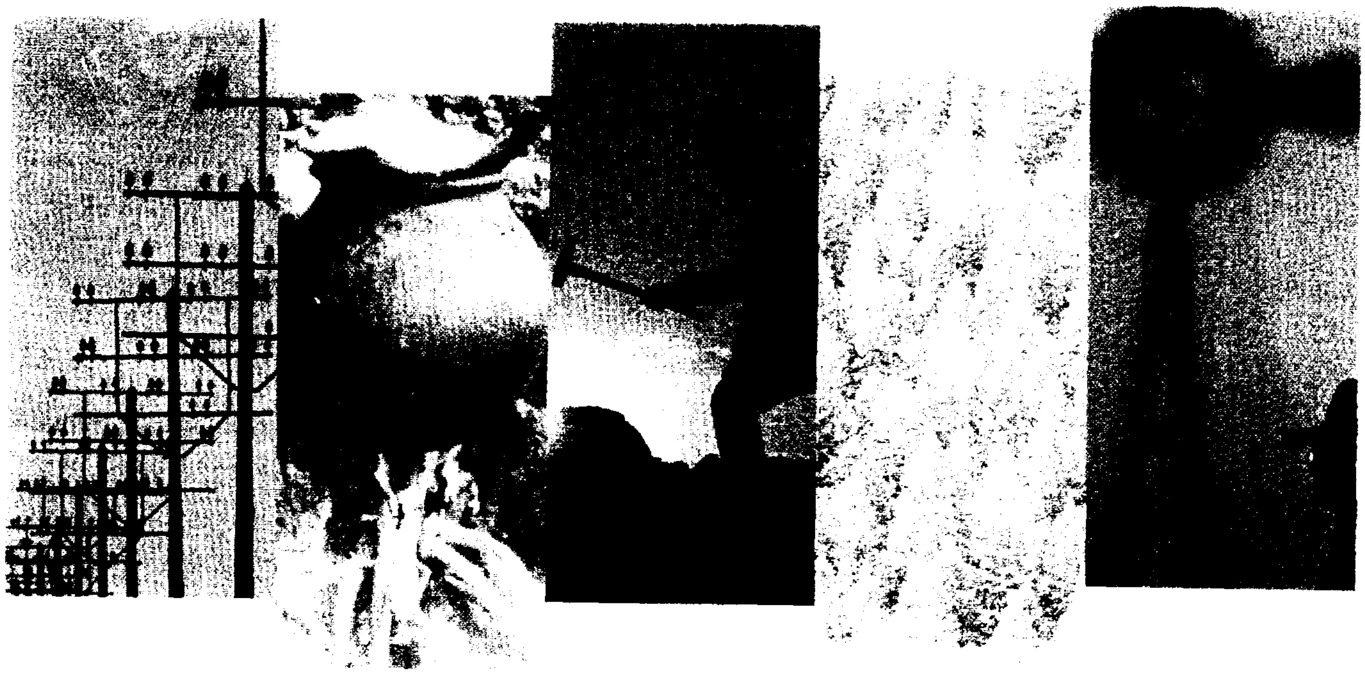
ESMAP TECHNICAL PAPER
009

Photovoltaic Applications in Rural Areas of the Developing World

21992



Energy

Sector

Management

Assistance

Programme

November 2000

ESMAP

Papers in the ESMAP Technical Series are discussion documents, not final project reports. They are subject to the same copyrights as other ESMAP publications.

JOINT UNDP / WORLD BANK
ENERGY SECTOR MANAGEMENT ASSISTANCE PROGRAMME (ESMAP)

PURPOSE

The Joint UNDP/World Bank Energy Sector Management Assistance Programme (ESMAP) is a special global technical assistance program run as part of the World Bank's Energy, Mining and Telecommunications Department. ESMAP provides advice to governments on sustainable energy development. Established with the support of UNDP and bilateral official donors in 1983, it focuses on the role of energy in the development process with the objective of contributing to poverty alleviation, improving living conditions and preserving the environment in developing countries and transition economies. ESMAP centers its interventions on three priority areas: sector reform and restructuring; access to modern energy for the poorest; and promotion of sustainable energy practices.

GOVERNANCE AND OPERATIONS

ESMAP is governed by a Consultative Group (ESMAP CG) composed of representatives of the UNDP and World Bank, other donors, and development experts from regions benefiting from ESMAP's assistance. The ESMAP CG is chaired by a World Bank Vice President, and advised by a Technical Advisory Group (TAG) of four independent energy experts that reviews the Programme's strategic agenda, its work plan, and its achievements. ESMAP relies on a cadre of engineers, energy planners, and economists from the World Bank to conduct its activities under the guidance of the Manager of ESMAP, responsible for administering the Programme.

FUNDING

ESMAP is a cooperative effort supported over the years by the World Bank, the UNDP and other United Nations agencies, the European Union, the Organization of American States (OAS), the Latin American Energy Organization (OLADE), and public and private donors from countries including Australia, Belgium, Canada, Denmark, Germany, Finland, France, Iceland, Ireland, Italy, Japan, the Netherlands, New Zealand, Norway, Portugal, Sweden, Switzerland, the United Kingdom, and the United States of America.

FURTHER INFORMATION

An up-to-date listing of completed ESMAP projects is appended to this report. For further information, a copy of the ESMAP Annual Report, or copies of project reports, contact:

ESMAP
c/o Energy, Mining and Telecommunications Department
The World Bank
1818 H Street, NW
Washington, DC 20433
U.S.A.

Contents

Tables

Box

Foreword

Recent and dramatic reductions in the costs of photovoltaic (PV) cells have drawn considerable attention to PVs as an answer to important energy problems in poor, rural, and peri-urban areas of the developing world. More affordable and flexibly designed PV systems are finding an increasingly wide market: pumping water for drinking and irrigation; powering telecommunications equipment and household and community appliances such as lights, televisions, and videocassette machines; and running vaccine refrigerators in rural health clinics. Presently, various programs for disseminating PV systems in rural areas for home and community use are being implemented or planned by many governments and international agencies.

The problem is that there is as yet no foolproof recipe for designing a successful PV dissemination program or project. The results of field experiences in several countries have been mixed, and no one can claim to know the answers to the many problems of design, financing, organization, and implementation. For this reason, analytical studies such as the present one serve an important purpose.

The report provides much useful data and information on the technology and its market niche in the developing world. It begins by reviewing PV components and systems, outlining the issues of rural energy and discussing both PVs and conventional rural electrification as potential answers to the problems. The report highlights market niches most appropriate for PVs and reviews the lessons of experience of several PV programs. It concludes with a discussion of the role of governments and funding agencies and how they can best develop and implement PV programs. More than simply providing information, the report gives a planner's perspective on PV systems in relation to rural energy planning. The author has long experience in the renewable energy field not simply as a technologist or economist but as a pragmatic observer of the development agenda, and this report is a frank expression of his perspectives.

The World Bank's Solar Initiative believes that the time has come for many renewable energy systems to be considered seriously in investment projects, not only because of environmental objectives but because of their economic and social merits. With this belief comes the responsibility for ensuring that project designers and planners have the best information on the merits and deficiencies of the prospective technologies. The report, which was partly funded by the Energy Sector Management Assistance Programme (ESMAP), should be viewed as one piece of the puzzle on how best to market PVs; other works now being published provide additional pieces.

Richard Stern
Director
Industry and Energy Department

Abstract

The cost of PV systems continues to fall. At the same time, experience is being rapidly gained in their practical use in the developing world. It is now clear they are going to play an increasing part in the provision of electrical services in the rural and peri-urban areas of many developing countries. But the limitations and problems of the technology must also be recognized. PVs are not a solution that can be applied universally throughout the developing world. Programs for their dissemination need to be firmly based on economic and technical reality.

This report examines the rural energy context within which PV programs must fit. The first chapter reviews the present position of PV technology and briefly describes the kits and systems commercially available for use in the rural areas of the developing world. The second chapter examines the rural energy background, describing how people manage to meet their energy needs across the huge areas of the developing world that remain untouched by conventional rural electrification programs. The next chapter looks at conventional rural electrification programs, their merits, and their inevitably limited scope. The fourth chapter looks at the potential niches for PVs, and how they compare in cost and level of service with their competition. A brief review of PV experience to date and the lessons learned is given in the fifth chapter, and the final chapter looks at the role of governments and funding agencies.

In the rapidly moving world of PV technology, there are still no rigid or readymade guidelines for energy planners and program designers. This report provides the necessary background information and highlights the questions that must be asked and the calculations that must be made whenever PV applications are being considered in the developing world.

Preface

Governments in the developing world are subjected to many sharply conflicting financial and social pressures. Public demand for improved services must always be set against the need to balance budgets and keep national debt burdens within manageable limits. Nowhere are these conflicts more clearly visible than in rural electrification. An electricity supply brings enormous benefits to rural people, and the pressure for rural electrification is heavy—and growing—in most countries. However, rural electrification is extremely costly, and the capacity of national power utilities to implement programs is limited. At present rates of progress, hundreds of millions of rural families have no hope of obtaining a conventional electricity supply within their lifetimes.

The use of photovoltaic (PV) technology to provide a minimal rural electrification service—pre-electrification, as it is sometimes described—has emerged over the past decade as one way of helping to resolve the rural electrification dilemma. PV systems can deliver an electricity supply wherever there is regular sunshine. The systems require no fuel, and it is usually much cheaper to install them in remote villages than it is to run a power supply line from a distant electricity grid.

Along with their advantages, PV systems share significant limitations. The amount of electricity typical household PV installations deliver is extremely small compared with the supply available from a grid, so households are greatly restricted in their use of electrical appliances. PV installations also have relatively high initial costs, and the incremental costs of increasing the supply are almost as high. Rather than opening the way to significant increases in electricity consumption and a gradual progression to the use of a full range of conventional household appliances and equipment, PVs can turn into a cul-de-sac. Thus, decisions on whether PVs represent the optimal technical and economic solution for rural electrification in any given case often turn on fine distinctions.

As is sometimes the case with any new technology, PVs have at times been promoted with a fervor in which the practicalities of cost, reliability, and the level of service delivered have been largely ignored. But this initial stage may already have passed for PVs, and it now appears that the technology can be assessed frankly on its technical and economic merits. People know what will and will not work. Moreover, costs are beginning to stabilize as manufacturing capacity builds—although further significant reductions through technical advances and economies of scale are expected.

Few people now doubt that PVs have an important and growing part to play in providing electrical services in the rural areas of the developing world, and many are also becoming aware that PVs have potential applications in the suburban and peri-urban areas of many developing countries, where many other families have little hope of getting access to a conventional electricity supply.

Given their growing acceptance and the careful distinctions that need to be made to determine their applicability and economic use, now is an opportune time for an overall review of the potential role of PVs in the developing world. The crucial questions for such a review include the following: What is the present status of commercially available PV technology? What services can PVs deliver and at what cost? What niches are they are suited to fill? How competitive are they with the alternatives? What actions should governments and funding agents take?

The scope of this report is deliberately limited to the present and the practical issues of energy supply in the developing world. It does not attempt to forecast where PVs are likely to be deployed in the medium to long term, when prices have fallen to half or less of today's levels, as predicted. The report's aim is rather to assess the present status of PVs as a competitive electricity supply source in programs promoted by donors or governments, or as an option for private individuals wishing to provide themselves with small amounts of electrical power.

The paper necessarily uses current and recent illustrative cost data. But these cost figures are not intended to "prove" that PVs are universally justifiable or unsuited for particular applications. Even a cursory scan of the literature shows that the installed costs of systems vary by factors of two and three, depending on the circumstances of each case. Thus, rather than provide spuriously authoritative data, the report seeks to illustrate the kind of questions that need to be asked in each case.

Acknowledgements

This ESMAP Technical Report was prepared by Gerald Foley and initially issued in 1995 as a World Bank Technical Paper 304 in the Energy Series.

The starting point of this study was an ESMAP working paper (Meunier 1993) prepared by Bernard Meunier with support from Philippe Durand, Willem Floor, and Robert van der Plas, all of whom are gratefully acknowledged. Special thanks are due to Willem Floor for his advice and encouragement in the writing of this report.

Many thanks are also offered to Peter Ahm, Douglas Barnes, Dick Dosik, David Hancock, Dolf Noppen, Robert van der Plas, and Ernesto Terrado, and to Loretta Schaffer, Mac Cosgrove-Davies, Anil Cabraal, and Frans Niewenhout of the Asia Alternative Energy Unit (ASTAE) team in the World Bank for their detailed, helpful and tempering comments on an earlier draft of this paper and for the copious additional information they provided.

Publication of this report was managed by Paul Wolman; Caroline McEuen did the initial copy editing; and Carole-Sue Castronuovo carried out the word-processing tasks.

1

Photovoltaic Technology

PV technology has developed rapidly over the past two decades—from a small-scale, specialist industry supplying the U.S. space program to a broadly based global activity with an annual turnover of about $800 million and an annual output of about 60 million peak watts (MWp) (Barlow, Derrick, and Gregory 1994). The past few years have also seen a major commercial shakeout and consolidation within the industry. A variety of mergers and takeovers have occurred, and some well-known names have disappeared or are no longer independent. ARCO Solar, for example, has been taken over by Siemens.

PV technology can now be regarded as mature, with internationally accepted standards and specifications for components. Research and development continue and will bring steady technical improvements and reductions in manufacturing costs. But the size of the industry and the scale of the investments already made in manufacturing plant have brought a much greater inertia, or stability, to the product market. Companies are reluctant to write off the large investments they have made in manufacturing plant before they have seen an adequate return. The broad outlines of PV technology at the market level are now rather firmly drawn for the remainder of the decade.

Availability of Solar Energy

Overall, the developing world is well-endowed with solar energy. Most developing countries are within or close to the tropics and have ample insolation (the total daily amount of solar energy reaching the ground). Moreover, they experience only small seasonal variations in insolation of about 25 percent between the best and worst months (even during the rainy season, most days in tropical countries usually have some hours of bright sunshine). This pattern contrasts sharply with that of the northern industrial countries, where the summer–winter variation in solar energy is one of the most significant obstacles to harnessing solar power in an economical manner.

Even under clear-sky conditions, however, variability is a key characteristic of solar energy. At any given point, the daily insolation rises from near zero at dawn, peaks around midday, and then declines again to near zero at sunset. As a rule, the peak solar energy intensity on a horizontal surface in the tropics under clear sky conditions is

1 kilowatt per square meter (kW/m^2). The corresponding daily total amount of energy is about 5 kilowatt hour per square meter (kWh/m^2). This increases to about 7 kWh/m^2 where the air is exceptionally clear (e.g., in a desert country such as Namibia); under slightly hazy or dusty conditions, the total is likely to be about 4 kWh/m^2.

Despite the general abundance of solar energy in the developing world, it is always necessary to check the assumed insolation conditions at each proposed PV site. In Pakistan, for example, where average daily insolation is generally in the range of 5 to 6 kWh/m^2, the December daily average in Lahore is only 2.8 kWh/m^2. Similarly, the insolation in two areas of Kenya that are just a few hundred kilometers (km) apart, Nyeri and Lokori Turkana, differs by nearly a factor of two—4.09 kWh/m^2 at the former and 7.56 kWh/m^2 at the latter.

Available solar energy can also be subject to major short-term fluctuations. The heavy cloud that occurs during the rainy season can cut the level of insolation to a small fraction of its peak level. Similarly, measurements during the dustiest time of the Harmattan wind in West Africa have caused reductions of 70 percent in the available solar energy. Factors in the immediate environment of the installation also need to be taken into account. A building, a tree, or a mountain can cut off most of the direct radiation on a system for a large part of the day.

Although high peak insolation values strengthen the case for harnessing solar energy, it is the period of minimum insolation, rather than the maximum, that is the crucial parameter in the design of most PV installations. This determines the size of the PV component of the installation and the amount of energy storage required to meet energy demand. Examination of the insolation records throughout the year is thus a necessary design step for all solar energy installations.

PV System Components

All PV systems are based on PV cells, which transform solar energy into electricity. At the manufacturing stage, the PV cells are assembled into modules, which, in turn, are assembled into the arrays that are erected on supports in the field.

A complete PV system to deliver electricity to an end use has a variety of components in addition to its PV array. These are often referred to collectively as the balance-of-system (BOS) components. Depending on the system, the BOS components may include a storage battery; a charge controller (also referred to as a load controller or charge regulator); an inverter; the module supports; and a variety of cables, clips, connectors, switches, junction boxes, and other small items. The BOS components in a PV system generally do not attract the same attention as the PV modules, yet they usually account for 40 to 50 percent of the total cost of an installation. Moreover, they are vitally important to its successful functioning. Failures of installations are far more likely to occur as a result of defects in the BOS components than in the PV modules.

PV Cells

Although in principle a variety of materials can be used for PV cells, silicon is the base material for virtually all cells produced commercially today. Three kinds of silicon cells are manufactured: crystalline, polycrystalline, and amorphous. The two crystalline varieties account for about three-quarters of total world production; the amorphous cells make up the rest.

In the manufacture of monocrystalline cells, a single large silicon crystal is sawed into the thin wafers needed to make the cells. This is a slow, costly, and wasteful process, but its efficacy has been amply demonstrated. Experimental cells made from monocrystalline silicon presently have efficiencies of up to 23 percent (Green and Emery 1994), whereas those on the commercial market generally have efficiencies of about 15 percent. Polycrystalline cells are cut from a block or ingot of silicon that has been cooled in a crucible. This technology has also proved itself over time. Experimental cells have efficiencies of about 17 percent, although those on the commercial market are typically in the range of 12 to 13 percent.

Amorphous silicon, often referred to as a-Si, came into wide use in the mid-1980s. The production technology is cheaper and less wasteful than the sawing used in the manufacture of crystalline cells. Several techniques are used to create the a-Si cells. In some, the cell material is drawn as a ribbon from the molten silicon; in others, it is deposited directly on a glass backing. The a-Si cells are less efficient than the crystalline varieties, however, with experimental values in the range of 12 to 13 percent. Moreover, a-Si cells are highly susceptible to degradation under bright sunlight, and their typical stabilized efficiencies are only 3 to 5 percent. The major use of these cells is in the supply of the tiny amount of electricity required to operate solar-powered electronic calculators, wristwatches, and other such devices.

Once the silicon wafers have been made, they are subject to a variety of treatments and finally fabricated into the PV cells themselves. A number of cells are embedded in soft plastic and fitted into an aluminum frame with a rigid plastic backing and a hardened glass cover to form a module. The electrical output of the module is expressed in terms of its peak output in watts (Wp) under standard laboratory conditions (insolation of 1 kW/m^2 on a horizontal surface at an ambient temperature of 25° C) and is usually in the range of 5 to 50 Wp.

Monocrystalline and polycrystalline cells have been described as the workhorses of the PV industry, and they currently account for virtually all outdoor PV applications. Although cheap, efficient, and acceptably stable amorphous silicon cells will probably come on the market within the next four or five years, they are unlikely to displace crystalline cells from outdoor uses to a substantial extent within the next decade.

Although PV cells and modules exhibited some durability problems in the early to middle 1980s, these difficulties have generally been overcome, and most makes now perform satisfactorily. Modules from reputable manufacturers now can be relied on to have lifetimes in the range of 15 to 20 years. Most manufacturers offer a warranty of at least 10 years. The warranty for amorphous cells, in contrast, is usually about 2 to 3 years.

Cell prices have fallen steadily from their extremely high level in the 1970s, when they first became commercially available. At present, the ex-factory price for reasonably large orders of crystalline silicon modules is about $4.00 to 5.00/Wp. The installed prices of arrays depend on transport and labor costs, profit margins, the size of the order, and a variety of other factors and are unlikely to be less than $7.00 to $8.00/Wp. For small orders in the rural areas of developing countries, the price is likely to range upward from $10/Wp.

The maintenance requirements of arrays are simple. The primary need is to keep the surface clean. Even a slight coating of dust can reduce the overall electricity yield significantly. It is also important to remove small objects that may fall on the array, such as bird droppings or leaves—not merely because such objects obscure some of the cells but because the shaded cells can become overheated from the energy of the other cells and may be permanently damaged (Burton 1992). It is also essential to ensure that the array as a whole is not shaded; even a small amount of shade can reduce the output by as much as 50 percent.

Batteries

Few energy demands follow the exact pattern of the sun's availability; hence, the electricity produced by PV systems generally has to be stored for use when it is required. The exact amount of storage needed depends on the importance of continuity of supply to the user. For example, although a householder may be prepared to cut down on the use of lights and TV during cloudy weather, a crucial application such as a telecommunications relay station or a PV-powered refrigerator in a health clinic must have enough electricity stored to cover all likely periods of low insolation or a temporary breakdown in the PV system. The length of time a system is designed to function without any solar energy input is referred to as its *period of autonomy,* usually measured in days.

PV systems generally use 12-volt lead-acid batteries. The much more expensive, rechargeable nickel-cadmium batteries are only used in small applications, such as rechargeable lamps. Standard car batteries are often used, but their limitations must be recognized and accommodated in the design of the system. Some manufacturers sell so-called solar batteries; these are also of the lead-acid type but have some modifications in design that make them more suited to the discharge patterns typical in a solar installation.

The problem with the use of car batteries in PV systems is that they are not designed for the demands of use in a solar PV system. Under normal use in a vehicle, the battery is discharged only slightly when the starter is used, and the charge is quickly restored once the engine is running. Under such conditions, lead-acid car batteries can last three or four years or more. But if the same battery regularly suffers a high discharge, its life is greatly reduced (the lifetime with regular discharge of 75 percent is about one-fifth that when the periodic discharge is 10 percent). Moreover, if the battery is discharged until it is completely flat, serious and permanent damage is done. Sealed or "no maintenance" batteries are particularly vulnerable to damage from deep discharge, and they are also liable to be damaged by large temperature variations; hence, many PV system designers strongly recommend against their use in PV applications in hot countries. Thus, although car batteries can perform satisfactorily in PV installations, considerable care is required in the design and operation of the system.

"Solar" batteries were designed to overcome some of the limitations of car batteries. The solar batteries incorporate a larger quantity of acid solution than car batteries and often include a greater amount of active material as well. This makes them better able to withstand the charge and discharge cycles of normal PV applications. These batteries also provide considerable extra capacity if they are discharged slowly. The capacity over a 100-hour discharge, referred to as C100, usually is twice that over an 8-hour or 10-hour discharge, referred to as C8 or C10. The 8-hour or 10-hour discharge capacities must be used when designing domestic PV systems, but the 100-hour capacity may be relevant in a telecommunications application where maximum security is required and battery storage capacity has to be sufficient to cover PV system downtime of up to a week.

There is a clear tradeoff between battery life and the size of the battery store. The greater the amount of battery storage provided, the lower the level of discharge and the longer the life of the battery, but the higher the initial cost. As a rule, the battery capacity in a domestic PV kit should be about five times the daily electricity consumption of the householder. Under normal insolation conditions, this limits the discharge to about 20 percent. Dealers and purchasers are always tempted, however, to undersize the battery to reduce the initial cost of a PV installation. Users may also be tempted to economize and install a smaller size when it comes to replacing the battery in a properly designed system.

The maintenance requirements of batteries are not onerous, but they must be carried out. The battery must be kept filled with distilled water, and special care is needed to ensure that this is done where the PV installation is in hot areas with low humidity. Distilled water must be used because impurities can damage the battery; the difficulty of obtaining distilled water in isolated rural areas in the developing world should not be underestimated. The battery terminals need to be cleaned and smeared with petroleum jelly at intervals of six months or a year. Because battery life and performance deteriorate significantly at temperatures above 30° C, the battery should always be positioned in a cool, well-ventilated area.

The lifetimes of batteries vary widely depending on how they are treated. In a system that is designed and maintained well, a car battery can last 4 to 5 years, but more typically it has a lifetime of 1 to 2 years. With careful maintenance and discharge levels not exceeding about 15 percent, a life expectancy of 8 to 10 years for "solar" batteries can be obtained, but an average of about 5 years is more likely under normal working conditions in the developing world.

Battery capacities are measured in ampere hours (Ah),[1] and those used in PV applications range from about 15 to 300 Ah. Battery costs depend on the capacity of the battery as well as the quality of materials and construction. Significant differences can be found between countries because of varying labor and materials costs or degrees of market competition. Car batteries generally cost about $1.00/Ah, but there is considerable variation. Good quality solar batteries are more likely to cost about $2.00/Ah.

Other Balance-of-System Components

An electronic charge controller is used to protect the battery from excessive charging and discharging. Those used in household PV systems operate by detecting the battery voltage, which rises or falls depending on the level of charge. The controller cuts off the charging current from the PV array when the voltage rises above the fully charged level; it also cuts off the load when the voltage drops below the acceptable level of discharge.

The degree of sophistication of charge controllers, and hence the protection they provide, varies considerably. The cheaper models usually only have overcharge protection, leaving the user to judge when the load should be disconnected to prevent excessive discharge. This need not be a problem if a battery of adequate size is used and care is taken in the management of the system—otherwise it is likely to lead to considerably shortened battery life. Some charge controllers are fitted with temperature sensors that allow the charging voltage to be reduced if the temperature of the battery exceeds 30° C, thus providing an additional safeguard against damage.

The costs of charge controllers vary widely depending on their features and place of manufacture. Typical costs for full-feature controllers produced in the industrial world are $100 and up, whereas models produced in the developing world that provide overcharge-only protection can be obtained for as little as $10. Charge controllers are often omitted from cheaper PV installations.

PV systems are usually designed to produce a direct current at 12 volts. Where a 220-volt alternating current is required, it can be provided through an electronic inverter. A significant power loss—up to 15 percent—may be incurred with the use of an inverter, but it has the advantage of allowing the use of standard domestic appliances. One of the main problems with using standard domestic appliances with PV systems, however, is that most appliances are not designed with energy efficiency as a primary consideration. Although this is not a significant problem for consumers connected to a mains supply, where the only effect is a few extra kilowatt hours on the monthly bill, it has a significant

1. The capacity in watt-hours is obtained by multiplying the capacity in ampere hours by the voltage. A 100-Ah 12-volt battery, for example, has a fully charged capacity of 1,200 Wh.

effect on a PV system, where energy inefficiency may sharply increase the area of the modules required and the overall cost of the system.

Other balance-of-system components include cables, connectors, switches, junction boxes, fuses, and other small items. Many of these are installed in the open, where they are exposed to harsh weather conditions; hence, they must be of good quality and carefully installed if the system is to operate properly. Corroded or damaged connections reduce the amount of electricity available to the system and may cause it to break down completely. Where thunderstorms are common, the systems may need lightning conductors as well.

It is also essential to ensure that the system of supports for the equipment is properly designed and erected. When the PV array is mounted on a building roof, it should be raised a short distance above the roof surface to allow for air circulation and to prevent excessive heat buildup. It must also be attached firmly enough to resist the lifting effects of the strongest winds likely to affect the area. In some Asian and Pacific countries, this means the system must be designed to resist hurricane-force winds. Access for regular cleaning must also be provided. Where arrays are mounted on the ground, they must have adequate foundations, usually concrete, and a secure fence to protect them from people and animals.

Field Efficiencies and Electricity Outputs

The overall efficiencies of PV systems in the field are considerably lower than the laboratory efficiencies quoted for the modules. The efficiency of the cells themselves, for example, falls by about 0.5 percent for every 1° C rise above the standard laboratory test temperature of 25° C. This can be quite significant in many tropical countries, where noon air temperatures often exceed 30° C, and modules frequently have temperatures of 60° C or higher. This can lead to a fall in the cell efficiency of up to 20 percent under peak insolation conditions.

It should also be remembered that not all commercially available cells achieve state-of-the-art efficiencies. This is especially true at the less expensive end of the range. Many bargain-price modules are made from old stock dumped at reduced prices by manufacturers who have moved to higher-quality products. Losses also occur in the cables, switches, load controller, and other equipment. It is therefore important that cable runs are kept as short as possible and cable diameters are of adequate size; use of long runs of cheap, thin cable can cause major losses. Loose or corroded connections increase these losses. Dust and shading also reduce the performance of the system below its theoretical maximum.

An overall loss of 10 percent of the rated output of the modules is often taken as a somewhat optimistic assumption in initial system sizing. Further losses occur in charging and discharging the battery. The general overall efficiency of the charge-discharge cycle is about 80 percent, but the losses can become significantly greater as the battery ages. The final output of electricity available to the consumer is thus about 70 percent of that derived from the rated output of the module. The effect of these losses can be seen by considering an area with a noon insolation of 1,000 watts per square meter (W/m^2) and an average daily total of 5 kWh/m^2. The theoretical daily output of a 100-Wp module under these conditions is 500 watt hours (Wh). Allowing 10 percent for array and wiring losses, this reduces to 450 Wh before battery storage. After battery storage, the net amount available for lights and appliances is about 360 Wh daily.

Sizing of PV Systems

Sizing of PV systems is as much a matter of judgment as of technical analysis. Security and reliability cost money. The benefits of higher design standards in greater reliability and enhanced product image must always to be balanced against the increased cost and reduced market for the systems. Because initial costs are the main barrier to wider use of PV systems, sellers and promoters of PV systems are greatly tempted to keep these costs to a minimum by reducing the margins in the system. Systems with an undersized PV array, a cheap car battery, and no charge controller may undersell ones designed to provide a higher level of performance and reliability.

A simple six-step design procedure for the initial sizing of PV systems has been developed by the South Pacific Institute for Renewable Energy in cooperation with the Pacific Energy Development Programme (included in Liebenthal, Mathur, and Wade 1994). The technique has been used successfully since 1987 and provides a reasonably conservative sizing methodology. The calculation method relies on a *generation coefficient,* which takes into account all the losses typically incurred in converting the insolation to usable electricity at a particular site. The generation coefficient is based on measurements of actual performance at the site or similar sites and is expressed in watt hours daily for each rated peak watt of the array. In other words, it is a pragmatic measure based on experience that takes into account all the factors influencing the performance of actual systems in operation. For small Pacific islands, the generation coefficient is typically 3.43; a 100-Wp panel would therefore produce 343 Wh of usable electricity per day in a typical solar home system.

Ultimately, the decision on the exact configuration of the system will rest with the designer—or seller. With market experience, customers will eventually be able to make judgments on the performance of equipment and the tradeoffs between cost and performance—as they do, for example, in the case of motor vehicles and other consumer goods. At the moment, however, it is extremely difficult for purchasers of PV equipment—whether they are private individuals, donor agencies, or governments—to establish whether the systems they are buying are overdesigned, underdesigned, or fairly priced.

PV Kits and Systems

The components that make up a PV system can be assembled in a variety of ways, depending on the intended application. These assemblies or kits can be divided into four general categories: lighting and small power kits designed for domestic use, often referred to as solar home systems (SHSs); water pumping systems; vaccine refrigerators; and small portable lamps or lanterns. PV battery-charging systems for use with car batteries have also been installed in a number of countries. A small number of centralized, village-level PV installations have also been constructed as demonstration projects in different parts of the developing world.

Solar Home Systems and Solar Lanterns

Solar home system kits consist of a module, load controller, battery, one or more lamps, and a power outlet. The most basic SHS kit has a 10-Wp module and an 8-Wp lamp and will provide about four hours of light each evening. A 20-Wp kit will, also include a power outlet and will provide double the electricity, 70 to 80 Wh, under reasonable insolation conditions. This will supply sufficient power to operate two lamps, or one lamp and a radio–cassette player, for about four hours.

A typical medium-range SHS kit has a 50-Wp module, which provides an average of about 180 Wh daily. This considerably increases the range of options for the household. It is sufficient, for example, to operate three or four lamps and a radiocassette player for four or five hours. By reducing the amount of power used for lighting, the householder can use a small black-and-white TV for several hours. Toward the upper end of the SHS range, a kit with two 50-Wp modules will provide up to 360 Wh daily, which offers considerable flexibility to the household in its choice of services. In this case, even a small color TV can be considered.

Rechargeable PV lanterns usually have a nickel-cadmium battery, although some have a lead-acid battery; an integral 2.5-Wp to 10-Wp PV module; and a 5-watt to 10-watt fluorescent lamp. They recharge in normal daylight—the brighter the better—and provide two to five hours of light. Some versions do not have their own PV module but are designed for recharging from a 10-Wp to 25-Wp stationary module.

Prices of SHSs have fallen substantially over the past few years. Table 1.1 lists recent installed prices for a range of SHSs in selected developing countries. As can be seen, the variations between countries are wide—the price of a 53-Wp system in Kenya or Sri Lanka is about three times that in Indonesia, for example. But because of the general absence of information on the quality of manufacture; the size of battery store provided; the kind of load controller, if any; and other relevant information, few firm conclusions can be drawn from such data since it is unlikely that the systems are comparable in performance. Among the other reasons for wide price variations between countries are tax regimes, labor costs, profit margins, and the degree of market competition. India, for example, uses high import duties to protect its indigenous PV industry, which also keeps retail prices high. Lack of competition, especially in tied-aid programs where the equipment is provided by manufacturers from the donor country can be particularly inflationary.

Table 1.1 Installed PV System Prices in Selected Developing Countries

Data source (year)	*Type of system*	*PV system size (Wp)*	*Installed price (US$)*	*Price per watt (US$)*
Kenya (1993)	SHS	53	1,378	26.00
Indonesia (1994)	SHS	50	420	8.40
Sri Lanka (1993)	SHS	20	300	15.00
	SHS	35	500	14.28
	SHS	53	1500	28.30
Philippines (1993)	SHS	48	640	13.33
	SHS	53	900	16.98
China (1994)	SHS	20	160 to 280	8.00 to 14.00
	SHS	10	93	9.30
The Gambia (1994)	SHS	15	560	37.00
	SHS	53	1,094	20.65
Mexico (1994)	SHS	50	700	14.00
Kyocera	Lantern	3.6	70	19.45

Note: All prices include taxes and duties. SHS = solar home system.

Sources: ASTAE (1995); World Bank/ESMAP (1994).

All such price lists must therefore be used cautiously when discussing the potential applicability of PV systems in the developing world. Quite apart from any consideration of the performance and reliability of equipment, low prices in one country may not be replicated in another. PV analysis is still an art of the particular. Cost evaluations of PV systems and comparisons with alternatives must always be based on the conditions and prices obtaining in the areas where they will be used.

The amortized costs of SHSs depend on the initial costs and the lifetime of the system components. Again, the variations are large, depending on the quality of the equipment and its installation. The PV modules should last an average of 15 years. Charge controllers have been a frequent source of problems in the past, but good quality makes now last about ten years. The greatest uncertainty is the battery.

Table 1.2 lists the monthly amortization figures for a range of kits with roughly mid-range prices (based on the sample shown in Table 1.1). The discount rate used is 10 percent; a 5-year life has been assumed for the lantern, and an overall life of 12 years for other kits. Battery replacements are assumed to take place every 4 years. On the basis of these rough amortization figures, the average cost per kilowatt hour supplied to the consumer is about $2.00.

Table 1.2 Monthly Amortization Costs for Representative PV Systems

System type/size	*Initial cost (US$)*	*Lifetime (years)*	*Battery cost (US$)*	*Monthly amortization (US$)*
Lantern	70	5	n.a.	1.49
Kit @ 20 Wp	300	12	60	4.42
Kit @ 50 Wp	750	12	120	11.64
Kit @ 100 Wp	1,300	12	240	20.65

Source: See Table 1.1.

PV Pumping Systems

In principle, a PV pumping installation is simple. It consists of a PV array to produce the electricity and a water pump. In practice, detailed technical design decisions must be made to match the system to the water supply source and the demand to be met.

For depths of up to seven meters, a surface-mounted, single-stage centrifugal pump, directly driven from the PV array, is generally used. For depths of 20 to 40 meters and a supply of less than 30 cubic meters a day, a submerged reciprocating positive displacement pump, often referred to as a jackpump, is customarily used. For greater quantities of water or greater pumping depths, a submerged motor and pump are generally used; this system normally runs on alternating current, which requires an inverter as part of the installation.

Batteries are sometimes incorporated into PV pumping systems. They can equalize the electric load, storing electricity from the peak insolation periods when the pumping capacity may exceed the well yield and allowing it to be used earlier or later in the day. This may enable savings to be made in the area of the array. Batteries, however, add complexity and cost to the system.

The energy requirements of pumping depend on the amount of water pumped and the total height it is raised—known as the hydraulic head. The formula for calculating the daily energy requirement, E, before any friction or other losses are taken into account, is

$$E = 2.725\, HV$$

where H is the hydraulic head in meters, V is the daily volume of water in cubic meters (m^3), and E is in watt hours. (Note that one m^3 = 1,000 liters. The product of volume and height in the equation is sometimes expressed in m^4 and provides a measure of the total pumping effort required to deliver a given quantity of water through a given height.)

The operating efficiency of the motor and pump system varies depending on the kind of equipment used. In a PV system it also changes with the insolation level. It is generally in the range 15 to 45 percent; an average of 30 percent is sometimes used for preliminary design purposes (the overall system efficiency, assuming a module efficiency of 10 percent, is thus about 3 percent). In other words, the minimum daily yield of the PV system needs to be roughly three times the theoretical pumping energy required. Detailed system design, of course, needs to be based on the equipment being used and the specific requirements of each site.

The costs of PV pumping installations vary widely depending on their size, location, and a variety of other factors. The PV component should generally have an installed cost of about $8,000 to $10,000/kWp. Much higher costs are found in cases where orders are small, installation costs are high, or manufacturers' and dealers' margins are not constrained by competition. The cost of the electricity from a 1,000-Wp system with an installed cost of $9,000 and a working life of 15 years is about $1.06/kWh, assuming an annual maintenance charge of 5 percent and a discount rate of 10 percent.

Vaccine Refrigeration

The joint World Health Organization/UNICEF Expanded Programme of Immunisation (EPI), which began in 1974, is the world's largest single primary health care program. One of the most crucial needs of the program is refrigeration of vaccines in its rural health clinics. In the mid-1980s, the EPI decided to adopt PV-powered refrigerators wherever they were economically and technically justified. About 3,000 PV refrigerators have now been installed throughout the developing world, about half of them in Africa.

The operating principles of photovoltaic refrigerators are similar to those of normal domestic electricity-powered models except that they use 12-volt or 24-volt direct current rather than 220-volt alternating current. They have more insulation than domestic refrigerators to reduce their energy use. Energy consumption figures range from as little as 0.15 kWh a day up to 1.0 kWh, depending on the refrigerator size, the operating conditions, and whether a freezer compartment is included. A fairly typical figure is 0.3 kWh a day when the average ambient temperature is 32° C.

The requirements for vaccine refrigeration are rigorous. Most vaccines must be kept within a temperature range of 0° to 8° C to retain their efficacy. Freezing a vaccine can be as damaging as exposing it to high temperatures; in both cases, the vaccine is rendered ineffective, and worse still, if administered, it gives an illusion of protection. Refrigerators used for vaccine storage thus must meet the performance requirements with a reasonable margin of safety.

WHO/UNICEF produced a set of performance specifications for photovoltaic refrigerator systems. Among other requirements, they must be able to run for a minimum of five days when the battery set is fully charged and the photovoltaic array is disconnected; during this time the internal temperature must remain within the range 0 to 8° C, with an outside temperature of 43° C. Manufacturers are obliged to provide a replacement warranty of 10 years for the solar array, five years for batteries, and two years for the remaining components. The regulations also state that if other loads, such as lighting, are included in the system, they must operate from a separate battery set, not the one that supplies the refrigerator. The charge regulator should give priority to recharging the refrigerator batteries fully before shifting to those for the other loads.

Table 1.3 lists details of the 1993–94 WHO/UNICEF–approved component and system manufacturers. Complete system prices vary according to manufacturer and capacity and range from $4,000 to $10,000 free on board (FOB). The additional costs of transport and installation differ by location, but the installed cost can easily be double the FOB figure. Although attention is usually focused on the cost of the PV array, it is not generally the most costly element. The breakdown of costs in a typical PV refrigerator installation in 1991 was as follows: 28 percent for the PV array; 37 percent for the refrigerator; 24 percent for batteries; and 11 percent for accessories (Technet 1991).

Table 1.3 Typical WHO/UNICEF–Approved Manufacturer Costs for Vaccine Refrigerator Systems

System supplier	*Vaccine storage capacity (liters)*	*Modules*	*Batteries*	*Regulator*	*System cost (US$)*
BP Solar	38	BP	BP Solar (6P363)	BP	5,000-5,500
Deutsche Aerospace	14	Deutsche Aerospace MQ36D	Varta bloc Hoppecke OP2S	D.A. (BCR)	4,500-5,500
	56				7,800-9,500
Dulas Engineering	56	Siemens	Lucas VYA SA	Dulas	9,105-10,075
			Varta bloc		8,540-9,480
FNMA	27	Photowatt Siemens	Steco Chloride	Photowatt SCI	5,700-6,500
Naps	30-35	Siemens Kyocera	Tudor Sonnak	Naps	5,000-5,800
Photocomm	17.5	Kyocera (LA361S1)	IBE	Photocomm PCVI	3,000-4,000
	80				4,500-6,000
	30				6,000-7,000
Polar Products	80	Siemens	IBE	Polar Products	5,200-5,900
R & S International	14	R & S RSM 45	Anker bloc 3SGA200	R & S	4,000-4,500

Note: Components of solar refrigeration units provided by qualified system suppliers. Costs are typical FOB whole-system costs.

Source: Product Information Sheets 1993/94, WHO/UNICEF.

Experience with EPI programs demonstrates that the common claim that the higher capital costs of photovoltaic refrigerators are outweighed by lower running costs does not appear to be borne out in practice. Repair and maintenance costs typically account for about 35 percent of the life-cycle costs of photovoltaic refrigerators, leading WHO to comment that "the general feeling among most people that 'solar will cost almost nothing' should be combatted" (WHO 1991). Typical annualized costs per refrigerator were $800 to $1,000.

The need to employ repair and maintenance technicians with specialized skills and the cost of replacement components were the main reasons for these high operating costs. A review of EPI experience with vaccine refrigerators makes the following observations:

> In comparison to gas or kerosene refrigerators which are well known to a large number of technicians or handymen, solar refrigerators are more sophisticated and require electrical and electronic skills which are seldom available in rural areas of developing countries. (Zaffran 1992: 4)

Where PV refrigerators do not have to meet the rigid requirements of vaccine storage, major economies are possible. The amount of battery storage provided can be greatly reduced, and because the permissible range of temperatures can be wider than for drug storage, the insulation can be reduced to be closer to that provided for normal domestic refrigerators. It is important to be sure that such refrigerators are not used for the storage of medical supplies.

Battery Charging Systems

PV systems can be used to provide commercial battery-charging facilities for families using a car battery. The operating principles are exactly the same as those in other PV installations in which a battery is charged. The load control system, however, needs to be more sophisticated to ensure that the charging of each battery is properly controlled. The system also needs to incorporate its own battery to store electricity that would otherwise go to waste when the full charging capacity of the system is not being utilized.

System costs will vary greatly depending on the number of batteries charged, the local insolation, and the design used. Box 1.1 provides a sample costing of a system intended to charge a maximum of eight batteries a day requiring an average charge of 40 Ah each. A fairly sophisticated load control system is required to regulate the charge to each of the batteries separately without undue waste of electricity. A battery is provided to store some of the electricity at times when the insolation is high or the number of batteries being charged is below the maximum. With the assumptions shown, the average cost for each charge is $1.92.

Box 1.1 Indicative Costs of a PV Battery Charging System

Assume a maximum of 8 batteries charged each day.

Electricity output required = 320 Ah

Required daily input at 70 percent overall system efficiency = 457 Ah = 5,500 Wh.

Assuming 4.5 kWh/m^2 in the worst month, number of 50-Wp panels required = 25.

Item	Cost ($)
50-Wp panels, 25	12,500
240-Ah battery	300
Load control system	1,500
PV support structure, wiring, charging bay, fence, and so forth	2,500
Installation	2,000
TOTAL	18,800
Repair, maintenance, and attendance @ 10 percent	1,880
Assume 10 year overall system life	
Monthly amortization at 10 percent interest	165
Repair, maintenance, attendance	156
TOTAL MONTHLY COSTS	345
Total number of batteries charged per month at 75 percent utilization of system capacity, 180	
Cost per charge	$1.92

Source: Author estimates.

Centralized PV Systems

Instead of separate PV kits in individual households, centralized PV electrification systems or "power stations" have been installed in a number of villages in different parts of the developing world. These centralized systems generally have outputs in the range of 10 to 30 kWp. They are usually designed to provide a 220-volt alternating current supply through a village distribution grid. The power station itself consists of a large area of PV modules; a control room housing the electronic load controllers, inverters, and switch gear; a battery store; and a backup diesel generator.

Rather than bringing economies of scale, such centralized PV systems can bring significant diseconomies because of the elaborate load-control and inverter equipment, large battery store, and backup diesel required by a central supply system. The construction of a distribution system in the village, which is not required when individual household kits are used, is another additional and costly item.

In practice, the investment costs of these projects have been extremely high. The 9-kWp station at the village of Notto in Senegal commissioned in 1987 cost $250,000, a 35-kWp station at Kaw in French Guyana cost about $800,000, and an 8-kWp station on Utirik Island in the Marshall Islands opened in 1984 at a cost of $280,000.

Although the costs of these centralized stations are likely to have declined with progress in PV technology, their investment costs are still likely to be 10 times that of a diesel generator with a similar output—the diesel generator is, in any case, required as a backup. Their repair and maintenance requirements are far more specialized than those for diesel systems. Their inflexibility and the high marginal cost of increasing their capacity are also major problems.

That centralized PV systems closely mimic conventional electrification systems but are much more restricted in the loads they can carry has also been a major source of discontent to the people connected to the system—especially if they are paying significant amounts of money for their supply. Because of the close resemblance of the distribution system to that of a conventional electricity supply, consumers naturally expect a much greater freedom in their choice of appliances and equipment than they actually are able to enjoy.

2

The Rural Energy Background

About 2.5 billion people live in the rural areas of the developing world, of whom perhaps 800 million have electricity provided by a national power utility. Most of the remaining 1.7 billion people have only the slightest prospects of obtaining a grid connection within the next decade or beyond. Contrary to what one might assume, however, the world outside the reach of the electricity grid is far from one of passive energy deprivation. Rather, it is characterized by a complex and dynamic evolution of energy demands with time, economic development, fashion, and rising aspirations. These demands are met by local entrepreneurs and traders, who often respond with considerable ingenuity and initiative to the changes taking place in the energy market.

This chapter sketches this process of simultaneously evolving energy demands and supply systems in rural areas of the developing world that lack a formal electricity supply. This is the background against which the merits of interventions to promote the use of PV systems or implement conventional rural electrification programs must be judged.

The Energy Demand Ladder

The demand for energy is derived from that for the services it provides or makes possible. At the most basic level of subsistence, the only energy required is for cooking and keeping warm. In rural areas of the developing world, this energy is almost invariably supplied in the form of biomass fuels, generally wood gathered from the immediate surroundings without any cash payments. But as a family's economic circumstances begin to improve, and they emerge from this subsistence existence, additional and more diversified energy demands begin to surface, and these can only be satisfied by commercial energy sources.

One of the highest priorities for most families as their disposable incomes rise is better lighting than can be provided by an open fire. Improved lighting provides opportunities for extending the working day; for reading and leisure activities; and, above all, for children's homework. The hope that, through education, children will be able to achieve a better standard of living than that attained by their parents is a major preoccupation of rural families in most areas of the developing world.

As disposable incomes continue to increase, demands emerge for electricity-using devices such as radios, radiocassette players, and small black-and-white TVs. Further up the income scale, families want color TVs, video players, fans, electric irons, small power tools and kettles, refrigerators, and other household appliances.

Communities exhibit a similar pattern of evolution in energy demands. As economic development takes place, or expectations are raised by comparisons with other areas, local demands emerge for street lamps; for lighting in schools, community centers, and religious buildings; for pumped drinking water; and for the refrigeration of vaccines and drugs in health clinics. The energy demands of shops, bars, restaurants, workshops, and other commercial enterprises also change to reflect the growing sophistication of their activities and the customer demands they are meeting.

Meeting Lighting Demands

Small kerosene wick lamps are probably the most widely used form of domestic lighting among rural families. The lamp consists of a small metal container or glass bottle with a fabric wick; it provides poor quality light, has little if any capacity for adjustment, usually produces smoke and smell, and represents a constant fire hazard. The kerosene consumption of such lamps depends on the size of the wick but is generally low; one liter of kerosene may last for 50 hours or more in a small lamp.

Candles fit into roughly the same niche as the small kerosene wick lamp. Candles are used virtually everywhere throughout the developing world. Like small kerosene lamps, their light output is low. They also smoke, flicker, are easily blown out, and pose a major fire hazard. The advantage of candles is that they are more or less universally available and cheap. A typical manufactured candle can be bought for $0.05 to $0.10 and lasts for five to six hours.

The next step upward on the lighting scale is the adjustable-wick kerosene lamp with a glass chimney that shields the flame from drafts. These lamps range from the cheap, small, and primitive to large, sophisticated, and expensive devices. The light output and kerosene consumption vary according to the size and level of light output chosen—a liter can provide 20 to 30 hours of lighting in lamps of small to medium size.

The kerosene or gasoline pressure lamp (often referred to as a Petromax) with an incandescent mantle has a much better lighting performance than the wick lamp. This kind of lamp, however, is difficult to light and is extremely sensitive to water or dirt in the kerosene. It can also be dangerous to operate. Fuel consumption varies greatly depending on the size and make of the lamp and the level of lighting chosen; an indicative figure is about 10 hours per liter. The liquefied petroleum gas (LPG) incandescent lamp, which draws its fuel from a pressurized LPG container, works on the same principle and has a broadly similar lighting performance, but it is little used in the developing world.

Torches (flashlights), usually powered by two R20-size (also commonly referred to as D size) dry cells, are widely used by rural people for moving about outdoors or for intermittent indoor use. With the cheap zinc-carbon cells usually sold in rural areas, they only provide 2 or 3 hours of continuous light, but with "long life" cells they can produce up to 15 hours of light. Because of their cost, they are impractical as a main source of lighting for domestic activities, but they are a valuable complement to whatever other form of lighting is being used because of their portability.

Where a 220-volt electricity supply is available, the most commonly used form of lighting is the tungsten-filament lamp. This provides a convenient technical standard against which other lighting sources can be measured. Hung from a ceiling, a 60-watt lamp gives a level of lighting, technically defined as the illuminance, of 75 lux on a horizontal surface 1.5 meters below.

Fluorescent lamps provide an alternative to the tungsten-filament lamp. These are available in a wide variety of sizes and designs. An electronic ballast is required for the start-up of the lamp. The energy efficiency of a fluorescent lamp is four to five times that of a tungsten-filament lamp, and a 16-watt fluorescent lamp thus has a light output roughly equivalent to that of a 60-watt tungsten lamp.

Fluorescent lamps that can be run on 12-volt direct current are also widely available. They are usually in the range of 8 to 20 watts and require their own specially designed electronic ballast. They are widely used in leisure applications in the industrial countries—in caravans (recreational vehicles), for example, where they are run from a 12-volt battery charged by the car engine. In the developing world, they are commonly used with a car battery that is taken to a commercial recharging center for recharging. Low-voltage incandescent lamps are also available and can be run from a car battery; like their higher-voltage counterparts, they have much lower efficiency than their fluorescent equivalents.

Table 2.1 provides comparative data on the performance and costs of different lighting sources. The figures for luminous flux give the rate at which light is emitted from each device and are therefore a measure of its brightness. The useful illumination provided by each kind of lamp, however, depends not just on its brightness but also on how its light is distributed. One of the major advantages of electric lamps is that their light can be directed downward onto a book or working surface. The light from kerosene and LPG lamps, in contrast, is mainly upward and horizontal; the fuel container blocks out the downward light, creating a shadow below the lamp. Thus, even if they are providing the same luminous output, these lamps are much less effective in providing a good light for reading or working.

Table 2.1 Indicative Data on Various Lighting Sources

Lighting method	*Luminous flux (lumens)*	*Fuel consumption per hour*	*Fuel price (US$)*	*Lamp cost (US$)*	*Lamp life (hours)*	*Cost per hour (US$)*
Candle	12			0.10	5	0.02
Kerosene wick lamp	40	0.03 liter	0.50/ liter	5	5,000	0.02
Kerosene pressure lamp	400	0.1 liter	0.50/ liter	25	5,000	0.06
60-watt electric lamp	730	60 Wh	0.15/kWh	0.5	1,000	0.01
8-watt fluorescent lamp	400	10 Wh [a]		5.0	8,000	0.04
with 60-Ah car battery			1.00/ recharge	60.0 [b]	2,500 [c]	
Torch (2 R20 cells)	15	2 cells/ 2 hours	0.15/ cell [d]	1.0	1,000	0.15

[a] Includes the power consumption of the ballast.

[b] Car battery price.

[c] Comprises 50 recharges, each providing 50 hours operation.

[d] See discussion of dry cell batteries below.

Source: van der Plas (1988).

Table 2.1 also lists typical running costs for each of the lighting sources. These must be viewed with considerable caution, however. The variations in fuel and lamp costs, as well as in the size and performance of the various lamps, are extremely large, both between and within countries, and even among neighboring families. In a given rural area, both the absolute cost figures and the cost ranking of the various sources are therefore likely to differ substantially from those in the table.

Even where firm cost and output ranking figures are available, it is difficult to make meaningful economic or financial comparisons between different lighting sources. The problem is that the nature of the lighting service provided by each source is so different. For example, no one would attempt to match the 730 lumens output of a 60-watt incandescent lamp by using 60 candles or 18 kerosene wick lamps in a single room. Similarly, the light provided by a 60-watt incandescent lamp is much cheaper per lumen than that from a torch, but the incandescent lamp cannot be put in a pocket and taken outside.

The practical reality appears to be that people accept a level of lighting consistent with their financial means and the technical limitations of the sources available to them. As more effective sources become available and affordable, people adopt them and generally increase their level of lighting. Thus, when a grid electricity supply is available, families that previously used a single kerosene wick lamp may choose to have three or four electric lights in the house, with perhaps another outside (see, e.g., Peskin and Barnes 1994). Although the grid supply enables them to obtain a given level of illumination at a much lower cost, families may actually increase their expenditures on lighting.

Radios, Cassette Players, Videos, TVs, and Electric Appliances

An ever-widening variety of audiovisual equipment and other electrically powered appliances are becoming available throughout the developing world. As exports from low-cost countries such as China build up and commercial competition intensifies, falling prices ensure that the market for these goods continues to expand.

Small battery-powered transistor radios are now found virtually everywhere in the developing world. With power consumptions of a fraction of a watt, these are satisfactorily and cheaply operated with AA dry-cell batteries. The power requirements of radiocassette players are considerably greater; larger models require four, six, or even eight R20 (D) cells. Depending on the amount of time the equipment is used daily and the quality of the cells used, the cells may require replacement as often as once a week.

The numbers of people in the rural areas of the developing world within reach of TV programs are growing steadily as countries extend their terrestrial networks and the number of broadcasting satellites increases. Small black-and-white TV sets, suitable for use with a 12-volt direct current supply, are now readily available, and obtaining a TV is becoming an increasingly high priority for rural families and communities. Power consumption is usually in the range of 15 to 20 watts, which can be provided by a car battery. The power requirements of color TVs are considerably greater and cannot practicably be provided by a car battery. Even a small color set requires 50 watts; a larger model may use up to 150 watts.

Most other domestic appliances have much greater consumptions and are only available in 220-volt alternating current versions, although small tabletop fans with a power consumption of 10 to 15 watts can be obtained in 12-volt versions. An electric cooking plate typically uses 1 kW, as does an iron; an electric kettle uses 2 to 3 kW. Small electric power tools use approximately 500 watts, a medium-size domestic refrigerator 100 to 150 watts, and a freezer up to 250 watts.

The prices of color TVs, larger items of electronic equipment, refrigerators, and other household appliances are generally well beyond the range of most rural family budgets. But this is not necessarily an insurmountable barrier to obtaining them. Many rural families are given these appliances as presents by family members working in the cities or abroad. As a result, color TVs, video players, fans, irons, and refrigerators often appear with surprising rapidity even in quite poor homes once they are connected to an electricity supply.

Energy Demands of Commerce, Small Industry, and Communities

Energy demands of the commercial sector, small industry, and communities in the rural areas follow a broadly similar evolution to those of households as economic activity increases. Indeed, the activities of many artisans and small commercial enterprises are carried out in people's homes. In the small-business sector, improved lighting invariably has a high priority. Bar and restaurant owners are usually eager to use radiocassettes, TVs, video players, and fans to attract customers. Refrigerators make it possible to sell cool drinks. Other large-scale power uses such as grain milling, metal working, and crop processing emerge as markets for their output develop.

At the community level, street lighting has a high priority. The provision of community facilities for video and TV is also widely popular. Many village communities look for ways to provide lighting for community halls, schools, and religious buildings. Larger villages may be prepared to invest in pumped water supplies. As health center services expand, they need refrigeration and high-quality lighting.

The Importance of Electricity

Looking at the evolution of energy demands in the rural areas, one of its most notable aspects is the role and importance of electricity. Even at the lowest economic levels, just above subsistence, radios and torches can make a significant improvement in living standards and are widely used. The amounts of electricity involved are tiny, but are absolutely essential.

Proceeding up the scale of rising prosperity, electricity is increasingly required to provide the services people demand. The emergence of different, and more effective, means of meeting these evolving electricity demands is a key feature in the rural development process.

Small-Scale Private Electricity Supply Options

Three small-scale private supply options are used to meet electricity demands in areas without a utility supply. These are disposable or rechargeable dry cells; car batteries that are taken to a recharging center; and diesel or gasoline generators to produce electricity for people's own use or for sale through small commercial distribution systems.

Dry Cell Batteries

Dry cell battery manufacture is a major worldwide industry. The total dry cell output in the industrial world is estimated to be about 12 billion annually, and China alone had a reported total output of 3.8 billion in 1992 (Batteries International 1993). Purpose-designed rechargeable cells have been on sale for many years, and recently devices for recharging virtually all common cell types have come on the market.

Dry cells come in a variety of sizes and voltages. The AA and R20 (or D) sizes are the most commonly used in the developing world. These supply electricity at 1.5 volts and can be joined in series to provide higher voltages. They are used to provide power for flashlights, radios, cassette players, and other such devices.

Cells are of four basic types. The cheapest and lowest capacity are zinc-carbon, which have been manufactured since the beginning of the twentieth century. Although usually extremely cheap, they have a much lower capacity than other kinds. A major problem with these cells is their tendency to leak when discharged, which can damage equipment or appliances. In the industrial countries zinc-carbon batteries have generally been superseded by other varieties, but they are still widely manufactured and sold in the developing world.

Zinc-chloride cells have three or four times the capacity of the zinc-carbon cell. They are not nearly as prone to leakage, but they cost considerably more. Alkaline-manganese cells have two or three times the capacity of zinc-chloride and, again, are more expensive. The common advertising claim for alkaline-manganese cells that they last "six times longer" is based on comparison with the zinc-carbon variety.

Rechargeable cells, sold as such, are of nickel-cadmium. Their fully charged capacity varies widely and may be as low as that of the zinc-carbon type. They need to be used carefully to obtain satisfactory performance. Irreversible chemical changes take place if they are fully discharged or left in a heavily discharged condition. Self-discharge also tends to be a problem with these cells; some may lose up to 30 percent of their capacity per month when not in use. They are not particularly suitable for intermittent or low-drain uses, such as in small radios, where replacement is only required every few months. In principle, these cells can be recharged several hundred times; in practice, however, the number is more likely to be in the range of 15 to 35 charges before their performance begins to fall off seriously because of chemical changes within the cell (Batteries International 1993). This can nevertheless represent a significant saving over the purchase of throwaway cells.

More recently, devices for recharging ordinary alkaline-manganese and zinc-chloride cells have come on the market at about $50. Although initially condemned as dangerous or ineffectual by some of the major dry cell manufacturers, the devices appear to work satisfactorily. They cannot, however, recharge cells that have been fully discharged or left for a long time in a heavily discharged state. Like the purpose-designed rechargeable cells, the recharged cells are subject to a heavy self-discharge rate and need to be reused promptly.

At first consideration, commercial cell recharging—for example, by PV systems—appears an attractive option for rural families, but it has serious practical difficulties. Cells need to be recharged and reused promptly, which means that users cannot wait until a number have accumulated before going to a recharging center. Nor can the recharged cells be stored until required. Disputes over the condition of cells brought for recharging are inevitable. It would be difficult to make handling costs competitive with new-cell prices because cells would require a full day's recharging.

The ideal application for rechargeable batteries is where they are heavily used and can be quickly recharged and replaced. Somewhat ironically, they are best suited for households with an electricity supply to drive the charger, where the main benefit they provide is that the cost of running large radiocassette players or other heavily used portable electrical equipment is substantially reduced. Small PV-powered chargers for private use are available but irrelevant where mains electricity is available and of only limited appeal in rural areas because of their $20 to $30 cost.

Table 2.2 provides some broad comparative data on the capacities of different cell types, but such information must be viewed with caution. Large differences can be found among manufacturers, especially at the cheaper end of the market; production costs and selling prices can be reduced simply by using less active material in the cell. The length of time and the temperature under which cells are stored can also have a major effect on their performance.

Table 2.2 Typical Capacities and Prices of Dry Cell Varieties
(ampere hours and U.S. dollars)

	Zinc-carbon		*Zinc-chloride*		*Alkaline-manganese*		*Zinc-cadmium (rechargeable)*	
Cell size	*Ah*	*$*	*Ah*	*$*	*Ah*	*$*	*Ah*	*$*
R20 (D)	1.3	0.20	4.0	0.75	9.0	1.75	1.5	3.50
AA	0.2	0.10	0.80	0.30	1.8	0.60	0.6	2.00

Source: Batteries International (1993); various.

Sample prices are also given in Table 2.2, but major variations from those shown are likely, depending on the cell type, the country of manufacture, and the level of any import duties. In the case of zinc-carbon R20 cells retailing at about $0.20, the cost of the electricity provided is $100/kWh. Electricity from the other varieties, at the prices shown in the table, is in the range of $120 to $130/kWh; the higher capacities are accompanied by substantially higher prices, and the cheap zinc-carbon cells can represent the better value. Using the AA cells, the price of electricity is two to three times greater.

Car-Battery Recharging

Car batteries are widely used by rural families throughout the developing world to provide power for lighting, radios, cassette players, and small black-and-white TVs. They are recharged for a fee at a center where the electricity is obtained from a grid supply or a diesel generator. Recharging centers may also offer an arrangement in which a discharged battery is exchanged for a charged one, similar to the system used with LPG bottles.

The batteries are standard 12-volt car batteries with capacities in the range of 60 to 120 Ah. Many are secondhand and in poor condition. As noted earlier, car batteries are not designed for the deep discharge and recharge cycles common when they are used for domestic electricity supplies. Such use leads to progressive deterioration of the capacity of the battery, and its effective working life is unlikely to be more than about 50 cycles—about 18 months at three recharges monthly. Greatly improved performance can be achieved by carefully avoiding heavy discharges. Some families use two batteries so that one is always available while the other is being recharged.

One Zimbabwean battery manufacturer provides a recharging service that addresses the problem of excessive discharge and shortened life. Users purchase a purpose-designed 14-Ah battery with the understanding that, on payment of the recharging fee, they can swap their discharged battery for one that is fully recharged. The batteries are fitted with an indicator system that displays a green light when the battery is within the acceptable discharge levels. When it reaches the danger level, a red warning light comes on, but if the load is immediately disconnected the green light is restored. Failure to disconnect results in a permanent red light, which voids the recharge agreement.

The fee paid at battery recharging centers varies considerably but tends to be about $1.00. A survey of 10 developing countries found an average of $1.25 for recharging a 100-Ah battery (Meunier 1993). Similarly wide variations can be found in car battery prices, depending on the quality and country of manufacture. As a general rule, costs can be estimated at $1.00/Ah. Assuming a purchase price of $60 for a 60-Ah battery, with an actual average capacity of 45 Ah and a working life of one year with weekly recharges at $1.00 each, the cost of the electricity provided is $4.17/kWh.

Few statistics are available on the prevalence of the use of car batteries for domestic electricity supplies, but the practice is evidently common. In Sri Lanka, a purpose-designed system, known as the Prashakthi Unit, was developed by the National Engineering and Research Centre, and about 100,000 of these systems, which sold at $50, were estimated to be in use in 1987 (Fernando 1988); a recent estimate is that about 400,000 families use car batteries for their domestic electricity supplies (Gunaratne 1994). Surveys in Senegal found that car batteries were used by 2 percent of the villagers in one area and 32 percent in another; a study in Peru found they were used by 10 percent of the rural families in the area surveyed (Meunier 1993). A World Bank study of northern Yemen found that car batteries were used by about 10 percent of the rural population, a total of about 120,000 families (ESMAP 1991). Another World Bank study reported their widespread use in Kenya (Hankins and Best 1994).

Small Privately Owned Generators

Throughout the developing world, millions of small privately owned generators are running on diesel, gasoline, or LPG. They are used to provide electricity to households, small factories and workshops, businesses, bars, restaurants, hotels, schools, hospitals, health clinics, pumping stations, and a myriad of other users. They usually deliver a 220-volt alternating current supply and provide power for lights, TVs, power tools, electric appliances, pumps, grain mills, and many other applications.

Generator sizes range upward from a few tens of watts to hundreds of kilowatts, but those of interest here are in the range of 0.5 to 7.5 kW. Costs vary widely, depending on the country in question, the technical specifications of the generator, the quality of construction, and the accessories provided, but are generally in the range of $400 to $600 per kilowatt for diesel units and somewhat less for gasoline.

Energy efficiencies for the smaller generator sizes are about 15 to 20 percent, yielding a consumption of 0.5 to 0.6 liter/kWh of electricity produced. The working life depends on the quality of the unit and how well it is maintained, but about 2,000 hours is typical of the smaller gasoline units, while diesel units of 5 to 10 kW should have a working life of 5,000 to 10,000 hours. The electricity costs, including amortization, tend to be in the range of $0.30 to $0.60 but are highly sensitive to fuel costs, the working life of the generator, and the level and regularity of the load it delivers. Any realistic analysis of the likely costs of a particular installation must be based on the locally appropriate data.

In many villages and small towns, local entrepreneurs provide an alternating current supply through a local mini-grid at a nominal 220 volts to neighboring households and, sometimes, workshops or businesses. The service may be available throughout the day or confined to the evenings. The quality and reliability of the supply is generally low—sometimes very low. Total investment costs for each consumer range from $100 to $400 (Meunier 1993).

These systems are most commonly found in Asia, North Africa, and the Middle East. Where the supply is provided as an evening-only service to domestic consumers, metering is not done, and consumers pay a flat charge based on the number of lights used. Although the daily fee may be $0.10 to $0.20, the actual price paid by the consumer for electricity may be $1.0/kWh or more.

In Yemen, this method of supply is particularly common. The World Bank found that about 460,000 families, some 38 percent of the rural population, obtained their electricity from private village-level suppliers using diesel generators (ESMAP 1991). The average generator size was about 5 kW. The service was typically provided for five to six hours daily, and charges were usually based on the number of lights. In some cases, however, much larger systems were found in which a supply was provided to more than 200 households, and a fairly sophisticated billing system was used. The average price charged for electricity was about $0.60/kWh. A further 85,000 households used their own small petroleum or diesel generators, with an average consumption of 32 kWh/month.

A rural electrification review of Indonesia (World Bank 1986) found some 17,000 village electricity supply systems of varying, but generally low, quality. The report observed that the "facilities tend to be precarious and unsafe . . . outages are frequent and repair expenses necessitate additional contributions from the customers" (World Bank 1986). Yet despite their high economic and financial costs and the often poor quality of their supplies, such local suppliers are clearly meeting local needs. In many developing countries, however, this kind of electrification is legally prohibited because the national utility has a monopoly over electricity supplies to the public.

Family Expenditures on Energy

Family consumption patterns and expenditures on energy vary greatly among countries and income groups. They are heavily influenced by the local price and availability of fuels as well as by social customs and other factors.

Figures for kerosene consumption vary particularly widely. Collection and comparison of data for kerosene is difficult because it is used for both lighting and cooking in some countries; especially where it is subsidized, it may also be used as a diesel fuel extender. In areas where it is the main lighting fuel, typical consumption figures range from 3 to 7 liters per household each month. The use of dry cells shows similarly large variations. A poor family with just a small transistor radio may only use two or three AA cells monthly, but a prosperous family with a cassette player and several torches may use 10 or more R20 cells monthly.

Table 2.3 presents data from surveys of villages in two areas of Senegal. It lists average monthly expenditures on various forms of lighting, dry cell batteries, and recharging car batteries. The overall average expenditure in the poorer village was $8.35 a month, and almost twice as high in the richer villages. Figures from Zimbabwe show expenditures of about $1 a month for low-income families using candles and kerosene, rising to $5 a month for those also using car batteries (Zimbabwe Energy Programme 1992). Data from the Dominican Republic show much higher monthly expenditures at all income levels, with low-income families spending $2.5 to $5.25, middle-income families spending $4.10 to $14.85, and upper-income families spending up to $30 (World Bank 1993).

Table 2.3 Monthly Energy Expenditures in Nonelectrified Villages in Senegal

	Villages in the Fatick region		*Villages in the Dagana region*	
Equipment used	*Households using the equipment (percent)*	*Monthly expenditure (US$)*	*Households using the equipment (percent)*	*Monthly expenditure (US$)*
Candles	8	3.50	2	2.80
Kerosene lamp	99	3.94	97	6.80
LPG lamp	3	4.20	9	3.48
Generator	1	12.0	2	10.00
Dry cell batteries	92	4.12	99	7.24
Car batteries	4	6.44	32	7.08
Radios and radiocassettes	90		98	
TV	2		32	
Expenditure/month		8.35		15.70
Average monthly family income		65.77		148.03

Source: Meunier (1993).

Summary data on monthly family expenditures from about a dozen developing countries are presented in Table 2.4. The figures show an average monthly expenditure of $2.30 each month by low-income families using candles and simple kerosene wick lamps. The next income group, with more or better kerosene wick lamps, uses twice as much kerosene and twice the number of candles and has a monthly expenditure of $3.80. The next-highest income group uses more kerosene and candles and has an additional expenditure on dry cell batteries, for a total of $8.00 monthly. The highest income group, which uses car batteries in addition to its expenses on kerosene, candles, and dry cells, has an expenditure of $17.60 monthly.

Table 2.4 Monthly Expenditures on Energy by Typical Rural Families in Nonelectrified Areas

Socioeconomic group	*Energy-using appliances in use*	*Monthly consumption*	*Monthly cost (US$)*
Low-income	Kerosene wick lamp	3 liters	1.70
	Candle	4 candles	0.60
Total			2.30
Lower-middle income	Kerosene wick lamp	6 liters	2.80
	Candle	8 candles	1.00
Total			3.80
Middle-income	Kerosene wick lamp	9 liters	4.25
	Candle	10 candles	1.25
	Radiocassette player	8 R20 batteries	2.50
Total			8.00
Upper-income	Kerosene pressure lamp	16.8 liters	7.90
	Candle	8 candles	1.00
	Radiocassette player	10 R20 batteries	3.10
	TV and car battery	2 recharges	2.50
		battery amortization	3.10
Total			17.60

Source: Meunier (1993).

These energy consumption patterns and the related expenditure figures can only be regarded as broadly indicative; the precise local picture will need to be confirmed in each case. Nevertheless, the table clearly illustrates the relationship between the energy demand ladder and family income. As family income increases, energy use increases and diversifies. It is particularly noticeable that the electricity component in the total expenditure not only increases in absolute terms but also forms a larger proportion of the total expenditure of the higher-income groups. In the highest-income group, it accounts for about 50 percent of the total expenditure on energy.

3

Conventional Rural Electrification

The vast majority of rural families would gladly accept a grid-based electricity supply if it were available and they could afford it. Governments are well aware of these feelings and know that these sentiments are not going to diminish. The social and political pressures for conventional rural electrification are intense, and that is why virtually all developing countries have, at least, a minimal rural electrification program.

Rural Electrification in Practice

The national power utility is responsible for electrification in most countries. The process followed is usually based, at least in principle, on that used with evident success for national electrification in the industrialized countries: moving from large demand centers to smaller ones. That is, the large urban areas—where the returns are largest and the investment costs are smallest—are electrified first. Then, supply networks are gradually extended to the peri-urban areas, the provincial centers, and finally the rural areas.

Similarly, the definition of rural electrification changes as the national electrification process advances. In most of Sub-Saharan Africa and the poorer countries of Asia, the term *rural electrification* is still used to mean bringing a supply to sizable provincial towns where perhaps 10 percent of the local population will take a supply. In countries such as Thailand or Jamaica, where the national electrification process is much further advanced, rural electrification means bringing a supply to small villages or even isolated farmhouses.

When the costs of extending a grid connection to a rural demand center are deemed excessive, an isolated diesel generator is used to supply local loads. Other generating sources such as small hydroelectric generators can be used, but, in the vast majority of cases, a diesel generator is the chosen solution. Where security of supply is not of major importance, a single generator can be used and may only be run for four or five hours in the evening. When the generator is out of commission for maintenance or repair, consumers are simply left without a supply.

If security of supply is considered important, a group of generators is used. This provides backup capacity when a generator is withdrawn from service. It also allows the generating capacity in operation at any given time to be matched more closely to the load on the system. This improves the efficiency of operation and reduces the fuel cost for each unit generated. As demand builds up, these local grids are extended into the surrounding areas. When the total demand reaches a level that justifies the cost, the subsidiary grid is connected into the main national or regional grid.

This progression from urban areas of maximum return and minimum cost to remote rural areas of minimum return and maximum cost makes both financial engineering sense. When it is time for the remote rural areas to be electrified, a large body of urban and industrial consumers are already paying their bills, and any cross-subsidies required to finance rural electrification can be widely spread and thus held to an acceptable level.

The ultimate objective in conventional electrification is to unify the country in a single grid or in a small number of integrated grids. This brings economies of scale in generation, distribution, and management of the system. Because the load is met by a series of linked power stations, the security of supply at the national level is increased. Once the national network is in place and operating properly, individual consumers will have a system that is, in effect, infinitely flexible in responding to their demand—that is, no supply constraints will limit their use of whatever household appliances they can afford to obtain.

Of course, this description of the national electrification process represents an ideal; electrification does not always proceed that way in practice, and in developing countries it often is far from optimal. In particular, rural electrification is notoriously subject to interference by politicians attempting to win favor with particular constituencies. As a result, grid extensions and isolated household connections may be provided in many areas where there are few technical or economic reasons for doing so. Moreover, the service provided by the utility does not always reach acceptable standards. Although many electricity utilities in the developing world are competent organizations that provide satisfactory and reliable supplies to their customers, many others are badly or corruptly run—to the point where the theoretical advantages of connection to the grid are virtually nullified by the poor quality and unreliability of the supply provided.

Experience has also shown pitfalls in the use of isolated diesel systems. Although some such systems are well maintained and function properly, others—particularly when they are dependent on poorly trained and undermotivated operational and maintenance personnel—have only a short working life before they break down irretrievably. Inability to obtain year-round fuel supplies can also result in an unreliable service, often with prolonged periods without any power. In Ethiopia and Mozambique, for example, the national power utilities are so hard-pressed for foreign exchange that the operation of isolated diesel systems has to be restricted for budgetary reasons.

Costs of Conventional Grid-Based Rural Electrification

The costs of conventional grid-based rural electrification vary greatly, both among and within countries. Local material and labor costs, the terrain, and the materials and construction standards adopted can all have a major effect on the overall construction and maintenance costs. All generalizations must therefore be viewed with caution, and practical policy decisions should always be based on verified local costs.

Line construction typically accounts for 80 to 90 percent of the expense of a rural electrification project. The cost of lines of medium or low voltage can be up to $20,000 per kilometer, especially in some Sub-Saharan African countries, but very much lower costs are reported elsewhere. One report cites a typical cost of 15-kilovolt (kV) line of $6,600 per kilometer in Yemen (ESMAP 1991). On the other hand, the electricity utility COPEL in Brazil quoted a mid-1980s figure of $3,500 per kilometer for 8-kV, single-phase distribution lines and as little as $1,500 per kilometer for 20-kV single-wire earth return lines (Dingley 1988).

Once the line construction costs have been established, the main determinant of the connection cost per consumer is the average number of consumers per kilometer of line. In areas of low population density, this may be five connections per kilometer or less. In Bangladesh, in contrast, where rural population densities are among the highest in the world, one of the criteria for providing a rural electrification service to an area is a minimum of 75 consumers per kilometer. Since the electricity authorities permit side connections to nearby houses, the average number of consumers may be 150 per kilometer or even more.

The average cost for each consumer connected is generally in the range of $400 to $600 in the densely populated countries of Asia. In North Africa, the costs are usually in the range of $1,000 to $1,200, but they can be considerably higher; for example, a study in Algeria in 1984 found the cost for each rural consumer was $1,675. Costs of $3,000 or more per consumer are reported in some areas. In thinly populated areas of Latin America and Sub-Saharan Africa, the distances are so large and the numbers of potential consumers so low that conventional rural electrification is prohibitively costly even for upper-income countries.

Table 3.1 provides two examples of the costs involved in providing a grid supply to a village with 50 consumers, each using 25 kWh monthly. The actual figures come from Pakistan and Yemen and show overall costs for each connection of $1,060 and $1,325, respectively. The distribution of the costs among the different elements is informative and significant. In both cases, about 70 percent of the costs are accounted for by the 11-kV feeder line. The cost per consumer is therefore extremely sensitive to the number of consumers. This number can be increased easily, and at a low marginal cost, once the main feeder line to the village is in position. The only additional capital investment required in the supply infrastructure as the number of consumers rises is a small transformer and the necessary distribution lines for each group of 25 consumers. This works out to about $200 for each consumer in the case shown. Whether prospects are realistic for significant growth in the number of consumers is therefore a critical aspect of the assessment of any such rural electrification project.

Table 3.1 Breakdown of Costs of Grid Connections in Pakistan and Yemen

Assumptions/system elements	*Pakistan*		*Yemen*	
	Quantity	*Unit cost*	*Quantity*	*Unit cost*
11-kV line	10 km	$3,870/km	7 km	$6,600
15-kVA transformer	2	$925	2	$900
Distribution lines		$4,620/ transformer		$4,000/ transformer
Number of consumers	50		50	
Consumption/consumer	25 kWh/month		25 kWh/month	
Annual maintenance cost		2% of investment		2% of investment
LRMC of electricity		0.087/kWh	$0.10	
Life of installation	25 years		25 years	
Discount rate	10%		10%	
Total investment cost		$53,000		$66,250
Connection cost per consumer		$1,060		$1,325
Cost/kWh (exclusive of lighting equipment)		$0.58/kWh		$0.76/kWh
Annualized cost of system		$167/consumer		$201/consumer

Source: Meunier (1993).

Similarly, the costs for each delivered kWh of $0.58 and $0.76 shown in the table are sensitive to the total consumption level. Here again, once the system is in place, increased consumption would not be restricted. For practical purposes, an 11-kV feeder line and a 240-volt domestic connection would remove any supply constraint on consumption at the village or the individual household levels. If the consumption of each household doubles from its initial level of 25 kWh a month over 10 years, for example—a common, indeed likely, occurrence in many places—the cost per kWh falls by about 40 percent in both cases. The introduction of a few small industrial loads such as grain milling would have a similar major impact on the average kWh cost.

Viewed in terms of the service provided to the individual household and the community, the grid connection offers the maximum degree of flexibility. Householders can use as many lights and appliances as they wish; the only restriction is their ability to pay for them and settle their monthly bills. Similarly, at the community level, no problem would arise in meeting the demands of local businesses, small industries, or community services.

But before citing such flexibility as a reason for providing grid supplies to a particular area, it is important to ensure that the load-growth projections are credible.

Numerous rural electrification schemes have been justified by overoptimistic load projections that failed to materialize. Where the likelihood of significant increases in consumption is small, the additional flexibility provided by the grid is irrelevant. Realistic load forecasting thus is central to the rational planning of grid-based rural electrification.

Costs of Decentralized Diesel-Generated Supplies

Where a load center, such as a provincial town or large village that is to be electrified is too far from the grid to be served economically, the utility generally constructs a local grid that is supplied by a diesel generator. The cost of the electricity supplied by such grids varies widely depending on the size of generator, the number of consumers, the consumption per consumer, the efficiency of operation, and several other factors. In general, the bigger the generating plant, the larger the number of consumers, and the higher their consumption, the lower the unit costs. As a general rule, a delivered electricity cost of $0.20/kWh, including fuel and depreciation, is possible under good conditions. In practice, the figure is generally higher, and it frequently reaches $0.40/kWh or more. Data from Niger, for example, show an average of about $0.60/kWh for isolated systems serving seven small provincial centers with 300 to 1,000 customers each.

Table 3.2 presents a breakdown of average costs for small installations in Pakistan and Yemen. As can be seen, the costs for each connected consumer, about $300 in both cases, are considerably lower than those for the grid systems in Table 3.1, as are the annualized costs and the cost per kilowatt hour (Meunier 1993). It is also worth noting that both of these diesel systems, under the conditions shown, are operating at a small fraction of their output capacity. A variety of daytime loads as well as additional evening consumption could be accommodated at no additional investment cost. If, for example, a doubling of the average consumption per customer were to occur, it would cause the delivered electricity cost to fall to $0.25 to 0.30/kWh.

As in the case of the grid connection, the service provided by the diesel system offers a high degree of flexibility for households and the community. There is effectively no technical constraint on the appliances that can be used or on the total monthly consumption at the individual household level.

At the aggregated village level, however, a buildup of load will require additional diesel generating capacity. This can be provided by adding diesel generators or replacing existing sets with larger units and using the old ones elsewhere. The marginal costs of expanding the system are therefore higher than in an area supplied from the grid. For this reason, and because the kilowatt hour costs on the grid are generally lower than those of isolated diesel systems, the system may reach a crossover point at which it becomes more economical to connect the local system to the grid rather than expand it as an independent entity.

Table 3.2 Breakdown of Costs for Small Diesel Supply Systems in Pakistan and Yemen

Assumptions/system elements	*Pakistan*		*Yemen*	
	Quantity	*Unit cost*	*Quantity*	*Unit cost*
Number of consumers	50		50	
Consumption/consumer	25 kWh/month		25 kWh/month	
Diesel generator cost		\$400/kW + \$160		\$450/kW + \$200
Fuel cost		\$0.173/liter		\$0.22/liter
Civil works		\$580		\$1,000
Distribution network		\$2,900		\$2,500
Repair and maintenance		10% of investment cost/ year		10% of investment cost/ year
Annual operating costs		\$700		\$740
Life of generator	8 years		4 years	
Interest rate	10%		10%	
Connection cost		\$52/consumer		\$52/consumer
Size of diesel generator		20 kW		20 kW
Daily operating time		6 hours		6 hours
Daily production		40 kWh		40 kWh/day
Annual fuel consumption		7,116 liters		7,116 liters
Investment cost		\$285/consumer		\$306/consumer
Cost/kWh		\$0.35/kWh		\$0.51
Annualized cost of system		\$105/consumer		\$151/consumer

Source: Meunier (1993).

Importance of Load Patterns

In addition to the average load per consumer, the pattern of electricity demand affects the delivered electricity costs in both grid and decentralized supply systems. In an ideal situation, daytime and evening load are more or less uniform, providing a high degree of utilization for the supply and distribution system.

In many low-income rural areas, however, the load pattern shows a high evening peak because daytime commercial activity is minimal, and the main load is thus domestic lighting. The result of this kind of heavily peaked load pattern is that much of the generation and distribution capacity is idle most of the time. This increases the cost for each unit supplied and reduces the chances of realizing an adequate rate of return from the investment in the system.

The efficiency of diesel generators is also affected by variations in the load supplied. In the case of a grid with a high evening peak, the efficiency of the generator when supplying the small daytime load falls to half or less of its efficiency at full load. This again increases the overall running costs of the system. Many local grids therefore operate only in the evenings. If daytime commercial loads begin to emerge, a choice emerges between extending the hours of grid service or relying on consumers to purchase their own generators to meet the new load.

Rural Household Electricity Consumption

Household electricity consumption shows large local and international variations, as is the case in most features of rural energy use. These variations are broadly related to income. Families with higher disposable incomes tend to consume more electricity. The length of time a family has had a connection also has an effect—family consumption usually grows with time. Consumption may also be significantly affected by costs, climate, culture, reliability of supply, and a variety of other factors. In some countries, for example, the utility sets such high building construction and house wiring standards for new consumers that electricity supplies are effectively restricted to upper-middle-class families who are likely to use a wide variety of appliances once they have access to the electricity supply. Other countries apply few such restrictions, and utility supplies are open to anyone who can afford the connection fee. This admits many poor families whose consumption is likely to be restricted to lighting.

Where lighting is the only significant use of electricity, monthly consumption tends to be in the range of 10 to 20 kWh monthly. Two 40-watt incandescent bulbs used for five hours each night, for example, have a monthly consumption of 12 kWh. A radiocassette player and a small fan can be used for 10 hours each day for an additional consumption of 10 to 15 kWh per month. A small color TV used for 6 hours a day will add a further 10 kWh a month. A family could accommodate all these uses, as well as that of an electric iron, within a consumption range of 50 to 60 kWh monthly.

The use of appliances with greater energy requirements pushes consumption up considerably. A refrigerator uses about 50 kWh and a freezer around 100 kWh monthly. Cooking, depending on the method used and the type of meals cooked, can use from 10 kWh up to 50 kWh each month. Water heating and, above all, air conditioning bring much higher consumption levels.

Table 3.3 provides a detailed breakdown of rural electricity consumption in the Philippines by end use and income group. It is based on an ESMAP (1992) survey of a total of 2,500 rural households and lists typical monthly consumptions by end use for consumers with particular appliances. It also gives a breakdown of the average consumption of the five income groups. In general, it shows that for each end-use, consumption increases with income. It also shows that some end uses—such as freezers, water heating, and air conditioning—are entirely confined to the upper-income groups. The bottom line of the table shows the average total consumption for each income group, ranging from 17 kWh monthly for the lowest up to 69 kWh monthly for the highest.

Table 3.3 Electricity Consumption by End Use and Income Group in the Philippines

(kilowatt hours)

	Monthly consumption by income group quintile					
End use	*First*	*Second*	*Third*	*Fourth*	*Fifth*	*All*
Lighting	12	14	27	16	20	19
Ordinary refrigerator	37	31	42	42	49	46
Freezer	n.a.	n.a.	n.a.	34	98	88
Black-and-white TV	5	7	8	6	6	6
Color TV	8	2	8	8	10	9
Air conditioner	n.a.	n.a.	n.a.	n.a.	233	233
Iron	5	5	8	11	11	10
Fan	5	4	5	6	8	7
Cooking	n.a.	13	16	21	45	35
Water heating	n.a.	n.a.	n.a.	13	20	19
Water pumping	n.a.	n.a.	8	24	22	21
Washer	n.a.	n.a.	n.a.	n.a.	16	16
Other	3	3	11	3	5	5
All uses	17	19	45	36	69	44

n.a. = not applicable.

Source: ESMAP (1992).

Although similar surveys in other countries will reveal considerable local differences in the total consumption figures and how they vary among income groups, the broad patterns are likely to be similar. It would certainly be expected that the tendency for higher-income families to have more end uses and to consume greater amounts of electricity would be repeated.

Criteria for Rural Electrification

A detailed discussion of the criteria for the selection of areas for rural electrification is outside the scope of this report. Nevertheless, it is useful to provide a broad outline of the areas that hold the greatest promise for the utilities' main rural electrification efforts. Under ideal circumstances, it is these areas that should receive priority because they are the most likely to benefit from a grid supply and to provide a reasonable return to the utility.

In a well-known paper, the World Bank (1975) suggested that the following indicators will provide a guide to areas suitable for rural electrification programs. The list is still valid:

- The quality of infrastructure, particularly of roads, is reasonably good.
- Agricultural output is growing.
- Evidence indicates a growing number of productive uses in farms and agroindustries.
- An area contains a number of large villages, not too widely scattered.
- Income and living standards are improving.
- Plans are in progress for developing the area.
- The region is reasonably close to the main grid (if the demand is particularly strong, remote regions may be considered, too).

The World Bank suggested that the financial goals of programs should be to cover operating and maintenance costs "quite comfortably" during the first three or four years; from this point to the tenth year, they should be able to service the debt of the program; and thereafter they should show a surplus that would enable them to make an increasing contribution to the costs of expansion.

When all these conditions are met, programs will usually succeed socially as well as meet, with some luck, their financial targets. At the beginning, a reasonably high proportion of the population in the area being electrified will take a connection. In the years after the completion of the program, an expanding number of families will take a supply. Many consumers will find new uses for electricity, so their consumption will continue to increase. Commercial and industrial consumers will make investments that depend on the availability of electricity, and new productive enterprises that rely on the use of electricity will be launched.

Each country can draw up its own criteria to the kind of area in which rural electrification is likely to be justified. It can also set out minimum acceptable financial and economic rates of return for the programs. These steps make it possible to choose rationally among areas to be electrified, to set priorities in the rural electrification plan, and to decide whether individual projects are justifiable or not.

In the Philippines, for example, the National Electrification Administration insists that projects by local rural electric cooperatives should be able to show a minimum 15 percent economic internal rate of return and be financially viable, taking loan repayments and operating costs into account. Relatively high tariffs, typically $0.12 to $15/kWh, low costs of grid extensions and distribution systems, and high numbers of consumers make it possible to electrify areas where the majority of loads are less than 20 kWh/month and still meet these criteria. Other countries, particularly in Sub-Saharan Africa, have much lower tariffs, higher construction costs, and far lower consumer densities. Under those conditions, it is much more difficult to find financially justifiable programs.

In Indonesia, a two-step planning process is used to select villages for electrification. An initial screening—based on such factors as the level of economic development in the village, its distance from the nearest grid connection point, the existing installed generating capacity, and the pattern of settlement—is used to select and rank villages in order of priority for electrification. The final selection is then made in discussion with regional government authorities (ASTAE 1995).

The overall financial position of the utility is another important consideration. The weaker the financial state of a utility, the more important it is to focus its rural electrification efforts on areas where a reasonable financial rate of return can be obtained. If this is done, as the network builds up and the number of profitable consumers increases, it eventually becomes possible to relax the electrification criteria on social and equity grounds and provide electricity to the financially less rewarding areas. If, on the other hand, utility resources are expended in the early stages on electrifying areas where an adequate rate of return cannot possibly be achieved, the utility becomes progressively weakened financially, managerially, and operationally, and the overall progress of rural electrification is jeopardized.

Slow Pace of Implementation of Conventional Rural Electrification

The technical merits of a grid supply, as well as the consumer benefits it brings, are evident. Equally obvious is the greatest limitation of the approach: The overall rate at which it is taking place is barely keeping pace with population growth.

Table 3.4 shows World Bank figures for population and rural electrification in the developing world between 1970 and 1990. Although it can be seen that the proportion of the rural population with an electricity supply has increased from 18 percent to 33 percent, the total numbers without a supply are just as great in 1990 as they were in 1970. Thus, despite major rural electrification efforts, and despite significant progress, hundreds of millions of rural people face only the remotest prospects of obtaining an electricity supply within the next decade or more.

Major variations can be found within these global totals, however. Table 3.5 shows that in a number of Asian countries—such as Malaysia, Thailand, the Philippines, and China—rural electrification has reached an advanced stage. For most of the other countries listed, the proportion of rural people connected is much lower. In India, for example, although massive rural electrification investments have been made since the early 1970s, and about 80 percent of villages have been connected to the grid, the proportion of households with a supply is just 22 percent.[2] In Bangladesh, which also has made major investments in its rural electrification program, the proportion of connected households is still only about 5 percent (the foreign exchange already invested or committed to the rural electrification program in 1988 amounted to about $378 million).

---

2. In the period 1976–84, the World Bank provided a total of $537 million in rural electrification loans, and USAID provided $189 million.

Table 3.4 Rural Electrification and Population Data (millions)

Population	*1970*	*1980*	*1990*
World	3,635	4,428	5,267
Developing country	2,543	3,185	3,919
Developing country, rural	1,929	2,287	2,482
Percentage with electricity supply, rural	18	25	33
Number with electricity supply	340	573	807
Number without electricity supply	1,589	1,715	1,663

Source: IENPD (1995).

Table 3.5 Proportion of Rural Families with an Electricity Supply, Selected Countries

Country	*Year*	*Rural population electrified (percentage)*
Asia		
Bangladesh	1988	5
China	1990	78
India	1988	22
Indonesia	1990	21
Malaysia	1990	80
Philippines	1993	51
Sri Lanka	1988	25
Thailand	1990	72
Latin America		
Costa Rica	1986	74
North Africa		
Jordan	1985	82
Morocco	1987	14
Yemen	1986	5

Source: Meunier (1993).

Even in countries with high levels of rural electrification, the absolute numbers without a supply are large. In Thailand, for example, some 1,000 to 1,500 villages are officially recognized as being outside the scope of the country's rural electrification program because of their remoteness or inaccessibility. In the Philippines, 51 percent of the rural population have a supply, which means that some 18 million rural dwellers do not. In the western provinces of China, with a population of 100 million, some 25 million are not expected to receive grid electricity even in the long term.

In most of Sub-Saharan Africa, rural electrification is at an early stage. The rural electrification efforts of the national electricity utilities in most countries are almost entirely concentrated on supplying provincial towns, where connection rates are usually 10 to 15 percent. Electricity supplies for small villages or individual rural households in these countries are not even under consideration. The ambitious national rural electrification program in Ethiopia, if implemented, would bring supplies to about 4 percent of the rural population by the year 2011. Similarly, a seminar on rural electrification in Mozambique, Tanzania, Zambia, and Zimbabwe found that rural electrification was virtually at a standstill in all four countries because of lack of funding (SEI 1993). Worse still, in some cases—The Gambia, for example—lack of funds has meant that rather than expanding, the existing rural supply system has been deteriorating and effectively contracting.

4

Identifying the Niche for Photovoltaics

The potential niche for PVs in the rural areas of the developing world can be simply defined; it is where satisfactory grid supplies are not available and are unlikely to be available within the next 5 to 10 years. The size of the niche is thus about 300 to 400 million households. But this is a purely theoretical figure that takes no account of the problems, limitations, and priorities of the real world. Identifying a practical niche for PVs means identifying the range of applications for which PVs are technically suitable, affordable for their potential users, and the least-cost solution compared with all the relevant alternatives.[3]

PVs versus the Grid

Much attention has been given to financial and economic comparisons between PVs and grid-based power. It has been demonstrated numerous times that running an 11-kV line a distance of 10 kilometers to provide a village with electricity for lighting is far less cost-effective than supplying the same load with PV household kits. But it does not necessarily follow that the PV solution is therefore justified or practicable or that PV systems are affordable or attractive to potential users.

The service provided by PVs is more limited than that provided by the grid in that PVs are essentially confined to lighting, with a few additional low-load uses such as cassette players or small TVs used for a few hours in the evening. PVs are appropriate here because they are free-standing; a long grid extension makes neither economic nor technical sense for such small loads, unless consumer density is extremely high. If a grid extension is provided where the density is low, the cost of the electricity will far exceed what can be recovered with locally acceptable tariffs, and the grid extension cannot be justified economically. The same arguments apply to isolated grids supplied by diesel

3. PVs have a variety of well-proven uses in providing power for telecommunications, remote signaling, and other such applications. These specialized uses, in which security of supply generally takes precedence over cost and the technically qualified staff of the implementing agencies are available for repair and maintenance, are not considered here.

generators; if the loads could be adequately supplied by PV systems, the diesel supply is almost certain to be economically unviable.

Where a genuine prospect of substantial load growth exists, however, the grid connection is technically the ideal way to provide electricity. Once the main feeder line is in position, no significant constraints remain on the number of consumers that can be connected or the loads they can impose on the system. The grid connection, therefore, opens the possibility of substantial growth in domestic, commercial, and small industrial consumption of electricity at low marginal costs. Hence, where it is economically justifiable, the grid is the first-choice option, and PVs are not likely to be competitive. It might even be taken as a rough guiding principle that the two options are sufficiently different to be mutually exclusive. Thus, the proper role of the grid extension is to provide electricity to areas where a substantial load already exists or is likely to develop in the reasonably near future. PVs are not a technology of choice here because they cannot provide the level of service required in such areas.

The present-day limitations of PVs are accurately, if rather irreverently, portrayed in one of the papers from a recent photovoltaic conference. Describing a rural consumer with a PV system, the paper asks:

> What does the solar "customer" get in this deal? A limited time of use every day for the few lamps he has. Affordable DC appliances? If he finds more than a black and white TV, radio cassette and a car ventilator he is lucky indeed. His city comparison usually has a color TV, a mixer, an electric iron, and even a fridge. . . . It is not much that the guy from the village sees in the workshop of his brother in the town: a drill, a grinder, maybe an old air compressor. But even those few things are still ages away from his new and modern PV installation. . . . So all is gloom? We might as well give up on PV electrification? Of course not; this paper just wants to stress the need to clearly identify the problems, set priorities, and admit the limitations of the PV technology presently available. (Kusche 1994: 1991)

Any neat division between areas in developing countries that are suitable for grid supplies and those that are not is largely vitiated by lack of investment funds, financially and managerially weak utilities, and a variety of other factors that are preventing the extension of electricity networks, even into areas where they are economically fully justified. This problem is especially apparent in many urban and peri-urban areas. Although such areas should be natural priority targets for expansion of the electricity supply, the run-down condition of the distribution system, lack of generating capacity, and shortage of funds mean they will not acquire a supply for years, or even decades. Although the grid connection may represent the technical and economic optimum, it may not reach many places for a considerable time.

Another factor indicating the need for care in assessing the kind of electrification that is most appropriate is the fact that in many regions the quality of grid supplies provided is extremely low. Breakdowns in generating equipment and distribution systems mean that supplies are only intermittently available. Reductions and fluctuations in voltage are so severe that customers either cannot use equipment or run the risk of having it damaged. Where such problems are already evident or are likely to be prevalent if the grid is extended, the attractions and advantages of connection to the grid are greatly diminished. Under these conditions—when the utility is unable to provide a grid supply or its quality is unacceptably low—people have to meet their energy needs as best they can from the sources available. PVs may be one of the options available. The question for energy consumers is whether PVs are preferable to nongrid alternatives.

Another possible niche for PVs is where, for social or political reasons, utilities are providing electricity supplies to areas in which these are not economically or financially justified. This lack of economic or financial justification may be the result of national tariffs that are set below the necessary level, or a relationship between the costs and likely load in an area that makes it fundamentally uneconomic to serve it with the grid. In both cases, providing PV kits to households may be a less uneconomic option for the utility. The question will then be whether it is technically and institutionally feasible, as well as acceptable to consumers.

The Pre-Electrification Concept

The term *pre-electrification* is sometimes used to describe the use of PVs to supply electricity to an area in advance of full grid electrification. Pre-electrification, in this sense, is not seen as a substitute for a full-scale conventional supply but as a complementary or interim approach. The idea is that it may meet small electricity demands in an area at a stage when providing a grid connection is not economically justifiable. In time, the people in the area can proceed to a full-scale grid supply.

Pre-electrification is something of a misnomer, however. The process envisaged is one of real, although limited, use of electricity. The question is whether, as conventionally assumed by advocates of the approach, the promotion of PVs as a preliminary form of electrification helps or hinders the move to a grid supply.

One of the problems with PV pre-electrification is that once a household has made its investment in a PV system, the type and magnitude of the electric load that can be supplied is largely fixed because of the high marginal cost of providing additional capacity. Even with increased capacity, the use of conventional appliances such as electric irons, kettles, cookers, power tools, and color TVs is excluded. If a grid supply becomes available, the PV panels, support system, battery, and load controller, which together account for around 80 percent of the cost of the installation, are no longer relevant. The investment in the PV system therefore does nothing to build up a conventional electricity demand. It also does not make families more able or willing to invest in a grid connection when it arrives, since doing so involves scrapping the greater portion of their investment in the PV system.

At the commercial level, the use of PV installations, however common, does not act as a first step toward large-scale productive electricity uses such as grain milling, metal working, or other small industrial or artisanal activities. Indeed, it can be argued that a large-scale investment in the provision of PVs in an area will slow rather than advance conventional electrification because it absorbs a large amount of the available investment capital for infrastructure. Some commentators have even alleged that PV electrification retards the development process itself:

> First, the community can no longer expand demand to new processes, locations and applications at low marginal cost. The market cannot rationally increase or be allowed to increase beyond the volume indicated by the high marginal cost of a photovoltaic system. Second, the installation of photovoltaics has pre-empted classical development. . . . The village is trapped at a subsistence level of electricity consumption. (Lucas; no date)

Although this undoubtedly overstates the case in relation to solar home systems (SHSs), it points to a real danger if a centralized, village-level PV power station is being considered. It must also be kept in mind if large-scale government or donor investments are being considered in the provision or subsidization of PVs for social purposes. Although some degree of salvage of sunk costs may occur, investments in PV pre-electrification are highly unlikely to be repaid by savings in the subsequent costs of providing a grid supply.[4] The value of PV systems lies in the immediate satisfaction of small-scale electricity demands they provide. It is on this basis—in their own right rather than as a step toward a quite different form of electricity supply—that PV programs need to be considered.

Where Do PV Systems Fit?

PV systems provide small amounts of electricity. Finding where they fit in the provision of rural energy supplies involves identifying where such amounts of electricity are required to provide the services that rural people demand.

Solar Home Systems

In rural areas without an electricity supply, people use candles, kerosene, and car batteries to provide the lighting and other services they want. Most, if not all, of these demands can also be met by using SHSs.

---

4. In Sri Lanka, suppliers buy back modules at prorated prices if the user obtains a grid connection. Similarly, in Indonesia, a secondary market for PV modules and controllers has emerged. Rural electrification cooperatives in the Philippines rent the modules and controller to the consumer and use them elsewhere when a grid connection is provided. PV owners in the Dominican Republic have kept their PV systems operational for their TVs because of the poor quality of grid supplies (M. Cosgrove-Davies, personal communication, 1994).

Table 4.1 breaks down "typical" expenditures on kerosene, dry cells, and battery recharging by rural socioeconomic group with the monthly amortization payments that would be payable on a range of PV household systems. The data on the household expenditures come from Table 2.4, where they are discussed in detail; the monthly amortization figures for the PV systems are taken from Table 1.2. The intention here is not to provide a definitive statement on the commercial competitiveness of PV systems in each case but rather to obtain a broad impression of how their cost and level of service compare with what is happening at present in each socioeconomic group.

Table 4.1 Comparison between "Typical" Family Expenditures on Energy and Monthly Amortization of PV Household Systems (U.S. dollars)

Socioeconomic group	*Appliances*	*Monthly expenditure*	*PV system*	*Price*	*Monthly amortization*[a]
Low-income	Kerosene lamp Candles	2.30	Lantern	70	1.49
Lower-middle-income	Kerosene lamps Torch	3.95	20 Wp	300	4.42
Middle-income	Kerosene lamps Radiocassette Torch	8.00	50 Wp	750	10.81
Upper-income	Kerosene lamps Radiocassette Torch TV and car battery	17.6	100 Wp	1,500	18.98

[a] At 10 percent; lantern life, 5 years; other systems, 10 years overall life; 5-year life for batteries.

Source: See Tables 1.2 and 2.4.

The most interesting point revealed by the table is that the PV systems are generally financially competitive in providing the services demanded in each socioeconomic group. This is a considerable change from even a few years ago. But again, the figures must be viewed with caution—they certainly do not apply in all countries because of the wide variations in prices and expenditure patterns. It also must be borne in mind that the amortization payments are somewhat artificial because payments for PV systems are rarely spread over 10 years. Where credit schemes are available, the repayment period is more likely to be 3 years, at an interest rate considerably higher than 10 percent.

Other practical considerations come into play when comparing the existing costs incurred by families with those of the PV systems. For the lowest-income group, which spends $2.30 a month on candles and kerosene, the monthly amortization of the cheapest PV system, a lantern, is about half this figure. But the purchase price of $70 for a single item is a considerable deterrent for poor families—the risk of breakage or theft, with the complete loss of such a major investment, is likely to be a major consideration. Perhaps most important of all is that the PV lantern, although it supplies much higher quality lighting than a kerosene wick lamp or a candle, is only a single lighting source. To provide the flexibility the family currently enjoys, the lantern must be supplemented with additional candles or kerosene, thus reducing or nullifying its cost advantage.

For the lower-middle-income household, the initial purchase price of the PV system is also a major hurdle; for many families, it would represent up to 50 percent of their annual income. Even if extended credit arrangements are available, a rigid commitment to monthly repayments is involved, as well as a need to purchase replacement batteries. This is quite different from the present pattern of expenditure of small amounts of money on a completely discretionary basis. If money is scarce, the family can cut down their purchases, or even do without. Although the PV system provides a higher standard of lighting, it is difficult to see it as an attractive proposition to many families in this income group.

For groups in the middle and upper income range, the purchase price of the PV system is still a significant obstacle. Nevertheless, disposable incomes and expectations are higher in these income groups. These families are not averse to making considerable investments—for example, to improve the quality of their dwellings. They tend to be prepared to incur substantial expenditures for a variety of other reasons as well. For middle-income families, who are spending considerable amounts of money on relatively poor lighting and large numbers of dry cells, a PV system that provides them with a substantial improvement in their living conditions can begin to look very tempting. For the upper-income family already using a car battery, the 100-Wp system would provide a more comprehensive electricity service of considerably higher quality, and at a lower cost than they are presently paying.

The comparisons shown in the table are, of course, arbitrary in many ways and are purely for illustrative purposes. A middle-income or upper-income family could easily buy a rechargeable lantern to supplement their present sources of lighting, for example. Similarly, an upper-income family may feel that a 20-Wp system to provide good lighting for one room and help economize on their use of a car battery is their best option.

A Zimbabwe report noted the use of 10-Wp systems by mining families living near Harare and commented on the management of these to provide electricity for TV:

> As the energy available is small, there are sometimes conflicts between the husband wanting his light and radio at night and the family wanting the radio during the day. The users were otherwise very adept at load management to achieve their ends. One owner wanted to use the system to power a television set. This is a huge load for such a small system. He discovered that if he used power sparingly, he could watch television all evening every third day. This met his needs and he was very happy with the system. (Zimbabwe Energy Programme 1992)

In summary, Table 4.1 supports the obvious point that the main market niche for SHSs is most likely to be among middle-income and upper-income families in rural or peri-urban areas. The PV option is particularly likely to be attractive to families that currently use car batteries for their electricity supply. For poor and lower-income families, the financial commitment and risk involved in the PV investment are hardly likely to be outweighed by the improved service it provides. In broad terms, this means that the present market niche for SHSs is likely to be in the top 10 to 15 percent of the rural and peri-urban population without a grid supply or an early prospect of obtaining one.

PV Water Pumping

It is widely agreed that safe, reliable, and accessible water supplies are critical to rural development and economic progress in developing countries. The United Nations, in cooperation with the World Bank and other development organizations, launched the International Drinking Water Supply and Sanitation Decade (1981–91) with the goal of providing safe drinking water and sanitation to all people in the developing world. Although progress has been made, it is estimated that nearly a billion people in the developing world still lack access to safe water supplies (Cabraal and others 1987).

Experience with rural water supply programs demonstrates that they are fraught with difficulties, and a large number of donor and government programs have fallen far short of their targets or failed completely. The main problems are usually social, cultural, and financial rather than technical. They also vary considerably depending on social conditions and the economic level and expectations of the target groups.

Water, an unconditional necessity of life, is available wherever people live. The minimum amount required for survival is small, considerably less than one liter per person per day, and the actual quantity used depends almost entirely on its local availability. In dry-land agricultural communities, outside the rainy season, for example, people generally rely on the amounts that can be carried in jars from the nearest available water source. These quantities are often far less than needed for hygiene and sanitation; the sources are frequently polluted; and the labor involved in water carrying is excessive and diverts time and energy from more productive, or more pleasant, activities. But, crucially for poor people, the supply is free.

It is easy to specify the ideal amount of water that should be made available to people—the WHO figure is 40 liters of clean water per head each day. What is difficult is translating this ideal into an affordable and sustainable program. In practice, this means finding communities prepared to commit themselves to the effort and financial expenditures involved in financing, operating, and maintaining a rural water supply to deliver these quantities of water.

Once water supply programs move beyond the provision of wells and hand pumps that can be maintained by the local community, the question of finance arises. Because of the large numbers of people to be served and the poor state of government finances in most developing countries, the provision of totally free, mechanically pumped supplies to everyone is impractical. Schemes must therefore be designed to gain at least partial cost recovery and local payment for operation and maintenance. Where water is supplied directly to households, this may be in the form of a charge for the metered amount supplied; otherwise people collecting water may be charged a fee by the pump operator.

Such payments conflict directly with the widespread conviction of rural people that water is a free good, for which they should not have to pay. Experience with water programs shows that a high proportion of rural people, faced with payments in cash, or even in kind, for a high-quality pumped water supply will opt instead for their traditional free source, however unsatisfactory it may be. This is particularly true of the poor, but also for women in general because they are commonly responsible for water supplies and often have limited access to cash. What outsiders may believe is appropriate does not necessarily coincide with the priorities people have for themselves. The provision of a high-quality, mechanically pumped water supply, for which people have to pay, as a replacement for a poor-quality but free system of wells or hand pumps, can have extremely regressive social effects, for example. Contrasting the views of the U.N. Decade shortly after its inception and those of the village, two Indian writers commented as follows:

> The Decade view: Clean water and adequate sanitation are basic needs for life, and these needs are overwhelming for humanitarian purposes.
>
> The village view: In an acutely water-scarce situation, a convenient water supply is an important priority—not just for drinking and domestic purposes, but also for irrigation. When some water is available, regardless of its quality, other priorities are overriding. (Chauhan and Gopalakrishnan 1983)

The results of the Decade seem to bear out the reservations of these commentators. It appears that just as families and communities climb an energy ladder as their incomes and aspirations grow, they make a similar progression with regard to water. Thus, at the subsistence level, people rely on their traditional free supply sources no matter how inadequate these are, as long as they yield enough for survival. As people become better off, their view of what constitutes an acceptable water supply changes, and they begin to demand higher standards of quality and greater quantities. With this may emerge a willingness to pay at least something, making it feasible to consider more powerful and sophisticated supply systems.

Comparisons between different kinds of supply service are thus difficult to make satisfactorily. Just as families do not attempt to match the level of service provided by an electric light by using vast numbers of candles, they will not expect a hand-pump supply system to deliver the quantities of water they obtain from a diesel or PV system provided by the government or a donor agency. Attempts to compare water supply technologies by normalizing the supply sources on the basis of a uniform level of water supply will therefore produce misleading results.[5] Rather than comparing systems on the basis of costs per liter delivered, people at the village level are more likely to judge the acceptability of a particular supply system on the basis of the contribution they are asked to make to its operation. This means that low-cost bucket-and-well or hand-pump systems that deliver relatively small quantities of water are likely to be the only practical options in low-income areas.

In higher-income areas, where a reasonable level of cost recovery is acceptable, motorized pumping is more likely to be a financially and socially viable option. It will also be possible in higher-income developing countries where the government is able and willing to subsidize rural water supplies as part of its rural development activities. In these cases, PV pumping systems come into direct competition with gasoline or diesel engines. Because the service provided—quantities of water pumped into a storage tank—is virtually identical regardless of the motive power used, the comparison hinges primarily on costs.

To illustrate the possible applicability of a PV pumping system in comparison with a diesel system, a water supply system with a daily electricity requirement of 5 kWh, whether for a village or for irrigation, can be used. For the purpose of the discussion, the pump and all the ancillary equipment, including the water tank, can be assumed to be identical for the two systems. Attendance and maintenance will be required for the motor and pump, and general supervision of the system will be needed in both cases.

To provide this amount of electricity in an area with a daily insolation of 4 kWh/m^2 in the worst month, an array with an output of 1,400 Wp would be required. If the installed cost is $10,000, assuming no additional charges for repair or maintenance of the array, a lifetime of 15 years for the system, and an annual interest rate of 10 percent, the annualized cost is $1,314.

The same water supply service could be provided by a 2.5-kW diesel system operating for two hours each day. The investment cost would be about $1,800. Assuming a fuel consumption of 1,000 liters yearly at $0.50/liter, annual repairs and maintenance at 15 percent of the capital cost, additional attendance beyond that required for the pump at $500/year, and a 10-year engine life, the annualized cost works out at $1,560. Under these assumptions, the PV system is about 16 percent cheaper than the diesel.

As the pumping energy requirements become larger, the competitiveness of the PV option is reduced. This is because the marginal costs of the increased supply capacity for the PV systems are so much greater than those for diesel. Suppose the pumping

5. This is done, for example, in Cabraal and others (1987), which compares hand pumps, diesel, and PV pumping systems and states that "A key feature of the analysis is that technologies are compared when they are providing the *same level and quality of service.*"

requirement is 10 kWh/day. The size of PV system required becomes 2,800 Wp, with an installed cost of $20,000 and an annualized amortization of $2,628. The same diesel generator as in the previous case can be used, running for four instead of two hours daily, with an additional cost of $500 a year for fuel.

The above calculations are presented for illustrative purposes. The actual availability of solar energy, the water requirements, and the investment and running costs of PV and diesel systems differ widely among countries and locations. In some cases, the niche where PV pumping is economically competitive may be relatively wide; in other countries, it may not exist at all. Only a careful local analysis will reveal which is the case.

Where fuel supply or skilled maintenance are problematic, a weighting may be given in favor of the PV system, but care must be taken to ensure that the necessary skills and spare parts are available for the repair and maintenance of the motor and pump. Inability to obtain reliable supplies of diesel fuel may be symptomatic of deeper problems that will make the operation and maintenance of the PV system equally problematic. Other factors may also have to be taken into account.. The small gasoline engines used for irrigation pumping in some countries may have a variety of other uses during the rest of the year. In Bangladesh, for example, many of the engines used for water pumping in the dry season are used as outboard motors for boats in the flood season. Finding the niche for PV pumping, in short, requires a careful assessment of local costs and conditions.

PV Refrigerators for Health Clinics

PV refrigerator systems are considerably more costly than kerosene or LPG units. A typical PV refrigerator system, including the PV array, battery, load controller, and refrigerator, costs from $4,000 to $10,000 before installation. Typical annualized costs are in the range of $800 to $1,500 (see "Vaccine Refrigeration," chapter 1).

Typical costs for comparable kerosene or LPG refrigerators are in the range of $1,100 to $1,500, and installation costs are negligible. An analysis carried out by the EPI in Uganda found that the annualized cost of LPG refrigerators, at a 3 percent interest rate, were about half those of the PV model—$453 a year in comparison with $939 a year (Rovero 1991). An EPI review in Indonesia found that the annualized cost of kerosene refrigerators was $366 a year, compared with $922 a year for the PV model (Larsen 1992).

An analysis by the EPI (Zaffran 1992) of the conditions that justify use of PV refrigerators concluded that the following would apply:

- No other fuel supply is available.
- Other fuel supplies are unreliable, and shortages are likely to disrupt immunization activities.

- A private fuel distribution system or one managed by the national EPI cannot be envisaged.

More recently this last item was amended after further experience with kerosene refrigerators. It is now thought that the unreliability and difficulty of operating these appliances makes them a generally unsatisfactory option. The present policy of the EPI is to select LPG refrigerators wherever possible because of their low costs and simplicity and reliability of operation. Otherwise, PVs are the system of choice, provided satisfactory arrangements can be made for regular maintenance and for carrying out repairs promptly when required.

PV Battery Charging

Car-battery charging services are found throughout the developing world. Technically suitable PV systems can be designed to fill this function, but the economics are highly problematic. With customary costs of about $2.00 for each charge, before profit, it is generally impossible to compete with commercially available services that use diesel generators or the grid. The commercially viable PV car battery charging niche in a given country, if indeed it exists, is thus likely to be small and specialized and can only be identified through detailed local investigation.

Centralized PV Power Stations

The progress that has been made in PV technology means that the costs of the centralized stations built in the 1980s would now be lower. Nevertheless, the inherent disadvantages of high capital investment and the lack of flexibility in meeting load growth of these stations remain.

Another major problem with centralized PV stations is that the equipment is extremely sophisticated, and repair and maintenance are costly, especially when technicians have to be flown in from the country of origin of the equipment. There also tends to be a high level of consumer dissatisfaction, because households connected to what *appears* to be a conventional grid expect the same level of service.

Interest in centralized PV systems has declined in the light of the experience gained to date. They do not appear to have a niche in the developing world, at least in the coming decade. A GTZ review stated, "Central-station village systems do not today constitute a viable alternative to diesel-based isolated grids, and not even a dramatic decline in the price of solar cells would alter this" (Biermann and others 1992).

5

Experience with Photovoltaic Electrification

The use of PVs in the developing world is growing steadily. A recent estimate (Luque 1994) is that between 100,000 and 200,000 systems have been installed. These include 37,000 in Mexico, 20,000 in Kenya, 16,000 in Indonesia, 15,000 in China, 4,500 in China, 1,000 in Brazil, and more than 300 in the Philippines (ASTAE 1995).

Donors and nongovernmental organizations (NGOs) have sponsored programs, though with extremely mixed results. Some have been highly successful; others have been complete failures. Commercial private sector dissemination of PV kits is also growing in a number of countries.

The self-sustaining commercial diffusion of PV systems, in full competition with the alternatives, is the clearest indication that PV technology has attained a valid and significant role in the rural areas of the developing world. The rural areas of many developing countries could see a diffusion of PVs like that of radiocassettes, TVs, video recorders, and other hi-tech consumer goods.

It is not possible to provide here a comprehensive survey of all the donor-assisted, government, and private sector programs completed or under way in the developing world. Instead, this chapter presents snapshots of some past and current activities that illustrate the lessons learned and the way in which the undoubted potential of PVs is gradually being realized in the developing world.

Donor and Government Support of PV Programs

Significant donor support for PV programs in the rural areas of the developing world began in the early 1980s. The agencies involved include the World Bank, WHO, United Nations Children's Fund (UNICEF), United Nations Development Programme (UNDP), the European Communities (EC), the United States, Japan, France, Italy, the Netherlands, Australia, and Belgium.

The nature of donor support varies considerably among programs. Programs supported by the Agence Française pour la Maîtrise de l'Energie (AFME), for example, usually provide subsidies of up to 90 percent of the capital costs. In some cases, the costs of the systems have been extraordinarily high—up to $14,000 for each household. This is because in a number of the countries that receive French support, such as Martinique, Guadeloupe, Guyana, and Réunion, rural customers have a legal entitlement to an electricity connection. The local utilities have found that a PV installation, even at these extremely high prices, can be the least-cost solution. Other donor agencies have provided more limited subsidies or credit facilities.

A large number of the early donor programs encountered a variety of technical and other problems. The EC-funded program for the Pacific Islands, implemented in the mid-1980s, for example, suffered from load controllers with excessive electricity consumption, modules with 20 percent lower efficiency than specified, and 100-Ah batteries with an actual capacity of 60 Ah (Dawson 1988). Similar equipment deficiencies occurred in many other programs.

Many programs badly underestimated problems of repair and maintenance in the mistaken belief that PV systems were virtually maintenance-free and could be cared for by untrained local people. The programs thus made little provision for regular maintenance visits by qualified technicians or for holding proper inventories of spare parts in readily accessible locations. Furthermore, systems were installed in isolated, widely separated areas, which made visits for repairs and maintenance difficult. As a result, many of these installations failed and were simply abandoned.

Another problem of the early programs was that they paid scant regard to the potential for replication of many demonstration projects. This was particularly true of the centralized village-level power stations. A 38-kW PV ice-making system installed at the Wadi El-Raiyan in Egypt to save diesel fuel had an estimated cost of $1.3 million and a payback period of more than a century.

Finally, the level of information and training provided to the recipients of systems was frequently inadequate. Many recipients were simply presented with equipment without being informed about how it had been designed or how it compared in cost or performance with the alternatives. Projects funded under renewable energy budget lines meant that any comparison with diesel was explicitly excluded. Operator training was often seriously deficient. In a funded PV pumping project in Ethiopia, for example, virtually no information on the systems or training of operatives was provided, much of the equipment was defective, and of the 30 systems shipped to the country, only 18 were installed, and only 3 are currently functioning.

Such experiences, coupled with overenthusiastic promotion, created a major credibility problem for PVs.[6] Outside the ranks of their devotees and promoters, PVs

---

6. Highly inflated claims for PVs are not entirely a thing of the past, as the following quotation shows: "Solar rural electrification programs can be considered as one of the most effective tools of sustainable rural development, enhancing many aspects of daily life. Involving local governments and the international aid community in this policy area is not only justified on environmental and economic grounds, but also as a tool of rural development which helps break the cycle of poverty for peasants" (Barozzi and Guidi 1993).

acquired a reputation as expensive, unreliable, and largely peripheral to the real needs of rural development. It has taken the technical improvements, price reductions, and the more measured approach of the past two or three years to counter such views and create a more positive attitude toward the potential contribution PVs can make to raising rural living standards in the developing world.

GTZ Programs

The German Agency for Technical Cooperation (Gesellschaft für Technische Zusammenarbeit; GTZ) has been among the most active donor agencies in promoting PVs since the early 1980s. Its program in the Philippines is one of the longest running donor-aided PV programs in the developing world (Santibanez-Yaneza and Böhnke 1992). One of the early activities of the Philippines program was the establishment of a Solar Energy Cooperative on Burias Island in the mid-1980s, which was to act as a marketing organization for PV household kits. The kits consist of a 50-Wp module mounted on a pole, a battery and load controller, two fluorescent lamps, and an outlet for a radio or radiocassette supply, at a total cost of about $640. More than 100 systems were installed, but problems arose within a year, and after two years more than half the batteries had failed. These technical failures led many people to refuse to pay the amortization on their systems, which undermined the financial basis of the program. Still, the program ultimately resolved the technical problems, and by 1993 optimism about the scheme's workability had led to the preparation of a new loan package for 400 units.

Another approach used in the Philippines program was to set up a financing arrangement with a Rural Electric Cooperative (REC) to enable it to acquire PV household kits in bulk.[7] The funds are provided to the REC in the form of a loan and carry the same terms as those applied to funds obtained for its conventional rural electrification activities from the National Electrification Administration. Consumers within the REC's franchise area who are not programmed to receive a conventional electricity supply are able to apply for a domestic PV system. They pay an initial charge of about $200, which covers the purchase of the wiring, batteries, lights, and load controller. They also pay a monthly rental of about $7.50 for the PV module. Systems are regularly inspected and maintained by REC technicians. To reduce the costs of the maintenance service, the PV systems are installed only in areas where a cluster of consumers is willing to take them.

The GTZ program is also helping with the dissemination of communal PV systems through the RECs on a number of other islands. On Guimaras Island, for example, PV units are being used to provide lighting and power for communal television at local community halls in the unelectrified part of the island. Some 50 units have been

7. Rural electrification in the Philippines is carried out by RECs, which are locally autonomous and financially self-sustaining organizations under the general supervision of the National Electrification Administration.

installed, for which the district councils pay a monthly charge of $7.50 for each unit to the local REC. The system, however, does not appear to be functioning particularly well; the REC has reported considerable difficulty in collecting the charge from some of the district councils.

Four PV battery-charging systems, each serving about 40 families, were installed in Isla Verde, about 100 km south of Manila. The maximum fee that could be charged was effectively set by the local commercial battery-charging services. Although the system works satisfactorily at a technical level, the revenue it earns is insufficient to cover much more than the operating costs.

Indonesian Banpres Project

One of the most ambitious government-assisted PV programs is the Banpres Project in Indonesia (World Bank/U.S. DOE 1993). The Indonesian government is strongly committed to its heavily subsidized conventional rural electrification program (cost recovery at present tariff levels is estimated to be about 50 percent), and it has been electrifying about 2,000 villages annually over the past decade. Providing PVs is seen as a way of bringing the benefits of electricity to villages with no prospect of receiving a conventional supply within the next 10 years. The Banpres Project is envisaged as a prototype for a much larger PV program in the future.

Criteria for village participation in the Banpres Project included the following:

- Villages have to be isolated but still accessible by a four-wheel vehicle.
- The area is not programmed for utility electrification in the next 10 years.
- The village wants electrification, but conventional methods of supply are not economic or practical.
- The KUD (Koperasi Unit Desai; local cooperative) has to meet managerial competence and capacity requirements.
- The level of insolation is adequate.
- The villagers can pay the initial cost and monthly fees.

The SHSs provided under the program consist of a 45-Wp to 50-Wp panel, charge controller, battery, and two lamps. Users pay an initial fee of about $25 and a monthly fee of about $3 for 10 years. This represents the repayment of a $500 loan at no interest. The fee is comparable with that paid by utility consumers. Users are expected to purchase replacement batteries when these are required. The system is designed to provide 7 to 8 hours operation daily for both lamps; by reducing the amount of lighting, a black-and-white TV can be used. About 3,000 SHSs were installed in 1991–92.

The lead organization in the project, BPPTeknologi (Badan Pangkajian dan Penerapan Teknologi), is drawn from a range of government ministries with rural development and energy responsibilities. It oversees the technical aspects of the program and manages the revolving fund created by the fees paid by SHS users. The actual field implementation is carried out through the cooperative system. The local cooperatives, KUDs, are responsible for fee collection, record keeping, and basic technical support, and they receive a small proportion of the monthly payments to carry out these activities. Private firms are responsible for supplying systems and components to BPPTeknologi's specifications and providing after-sale service and training to KUDs.

The results of the project so far have been promising, but some indications of possible future problems are apparent; these relate to fee payments, especially when batteries begin to require replacement; levels of maintenance; and the reactions of consumers when they find they cannot expand systems to meet their growing electricity demands. The progress of the project will be watched with considerable interest; it could have many valuable lessons for its extension to other areas of Indonesia (plans are being made to expand the program to 40,000 units and to supply 1 million homes over a 10-year period) and for other countries.

Sri Lanka Pansiyagama Project

The Pansiyagama project (Gunaratne 1994) was designed to provide SHSs to 1,000 families in the northwest of Sri Lanka. It was supported by a $1.5 million soft loan from the Australian government. All 1,000 systems were installed by May 1991. The systems cost about $1,000 each, but they were provided on extremely favorable, subsidized terms to householders who made a downpayment of $15 and agreed to pay $2.50 per month for 20 years. This monthly payment plan was chosen because it was comparable with the pattern of typical household expenditure on kerosene.

The project quickly encountered problems, however. A number of relatively minor technical problems emerged, and householders used them as an excuse for withholding their monthly payments. Other users then began to lodge false complaints to justify their own failure to pay. As a result, maintenance technicians stopped taking complaints seriously. The whole project was in danger of being discredited, as the level of payments dropped to 20 percent. It took a major effort to restore the project's credibility and functioning. The project carried out a systematic review of all the installed systems and held consultations with users on how best to proceed. A long-term maintenance contract has now been signed with a local company, and the project is confident that the level of repayments can be restored to an acceptable level.

The "top down" nature of the project, in which the systems were provided by the government, is seen as one of the main reasons for the problems encountered. The provision of systems at a cost equivalent to that for kerosene lessened the value households placed on their systems. It also made it difficult for commercial companies to sell systems at normal prices in the area. Nevertheless, the project now appears to functioning properly and has provided valuable lessons.

Tuvalu Program

Another example of a quite different donor-assisted program is from the small Pacific island country of Tuvalu (see Conway and Manao 1990 and Liebenthal, Mathur, and Wade 1994). The country has a total land area of 24.2 square kilometers (km^2) and is spread over 1.2 million km^2 of ocean. The total population is 8,500.

In 1984, Save the Children Fund embarked on a program to provide PV kits to households on the outer islands with seed money from U.S. Agency for International Development (USAID). A coordinating body, Tuvalu Solar Electric Cooperative Society (TSECS), was established, and a total of 170 SHSs were installed. They were equipped with 35-Wp modules but were not fitted with charge regulators, which led to numerous battery failures, often within six months of installation. The units also turned out to be undersized for their use. In 1985, the European Communities (EC) provided 150 units of the same size. Although these units were equipped with charge controllers, the controllers were faulty, and the batteries were also unsatisfactory. The component problems were resolved by a French grant for replacement controllers and batteries, which allowed all the systems to become operational. Finally, an additional EC grant was obtained that was used to upgrade the systems; they now each have two 42-Wp panels.

The PV program is now run entirely by the TSECS, which is a registered commercial enterprise and is expected to be financially self-sustaining. It has about 300 members, all of households that have been supplied with PV systems. At present, membership is limited by the availability of systems rather than by any lack of households wishing to participate. The EC will provide 175 additional systems, which will bring the operational total to about 500.

The initial joining fee is about $40, and a monthly fee of about $5 is assessed for a single-panel unit ($6 for a double-panel unit). The TSECS is responsible for repair and maintenance, which is carried out by a permanent paid technician on each island. The fees paid by the members currently cover the operational expenses of the TSECS but not the capital investment costs. A demand for units with more power is emerging, and plans are to install systems with up to eight panels suitable for powering refrigerators and VCRs. The fee structure would be revised accordingly.

Despite its early technical vicissitudes, the Tuvalu program now appears to be working well. It has a good rate of fee collection, which provides coverage of the continued operating expenses of the program. The crucial issue of maintenance is being addressed in a professional manner. The existence of the TSECS also provides a vehicle for arbitration of technical and financial disputes between fee collectors and users, and acts as a focus for external assistance.

Summary Data on Donor SHS Programs

Table 5.1 displays some details of a range of donor-aided programs carried out from the mid-1980s to the early 1990s. Few follow-up studies are available, however, which means that figures for installations—and especially data for the numbers of systems presently functioning—need to be treated with caution. Anecdotal evidence suggests that after the end of donor funding and technical support, many installations develop faults and are not repaired.

Table 5.1 Selected SHS Projects with Government and Donor Support

Country	*Program date*	*Source of support*	*Peak output of PV system (Wp)*	*Installed price (US$)*	*Number of units*
Dominican Republic	1986–92	United States, initially	38	500	2,000
Guyana		AFME	90-540		Hundreds
Indonesia	1987–92	Holland/GTZ	40	400	400
Indonesia	1991–92	Government	40-50		3,000
Martinique/ Guadeloupe	1987–91	AFME	320-540	10,000–14,000	400
Mexico		Government			37,000
New Caledonia	1985–92	AFME	80-960	3,000–10,000	1,500
Peru		GTZ	40	450–500	1,000
Philippines		GTZ	50	570	1,000
Polynesia		AFME	320-960		3,000
Réunion		AFME	160-400		200
Rwanda		GTZ	20	750	Hundreds
Senegal		GTZ/France	50	530	400
Sri Lanka	1992	Australia			1,000

Source: Meunier (1993).

PV Water Pumping

The vast majority of PV pumping installations have been provided through subsidies from donor agencies or NGOs. Firm and detailed information on costs, especially in comparison with alternatives, is difficult to obtain.

One of the largest programs is in Thailand, where the government's Department of Civil Works has the mandate to provide village water supplies (Kirtikara 1994). Some 95 percent of the country's 60,000 villages have been provided with grid electricity supplies, but the remainder are too remote or inaccessible for this to be economically feasible. PVs have been chosen as the least-cost option to provide pumped water supplies to many of these villages.

At the end of 1993, a total of 350 systems, with an average capacity of about 1 kWp, had been installed, and 600 additional units were planned for 1994–96. The equipment is provided by the Department of Civil Works with government funding, and villages contribute labor and building materials. Village water pumping committees are formed to ensure the operation of the installation, the equitable distribution of water, and the collection of fees to cover repairs and maintenance.

In an effort to fill the present information gap and provide the necessary information for policymaking, GTZ has initiated a large-scale test program of PV pumping systems. In Zimbabwe, 15 pumping systems are being installed to provide water supplies to schools, villages, businesses, and other users under normal operating conditions. The installations are fitted with automatic data loggers to monitor technical performance. The project will also carry out cost comparisons with other water supply options. The first four systems were installed in 1993, and six were planned for 1994. The local private sector is involved extensively in the installation, maintenance, and monitoring of the systems, and the project is due to last for four years.

PV Vaccine Refrigeration

The EPI carried out an extensive review of its vaccine refrigerator programs in four countries: Uganda, Indonesia, The Gambia, and Papua New Guinea (Rovero 1991; Larsen 1992; Hart and others 1992; Erkkila 1990). The broad conclusion was that the reliability of solar refrigerators was considerably higher than that of kerosene models but little different from that of LPG models. Nevertheless, numerous problems arose with the solar systems.

The failure rate for photovoltaic refrigerators is relatively high. The Uganda survey found records of 240 breakdowns in a total of 760 operating years, an average of about one every three years. It noted that the solar refrigerators have no apparent performance or reliability advantage over gas systems, with the exception of insecurity of gas supply (Rovero 1991). In The Gambia, the average mean time between failures was just under four years.

Papua New Guinea had about 70 photovoltaic refrigerators at the time of the review in 1990. Most of these were donated by NGOs or charities such as Rotary International. A comment on the program, which cost about $450,000, noted that "no attention whatsoever was paid to proper equipment selection, qualification of system suppliers, users' training and maintenance" (Zaffran 1992). The survey results graphically illustrate the consequences. Of the photovoltaic installations, 12 were not working properly. Problems included battery and other technical failures, lack of operating knowledge on the part of clinic staff, and shading of the array. In one case, the solar refrigerator had been connected to the mains electricity.

The review of the Indonesian program, where 100 solar refrigerators have been installed, found that although installation had been carried out satisfactorily, subsequent operation and maintenance were extremely poor. One-third of the 21 installations inspected were not working at all or were not maintaining correct storage temperatures; moreover, most of the faults had not been recognized or reported by the operators. Spare parts were in serious shortage, user training was poor, routine maintenance was not being carried out, and training of maintenance technicians had been largely ineffective (Larsen 1992).

In The Gambia, the survey found widespread problems with roof-mounted arrays. None were provided with ladders or access for cleaning; some were heavily shaded. Fences were too close to some of the ground-mounted units and shaded them; in one case, the shading was increased because the fences were used for drying clothes. The survey commented that "installation work conducted by the local agent of Noack Solar is appalling" (Hart and others 1990).

The results of a review of an EC-funded photovoltaic refrigerator program in the Pacific were similar. One of the refrigerator models consumed nearly 50 percent more energy than the manufacturer's specifications. Its batteries were almost permanently flat and were not operating properly 70 percent of the time. Other problems included corrosion of refrigerator cabinets within six months of installation, damage to electrical circuitry from refrigerator leakage, and heavy shading of arrays. In many cases, the array was too heavy for the roof on which it was mounted, and access for cleaning was difficult and dangerous. In one clinic the unit was so oversized for the vaccine storage needs required that the spare space was being used to store fish and water (Dawson 1988).

Experience in Ghana reveals a similar pattern of problems. Only about half of the 77 installed units are in operation. In a program funded by the World Bank in 1989–90, 30 refrigerators were installed; of these, 17 had stopped working after three months, and all 30 eventually failed. A review of the program found defective modules, batteries, and other components, as well as poor levels of knowledge and operating skills (Essandoh-Yeddu and Ofusu 1994).

This is not to suggest that photovoltaic refrigerators cannot work effectively; many do. Nor does it imply that kerosene and LPG refrigerators do not have their own problems. It does, however, strongly reinforce the comment from the Papua New Guinea review that "Contrary to the unfortunately common perception, solar refrigerators are not miracle machines which can be forgotten once installed and have no need of maintenance and repair thereafter. Indeed, experience has shown that EPI solar refrigerator projects, without careful planning, preparation, and a well-established support system for maintenance have minimal chances of succeeding" (Erkkila 1990).

Centralized PV Systems

The technical and financial performance of centralized PV power stations in the developing world has generally been poor. A 13-kWp PV village power station constructed by GTZ in 1982 to supply 60 families on the Philippine island of Balucan, for example, proved too expensive for commercial operation. It was decommissioned after four years, and the PV components were reused in other projects. The Notto station in Senegal also suffered a variety of operational problems, as did the Utirik station. A 31.5-kWp station built at Mitto in Ethiopia suffered a variety of operational problems and was abandoned. In this case, however, some 600 of the 900 modules used in the array were stolen and are reputed to have been locally combined with car batteries for use as makeshift SHSs.

The Utirik Island project has been carefully examined. The background of the project was that the islanders had received $100,000 for investment in community facilities in compensation for being contaminated with cancer-causing radioactivity from the Bikini Atoll thermonuclear tests. They were persuaded to invest these funds in the PV station, with the rest of the funding provided by the U.S. Department of Energy and the National Aeronautics and Space Administration (NASA).

The 120-volt direct current supply was "hard wired" so that the number, type, and location of the end uses could not easily be changed. A review of the project found a high level of dissatisfaction among the islanders. Numerous attempts had been made to change the equipment in use and add additional loads. Many islanders were disappointed that TVs and washing machines could not be used. Moreover, because power was only switched on in the evening, none was available for the installed refrigerators during the day (Energy Sources International 1987).

Private Sector Experience

Commercial sales of PV kits are proceeding throughout the developing world and have reached substantial levels in a number of countries.

Sri Lanka

Sri Lanka provides an example of commercial PV programs. A private company called Power and Sun (now called Solar Power and Light Company) was set up in 1986 to assemble modules and promote the sale of PV systems in the country. It began with a market survey, which indicated a possible market of 100,000 to 215,000 SHSs, principally among users of car-battery systems. The company received local financial backing and set up a factory, in partnership with a Canadian company, to mass-produce modules in two sizes, 18 Wp and 35 Wp. Marketing began in July 1988.

A variety of marketing methods was developed. One involved a "Corresponding Agents Program," which provided educated but unemployed youths from villages with a three-day training course and sent them back as agents for the company. The agents earn commissions on sales and service visit fees. In 1991 the company formed a link with Singer Ltd., a leading consumer goods manufacturer, to carry out the marketing of systems. Up to 1992 the company had sold 2,500 kits at $240 for the small unit and $395 for the large unit. Although a three-year credit scheme is available, about 80 percent of the units have been bought for cash.

One of the early problems was that the company only sold the modules; others provided the remaining components. This led to many failures from substandard components such as lights, batteries, and wiring. The problems were only resolved when the company took responsibility for the marketing of complete kits and the provision of service after the sale (Perera and Gunaratne 1992). Several other companies have entered the market, and total private sector sales are estimated at about 4,500 units.

Kenya

Kenya is the major success story to date for large-scale private sector diffusion of household PV systems. It is estimated that at least 20,000 PV units have been sold since 1987 (Hankins and Best 1994). This is more than the total number of rural consumers connected under the national power utility's Rural Electrification Programme.

The deployment of PVs on a significant scale in Kenya began in the early 1980s and was carried out almost entirely within government and donor projects. Among these were PV power supplies for remote telecommunications purposes, an OXFAM project to supply 52 pumps to Somali refugee camps, the provision of PV refrigerators under the EPI, and PV-powered electric fences in game parks. It is estimated that by 1993 approximately 1 megawatt (MW) of PVs had been installed under such programs.

The participation of substantial donor programs allowed PV modules and system components to become known and available in Kenya. The programs also provided a basis for the development of local capacities in component assembly and in the installation, repair, and maintenance of PV systems. In addition, they created a widespread public awareness of PV technology and its potential for meeting small-scale electricity demands in rural areas. As a result, substantial numbers of PV kits began to be sold commercially to private householders beginning in the mid-1980s.

The dynamic and competitive private sector in Kenya, which was capable of seizing the market opportunity presented by PVs, has been a major factor in the diffusion of PVs. As a World Bank report comments

> Over twelve firms supply photovoltaic equipment to households. Hundreds of agents, service personnel and technicians form the infrastructure of Kenya's photovoltaic economy. At least three firms assemble inverters and wind transformers for baton-type fluorescent lamps. Kenya's private sector, from large multinational firms to local cottage industries, is a driving force in the expansion of photovoltaics in the country. (Hankins and Best 1994)

The purchasers of PV systems are usually better-off farmers, teachers, and other government employees, rural business people, and city-based workers with homes in the rural areas. Marketing is carried out through press and radio advertising and demonstrations at agricultural shows. A typical system includes a 40-Wp to 50-Wp module and four lamps with a locally made battery. The charge regulator is frequently omitted to reduce the cost of the system.

The selling prices for units are high in comparison with those in Asian countries such as the Philippines. The mid-1993 purchase price of a 53-Wp system, including a local 100-Ah battery, four fluorescent lamps, a charge regulator, and ancillary equipment and wiring, was $922. The installed price was $1,378. These prices include a total import duty and value added tax of $263, approximately 40 percent of the tax-free purchase price of the components.

It is noteworthy that the Kenyan government has adopted a hands-off attitude toward private sector PV activities. The rapid growth in sales has occurred because of the relatively prosperous and sophisticated rural middle class in the densely populated and fertile highlands of the country. The great majority of the people living in these areas have no realistic possibility of obtaining an electricity supply within the next 5 or 10 years under the country's rural electrification program. PVs thus provide an expensive, but effective and convenient, means of meeting their needs for high-quality lighting and power for radiocassette players and TVs.

Private Sector Summary Data

Table 5.2 shows some details of private sector diffusion of PVs in a number of countries. It is noteworthy that the highest sales are in Kenya, where the price is also the highest. This reinforces the view that the crucial elements in determining the rate of diffusion of PV technology are the absence of any realistic prospect of a conventional electricity supply and the existence of prosperous rural families eager to obtain the benefits of improved lighting and power supplies for their TVs.

Table 5.2 Private Sector PV Sales in Selected Countries

Country	*Typical peak system output (Wp)*	*Typical installed price*	*Numbers installed*
Dominican Republic	38	500	4,000
Lesotho	35-40	900-1,000	Hundreds
Kenya	50	1,400	20,000
Sri Lanka	18-35	240-395	4,500
Zimbabwe	20-50	750	3,000

Source: Meunier (1993).

Lessons from Experience in PV Promotion Programs

A wide variety of general and detailed lessons have been learned from the experience of PV promotion programs. The principal among these are briefly outlined below.

Realistic Financial Charges

Heavily subsidized programs that rely on the donation of PV systems to rural communities have an extremely poor record. Although people may be willing to use and enjoy the PV systems provided, they will not maintain them properly, repair them, or replace them. The benefits of such programs are transitory and do little, if anything, to promote a self-sustaining dissemination of PV systems. By undercutting the private sector, they may actually retard the development of a self-sustaining PV market.

Practical Design and Installation Problems

The practical problems of designing and installing significant numbers of PV systems in the rural areas of the developing world were seriously underestimated in many programs. The variations in patterns and intensities of insolation were not always taken into account, and systems were inappropriately sized or located. The quality of cables, clips, switches, and ancillary equipment was often not given the attention it deserved. Installation was frequently poor—panels were insecurely fixed, oriented the wrong way, or shaded by trees.

Although standards of component manufacture and the design and installation of systems have greatly improved, faults can still occur in all of these areas. Thus, PV programs need to be carefully designed and targeted, system components checked, and installation properly supervised if the programs are to succeed.

Repair and Maintenance Arrangements

Perhaps the greatest weakness of PV programs to date has been the serious underestimate of the need for adequate repair and maintenance systems. Although the repair and maintenance needs of PV installations are much lower than those of diesel engines, for example, they must still be met, or the PV unit will inevitably go out of service. Problems are found among privately installed systems as well as those in institutions such as health clinics and schools. As a rule, it can be assumed that systems will break down and fall into disuse unless proper, regular preventive maintenance and repair service are provided.

Simply providing training courses for technicians will not meet this need. Unless these technicians are employed and appropriately compensated for their knowledge, they will not consolidate their skills, and the training will be wasted. Major emphasis in program planning must therefore be given to establishing sustainable repair and maintenance services.

Need for Adequate Information for Consumers

User surveys have shown that people trading up from kerosene and candles or car-battery recharging are generally satisfied with the superior service provided by a PV system. But continued satisfaction depends on properly informing customers in advance about what PV systems can and cannot do. Where customers' initial expectations have been too high, and they have thought they were buying into a full-scale electricity service that would allow use of conventional domestic appliances, they have been disappointed and resentful. Similarly, customers must be properly informed on the proper way to use and maintain their systems if they are to get satisfaction from their purchase.

Need for Adequate Management Skills in Local Organizations

Where local PV cooperatives are set up, or are used for running PV programs, a realistic assessment of their managerial skills must be carried out. Cooperatives also require adequate, ongoing monitoring and support. This is particularly important if they are responsible for collecting fees and paying for repair and maintenance services. Setting aside money for future repairs can be difficult for village organizations, especially—and ironically—when systems are well designed and reliable and show no signs of failure in the first few years.

Independent auditing and control over the cooperative's operations are likely to be essential in many cases. Similarly, strict control must be maintained over the implementation of disconnection policies for failure to pay fees or to look after systems properly. If excessive leniency is shown to some, morale is lowered, payment default increases, and the financial viability of the program is undermined.

Need for Realistic Assessment of Comparative Costs

Where donor or government programs are intended to stimulate and develop a commercial market in PV systems, it is essential to carry out realistic economic and technical evaluations and to compare costs with conventional alternatives. This has frequently not been done, and the lack has led to installation of systems that are uncompetitive with their conventional alternatives. As a result, even if these programs succeed at a technical level, once the funding is finished, the installed systems are unlikely to be replaced at the end of their working life or to be repaired if they break down. Still less are they likely to be adopted by other potential users.

PV demonstration or promotional programs, if they are to lead to sustainable and self-supporting self-dissemination of PV systems, must genuinely represent technically satisfactory, least-cost, and affordable solutions to their target groups of potential users.

6

The Role of Governments and Funding Agencies

Photovoltaics, as this report shows, can be commercially competitive with alternative means of meeting small energy demands in many rural areas of the developing world, and governments can take a variety of actions to stimulate the markets in these areas. In many other areas in the developing world, however, although little if any commercial market exists for PV systems, programs to promote and disseminate PVs are often advocated. This raises questions of subsidies and sustainability. Deciding on the optimal extent of government and donor agency involvement in PV programs therefore raises a number of complex financial, institutional, and social issues.

Stimulating and Encouraging the Commercial Market

Some good reasons and some successful precedents, such as Kenya, can be cited for arguing that the optimal government role in the commercial PV market is the minimal involvement possible. In this view, PV systems are purely consumer products, analogous to TVs, refrigerators, or other relatively high-priced electrical goods aimed at the middle-income and upper-income market, and their promotion and servicing are best left to the private sector.

Somewhere short of the austere view that everything should be left to the market is the recognition that the state, in its role as a promoter of public welfare, can take a variety of legislative measures to facilitate the wider use of PVs without bringing government directly into the business of disseminating PV systems for private use. In particular, governments can help make PVs available to groups whose low income would preclude PV ownership without assistance. Governments can also provide information to enable people to make more informed market choices, and they can put in place measures to protect consumers against fraud or dangerous goods.

Credit

Lack of the relatively large cash sums required for the purchase of PV installations is the most significant obstacle to their wider use by rural families. Here, governments and donor agencies can make some of their most effective interventions by ensuring that initial funding is made available where necessary. A variety of approaches are possible, but most depend on the provision of initial monies to set up some kind of revolving credit fund.

In some cases, the credit provided to the householder may be restricted to the purchase of the PV module. This avoids the difficulties encountered when households take out loans to buy components such as batteries, lamps, or appliances that may have lifetimes shorter than the loan period. The PV array, which has a lifetime of 10 to 20 years, retains most of its value and can be confiscated and reused if the consumer defaults on the loan.

Hire-purchase is another possibility. In this arrangement, the installation remains the property of the vendor until the full purchase price has been paid. This provides both the householder and the vendor with certain safeguards. If the equipment breaks down, the repayments can be stopped until it is repaired; at the same time, if the householder defaults on payments, the vendor is legally entitled to recover the equipment. Yet another option is a leasing arrangement in which the householder makes regular payments to the leasing agency, which continues to own and maintain the equipment.

Long-term rental of the system is yet another alternative. This arrangement is widely used for the acquisition of TVs and could apply equally to PV systems. In this form of rental, the renting agency retains ownership of the system and is responsible for its maintenance and repair as long as the householder continues to pay the rent.

A variety of agencies can be used for the implementation of such credit schemes, including state or commercial banks, farmers' credit unions, or specially established PV funding organizations. A great deal of experience has accrued in the provision of small loans for diverse purposes in the rural areas of the developing world. Where such schemes are already in place, their extension to include the rental or purchase of PV systems may be possible.

Commenting on its own experience of rural credit arrangements, GTZ (Biermann and others 1992: 16) noted:

> However, all of these approaches have one problem in common: each involves the collection of small loan installments from users living in widely scattered rural settlements, a time consuming task which pushes up the administrative costs to such a high level that private vendors—and many utility companies as well—will find that credit extension to SHS owners is unprofitable. Thus, it is extremely important to encourage the initiation of self-help financing activities by cooperatives, especially since these institutions are also working to eliminate other infrastructural deficits in rural regions (e.g., substandard drinking water supply, lack of roads).

The level of skills and commitment required and the organizational difficulties of setting up a system for recovering the costs of PV systems should not be underestimated.

Administrative weaknesses, poor service or maintenance arrangements, and leniency in dealing with defaulters can all precipitate widespread defaulting on payments and the effective collapse of the credit scheme. Where no cooperatives or equivalent rural organizations exist with the ability to handle financial matters, considerable caution should be used before attempting to set up such organizations solely for PV dissemination.

Information and Training

People need to be made aware of the existence of PV technology, what systems can provide, and, equally important, what they cannot. They need to be told of the need for maintenance and how to carry it out. They need to know about the management of loads on the system—for example, restricting the use of lights and appliances during cloudy periods—to obtain the best service from their PV systems.

Where the only information provided to the public comes from PV promoters and salespeople, the view presented of the technology and its capabilities may be overoptimistic. The information can downplay the reality, with its recurrent costs and need for maintenance and after-sale services. Governments, preferably in collaboration with vendor associations, can provide the information required by the public in order to make informed PV equipment choices.

The technicians involved in the installation, maintenance, and repair of PV systems need to be trained if they are to do their jobs properly. Where local communities are expected to take over the administration of programs and the collection of loan repayments, the personnel who will carry out these tasks need to be properly trained and equipped. Governments can respond to these needs by ensuring that the necessary training courses are made available in schools and technical colleges, with courses and curricula designed in collaboration with private sector PV providers.

Setting Standards

PV kits are costly and relatively sophisticated pieces of equipment. It is extremely easy for purchasers to suffer at the hands of incompetent or unscrupulous vendors or installers. Deliberate undersizing of batteries and the area of panels or the omission of charge controllers are common ploys to reduce the initial costs of installations. Installation is often poorly carried out, with panels facing the wrong way, shaded by trees or buildings, or inadequately fixed to their supports. All of these errors can lead to poor performance or the complete failure of installations.

Governments can protect the public by setting standards for PV suppliers and taking measures to ensure they are observed. National standards normally should be based on accepted international standards. Where the national capacity exists, arrangements for testing and certification of products can be made at the national university or other qualified institution, which can also provide a certification service for local PV dealers.

One of the most effective methods of ensuring that realistic standards are set and observed can be the establishment of PV trade associations pledged to their observance. Governments should encourage the formation of these associations, provide official recognition, check that they are functioning properly, and help strengthen their effectiveness by ensuring that their achievements receive adequate publicity.

Local Manufacture

Local manufacture of PV systems and components can bring advantages through lower costs, reduced imports, and greater accountability among suppliers. It can thus stimulate the development of commercial PV markets. It also has major pitfalls. Inexperienced local companies, on the early part of their learning curve and inadequately supervised, can seriously discredit the technology and set back its dissemination for years. Governments or donor agencies attempting to promote local manufacture should therefore proceed slowly and carefully.

The first step toward local manufacture is to encourage the local assembly of kits. The success of this effort will depend on local technical capabilities. Donor agencies involved in PV programs, especially those working with PV companies from their own countries, are in a strong position to insist that these companies delegate as much as possible of the assembly and installation work to local companies.

As familiarity with PV systems grows and national standards become established, manufacture of components can be encouraged. In a country with a well-developed industrial infrastructure such as the Philippines, with the capacity to manufacture batteries, low-voltage direct current lamps, load controllers, and PV system components, the only need is to ensure that adequate standards are set and maintained. Where the local manufacturing base is more restricted—for example, in Zimbabwe, where batteries are manufactured but other component manufacturing capacities do not yet exist—a gradual buildup through partnership arrangements with donor-country companies may offer the best way forward.

In the smaller developing countries, progress in local manufacturing of PV system components, as is the case with other products, is likely to remain small. Of course, in larger developing countries with well-developed infrastructures, manufacture and assembly of most system components would be feasible. Such countries can also act as suppliers to other countries in their regions, or indeed compete in the global market. It is still premature, however, to expect cell manufacture to become widely dispersed in the developing world. The production of PV cells is therefore likely to remain the domain of a relatively small number of large multinational companies for at least the next decade.

Import Duties and Taxes

One of the most common pleas by promoters and vendors of PV equipment is that import duties and taxes on components and kits should be reduced or abolished. The question is, however, a contentious one. Some governments believe that PV equipment should be exempted because it is used for harnessing a renewable energy source and therefore deserves special treatment. Others feel that PV kits, as consumer goods acquired by upper-class and middle-class families for consumption rather than production, should bear the full burden of taxes and duties levied on such products.

Removal or reduction of import duties and taxes can certainly encourage PV use by lowering prices. Whether the benefits of achieving this justify the loss in revenue is a matter for detailed assessment by each country, but where substantial subsidies are provided for kerosene or conventional rural electrification, it would appear reasonable for governments to reduce or eliminate taxes and duties on PVs.

Noncommercial and Subsidized Promotion and Dissemination of PVs

No matter how effectively the commercial PV market is encouraged, it is only going to serve a small proportion of those now living in the rural areas of the developing world. For the majority, the costs of PV systems, even when long-term credit arrangements are available, are simply too high. The only hope the majority of people have of obtaining a PV system is that it will be provided on a noncommercial and subsidized basis.

Such programs of subsidized PV dissemination have been widely advocated. The most ambitious is perhaps that entitled "Power for the World" (Palz 1994), which has been advanced by the European Commission. This would provide PV electrification to all the developing world's villages over a 20-year period at an estimated investment cost of $3 billion annually. This is well within the discretionary spending capacity of the industrial world; it amounts to just 1 percent of its annual military expenditure. At the same time, the record of efforts to provide subsidized PV equipment to the developing world is poor. Few programs have proved sustainable or have led to the spontaneous dissemination of the technology beyond the target group. Considerable care is needed in the precise definition of the objectives and design of such programs if they are to succeed.

What Kind of Implementing Agency?

One of the critical requirements in any large-scale program for the dissemination of PVs is an effective implementing agency. In considering this, it is tempting to look for analogies with conventional rural electrification.

Governments have always supported conventional rural electrification for social and political reasons. They have accepted that the high initial costs and generally slow buildup of loads mean that it is rarely possible for programs to be financially self-sustaining or to show an acceptable economic rate of return in their early stages. If rural electrification is to take place, it is generally accepted that some degree of subsidy will be required.[8]

8. The level of this subsidy is a matter for debate. Moderate levels of cross-subsidy or exchequer grants for capital investments are usually deemed acceptable, provided that at least operating costs are covered by tariffs. Large, open-ended subsidies for operating costs are increasingly seen as unacceptable.

It could be argued that once the principle of a government subsidy for conventional rural electrification is accepted, similar support should be provided for PV dissemination. There would appear to be no logical or equity distinction that would make rural families who are outside the scope of conventional rural electrification unworthy of similar subsidies to obtain PV kits. The utility, instead of ignoring the areas where the grid is too costly, could provide households with PV kits. This argument, however, ignores some of the fundamental differences between conventional and PV electrification and the role of governments and implementing agencies in each process. For example, a government or other actively engaged central authority is essential for conventional rural electrification, whether it is subsidized or not. This is because conventional rural electrification has to be carried out within the framework of the overall electrification program of the country. Areas can only be economically electrified when a minimum number of consumers are willing to take a supply, and this must be established in advance. Projects typically have investment budgets of millions of dollars, and often very much more. Conventional rural electrification is, in short, a process that needs careful overall planning if it is to take place at all, let alone in a rational and cost-effective manner. In most developing countries it is only the government or the national power utility that is in a position to fill this role. If it is not filled, rural electrification will simply not happen.

In contrast, PVs require no general physical infrastructure. Hence, decisions on whether or not to take a service can be made by individual families, more or less independently. Provided an effective repair service is within reach, it matters little whether ten or a hundred families with PV systems are in a particular area. New consumers have no effect on the costs incurred by the others. The amount of overall planning or coordination required is much less than that for conventional rural electrification.

Some other important differences between rural grid electrification and PV electrification are worth noting. The principal concerns of the electricity utility and the bulk of its operational, repair, and maintenance activities are focused on the infrastructure, the generating plant, transmission system, and distribution network. Its concern for the individual household, apart from meter reading, effectively stops at the low-voltage system takeoff point for the house connection. The exact reverse is the case with PV systems. No overall supply system exists; everything is devolved to the individual household level. Repair and maintenance, rather than being concentrated on the supply infrastructure, are diffused among all the households with PV systems.

PV electrification is thus not an activity that plays to the natural strengths of an electricity utility. If it is to be undertaken by the utility, it requires the development of an additional range of skills and capabilities. In the poorer developing countries, where utilities are frequently underfunded, have too few resources, and are incapable of carrying out the basic tasks of repair and maintenance on the existing systems, asking them to take on PV electrification is pointless. Only in the better-off developing countries, at an advanced stage in their rural electrification program and with properly funded and well-run utilities, does it become feasible to consider allocating responsibility for PV electrification to the utility. This has been done, for example, in Mexico.

In the absence of the national utility as a national PV agency, the choice of existing organizations with the necessary technical skills and a national outreach tends to be limited, especially in the poorer developing countries. Building such an organization from scratch is likely to be a long and difficult process. The alternative is to build on existing organizations with a technical outreach capacity, including skilled technicians, vehicles, equipment, properly run stores, regional depots, and adequate financial and managerial capabilities. Organizations that could meet these criteria could include national ministries of works or effective local NGOs. Again, the process of cultivating the necessary capacities is likely to be slow.

Apart from any questions of funding, the practical problems of finding or creating adequate implementing agencies are likely to be among the most difficult issues faced by PV program promoters. In many developing countries, especially the poorer ones, they may turn out to be one of the main limiting constraints on effective action.

The Question of Subsidies

The provision of subsidies for large-scale programs of PV electrification should always be approached with caution. This well-intentioned measure can give rise to a variety of problems and unwanted side-effects. In the extreme case, it can be counterproductive and set back the wider dissemination of PVs.

One of the main effects of subsidized programs is that they tend to undermine the development of a commercial market, since families will not purchase PV equipment if they can obtain it more cheaply through a subsidized program. One way to overcome this conflict is to provide a general subsidy on all equipment, whether through government or private channels. This arrangement requires a high degree of control if it is not to be abused (much of the LPG equipment and the bottled gas subsidized under Senegal's butanization program, for example, made its way to neighboring countries). Unless extremely carefully managed, subsidized-equipment programs can turn out to be a large and open-ended drain on government funds. They can also lead to a high degree of control by the bureaucracy and a stifling of commercial markets and competition.

Subsidizing PVs also raises questions of equity and development priorities. The main beneficiaries will generally be better-off families whose expenditures on commercial energy are already high and who will obtain higher standards of lighting and other amenities at lower costs. The poor, with more pressing priorities and lower disposable incomes, will be less willing to make an investment even in a subsidized PV system and will realize lower benefits if they do. The program, in other words, will channel scarce rural development funds toward the better-off rather than the poor. It may also be argued that providing the better-off with easier access to consumer goods is scarcely a high priority in a large number of areas where so many more basic needs remain unfulfilled.

Subsidies therefore must be used with considerable care. Their purpose needs to be clearly and explicitly defined. They must be carefully targeted and limited so that they do not become open-ended. In general, they should be used for nonrepeating or infrastructural expenditures, such as setting up revolving funds for credit, providing public information, training technicians, establishing standards, and establishing consumer protection measures.

Public Services

Governments are necessarily involved, and donor agencies have traditionally played an important role, in a range of public services—such as health, education, and other areas of welfare provision. The need for substantial subsidies in the provision of these services is universally accepted. In general, energy accounts for only a small fraction of total costs, and it is rarely the decisive factor in providing the service.[9] The primary concern is that whatever method is used, the energy supply should be reliable and adequate for its purpose.

PVs may be the optimal energy supply source in some of these cases. This is likely to be true, for example, in health clinics where LPG vaccine refrigerators are not practicable. The same may also apply to water pumping, street lighting, or other services. The crucial requirement in all cases is that the energy supply is seen in its proper perspective in the overall planning of the service and that the supply method chosen is adequate for its purpose and the least-cost alternatives available. This means that all the alternatives should be properly considered.

National Review

The potential PV niche, its precise delineation, and the practical potential for filling it vary enormously between developing countries. For an adequate evaluation, consideration must be given to a variety of elements, such as rural income levels; the rate at which conventional rural electrification is being provided; the price and availability of PV equipment; the price of conventional fuels; the availability of technical skills for installation, repair, and maintenance; the level of public awareness of PVs; and a variety of other local factors. The need for specific government or donor involvements will similarly vary among countries.

The most effective way to identify the optimal path and the steps that need to be taken by the various parties concerned is to carry out a national PV review. This should examine the experience to date with PVs and identify the niches in which the technology is already relevant or could become in the near future, as well as the obstacles to the realization of its potential and the costs and benefits of removing these obstacles. In the

9. In the case of adult education in the rural areas, for example, the main constraints are the lack of qualified teachers and materials, absence of an adequate curriculum structure, and like factors rather than the absence of an electricity supply.

review, careful attention should be paid to the demand side, examining the services people are prepared to pay for, and where PVs are relevant in providing them.

Such reviews of the potential for PVs should not be the promotional exercises they have so often been in the past. They should fully and realistically consider the competitiveness and suitability of PVs compared with the available alternatives. Attempts to force PVs into applications in which they are not financially competitive and self-sustaining bring few if any development benefits and discredit the technology rather than assist its promotion.

In relation to government and donor PV programs, the review should identify where they are relevant, estimate the costs and benefits of carrying them out, and identify the measures required to ensure they are sustainable and replicable. In the consideration of private sector involvement, the aim should be to identify imperfections in markets and distribution systems and to specify ways of removing them to allow the private sector to meet the market demands it is best equipped to serve.

The review should be as concrete and specific as possible. Prices should be realistic, based on experience rather than on optimistic projections. Where actions are called for, they should be specific—the agencies required to carry them out should be identified, and any costs should be quantified. The production and publication of the review will ensure that there is a realistic and practical basis for the formulation of government policy toward PVs. It will also provide a clear framework for donor interventions, as well as facilitating the involvement of the private sector.

References

ASTAE (Asia Alternative Energy Unit). 1995. "Best Practices for Photovoltaic Household Electrification Programs: Lessons from Experiences in Selected Countries." Draft final version. World Bank, Asia Technical Department, Asia Alternative Energy Unit, Washington, D.C.

Barlow, R., A. Derrick, and J. A. Gregory. 1994. "The Photovoltaic Industry and Prospects 1995–2005." Paper presented at the Solar for Health Symposium, World Health Organization, Geneva.

Barozzi, L., and D. Guidi. 1993. *Prospects for the Expansion of Solar PV Technology in the Developing World.* Rome: WWF Italy.

Batteries International. 1993. "Who Says You Cannot Recharge Dry Cells?" Special feature, October.

Biermann, E., and others. 1992. *Basic Electrification for Rural Households: GTZ's Experience with the Dissemination of Small-Scale Photovoltaic Systems.* Eschborn, Germany: GTZ.

Burton, R. 1992. "Introduction to PV Technologies: Technical Issues." Paper presented to the Regional Solar Electric Training and Awareness Workshop, Nairobi, March. African Development Foundation and KENGO, Nairobi.

Cabraal, A., and others. 1987. "A Comparative Assessment of Photovoltaics, Handpumps and Diesels for Rural Water Supply." Sandia National Laboratories report for U.S. Department of Energy.

Chauhan, S. K., and K. Gopalakrishnan. 1983. *A Million Villages, a Million Decades?* London: Earthscan.

Conway, J. M., and S. Manao. 1990. "Solar Power in Tuvalu." Paper presented at the Joint UNDP/ESMAP Pacific Household and Rural Energy Seminar, Vanuatu.

Dawson, B. 1988. "SPEC Experience with Photovoltaic Projects in the Pacific." Suva, Fiji: SPEC.

Dingley, C. 1988. "A Review of Electrification Programmes in Six Countries." Department of Electric and Electronic Engineering, University of Cape Town, South Africa.

Energy Sources International. 1987. "Photovoltaic Power on Remote Islands in the Pacific: The Experience of Utirik Republic of The Marshall Islands." Report prepared for the Republic of the Marshall Islands, the Trust Territory of the Pacific Islands, and the U.S. Department of Energy.

Erkkila, M. 1990. *Evaluation of Solar-Powered Refrigerators, Western Province, Papua New Guinea.* Geneva: EPI, WHO.

ESMAP (Energy Sector Management Assistance Programme). 1991. "Republic of Yemen: Household Energy Strategy, Phase I: A Preliminary Study of the Northern Governates." World Bank, Industry and Energy Department, Washington, D.C.

———. 1992. "Philippines: Defining an Energy Strategy for the Household Sector: Vol. II, Consumption Survey." World Bank, Industry and Energy Department, Washington, D.C.

Essandoh-Yeddu, J., and K. O. Ofusu. 1994. "Evaluation of the Performance of Solar Photovoltaic Powered Refrigerators in the Health Sector of Ghana." Paper presented at the 12th European Photovoltaic Solar Energy Conference, Amsterdam, April.

Fernando, J. P. 1988. "Rural Electrification in Sri Lanka." Draft report for Panos Institute, London.

Green, Martin A., and Keith Emery. 1994. "Solar Cell Efficiency Tables (Version 3)." *Progress in Photovoltaics: Research and Applications* 2: 27–34.

Gunaratne, L. 1994. "Solar Photovoltaics in Sri Lanka: A Short History." *Progress in Photovoltaics: Research and Applications* 2: 307–16.

Hankins, M., and M. Best. 1994. "Photovoltaic Power to the People: The Kenya Case." Draft ESMAP document, World Bank, Industry and Energy Department, Washington, D.C., January.

Hart, T., and others. 1990. *Solar Refrigeration in The Gambia: Programme Survey.* Geneva: WHO.

IENPD (Industry and Energy Department, Power Development, Efficiency, and Household Fuels Division, World Bank). 1995. "Energy Strategies for Rural and Poor People in the Developing World." Draft paper, World Bank Industry and Energy Department, Washington, D.C.

Kirtikara, Krissanapong. 1994. "Photovoltaic Water Pumping Program: Thailand." Paper presented at Techno Indochina, Conference on Science and Technology for Indochina, Bangkok.

Kusche, K. 1994. "PV Rural Electrification: Really an Alternative?" Paper presented at the 12th European Photovoltaic Solar Energy Conference, Amsterdam, April.

Larsen, G. A. 1992. *Solar Refrigerators for EPI Vaccine Storage in Indonesia: Programme Review.* Geneva: EPI, WHO.

Liebenthal, A., S. Mathur, and H. Wade. 1994. *Solar Energy: Lessons from the Pacific Island Experience.* World Bank Technical Paper 244, Energy Series. Washington, D.C.

Lucas, N. J. D. (No date.) "Subsistence Electricity: Renewable Energies and Development." Energy Technology Division, Asian Institute of Technology, Bangkok. Processed.

Luque, A. 1994. "Scientific Conclusions of the 12th European Photovoltaic Solar Energy Conference." Amsterdam, April.

Meunier, B. 1993. "Document du travail sur la pre-electrification solaire individuelle." Working Paper. World Bank, Industry and Energy Department, Joint UNDP/World Bank Energy Sector Management Assistance Programme, Washington, D.C.

Palz, W. 1994. "Power for the World: A Global Photovoltaic Action Plan." Paper presented at the 12th European Photovoltaic Solar Energy Conference, Amsterdam, April.

Perera, V., and L. Gunaratne. 1992. "Photovoltaics, Entrepreneurship and the Developing World: An Insight into the Establishment of a Solar Energy Industry in Sri Lanka." In *Proceedings of the Regional Solar Electric Training and Awareness Workshop, Nairobi.* Washington: African Development Foundation.

Peskin, Henry M., and Douglas Barnes. 1994. "What is the Value of Electricity Access for Poor Urban Consumers?" Industry and Energy Department, Power Development, Efficiency, and Household Fuels Division, World Bank, Washington, D.C. (Background paper for *World Development Report,* May 1994.)

Rovero, C. 1991. *Cost Analysis of Health Centre Vaccine Cold Chain in Uganda.* Geneva: EPI, WHO.

Santibanez-Yaneza, G. G., and H.-W. Böhnke. 1992. *The Philippines's Rural Photovoltaic Electrification Scheme.* Quezon City, Philippines: National Electrification Administration.

SEI (Stockholm Environment Institute). 1993. "Rural Electrification in Mozambique, Tanzania, Zambia, and Zimbabwe." Synthesis report from the SEI/BUN (Biomass Users' Network) Workshop on Rural Electrification, Stockholm Environment Institute, Sweden.

Technet. 1991. *Report of 1991 Technet Consultation.* Geneva: EPI, WHO.

van der Plas, R. 1988. "Domestic Lighting." Working Paper, World Bank, Industry and Energy Department, Washington, D.C.

WHO. 1991. *Cost Analysis of the Solar Cold Chain in The Gambia.* Geneva: WHO.

WHO/UNICEF. 1993. *Product Information Sheets 1993/1994.* Geneva: WHO.

World Bank. 1975. *Rural Electrification.* Washington, D.C.

———. 1986. "Indonesia Rural Electrification Review." East Asia and Pacific Regional Office.

———. 1989. "Pakistan: Assessment of Photovoltaic Programs, Applications and Markets." Household Energy Unit, Industry and Energy Department, Washington, D.C.

———. 1993. "Comparative Study of Solar Photovoltaics for Household Electrification: Dominican Republic." Asia Technical Department, Asia Alternative Energy Unit, World Bank, Washington, D.C.

World Bank/ESMAP. 1994. Draft data. World Bank, Industry and Energy Department, Washington, D.C.

World Bank/U.S. Department of Energy. 1993. "Comparative Study of Solar PV in Developing Countries: Indonesia." World Bank/U.S. Department of Energy, Washington, D.C.

Zaffran, M. 1992. *PVs in Developing Countries: Solar Energy for Primary Health Care.* Geneva: WHO.

Zimbabwe Energy Programme. 1992. "Dissemination of Photovoltaic Systems in Zimbabwe." Report prepared by Aptech Ltd. for Ministry of Energy and Water Resources and Development.

Joint UNDP/World Bank
ENERGY SECTOR MANAGEMENT ASSISTANCE PROGRAMME (ESMAP)

LIST OF TECHNICAL PAPER SERIES

Region/Country	*Activity/Report Title*	*Date*	*Number*
	SUB-SAHARAN AFRICA (AFR)		
Kenya	Field Performance Evaluation of Amorphous Silicon (a-Si) Photovoltaic Systems in Kenya: Methods and Measurement in Support of a Sustainable Commercial Solar Energy Industry	08/00	005/00
Uganda	Report on the Uganda Power Sector Reform and Regulation Strategy Workshop	08/00	004/00
	EAST ASIA AND PACIFIC (EAP)		
Vietnam	Options for Renewable Energy in Vietnam	07/00	001/00
China	Assessing Markets for Renewable Energy in Rural Areas of Northwestern China	08/00	003/00
Thailand	DSM in Thailand: A Case Study	10/00	008/00
	GLOBAL		
	Impact of Power Sector Reform on the Poor: A Review of Issues and the Literature	07/00	002/00
	Best Practices for Sustainable Development of Micro Hydro Power in Developing Countries	08/00	006/00
	Mini-Grid Design Manual	09/00	007/00
	Photovoltaic Applications in Rural Areas of the Developing World Bank	11/00	009/00

10/17/00

ESMAP

The World Bank

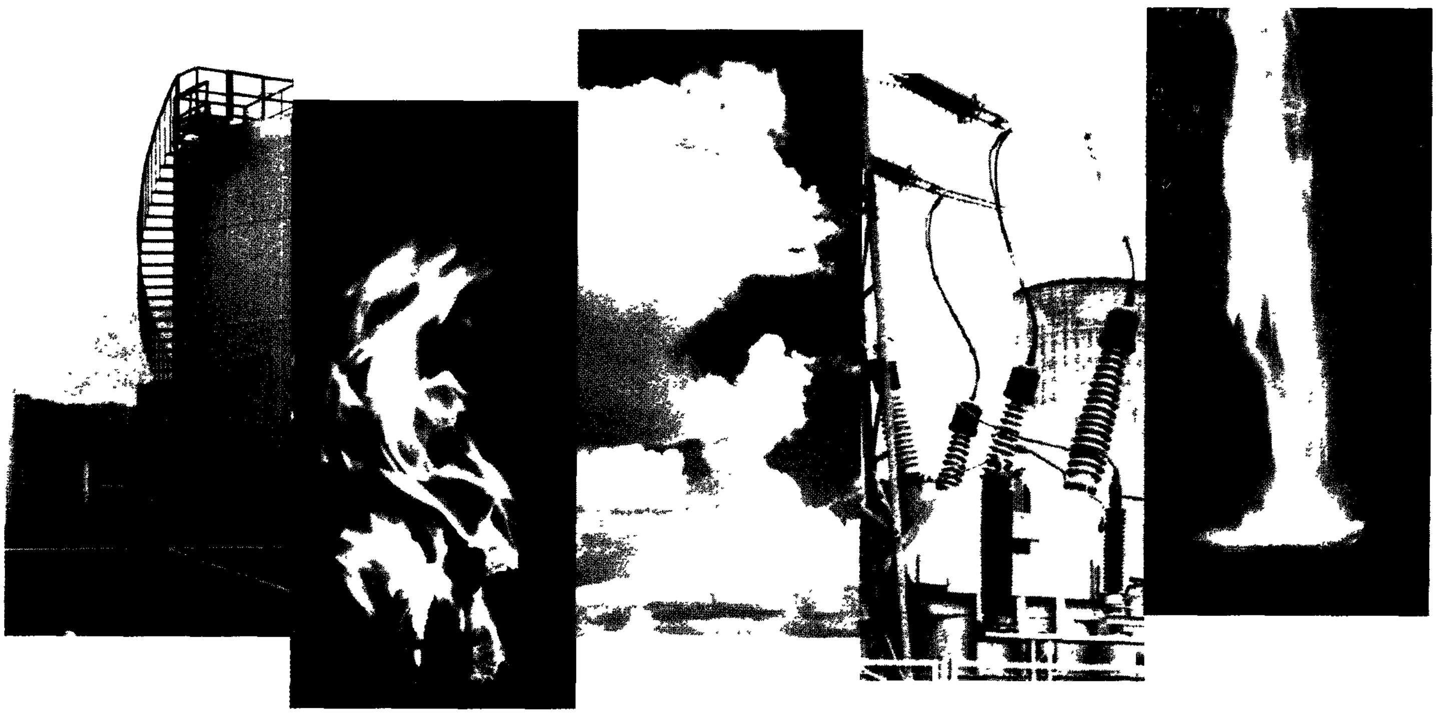
1818 H Street, NW

Washington, DC 20433 USA

Tel · 1.202 458 2321 Fax : 1 202.522 3018

Internet· www.esmap org

Email: esmap@worldbank org



A joint UNDP/World Bank Programme