates the calculations. In particular the cost of battery storage increases markedly as the average number of days of low radiation or cloud per month increases. For example Cape Town, with it's cloudy winters has the most expensive PV costs in RSA even though the yearly sunshine average is amongst the highest (Williams 1988, p62).

The estimation of this number of days, termed the 'Loss of Energy Probability' (LOEP), is considered in Appendix A.

The following graph shows the effect of the insolation changing from 3 kWh/m²-day to 6 kWh/m²-day as a function of module cost. The values chosen are for an output of 37,5 kWh/day.

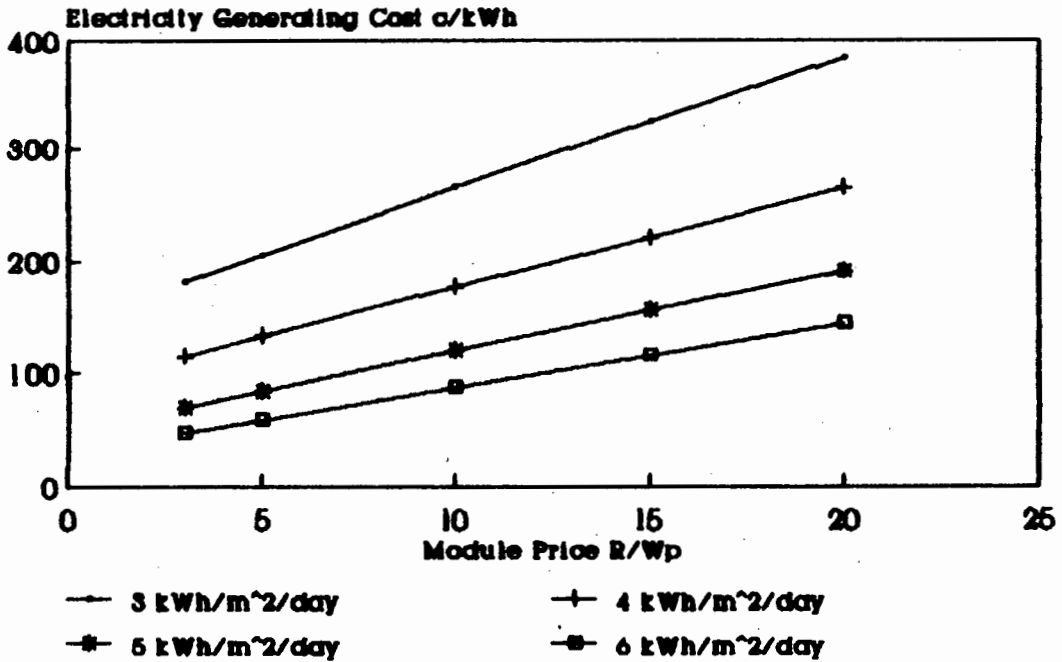


Figure 5.3 Cost of PV electrical power generation versus Module cost for a range of insolation levels

5.3.5 PV System Costs versus Discount Rate

As expected with a technology which is initially capital intensive, the cost of generated power increases with increased discount rate.

For the 37,5 daily load:

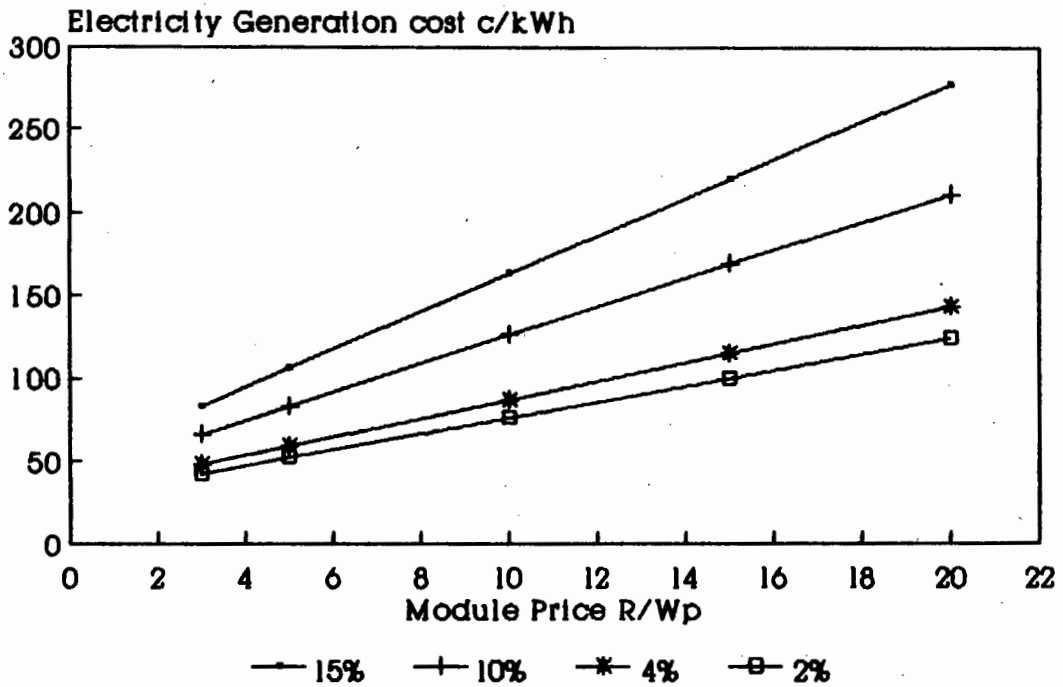


Figure 5.4 Cost of PV electrical power generation versus Module price for a range of Discount rates.

5.3.6 PV System Costs versus Battery type

The calculated costs show little variation between the use of traction and PV special batteries. However, with the short life expectancy of the SLI batteries a significant increase in costs is experienced with this option, as is illustrated below:

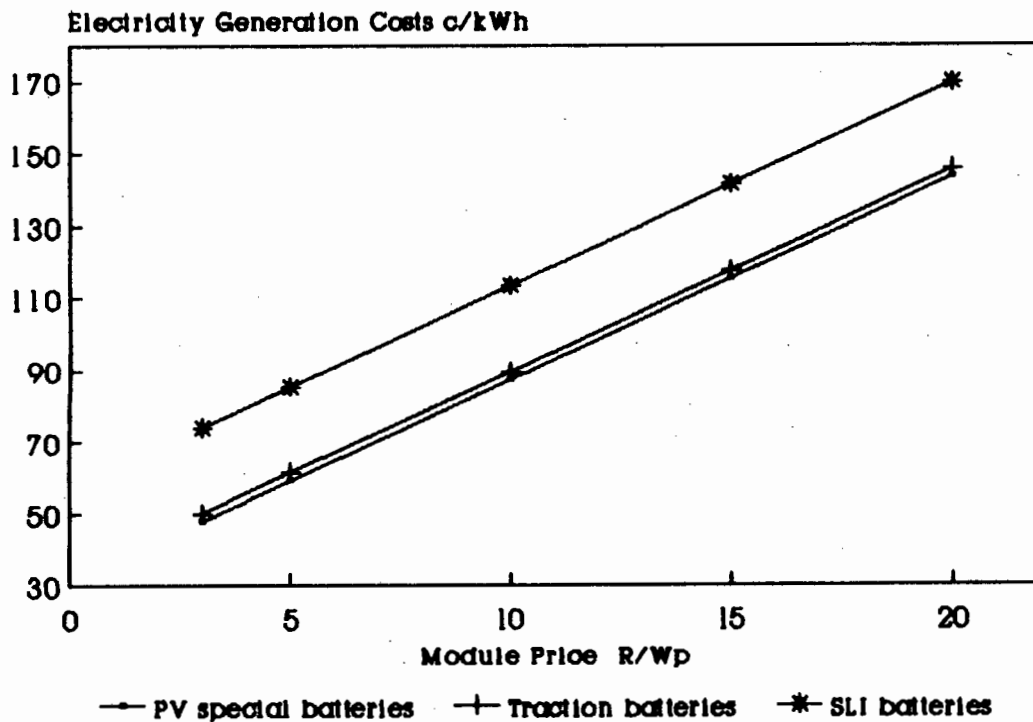


Figure 5.5 Electricity Generation costs versus Battery type.

5.4 COSTS OF CONVENTIONAL ALTERNATIVES

The term 'conventional alternatives' applies to those methods of providing light or electricity presently in general use. In this section three specific alternatives to PV systems are discussed:

- (1) Paraffin lamps for small systems
- (2) Petrol gensets for medium systems
- (3) Diesel gensets for large systems

Also, the 'costs' referred to above apply to the final unit cost of output electricity and are measured in cents per kilowatt-hour.

5.4.1 Key factors affecting costs of alternatives

(1) Size

Unlike PV systems, which are modular by nature, the size of conventional systems affects the unit cost of power produced. In general, the unit cost decreases with increased power output. Typical usage shows that large diesel gensets are cheaper to run than small diesel gensets.

(2) Technology

The system specification usually conditions the choice of a suitable technology, and hence the final cost. A very small application (for lighting, say) would use a paraffin lamp but medium sized applications might use either a petrol or a diesel generator set. Large systems are supplied by diesel generators.

(3) Fuel Price

Cost estimates include the base price of the fuel. Escalation rates attempt to take into account the variation in this cost over the projected lifetime of the system.

A further complication met when using conventional alternatives in remote areas is the extra expense involved in obtaining continuous fuel supplies and the problem of interrupted power when fuel supplies are insufficient. By contrast, PV systems do not have these problems.

(4) Discount rate

As with PV systems, the discount rate reflects the economy and the ease of obtaining capital. A figure of 4% is taken as the basis for the initial analysis

5.4.2 Paraffin lamps

In the very smallest PV case considered previously, where power was used for lighting only, the most commonly used alternative is a paraffin (kerosene) lamp. Whilst costs in c/kWh are not readily obtained for paraffin lamps it was thought useful to present a cost comparison based on annualized life cycle costs. Details of the cost calculation may be found in Appendix D1.

The same load requirement is considered as the small PV case above; i.e. one lamp burning for four hours a day (although the quality of light from the paraffin lamp is inferior to the PV powered fluorescent lamp).

5.4.2.1 Photovoltaic System and Paraffin lamp compared:

The graph following shows that the paraffin lamp is cheaper to run for all scenarios except for low discount rates with 'best case' PV conditions when costs become close.

What is not evaluated by this graph is the difference in quality of the resultant light produced. In this area the PV system is markedly superior using, as it does, a fluorescent tube for illumination.

Further, the fumes, pollution, maintenance needs and general messiness of a paraffin lamp in comparison to the ease of use of electricity cannot be quantified in the above cost comparison.

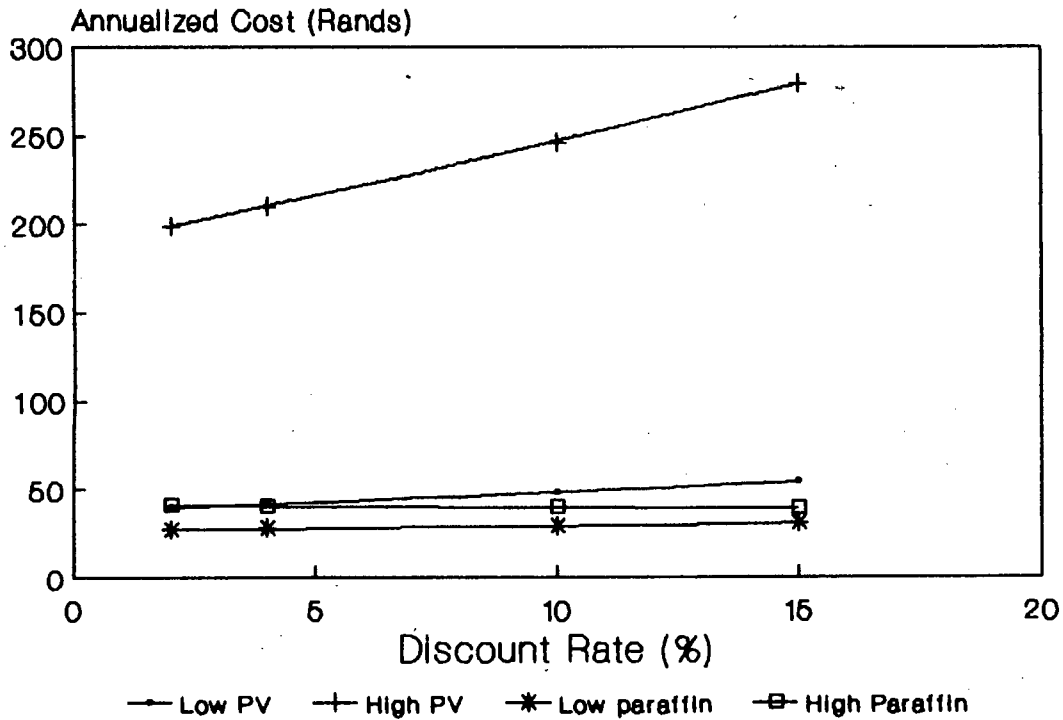


Figure 5.6 Life cycle costs of a Paraffin Lamp and a small PV powered system compared.

'High PV' = Module Price 20 R/Wp Insolation: 3 kWh/m²/day

'Low PV' = Module Price 3 R/Wp Insolation: 6 kWh/m²/day

'High Paraffin' = Escalation rate of paraffin + 5%

'Low Paraffin' = Escalation rate of paraffin - 5%

5.4.3 Petrol Generators

Petrol Gensets are normally available for local domestic markets in a range of sizes to 5 kW. Although larger units can be ordered, it is assumed in this survey that this 'off-the-shelf' range is the most applicable to the cost comparisons under consideration.

5.4.3.1 Petrol genset system assumptions:

Variables affecting costs were standardized as follows:

Overall system lifetime: 20 years

- Genset:
- (1) Run at 3/4 rated load
 - (2) Fuel consumption as per specifications for 3/4 load
 - (3) Petrol: 93 Octane at an average RSA price of 92 c/l
 - (4) Lifetime: 3000 hours
 - (5) Maintenance:
 - (i) 50 hour service consisting of an oil change with both the air filter and plugs being cleaned.
 - (ii) 500 hour service consisting of a minor overhaul listed by the distributor as R 120 inclusive of parts and labour.

- Batteries:
- (1) Type: Traction
 - (2) Cost: R 283.30/kWh
 - (3) Lifetime: 7 years
 - (4) Discharge: 50 %
 - (5) Efficiency: 85%
 - (6) Charge rate (amps) = 20% of Amp-hour rating

- Battery Charger: (1) One replacement is allowed for during the 20 year system lifetime
(2) Efficiency: 90%

Since the comparison is to be made with PV systems which produce DC, the genset system is also costed for a 20 year lifetime (with a number of replacements) and designed so that the final output is also DC. The configuration used is illustrated by the following schematic :

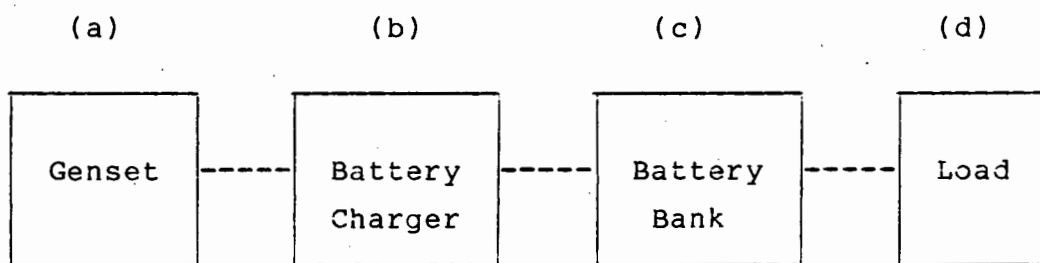


Figure 5.7 Petrol genset system schematic.

5.4.3.2 Petrol Genset costs:

The costs for a genset unit are complicated by the interplay of a number of variables. Capacity factor, as defined below, is a measure of the effective use of the engine and is often low in practice due to mismatching of output with loads. It has been assumed in this study that the engines will be run at an optimal performance rate, i.e. at three-quarters load, in order to achieve fuel economy and the specified lifetime. In this way a high capacity factor is also realized.

Capacity Factor is the ratio:

$$\frac{\text{Actual power delivered during a given time}}{\text{Maximum power that can be delivered in the same time}}$$

Another variable to be considered is the Load Factor, which is defined as:

$$\frac{\text{Actual energy delivered per 24 hours}}{\text{Maximum energy that could be delivered per 24 hours}}$$

Both these variables affect the final unit cost of the electricity produced. A further constraint imposed upon the system is the charging rate for the batteries. In order to optimize the lifetime of the cells a normal 'rule of thumb' is to assume a maximum charging rate (in amps) of 20% of the rating of the battery (in amp-hours). The daily output of the engine is limited by this condition, and the load factor consequently determined.

Maintenance is assumed to be as per manufacturers specifications, and costed accordingly. It is often doubtful whether such preventative maintenance would be carried out under actual remote area conditions where engines tend to be run with minimal or zero servicing until a breakdown occurs (Williams, 1988 p 42).

The range of sets considered was from a nominal output of 550 W to 5 kW. The following chart lists the results of the calculations:

Model EG	Cost Rands	Final Output kWh/day	Life Years	Battery Rating kWh	Petrol Consum. l/h	Cost/year Rands	Maint. Cost Rands	Battery Charger Rating/Cost	Genset	NPV Battery Rands	Batt.CH	OMPV Rands	Life cycle costs LCC	c/kWh	
550	1029	0,947	2,8	1,894	0,50	494	432	25	1139	4750	718	769	12577	21519	458
1000	1595	1,688	2,8	3,375	0,64	632	432	56	1445	7370	1280	976	14460	28082	335,46
1400	1895	2,355	2,8	4,711	0,75	740	432	79	1667	8750	1780	1130	15928	32484	278
1800	1995	3,036	2,8	6,073	0,80	790	432	101	1890	9220	2300	1280	16607	35013	232,56
2000	2495	3,374	2,8	6,747	1,10	1086	490	112	2000	11500	2560	1350	21418	41434	247,68
3500	3895	5,904	2,8	11,808	1,80	1777	490	197	2834	18000	4470	1910	30809	65263	222,89
4500	4295	7,592	2,8	15,184	1,95	1925	490	253	3389	19800	5750	2290	32820	72646	192,95
5000	5495	8,434	2,8	16,868	2,10	2073	490	281	3723	25400	6390	2510	34832	83129	198,75

Table 5.2 Petrol Genset costs.

A detailed calculation for the EG 1000 is given in Appendix D₂.

Expressed graphically the reduction in annualized cost is apparent with increased power rating:

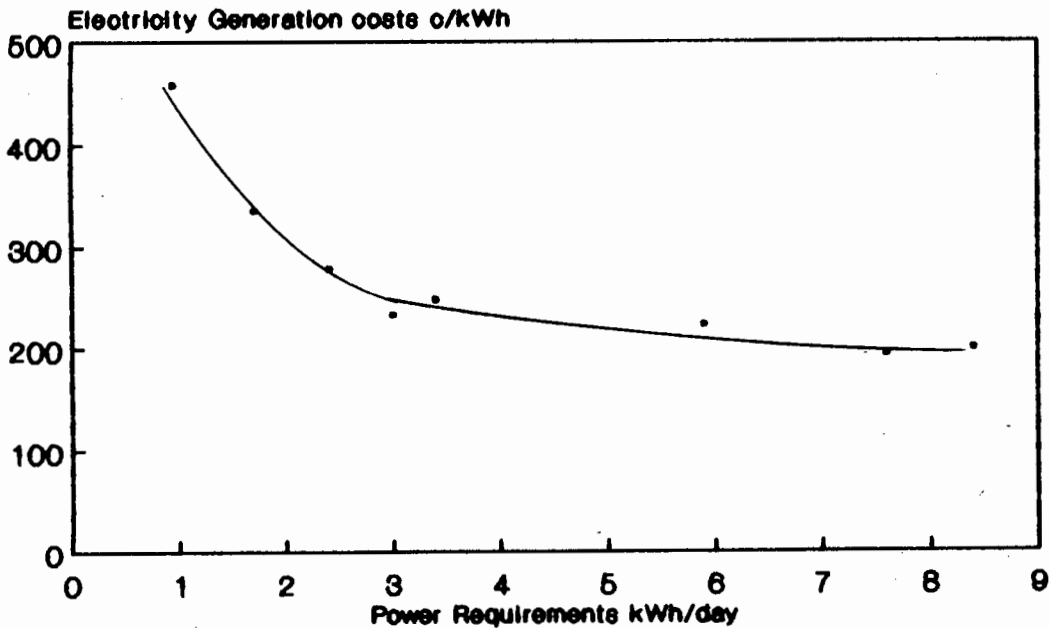


Figure 5.8 Petrol Genset Electricity Generation costs.

5.4.4 Diesel Generators

The conventional method of meeting remote area power requirements has been diesel generators. These units are available from ratings of three kilowatts to large systems giving some hundreds of kilowatts output. The median size used by farmers in South Africa was found from the results of a questionnaire to be in the 5 kW range with larger units around 100 kW output being utilized on dairy farms and large irrigated farms using central pivot sprinkler systems (Williams, 1988, p6).

Two previous studies have measured actual generating costs of diesel sets in the field in South Africa (Williams, 1986; Morris, 1988) and these are reported below.

	Genset Rating kW	Power/day kWh	Hours/day	Capacity Factor	Cost c/kWh
1	9,40	14,13	6	0,24	84,66
2	9,00	16,44	8	0,34	90,80
3	4,90	5,07	4	0,25	114,42
4	7,50	5,58	4	0,23	120,95
5	7,50	9,42	8	0,20	124,21
6	3,70	5,37	6	0,30	145,61
7	7,50	8,37	8	0,17	145,50
8	3,70	4,32	8	0,18	158,75
9	7,50	6,22	6	0,17	171,11

Table 5.3 Diesel genset field costs.

Source: Williams, 1988 p45

The work of Morris focuses upon the diesel genset and PV systems installed in the Kruger National Park. The results of the costing of the Diesel Genset systems are:

Location	Genset Rating kW	Power/day kWh	Hours per day	Capacity Factor	Cost c/kWh
Woodlands	5,6 kW	16,56 (Av)	11,15(av)	0,3 (Av)	337
Shingwedzi	180 kW 200 kW	2605	24	0,49 - 0,66	33,7
					(monthly averages)

Table 5.4 Kruger National Park Genset costs.

Source: Morris, 1988, p 160 and p 178

The second system consists of two sets, each capable of supplying 98% of the typical daily load demand whilst the other is on standby or being maintained. Although economies of scale are involved, the low unit cost of 33,7 c/kWh for the larger system also demonstrates the advantages of suitable load matching resulting in a high capacity factor. Kenna (1987) in his summary also points out that economies of scale play a part since operator and repair costs are similar from machine to machine virtually regardless of output.

Optimization of the Woodlands genset-plus system produced a more reasonable costing of 172 c/kWh. The main reason for the high unit cost of 337 c/kWh is attributed to an inefficient operating regime resulting in the low capacity factor (Morris, 1988, p161).

The term genset-plus refers to the use of a battery bank to provide the output to loads, with the genset being used at maximum efficiency for a specific time to charge the batteries. A high capacity factor results. This is by way of comparison with gensets which provide direct power without storage, usually at low capacity factors.

Williams (1988) also calculated the theoretical generating costs for a wide range of conditions based on manufacturers specifications and ruling prices in 1986.

Although these data have not been adjusted to 1988 prices they are presented in the following graph with the rest of the data listed above.

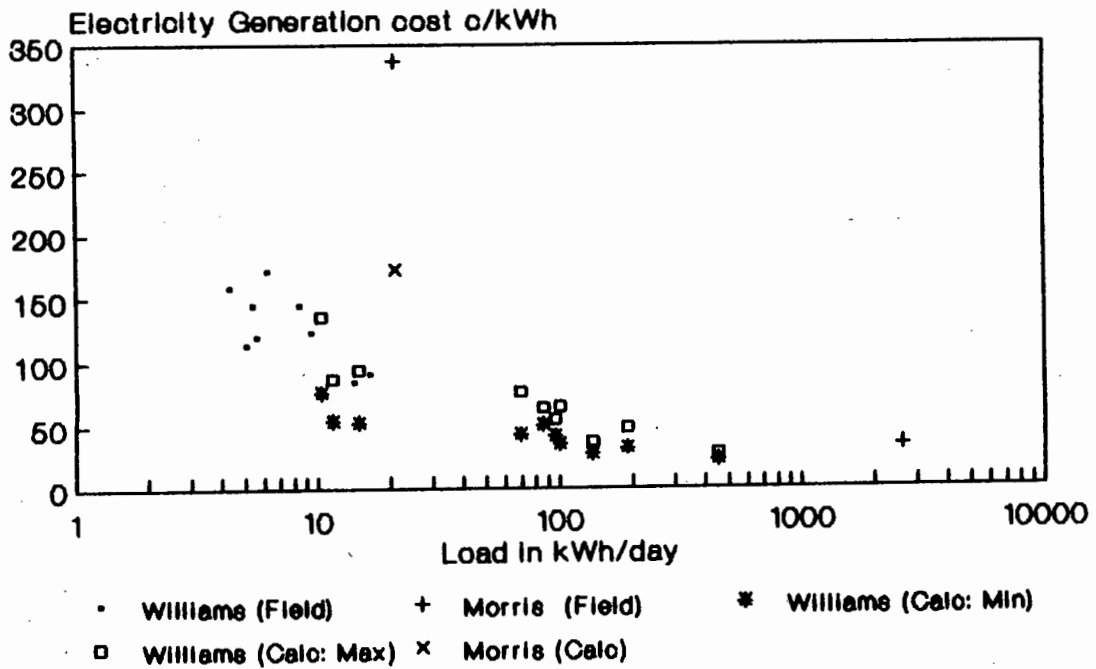


Figure 5.9 Diesel Generator Electricity Generation costs. Sources: Williams, 1986 and Morris, 1988

5.5 COST COMPARISON OF PV TO ALTERNATIVES

The foregoing costs for PV, petrol and diesel generating units are presented on one graph in Figure 5.10 with individual points obtained by Muller and Morris excluded for the sake of clarity.

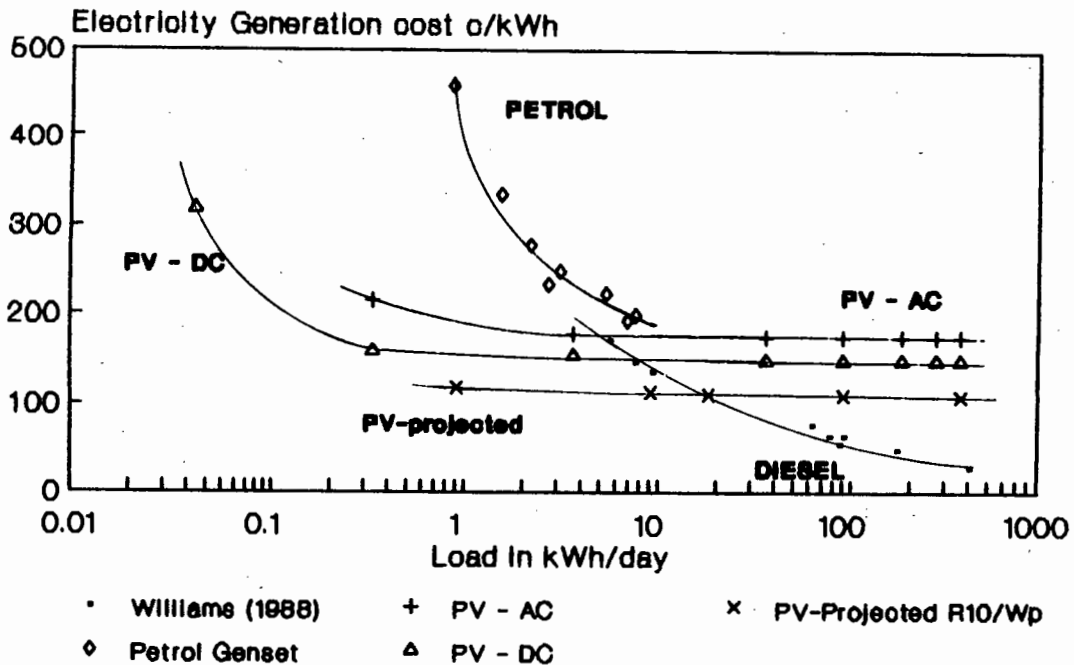


Figure 5.10 Electricity Generation Costs Compared.

Source: Diesel points: Williams, 1988

The petrol generator costs, calculated in December 1988 are higher than PV costs for all cases considered, and are likely to become even more so as the price of petrol escalates. The increase of 10c/liter in January 1989 being a case in point.

The cost of Diesel generated electricity is not so clear cut. The points obtained by Williams are based upon 1986 prices. The curve presented here represents the upper costs calculated at that time. The results of the depreciation of the Rand and the effects of inflation would be to push the diesel curve upwards. Particularly affected are those units which are imported or, as is more usual, those units which use a high percentage of imported parts. For instance, price increases for the genset itself have ranged from 15% to 48% during 1988, depending upon the model (Pers. comm. Lister agent, Cape Town).

It should also be noted that the calculated values shown for Williams (distinguished in Figure 5.9 but not in the figure above) are best case costs. Morris points out that in practice the costs are likely to be 50% to 500% higher "depending on the actual circumstances under which the sets are run" (Morris, 1988, p209).

It would appear, then, that in the range up to some 10 kWh/day, PV produced electricity can be directly competitive to Diesel Gensets. Between 10 and 20 kWh/day is a 'grey' area which depends on a number of financial and other parameters. For instance, Kenna (1987) suggests, from the results of the survey made in Kenya, that PV systems should be considered "whenever the diesel/load match is relatively poor".

This comment is borne out by Morris who suggests that for loads up to 30 kWh/day and where the load factor is less than 0,4 that PV systems would be advantageous.
(Morris, 1988, p211)

The graph indicates that for loadings greater than 20 kWh/day Diesel gensets are more economic, although a more detailed analysis of operating conditions needs to be undertaken to obtain precise 'cross-over' points.

If a projection is made into the 1990's then as the price of PV modules fall and the cost of Genset produced electricity rises, the range over which PV systems are directly competitive will widen. This is graphically illustrated in the projected PV cost line based on a module price of R10/Wp.

In the meantime, it makes sense for an off-grid user to explore the possibility of installing photovoltaic systems instead of Diesel gensets to produce the required power in all but very large daily load demands.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

Photovoltaic produced electricity has proved itself to be an economic proposition not only in many developing countries around the world but also in areas remote from the national grid in both developed and developing regions of Southern Africa. The technology is now challenging the position of conventional sources of energy, such as petrol and diesel generating sets, for power production involving daily demands greater than previously thought viable.

In earlier days the United States played a dominant role in module production, but more recently Japan has become a strong competitor. Whilst the U.S.A. has concentrated on the power module market, the Japanese have concentrated on amorphous silicon technology with its multitude of consumer applications. International production of modules is now nearly 30 MW per year with expectation by some sources that this quantity will rise to over 100 000 MW by the year 2010 provided the innovation and technical progress, which is a hallmark of this comparatively young industry, continues at the same pace.

In the continuing drive for a lower generating cost of electricity, emphasis is placed upon increasing the efficiency of the PV cells by innovative techniques, and also by experimentation with a wide range of semi-conductor materials.

The limits of theoretical efficiency have been raised as the physics of semi-conductors is explored, with researchers having recorded laboratory efficiencies in excess of 30% for certain types of cells. The work of such researchers also concentrates on pushing practical efficiencies towards theoretical limits.

Efficiencies experienced outside the laboratory have not yet reached theoretical limits although commercial modules produced from single crystal silicon have been reported with an efficiency of 18,9%, whilst recorded efficiencies of amorphous silicon power modules are reported at close to 10%.

Initial prices of PV modules were high with applications limited to space vehicles. The relentless drive of companies competing for world markets coupled with technical innovation has had the effect of forcing down the price of PV cells to a point where the goal of competing with the utility generation of electricity is considered to be a possibility by the turn of the century.

6.2 DEVELOPING COUNTRY APPLICATIONS

At the present time PV systems are finding their greatest niche in the remote areas of developing countries where their use, under certain conditions, has proved to be viable for the supply of electricity in five main areas:

- (1) water pumping;
- (2) communications;
- (3) vaccine refrigeration;
- (4) lighting and home power systems; and
- (5) multi-use systems.

The following experiences, gained from installations in developing countries, are worthy of mention:

(1) Water Pumping

Comparison with alternative power sources shows that PV powered pumps are viable for hydraulic heads up to 625 m⁴/day, more than twice the quantity previously established. For larger heads the cross-over point depends upon specific parameters such as diesel genset lifetime. Successful installations involve factors such as effective training of personnel and proper use of solar and well data.

(2) Communications

Compared to diesel gensets, PV systems have proved to be the least cost option for power ranges up to 5 kWh/day. For the range up to 24 kWh/day specific parameters such as diesel fuel costs and diesel lifetime become significant factors determining exact cross-over points. Reliability of PV systems was found to depend upon the careful selection of field proven 'balance of system' equipment.

(3) Vaccine Refrigeration

Comparison with paraffin powered refrigerators evinces no clearcut ranges for financial viability, rather the factors which predominate are the cost of capital and debt servicing, in the case of PV systems, and the problem of vaccine wastage in the case of the paraffin refrigerators. PV powered systems have proved to be reliable in many countries with operational availability higher than their paraffin powered counterparts.

Significant factors for successful systems are credible solar resource data, refrigerator power consumption data, effective user training and coordination with local customers.

PV systems are able to compete satisfactorily with conventional alternatives to supply electricity and are in all cases competitive with petrol generators and competitive with small diesel sets for levels up to 20 kWh/day (refer to figure 5.10 or 6.1). With expected falls in module prices and increases in diesel costs, this upper limit will rise.

6.3.1 Technical issues

A number of important issues, relevant to the successful design of PV systems, have emerged as a result of the involvement of the E.R.I. with demonstration projects in South Africa and were discussed fully in Chapter Four. They are briefly summarised below:

(a) Load Estimation and utilisation levels

The correct estimation of load requirements is identified as a major factor in the economical design of PV systems. The problem of low load capacity factors is not unique to petrol or diesel generators but affects all stand-alone systems. In renewable energy systems such as PV's where most of the costs are associated with the initial capital outlay, the consequences of low load utilisation are exorbitant unit power costs. On the other hand, PV's provide a high value service and the effective weekly cost of PV power, seen from this standpoint, may appear reasonable and affordable.

(b) Balance of system components

The cost of batteries plays a significant role in total costing of systems. The correct selection of these units is thus essential for economic and reliable design though little information is available locally to assist designers in this task. Few specialist PV batteries are available locally, either.

Unless accurate battery characteristics are known, voltage regulators cannot be efficiently matched to the system. In addition, local quality control of regulators is variable with resultant field failures of these units experienced in the projects.

As with the other components, correct sizing of inverters is essential for economic operation though the use of multiple dedicated inverters may be a solution to the efficiency problem. The use of inductive loads should be carefully examined with a view to reducing inverter costs.

(c) PV modules

On site measurements of PV module performance indicated large discrepancies from manufacturers specifications. This experience highlights the need for independent measurement and assessment of locally available PV modules, particularly those which are assembled in this country.

It has also been suggested that the performance of PV modules is sensitive to the angle of incidence and also the spectral distribution of incident solar radiation. The latter factor may be of particular relevance in the polluted atmosphere of the Witwatersrand and the Eastern Transvaal.

(d) System design

The monitoring of the PV demonstration projects has provided useful data on expected operating efficiencies, particularly of batteries and regulators. It has also provided a clearer understanding of the interaction between system components and of the importance of matching loads to PV output characteristics.

Perhaps one of the most important aspects of design is the reliable, but economic sizing of PV systems. The trade off between conservatively sized systems with large autonomy, and more accurately sized systems which have a risk of occasional failure during extended periods of low radiation, can best be resolved through the use of 'Loss of Power Probability' sizing techniques. These are either based on full computer simulation programmes which utilize historical hourly insolation data or on shorthand methods which make use of statistically compressed weather data.

Cowan (1989) has shown that many previously used loss of power probability sizing methods are flawed and has proposed an elegant new approach which focuses mainly on extended periods of low insolation when the system is likely to fail. This technique has potential for incorporation into a practical computer sizing tool which will allow optimal choice of PV/battery combinations for a desired loss-of-load probability.

These techniques are potentially extremely useful in developing areas where designing a PV system for an expected failure of, say, three days per year might result in a very much more affordable (and acceptable) system than one which is oversized to guarantee full autonomy and maximum reliability.

On the other hand, full computer simulation tools, although expensive in computer time, are also important in that they allow a fuller engineering analysis of expected system performance.

(e) Solar insolation data

The availability of accurate solar radiation data is critical for solar system designs. Until recently, even average monthly data was not readily available for many sites in South Africa. Long term data is also important if loss of power probability design methodologies are to be used.

Measured solar radiation data is available for horizontal surfaces only. Various isotropic and anisotropic models have been proposed to convert this data to tilted surface values. No work has been done to investigate the applicability of these models to South African conditions.

6.3.2 Institutional/Social issues

The experience of projects in South Africa has confirmed the findings gathered from experiences in developing countries around the world. Whilst a project may be expertly engineered, it can fail for a number of 'institutional or social' factors which range from the lack of an effective spares and backup service to incorrect relationships with the local community or end-users. Thus extreme care should be taken that such factors are taken into account at the earliest possible stages of planning and are effectively implemented. Appropriate financing schemes are also vital for successful and widespread use of PV's in developing areas.

6.3.3 Economics of South African PV applications

The following graph sums up the cost of PV systems compared with the common conventional alternatives, namely petrol and diesel gensets.

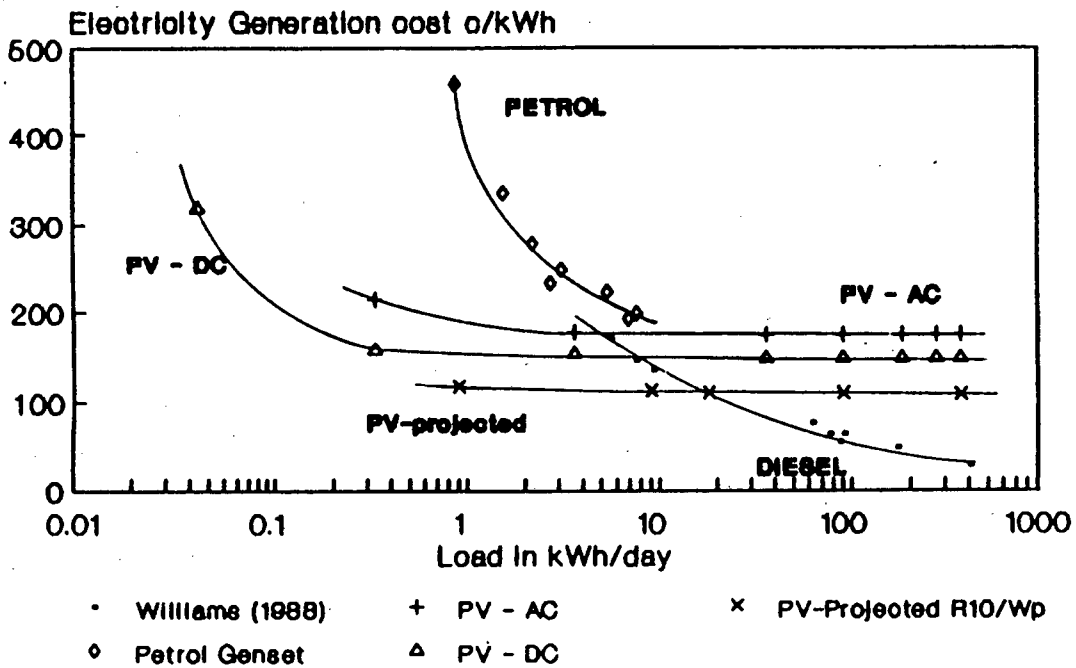


Figure 6.1 Electricity Generation Costs Compared.

Source: Diesel points: Williams (1988)

(also Figure 5.10)

The most significant finding is that the crossover point between PV generated electricity and diesel generated electricity is for a higher daily power requirement than was thought.

PV supplied electricity is now economically competitive up to 10 kWh/day. Above this quantity various parameters come into play which move the crossover point one way or the other. In the medium term, a PV price of 10 R/Wp is expected which will result in a crossover value of 20 kWh/day.

However, the cost of diesel gensets will rise and push the diesel line higher. Thus the expected crossover point will drift towards 20 kWh/day even without the expected fall in module price.

In the longterm a large number of factors come into play affecting the rate at which the cost of PV modules will fall and the rate at which diesel generated electricity will rise.

If the longterm aims of the United States Department of Energy are met then PV generated electricity will, in certain circumstances, be competitive with grid electricity early in the next century.

6.4 RECOMMENDATIONS

From the previous discussion, several areas have been highlighted as requiring further work:

6.4.1 PV System Design

The South African PV market is still in its infancy and it is important that the industry develops a professional reputation for the supply of reliable, but also economically sized systems. The experience of the large PV programme in the Ciskei has demonstrated how badly engineered systems can be disastrous for the reputation and future potential applications of photovoltaics.

Few local suppliers can determine accurately the optimum photovoltaic/battery combination for a particular load and none can provide an assessment of expected loss of load probabilities. Arbitrary design sizing methods, or some 'rule of thumb' are clearly not acceptable. Design packages from overseas are not ideal either. These contain dubious weather data and exclude loss of power probability analysis.

It is thus recommended that efforts, such as those being undertaken at the ERI, to develop accurate and practical local design tools continue to be supported. It is clear from international contacts made by the ERI (for example Sandia National Laboratories in the USA) that valuable work can still be done in this area, and that the methodologies developed by the ERI are in the forefront of this work.

This a long term effort where computer programmes need to be enhanced, updated and validated, and technology transfer to the local PV industry needs to be accomplished.

Various levels of design tools are required. Their level of sophistication will vary according to the end purpose. System planners may require comparatively crude methodologies whilst researchers will require full simulation models in order to improve understanding of system dynamics and further improvement of design procedures.

Modelling work requires detailed knowledge of the performance characteristics of sub-components, and also of long term solar radiation variability. Further work is required in these areas as detailed below.

6.4.2 Batteries

Adequate data on the performance of batteries is not available either for accurate modelling work or even for the selection of appropriate batteries for PV systems. The work being undertaken at the ERI in this regard should be supported. A micro-computer controlled charge/discharge rig is being built but has received no support from industry thus far.

6.4.3 Regulators

The performance of regulators varies widely. There is a need for a research project which classifies the different types available and undertakes a comparative assessment of operating characteristics based on bench tests.

6.4.4 PV Modules

It is recommended that a testing laboratory be established to independently verify and characterise the performance of locally available PV modules. Research could also be undertaken in the tilt-angle and spectral response of panels.

6.4.5 Solar Radiation Data

A solar radiation handbook is being published by the ERI which provides extensive maps and aggregated data for sites in Southern Africa. It is recommended that further work be undertaken on the development of appropriate statistical and analytical tools to account for long term variation. It is also recommended that models for converting horizontal solar radiation to tilted surface values be experimentally validated at different sites in South Africa.

6.4.6 Hybrid Systems

PV systems can be combined economically with diesel generator back-up units either to cater for peak loads or to reduce storage requirements. It is recommended that research be undertaken in order to develop design techniques to optimise such combinations, and also to develop optimal hybrid control units.

6.4.7 Institutional Finance

Although PV's have been shown to be more economical for low daily loads, on a life cycle costing basis, than petrol or diesel generators; the major obstacle for the potential buyer is still the initial capital purchase of the PV system. Such capital is not easily obtainable by communities in developing areas. Thought should be given by development agencies to financial packages which will distribute this cost over much longer periods thus making PV systems more affordable.

6.5 CONCLUSION

This report has shown that photovoltaics are a viable and appropriate technology for developing areas in Southern Africa. With continued rapid technological innovation, costs continue to fall, making photovoltaics an attractive proposition for an increasingly wider range of applications.

There is still very little awareness of the potential of PV's by possible users in South Africa. However, it is to be expected that as the technology spreads, so also will the awareness and understanding of its advantages.

The benefits to be obtained from the use of photovoltaic power, in preference to any of the conventional alternatives, have been examined and found to be real. It is apparent that once the dissemination of the technology occurs, markets will widen as this potential is fully recognised.

Specific recommendations have been made which, if implemented, will enhance local expertise and will result in improved design practice. It has been argued that affordability of PV systems is a critical issue in developing areas. More appropriate financing schemes will, in part, ameliorate this problem. However, there is still much scope for design practices which result in optimally sized and more affordable systems at an acceptable loss of power probability. The development of such design practices requires a thorough understanding of system dynamics, the operating characteristics of individual components and reliable data on expected loads and insolation levels.

South Africa, with its unique situation of technical and intellectual resources in close proximity to the problems of developing areas, can play a leading role in the development of sophisticated, but ultimately useful and practical, design methodologies and practices. Close co-operation should thus be encouraged between the local PV industry, universities, and research institutes and development agencies.

Finally, it should be remembered that photovoltaic technology is based on the use of one of the most abundant elements in the earth's crust (silicon) and it relies upon a renewable energy source. With continued technical advances and cost reductions, photovoltaics thus have the potential to provide not only for remote area power supply needs but also, in the long term, for electrical power requirements closer to metropolitan centers.

Photovoltaics will be able to do this in a sustainable and pollution free basis - issues which will, one day, become paramount as the greenhouse affect, largely induced by thermal power stations, becomes more pronounced.

Photovoltaics thus remain one of the most elegant methods of generating electricity and are guaranteed an important long term role in future energy supply options.

APPENDIX A

A.1 PV SIZING METHODOLOGY

PV Sizing Methodology

The sizing methodology used is that described by Borden et al (1984, section two). It is directly applicable to stand-alone systems, estimating the life cycle costs for specified loads, a given site and a desired level of system availability. The methodology permits comparison to conventional systems, thereby facilitating final selection of the preferred generating option.

The appropriate equations for each step, with explanation of the variables involved, are listed after this introduction. The result of carrying out this sequence is to establish the sizes of the photovoltaic array, batteries and regulators required to run the specified system, and from which the final step of life cycle costing may be taken.

Life cycle costs are calculated and discounted to give present values. As a final method of comparison, the annualized energy costs are determined together with the energy cost in cents per kilowatt hour. These results enable comparisons between different systems to be made.

The photovoltaic sizing and costing methodology is illustrated by the following diagram:

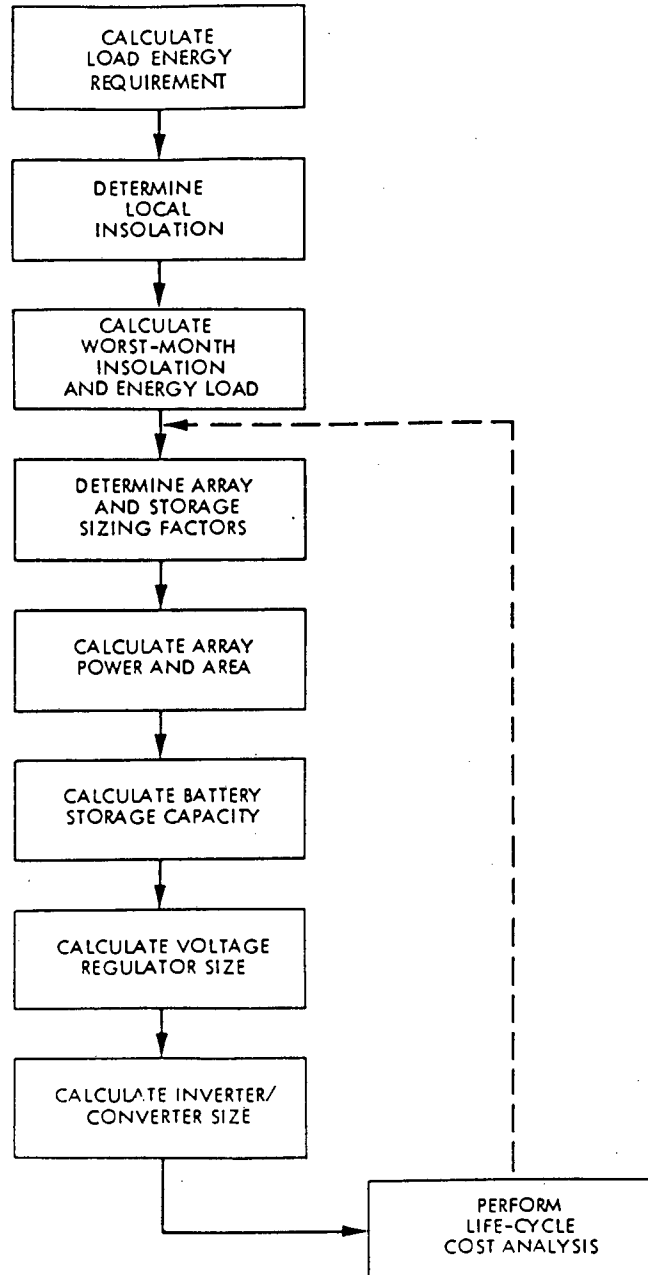


Figure: A.1 The sequence of steps in sizing a remote, stand alone photovoltaic system.

Source: Borden et al (1984, p2-2)

Other sizing procedures are explored by Borden et al (1984, PC-2). It is clear that the procedure adopted in this study yields results similar to those of the three other approaches discussed. However, it is to be recognized that these various approaches can yield different results due to built-in design margins or the selection of different loss-of-energy probability values. As is pointed out (ibid, PC-3) there is a strong argument for the use of an LOEP-based sizing approach so as to obtain a degree of uniformity in the level of performance of the alternatives being sized.

Method	Load kWh/day	Array size, Wp	Battery storage size Wp
NASA	4,2	3000	42
ROSSA	4,2	3140	42
SOLAREX	4,0	3150	30
BORDEN et al	-	3020	42

Table A.1 Array and Battery Storage Sizing Comparison.
Source: Borden et al (1984, PC-2)

Considering figure A.1:

Step 1 Calculation of the load energy requirement

The average daily load demand to be met by the photovoltaic system is established by calculating the energy drawn by each load element during a 24 hour period and summing them (Equation 1). If these prove to be highly variable then a monthly average may be taken.

However, if the load demand variation is appreciably high or the load demand peaks appear on consecutive days then it could be necessary to use the peak load levels for sizing purposes, as the system might be inadequately sized to accommodate cloudy periods coinciding with these high load periods.

Step 2 Determination of local insolation values

Insolation data for tilted surfaces is not available for sites in Southern Africa. Monthly average readings are obtainable, for a number of specific sites, of the insolation falling on a horizontal plate together with the diffuse radiation plate. (CSIR, 1971, Table 1). (A solar radiation data handbook is due to be published by the E.R.I. in 1989).

For the base case, a computer programme calculated the insolation falling on the array for a variety of tilt angles. (Muller, 1987 p65). Optimization procedures produced a tilt angle for the array which enables the modules to receive the maximum insolation, on a yearly basis. Muller determined this to be 35 degrees, with a minimum insolation value of 21,7 MJ/m². for the Omdraaisvlei site. This radiation level was taken as the base case design.

Step 3 Calculation of worst-month insolation and energy load

In this sizing methodology, the PV system is designed to meet the energy demand of the "worst" month of the year; that is to say, the month which has the smallest ratio of solar energy radiation on the array to the load energy demand. The system will then be able to meet the demand at any other time of the year.

The "worst" month is best identified by tabulating daily average insolation data for each month of the year along with the corresponding daily average load demand.

For each pair of insolation and load values the ratio is calculated. The smallest ratio is noted for each tilt angle chosen, and the largest of these identifies the best "worst month" for this sizing methodology.

Step 4 The determination of Array and Storage sizing factors

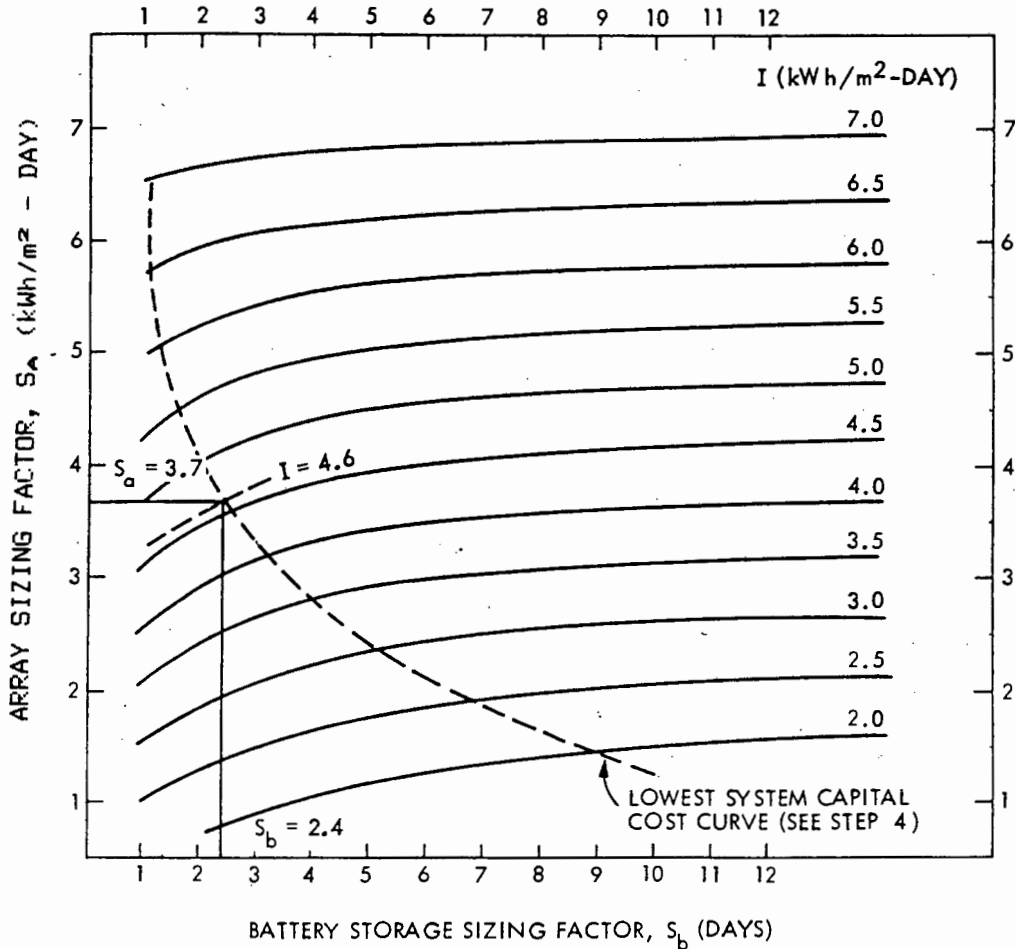


Figure A.2 PV Array Sizing Nomograph.

Source: Borden et al, 1984 p2-9

These factors, S_a and S_b, are used in subsequent calculations and are obtained from prior analysis of how the photovoltaic system loss of energy probability (LOEP) depends on array and battery storage size. The LOEP is an estimate of the probability that during a given time period, the energy output of the power system will be insufficient to meet the energy load demand.

This methodology uses a worst month LOEP value of 0,1. This amount is roughly equivalent to that of conventional competitor power systems such as diesel, etc. (Borden et al, 1984, p2-8).

The insolation determined previously, for worst month conditions, is used to obtain the intersection point with the dashed 'lowest system capital curve'. The values of S_a and S_b are then read off from the axes. The position of this dashed line has been derived from cost experience in remote, stand-alone system applications.

Borden et al note that this curve is based on initial costs only and does not take into account such life cycle cost factors as operation, maintenance and other financial cost variables. An iterative technique, represented by the dashed line in Figure 5.1, is necessary to produce the lowest life cycle costing.

Estimation of the load fractions supplied by the array and storage

The energy load fraction supplied by the array, F_a , is that portion of the load energy that flows directly from the array to the loads as against F_b which is the fraction reaching the load from battery storage.

Methods are available to estimate these fractions though F_a may be taken as zero and F_b as one. This simplifying assumption, adopted in this study, can result in oversizing since in most applications the load is, in part at least, supplied by the array directly thus avoiding storage losses.

Steps 5 to 8

Substitutions are made in Equations 2 and 3 to obtain the Array peak power and area. Equation 4 then gives the battery storage size.

The voltage regulator should be sized to take the maximum amount of array power likely to be available to charge the batteries. The maximum steady-state load power requirement is used to size the inverter or converter. If inductive loads are used then it is to be noted that the starting current can be as large as 4 to 5 times the rated motor requirements.

Sizing equations

The equations used to size the system and to calculate the life cycle costs (LCC) are listed:

Equation 1

$$P_a = \frac{L_{td} \times 1000}{S_a \times F \times e_{i/c} [f_b (e_{vr} \times e_b) + f_a]}$$

- Where L_{td} = Total daily energy load in kilowatt-hours per day
 P_i = Power drawn by load element 'i' while it is in service (W)
 D_i = Amount of time per day in hours that load element 'i' is in service
 n = number of separate load elements.

Equation 2

$$L_{td} = \sum_{i=1}^n P_i D_i / 1000$$

- Where P_a = Array power in watts
 L_{td} = Load
 S_a = Sizing factors for Array
 F = Factor to account for array degradation
 e_{vr} = Efficiency of Voltage Regulator
 e_b = Efficiency of Battery
 F_a = Fraction of load energy supplied by array

F_b = Fraction of load energy supplied by battery
 $e_{i/c}$ = Inverter/converter efficiency
1000 = 1000 W/m²; a term to convert S_a into an equivalent number of hours per day that 1000 W/m² insolation would be received by the array.

Equation 3

$$A_a = \frac{P_a}{e_m [1 + P_{TC} (T_{op} - 28^{\circ}\text{C})] \times 1000}$$

Where A_a = Array area in square meters
 P_a = Array Power in Watts obtained from Equ.2
 e_m = Module efficiency at standard test conditions (STC)
 P_{TC} = Module temperature coefficient; typically 0,005/°c
 T_{op} = Module operating temperature in degrees Celsius
1000 = 1000 W/m² at standard test conditions

Equation 4

$$E_b = \frac{L_{td} \times S_b}{d \times e_{i/c}}$$

Where E_b = Rated battery energy storage in kWh
 L_{td} = Worst month average daily energy load in kWh/day
 S_b = Battery sizing factor in days
 d = Maximum allowable depth of discharge
 $e_{i/c}$ = Inverter/converter efficiency

Costing Equations

Equation 5

$$\text{Initial Costs (IC)} = [1 + \text{Indirect Costs(\%)} + \text{Installation costs(\%)}] * [\text{Delivered Costs}]$$

$$\text{or IC} = (1 + \text{IND} + \text{INST}) [(\text{MOD} * P_A) + (\text{ABOS} * A_A) + (\text{CONV} * W_{DC}) + (\text{INV} * W_{AC}) + (\text{REG} * W_{MAX}) + (\text{BAT} * \text{BWh})]$$

where

- IND = fractional indirect costs on equipment including engineering, management, and contingency fees.
- INST = fractional cost on equipment for installation, site preparation, testing, and checkout cost of the system.
- MOD = module cost in Rands per peak watt of array
- P_a = peak watts of solar array (DC)
- ABOS = area-related balance-of-system cost per square meter of array including cost of array structure, land, wiring, connectors, etc.
- A_a = array area in square meters
- CONV = converter cost per peak watt (DC)
- W_{DC} = rated size of converter in peak watts (DC)
- INV = inverter cost per peak watt (AC)
- W_{AC} = rated size of the inverter in peak watts (AC).
- REG = voltage regulator cost per peak watt (DC) of maximum regulator input power.
- W_{max} = maximum voltage regulator input power
- BAT = battery cost per kilowatt-hour of energy storage
- BWh = battery storage size in kilowatt-hours

Equation 6 $BR = (BAT \cdot BWh) (1 - SV) + LREP$

Where BR = Cost for each replacement of storage battery
 BAT * BWh = Delivered cost of batteries
 SV = Fractional salvage value of batteries at
 time of replacement
 LREP = Labour cost of battery replacement (in base
 year Rands)

Equation 7

$$RPV = \sum_{j=1}^{nrep} BR \times \left(\frac{1 + esc_b}{1 + dr} \right)^{j \times k}$$

Where

 j = Counter for number of battery replacements (1, nrep)
 k = Battery lifetime (years)
 j * k = Constrained to be strictly less than photovoltaic
 system lifetime or lifetime used in LCC analysis
 BR = Single time battery replacement cost from Equ. 6 in
 base year Rands
 esc_b = Real (above inflation) annual escalation rate for
 storage batteries
 dr = Discount rate (cost of money to system owner,
 typically defined as 10%(real) for government
 applications)

Equation (7) is used to calculate the cost of replacing any piece of capital equipment, hence the above can be rephrased as follows:

$$RPV = \sum_{j=1}^{nrep} REP \times \left(\frac{1 + esc_b}{1 + dr} \right)^{j \times k}$$

Where

j = Counter for number of Unit replacements (1,nrep)

k = Unit lifetime (years)

j*k = Constrained to be strictly less than the lifetime used in LCC analysis

REP = Single time Equipment replacement cost in base year Rands

esc_b = Real (above inflation) annual escalation rate for the particular piece of equipment

dr = Discount rate (cost of money to system owner, typically defined as 10%(real) for government applications

Equation 8

$$OMPV = OM \times \left(\frac{1 + esc_{om}}{dr - esc_{om}} \right) \times \left[1 - \left(\frac{1 + esc_{om}}{1 + dr} \right)^N \right], \text{ if } dr \neq esc_{om}$$

or $OMPV = OM * N$ if $dr = esc_{om}$

Where

OMPV = Present value of operation and maintenance costs

OM = Annual operation and maintenance costs in base year Rands

esc_{om} = Real (above inflation rate) annual escalation rate for operation and maintenance activities (fraction), typically 0%

dr = real discount rate (fraction)

N = System lifetime.

Equation 9 $LCC = IC + RPV + OMPV$

Where $LCC =$ Life cycle costs

Equation 10 Levelized annual cost in cents/kWh.

$$A = C \cdot i / [1 - (1+i)^{-n}] \cdot 100 / K$$

where

C = present value of the costs in Rands

n = number of interest periods taken over the expected life.

i = interest rate per period.

K = The total power produced per year in kWh.

APPENDIX B

B.1 MEAN TOTAL MONTHLY/ANNUAL RADIATION (kWh/m²) MONTH

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOT
ALEXANDERBAY													
Global	259	209	196	151	128	107	116	143	171	213	242	257	2192
Diffuse	58	50	46	34	28	25	28	35	45	56	55	58	518
BLOEMFONTEIN													
Global	231	191	182	147	130	112	125	149	177	212	231	251	2138
Diffuse	70	57	53	38	30	23	27	34	46	58	63	69	568
CAPE TOWN													
Global	247	200	182	126	91	71	83	107	141	195	226	246	1915
Diffuse	57	45	40	35	28	24	27	35	46	52	60	58	507
DURBAN													
Global	171	151	136	111	91	84	88	101	112	133	144	160	1482
Diffuse	75	59	49	36	27	22	24	32	45	57	63	67	556
GROOTFONTEIN													
Global	247	194	162	131	105	95	102	127	158	190	221	230	1962
Diffuse	53	47	39	31	23	20	20	26	38	46	48	45	436
KEETMANSHOOP													
Global	258	213	183	162	133	121	126	154	182	219	240	246	2237
Diffuse	55	50	38	27	21	19	20	29	38	42	45	43	427
NELSPRUIT													
Global	176	164	148	134	116	109	114	121	135	141	147	169	1674
Diffuse	78	63	52	38	26	24	25	33	46	56	64	70	575
PORT ELIZABETH													
Global	217	174	143	112	86	74	81	101	128	162	188	202	1668
Diffuse	70	57	45	34	25	21	22	31	44	56	64	65	534
PRETORIA													
Global	196	166	148	128	116	109	115	137	160	174	178	193	1820
Diffuse	72	61	52	39	26	22	23	28	38	50	58	60	529
ROODEPLAAT													
Global	206	176	158	135	120	108	114	133	159	174	183	194	1860
Diffuse	73	61	50	38	25	22	24	30	40	50	59	63	535
UPINGTON													
Global	248	204	173	146	120	107	111	145	168	202	232	234	2090
Diffuse	49	42	36	32	23	22	20	25	35	35	38	40	397
WINDHOEK													
Global	219	182	175	158	143	131	139	160	182	207	214	214	2124
Diffuse	69	57	50	33	23	20	18	25	36	44	49	51	475

Source: Eberhard A. et al, 1989.

APPENDIX C

C.1 PV SYSTEM COSTS

C.1.1 SMALL PV SYSTEM SIZING AND COSTING (0,0366 kWh/day)

C.1.2 MEDIUM HOME PV SYSTEM PRINTOUT (0,366 kWh/day)

C.1.3 LARGE HOME PV SYSTEM PRINTOUT (37,5 kWh/day)

C.1.4 COMMUNITY CENTER PRINTOUT (400 kWh/day)

C.1.1 SMALL PV SYSTEM SIZING AND COSTING

Appendix A shows full details of the equations referred to in this costing

(A) Calculation of load energy requirements

Equation 1.
$$L_{td} = \sum_{i=1}^n P_i D_i / 1000$$

Substituting
$$L_{td} = (11*4)/1000$$
$$= 0,044 \text{ kWh}$$

(B) Determination of local Insolation and identification of worst month insolation and energy load

These values are standardized (Appendix A).

(C) Determination of array and storage sizing factors

These values are standardized (Appendix A).

(D) Calculation of Array Power and Area

From Equation 2.

$$P_a = \frac{L_{td} \times 1000}{S_a \times F \times e_{i/c} [f_b (e_{vr} \times e_b) + f_a]}$$

Substituting, assuming $F=0$

$$\begin{aligned} P_a &= (0,044 * 1\ 000) / (5,05 * [1(0,95 * 0,85) + 0]) \text{ Watts.} \\ &= 10,8 \text{ W}_p \end{aligned}$$

The above assumes $F_a = 0$ and $F_b = 1$ as all the array energy passes through battery storage before passing to the load.

(E) Calculation of Battery Storage Capacity

Equation 4.

$$E_b = \frac{L_{td} \times S_b}{d \times e_{i/c}}$$

Substituting

$$\begin{aligned} E_b &= \frac{0,044 * 1,16}{0,4 * 1} \\ &= 0,1276 \text{ kWh} \\ &= 0,1276 * 1000/12 \\ &= 10,63 \text{ Amp hours} \end{aligned}$$

(F) Calculation of Voltage Regulator size

A suitable sized unit costs 50 Rand.

(G) Life cycle cost analysis

(i) Initial Costs

From Equation 5

$$IC = [1 + \text{Indirect Costs (\%)} + \text{Installation costs (\%)}] * [\text{Delivered Costs}]$$

substituting

$$IC = [1 + 0 + 0] * [(10,8 * 20) + 50 + 65] \\ = R331,48$$

(ii) Battery cost

From Equation 6. $BR = (BAT * BWh) (1 - SV) + LREP$

substituting $BR = (65)(1 - 0) + 0$
 $= R 65$

ignoring the scrap value

(iii) The present value of Battery replacements (RPV)

From Equation 7.

$$RPV = \sum_{j=1}^{nrep} BR \times \left(\frac{1 + esc_b}{1 + dr} \right)^{j \times k}$$

Using an escalation rate of zero and a discount rate of 4,00%

gives $RPV = 65,00 * [(1+0)/(1+0,04)]^N = 63,00 * 0,9615^N$

Assuming the battery will be replaced every 2 years, the RPV can be calculated from the above and is equal to

Number of Replacement	End of Year	RPV	Rands
1	2	$65,00 * 0,9615^2$	= 60,09
2	4	$65,00 * 0,9615^4$	= 55,55
3	6	$65,00 * 0,9615^6$	= 51,36
4	8	$65,00 * 0,9615^8$	= 47,48
5	10	$65,00 * 0,9615^{10}$	= 43,89
6	12	$65,00 * 0,9615^{12}$	= 40,48
7	14	$65,00 * 0,9615^{14}$	= 37,52
8	16	$65,00 * 0,9615^{16}$	= 34,68
9	18	$65,00 * 0,9615^{18}$	= 32,06

Total = R 403,11

(iv) The present value of operation and maintenance (OMPV)

Equation 8.

$$OMPV = OM \times \left(\frac{1 + esc_{om}}{dr - esc_{om}} \right) \times \left[1 - \left(\frac{1 + esc_{om}}{1 + dr} \right)^N \right], \text{ if } dr \neq esc_{om}$$

substituting

$$OMPV = [(1,00/100) * 331,48] \left(\frac{1+0}{0,04} \right) \left[1 - \left(\frac{1+0}{1+0,04} \right)^{20} \right]$$

$$OMPV = (3,32) * 25 * 0,4564$$

$$= 37,82$$

Assuming a system life of 20 years, an escalation rate of zero and the discount rate as 4%

(v) Sum to life cycle costs

Equation 9.

$$LCC = IC + RPV + OMPV$$

Substituting

$$\begin{aligned} LCC &= 331,48 + 403,11 + 37,82 \\ &= 772,41 \text{ Rands} \end{aligned}$$

Levelized annual cost in cents/kWh

$$A = C \cdot i / [1 - (1+i)^{-n}] \cdot 100 / K$$

Substituting

$$\begin{aligned} A &= 772,41 \cdot 0,04 / [1 - (1+0,04)^{-20}] \cdot 100 / K \\ &= 772,41 \cdot 0,0736 \cdot 100 / k \\ &= 56,85 \cdot 100 / [0,044 \cdot 365] \\ &= 353,98 \text{ cents/ kWh} \end{aligned}$$

Figures are very close to that of the programme, the printout of which follows.

CALCULATION OF PV POWER COST

ARRAY

Required array power, Pa 10.80 W
 Required array area, Aa 0.10 sq m

INSTALLED, ICpv R 215.93

BATTERIES

Required batt. storage, Ebat 0.13 kWh
 Installed cost, ICbat R 65.00

ANCILLARY EQUIPMENT (Voltage reg and inverter)

Voltage regulator, IReg R 50.00
 Inverter, ICinv R 0.00
 Installed cost, ICanc R 50.00

SUMMARY OF SYSTEM SPECIFICATIONS AND COSTS

I	Required array power, Pa	10.80 W	I
I	Required array area, Aa	0.10 sq m	I
I	Required batt. storage, Ebat	0.13 kWh	I
I			I
I	Total installed cost, ICtot	R 330.93	I
I			I
I	Annual O&M cost, OM	R 2.81 /year	I
I	O&M present value, PVOM	R 38.18	I
I			I
I	Battery type, BATYP	Automotive	I
I	Battery replacement costs, BR	R 65.00 /set	I
I	Number of replacements in system life	9.00	I
I	Replacement present value, RPV	R 403.45	I
I			I
I	System life-cycle cost, LCC	R 772.56	I
I			I
I	Annualised unit cost/kWh, UC	353.96 c/kWh	I

CALCULATION OF PV POWER COST

ARRAY

Required array power, Pa 10.80 W
 Required array area, Aa 0.10 sq m

INSTALLED, ICpv R 215.93

BATTERIES

Required batt. storage, Ebat 0.13 kWh
 Installed cost, ICbat R 65.00

ANCILLARY EQUIPMENT (Voltage reg and inverter)

Voltage regulator, ICreg R 50.00
 Inverter, ICinv R 0.00
 Installed cost, ICanc R 50.00

SUMMARY OF SYSTEM SPECIFICATIONS AND COSTS

I	Required array power, Pa	10.80 W	I
I	Required array area, Aa	0.10 sq m	I
I	Required batt. storage, Ebat	0.13 kWh	I
I			I
I	Total installed cost, ICtot	R 330.93	I
I			I
I	Annual O&M cost, OM	R 2.81 /year	I
I	O&M present value, PVOM	R 38.18	I
I			I
I	Battery type, BATYP	Automotive	I
I	Battery replacement costs, BR	R 65.00 /set	I
I	Number of replacements in system life	9.00	I
I	Replacement present value, RPV	R 403.45	I
I			I
I	System life-cycle cost, LCC	R 772.56	I
I			I
I	Annualised unit cost/kWh, UC	353.96 c/kWh	I

CALCULATION OF PV POWER COST

ARRAY

Required array power, Pa 89.81 W
 Required array area, Aa 0.87 sq m

INSTALLED, ICpv R 1796.12

BATTERIES

Required batt. storage, Ebat 0.85 kWh
 Installed cost, ICbat R 240.76

ANCILLARY EQUIPMENT (Voltage reg and inverter)

Voltage regulator, ICreg R 228.00
 Inverter, ICinv R 0.00
 Installed cost, ICanc R 228.00

SUMMARY OF SYSTEM SPECIFICATIONS AND COSTS

I	Required array power, Pa	89.81 W	I
I	Required array area, Aa	0.87 sq m	I
I	Required batt. storage, Ebat	0.85 kWh	I
I			I
I	Total installed cost, ICTot	R 2264.88	I
I			I
I	Annual O&M cost, OM	R 20.37 /year	I
I	O&M present value, PVOM	R 276.82	I
I			I
I	Battery type, BATYP	Automotive	I
I	Battery replacement costs, BR	R 240.76 /set	I
I	Number of replacements in system life	2.00	I
I	Replacement present value, RPV	R 322.01	I
I			I
I	System life-cycle cost, LCC	R 2863.71	I
I		-----	I
I	Annualised unit cost/kWh, UC	157.73 c/kWh	I

CALCULATION OF PV POWER COST

ARRAY

Required array power, Pa 9201.43 W
 Required array area, Aa 88.65 sq m

INSTALLED, ICpv R 184028.64

BATTERIES

Required batt. storage, Ebat 72.56 kWh
 Installed cost, ICbat R 31238.16

ANCILLARY EQUIPMENT (Voltage reg and inverter)

Voltage regulator, ICreg R 850.00
 Inverter, ICinv R 0.00
 Installed cost, ICanc R 850.00

SUMMARY OF SYSTEM SPECIFICATIONS AND COSTS

I	Required array power, Pa	9201.43 W	I
I	Required array area, Aa	88.65 sq m	I
I	Required batt. storage, Ebat	72.56 kWh	I
I			I
I	Total installed cost, ICTot	R 216116.80	I
I			I
I	Annual O&M cost, OM	R 2152.67 /year	I
I	O&M present value, PVOM	R 29255.46	I
I			I
I	Battery type, BATYP	Automotive	I
I	Battery replacement costs, BR	R 31238.16 /set	I
I	Number of replacements in system life	1.00	I
I	Replacement present value, RPV	R 21103.39	I
I			I
I	System life-cycle cost, LCC	R 266475.65	I
I		-----	I
I	Annualised unit cost/kWh, UC	143.25 c/kWh	I

CALCULATION OF PV POWER COST

ARRAY

Required array power, Pa 1.15E+05 W
 Required array area, Aa 1.11E+03 sq m

INSTALLED, ICpv R 2.31E+06

BATTERIES

Required batt. storage, Ebat 9.11E+02 kWh

Installed cost, ICbat R 3.92E+05

ANCILLARY EQUIPMENT (Voltage reg and inverter)

Voltage regulator, IReg R 1.13E+05

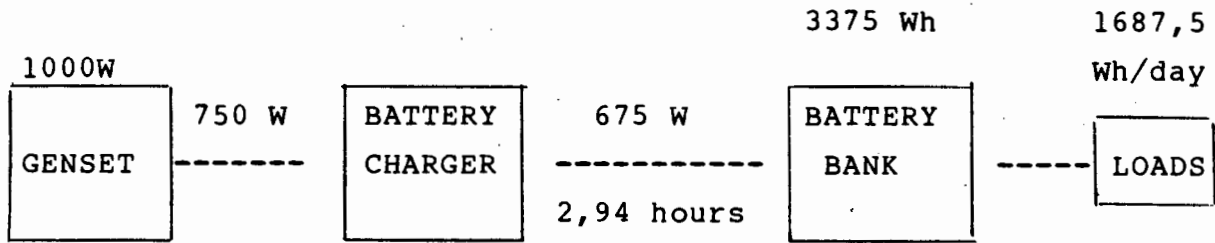
Inverter, ICinv R 1.87E+04

Installed cost, ICanc R 1.32E+05

SUMMARY OF SYSTEM SPECIFICATIONS AND COSTS,

I	Required array power, Pa	1.15E+05 W	I
I	Required array area, Aa	1.11E+03 sq m	I
I	Required batt. storage, Ebat	9.11E+02 kWh	I
I			I
I	Total installed cost, ICtot	R 2.83E+06	I
I			I
I	Annual O&M cost, OM	R 2.70E+04 /year	I
I	O&M present value, PVOM	R 3.67E+05	I
I			I
I	Battery type, BATYP	Automotive	I
I	Battery replacement costs, BR	R 3.92E+05 /set	I
I	Number of replacements in system life	1.00E+00	I
I	Replacement present value, RPV	R 2.65E+05	I
I			I
I	System life-cycle cost, LCC	R 3.47E+06	I
I		-----	I
I	Annualised unit cost/kWh, UC	174.65 c/kWh	I

Diagram



COSTS (DECEMBER 1988)

(a) Initial Costs

(i) Genset R 1595

(ii) Battery Cost

Battery capacity = 3,375 kWh

Hence cost = 3,375 * 283,30 = 956 R

(iii) Battery Charger R 1445

(b) NPV costs

Referring to Appendix A we have:

$$RPV = \sum_{j=1}^{nrep} REP \times \left(\frac{1 + esc_b}{1 + dr} \right)^{j \times k}$$

Where

j = Counter for number of Unit replacements (1,nrep)

k = Unit lifetime (years)

j*k = Constrained to be strictly less than the lifetime used in LCC analysis

REP = Single time Equipment replacement cost in base year Rands

esc_b = Real (above inflation) annual escalation rate for the particular piece of equipment

dr = Discount rate (cost of money to system owner)

A system lifetime of 20 years is assumed so as to correspond with PV system lifetimes.

An escalation rate of zero and a discount rate of 4,00% are used.

(i) Genset

The lifetime assumed is 3000 hours, which gives 2,8 years at 2,94 hours per day

The present value of Genset replacements (RPV) is given by Equation 7:

$$RPV = \sum_{j=1}^{nrep} REP \times \left(\frac{1 + esc_b}{1 + dr} \right)^{j \times k}$$

substituting:

$$RPV = 1595 * [(1+0)/(1+0,04)]^n = 1595 * 0,9615^n$$

Since the Genset will be replaced every 2,8 years, the RPV can be calculated from the above and is equal to

Number of Replacement	End of Time	RPV	Rands
1	2,8 years	$1595 * 0,9615^{2,8}$	= 1428,96
2	5,6 years	$1595 * 0,9615^{5,6}$	= 1280,20
3	8,4 years	$1595 * 0,9615^{8,4}$	= 1146,92
4	11,2 years	$1595 * 0,9615^{11,2}$	= 1027,53
5	14,0 years	$1595 * 0,9615^{14,0}$	= 920,56
6	16,8 years	$1595 * 0,9615^{16,8}$	= 824,73
7	19,6 years	$1595 * 0,9615^{19,6}$	= 738,87

Total = 7367,77

(ii) Batteries

The present value of Battery replacements (RPV).

Is given by

$$RPV = \sum_{j=1}^{nrep} BR \times \left(\frac{1 + esc_b}{1 + dr} \right)^{j \times k}$$

substituting $RPV = 956 * [(1+0)/(1+0,04)]^n = 956 * 0,9615^n$

Since the Batteries will be replaced every 7 years, the RPV can be calculated from the above and is equal to

Number of Replacement	End of Time	RPV	Rands
1	7 years	$956 * 0,9615^7$	= 726,28
2	14 years	$956 * 0,9615^{14}$	= 551,76
		Total	= 1278,04

(iii) Battery Charger

The present value of the Battery charger replacement (RPV).

Is given by

$$RPV = \sum_{j=1}^{nrep} REP \times \left(\frac{1 + esc_b}{1 + dr} \right)^{j \times k}$$

substituting

$$RPV = 1445 * [(1+0)/(1+0,04)]^n = 1445 * 0,9615^n$$

Allowing for one replacement after 10 years

Number of Replacement	End of Time	RPV	Rands
1	10 years	1445 * 0,9615 ¹⁰	= 976
			Total = 976

(c) The present value of operation and maintenance (OMPV)

Referring to Appendix A, Equation 8:

$$OMPV = OM \times \left(\frac{1 + esc_{om}}{dr - esc_{om}} \right) \times \left[1 - \left(\frac{1 + esc_{om}}{1 + dr} \right)^N \right], \text{ if } dr \neq esc_{om}$$

Where

OMPV = Present value of operation and maintenance costs

OM = Annual operation and maintenance costs in base year
Rands

esc_{om} = Real (above inflation rate) annual escalation rate
for operation and maintenance activities
(fraction), typically 0%

dr = real discount rate (fraction)

N = System lifetime.

Assuming a system life of 20 years, an escalation rate of zero and the discount rate as 4%

Substituting

$$OMPV = \frac{\text{Annual Cost of Petrol/Maintenance}}{\text{Petrol/Maintenance}} * \left(\frac{1 + 0}{0,04} \right) \left[1 - \left(\frac{1 + 0}{1 + 0,04} \right)^{20} \right]$$

$$OMPV = \frac{\text{Annual cost of Petrol/Maintenance}}{\text{Petrol/Maintenance}} * 13,590$$

(i) Petrol costs

Consumption = 0,64 l/h.

Hence petrol consumption/day = 2,94 * 0,64 = 1,88 l/day.

Cost per year = 1,88 * 365 * 92/100 = 632 Rands assuming an average price for the 93 Octane fuel used of 92 c/l.

Hence the present value = 632 * 13,590 = 8589 Rands

(ii) Maintenance costs

a) 50 hour service carried out [2,94 * 365]/50 times per year
Assuming no labour charges then cost is given by

$$[2,94 * 365]/50 * 2,70 * 3 = 173,84 \text{ Rands}$$

b) 500 hour service carried out [2,94 * 365]/500 times per year at the agents estimated cost of R 120 gives

$$[2,94 * 365]/500 * 120 = 257,54 \text{ Rands}$$

Giving OMPV = [173,84 + 257,54] * 13,59 = 5871 Rands

(c) Life Cycle Costs

$$\text{LCC} = \text{IC} + \text{NPV} + \text{OMPV}$$

Substituting the values listed and calculated previously

$$\text{IC} = 1595 + 956 + 1445 = 3996 \text{ Rands}$$

$$\text{NPV} = 7367,77 + 1278,04 + 976 = 9621,81 \text{ Rands}$$

$$\text{OMPV} = 8589 + 5871 = 14460$$

Hence we have

$$\text{LCC} = 3996 + 9622 + 14460 = 28078 \text{ Rands}$$

(d) Levelized annual cost in cents/kWh

Referring to Appendix A we have:

$$A = C \cdot i / [1 - (1+i)^{-n}] \cdot 100 / K$$

where

A = The levelized annual cost in c/kWh

C = present value of the costs in Rands

n = number of interest periods taken over the expected life.

i = interest rate per period.

K = The total power produced per year in kWh.

Substituting

$$A = 28078 \cdot 0,04 / [1 - (1+0,04)^{-20}] \cdot 100 / K$$

$$= 28078 \cdot 0,0736 \cdot 100 / K$$

$$= 28078 \cdot 0,0736 \cdot 100 / [1,688 \cdot 365]$$

$$= 335,41 \text{ cents/ kWh}$$

Note that the program used on the Lotus spreadsheet gave a value for the Annualized cost of 335,46 Rands. (Chapter 5, table 5.2)

APPENDIX E

E.1 Brochures from firms offering PV Systems

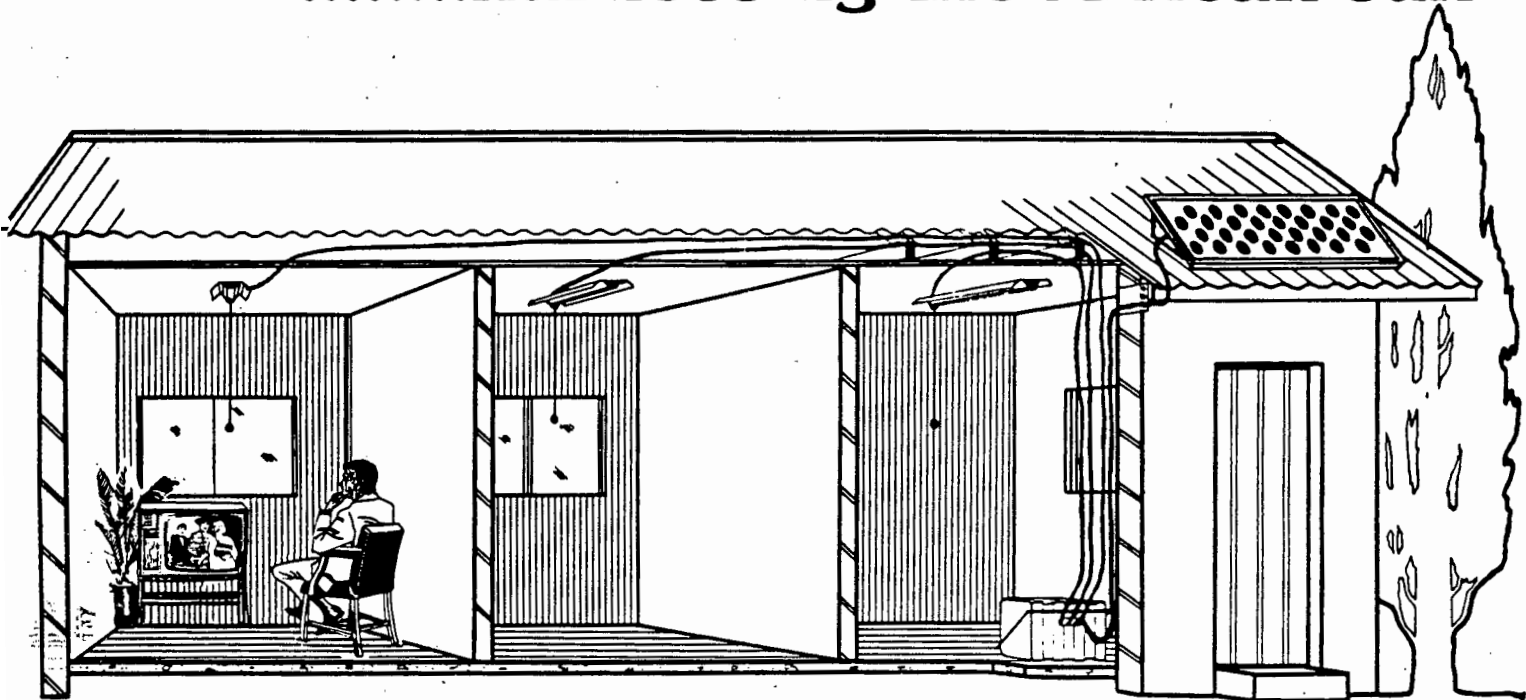
TELELITE

LIGHT POWERED FROM THE SUN

If you don't have electricity.....

USE BP SOLAR

.....harnessing the African sun



The Telelite solar lighting system offers you **FREE**, reliable and convenient electricity - from the sun.



BP SOLAR

solar lighting system

M40

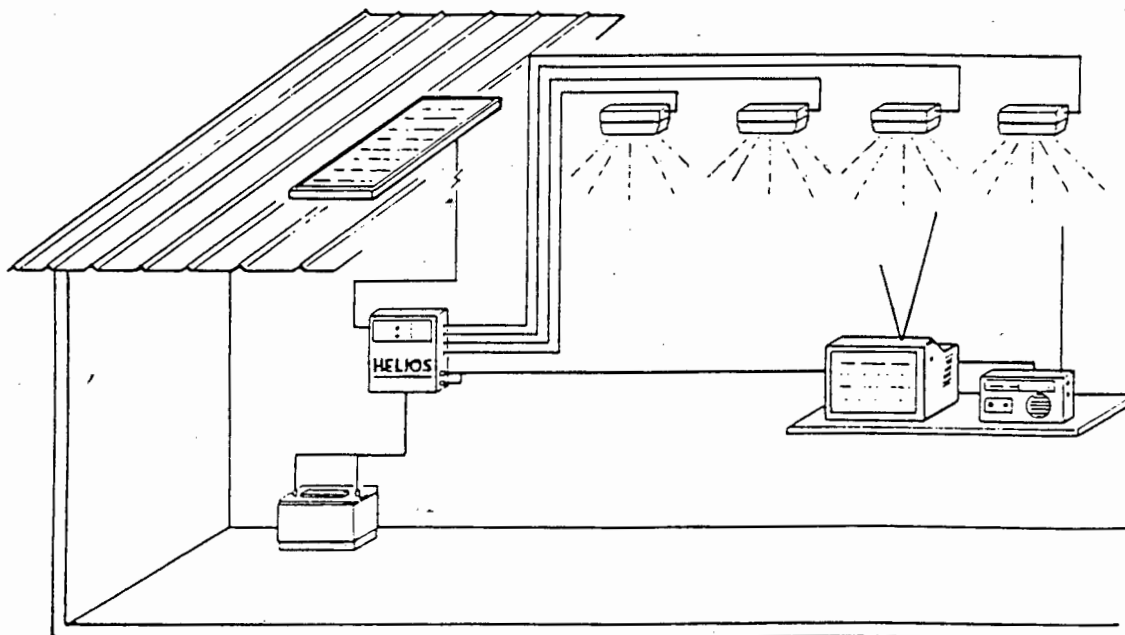
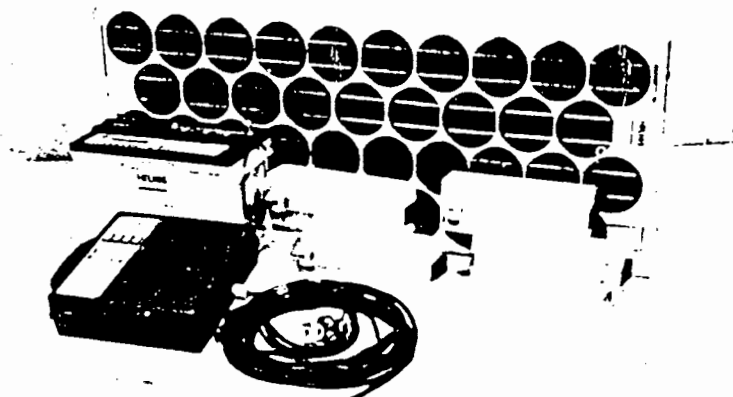
M40 is a solar system for lighting of rural houses, health centres, public offices, etc.

Every night free electric energy will be available to power the four fluorescent lamps for a total number of about 10 hours/night. Each lamp has a light intensity equivalent to a 60 Watts incandescent light-bulb.

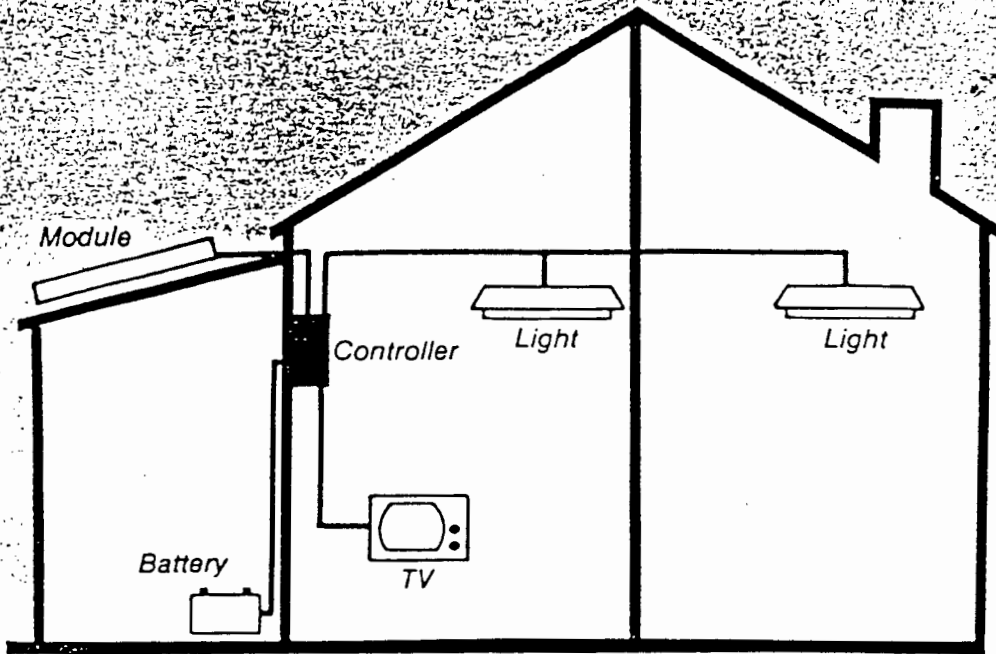
M40 is equipped with a 20 Amps power output plug where other appliances can be connected (i.e. other 16 extra lamps, radio set, portable TV, etc.).

M40 main features are:

- maintenance free.
- very easy to install (all components are preassembled and ready to be connected by plugs)
- long lifetime (typically more than 15 years)
- lightweight and easy to be transported
- all components (solar panel, battery, lights, wires, switches, etc.) are enclosed in
- no monthly electric bills.



POWER FROM THE SUN



One of our typical installations

Introducing the new SPC Home Power Kit, Model HPK160 - an easy-to-install do-it-yourself system that turns the sun's energy into electric power for your home.

Specially designed for homes that are remote from electric utility lines, the new kit from Messina harnesses the natural energy of the sun to provide electricity for lights, radio, TV, and other small appliances.

Here's how it works. The key to the system, the SPC photovoltaic solar power module, is mounted on your roof to catch the sun.

The solar cells in the module convert the sun's radiant energy into electrical current which travels through cables and is stored in a battery, ready for use in operating lights or small appliances.

Fast, easy installation

Most users report that the system can be installed in less than four hours. The kit includes comprehensive instructions for site selection, placement of the module, wiring, installing the battery, and operating and troubleshooting the system.

Everything you need

The SPC Solar Home Power Kit, Model HPK 160, includes everything you need to install the 12-volt DC power system, except for a battery that you can purchase as an option.

The kit contains: an LG 160-12 (industrial grade) Photovoltaic Power Module, electronic control centre, three high efficiency fluorescent lights, a receptacle and matching plug for powering 12-volt DC equipment, plus all wires, terminals, connectors, and hardware.

The natural choice

The new home power kit from Messina provides a reliable source of electricity for your home (or camper or sailboat). Unlike noisy gas or diesel generators, this system is virtually maintenance-free, with no monthly electricity bill.

If you need more power, the system is expandable. Find out how you can harness the natural energy of the sun to power your lights and small appliances.

The HPK 160 contains:

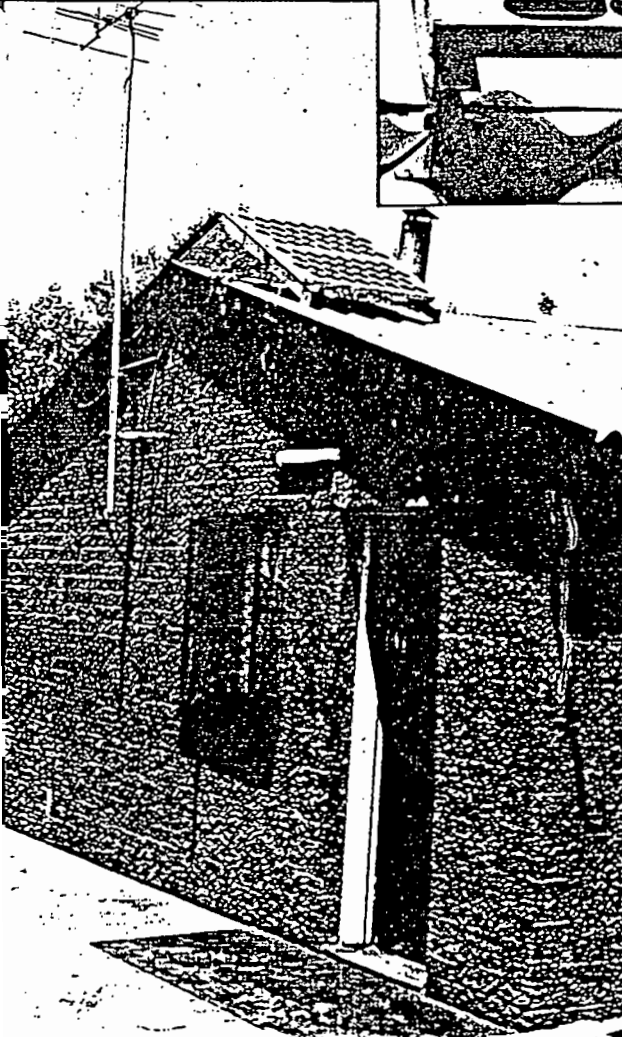
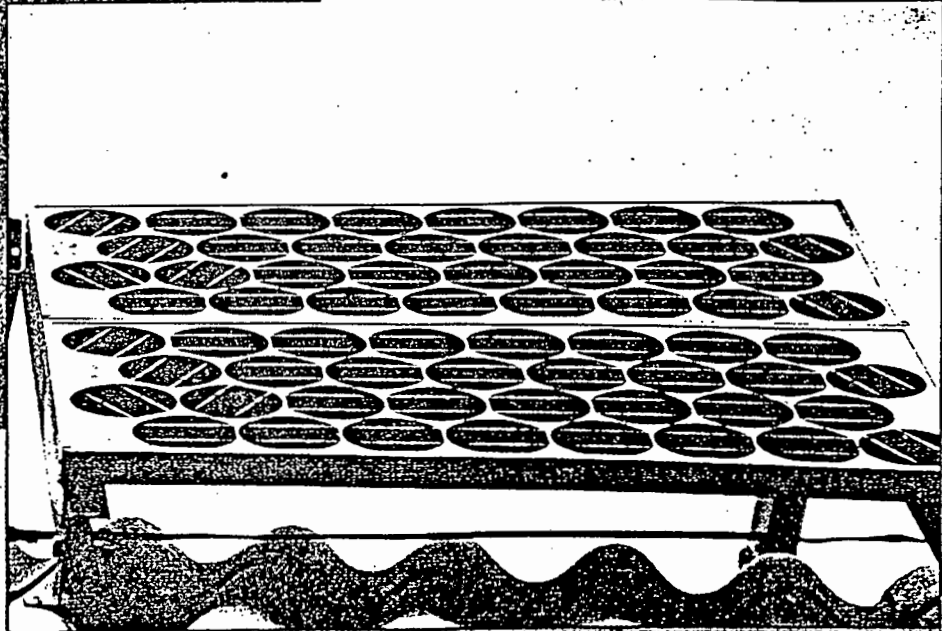
- 1 LG 160-12 module
- 1 set mounting hardware
- 1 system controller
- 1 set wiring and fasteners
- 1 12 volt plug and receptacle
- 3 15 watt high efficiency fluorescent lights
- 1 12 volt battery (optional)

Available from:

MESSINA ELECTRONICS

"Tomorrow's solutions today"





IT'S SO EASY!

(1) A PERSONAL LOAN FROM A BUILDING SOCIETY OR BANK.

(2) HIRE PURCHASE FROM A BUILDING SOCIETY OR BANK.

(3) HOME IMPROVEMENT PLAN OR BOND FROM AS LITTLE AS

R23 PER MONTH

(4) OR CASH WHICH ALLOWS FOR A 5% DISCOUNT!

NO MORE MONTHLY EXPENSES ON PARAFFIN, LAMPS, OIL, CHARGING OF BATTERIES OR CANDLES.



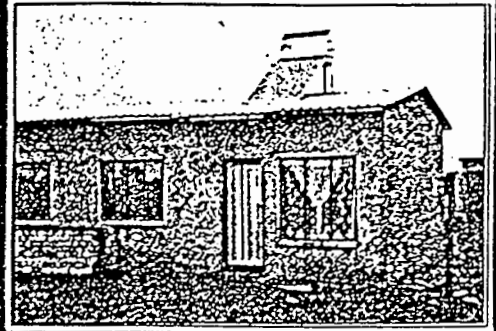
APPLY NOW FOR IMMEDIATE INSTALLATION.

PHONE: SOLAR TECHNIQUE

(JHB) 868-154 OR 864-3152

HEAT & ELECTRICITY

SUN POWER



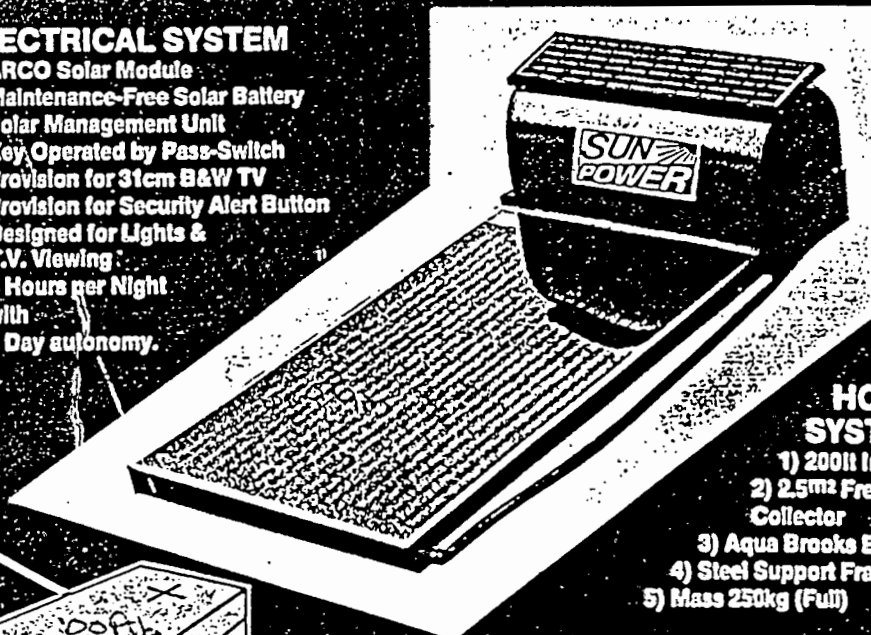
A PACKAGE THAT PROVIDES FREE HOT WATER & POWER FOR LIGHTS AND TELEVISION

ELECTRICAL SYSTEM

- 1) ARCO Solar Module
 - 2) Maintenance-Free Solar Battery
 - 3) Solar Management Unit
 - 4) Key Operated by Pass-Switch
 - 5) Provision for 31cm B&W TV
 - 6) Provision for Security Alert Button
 - 7) Designed for Lights & T.V. Viewing
- 4 Hours per Night with 5 Day autonomy.

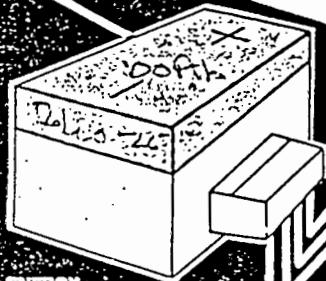
APPLICATIONS

- Urban Low-Cost Housing
- Game Parks & Pleasure Resorts
- Rural Clinics & Schools
- Farm Labourers Accommodation
- Areas without ESCOM Power



HOT WATER SYSTEM:

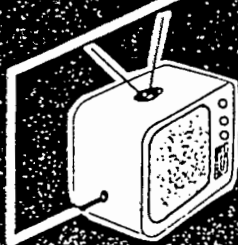
- 1) 200lt Insulated Storage Tank
- 2) 2.5m² Freeze Resistant Solar Collector
- 3) Aqua Brooks Ball Valve
- 4) Steel Support Frame
- 5) Mass 250kg (Full)



ENERGY CONTROLLER



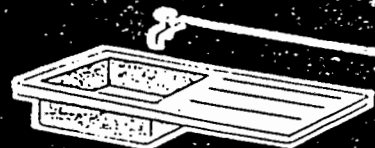
LIGHTS



31cm PORTABLE B&W TV

ADVANTAGES:

- 1) Zero-Running Cost.
- 2) Built in Load Shed & Light Sensing.
- 3) No Maintenance.
- 4) Safe for the User 12V DC
- 5) Long Life Expectancy.
- 6) Reliable, Clean Source of Energy.



KITCHEN SINK



SHOWER

MARKETED BY: SUNPOWER MARKETING TEL: (011) 787-0082/886-3124 P.O. BOX 56168 PINEGOWRIE 2123
 NATAL: SOLAR BEAM (031) 839585 W. TVL: TIME HOUSING (018) 28537/23735 OFS: SUNPOWER MARKETING (0171) 76080

Stable Price R15450

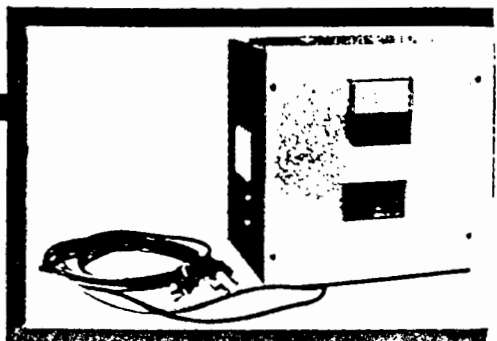
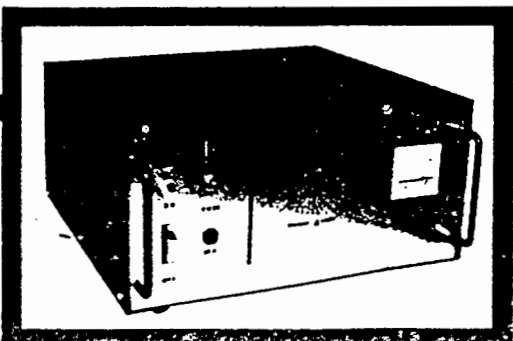
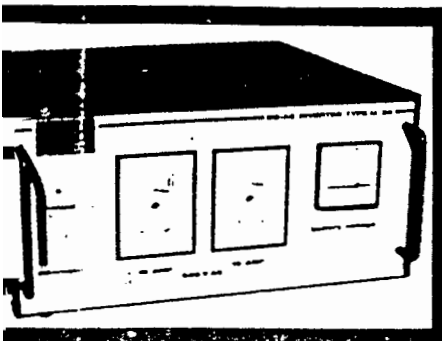
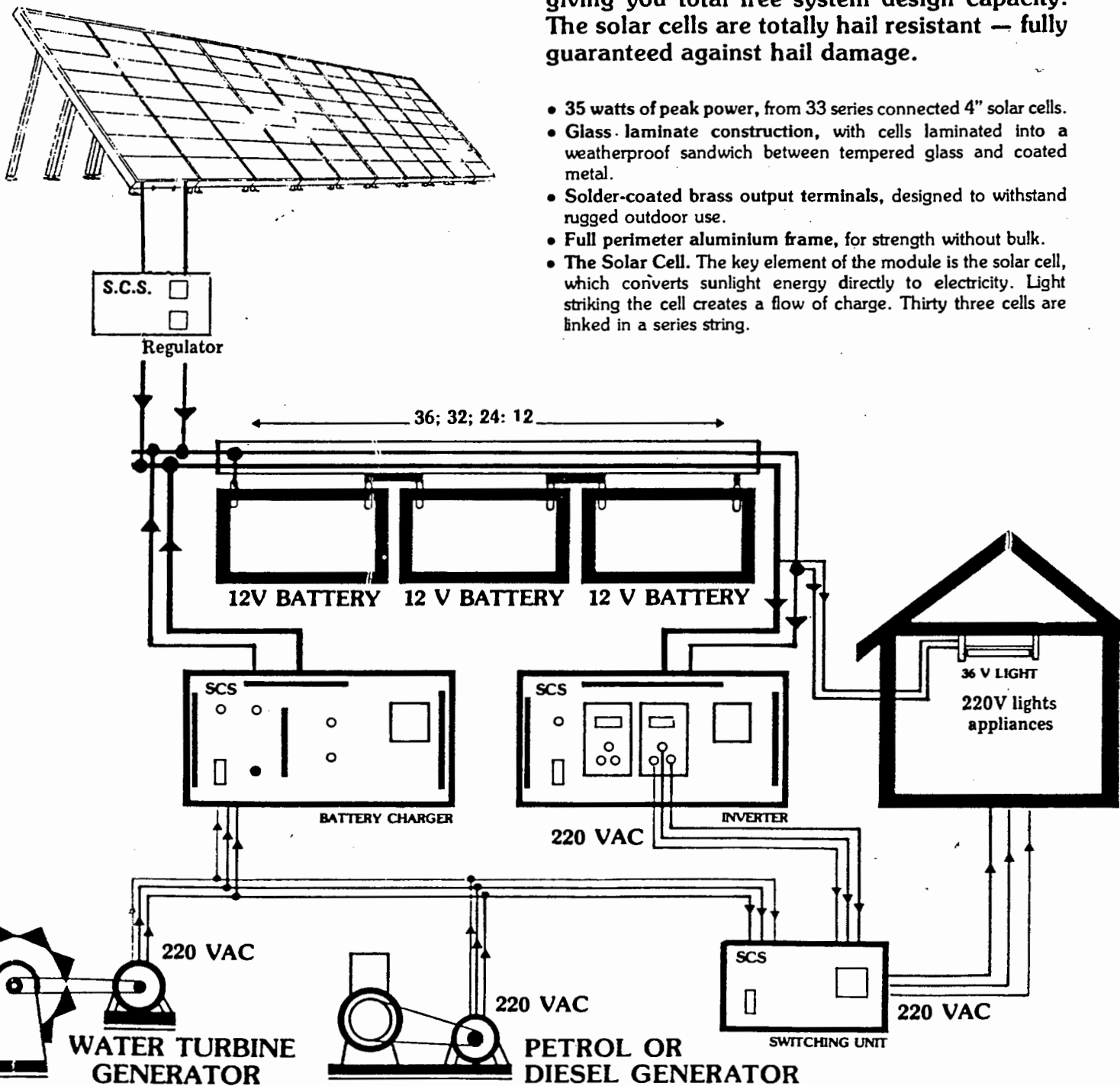
Use Solar Power "IT'S FREE!"
SOLAR VOLTAIC HOME ELECTRICS
SOLAR ARRAY (to be sized for end user need)

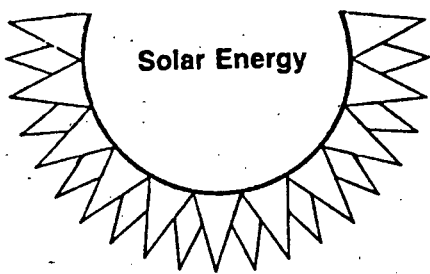


GENERAL ARRANGEMENT

SOLAR ARRAYS are built up to suit your individual needs. It is a simple add-on system giving you total free system design capacity. The solar cells are totally hail resistant — fully guaranteed against hail damage.

- 35 watts of peak power, from 33 series connected 4" solar cells.
- Glass laminate construction, with cells laminated into a weatherproof sandwich between tempered glass and coated metal.
- Solder-coated brass output terminals, designed to withstand rugged outdoor use.
- Full perimeter aluminium frame, for strength without bulk.
- The Solar Cell. The key element of the module is the solar cell, which converts sunlight energy directly to electricity. Light striking the cell creates a flow of charge. Thirty three cells are linked in a series string.



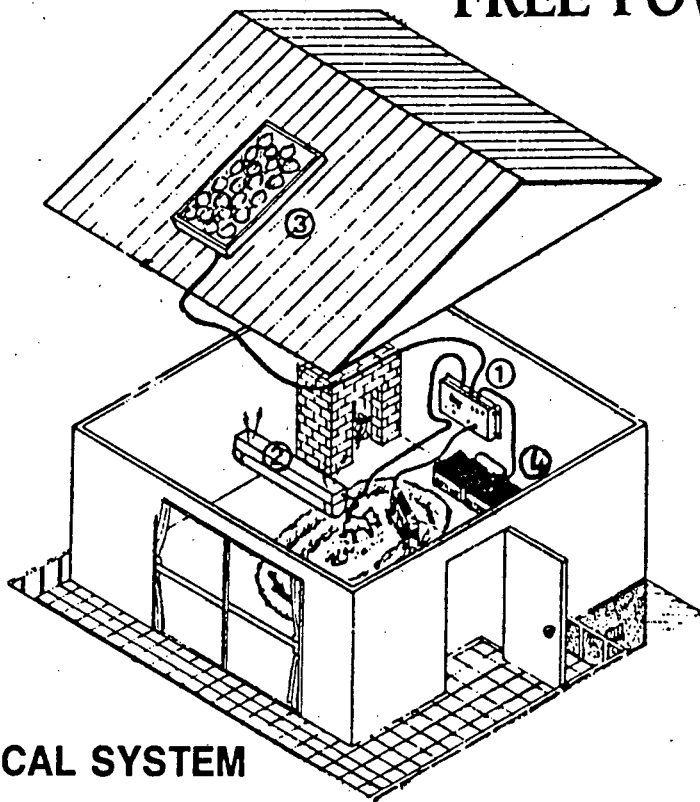


- 250 -

WE'

LIGHT UP YOUR LIFE

FREE POWER FROM THE SUN



FAST

EASY

TYPICAL SYSTEM

PERMANENT

1. BATTERY REGULATOR

2. FLUORESCENT LIGHT UNIT

3. VOLTAIC SOLAR GENERATOR

4. STORAGE BATTERY

● VOLTAIC 25 - FOR 3 LIGHTS (8w) FOR 3 HOURS

● VOLTAIC 35 - FOR 3 LIGHTS (8w) FOR 2 HOURS AND PORTABLE BLACK AND WHITE TV FOR 5 HOURS

● BASIC INSTALLATION CAN BE EXTENDED FOR MORE POWER BY ADDING ADDITIONAL SOLAR GENERATORS

● SOLAR SYSTEM CAN ALSO BE USED FOR 12v HI-FI SYSTEMS AND RADIOS

KITS CONTAIN

ONE BY V12/25 SOLAR GENERATOR

OR

ONE BY V12/35 SOLAR GENERATOR

BATTERY

REGULATOR UNIT

3 (8w) FLUORESCENT LIGHTS

CABLE/TERMINALS

TV PLUG AND SOCKET (V12/35 KIT)

PANEL MOUNTING FRAME

COST:

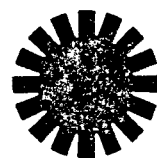
KIT 12/25

KIT 12/35

PRICES EXCLUDE G.S.T.

VOLTAIC
(PTY) LTD

Reg. No. 82/06961/07



P.O. BOX 912-304
SILVERTON
0127
RSA

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