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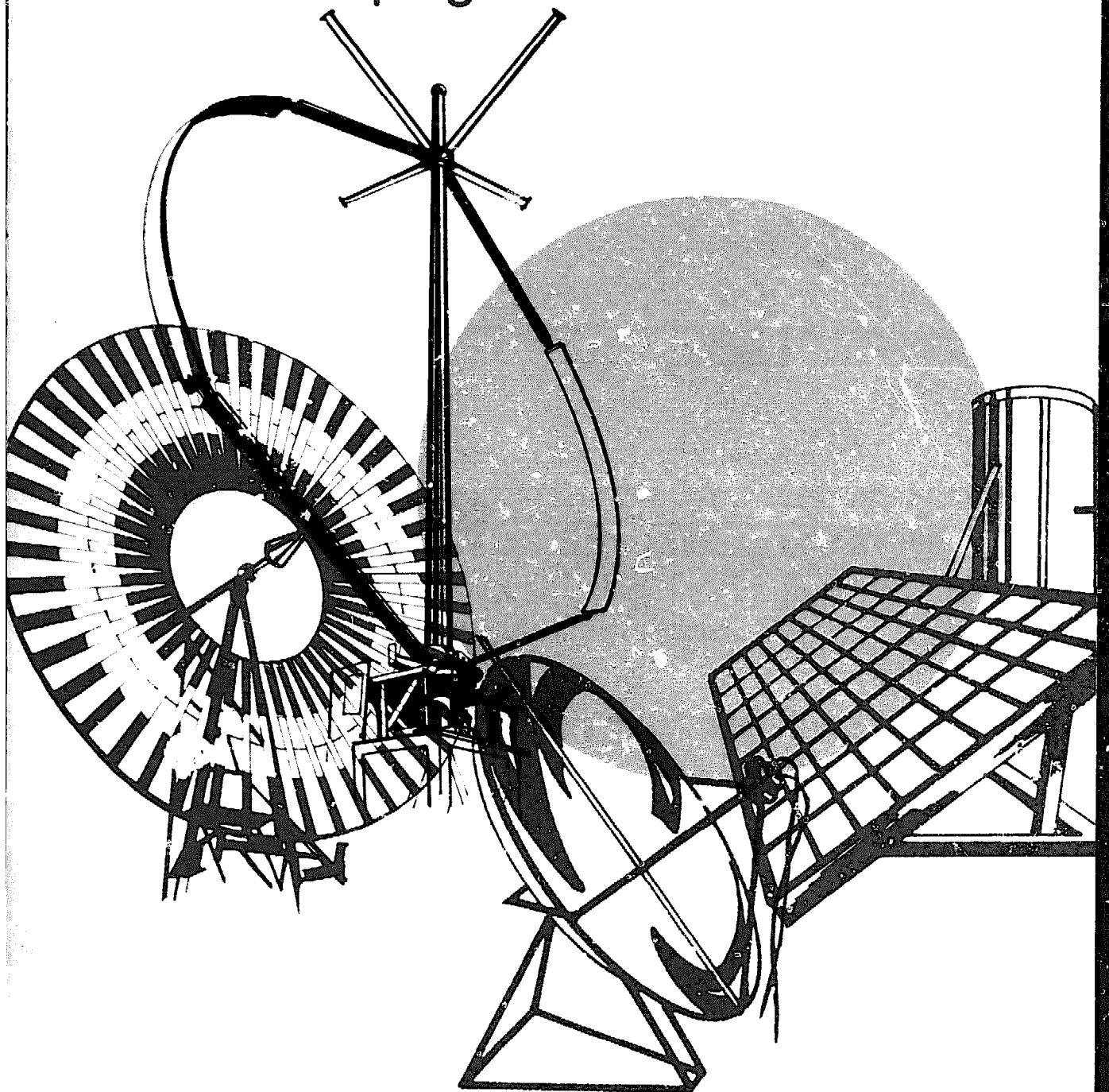   2101 Constitution Avenue
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SUPPLEMENT
Energy for Rural Development
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Renewable Resources and Alternative Technologies for Developing Countries

Advisory Committee on Technology Innovation
Board on Science and Technology for
    International Development
Commission on International Relations
National Research Council

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Preface

In 1976, the National Academy of Sciences published *Energy for Rural Development: Renewable Resources and Alternative Technologies for Developing Countries*, a report prepared by an ad hoc panel of the Advisory Committee on Technology Innovation (ACTI). ACTI was formed in 1971 by the Board on Science and Technology for International Development (BOSTID). The 1976 report was an outgrowth of ACTI's ongoing interest in renewable energy sources for rural areas.

The original book (published in both English and French) presented information on a variety of subjects, including direct uses of solar energy (heating, cooling, distillation, crop drying, photovoltaics), indirect uses of solar energy (wind power, hydropower, photosynthesis, biomass), geothermal energy, and energy storage. Both a nontechnical section and a technical section on each of these subjects were included. The report was not intended to be a detailed "how-to" manual on energy devices; rather, it was intended to report on the state of the art, tell who was doing what, and direct the reader where to go for detailed information. Assessments were made of the short-, intermediate-, and long-term applicability of each technology for developing countries.

In the 5 years that have passed since publication of *Energy for Rural Development*, significant changes have occurred in the world energy picture. The world's heavy dependence on oil and rapidly rising energy costs have affected the developing countries in particular. It is critical, therefore, that up-to-date information on renewable energy resources and alternative technologies, preferably those available locally, be provided.

Although there have been few remarkable new discoveries in the past 5 years, steady progress has been made in research and development on renewable energy resources and alternative technologies. This supplement includes

information on new technologies developed during this period and on advances made in technologies described in the original volume. Like that volume, this report serves merely to direct the reader where to go for more information, and is not intended to be a "how-to" manual or detailed catalog. Almost all of the subjects in the original book are discussed again—some only briefly. There are new discussions of the use of pedal power and conditioning of electric power.

Because the information presented here builds on material provided in the 1976 report, the original panel was not reconvened to prepare this supplement. Instead, William L. Hughes, chairman of the original panel, called upon various specialists to assess developments over the past 5 years in renewable resources and alternative technologies and served as editor for the material that they provided.

A number of scientists, listed in the front of this volume, made valuable contributions to this report. Their efforts and support are greatly appreciated. In addition, the comments and criticisms of those who reviewed the manuscript proved particularly useful. They include: Charles E. Backus, Arizona State University; J. L. Birchfield, Georgia Institute of Technology; James C. Bresee, North Carolina Energy Institute; William R. Breslin, Volunteers in Technical Assistance; Norman L. Brown, Agency for International Development; David E. Cooper, Southern California Edison Co.; Erich Farber, University of Florida at Gainesville; Jack J. Fritz, Agency for International Development; Elmer L. Gaden, Jr., University of Virginia; Stephen A. Goulden, Cetus Corporation; Carl J. Heise, Lorton, Virginia; Ronald Judkoff, Solar Energy Research Institute; Thomas A. Lawand, Brace Research Institute; George Löf, Colorado State University; M. M. McGinty, Eagle–Picher Industries, Inc.; John C. Orth, The Montana Energy and MHD Research and Development Institute, Inc.; David Pimentel, Cornell University; David W. Rabenhorst, Johns Hopkins University; Roger Revelle, University of California at San Diego; Warren Rice, Arizona State University; Albert D. Sheppard, Georgia Institute of Technology; Neil N. Turner, General Electric Co.; and C. C. Warnick, Idaho Water Resources Research Institute.

LIST OF ABBREVIATIONS

a	acre	kmph	kilometers per hour
AC	alternating current	kVA	kilovolt ampere
amp	ampere	kW	kilowatt
amp-hr	ampere-hour	kWe	kilowatt-electric
Btu	British thermal unit	kWp	peak kilowatt
°C	degrees Celsius	l	liter
cfm	cubic feet per minute	lb	pound
cm	centimeter	m	meter
DC	direct current	m^3	cubic meter
°F	degrees Fahrenheit	μ	micron
ft	foot	mi	mile
ft^3	cubic foot	MJ	megajoule
ft-lb	foot-pound	mm	millimeter
gal	gallon (U.S.)	mph	miles per hour
GWp	peak gigawatt	m/sec	meters per second
ha	hectare	MW	megawatt
hp	horsepower	MWp	peak megawatt
hr	hour	ppm	parts per million
Hz	Hertz	°R	degrees Rankine
J	joule	rpm	revolutions per minute
in.	inch	sec	second
°K	degrees Kelvin	W	watt
kg	kilogram	Wp	peak watt
kJ	kilojoule	Wh	watt-hour
km	kilometer	yr	year

Contents

Introduction

This supplement to *Energy for Rural Development: Renewable Resources and Alternative Technologies for Developing Countries* is concerned with small, low-cost, locally operated energy systems. For that reason, it does not include alternatives such as tidal energy, large-scale wave energy, and ocean thermal gradient systems, which may well become important in the future, but will probably require large-scale capitalization. This does not imply, however, that large capital projects are necessarily inappropriate for developing countries. Where potential loads, cost-benefit ratios, ecological considerations, and financing are favorable, such projects should be considered.

With some exceptions, most of the technologies discussed in the original volume and this supplement are not ready for extensive application in developing countries. Either the cost is too high relative to current conventional energy sources or the current technology is not sufficiently reliable. Yet the energy technologies discussed here are based on well-established scientific principles, seem the most susceptible to significant improvement through purely technological innovations, and can probably soon be applied. They represent, therefore, highly promising possibilities for the developing countries in the future.

Applying any energy technology to developing countries entails a number of quality and cost considerations.

In past years there has been a tendency to compare energy outputs in terms of kilowatt-hours (or Btus) produced. Thus a fire burning 25 kg (55 lb) of wood per hour is equivalent to a 100-kW electric generator by such comparisons, even though the former could never perform the functions of the latter.

It seems desirable, therefore, to make a distinction between "low-grade" and "high-grade" energy. Low-grade energy is, generally, low-temperature

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heat. Some examples are relatively unconfined thermal energy, such as heat from open fires or flat plate solar collectors, or exhaust heat from steam electric power plants. Liquid and gaseous fuels represent high-grade energy sources.

Anything that requires mechanical or electrical power usually requires a high-grade energy source. Although some developing countries have abundant biomass that could provide adequate total energy, changing low-grade energy to high-grade energy to fuel vehicles and perform other useful work is generally expensive, difficult, and inefficient. For uses that require only low-grade energy, such as space heating, crop drying, sterilization, and pasteurization, direct use of available low-grade energy is usually more efficient.

Thus the overall energy problem facing developing nations—and many developed nations as well—is threefold:

1 To use low-grade energy as effectively as possible

2 To find better ways to convert low-grade energy to high-grade energy

3 To use both natural and synthesized high-grade energy as effectively as possible

Regarding costs, quite often the per unit (e.g., kilowatt-hour) cost of an alternate energy system is greater than the cost from a large, capital-intensive system for the same kind of mechanical or electrical energy. What is often forgotten, however, is that the rural villager in a developing country seldom has a choice between two such systems. Hypothetically, his options for producing electricity might include a wind generator, a solar photovoltaic system, or a small generator requiring fuel. In addition to choosing among these options, he must decide whether he in fact needs electricity to improve his life, or whether he can obtain an equal or better improvement at less risk by spending his time, effort, and money in other ways.

Costs must also be considered at the national level. Most developing countries, by necessity, have strict controls on the use of scarce foreign exchange for the purchase of imported energy, goods, and services. This, in turn, means that energy systems used in developing countries should be manufactured locally to the extent consistent with reasonable economy. Energy-use planning in any developing country should, therefore, determine what can and cannot be produced locally.

Since many of the technologies in this book will involve operational problems, there is a significant need for pilot programs to identify the day-to-day difficulties and provide workable (and publishable) solutions.

ORGANIZATION OF THIS BOOK

The organization of this supplement is similar to that of the original volume. Part I, devoted to direct uses of solar energy, discusses the current state of

the art in photovoltaics and passive and active uses of solar energy in building designs. These discussions do not, of course, cover the range of possibilities of solar energy, but like all the other sections of this book are intended to supplement the original publication.

Part II is concerned with indirect uses of solar energy, including wind energy, energy from falling water, and energy from biomass. The wind energy section reviews the application of small wind power systems, in particular Rockwell International Corporation's wind program, sponsored by the U.S. Department of Energy, which has been testing and operating a wide variety of small wind systems for some years. The section on energy from falling water covers the well-established technology of small-scale hydroelectric systems (which have much applicability now wherever sites are available) and the isothermal hydraulic compression of air, a technology touched on only briefly in the original book. The section on energy from biomass is divided into four parts:

- The anaerobic digestion of human, animal, and agricultural wastes
- The use of aquatic plants as a method of sewage processing and subsequent production of biogas and fertilizer by anaerobic digestion
- The production of alcohols for liquid fuels
- The pyrolytic reduction of biomass to combustible gases, liquids, and char

Part III is concerned with other energy technologies. New developments in the field of geothermal energy are presented. A section concerned with energy storage discusses advanced batteries applicable to wind and photovoltaic systems, and presents a realistic evaluation of "super flywheels," devices that store energy in mechanical form. Completely new material is presented on the possibilities of using pedal power more productively for many jobs by employing special devices that utilize mechanical leverage. This is followed by an up-date on Stirling engines, external combustion engines that could use a variety of solid or liquid fuels, as well as solar energy inputs. Finally, a short discussion is presented on the conversion (or more properly, conditioning) of electrical energy from renewable sources to conventionally usable electricity.

Appendixes to this report include a list of manufacturers of energy-related devices, centers of research and development undertaking work on such devices, and a list of suggested reading.

The original volume of *Energy for Rural Development* included a nontechnical section for readers unfamiliar with technologies it described. Because this supplement does not include such a section, readers may wish to refer to the earlier book for definitions and descriptions of technologies discussed in this volume. To facilitate this, an index to both books is included at the end of this report.

PART *I*

DIRECT USES OF
SOLAR ENERGY

Photovoltaics

Encouraging advances have been made in photovoltaic devices and systems applications during the past 5 years; pricing and efficiency goals have been met and, in many cases, exceeded. In the United States, costs per peak watt dropped from $22/Wp in 1976 to as low as $7/Wp in 1980. The industry is beginning to mature, and a glance at the number of companies currently making either cells or systems reflects the industry's enhanced status (see Appendix A).

Worldwide, research and development activities directed toward photovoltaic devices (solar cells) have increased dramatically. Further, manufacturers of these devices—an industry restricted for the most part to industrialized countries—realize that the production volumes needed to continue the trend of declining manufacturing costs must result from growing demand. With an increase in production volumes and improvement of manufacturing techniques, actual production of solar cells could be transferred eventually to locales in developing countries with adequate potential as manufacturing sites. Initially, however, most developing countries will have to continue to import these devices.

Applications of photovoltaic systems in developed and developing countries have increased in complexity from the initial powering of educational television sets in remote locales, to the powering of water pumps for potable water, to current projects in Mali, Upper Volta, Saudi Arabia, and the southwestern United States to satisfy the other mechanical and electrical power needs of isolated villages and towns. These latter projects will provide baseline data on both the technical aspects (i.e., reliability, maintenance, lifetime, etc.) and, equally important, the socioeconomic impacts of decentralized rural electrification by photovoltaic systems.

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Manufacturing techniques for terrestrial photovoltaic systems have been greatly improved during the last 5 years, resulting in price reductions. Several governments have established programs to meet reduced price goals for silicon-based solar cell modules. The U.S. goals for photovoltaic modules call for a 1986 price of $.70/Wp (in 1980 U.S. dollars) at a production level of 500 MWp. Present quotations of $7-$10/Wp, with an estimated 1980 production of 2 MWp, fall in line with the U.S. goals monitored by the U.S. Department of Energy (DOE). Actual DOE goals call for prices for photovoltaic modules (in quantities of tens of kilowatts) to decrease to $2.80/Wp by 1982, $.70/Wp by 1986, and $.15-$.50/Wp by 1990 (all in constant 1980 U.S. dollars). A yearly budget of well over $150 million per year is being projected over the next 8 years to meet these goals (U.S. Department of Energy 1979).

In France, the Commissariat à l'Energie Solaire (COMES) has established price goals of $1.60-$2.50/Wp by 1985, and COMES and the Centre National de la Recherche Scientifique are each spending $4-$5 million on photovoltaic research. In the Federal Republic of Germany, the prospect of developing export potential stimulated the Ministry of Research and Technology to establish an 8-year, $76-million program to perfect a photovoltaic system utilizing polycrystalline silicon. The program goal is to develop arrays cheaper than $2.40/Wp by 1985. Both Italy and Great Britain have smaller, established research programs. The European Community plans to spend over $23 million in the next 4 years for photovoltaic system development. A major goal is to build several generating plants of 300-400 kW each. Japan established a multimillion dollar project in 1974 to develop a strong manufacturing base for photovoltaic devices by 1985. India has established a price goal of $2.80/Wp by 1985, a price considered to be the threshold for economic water pumping in rural India. Efforts and economic goals of the Soviet Union have not been publicized. An excellent review of many programs under way outside the United States is given in an article by Palz (1978). In addition to these programs, private industry is spending tens of millions of dollars on research and development. (See Appendix B for a list of photovoltaic research programs under way.)

RECENT TECHNOLOGICAL ADVANCES

Single-Crystal Silicon Photovoltaic Arrays

The largest single program attempting cost reductions on single-crystal silicon photovoltaic arrays is the DOE-sponsored Low-Cost Solar Array Project administered by the Jet Propulsion Laboratory of the California Institute of Technology. This program is designed to achieve the DOE goals of $2.80/Wp by 1982 and $.70/Wp by 1986. The program is divided into four tasks (production of polycrystalline silicon material, formation of poly-

TABLE 1   The 1986 price allocation guidelines (1980 U.S. dollars) for the
Low-Cost Solar Array Project

	Goals	
Silicon (polycrystalline)	$14/kg	$.035–.117/Wp[a]
Sheet alternatives:		
–Czochralski ingot and slicing	$28.90/m² of wafer	$.204/Wp
–Heat Exchange Method (HEM) ingot and slicing	$35/m² of wafer	$.246/Wp
–Edge-defined film growth (EFG)	$24.20/m² of wafer	$.214/Wp
–Web dendritic	$39.30/m² of wafer	$.297/Wp
–Silicon on ceramic (SOC)	$20.30/m² of wafer	$.196/Wp
Cell fabrication	$21/m² of cells	$.141–.192/Wp[a]
Encapsulation materials	$14/m² of module	$.098–.139/Wp[a]
Module assembly	$14/m²	$.098–.139/Wp[a]
Module totals		$.70/Wp

[a]This range is caused by the use of different sheet technologies.

crystalline silicon into large, single-crystal sheets, encapsulation, and development of production processes and equipment). Some associated support activities are engineering, operations, and project analysis and integration. ,

The goals of the overall Low-Cost Solar Array Project are summarized in Table 1. The goals are aggressive, but many manufacturers are confident that the 1986 DOE goals are attainable.

In France, the Centre de Recherches Nucléaires and the Laboratoires d'Electronique et de Physique Appliquée are looking at improved or low-cost diffusion techniques for the manufacture of single-crystal silicon. Most of the remaining industrialized countries are monitoring the single-crystal programs and preparing for eventual entry into the marketplace.

Multigrained Silicon and Amorphous Silicon

Two other outgrowths of silicon solar cell technology have emerged: the use of multigrained silicon and amorphous silicon. The multigrained (or polycrystalline silicon) cells have been demonstrated to have high efficiency (11 percent) and are being mass-produced by two companies. Heliotonic GmbH, a subsidiary of Wacker-Chemitronic GmbH (FRG), is producing a cast polycrystalline silicon in brick form. With government support, Wacker has established a program with AEG-Telefunken in which Wacker supplies the polycrystalline silicon bricks and Telefunken produces the modules. The cells will cost less than the Czochralski-grown, single-crystal cells, and the process is more amenable to mass production with higher production rates. Semix,

Inc. (a subsidiary of the U.S.-based Solarex Corporation), which is manufacturing polycrystalline silicon in the same form (a cast brick), has set up a production facility, and reportedly is making a 15 percent-efficient cell at a cost of $4-$6/Wp. Although efficiencies that high have only been documented in the laboratory, the price range is reasonable compared to single-crystal cell prices.

Development of thin-film polycrystalline silicon cells is still in the research stage. DOE, through the Solar Energy Research Institute (SERI) in Golden, Colorado, is sponsoring 17 contracts at a total cost of $2.9 million. More research needs to be done even before cost estimates can be made for thin-film polycrystalline silicon cells.

Cells based on amorphous silicon-hydrogen alloys are an even more infant technology than the thin-film silicon, yet hold great promise to provide a very low-cost cell. A principal advantage is that such cells would absorb light many times more effectively than single-crystal silicon. DOE, through SERI, is devoting almost $3 million in 17 contracts to attaining an efficiency of 7 percent for present amorphous cells.

Japanese laboratories are actively developing amorphous silicon cells, and efficiencies of 4.3 percent have been reported by Sanyo. Great Britain is also actively pursuing the amorphous silicon fields at both Dundee University (which has reported a laboratory cell efficiency of almost 5 percent) and the University of Sheffield.

Cadmium Sulfide/Cuprous Sulfide

Materials other than silicon can be used for photovoltaic devices. Cadmium sulfide (CdS) in conjunction with cuprous sulfide (Cu_2S) has been used for over 15 years for photovoltaic conversion. Theoretical efficiencies of 16 percent have been calculated, but only a 9.1 percent conversion efficiency has been reported, with practical limits felt to be just over 10 percent.

The importance of encapsulation was realized when the deleterious effects of humidity on bare cells were discovered. This discovery led to research on the stability of cells. SES, Inc., a subsidiary of Shell Oil Co. (USA), has established a production facility and has been field testing new cell designs for the past 2 years. They anticipate making the modules commercially available and cost-competitive with the silicon modules by the early 1980s. DOE hopes to demonstrate a thin-film cell by 1990 that can be produced for $.15-$.40/Wp. Both SES, Inc. and the Institute of Energy Conversion (IEC) of the University of Delaware find these figures attainable, but IEC feels that a price of $.50/Wp should be possible by 1984.

Studies by Westinghouse (USA) indicate that 1986 prices for the CdS/Cu_2S cell will range from $.75 to $.86/Wp for an 8 percent-efficient module with a size of 2 ft (.61 m) x 8 ft (2.44 m). The University of Stuttgart in the Federal Republic of Germany is establishing a pilot production line to pro-

duce cells with efficiencies close to 7 percent. Activities are also under way in France, Belgium, Mexico, Great Britain, Italy, Iran, India, and Japan to further the development of CdS-based cells.

Screen Printing and Spray Deposition

Two of the most exciting new prospects in the fabrication of cell materials are screen printing and spray deposition. The screen-printed cell has recently emerged in Japan. Screen printing is a very inexpensive process that is amenable to mass production. Reported efficiencies of over 8 percent have prompted DOE to encourage research activities in the United States on this process as well as on the spray deposition technique, a low-cost technique in which the CdS is sprayed onto the substrate and heated to form the active layer.

Gallium Arsenide

Another material that has achieved commercial feasibility is gallium arsenide (GaAs). Like silicon, this material is single-crystal, but it is capable of higher conversion efficiencies than silicon and is much more costly to process. GaAs is being considered for applications where concentrated sunlight is used; however, concentrators might not be used extensively in developing countries because of the more complex system required to track the sun (as opposed to the stationary flat-plate modules).

Of greater significance to flat-plate technology is the research being conducted to develop either thin-film or amorphous GaAs. The thin-film (or polycrystalline) GaAs effort has achieved efficiencies of 6-9 percent. Cal Tech's Jet Propulsion Laboratory is also working in this field, and hopes to reach 15 percent efficiency at $.70/Wp. Amorphous GaAs work is being started at Harvard University, but results will probably not be available for several years. Work on GaAs is also being undertaken in France, Japan, Great Britain, and by the Commission of the European Communities, principally in concentrator applications.

Other Research

Research is being supported in such areas as electrochemical photovoltaic cells, and with cadmium telluride, indium phosphide, cuprous oxide, polyacetylene, zinc phosphide, cuprous selenide, and a variety of lesser-known materials.

Balance of System (BOS)

A field of increasing importance, and one that has been neglected for years, is "balance of system" of a photovoltaic installation. BOS represents all of the system except the photovoltaic modules and includes structures, power

conditioners, and storage. Work is being done to develop new low-cost support structures, increase efficiencies of power converters, and lower the costs of storage, as well as to examine new storage techniques. As these programs advance, the prices of complete systems could drop and system reliability will be improved. Present lifetime expectations are 20 years for modules, 10-12 years for power converters, and 8-10 years for storage (if batteries are used). It is hoped that costs of complete systems without storage will reach approximately $2/Wp by 1986.

Information on photovoltaic devices has become increasingly available over the last several years, but information on the needs of people in developing countries has only recently begun to flow to manufacturers. (See Appendix C for listing of recent publications on photovoltaics.)

RECENT APPLICATIONS OF PHOTOVOLTAICS IN RURAL AREAS

Telecommunications

In 1975, over 4,000 photovoltaic-powered educational television sets (ETVs) were installed in Niger and the Ivory Coast (Weiss 1976). The success of this system in education in rural villages has been demonstrated, and expansion is anticipated. An Ivory Coast firm projecting the production of more than 13,000 photovoltaic-powered sets in the next decade (Sloop and Watt 1979). Weiss and Pak (1976) estimate a worldwide demand of 10 MW for ETVs by the early 1980s and conclude that photovoltaic-powered sets presently have an economic advantage over alternative systems.

Another remote telecommunications application, operated since 1977 by the Mexican government, utilizes 36 W of photovoltaic power, operates a rural telephone station, and is unique in that all components of the system were designed and produced in Mexican laboratories. It is anticipated that 70 more stations will be installed in rural areas and a solar cell pilot production line is being set up to produce 20 kW/yr (Perez, *et al.* 1978).

Irrigation

In Mead, Nebraska, a 25-kWp irrigation system, larger than most rural applications, has provided important base-line information on silicon module reliability and system design (Figure 1). This project, sponsored by DOE, has shown a module failure rate of 2 percent in 2 years (Forman 1979) and has provided important statistical information on such aspects as soiling and cleaning (Forman 1978). In the 2 years that it has been in operation, the system has provided power with less down time than the local utility. Fur-
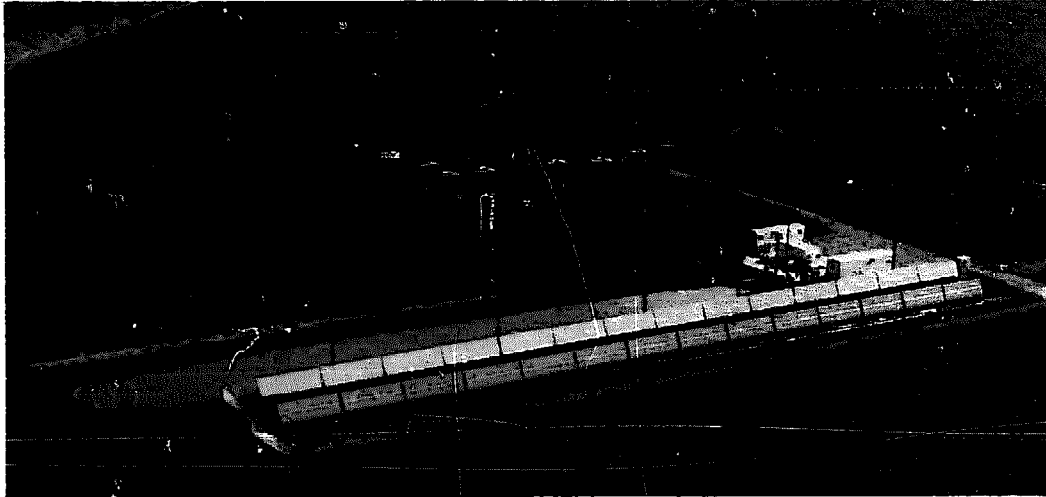
FIGURE 1 A 25-kWp photovoltaic-powered irrigation system at Mead, Nebraska, sponsored by DOE.

ther U.S. applications of photovoltaic devices to irrigation systems have been identified and analyzed (see Twersky and Fischbach 1978).

A study pertinent to irrigation systems conducted by the U.S. National Aeronautics and Space Administration (NASA) at its Lewis Research Center states that under present cost goals, a utility grid extension of greater than 5-7 mi (8-11 km) makes the use of photovoltaic systems attractive (Rosenblum, *et al.* 1978b). The study also projects a 6-GWp market in foreign water pumping applications, and a significant market penetration in 1981 or 1982 as systems become economically feasible. But the study cautions that a 4-year lead time is necessary to evaluate and test planned systems, and that those systems will be paced by costs, government attitudes, and sources of funding.

Several other sources have also presented prospects for photovoltaic power in pumping applications in rural areas (see Agarwal 1978; Sangal, *et al.* 1978; Campana, *et al.* 1976).

The Republic of Mali has had extensive experience with photovoltaic systems (W. Mackie, SERI, Golden, Colorado, personal communication 1979). At least five systems have been installed, most with French assistance, and are used primarily for pumping water in rural areas (Figure 2). Figure 3 shows a 16-kWp system being installed at a hospital. This system will provide power for water pumping, refrigeration for pharmaceuticals, and lighting and cooling for the operating rooms.

Under a program financed by the U.S. Agency for International Development (AID) and administered by the Solar Energy Research Institute, four more water pumping stations will be installed in four regions. The 2-kW photovoltaic array-powered stations will also feature 20-30 m^3 (706-1,059 ft^3) of water storage, and are a part of a completely packaged pumping
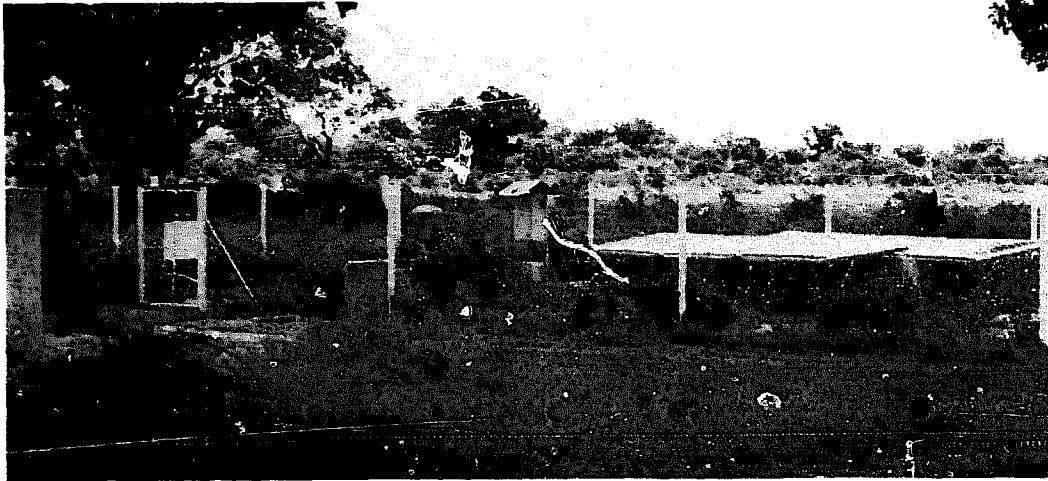
FIGURE 2   Remote photovoltaic-powered water pump in Mali. (Photograph courtesy of W. Mackie, SERI, Golden, Colorado)
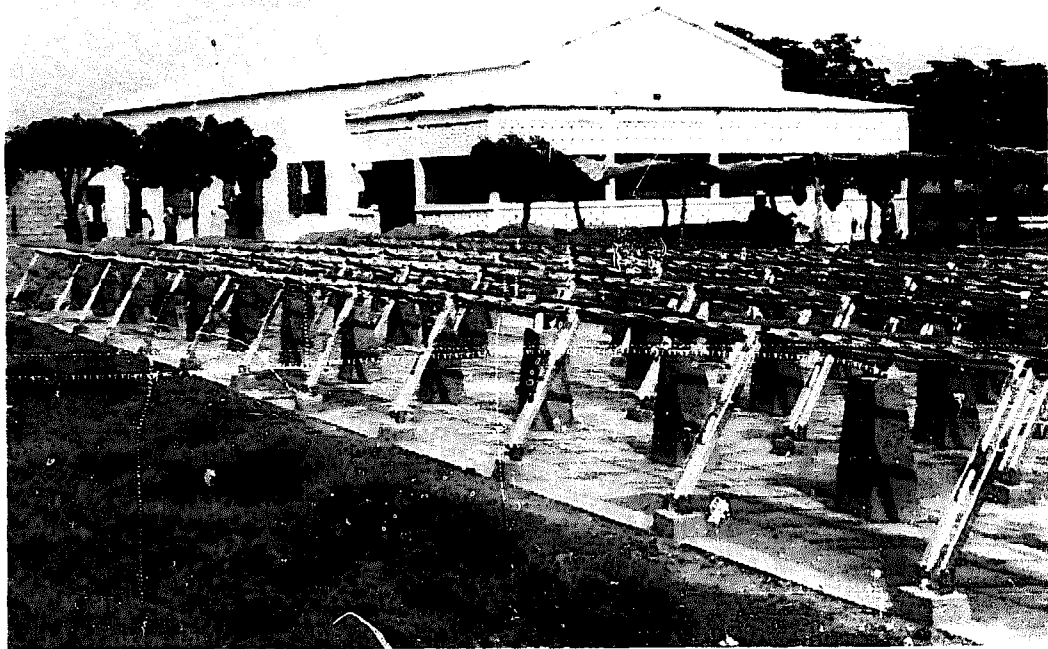
FIGURE 3   A 16-kWp photov...taic array being installed at the Djiola Hospital in Mali. (Photograph courtesy of W. Mackie, SERI, Golden, Colorado)

system offered by Pompes Guinard of France. No electrical storage is planned for the systems, which will be installed by Peace Corps Volunteers.

Total Village Power Needs

Photovoltaic systems that meet the major electrical power needs of a village are also being implemented. It has been estimated that a 10-kWp system is

necessary to meet the initial total demand of a typical village of 500 in Upper Volta or Ethiopia (Kern 1978; BDM Corporation 1978). These demands would include potable water supply, irrigation, ETVs, school/shop lighting, milling, refrigeration, and site-specific light cottage industry applications.

One study of the use of photovoltaic power systems in 19 developing countries concludes that those systems can presently operate at an energy cost of $1.60-$2.20/kWh (Hein and Siddiqi 1978). This cost will likely be reduced to $.25-$.50/kWh by 1983-85. The study also points out the advantages of the modularity of photovoltaic systems in overcoming the problem of initial high capital outlays for unused central station capacities.

Two further studies have examined the market potential and costs of village power systems. In the first, the authors estimate a potential of 10 GWp for foreign market applications in village power, with an average usage of 24 Wp per person (Rosenblum, *et al.* 1978a). The authors conclude that if DOE price goals are met, 20 GWp could be required by the year 2000. A second study analyzes the energy costs of photovoltaic systems versus diesel and utility extension (Rosenblum, *et al.* 1979). As shown in Figures 4 and 5, photovoltaic systems are presently competitive in applications
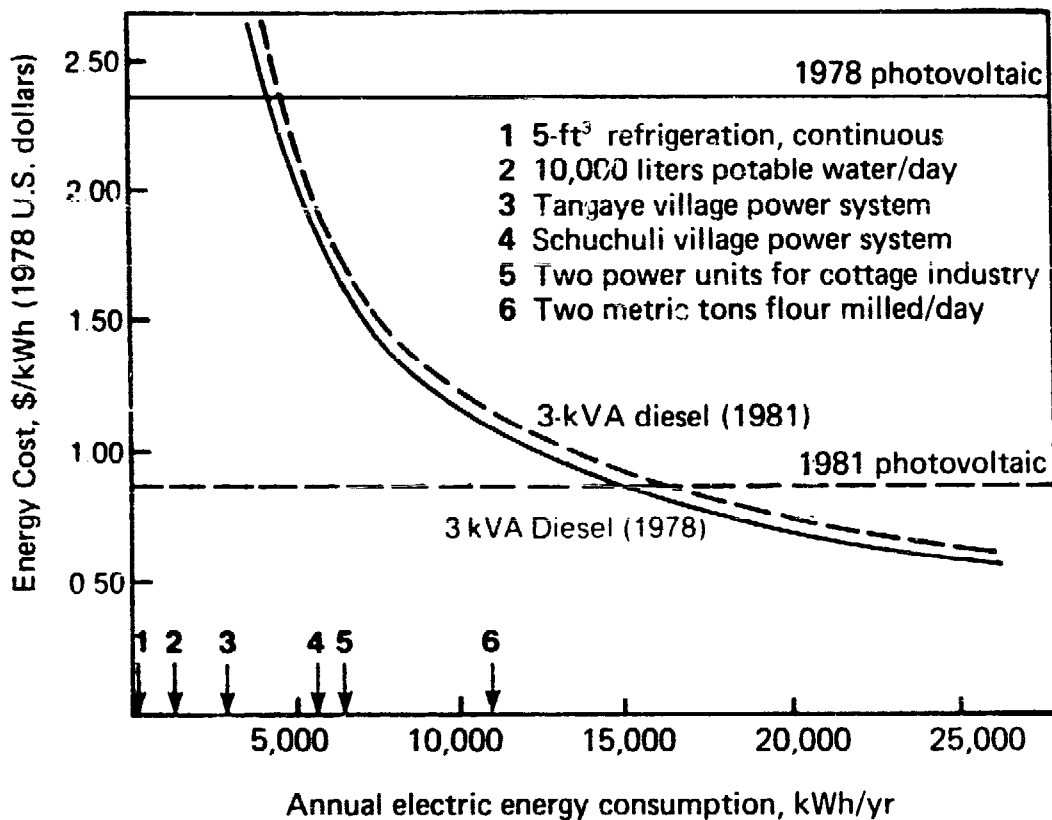
FIGURE 4 Photovoltaic and diesel energy cost comparisons. (Source: Rosenblum, *et al.* 1979)
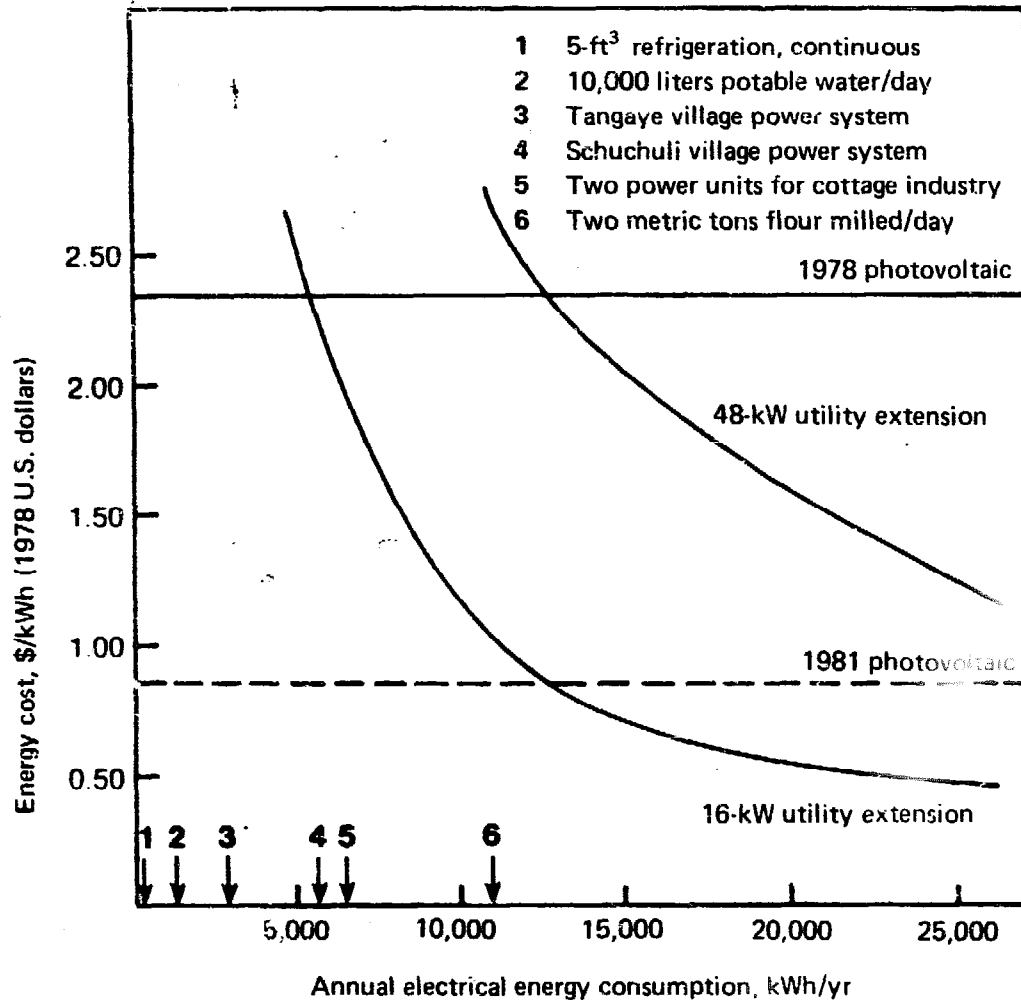
FIGURE 5   Comparisons of photovoltaic and utility extension energy costs. (Source: Rosenblum, *et al.* 1979)

requiring less than 5,000 kWh/yr ($\sim$1 kW capacity), and by 1981 will be competitive for many larger applications.

NASA-Lewis Research Center has successfully implemented two photovoltaic stand-alone village power systems (Rosenblum, *et al.* 1979; Ratajczak and Bifano 1979). The first of these two systems was installed on March 1, 1979, in Tangaye, Upper Volta. This project, sponsored by AID, is designed to study the social and economic effects of providing an electric-powered water pump and grain mill, which relieves the village women of their daily 1- to 2-hour routine of hand flour milling and water lifting. Financial considerations limited the photovoltaic system size to a 1.8-kWp, 120-volt DC array, with 540 amp-hr of battery storage (Figure 6).

The second application is a 3.5-kWp, 120-volt DC photovoltaic array installed in the village of Schuchuli, which is inhabited by about 100 people and located on the Papago Indian reservation in southwestern Arizona. The

FIGURE 6   A view of the 1.8-kWp solar cell arrays (right center) in the village of Tangaye, Upper Volta, that power a water pump and grain mill. The pump supplies the water-dispensing tank (center). The grain mill, operated as a cooperative by the village, is located in the building behind the tank. This installation, funded by AID and the Government of Upper Volta and under the technical management of the NASA–Lewis Research Center, is intended to explore potential new energy. (Photograph courtesy of NASA–Lewis Research Center, Cleveland, Ohio)

power supply is used for water pumping, lighting, refrigeration, and services for village housekeeping.

The system, consisting of 24 photovoltaic panels, was inaugurated in December 1978. Direct-current systems were used to avoid the power losses, costs, and additional complexities of the DC-AC inverters, and battery storage of 2,380 amp-hr capacity was incorporated to provide power at night or during low insolation periods. Portions of the array may be disconnected automatically to prevent overcharging of the batteries, and automatic load shedding prevents excessive discharging of the batteries.

Saudi Arabia and the United States have undertaken a joint project to provide a 350-kWp system to supply the electrical needs of Al Jubaylah in Saudi Arabia. This system, with complete electrical control and battery storage, will have a diesel generator back-up to supply additional power needs. Although presently in the design stage, it is anticipated that the system will be completed by 1983, with technological transfer playing a significant role in the project.

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Sun/Earth-Tempered Building Designs

The principal function of a well-designed building is to provide human comfort. An architecturally integrated design, combining good thermal characteristics and concern for human comfort and aesthetics, is the emerging proper house design in industrialized countries, although it has been the basis for construction of dwellings in many parts of the developing world for centuries.

When heating is needed to maintain human comfort, a *sun-tempered design* uses a building as solar collector and stores heat within the mass of the building. One form of this design, *passive solar*, maximizes a building's solar gains, minimizes thermal losses, and maintains human comfort without the use of mechanical energy. It includes such elements as solar energy collection and thermal storage, control, moderation, and distribution. An *active solar* system requires equipment such as solar collectors, heat storage containers, and electrical or other man-made energy to power pumps and fans for air control and distribution.

Sun-tempered designs differ principally in the placement of the thermal storage mass and retrieval of the stored heat by reradiation and natural convection. House designs that make use of solar energy range from strictly passive to strictly active, with many designs falling into the hybrid class that combines elements of active and passive systems.

Earth-tempered (or earth-sheltered) designs make use of the earth to moderate extremes in the ambient temperature (Figure 7). Several feet below the earth's surface the temperature is relatively constant year-round, and very constant diurnally. At this level, the temperature is also higher than the ambient air temperature in winter and cooler in summer. Covering or surrounding a building with earth provides an effective "flywheel effect," which maintains more uniform interior temperature on a diurnal basis. In addition,

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FIGURE 7   Modern, earth-sheltered home near Stillwater, Oklahoma. (Photograph courtesy of Energy Engineering Laboratory, Oklahoma State University)

earth sheltering of a building reduces seepage of heated or cooled air through fissures in the structure.

In most developing countries, the existing, traditional rural architecture has usually met environmental constraints by making use of the materials, labor, and fuel available. For example, a raised hut, open on all sides for natural ventilation, with a large overhanging roof for shade, an open interior for air circulation, and built entirely of indigenous materials, is a building form found widely in the hot, humid climate of Southeast Asia.

Many of the building designs described here briefly are directed toward providing heat and thus may be more applicable in those developing countries with high altitudes or in the northern latitudes. Furthermore, since electricity is often not available in these areas, they are restricted to the use of strictly passive solar designs. Should photovoltaic cells or some other decentralized sources of electric power become economically available in developing nations, hybrid or active solar designs could come into eventual use for both heating and cooling, particularly in schools, public office buildings, etc. For that reason, they are included here.

SUN-TEMPERED DESIGNS

Features common to all passive solar sun-tempered building designs include good insulation; large glass windows (glazings) facing south (in the Northern Hemisphere); small north, east, and west windows; a large interior thermal

mass; and various other thermal conservation techniques (e.g., double glazing, night-time insulation of windows, air-lock entrances). Some form of auxiliary heat is required; wood stoves have been popular with and aesthetically pleasing to owners of passive solar homes.

Direct Gain Design

This design uses large south-facing (north-facing in the Southern Hemisphere), double-glazed and/or night-insulated windows to collect the incoming solar radiation. To carry out this simple, potentially inexpensive design, a certain amount of wall and floor surface area must be constructed of materials appropriate for thermal storage, such as adobe, brick, concrete, or ceramic tile. The extent of the surface area is more critical than the thickness of the materials. The mass of the building prevents the interior from overheating during the day and overcooling at night. Building mass is most effective as thermal storage if it is directly exposed to the incoming solar by radiation. This necessitates use of bare stone floors and masonry walls for best thermal performance. Insulated drapes or shutters that can be opened when the sun is available and closed at night or during extended periods of cloudy weather are helpful in reducing heat losses through the large south window and in maintaining a radiantly uniform environment.

Mass Wall Design (Trombe Wall)

Trombe walls (named after French engineer Felix Trombe) are generally constructed of adobe, stone, or concrete, with vents top and bottom. For this design. a vertical, massive wall is constructed directly behind a south-facing window to absorb and store the incoming solar energy (see Figure 8). Typically an air gap of about 4 in. (10.16 cm) is allowed between the interior
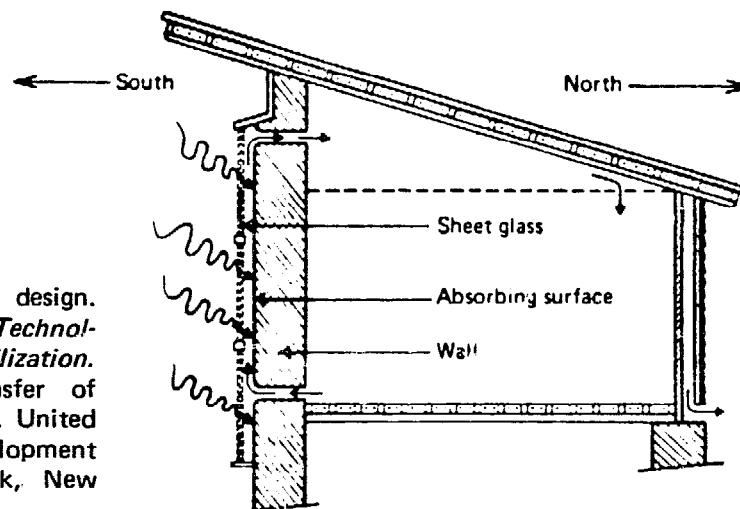
FIGURE 8 Mass wall design. (Source: UNIDO (1978) *Technology for Solar Energy Utilization.* Development and Transfer of Technology Series No. 5. United Nations Industrial Development Organization, New York, New York, USA, p. 23.)

surface of the window and the exterior surface of the wall, which is usually painted black for maximum absorption. The outer surface of the wall and the air gap become quite hot on sunny days, approximately 130°-160°F (55°-70°C), even in cold climates.

Heat is transferred into a building in two ways. If heat is required during the day, vents are placed high and low in the wall to transfer heat (approximately 30 percent) immediately by convection. The remaining heat is conducted through the wall. Depending on wall thickness, which is typically 8-16 in. (20-40 cm), the inner surface reaches its maximum temperature approximately 6-8 hours after maximum irradiation. Thus heat is available in the evening when heating loads on the building tend to be greatest. Mass walls are a popular retrofit design.

Mass walls can also be constructed of containers filled with water. Heat is transferred more rapidly through these walls than masonry walls. However, the high heat capacity of the water and the high storage effectiveness achieved as a result of the isothermal tendencies of the fluid permit energy to be stored at lower temperatures. This increases the efficiency of the water wall system somewhat beyond that of the mass wall system.

Greenhouse Designs

A solar greenhouse does not need large amounts of man-made heat for proper operation. It requires double glazing and/or night insulation, a storage mass, the proper glazing tilt (a compromise between heat and plant production in all but the months around the winter solstice), and an insulated upper roof and northern wall. For an attached solar greenhouse, the northern wall is replaced by an adjoining structure that receives excess heat from the greenhouse during the day. Solar greenhouse designs have become popular in recent years, particularly to those undertaking solar retrofit of structures.

Hybrid Designs

Such designs can be hybrids of different passive designs, or a combination of passive and active solar components. A common example of the latter is based on a collector and some storage in an architecturally integrated design (e.g., direct gain or greenhouse), with the control and distribution of reserve heat storage handled by active means (e.g., a rock storage bin thermally charged and discharged by means of thermostatically controlled air fans).

EARTH-TEMPERED DESIGNS

Earth tempering of a building reduces exposure of the building skin to swings in the ambient temperature, both diurnally and seasonally, and reduces heating or cooling losses through cracks in the building's thermal envelope (see Figure 7).

Earth-tempered buildings should have well-insulated roofs and upper outside walls in order to minimize heat transfer to the earth that is closest to the ambient air and hence shows the greatest temperature changes (seasonally and diurnally) and differences from the interior air temperature. To retain the earth, the walls and roof must be strong and massive. Stone, concrete, and heavy timbers are widely available materials that have been used successfully. Good drainage and waterproofing are necessary to prevent dampness and condensation problems.

Earth itself is a poor insulator, with a relatively high thermal conductivity. Because of its high heat capacity, earth does have a large thermal reactance to varying temperature differences across its boundaries; that is, earth tempering resists changes in temperature between inside and out.

Earth Roof Designs

An earth roof, usually combined with piling up of earth (berming) around the walls of a dwelling (generally done on the north, east, and west walls of the structure in the Northern Hemisphere), further reduces temperature swings. The thickness of the earth roof should be no more than about a meter (3.2 ft) for structural reasons, unlike earth berming where earth can be deposited several meters thick in a lateral direction. The use of (exterior) insulation under earth roof coverings is even more crucial than with earth-bermed designs.

Underground Designs

Underground designs are the extreme in earth-tempered schemes. The walls and roof are totally underground, often several meters or deeper, and light is admitted through skylights or clerestories. In designs using passive solar features, the south wall is exposed to the winter sun. Underground structures may be dug into the south-facing side of a hill or constructed in a flat area with total earth berming (no north, east, or west windows) as a final step. The method selected depends most critically on the depth of the water table.

Earth Cooling

Earth cooling is one of the benefits of earth-tempered designs, particularly in areas where high humidity does not permit effective cooling by evaporation or radiation from above-ground structures. Earth roofs are usually planted in grasses and small plants which help cool the building and stabilize the roof.

Another cooling method is use of air-cooling tunnels through which outside air is drawn from some cool spot (e.g., the shaded northern side of a hill) and vented into the northern or cooler side of the building. Warm air exits from roof vents, drawing in cooler air by thermosiphoning. Cooling by

this method is currently being investigated, since the cooling reservoir is depleted more quickly in an earth tunnel than in underground designs. Because the volume of earth that can interact with the fresh air on a daily thermal discharge/recharge cycle is limited, earth tunnels require careful design, both for thermal transfer and for dehumidification. Earth tunnels should be particularly attractive for use with above-ground passive solar buildings in humid climates.

PART II
INDIRECT USES OF SOLAR ENERGY

Wind Energy

Cost projections for advanced wind machines under development show that the gap between wind energy costs and the cost of utility power is narrowing, but largely due to dramatic increases in the prices of oil, coal, and nuclear energy. Unfortunately, these increased energy costs will eventually result in higher material and production costs for wind systems.

Wind system manufacturers have shown increased interest in exporting their products. Aerowatt (France), Lubing (FRG), and Dunlite (Australia) systems are widely accepted throughout the world. However, in general, U.S. manufacturers have not yet begun to investigate foreign markets, and few of them have even the beginnings of a foreign distribution network in place. This situation may change dramatically within the next 5 years.

This chapter describes high-technology advances that, by reducing wind energy costs and increasing machine reliability, may make manufactured wind systems attractive to developing countries in the near future. Low-technology advances that are now applicable to developing countries are also described, including information on newer "home-built" systems that can be constructed using locally available materials and labor. In addition, this chapter includes a description of some of the accessories now available for wind machines, an overview of commercially available wind machines, and a description of the research programs under way in several countries.

Increased interest in wind energy in the United States has resulted in the publication of numerous helpful books, reports, and other publications. For developing countries, the most informative among these are *Wind Power for Farms, Homes and Small Industry* (Park and Schwind 1978) and *A Siting Handbook for Small Wind Energy Conversion Systems* (Wegley, *et al.* 1978) (see Appendix C for a complete listing).

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HIGH-TECHNOLOGY ADVANCES

No important changes in the configurations of currently available wind systems have appeared since 1976, and recent advances have been made using technology that has been known for at least 40 years. (See Appendix A for a listing of manufacturers of wind energy systems and Appendix B for a listing of research institutions addressing wind energy systems.)

Changes that have occurred in the state of the art for wind turbine generators (WTGs) during the past 4 years, include (1) replacement of the upwind rotor with the downwind rotor as the most commonly used horizontal-axis configuration, (2) emergence of the vertical-axis rotor as a major competitor with the horizontal-axis machine, and (3) growing prevalence of alternating current-output WTGs. Other important developments are the increasing role of governments (particularly the United States) in supporting development of these systems and advances in mechanical-output wind machine technology.

Electrical-Output Wind Machines
(Wind Turbine Generators)

Downwind Versus Upwind Rotors. Upwind machines have dominated the world market for 40 years and are, for the most part, still available. Increasingly, however, downwind rotors are being used in the design of wind machines. Such rotors can reduce system complexity and, by eliminating the tail and tail-furling mechanisms, could be less costly. Systems using downwind rotors include Enertech (Figure 9), Grumman, Kedco, Whirlwind, and Storm Master (Wind Power Systems, Inc.)—all developed within the last 4 years by U.S. manufacturers. In addition, all but one of the small horizontal-axis prototypes being developed under U.S. Government sponsorship have downwind rotors.

Despite the potential economic advantages of the downwind rotor, its superiority over tail-oriented systems has not been shown from an operational standpoint. System reliability, performance, and cost should be considered more important than rotor configuration when selecting or designing a system.

Darrieus and Other Vertical-Axis Rotors. The Darrieus vertical-axis rotor (Figure 10) has received considerable attention in the United States and Canada. First designed by J.G.J.M. Darrieus in 1927, this system has three advantages over horizontal-axis systems because it does not require: (1) a rotor-orientation system, since its entire rotor area is always exposed to the wind; (2) slip rings to pass energy to the base of the tower as with horizontal-axis systems; and (3) pitch control for its blades. Inherent in the third advantage are two disadvantages of this system. Because the orientation of the

blade with respect to the axis remains stationary throughout each revolution, the angle at which the wind strikes the airfoil is not always optimum, which results in reduced performance as compared with ideal horizontal-axis systems. Further, because one or both of the blades are not in an optimum position at any given point in the rotor path, the Darrieus needs start-up assistance, provided either by an auxiliary motor or an auxiliary rotor that self-starts. Theoretically, the Darrieus rotor is inherently stronger than horizontal-axis rotors because the curved blades are attached at each end of the central mast.

Sandia Laboratories (Albuquerque, New Mexico), under a contract with the U.S. Department of Energy (DOE), has developed a troposkein (turning rope) Darrieus blade to increase rotor life and reduce dynamic frequency coupling between the rotor and tower. Dominion Aluminum Fabricating, Ltd. (Canada) has been marketing 14-kW and 34-kW systems for several years. Alcoa Corporation (USA) has developed an inexpensive blade extrusion method for troposkein Darrieus rotors and is the major source of blades for machines produced by Tumac, Dynergy, and other U.S. manufacturers.
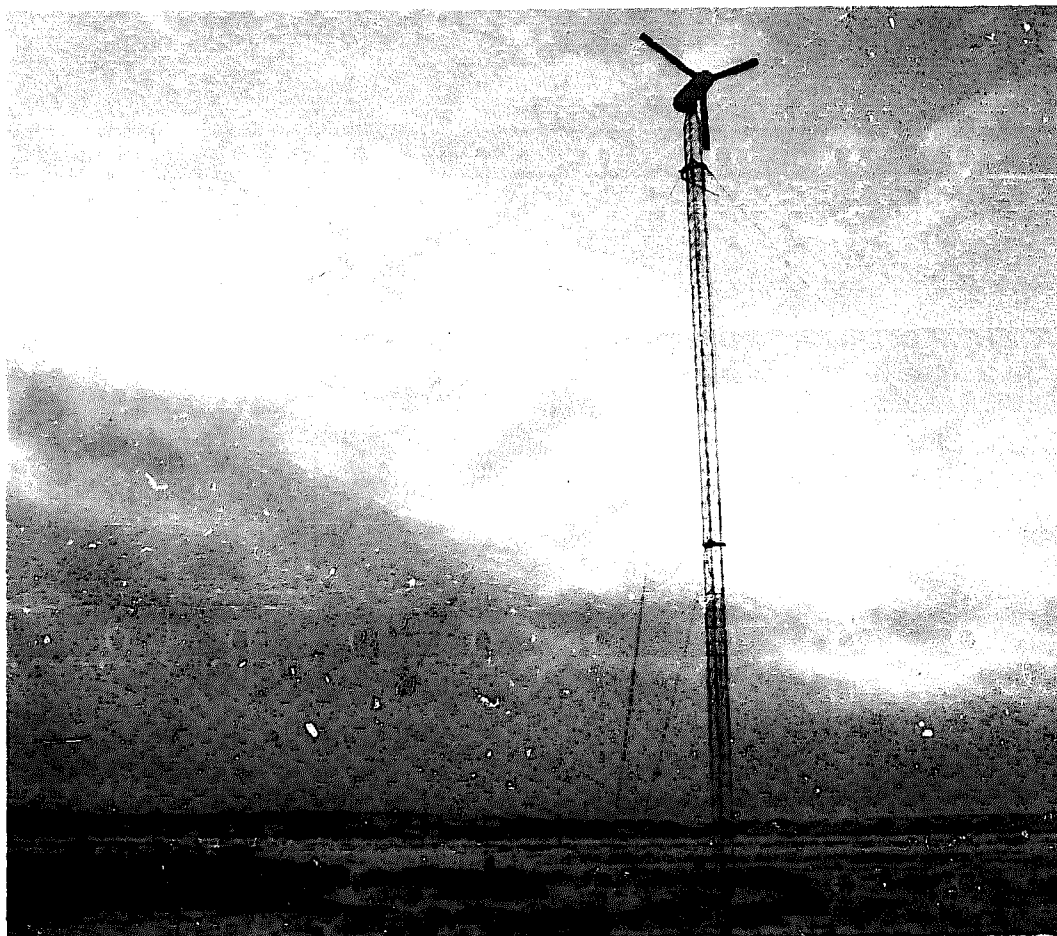
FIGURE 9   Enertech 1500 downwind turbine generator.
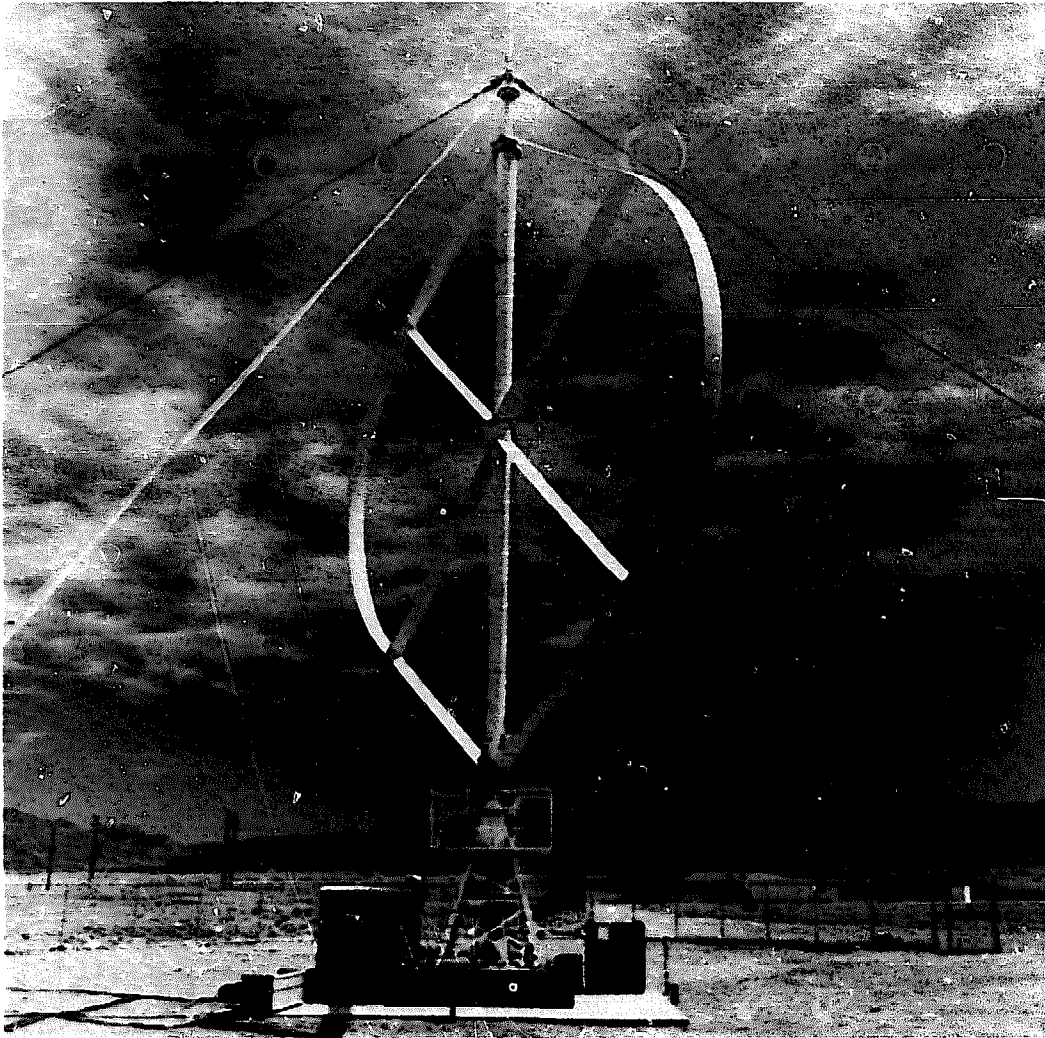
FIGURE 10   A 17-m (56-ft) Darrieus wind system located at Sandia Laboratories, Albuquerque, New Mexico.

Several U.S. companies (e.g., Pinson Energy Corporation and McDonnell Douglas Corporation) have developed vertical-axis "cyclogiros," which overcome the performance losses of the Darrieus by using blade pitch regimens that are scheduled throughout each rotor revolution (Figures 11 and 12). However, the increased performance of these machines over the Darrieus is somewhat offset by the complexity of their mechanical and electrical control systems.

In Great Britain, P.I. Enquiries, Ltd. is marketing the Variable Geometry Vertical-Axis Wind Turbine, which has "coned," not adjustable-pitch, blades for protection in high winds. Coning reduces the swept area of the rotor, which in turn reduces blade loading and angular velocity (revolutions per minute). One advantage of this system is that only one strut is used to support each blade instead of the two commonly used in cyclogiro systems. Coning is
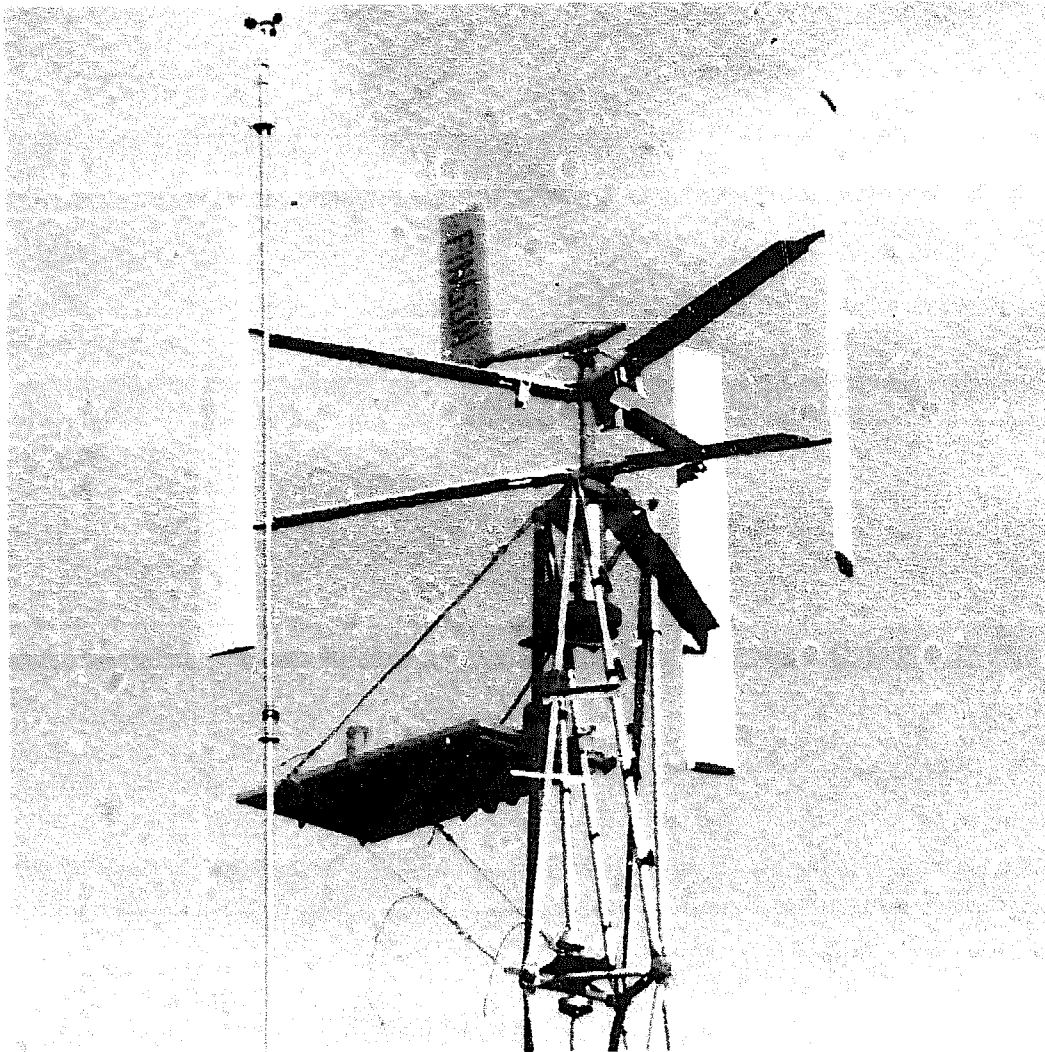
FIGURE 11   Pinson C2E Cycloturbine (4 kW).

centrifugally activated at a prescribed rpm by springs attached to the blades by long tie-wires.

A simpler vertical-axis design—one that may be particularly useful to developing countries because of its structural simplicity and ease of manufacture—is the straight-bladed, pitchless, vertical-axis wind turbine. Its rotor blades are only attached at their bottom ends to the generator shaft; thus no central tower is required as in Darrieus systems. A major disadvantage of this machine is the loss of swept area compared with horizontal-axis blades of equal length, which results from the fact that the swept area of this rotor describes a cone, whereas the swept area of a horizontal-axis wind turbine describes a circle. This loss must be made up by eliminating slip rings and by using a blade pitch mechanism and/or very inexpensive blade materials. A prototype has been developed in the United States by the Oregon Offshore Public Power
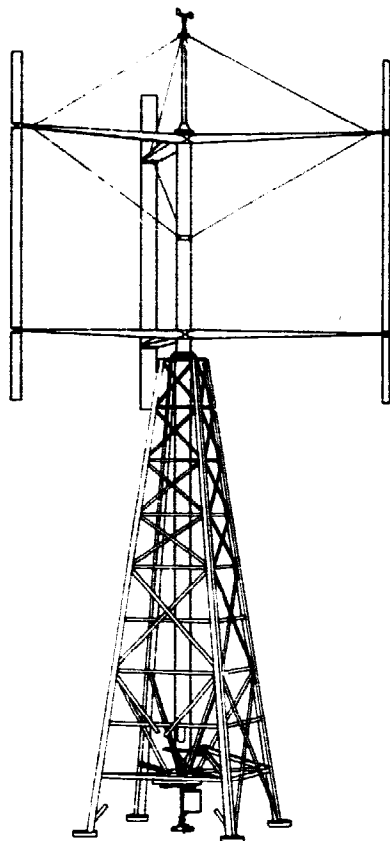
FIGURE 12   McDonnell Douglas 40-kW Giromill for electrical or mechanical applications (prototype).

Services*; however, little or no controlled testing of this design has been performed.

Vertical-axis machines currently available cost from $9,000 to $15,000 for a 2-4-kW unit compared with $3,000-$8,000 (1979 prices) for horizontal-axis machines of similar output.

Electrical-Output Systems. Of the more than 50 electrical-output models available in the United States during 1979, over half had generators that produced alternating current. Both synchronous and induction generators are used for these machines, but one drawback of the latter, especially for use in developing countries, is that they must be tied to an electrical grid to produce the 60-Hz (or 50-Hz) power commonly used by appliances and motors. Power from synchronous generators can be used directly, but they are more costly than induction generators.

The simplest system for AC-output utility interconnections (from the user's point of view) is now represented by the 3-blade downwind Enertech 1500, a 1.5-kW (rated) system that drives a 1.65-kW induction generator. The machine's integrated solid-state control system can be connected directly to a utility through a simple 3-pronged plug inserted in a standard electrical outlet.

*4000 N.E. Columbia Road, Portland, OR 97303, USA.

U.S. Government-Sponsored Development

In 1976, in an effort to stimulate private industry's production of wind machines of appropriate sizes and characteristics for high-potential applications, the U.S. Energy Research and Development Administration contracted with Rockwell International for the development of a national test site for small windmills at Rocky Flats, near Golden, Colorado. As part of the overall project's hardware development program, outside organizations were funded to design and develop small wind energy conversion systems (SWECS) in three power ranges—1-2 kW, 8 kW, and 40 kW (Table 2). Although the prototypes developed under this program are high-technology units with relatively sophisticated power and control systems, they could soon become applicable in developing countries.

TABLE 2 Characteristics of small wind energy conversion systems (SWECS) currently being developed in the United States (tentative).*

	Developer	kW output @ 20 mph	Diameter	Generator	Configuration/ features
	Enertech Corp.	2	5 m (16.4 ft)	Alternator	2-Blade downwind, horizontal axis, variable pitch
High reliability (1–2 kW)	North Wind Power Co., Inc.	2	5 m (16.4 ft)	Direct-drive alternator	3-Blade upwind, horizontal axis, cyclically fixed pitch
	Aerospace Systems Pinson	1	2.4 m X 4.6 m (8 ft X 15 ft)	Alternator	3-Blade, vertical axis, cyclically variable pitch
	Windworks, Inc.	8 kW	10 m (33 ft)	Direct-drive alternator	3-Blade downwind, horizontal axis, variable pitch
8 kW	United Technologies Research Center	9 kW	9.5 m (31 ft)	Induction	2-Blade downwind, horizontal axis, variable pitch
	Grumman Energy Systems	10 kW	10 m (33 ft)	Induction	3-Blade downwind, horizontal axis, variable pitch
40 kW	Kaman Aerospace Corp.	40 kW	19.5 m (64 ft)	Induction	2-Blade downwind, horizontal axis, variable pitch
	McDonnell Douglas Corp.	40 kW	12.8 m X 17.7 m (42 ft X 58 ft)	Induction	3-Blade, vertical axis, cyclically variable pitch

*At the conclusion of each contract for these devices, design information and production drawings will be available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22151, USA.

The three sizes of SWECS currently under development could fulfill widely different applications. The 8-kW wind systems, adequate for individual residences and small farms in the United States in moderate wind regimes (except for heating purposes), might well be useful for village use and irrigation pumping in developing countries. As most applications for 8-kW machines in the United States are expected to involve interconnections with existing electric power sources, these systems are being designed to provide 120/240-volt AC, 60-Hz output for tie-in with a utility power line (see Figures 13, 14, and 15). By contrast, the 1-2-kW systems (24-volt DC for charging batteries) are intended for noninterconnected remote application where servicing would be on an annual basis at best. These systems must satisfy stringent reliability requirements. Finally, the 40-kW systems are intended for irrigation applications as well as for small communities or factories. Two types of output are specified for this size range: (1) mechanical output for use with deep-well pumps, and (2) electrical output for both
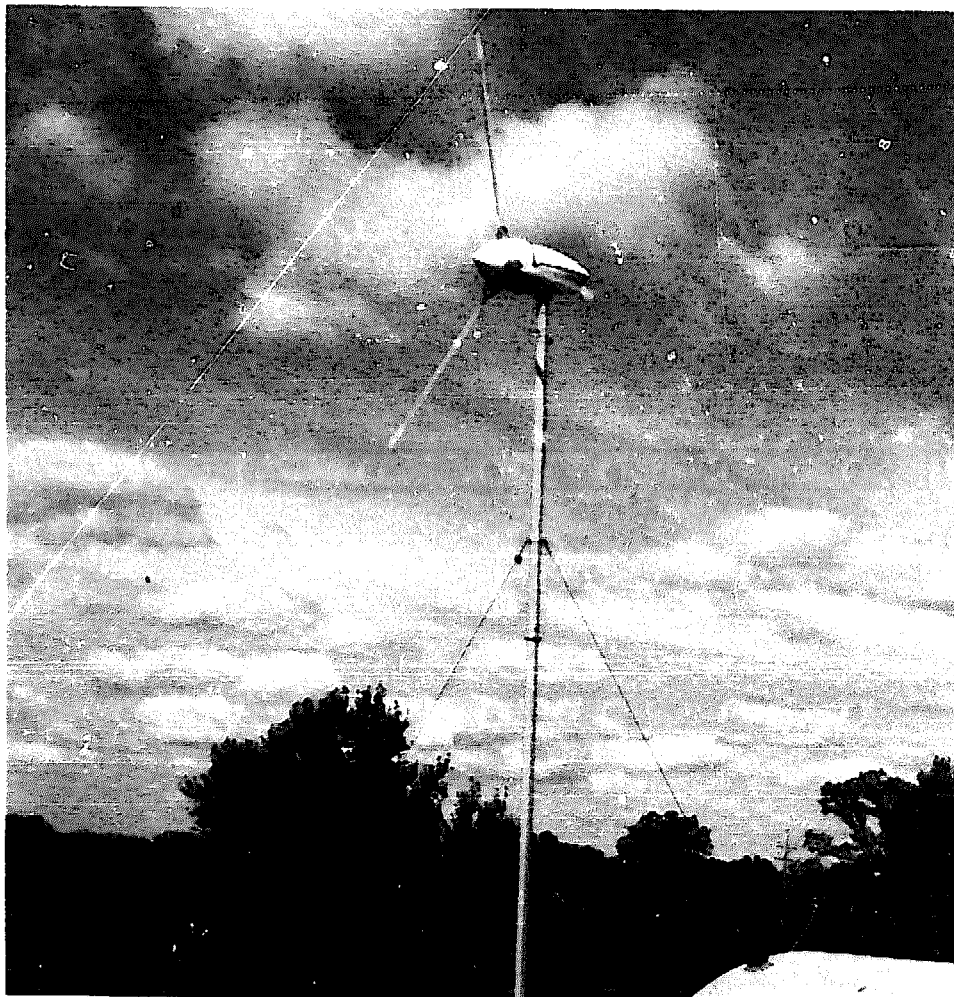
FIGURE 13   An 8-kW prototype system developed by Windworks (USA) which incorporates a direct-drive, 10-kW alternator with samarium–cobalt magnets.

FIGURE 14 An 8-kW prototype system with a flex-beam rotor developed by United Technologies Research Center (USA).

tie-in with a utility and stand-alone applications that require 440-volt AC, 60-Hz output.

Mechanical-Output Wind Machines

Significant developments in mechanical-output systems include the previously mentioned, relatively large (40-kW) prototypes designed for electrical or mechanical output. Two mechanical-output wind machines not mentioned in the first edition of *Energy for Rural Development* are being manufactured by Sparco (Denmark) and Bowjon (USA). The Sparco Windmill is available with a diaphragm (Model D) or piston (Model P) pump. It is a very small machine with a diameter of only 1.27 m (4.1 ft), and its two cast-aluminum blades generate enough torque to pump up to 225 1 (59 gal) of water per hour for low-lift (up to 10-m) operations.

The Bowjon, a somewhat larger machine, uses an air compressor to generate the power required to run an "air lift pump" for deep submersed pumping. This windmill has a 2.4-m (; ·ft) diameter rotor with four galvanized steel blades, and it is capable of pumping 908 1/hr (240 gal/hr) through a 2.54-cm (1-in.) water line when lift is 9.1 m (30 ft) and submergence is 18.3 m (60 ft). Submersions of up to about 60 m (200 ft) are possible using a 1.25-cm (.5-in.) water line (about 190 1/hr). One particularly attractive feature of this
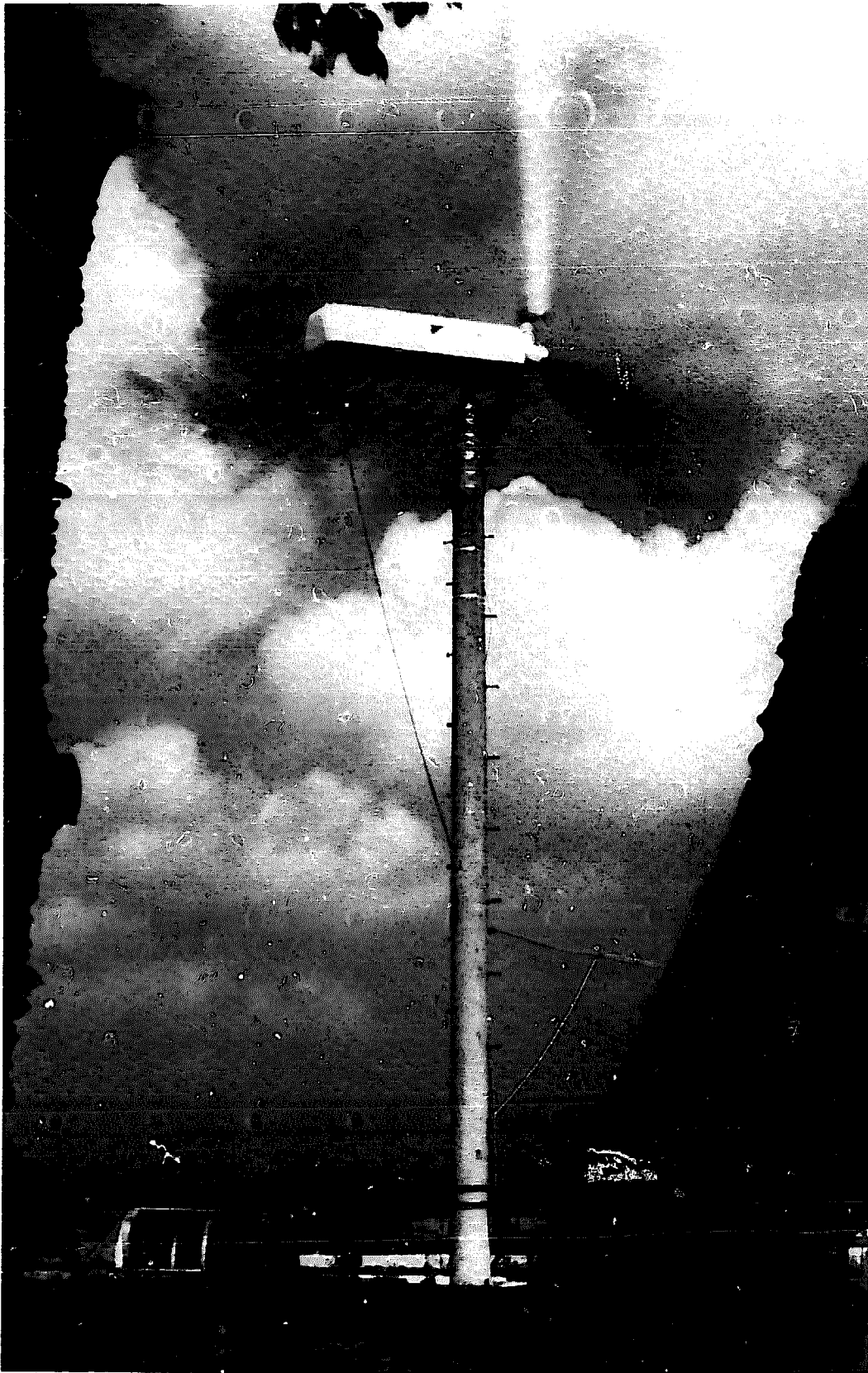
FIGURE 15   An 8-kW prototype developed by Grumman Energy Systems (USA) incorporates three extruded aluminum blades in a coned downwind rotor.

windmill is that it can be located as far as .4 km (.25 mi) from the well or water source, which allows the user greater siting flexibility. The U.S. price for this system in 1979 was $700.

LOW-TECHNOLOGY ADVANCES

Low-technology wind systems can be easily built and maintained using local labor. Although these systems may be less efficient than more sophisticated systems, overall performance per unit cost may well prove superior due to the use of locally available labor and second-hand parts.

In addition to the home-built mechanical-output windmills described in the first edition of *Energy for Rural Development*, most mechanical-output systems manufactured by Heller-Aller (USA), Aermotor, (USA), Dempster (USA), Lubing (FRG), and Sparco (Denmark) qualify as low-technology systems because of their simple design. Furthermore, several new systems have emerged since 1976, including the Princeton sailwing (Figures 16 and 17) and a modification called "The Quixote."

A   Center disc
B   Sailvane rotor blade
C   Boom-mast fitting
D   Boom
E   Fin
F   Trim tabs
G   Mast
H   Shrouds (six)
I   Power output shaft
J   Azimuth bearing
K   Rotor bearing
L   Lance
M   Drag cable
N   Peripheral cable
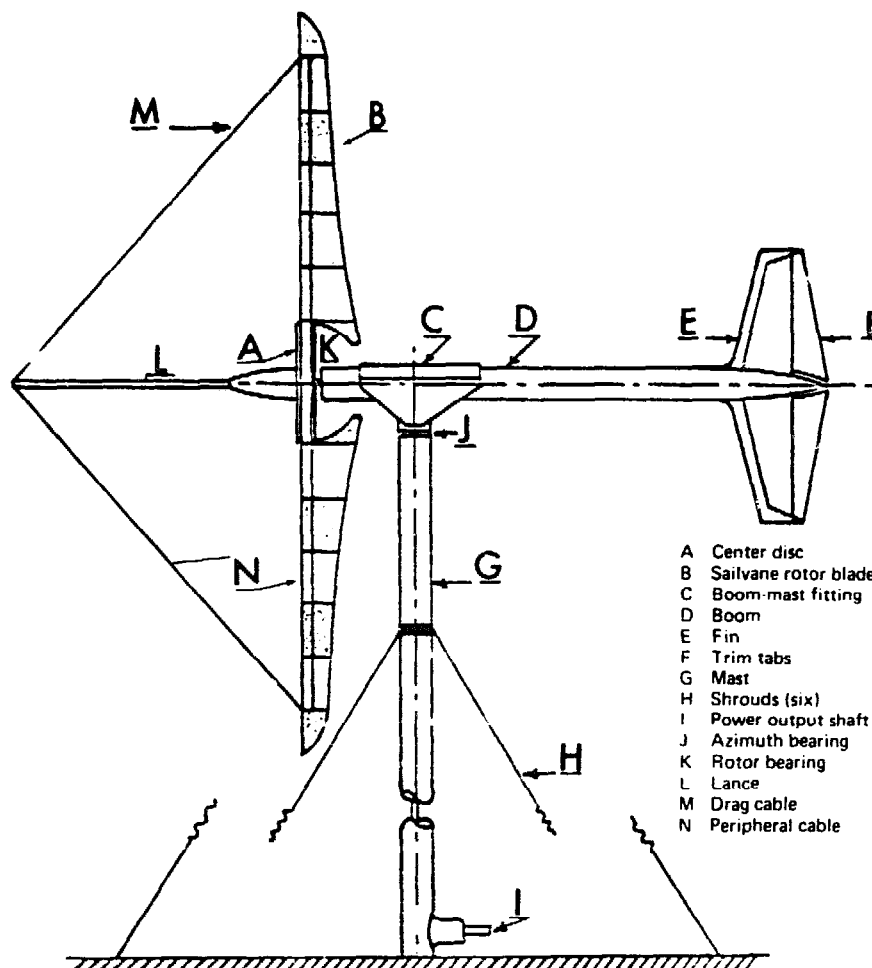
FIGURE 16   Schematic of the Princeton sailwing.
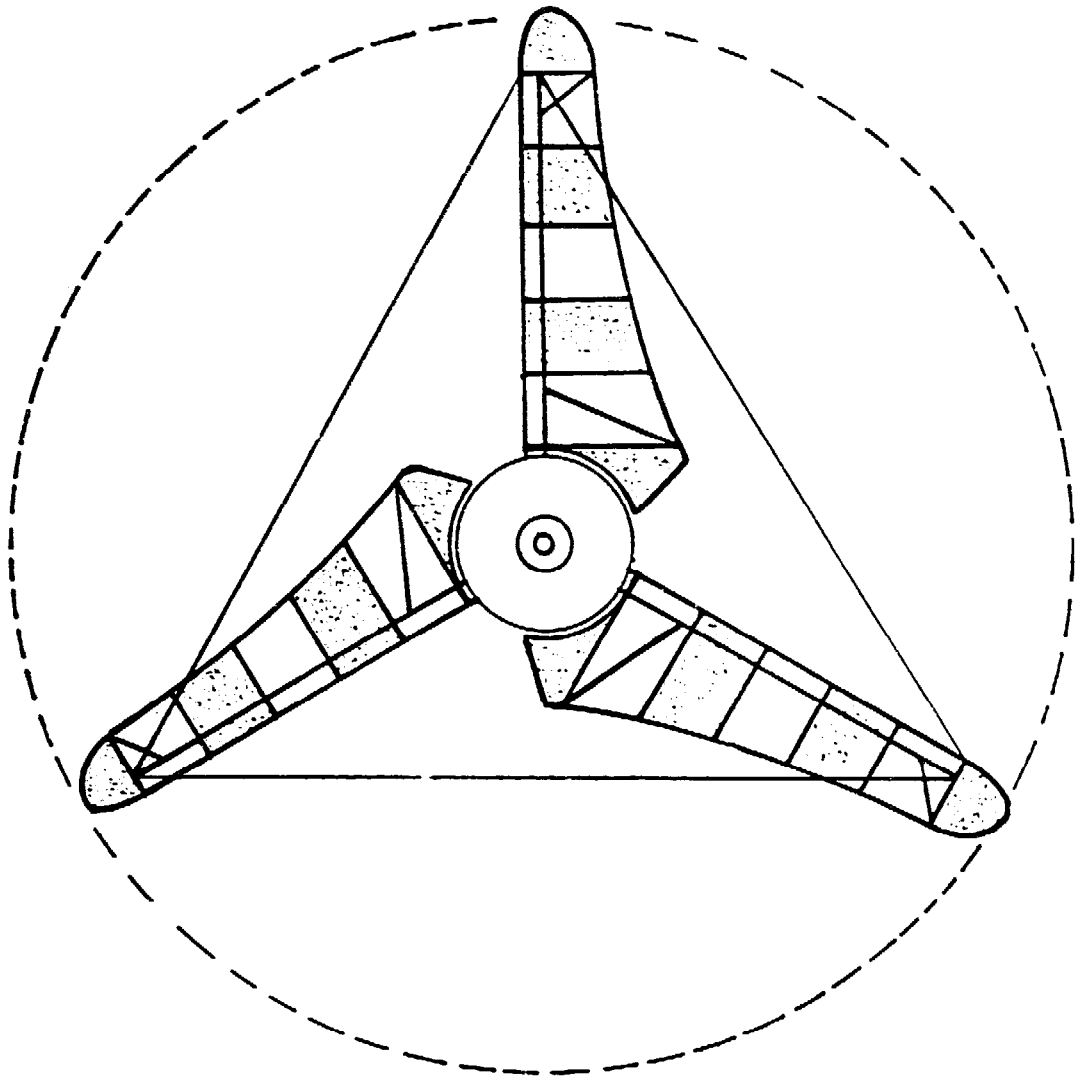
FIGURE 17   Schematic of the Princeton sailwing rotor planform.

The Princeton and Quixote Sailwings

The Princeton sailwing is based roughly on the design of water pumping windmills used on the island of Crete for hundreds of years. It incorporates modern structural materials and aeronautical technology in a machine designed specifically for developing nations.

The basic design (Figures 16 and 17) consists of a 3-blade upwind rotor connected to a single disc-shaped hub at one end of a long horizontal boom. In a technique borrowed from the ancient Cretan windmills, the blades are braced both by a connecting cable and by drag cables connecting each blade

tip to a lance protruding forward from the rotor. These cables strengthen the very light rotor. The machine's tail, which resembles that of an aircraft, has trim tabs designed to offset the twisting action of torque produced during operation. An azimuth bearing at the point where the mast (tower) fits the boom permits the tail to orient the rotor freely with the wind.

The sailwing's simple drive train consists of three shafts running through two gearboxes—one at the right angle where the tower meets the boom and one at the right angle at the base of the tower. The mechanical output of the turbine can be used to operate virtually any kind of energy conversion device—water churn, water pump, air compressor, or electrical generator.

Most of the sailwing's structural components are aluminum, and dacron is usually used for the sails. The designer recommends that only the materials specified be used if electrical output is planned.*

"The Quixote" is a modified version of the Princeton sailwing.†

Other Home-Built Systems

Other plans available in the United States include the "Budget Windcharger," a 1.2-kW, horizontal-axis sailwing wind turbine generator and a simple 2–5-kW wind turbine design that comes in 12-ft (3.6-m) and 16-ft (4.8-m) diameters.‡

A good model for low-technology, cottage-industry wind machine production is provided by the many "backyard" manufacturing operations in the United States. One such operation, Dragonfly Wind Electric in Elk, California, is marketing kits and unassembled or assembled versions of a very simple horizontal-axis machine similar to the tilt-axis North Wind 2-kW DOE prototype and the now defunct Parris–Dunn machine. This electrical-output system uses automotive single-pulley alternators or generators with output ranging from 500 to 2,000 W. With a 42-amp Chrysler alternator, the 8-ft (2.4-m) diameter system is designed to produce about 500 W in a wind speed of 17 mph (28 kmph). The major advantage of this kit is its low cost.§

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*Plans for the system are available from: Forrestal Campus Library, Princeton University, Princeton, NJ 08540, USA.

†Plans for "The Quixote" are available from: Flanagan's Plans, P.O. Box 891, Cathedral Station, New York, NY 10025, USA. The plans include detailed blueprints, a step-by-step instruction booklet, and a parts list. No welding or complicated metalworking are required.

‡Plans for the "Budget Windcharger" are available from: MI Plans Service, Fawcett Building, Greenwich, CT 06030, USA. Plans for the 2–5-kW design are available from: Environmental Action Reprint Service, 2239 East Colfax, Denver, CO 80206, USA.

§The kit costs $150 without alternator or voltage regulator and with unbalanced blades and unfinished materials. The unassembled version costs $200 (same as the kit, except holes are drilled), and the assembled version, $300 (unassembled blades).

ACCESSORIES AND TOWERS FOR WIND MACHINES

Batteries and inverters are used with many energy systems, not just wind machines, and they are discussed in two later chapters of this supplement, "Energy Storage" and "Solid-State Electric Inverters," respectively.

Instructions for building simple wooden derrick towers were included in the first edition of *Energy for Rural Development*. In addition, guyed or freestanding steel pipes and wooden poles are suitable.

Tower selection becomes much more critical when a high-rpm wind turbine generator is involved. Dynamic interactions among the rotor, yaw system, drive mechanism, and the tower can create harmonically related vibrations that decrease system life and even result in failures. Communications or radio towers that are available commercially worldwide are most commonly used for wind turbine generators. One U.S. manufacturer of such towers, the Rohn Tower Division of Unarco Industries,* is fabricating special towers to accommodate any wind machine. Sectional towers specifically designed for wind machines are also available from Solargy Corporation.†

The octahedral tower, designed by U.S. engineer, designer, and architect Buckminster Fuller, is a relatively low-cost design that offers complete rigidity, an aerodynamically clean profile, and ease of installation. Composed of sections of galvanized steel pipe, the octahedral tower is bolted together from the ground up.‡

WIND POWER APPLICATIONS

Electrical Applications

These applications fall into three categories: interconnected AC, noninterconnected AC or DC, and remote DC.

Interconnected Applications. For this application, total or surplus power from the wind system is fed into utility lines. The wind system must, therefore, produce power that is compatible in frequency and phase with that in those lines. This can be accomplished by either (1) using a synchronous generator with revolutions per minute and resultant frequency regulated by a sophisticated control system, (2) using a nonsynchronous alternator with a line-commutated inverter, or (3) using an induction generator that uses utility power as a reference to produce compatible alternating current.

The first method is generally not appropriate for small wind systems because it requires expensive pitch change and electronic control mechanisms.

*P.O. Box 2000, Peoria, IL 61656, USA.
†17914 E. Warren Avenue, Detroit, MI 48224, USA.
‡The octahedral tower is available from several U.S. distributors, including Natural Power, Incorporated, New Boston, NH 03070, USA.

The second method is commonly used for small wind systems, but it requires the additional cost and complexity of a battery bank, inverter, and the switches and wiring needed to interconnect these components. In addition, losses associated with conversion and reconversion of wind system output reduce considerably the cost-effectiveness of the entire system. The third method appears to be the optimal choice for developing countries as it is the least expensive of the three methods and the least complex. Even though wind turbines with nonsynchronous alternators are generally less expensive, the cost of power conditioning equipment required for interconnection more than offsets this advantage.

Noninterconnected AC or DC Applications. For this application, the wind system is dedicated to one or more loads, and surplus is not fed into power lines. More options are thus open to the user. Many appliances are flexible in terms of the quality of power they will accept, particularly those operated by motors that do not have to have a precise speed. Electric lights have relatively wide frequency operating ranges. DC lights can also be used, and resistance heaters can be operated with virtually any type of AC or DC power.

Examples of noninterconnected AC applications include: electric water pumps for irrigation, residential or industrial applications requiring AC power, heaters and blowers for crop or material drying, and large-scale cooling or ventilation systems. One AC-output wind turbine generator can satisfy both AC and DC power needs at one site. With the installation of a rectifier and a battery bank, energy for DC lights and small resistance heating loads can be stored for use when the wind is not blowing.

DC-output systems are used most efficiently with DC lighting, resistance heating, and appliances with DC motors. An inverter (not line-commutated) can be used to operate AC appliances, but higher cost and output losses are the primary penalties. Most DC-output systems have AC generators, the output of which is rectified. This power production mode is dictated by the high cost of DC generators.

Remote DC Applications. A wind machine is backed up by batteries or other storage systems for this application. Examples of excellent remote applications for DC-output systems include telecommunication relay stations, meteorological stations, rail signaling systems, marine and air navigational aids, and remote pumping stations. Machines used for such applications typically have relatively low output ratings of 20 W to 4 kW. In developing countries seeking to install or improve communications networks, remote DC-output wind systems can be used instead of oil- or gas-powered generators, with the advantages of reduced fuel costs and the possibility of unattended operation over several months to a year or more. Such systems could also be used as a heat or light source in remote communities where labor for maintenance is not available. Aerowatt (France) has designed its systems specifically for

remote applications. In the United States, the North Wind Power Company, Inc. has begun to market a 2-kW system developed under contract to DOE.

Mechanical Applications

Such traditional mechanical applications as water pumping for irrigation or domestic water use, pond aeration, and grain grinding are still among the most economical uses of wind power, using any high-torque, low-rpm wind system. The most promising new application, the water churn heating concept, involves heating water by mechanical agitation.

Because combustion fuels can heat water more efficiently, the age-old principle of raising the temperature of water by means of a mechanical brake or churn has not been applied. With the use of wind power, however, mechanical means are the most direct way of heating water to usable temperatures. Furthermore, mechanical heating can be used with virtually any wind machine now available. High-rpm systems are preferable, but high-torque water pumpers can also power water churn systems with the aid of speed-increasing gearboxes.

The range of applications of water churns, powered by windmills or water wheels, covers all processes that require water heating, including producing steam for industrial processes, supplementing home or community heating systems, and producing hot water for use in grain drying and water desalination.

One of the primary advantages of the water churn is its excellent applicability to a wind system. Because both devices involve fluid processes that operate with a cubic power/speed relationship, the water churn's power output will be matched to the wind turbine's output at any wind speed. As a result, the conversion efficiency of such a system is almost 100 percent, with the exception of frictional losses. Heat losses can be kept to a minimum with adequate insulation.

The Water Twister Model 12, suitable for use with small wind machines, has been developed by the All-American Engineering Company (Figure 18). This model has a rated output of 6 hp at 500 rpm and 47 hp at 1,000 rpm. Costs for this system ($3,000 in 1979) are already comparable with those of electrical generators of similar output. The Water Twister is now produced in limited quantities, but the manufacturer estimates that increased production may reduce costs to under $1,000 per unit (1979 U.S. dollars).

Water churn research is now being conducted at Cornell University (Ithaca, New York) within a DOE-funded project entitled "Development of a Wind-Power Water Heating System for Daily Application." A churn simpler in design than the Water Twister is being used in this project.

Considerable work on the water churn concept has also been performed in Denmark. In Skive, Jutland, a water brake powered by a vertical-axis wind turbine was tested in a "low-energy," one-family home in conjunction with passive solar heating and flat-plate collectors. The churn used was a simple
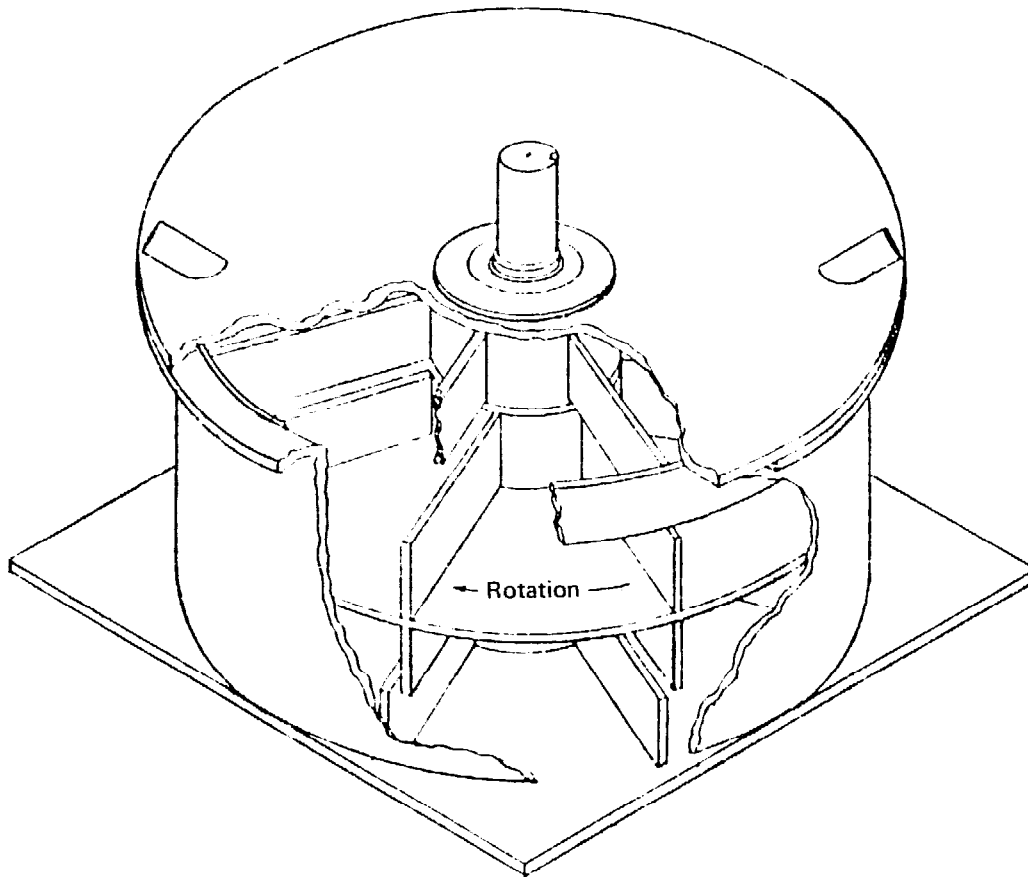
FIGURE 18 Cutaway schematic of the Water Twister manufactured by the All-American Engineering Company (USA).

star-shaped paddle wheel, .45 m (1.5 ft) in diameter. Coupled to the wind turbine through a 1:15 gearbox, the water churn produced 2 kW of power at 225 rpm (see Appendix B for a list of sources of information on Danish research efforts).

CURRENT ACTIVITY IN THE WIND INDUSTRY

United States

A number of new systems have emerged since publication of *Energy for Rural Development* in 1976 (see Appendix A for a complete list of manufacturers). In the 1-2-kW output range are the Enertech 1500, the Whirlwind Model A, the Sencenbaugh Model 1000 series, the Aero Power SL 1500, and the Kedco 1200 series. All but the Sencenbaugh are designed for utility interconnection and have induction generators designed primarily for that purpose.

Somewhat larger machines (2-5 kW) are the Astral/Wilcon AW 10-B, the Product Development Institute Wind Jennie, Kedco 1600 series, Dakota Wind & Sun, Dynergy Corporation 5-m Darrieus, the Pinson Energy Corporation

Cycloturbine Model C2E, and the Independent Energy Systems Skyhawk. Most of these systems are designed for utility connection, but can be adapted to other uses.

Probably the most important development in the United States is the emergence of several larger wind systems that could provide power for small communities and villages, including the Millville 10-kW system, the Dakota Wind & Sun 10-kW system, the Windgen 25 (25 kW) manufactured by the Wind Engineering Corporation, and the Jay Carter Enterprises Mod 25 (25 kW).

Mechanical-output systems available from U.S. firms include the Aermotor, Heller–Aller, and Dempster fan-type water pumpers, and the Bowjon compressed-air water pumper.

New firms are entering the U.S. wind industry each year and established firms are continually improving old systems and developing new ones. Within the next 2 years, the most likely additions to the list of available systems will be several of the 1–2-kW, 8-kW, and 40-kW prototypes developed under DOE contracts, a 20-kW system now being developed by U.S. Wind Power for the California State Department of Energy, a series of Darrieus wind turbines developed by Alcoa, and an 8-kVA system developed by the Jacobs Wind Electric Co., Inc.

The U.S. Federal Wind Energy Program, within DOE, has been the most diverse and active government effort in the world in recent years. Development efforts range from small (1–100-kW) systems to giant multimegawatt systems. Test and evaluation efforts for small systems are conducted under contract by Rockwell International at Rocky Flats (Golden), Colorado. Farm application tests are managed by the U.S. Department of Agriculture's Research Service in Beltsville, Maryland. Field tests of 100-kW, 200-kW, 2-MW, and 2.5-MW systems developed under contract to the U.S. National Aeronautics and Space Administration's Lewis Research Center in Cleveland, Ohio, are either under way or planned at locations throughout the United States. Candidate sites for large systems are selected and evaluated with the assistance of Battelle–Pacific Northwest Laboratories, which is also conducting research on wind characteristics. Analytical research and coordination of the dissemination of information are performed at the Solar Energy Research Institute in Golden, Colorado.

Canada

In 1977, about $500,000 was allotted for wind energy research and development to be dispensed by Canada's National Research Council, the designated lead agency in the field of renewable energy research. In 1979, the total national expenditure in Canada, including that by industry, was approximately $2 million.

Dominion Aluminum Fabricating, Ltd. has been involved in the development and marketing of Darrieus wind turbines for several years. Bristol Aerospace, Ltd. has developed a 9-ft (2.7-m) diameter vertical-axis wind turbine, which has successfully powered a remote unmanned weather station in the Arctic Sea for over a year without maintenance. Developed in cooperation with the University of Manitoba, the Bristol systems are self-starting and are equipped with low-speed multiple alternators.

Winflo Power, Ltd. is now manufacturing horizontal-axis wind turbines that range in output from 300 W to 2.5 kW. The 2.5-kW machine has a cut-in wind speed of 7 mph (11 kmph) and produces its rated output at 22 mph (35 kmph).

Crowfield Associates, Ltd. is planning to produce a wind power heating system utilizing a 12-kW (23 mph or 37 kmph) vertical-axis wind turbine with two straight blades.

Europe

Over the past 5 years, Europe has experienced a renewed interest in the use of wind energy. Most countries now have government-sponsored wind energy programs.

Denmark's wind energy program, instituted in 1975, is currently emphasizing large wind turbine generators. However, a second stage that includes small WTG development was just getting under way in 1979. The Danes have constructed the Tvind-WTG, a 3-blade machine with a downwind rotor, 54 m (177 ft) in diameter, and a rated output of 2 MW.

The Federal Republic of Germany has initiated the GROWIAN (Grosse Windenergie-Anlage) Program as a main line for research and development. Several projects are under way aimed at adapting small wind energy conversion systems to special types of utilization, including development of a 20-kW wind energy conversion system in cooperation with the Centro Técnico Aerospacial in Brazil.

The Netherlands began a 5-year program in 1976, designed to study the feasibility of wind energy conversion. The Dutch have also initiated a research and development program that has produced a 5-m (16-ft) vertical-axis wind turbine for experimental testing.

Sweden is now testing a 75-kW wind turbine manufactured by Saab-Scania as part of the National Swedish Wind Energy Program managed by the National Board for Energy Source Development. However, the major thrust of this program is aimed at developing large wind energy conversion systems.

Several manufacturers of wind machines are located in Europe (see Appendix A). The French company, Aerowatt, currently manufactures wind machines ranging in output from 30 W to 100 kW. Lubing Maschinenfabrik (FRG) is manufacturing several types of wind pumps, as well as a wind

turbine generator with an output of 400 W. Elektro GmbH Winterthur of Switzerland has models available that produce outputs of from 50 W to 10 kW. P.I. Enquiries, Ltd. (Great Britain) is producing the Variable Geometry Vertical-Axis Wind Turbine in 4.5-m (1-kW) and 6-m (4-kW) sizes. In Denmark, manufacturers emphasize heating applications for their wind systems. A 5-blade vertical-axis machine manufactured by Dansk Vindkraft Industri Aps, a 10-kW fan-type system manufactured by S-J Wind-Power ApS, and 22-55-kW systems manufactured by Riisager El-Vindmolle are all major models available. Systems with outputs of 20-200 W designed for remote DC applications are produced by Naestved Maskin Elektro. The Swedish firm Ingenjorsfirma Ture Ekenburg AB manufactures a 3-blade upwind system rated at 10 kW in winds of 43 kmph (27 mph). Finally, Domenico Sperandio & Ager of Italy markets electrical-output systems rated at up to 1 kW. These include the Garbino 250 W (12 volts), the Turbine 500 W (24 volts), and the Monsone 1 kW (48 volts).

USSR

Although accurate information is difficult to obtain, it appears that the USSR is planning to embark soon upon an ambitious wind energy project that will take the form of a 700-mi (1,126-km) network of large wind machines to generate electricity in northwestern Russia. The plan involves erecting 238 wind generators with a rotor diameter of over 50 m (164 ft). Each machine will have a generating capacity of 1 MW. Several smaller 100-kW machines have been installed to produce power locally along the Baikal–Amur railway line. The USSR Energomashexport and the USSR Institute for Farm Electrification I-U Veshniakovski have both been listed as producing and developing wind machines, including numerous models from 500 W to 25 kW.

Costa Rica

The Costa Rican Technological Institute (Instituto Tecnológico de Costa Rica) has established an investigation center, which, among other things, is designed to help small villages or communities develop sources of energy (wind power, primarily) by making maximum use of local materials and labor. Uncomplicated construction and maintenance are emphasized.

Australia and New Zealand

In Australia, Davey-Dunlite manufactures wind machines with outputs of 1-5 kW, which are distributed worldwide.

In New Zealand, a Wind Energy Task Force was established in 1974 to co-ordinate wind engineering, power systems, and meteorological expertise. Lincoln College in Canterbury has built a 6-m (19.6-ft) diameter, 1.5-kW, Cretan-type sail windmill for test and demonstration purposes. A German

"Flip-Flop" (Schlagflugelwind-pumpe) wind machine design is also being studied.

Japan

Japan Wind Power Generator Co., Ltd. is manufacturing wind machines with outputs ranging from 6 W to 1 kW and up. According to the manufacturer, these machines can be used to provide power for remote areas, meteorological stations, and ships.

REFERENCES

Park, J. and D. Schwind (1978) *Wind Power for Farms, Homes and Small Industry*. Nielsen Engineering and Research, Inc. Available from the National Technical Information Service, Order No. RFP-2841/1270/78/4, 5285 Port Royal Road, Springfield, VA 22161, USA.

Wegley, H. L., *et al.* (1978) *A Siting Handbook for Small Wind Energy Conversion Systems*. Battelle-Pacific Northwest Laboratories, PNL-2521. Available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, USA.

Energy from Falling Water

Hydroelectricity and isothermal hydraulic air compression, two technologies dependent in different ways upon falling water, were not discussed at length in the original volume of *Energy for Rural Development* as these are well-established technologies for which there have been few recent new developments. However, these technologies are in many ways now being "rediscovered" for use in developing countries and are being widely applied there. (See Appendix C for suggested reading on hydropower and isothermal hydraulic air compression.)

SMALL-SCALE HYDROELECTRIC SYSTEMS

The development of hydraulic turbines has slowed since the 1960s, and current work has been directed more toward the design of hydroelectric equipment packages for cost-efficient systems.' Small-scale hydroelectric systems generally fall into two categories: micro-hydro, 0–100 kW, and mini-hydro, 100–1,000 kW. Whether an installation falls into the category of micro-hydro or mini-hydro is determined primarily by the amount of energy available at the site. The physical principles involved are the same for all hydroelectric systems.

As the energy output of a hydro system becomes smaller, every aspect of the system must become simpler and faster to implement. This not only applies to a system's design, civil works, and plant distribution, but also to the organization and techniques used to install and operate the equipment over its life.

With the availability of new materials (i.e., bearings, generators, and control electronics), it has become possible to obtain small-scale hydroelectric

systems that have an installed cost ranging from $800 to $1,800 per kilowatt and require less than 5 percent of invested capital per year for operation and maintenance. Such systems can have useful lives of 30–40 years and can be operated automatically from remote locations. These systems can be easily installed in a matter of months or less by unskilled labor. The small-scale approach to hydropower can best be illustrated by the following description of the installation of a typical 5-kW hydroelectric system.

Example: Installation of a 5-kW Hydroelectric System

The water source for this system is a mountain spring located 470 ft (143 m) above the turbine installation in the valley below. The water diversion system (Figures 19 and 20) consists of a primary and secondary sump and screening system that allows the water velocity to decrease and precipitate heavy suspended solids. Then, 130 gal of water per minute (492 1/min), as shown in Figure 21, are drawn up a 6-in. (15-cm) syphon through a screen and carried 2,500 ft (762 m) down the mountain to the power house where a pressure of 173 lb/in.^{2} (12 kg/cm^2) is developed at the nozzle of the 4-in. (10-cm) pitch diameter impulse turbine (Figure 22). The turbine is directly connected to a 5-kW, 3,600-rpm, 120/240-volt, single-phase, 60-Hz brushless generator with permanently lubricated bearings. Voltage and frequency are controlled by the
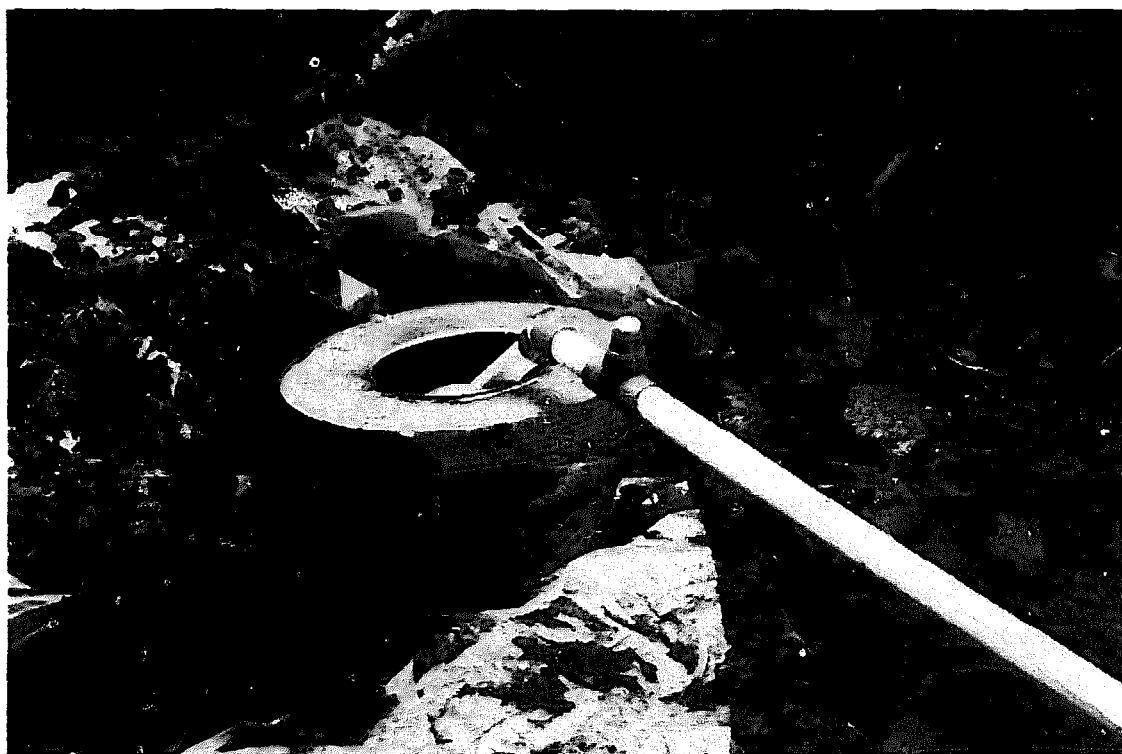

FIGURE 19   A 3-in. (7.6-cm) PVC pipeline carrying 130 gal of water per minute (492 1/min) over a distance of 2,500 ft (762 m), developing a net head of 400 ft (122 m), and producing 5 kW of electrical energy (see the nomograph in Figure 25). (Photograph courtesy of Independent Power Developers, Inc., Sand Point, Idaho)
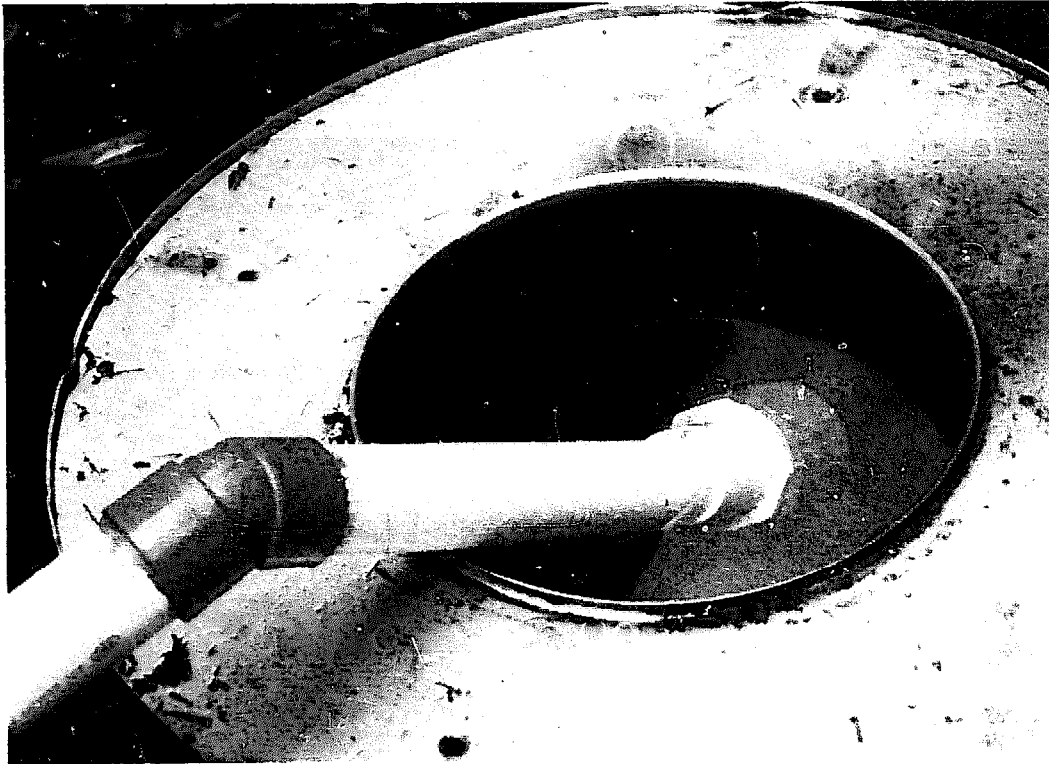
FIGURE 20   Close-up of water intake showing a 6-in. (15-cm) syphon that allows the
silt to settle out before being drawn into the pipeline. This line provides the water supply
for domestic use, livestock, gardens, fire protection, and electrical generation. (Photo-
graph courtesy of Independent Power Developers, Sand Point, Idaho)

electronic governor (Figure 23), which together with the controller allows
automatic operation with a wide combination of turbine generator sets or DC
to AC conversion.

The electronic governor makes it possible to keep the alternator at essen-
tially full load to prevent the turbine from overspeeding. This device can be
designed in such a way that it selects loads to match the alternator output
according to a predetermined set of priorities. Thus if the water supply in-
creases or decreases, the governor keeps the speed essentially constant, ad-
justs the alternator output for maximum possible power output, and selects
the priority loads to which that power is delivered.

The two nomographs shown in Figures 24 and 25 show the relationship
between the various parameters. The lines drawn on the nomographs are for
the example just presented. These nomographs can be used to obtain prelimi-
nary design numbers for a wide variety of hydroelectric installations.

The importance of keeping the load factor high is illustrated in the simple
nomograph devised by R. G. Ramakumar of Oklahoma State University and
shown in Figure 26. The lines emanating from the lower left represent con-
stant load factors. Load factor is simply the average power output of the gen-

erating equipment, divided by its rated power output. The more electrical power used, up to the rated capacity of the system, the closer the system load factor comes to 1.0 and the lower the cost per kilowatt-hour. Micro-hydro-electric systems normally have a load factor range of between 0.6 and 1.0.

As an example, if an installation costs $1,100 per installed kilowatt and has a load factor of 0.7 (that is, the unit delivers average power equivalent to 70 percent of its full load capacity), a vertical (solid) line is drawn from $1,100 on the horizontal axis to the 0.7 load factor line. A horizontal (solid) line is
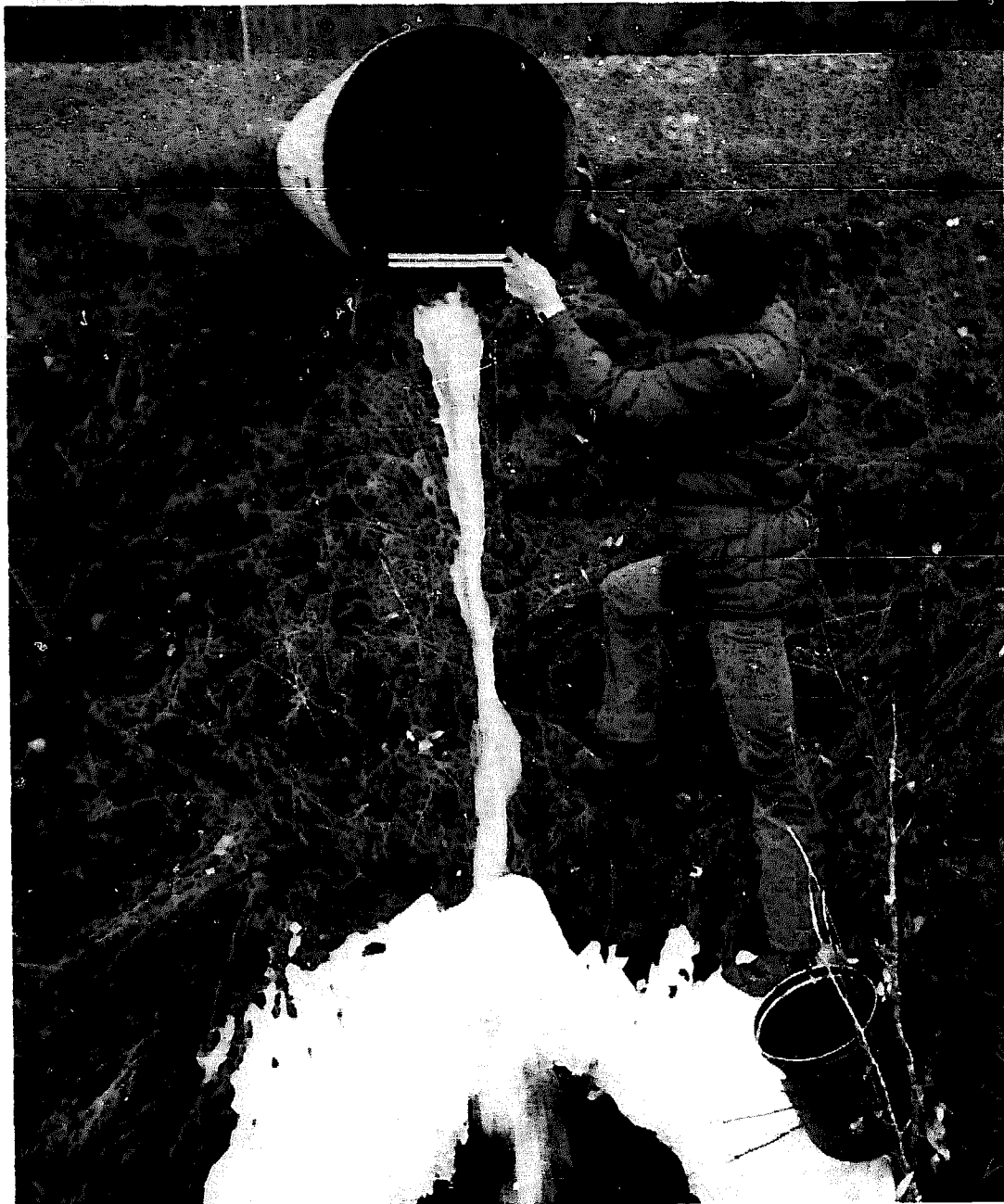

FIGURE 21 One hundred and thirty gallons of water per minute (492 l/min). See the nomograph in Figure 24. (Photograph courtesy of Independent Power Developers, Sand Point, Idaho)

then drawn over to the right-hand vertical axis to get a cost per kilowatt-hour of 21 mills or $.021. If the load factor were 0.3 (dashed lines), then the cost would be $.046 and so on. In each case, this is that part of the cost attributable to capital investment and operation and maintenance. Since there is no fuel cost in micro-hydroelectric systems, this becomes essentially the total cost. The nomograph in Figure 26 assumed a 7.5 percent interest rate, an operation and maintenance (O&M) cost of 3 percent of capital costs, and a 35-year amortization. Similar nomographs have been worked out for a wide
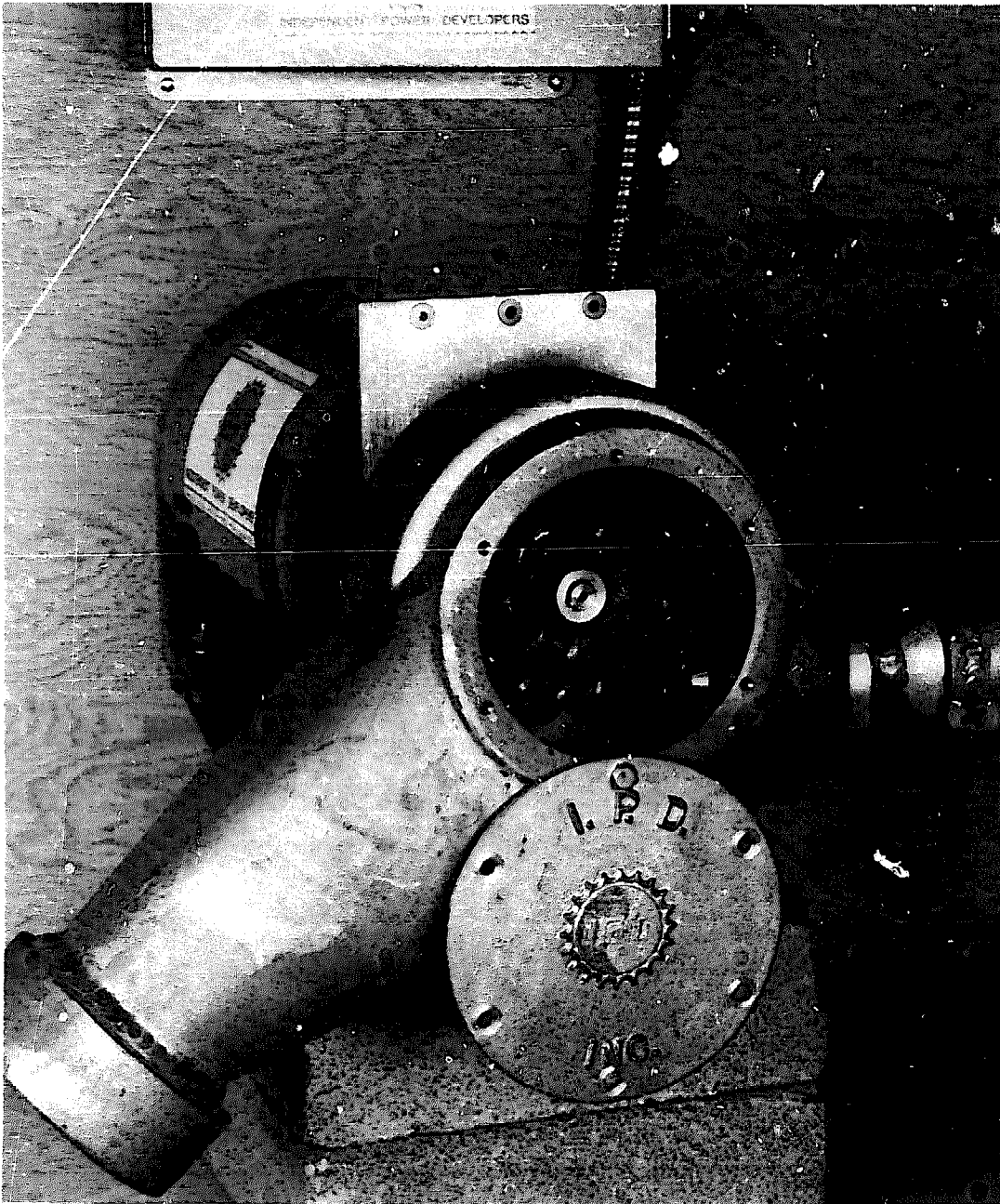

FIGURE 22   Close-up of the impulse turbine and nozzle on the 5-kW turbine generator set, which weighs 130 lb (59 kg), including the speed control. (Photograph courtesy of Independent Power Developers, Inc., Sand Point, Idaho).
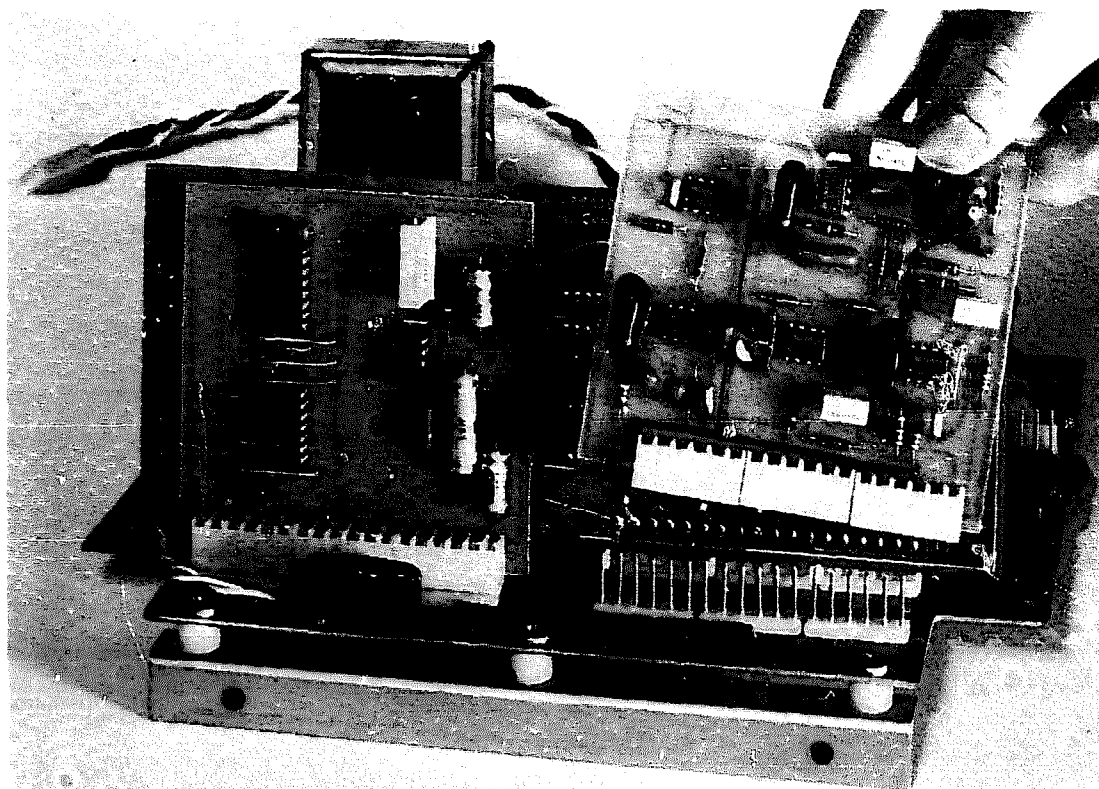
FIGURE 23 Electronics for speed governor and voltage control. A malfunctioning card is simply replaced by a spare and then mailed to the nearest repair station. (Photograph courtesy of Independent Power Developers, Inc., Sand Point, Idaho)

variety of interest, operation and maintenance, and amortization figures.* Placing real economic value upon the electricity produced, of course, depends entirely on having a beneficial and valuable use as much time as possible for as close to 100 percent of the energy available as possible.

In any economic analysis of hydroelectric systems, it is important to look at the proportion of the budget spent on civil works, generating equipment, transmission, and operation and maintenance. A study of the economics of micro-hydro systems in both developed and developing countries has shown invested capital to be allocated as follows: civil works, 24–52 percent; generating equipment, 30–40 percent; transmission, 10–30 percent; and operation and maintenance, 3–8 percent. These percentages were derived from installed cost data in Nepal, Bolivia, Peru, Panama, Guatemala, and the United States, and the sample included 63 installations with powers ranging from 3 kW to 100 kW. Typically, the lower the head (elevation) the higher the installed cost per kilowatt. Of course, all of these percentages can vary widely depending on individual circumstances.

*These can be obtained from the Engineering Energy Laboratory, Oklahoma State University, Stillwater, OK 74078, USA.
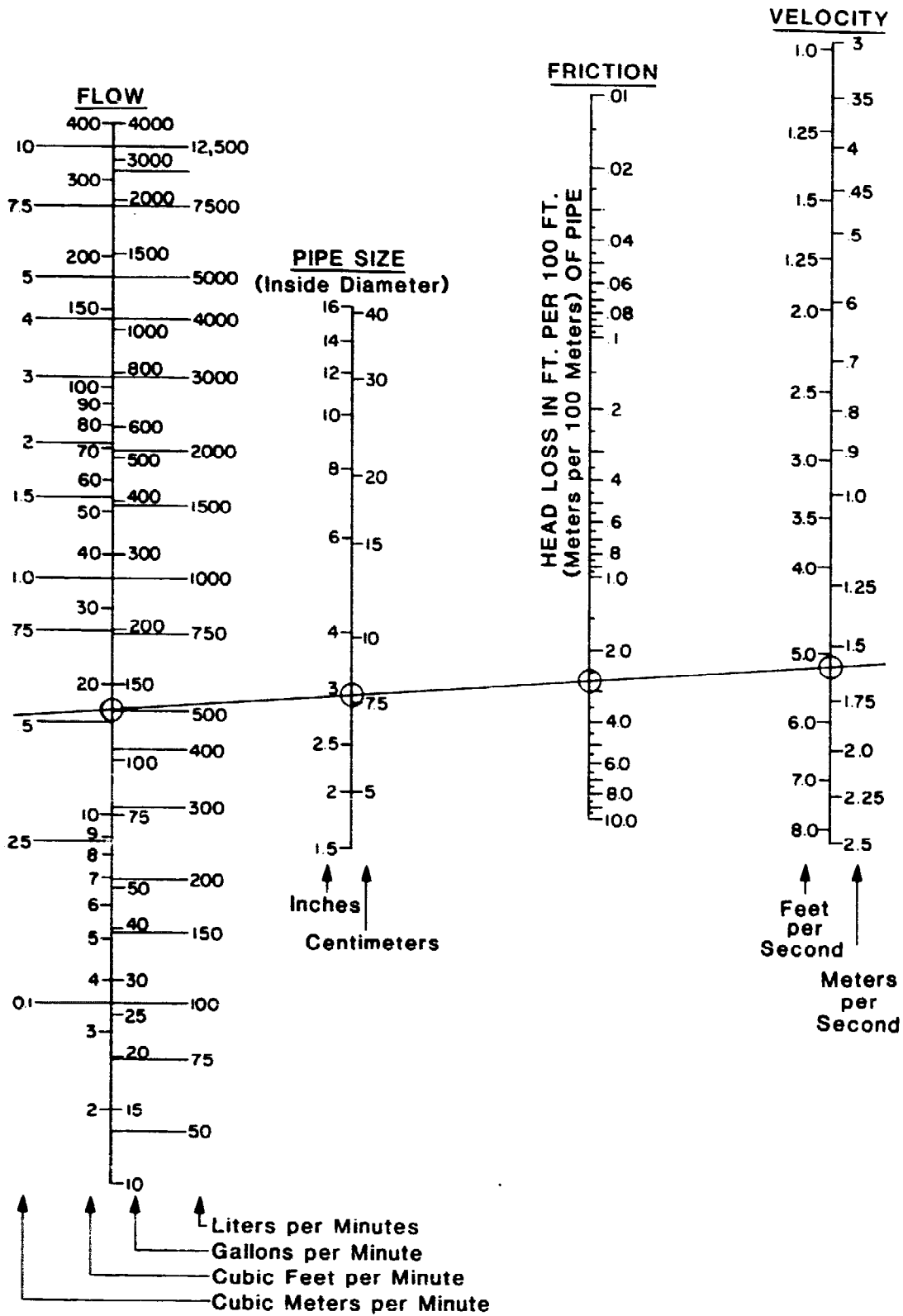
FIGURE 24   Hydroelectric system sizing nomograph relating flow, pipe size, frictional losses, and velocity.
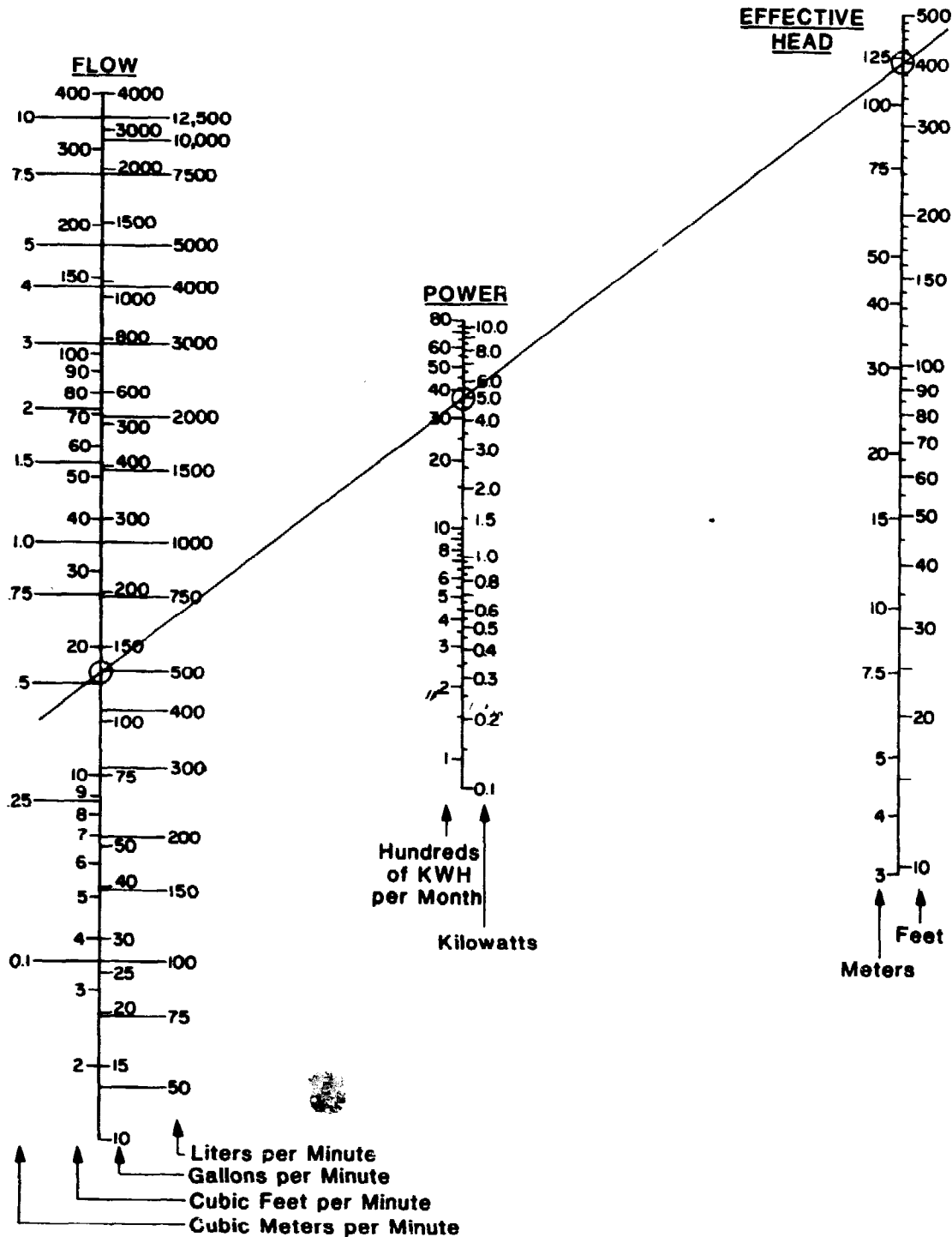
FIGURE 25 Hydroelectric system sizing nomograph relating flow, power available, and effective head. For larger hydroelectric power requirements, one need only consider the fact that for any given head, power availability is directly proportional to water flow.
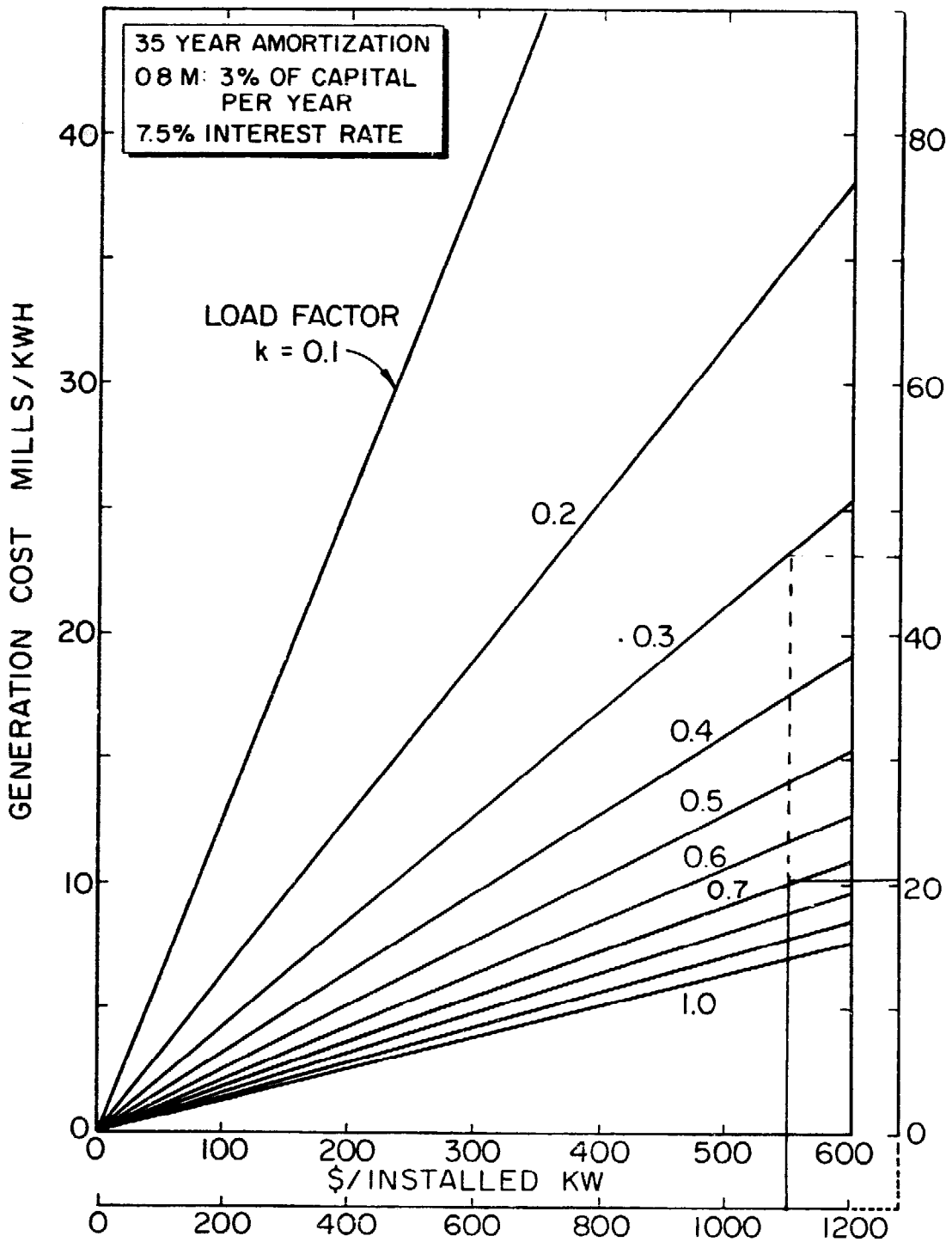
FIGURE 26   Nomograph for determining cost per kilowatt-hour attributed to capital, operation, and maintenance costs (devised by R. G. Ramakumar, Oklahoma State University, Stillwater, Oklahoma).

Sources of Information on Small-Scale Hydroelectric Systems

A number of organizations located both in the United States and in other countries publish information on this technology, and they could be of assistance in contacting suppliers of hydropower equipment (VITA 1980). In the United States, Volunteers in Technical Assistance (VITA) and the National Center for Appropriate Technology (NCAT)* have published material that enables one to determine the power potential of a water resource and measure the head and flow rate, and gives instruction for the actual installation of micro-hydro systems (VITA 1967, n.d.; NCAT 1979). The Swiss Center for Appropriate Technology (SKAT) will answer inquiries from developing countries on micro-hydro and other types of water power systems (SKAT n.d.). In Great Britain, the Intermediate Technology Development Group (ITDG)† distributes publications on small-scale water power development and responds to inquiries on micro-hydro and other aspects of hydropower. Groupe de Recherche et d'Echanges Technologiques (GRET)‡ in France has a number of documents on micro-hydro and other forms of water power. In Colombia, the Center for Integrated Rural Development of Las Gaviotas (Universidad de los Andes, Bogotá) does research, development, and testing and training in water resources and other areas, and distributes hydropower technical reports in Spanish. In Papua New Guinea, the Appropriate Technology Development Unit (ATDU)§ of the University of Technology conducts research on and does pilot production of micro-hydro systems. (See Appendix A for a list of manufacturers of small-scale hydroelectric systems and Appendix C for a list of suggested reading on this subject.)

HYDRAULIC AIR COMPRESSION

Prior to the widespread use of electricity and the internal combustion engine, compressed air was considered a source of primary power, and falling water was considered a prime source of power for air compression and storage. This technique was used extensively until the beginning of the 20th century when

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*Volunteers in Technical Assistance, 3706 Rhode Island Avenue, Mt. Rainier, MD 20822, USA; National Center for Appropriate Technology, P.O. Box 3838, Butte, MN 59701, USA.
†Intermediate Technology Development Group, 9 King Street, London WC2E NH, England.
‡Groupe de Recherche et d'Echanges Technologiques, 34 Rue Dumont d'Urville, 75116 Paris, France.
§Appropriate Technology Unit, University of Technology, P.O. Box 793, Lae, Papua New Guinea.

less capital-intensive and more easily acquired sources of energy became available. Since that time, the technique has become a forgotten art, and most scientists, engineers, and technicians educated in the last half of this century are simply not familiar with the fact that air can be isothermally compressed using falling water. (See Appendix C for a listing of recent literature on this subject.)

The Process

This relatively simple process is illustrated in Figure 27 (in the interests of simplification, some details have been omitted). When water is allowed to fall through a long, enclosed column (such as a vertical pipe or even a mine shaft in rock), it will capture a significant amount of air at the top of the column. As the completely enclosed column of water falls, the bubbles are carried to the bottom of the column and compressed as they go down. The heat of the compression that results is immediately absorbed from each bubble by the surrounding water. Since the specific heat per unit volume of water is many times that of the compressed air, the temperature of the water does not rise significantly and the effect is equivalent to isothermal compression of the air.

At the bottom of the column, the water passes slowly through an enclosed chamber in which the bubbles have time to rise. Since the air in the bubbles is at the head pressure of the water, the enclosed chamber is thus filled with air at a pressure equal to the water head pressure.

For safety reasons, the bottom level of the compressed air must never be allowed to reach the bottom water inlet or outlet level in order to prevent
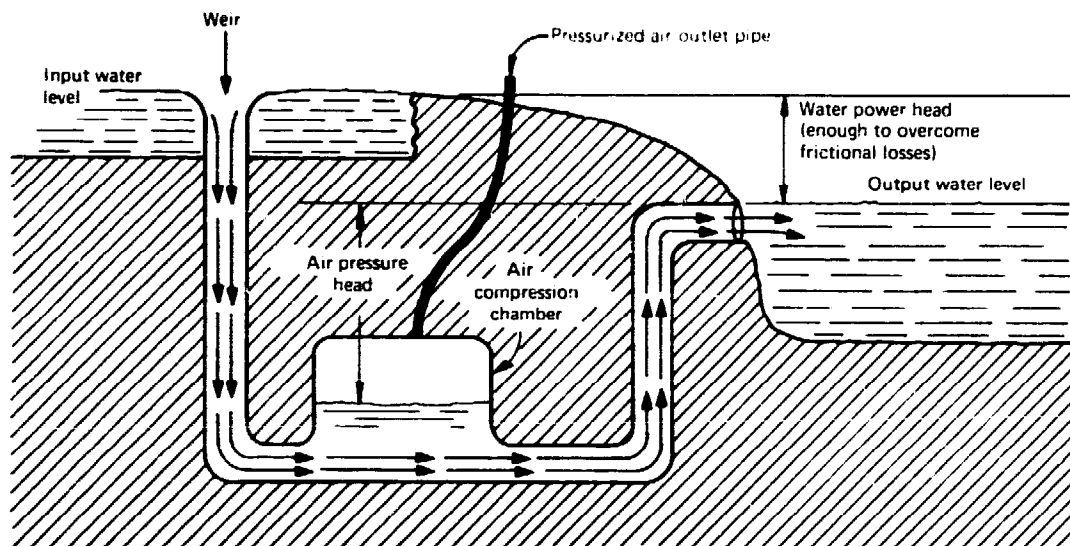

FIGURE 27   Simple illustration of a hydraulic air compressor.

backflow of air up the intake. A simple blow-off air line must be installed just above the storage tank inlet and outlet.

Such compressors have several desirable operating characteristics: (1) air is compressed isothermally, which means high thermodynamic efficiency; (2) compressors have no moving parts, and thus maintenance is minimal and service life maximal (at least 50 years); (3) within limits, the pressure attainable is a design feature determined solely by the placement of the air–water separator below the tailrace elevation; and (4) as should be expected, the higher the flow head (the distance between the elevated source of water and the tailrace), the more air can be induced and compressed, and hence the more power available.

Analysis of a large number of old compressors reveals a very simple relationship between the flow head available, the quantity of water flowing, and the quantity of air induced and compressed. If the flow head and quantity of water flowing are known, one can determine the quantity of air that can be compressed to a predetermined pressure and, in turn, the amount of work that can be performed.*

Applications of Hydraulic Air Compression

Compressed air can be used as a means of energy storage; to run a wide variety of pneumatic tools, machinery, and control equipment; or to turn a turbine wheel and provide rotary mechanical power, which, in turn, can be used to generate electric power. When compressed air is expanded through a turbine

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*The simple functional relationship between the head, quantity of flowing water, and amount of air compressed is as follows in both English and metric units:

(English)   (Metric)

$$\frac{Q_A}{Q_W} = \frac{h}{100}$$ $$\frac{Q_A}{Q_W} = \frac{h}{30.48}$$

and   and

$$W_A = \frac{h}{1,307} \, Q_W$$ $$W_A = \frac{h}{24.82} \, Q_W$$

where
h = head in ft (m)
Q_A = air induced in ft^3/sec (m^3/sec)
Q_W = water rate in ft^3/sec (m^3/sec)
W_A = lb of air/sec at 59°F (kg of air/sec at 15°C)

Once the actual amount of compressed air is determined for a system, the theoretical energy available from reversible adiabatic (isentropic) expansion can be calculated in

and is actually doing work, the temperature of the exit air drops significantly, thus providing refrigeration as a side benefit (or perhaps in many cases the main benefit). If compressed air is heated prior to passing through the expander turbine, the energy output of the turbine can be increased significantly, thus converting low-grade (heat) energy to high-grade (mechanical) energy. If a significant amount of heat is added, the hydraulic air compressor could be used, for example, to provide input air for a large gas-fired turbine electric generator. Under proper design conditions, the fuel consumption of such a gas turbine generator could be reduced to perhaps half of that required (for any given amount of electricity produced) if the gas turbine had to compress its own air. The net amount of electricity produced could be higher than that produced by a hydroelectric system using the same falling water plus the gas turbine operating alone.

Whether low-grade heat is added or not, the exit air can be relatively cool (or even cold) and the refrigeration benefit need not be lost. Since its operating temperature would be fairly low, the turbine can be made of a variety of common metals. Such turbines can be manufactured at relatively low cost, and could be fabricated in some developing countries.

In many countries in which hilly or semi-mountainous land is farmed, irrigation can be a problem. In combination with an air lift pump, the hydraulic air compressor can be used to lift water to any reasonable height.

Finally, hydraulic air compressors are useful in mining operations (their original purpose), including mine ventilation and the operation of mining equipment. While the original application was in hardrock mining, the system

terms of the fundamental relationships between temperature, pressure, and volume as follows:

$$W = \frac{mR}{0.4} \quad (T_1 - T_2) = \frac{P_1 V_1 - P_2 V_2}{0.4}$$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{0.4} = \left(\frac{P_2}{P_1}\right)^{0.2857}$$

where subscripts indicate initial and final values for temperature, pressure, and volume, and

m = mass of air captured and compressed in lb (kg)
R = gas constant, 1545 ft-lb/$^{\circ}$R (8.314 J/$^{\circ}$K)
W = work done in ft-lb (J)
P = pressure in lb/ft^2 (Newtons/m^2)
T = temperature in $^{\circ}$R ($^{\circ}$K)
V = volume of air in ft^3 (m^3)

Any figures for work or energy available calculated from the above equations must, of course, be multiplied by the efficiency of whatever turbine or other expander is used.

could be used to pressurize water for placer mining or to elevate water for gravity washing in small applications.

All of the above applications require a rudimentary system with a minimum of moving parts, minimal maintenance, and a long service life.

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Energy from Biomass

INTRODUCTION

Energy can be derived from a wide range of biomass products, but with varying implications for agriculture. Adding the pressures of energy demand to intensive crop production can aggravate such problems as depletion of soil nutrients and of organic matter, which is critical to the maintenance of soil tilth, water infiltration and holding capacity, and a range of other physical and chemical properties.

In contrast, biomass energy recovery systems that include crop material, utilize animal wastes, provide animal feed, or return nitrogen, phosphorus, and potassium to the land can greatly increase the efficiency of many small farms in developing countries by encouraging integration of the components that result in higher production efficiency.

The intensive agricultural systems so common to developing nations are not totally lacking in energy potential, despite the problems just cited. For example, the lowland rice paddy is a biologically stable crop cultivation system (Geertz 1963): its anaerobic conditions create a chemical balance that makes low-concentration soil nutrients more readily available; considerable nitrogen is fixed in the paddy water by free-living organisms (IRRI 1977); and little soil erosion occurs. Rice straw can be converted to energy in some situations in which other uses do not take priority. Sugar cane is another relatively stable biological system, and it can be cultivated solely for energy use. There are, however, far greater overall benefits in intensive agricultural systems when energy recovery is a by-product.

Perennial cropping systems—shrubs and trees—have high untapped potential for the use of new technologies that convert sunlight to usable energy via biomass. Such systems would be concerned primarily with the production of

cellulose rather than the protein–starch–carbohydrate production of intensive agriculture. Conversion methods include combustion, charcoal production with a heat by-product, the various pyrolysis processes, or enzymatic hydrolysis to sugars and fermentation to alcohol.

Conversion technologies for producing fuels from biomass can be divided into two categories: biological and thermochemical. Biological conversion processes, as applied to developing countries, were not only treated in the original volume of *Energy for Rural Development*, but also in *Methane Generation from Human, Animal and Agricultural Wastes* (National Research Council 1977) and a forthcoming publication of the National Academy of Sciences, *The Potential for Alcohol Fuels in Developing Countries* (working title). These processes are covered in the following sections on "Anaerobic Digestion," "Energy Farms Utilizing Aquatic Plants and Wastewater," and "Ethanol (Alcohol) Production." Thermochemical conversion processes are discussed in a section that focuses principally on direct combustion and pyrolysis, which are near-term technologies of importance to developing countries. (See Appendix C for an extensive list of suggested reading on energy from biomass.)

ANAEROBIC DIGESTION

It is only logical that developing countries, which are largely rural, have taken a great interest in biogas, the gas produced as a result of the anaerobic digestion (biomethanation) of biomass. Agricultural and animal wastes, the major raw materials for biogas production, abound in the rural areas, and the rural populace, who are especially vulnerable to the price and supply fluctuations of conventional fuels, can benefit directly from family- and community-size biogas systems.

Microbiological conversion of organic material into methane gas through anaerobic digestion has been studied extensively, and in recent years has been of particular interest in countries facing shortages of coal and petroleum. The basic principles involved in this process are thoroughly discussed by Singh (1971); in the National Academy of Sciences (NAS) publication, *Microbial Processes: Promising Technologies for Developing Countries* (National Research Council 1979); and in a forthcoming NAS publication, *Food, Fuel, and Fertilizer from Organic Wastes*. Diagrams for simple digesters, particularly for animal wastes, can be found in these books. Because this process is discussed in such detail elsewhere, only a brief summary is presented here. (See Appendix A for a list of manufacturers and designers of methane digesters.)

The Process

Biomethanation is the anaerobic digestion (without free oxygen) of organic material. This process produces biogas, which consists of carbon dioxide and

methane with lesser amounts of nitrogen and traces of hydrogen sulfide and hydrogen. The percentage of methane in the total volume of biogas produced during this process is highly dependent on the control of certain parameters— substrate, carbon-to-nitrogen ratio, temperature, the pH, organic loading rate, and solids concentration—all of which influence the delicate microbial population balance between the acid-forming bacteria and the methanogenic bacteria. In brief, these parameters should be adjusted as follows in order to generate the greatest volume of methane in the shortest period of time.

Substrate. The initial substrate or organic material must have a high carbon content, mainly in the form of cellulose, hemicellulose, sugars, lipids, and protein. The substrate should also be low in lignin which is nonbiodegradable and hinders the microbial breakdown of the cellulose.

Carbon-to-Nitrogen Ratio. The optimal C/N mass ratio is 30:1. A higher ratio indicates a substrate that is deficient in nitrogen, which would result in the biodigestion ceasing when the nitrogen has been depleted and before all the available carbonaceous material has been converted to methane and carbon dioxide. A lower C/N ratio usually indicates that there will be loss of nitrogen during the digestion process.

Temperature. Sudden temperature fluctuations will slow down or stop the process. The optimum temperature range is generally from 33° to 38°C (91° to 100°F), or the so-called mesophilic range. Biodigestion will proceed at a slower rate below 33°C, essentially stopping at 10°C (50°F), and will proceed in the temperature range of from 54° to 60°C (129° to 140°F) with the so-called thermophilic bacteria. However, this group of bacteria is extremely sensitive to temperature fluctuations. Further, a greater amount of the energy is utilized to maintain the biodigester at this high temperature unless solar energy is used for temperature control.

pH Factor. The optimal pH range is from 7.0 to 7.2, but the pH may vary between 6.6 and 7.6. If the system is upset, the pH usually drops due to excessive acid production, a condition that may be difficult to correct. Careful addition of lime to raise the pH to near 7.0 may restore the system to normal.

Agitation. Some daily mixing is desirable to keep heavier material distributed throughout the system. The amount of agitation required (if any) is highly dependent on the type of feedstock used.

Solids Concentration. Terrestrial plant material and animal wastes generally require dilution with water to reduce the solids concentrations to 7-9 percent. A minimum amount of water should be added to aquatic vegetation

since the initial solids content is generally below 7 percent of the fresh weight (see "Energy Farms Utilizing Aquatic Plants and Wastewater").

Organic Loading Rate. Continuous-feed digesters can be easily upset by adding fresh substrate too rapidly. The optimal loading rate varies according to such parameters as digester design, substrate, and temperature. Thus it is difficult to give any general advice as to how to adjust this variable for optimal production of gas.

Recent Technological Developments

In the past 5 years, significant advances have been made in methane production by anaerobic digestion. A paper by Klass (1980) presented to the 1980 Bio-Energy World Congress and Exposition describes recent developments in this area, many of which apply for the moment only to large-scale, municipal-type digesters found in urban areas.

Feedstock Evaluation. Considerable work has been aimed at better understanding the anaerobic biodegradability of organic components and predicting the performance of a particular feedstock under anaerobic digestion conditions without conducting long-term batch digestion tests. Recent work includes studies of the effect of molecular structure on fermentation (Chou, *et al.* 1977), the use of kinetic constants to predict methane production (Chen and Hashimoto 1979), and rapid methods of predicting biodegradability based on substrate composition (Chandler, *et al.* 1979).

Methane yields in an anaerobic digestion process can be increased by pre-treating the feed (e.g., acid hydrolysis of cellulose, alkaline treatment to break up lignocellulose complexes) so that the complex organic structures, especially the polymers, are broken down to lower molecular weight species which are then more susceptible to microbial degradation. Gossett, *et al.* (1975) and McCarty, *et al.* (1979) have made detailed studies of the effects of acid and alkaline treatments on methane production.

Digester and System Designs. Stirred-tank reactors, usually in the complete-mix mode, are still the most commonly used digestion systems, but other digester designs are being developed—for example, plug-flow, two-phase, and fixed-film.

Plug-flow digesters, proposed for low-cost, small-scale systems, are reportedly quite suitable for such feeds as dairy cattle manure (Jewell, *et al.*, 1979a). When compared to the complete-mix digestion of dairy cattle manure under mesophilic conditions in farm-scale digesters, the plug-flow unit provides higher methane yields and more efficient destruction of volatile solids. The plug-flow tank costs about $10,000 compared to $30,000 for the

complete-mix digester. These systems have been in operation on Michigan and Wisconsin farms for several years (Abeles, *et al.* 1978).

In a two-phase digestion system (for insoluble substrates), the acid- and methane-formation phases are physically separated by control of the detention time and the loading rate of the volatile solids (Ghosh, *et al.* 1975; Ghosh and Klass 1978; Norrman and Frostell 1977). Two-phase digestion permits optimal operating conditions for each microbial population, which means shorter detention times and more efficient conversion to methane.

Digesters that contain solid supports for anaerobic organisms seem promising for both efficient waste stabilization and methane production (Pitt and Genung 1980; Jewell 1980; Jewell, *et al.* 1979b). Digesters in the experimental stages include a 5,000-gal/day (18,926 l/day), fixed-film, upflow bioreactor (ANFLOW) containing a packed bed of ceramic Rasching rings; settled sewage sludge and upflow bioreactors containing small particles that behave like fluid beds; and anaerobic, attached-film, expanded-bed bioreactors (AAFEB), which reportedly are effective for treatment of primary settled sewage. A 50,000-gal/day reactor is now being developed to demonstrate ANFLOW. It is anticipated that methane will be recovered at yields of about 5 ft^3 (.14 m^3) for each pound of BOD (biochemical oxygen demand) destroyed in the process.

One difficulty with anaerobic digestion systems is that the organics are not completely gasified in the process; residuals are always left in the digester effluent. An innovative approach to this problem combines anaerobic digestion and thermal gasification (Chynoweth, *et al.* 1980; Anonymous 1979). The Institute of Gas Technology (USA) has developed the BIOTHERMGAS process in which anaerobic digestion, dewatering, steam-oxygen gasification, and catalytic methanation of the hydrogen-rich gas from the thermal gasifier are combined in that order to produce methane. Thus refractory organics from the digester are completely gasified, and waste heat as well as ammonia and inorganic nutrients can be recycled from the thermal gasifier to the digesters.

Anaerobic digestion and thermal processing can be combined in yet other ways. Four alternatives for conversion of refuse-derived fuel (RDF) to electric power via gas have been analyzed, namely (1) mesophilic digestion with the residue used as landfill, (2) mesophilic digestion with thermal processing of the residue, (3) thermophilic digestion and thermochemical processing of the residue, and (4) mesophilic digestion of RDF's food-waste fraction and thermochemical processing of the fiber fraction. The latter route was found to be the most economically attractive. The cost of producing fuel gas by these processes ranges from $2.46 to $14 per million Btus at a capacity of 2,000 t/day. If efficiency can be optimized and credits for disposal of municipal solid waste of $7.50-$10/t obtained, the cost of using gas produced

by these methods could approach present costs for fuel oil (Anonymous 1979).

Because steel tends to corrode over a period of time when used in anaerobic digesters, one recent design has evolved that obviates the need for steel. The bag digester (Figure 28) is a sausage-shaped bag made of 0.55-mm (.02-in.) thick Hypalon, which is laminated with neoprene and reinforced nylon (Skrinde 1978). It is provided with a polyvinyl chloride (PVC) inlet and outlet. Advantages of bag digesters, which originated in Taiwan, are reported to be low-cost mass production capabilities and easy transportability. They are available in both circular and rectangular configurations and in sizes from 5 to 100 m³ (177 to 3,531 ft³).

A host of variations in biogas plant configurations has been developed (Figures 29-36), incorporating design features particular to the type of feedstock used, construction materials available, and ultimate uses of the byproducts that are produced.

Production Parameters. Loading rate, detention time, and temperature probably have the most influence on the methane generation process. Ideally,
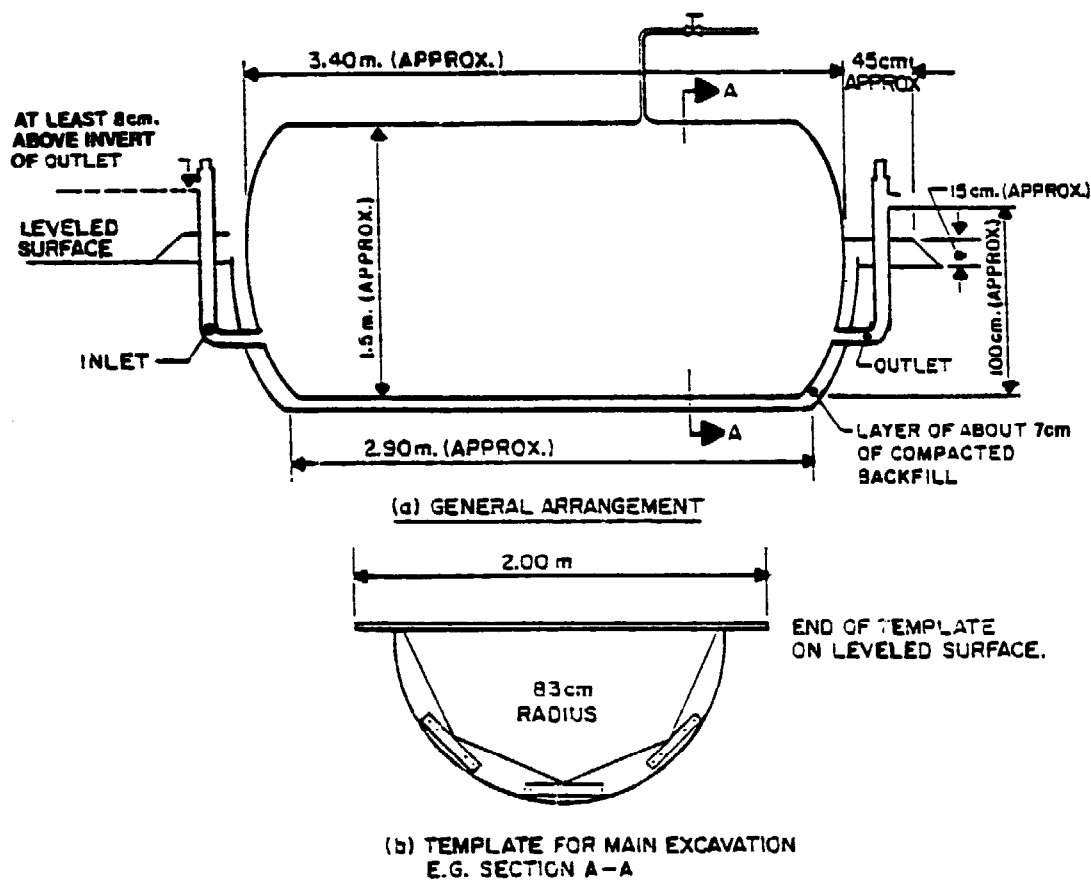
FIGURE 28   A 5-m³ bag digester. (Source: Skrinde 1978)

digesters should be loaded as much as possible for the shortest period of time consistent with high methane yield and destruction of volatile solids. Many projects have been working toward these goals (see Bryant, *et al.* 1976; Hashimoto, *et al.* 1978; Schellenbach 1980; Wujcik and Jewell 1979).

Additives. Considerable work has been done the last few years aimed at using additives—coal and flyash, carbon, lactobacillus cultures, enzymes, and growth factors such as amino acids—to improve digestion. Radiation, although not strictly an additive, has also been evaluated (see Spencer 1978;
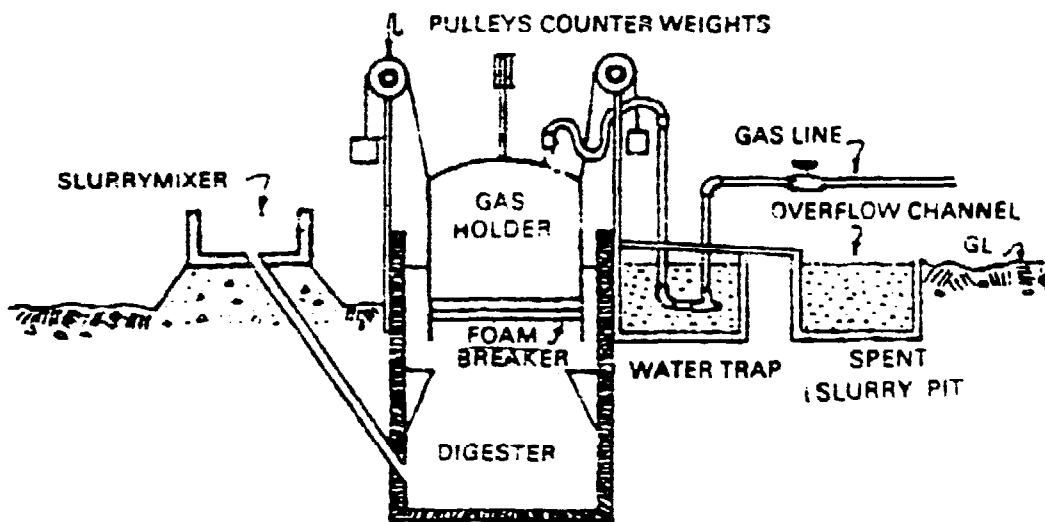
FIGURE 29   Gobar gas plant (Indian Agricultural Research Institute) with overflow outlet, designed by Patel, India. (Source: Maramba 1979)
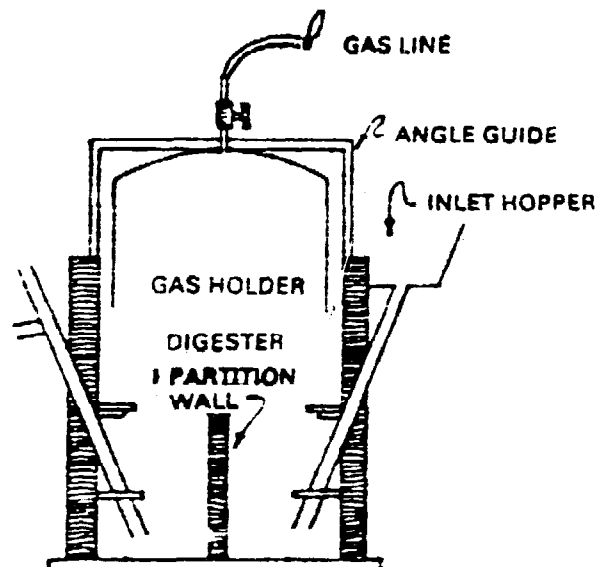
FIGURE 30   Gobar gas plant (Central Public Health Engineering Research Institute, India) with pipe outlet; Indian design. (Source: Maramba 1979)
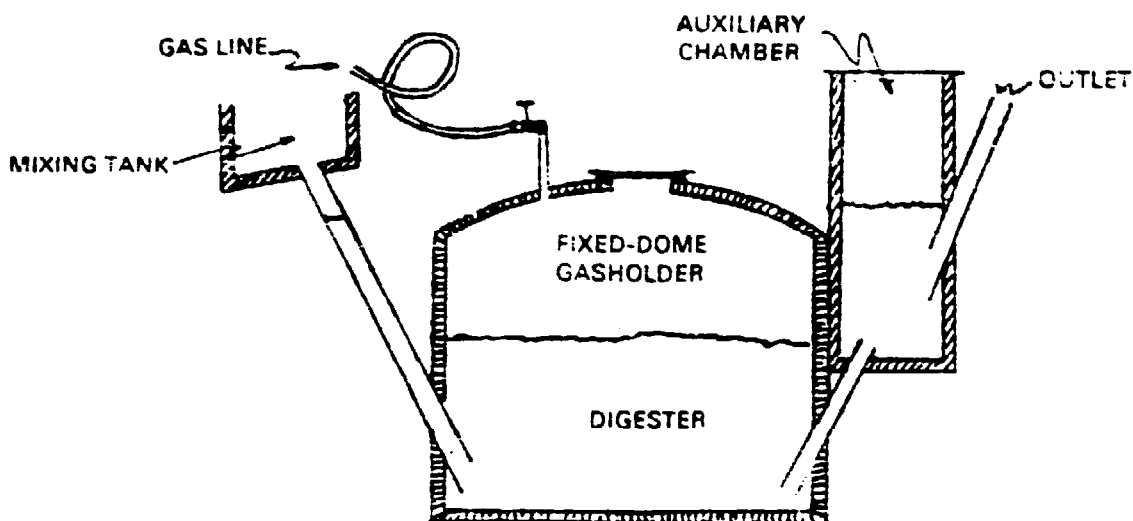
FIGURE 31 Fixed-dome, continuous-feed biogas plant, Maya Farms, the Philippines; Chinese design. (Source: Maramba 1979)
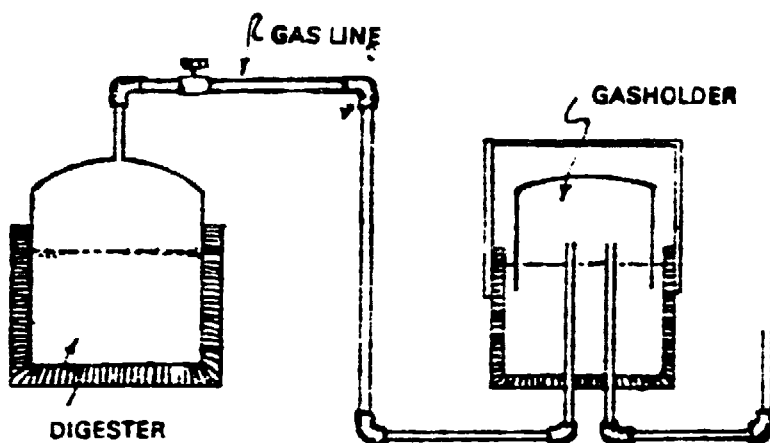

FIGURE 32 Belur Math gobar plant, Calcutta, India. (Source: Maramba 1979)
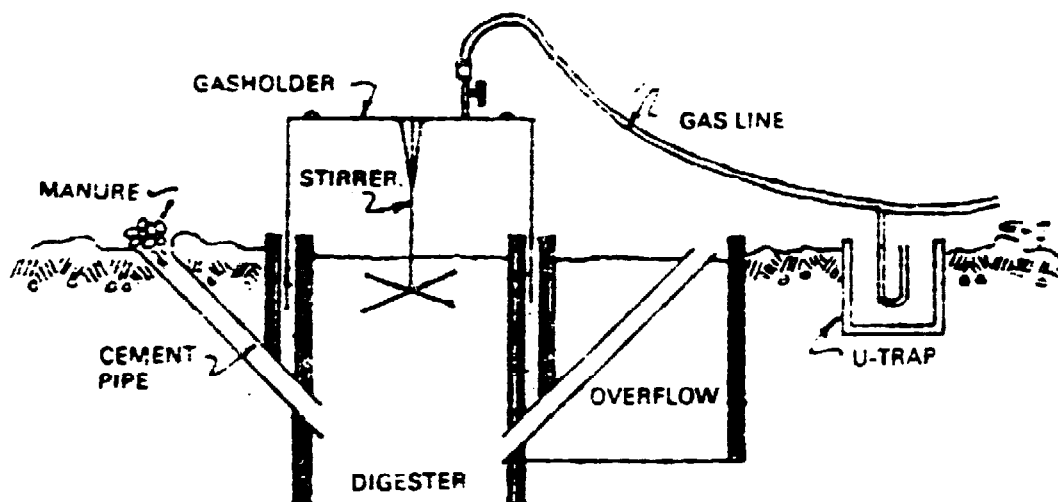

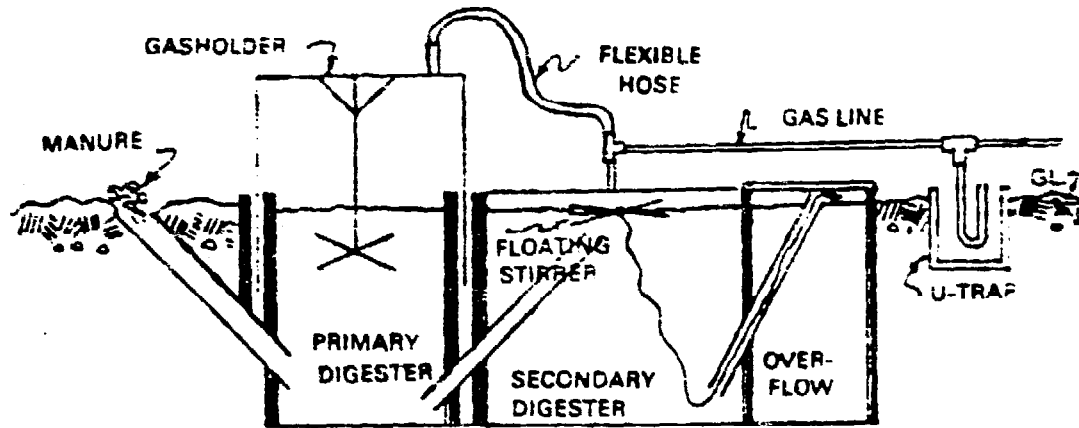**FIGURE 33** Taiwanese single-stage biogas plant. (Source: Maramba 1979)

FICURE 34   Taiwanese two-stage methane generator. (Source: Maramba 1979)
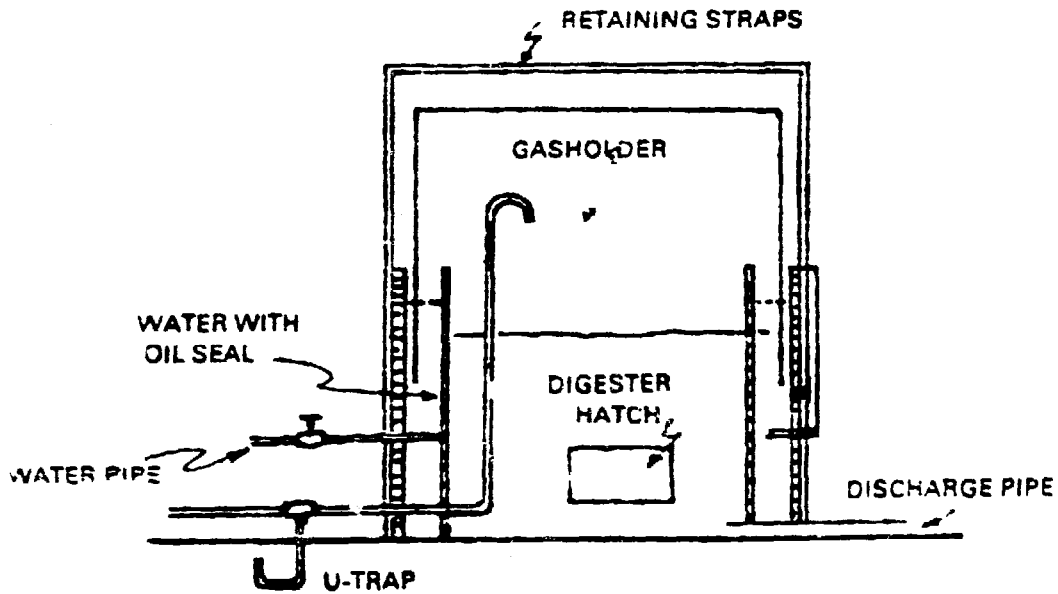

FIGURE 35   Kenyan batch digester. (Source: Maramba 1979)
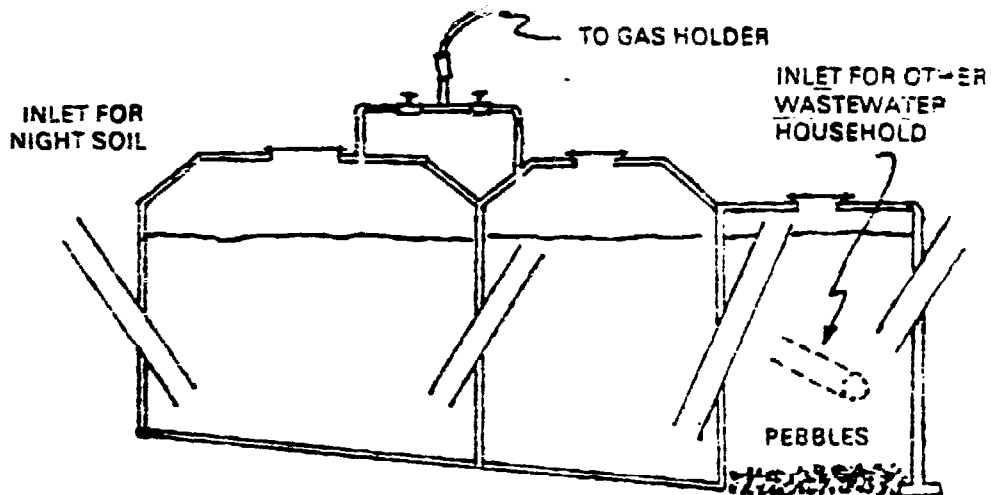

FIGURE 36   Night soil digester, designed by D. Bautista, the Philippines. (Source: Maramba 1979)

McConville and Maier 1978; Ghosh and Klass 1980; Bullock, *et al.* 1980; Novak and Ramesh 1976; Gottschall, *et al.* 1978). Refinement of the additives as well as treatments that can improve digestion performance and careful economic analysis should facilitate selecting practical methods for commercial use.

Applications in Developing Countries

Using known technology to produce biogas to satisfy a significant portion of human needs has been approached differently in various countries and by various organizations (see Skrinde 1978).

In 1974, the Economic and Social Commission for Asia and the Pacific (ESCAP), a United Nations organization, adopted the Colombo Declaration which stated that energy was one of its most urgent priorities for action. Subsequently, ESCAP undertook a program designed to accelerate the development of the biogas industry throughout Asia.

India is carrying out an extensive program of biogas research and plant construction. During the past 30 years, such institutions as the Indian Agricultural Research Institute, New Delhi; the Khadi and Village Industries Commission (KVIC), Bombay; the Gobar Gas Research Station, Ajitmal; and the Planning Research and Action Institute, Lucknow, have accumulated useful information on the anaerobic fermentation of cow manure (known as "gobar" in Hindi). The KVIC began playing a key role in the extension of biogas plants throughout India in the 1960s, and by 1978 the number had reached 50,000, with an ultimate target of 100,000 units (see Sathianathan 1975; Subramanian 1977).

Standard biogas plant designs utilizing concrete tanks, concrete inlet and outlet basins, and steel covers serving as floating gas holders have been developed and published by KVIC (1974). These digesters have no pumps, motors, mixing devices, or other moving parts, and digestion takes place at ambient temperature. Detention time by volume is generally about 30 days. The digesters contain a baffle in the center to avoid mixing new material with digested sludge. These are primarily single-family units.

A number of large-scale biogas plants are also operating in India. The Bharatya Agro Industries Foundation (BAIF) has a 12,000-ft^3/day (340-m^3/day) plant operating at the village of Uruli Kanchan (near Poona), using the dung from a cattle-breeding operation (approximately 600 cows). The gas produced is used for cooking, lighting, generating electricity, and pumping water.

Under the direction of the Gobar Gas Research Station in Ajitmal, a community biogas plant has been installed and is operating successfully in the village of Fatah-Singh-Kapurva (Uttar Pradesh). This plant, operating on dung supplied by the villages, provides cooking gas, village lighting (electric), water pumping, and grain milling.

Several other community biogas plants are being installed throughout India, including one designed by A. K. N. Reddy and the ASTRA (Application of Science and Technology to Rural Areas) group at the Indian Institute of Science, Bangalore. This plant will supply cooking gas, only during cooking hours, to all 60 houses in a village. The gas will also be used to pump drinking water for the village, to provide three hours of electric lighting in each house, and to mill rice husk and lime for cement. The proceeds of the sale of the cement will pay the wages of the five people needed to operate the system. The residue (fertilizer/soil conditioner) will be distributed to farmers on a pro rata basis, determined by the amount of dung contributed.

In view of the economic advantages inherent in large-scale community biogas systems (National Research Council 1977), the progress of these systems in India will be of great interest.

In the Republic of Korea, considerable research and development work has been carried out under the direction of the Organization of Rural Development (ORD), and 25,000 digesters have been installed. The severe Korean winter and the fact that Korea does not have a cattle-based economy have influenced the biogas program. From 1969 to 1976, ORD conducted a major campaign to encourage the construction of biogas plants that digest both animal and human wastes. The Institute of Agricultural Engineering and Utilization and the Rural Guidance Bureau are in charge of development and application, respectively.

The Korean government was subsidizing 33-50 percent of the cost of new biogas plants, but this subsidy has been discontinued, and the number of new units being constructed has declined. Only 4,000 new units were constructed in 1975, and in 1976, ORD discontinued the installation of demonstration family digesters. Shortage of animal wastes, difficulty in collecting wastes, and the rapid urbanization of rural areas have resulted in discontinuing the use of a number of small digesters.

In Pakistan, nearly 100 biogas plants have been built, and there is growing interest in the biogas industry. The government has been supplying free gasholders, provided that farmers build their own digesters. Extension of the program has been hampered by low temperatures from November to March and the high cost of imported steel for fabrication of gasholders. The Appropriate Technology Development Organization of Pakistan has recently been engaged in the design and construction of 10 m³-capacity (353 ft³), fixed-gasholder digesters, based on Chinese technology. One such unit was constructed near Karachi in 1976 at a cost of $590.

In the Philippines there is a growing interest in biogas systems, arising essentially from their use for pollution control and their public health benefits. Some biogas units have been installed through a program of the National Institute of Science and Technology (Maramba 1979). At Maya Farms, where

an integrated agroindustrial complex of 7,500 hogs* has been established, 48 digesters of 22 m³ (777 ft³) each are operating on a batch cycle of 30 days. Stirring is carried out for two minutes each day, and digested sludge from finished batches is used as a starter. The gas produced is used within the farm-processing complex as a source of fuel for canning, rendering, cooking, generating electricity, deep-well pumping, and other purposes. Digesters using hog wastes are also located at the Daughters of Charity Mission in Rizal; the University of the Philippines, Los Baños; and the University of the Philippines, Quezon City.†

Biogas utilization in Thailand started on a small scale 5 years ago, and now there are 225 units in the country. Biogas plants have been promoted by the Agricultural Economics Department, the Sanitation Division of the Health Department, the Applied Scientific Research Corporation, and the Animal Husbandry Department of Kasetsart University, with subsidies from the government for the gasholders. Plans call for building 50 digesters every year, but with no additional subsidy from the government. The present emphasis of biogas plants in Thailand is on waste treatment rather than on energy production.

Approximately 12 biogas plants are operating throughout Indonesia, with numerous experimental units being evaluated to reduce construction costs.

Seven million plants have reportedly been built in the People's Republic of China, and emphasis has been placed on a design that destroys bacteria and parasitic eggs in human and animal wastes so that the digested slurry can be safely applied to crops (McGarry and Stainforth 1978).

Integrated Farming System (IFS)

In an integrated farming system (Figure 37), the anaerobic digestion of biomass provides pollution control, biogas production, nutrient and fertilizer effluents, and feed supplements for rural areas. Optimization of the IFS to provide fuel, food, and fertilizer for rural areas in developing countries is thought to be accomplished most easily as follows. Raw wastes are fed on a continuous basis (twice a day) to a digester with a specified volume of water

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*The operation is now undergoing expansion to handle ultimately 18,000 animals.
†One of the more interesting aspects of the Maya Farms approach is the integrated recycling of the digested sludge and the liquid effluent from the digesters. The sludge is dried in open "ponds" and the dried material is mixed with pig feed at a rate of 10 percent. Aside from the saving in feed this represents, farm managers have found that vitamin B_{12} and other unidentified growth factors in the sludge accelerate growth rates by 15 days. The total saving in feed repaid the cost of the biogas installation in 2 years.

Liquid effluent from the digesters, together with pig sty washings, are sent to a pond where they supply nutrients for the growth of algae used as food by a colony of ducks. The droppings of the ducks in turn provide food for tilapia that are grown in the pond. The fish are sold as food to farm workers and others in the area, and the ducks are slaughtered and canned, providing the operation with additional income.
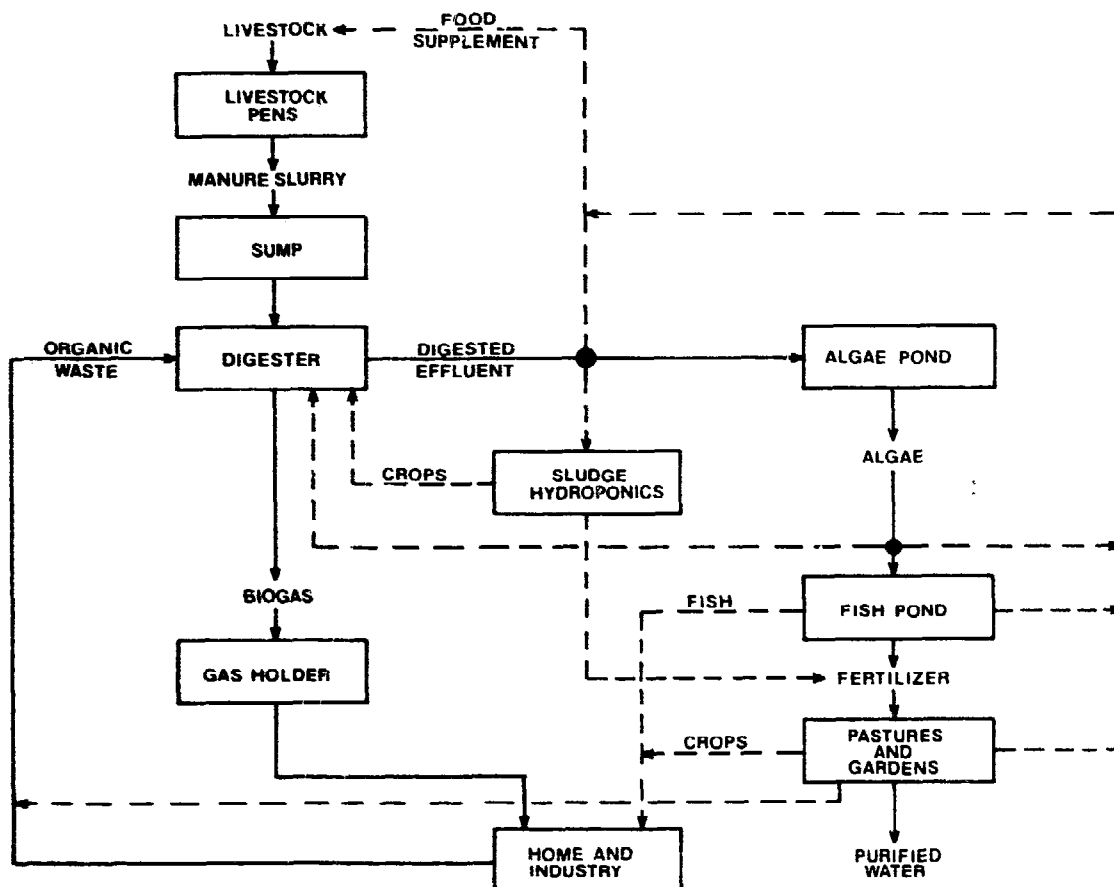
FIGURE 37   Integrated farming system.

for proper dilution. If the digester is covered with a greenhouse structure or other material, digester temperatures can be maintained at a particular level to assure maximum gas production for the type of waste used and surrounding environmental conditions.

Effluent (or sludge) from the digester is then sent to algae basins which are only a few inches deep in order to promote maximum algal growth and water stabilization. Some of the algae may be harvested to serve as a protein supplement in animal feed, or may be returned to the digester as raw feedstock. Effluent from the algae basin or pond then flows into deep fish ponds where fish and ducks can feed on plankton in the pond.* Mineralized nutrients in the pond waters provide a favorable aquatic habitat for the growth and eventual proliferation of a natural, biological aquatic ecosystem. The effluent from the fish ponds is then used in vegetable gardens and on crops as irrigation water containing sufficient nutrients to promote maximum growth of food, animal feed, and fiber. If the system is designed properly, it will

*Certain types of fish will also feed on the algae.

work by gravity flow, so that loading the digester with the raw waste slurry is the only required task. If animal wastes are to be used, this task could be conveniently accomplished by installing slatted floors in animal pens or barns to permit the wastes to be dropped directly into a digestion mixing chamber.

An integrated approach to waste recycling such as the one mentioned above can be economically viable, particularly if the main objective is self-reliance at the village level. Case studies of the application of such technology in rural areas of India, Korea, and the Philippines (as described in the previous section) have produced favorable economic evaluations of the process, based solely upon direct economic benefits of the system's end-products. In India and Korea, the anaerobic digestion process has produced methane with a higher economic value (resulting from the conservation of other domestic energy sources such as rice straw, wood, coal, or oil) than the cost of its production, while at the same time, a safer, more efficient fertilizer is produced than otherwise would be available. In the Philippines, the integrated farming system using sludge recovery and processing to provide pollution control, production of animal feed supplements from sludge solids, and liquid effluent to grow algae, fish, and aquatic vegetation for food and energy, has produced direct benefits well in excess of production costs (Maramba 1979).

ENERGY FARMS UTILIZING AQUATIC PLANTS AND WASTEWATER

In the last few years, the concept of using vascular aquatic plants for biological waste treatment and nutrient reclamation systems has become very popular in the United States and other industrialized countries. Highly productive vascular plants (such as the water hyacinth, *Eichhornia crassipes*), instead of algae, growing in wastewater ponds, are used to absorb the nutrients (and pollutants) and produce biomass (organic material) which can be harvested, processed, and returned to the environment in the form of fertilizer, feed, or energy. In a sense, this form of waste treatment can be considered an "energy farm" when plants are maintained to achieve maximum productivity, harvested, and then anaerobically digested to produce biogas.

The recognized techniques of producing biogas from the harvested plant material have not changed much in the last few years. However, a single large-scale system that encompasses both waste treatment/nutrient reclamation using vascular aquatic plants and energy production from the harvested plant material has yet to be devised. Vascular aquatic waste treatment systems are located at Coral Ridge Development in Coral Springs, Florida; the National Space Technology Laboratories (NSTL) of the U.S. National Aeronautics and Space Administration (NASA) near Bay St. Louis, Mississippi; Rio Hondo, Texas; and Disney World, Florida. A demonstration project at San Diego, California, is planned, and the waste treatment part of this system was due to

be installed by late 1980. Energy production as an integral part of several of these systems is being considered, but a definite time schedule for this aspect of these projects has not yet been adopted.

According to a publication of the National Academy of Sciences, *Making Aquatic Weeds Useful: Some Perspectives for Developing Countries* (National Research Council 1976), "The recovery of fuel from aquatic weeds, even if on a small scale, has interesting implications, especially for rural areas in developing countries. As many developing nations have an apparently inexhaustible supply of aquatic weeds within their borders, this potential energy source deserves further research and testing."

Due to widespread interest in the United States, this new waste treatment method should be well developed and perfected in the next 5 years. Designing and testing an optimum harvesting system is still the biggest single problem; however, this may not be a problem in developing countries where small, individual systems may be more practical and hand harvesting is a feasible alternative.

Vascular Aquatic Plants

A variety of aquatic plants has been studied for use in aquaculture waste treatment systems, and thus, potentially, energy farms. The water hyacinth has received most of the research attention in tropical and subtropical climate zones (Figure 38), and a large research program in this field has been sponsored by NASA (Wolverton and McDonald 1976, 1979a, 1979b; McDonald

FIGURE 38   Water hyacinths (*Eichhornia crassipes*) growing on a domestic sewage lagoon.

and Wolverton 1980). Other research projects have been conducted by Dinges (1978) and Cornwell, et al. (1977). Emergent aquatic plants such as the bulrush (*Schoenoplectus lacustris*) and submerged plants such as elodea (*Elodea canadensis*) have been studied by Seidel (1976) and McNabb (1976), respectively, for wastewater reclamation in northern climates. Since most developing countries lie within tropical and subtropical climate zones, further discussions will be confined to aquatic species that can be used in these areas.

Aquaculture waste treatment systems used in conjunction with energy farms should be designed to maximize biomass production; consequently, nutrient removal would also be maximized. To date, several designs for a total system have been suggested, but each has its advantages and disadvantages. Total daily wastewater volume, nutrient and organic concentration in the influent waters, climate, availability of land, mode of harvesting, and degree of purification and nutrient removal are some of the more important variables that must be carefully considered in choosing a suitable design.

Wolverton (1979) recently published design characteristics for small wastewater treatment systems applicable to U.S. needs. A more comprehensive engineering handbook compiled under contract with NASA is now available (Wolverton and McDonald 1980). Other pertinent references on aquaculture and wastewater treatment are listed in Appendix C.

Following is a brief description of some of the system management problems that have to be considered for this method of treatment regardless of whether it is carried on in a developed or developing country.

Harvesting. An aquaculture system designed for maximum biomass production will generally need harvesting every 3–4 weeks to maintain optimal growth conditions. The need for mechanical harvesting depends on the size of the system and the availability of inexpensive labor for hand harvesting as a substitute. Mechanical harvesting would not be economically practical for small aquaculture systems servicing only a few families.

A variety of harvesters has been built to harvest aquatic plants, and most were designed to remove water hyacinths (see National Research Council 1976; Wolverton and McDonald 1979c). Two of these harvesters are shown in Figures 39 and 40. Water hyacinth harvesters can generally remove anywhere from 9 to 90 tons of plants per hour depending on plant density, lagoon configuration, and operator skill in using the harvester.

Prevention of Spreading of Aquatic Weeds to Unwanted Areas. If water hyacinths or any other aquatic plants used for waste treatment are already established in the waters receiving the discharge, no special care is needed to prevent the plants from spreading. However, if this is not the case, screen barriers at the discharge point should be constructed to prevent uncontrolled growth in areas where plants are not wanted. The levees or retaining banks of
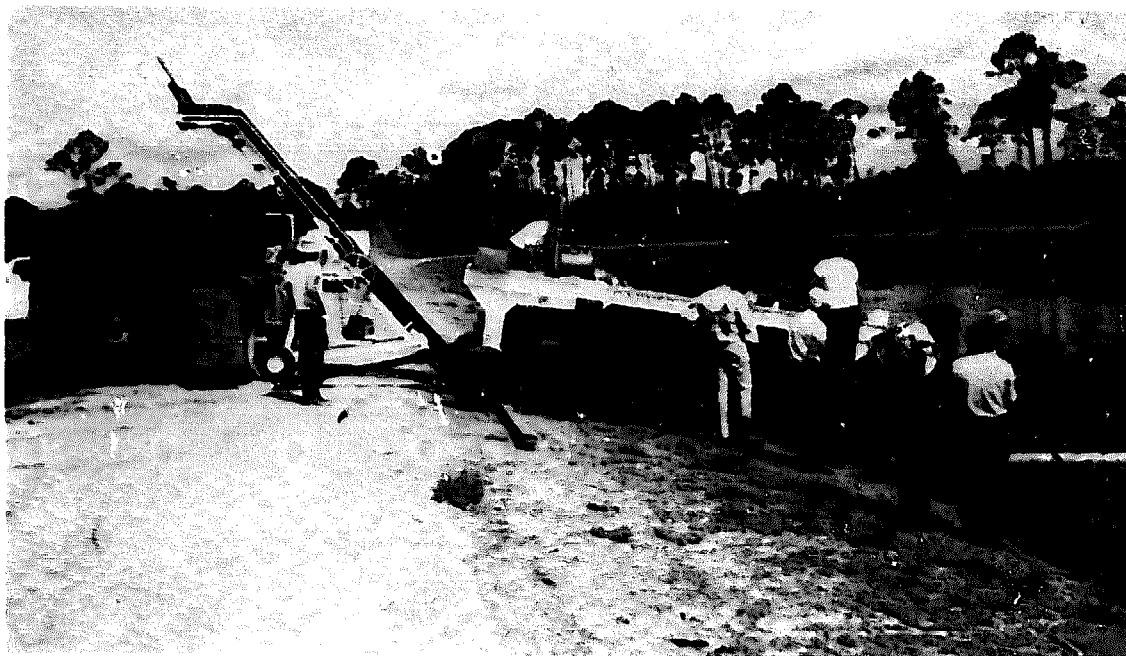
FIGURE 39 Water hyacinth harvester consisting of a rotary pick-up head, chopper, and conveyor belt.

lagoons should be sufficiently high to prevent any flood waters from sweeping plants into uncontaminated areas.

Odor Control. Aquatic plant wastewater treatment systems receiving light to medium daily organic loads (generally expressed in units of kg BOD_5/ha/ day) present no odor problems. The BOD_5, or 5-day biological oxygen demand, measures the amount of oxygen required by aerobic bacteria to stabilize the organic matter in 5 days. If sufficient oxygen is not supplied to the waters to keep the system aerobic, or at least the upper portion aerobic, then anaerobic bacteria will also be present. These bacteria cause gaseous chemicals such as hydrogen sulfide to be liberated, which can create the foul odors normally associated with overloaded wastewater treatment systems.

A system receiving approximately 50 kg BOD_5/ha/day (44.5 lb BOD_5/a/ day) or less will fall into the light- to medium-loaded range. In general, if this system is covered with aquatic weeds and harvested when needed, it will not emit odors. A system receiving a heavier load and covered with aquatic plants will emit odors at night when the plants are photosynthetically inactive. This problem can be corrected by either adding supplemental mechanical aeration at night or keeping the plants thinned out enough to allow some algal growth and natural aeration from wind action. A recent study of a duckweed-covered system (*Spirodela, Lemna*, and *Wolffia*) proved that this type of system receiving a heavy organic load could be odor-free (Wolverton 1979). The duckweed was so thick that it acted as a natural sealant and prevented the hydrogen sulfide from being emitted from the lagoon and causing foul odors.

FIGURE 40 Conveyor harvester receiving plants from a pusher boat in foreground.

Mosquito and Insect Control. Aquaculture systems that are not kept totally anaerobic may be stocked with mosquito fish (*Gambusia affinis*). These small fish feed on the mosquito larvae and serve as effective, natural "larvicides."

Water hyacint'is and other aquatic weeds may occasionally be damaged by insects, especially the spider mite (*Bryobia praetiosa*). If damage is severe, a light application of an insecticide such as Malathion may be required.

Nutritive Value of Sewage-Grown Aquatic Plants

The nutritive value of aquatic plants generally reflects the fertility of the
waters in which they are grown. This phenomenon can be easily seen from
the difference in the two plants shown in Figure 41. In one study by Wolver-
ton and McDonald (1978) in which water hyacinths were grown in four waste-
water treatment systems receiving nutrient loads from very light to very
heavy, the crude protein in the whole plants varied from 9.7 percent to 23.4
percent of dry weight, and phosphorus content ranged from 0.31 percent to
0.89 percent of dry weight. Tables 3 and 4 depict the moisture content of
vascular plants—water hyacinth (*Eichhornia crassipes*), duckweed (*Spirodela,
Lemna,* and *Wolffia*), and water pennywort (*Hydrocotyle ranunculoides*)—

FIGURE 41   Visual comparison of plant differences when grown on a nutrient-rich
medium such as a domestic sewage lagoon and on an unpolluted lake. The water hya-
cinths were approximately the same age and collected on the same day.

TABLE 3 Proximate composition (dry weight basis).

Plant	Crude protein (%)	Fat (%)	Crude fiber (%)	Ash (%)	Total carbohydrates (%)
Water hyacinth	23.4	2.20	17.1	20.4	36.9
Water pennywort	22.4	2.19	11.8	17.4	58.0
Duckweed	37.1	3.40	15.6	12.5	47.0

TABLE 4 Nutrient and mineral composition (dry weight basis).

Plant	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Sodium (%)	Calcium (%)	Copper (ppm)	Zinc (ppm)	Iron (ppm)	Sulfur (%)
Water hyacinth	3.74	0.85	3.45	1.63	0.56	42.0	48.0	2260	0.40
Water pennywort	3.58	0.42	3.33	1.34	0.77	11.5	59.4	7490	0.31
Duckweed	5.94	1.01	2.13	0.74	0.88	14.1	1885.0	1450	0.85

that have been grown in highly enriched, domestic sewage lagoons. These plants, like many other aquatic species, would be excellent sources of protein and minerals. The sludge remaining after biodigestion would contain all of the minerals and most of the nitrogen and sulfur present originally in the plants. This sludge, which is completely stabilized, could be air-dried and used as a natural fertilizer for crops or even for mineral recycling in a "perpetual" biomass system for energy production.

Producing Biogas from Aquatic Plants

The simple biodigester designs currently available are particularly suited for digesting animal manure. Extensive use of this method on an individual home basis is found in India. However, even the simplest of biodigesters requires some daily attention and knowledge of biodigestion in order to generate a sufficient volume of methane safely and reliably to make the effort worthwhile. Simple batch digesters require the longest digestion times. (See the preceding section on anaerobic digestion for a more thorough discussion of energy from biogas and the NAS publication, *Methane Generation from Human, Animal and Agricultural Wastes* [National Research Council 1977].)

If fresh plant material is used, the plants should be chopped, crushed, or blended in some manner prior to loading in a digester in order to shorten the digestion time by increasing the surface exposure for bacterial attack. Choppers that can be adapted to this use are commercially available for grinding a variety of agricultural products (see National Research Council 1976). However, the initial investment, operation, and maintenance costs of these machines could only be justified for large installations.

A new approach to anaerobic digestion is currently under development by NASA's National Space Technology Laboratories, incorporating an "anaerobic filter" into the digestion system (Wolverton and McDonald 1979b). As depicted in Figure 42, the first chamber holds all the pulp and plant juice. The anaerobic filter in this case consists of small rocks (pea gravel) which provide a large surface area for bacterial growth. The plant juice is periodically circulated through the anaerobic filter and exposed to a mixed culture of the acid-forming and methanogenic bacteria. Preliminary results with this technique indicate that complete digestion of fresh plant material such as water hyacinth, duckweed, and kudzu (*Pueraria lobata*, a prolific terrestrial plant) can be accomplished in an average of 23 days with no loss in total methane production over the old batch or continuous-feed methods.

ETHANOL (ALCOHOL) PRODUCTION

In the years since publication of *Energy for Rural Development*, a growing body of information and practical experience has been gathered on ethanol production in the United States and elsewhere. Currently, a small but rapidly

growing number of plants are producing ethanol on a daily basis, making available, probably for the first time, hard data on the costs of and energy balances for producing 150–200-proof alcohol (75–100 percent alcohol, 25–0 percent water by volume). This experience also provides information on the training necessary to operate such plants successfully.

Because of the greater availability of information (rather than the discovery of any new knowledge), many concerns that have previously been the subject of much disagreement can now be scrutinized in the light of experience.

One concern about ethanol production is whether the amount of energy obtained from alcohol sufficiently exceeds that used in the planting, growing, harvesting, transportation, crushing, heating, and distillation needed to produce it. Unfortunately, the response to this concern is not at all clear-cut and depends a great deal on the individual situation.

Many things can be done, however, to improve this energy balance. By locating a distillery near its feedstock source, for example, transportation energy can be saved. Heat for cooking (only required for starches used as feedstock, not sugars) can be provided from wood, wheat straw, or other waste cellulose and lignin materials. Solar energy can also be used for cooling and for distillation, and a simple heat recovery system can be employed after fermentation (to preheat the liquid or so-called "beer"), using heat from the condensed stillage. Besides improving the energy balance, such techniques mean that low-grade (and perhaps otherwise unusable) energy is used to produce high-grade energy.
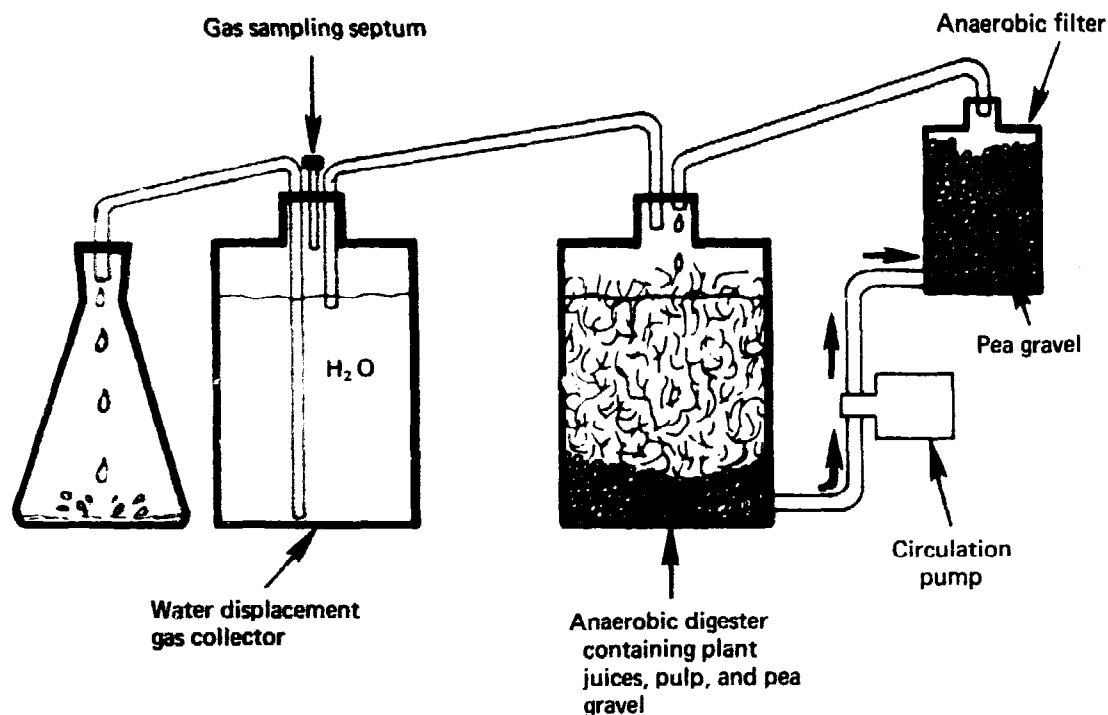
FIGURE 42 Two-stage anaerobic digester system for producing methane.

Another concern about alcohol production is that fermentation of starch, sucrose, or glucose consumes feedstock materials that could serve as animal fodder or human food. In a world facing chronic food shortages, some individuals question the wisdom of adding still another consumer to the food chain. Thus each developing (and developed) country will have to study its basic needs and resources carefully, and then choose the energy paths that best serve those needs. Alcohol production may fit well in some countries and not at all in others.

Operation and Production Rates of a Typical Fuel Alcohol Production Plant

Although alcohol can be produced by individuals with the crudest of equipment, alcohol production can probably be carried out most efficiently in developing countries at the local village or farm cooperative level. The number and size of alcohol production plants would then be balanced against the problems of transporting the feedstock.

This section will describe briefly the operation of an alcohol plant (batch process) that makes about 1,250 gal (4,731 l) of 190-proof alcohol per day (see Figure 43). This is not a general description of all plants, as plants vary according to available feedstocks, process energy sources, enzyme sources, etc. Such a plant will require about 15 t (13.6 metric tons) of dry grain (such as corn, wheat, barley, etc.), although anything with a considerable amount of sugar or starch is a possibility. Perhaps up to half of the grain can be salvaged for other uses in some cases. If the input feedstock is a root vegetable or a sugar source, the amount of material needed is determined by the starch or sugar, cellulose, and water content. Before an alcohol plant is constructed, indigenous feedstocks should be analyzed in order to forecast alcohol productivity.

As shown in Figure 43, the input stock must first be cleaned by some appropriate process and then pulverized. The grain grinder shown in Figure 44 can handle the 15 t of grain a day needed for the 1,250-gal/day plant described here. For root crops it is desirable, where practical, to remove as much of the cellulose fiber as possible, leaving mostly starch to be converted.

If the input is primarily sugar (as in sugar cane juice, fruit juices, etc.), the cooking step may not be necessary, unless there is a sterilization problem. However, input that is primarily starch must be cooked to help break up the long molecules so they can be more easily fermented. In such a case, water is added so that the resulting mixture is about 20 percent solids by weight. For the plant described here, the cooking vat would probably hold about 12,000 gal (45,423 l).

The starch/water mixture is then held at 212°F (100°C) for about one-half hour to help break down the starch and to kill bacteria. Often a commercial
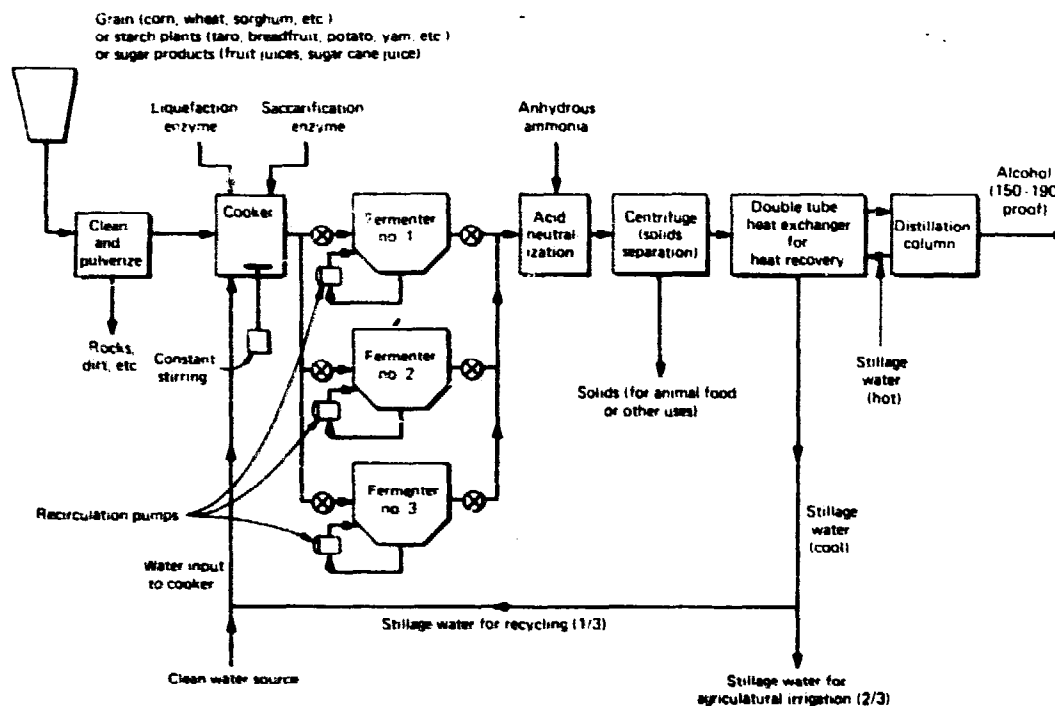
FIGURE 43 Flow diagram of a batch alcohol plant.

liquefaction enzyme is added at this stage to help break down the long starch chains. The cooking process is more effective if the mixture is stirred continuously.

The heat for cooking (and later for distillation) is often provided by a steam boiler, which can be fired by a variety of waste agricultural materials as well as by oil or natural gas. Figure 45 shows a steam boiler that uses 7 rolls of wheat straw (about 7,720 lb or 3,500 kg) per day to produce 1,250 gal of alcohol per day, all cooking and distilling energy included.

After cooking for one-half hour, the mixture is cooled to $170°F$ ($77°C$) and more liquefaction enzyme is added. The mixture is then cooled to $120°F$ ($49°C$) and a saccharification enzyme is added to convert the starch to sugar. The batch is then cooled further to $90°-95°F$ ($32°-35°C$), when it is pumped into one of several fermentation tanks. A proper yeast is then added.

It is essential that the fermentation tank be extremely clean before the batch to be fermented is pumped in, in order to destroy competing microorganisms. Scrubbing a tank down with soda ash between batches and keeping the tank completely full during fermentation will generally restrict the production of vinegar. For safety's sake, any person scrubbing down a tank must wear a sealed air mask with a fresh air supply. Because it is heavier than air, the carbon dioxide produced by the fermentation tends to stay in the tank, which could lead to asphyxiation.

Fermentation takes two or three days, depending on temperature. A small, continuously operating pump could serve both to slowly remove the heat
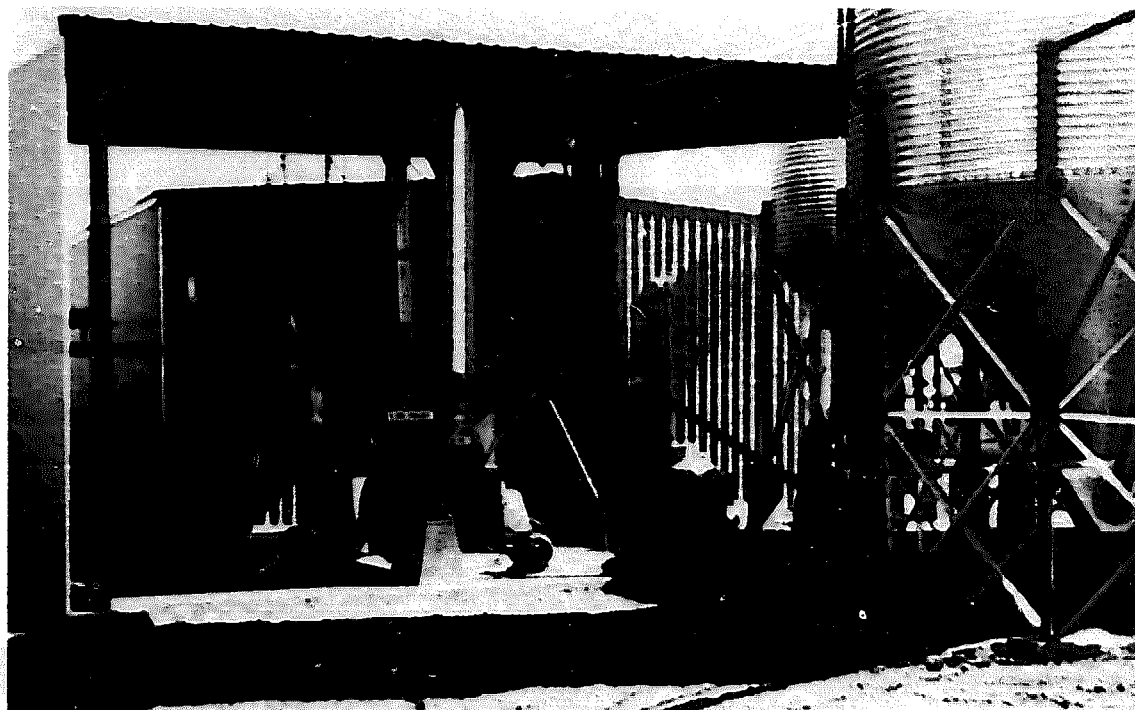
FIGURE 44 Grain grinder for 1,250-gal/day plant.

generated during fermentation and to stir the mixture. About three tanks are needed if the distillery is to run continuously.

After fermentation stops (determined by the fact that no more carbon dioxide is being produced), the so-called "beer" is ready for distillation. The input mixture ratio (20 percent starch by weight in this case) should have been adjusted so that all of the sugar was used up before the alcohol concentration became high enough to kill the yeast. Since the beer is slightly acidic at this point, it is desirable to add a small amount of anhydrous ammonia or some other appropriate base. This allows all subsequent plumbing to be made of relatively inexpensive carbon steel rather than expensive stainless steel. (Because the only high temperatures are found in the cooker, inexpensive plastic pipe can be used throughout the system until the heat recovery system just before the distillation column is reached.)

The solids must be removed before distillation, which is most easily done with a centrifuge. These solids (from grain feedstock) have significant nutritional value as an animal feed supplement and thus will not be wasted. Generally, any economic analysis of alcohol production costs should include a credit for these by-products of fermentation.

The liquid is next passed through a double steel wall heat exchanger, heated by the just-condensed water returning from the distillation column. This heat recovery step significantly reduces the input fuel required for distillation.

The kind of distillation column (and distillation energy) required is determined in part by the concentration of alcohol needed. The management of

the distillation column temperature is critical. At the bottom, the input temperature is 212°F (100°C) and at the top 173°F (78.5°C). If only fuel is desired, and not drinking alcohol, one distillation will suffice (even if alcohol as pure as 190 proof is required), although generally two separate columns will be used. Figure 46 shows a distillation column for the kind of plant just described, which is really two columns in tandem. Although a variety of distillation columns can be used, a large condensing surface is required. Alcohol of 100 proof, or possibly higher, has been obtained with a simple distillation column consisting merely of enclosed tubes packed with rocks.

If the alcohol produced is used as fuel directly (without mixing it with gasoline), 150 proof is adequate, and considerably less distillation energy is required per gallon (or equivalent Btu) output.

As shown in Figure 43, some of the plant's stillage is used as make-up water and the remainder as irrigation water. This takes advantage of the nutrients as well as the water. Research is being done in several countries (e.g., the United States and the Philippines) to determine the possibility of using stillage as a human food supplement.

Many variations are possible in the above process. Alcohol production has become very active in the last 2 or 3 years, and will undoubtedly remain so for the intermediate future.

Adapting Alcohol Processes to Developing Countries

Much can be done to simplify the process just described in order to adapt it (or similar processes) to situations in developing countries. Although the special materials required for this process (e.g., liquefaction and saccharification

FIGURE 45   Steam boiler designed to operate from rolls of wheat straw (in background).
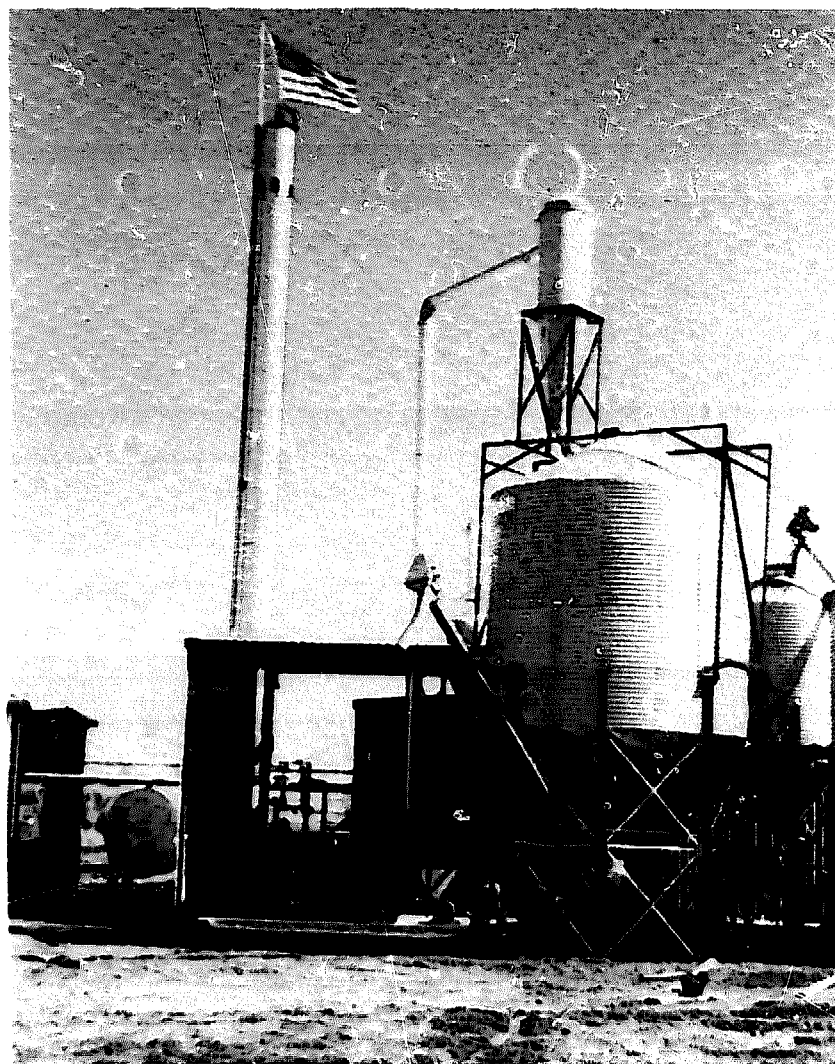
FIGURE 46   Distillation column (tall column in background) for 1,250-gal/day plant.

enzymes, anhydrous ammonia, yeast, caustic soda) may have to be imported initially by some countries, local capabilities for producing these materials could eventually be developed where they do not yet exist.

Concerning the necessary equipment, a sophisticated steam heating system for the cooker and distillation column may not be required if indigenous fuels or perhaps even solar energy can be utilized. The cooking vessel itself could be ceramic. Effective distillation columns could be made from rocks, although a second column with steel condensation plates may be required to achieve the desired 150-proof minimum. When cheap indigenous fuels are available, there is little need initially for a double tube heat exchanger for heat recovery. It would be one of the more expensive and difficult items to obtain or fabricate locally in some countries. Fermentation tanks can be made of hardwood as they have been for centuries. The type of wood required would be less critical than that needed for producing drinking alcohol. Finally, a centrifuge is only one means of removing solids. Settling tanks can also often be used for nonsuspended solids, with simple filter presses used to

improve liquid recovery. In some cases, the fermented mixture can be simply heated directly (with the alcohol and some water being driven off) and the high-nutrient residue can then be cleaned out later.

In short, alcohol production plants of reasonable size can be built and operated as a village or farmers' cooperative project. Although such plants may not be as efficient in their use of labor, these considerations can often be secondary to the problems of providing employment and producing fuel locally.

Use of Ethanol as a Substitute Fuel
for Internal Combustion Engines

Ethanol can be used as a fuel for internal combustion engines, and direct or gas-fired turbines can also use alcohol as a fuel with few problems.

The use of fuels consisting partially or totally of alcohol to run the spark ignition-type engine has received much attention in recent years, particularly in Brazil and the United States. The practice of mixing ethanol (of at least 190 proof) with gasoline has now become widespread in both countries. Mixtures of up to 20 percent alcohol and gasoline have been used. In the United States, the current standard mixture (so-called gasohol) is 10 percent ethanol, and experience indicates that most automobiles can run on this mixture, without carburetor adjustment, provided the alcohol remains well above 190 proof. At lower proofs, water separation can occur in certain cold weather situations, which sometimes results in difficult starting and rough-running engines.

Careful dynamometer tests run by several laboratories, including John Deere and Company (USA), indicate that with careful tuning, spark ignition engines running on gasohol can be operated with *slightly higher* fuel efficiencies than when running on gasoline alone. Thus, from a technical point of view, a 10 percent mixture of alcohol and gasoline is quite feasible. There has not yet been enough long-term experience to indicate whether problems with corrosion or undue engine wear will occur, but no such problems appear to be developing with any regularity. A few automobiles have required minor carburetor adjustments to achieve satisfactory performance.

When the spark ignition engine is fueled by ethanol alone, alcohol as low as 150 proof can be used and still allow satisfactory engine operation. However, the carburetion must be adjusted, including changing the jets, and certain types of rubber gasket material that may be damaged should be replaced. A technique of simply vaporizing the alcohol with heat from the exhaust manifold and feeding the vapors into the intake manifold has met with considerable success in several places. Thus the conventional carburetor is eliminated altogether.

An engine operating on ethanol alone can be difficult to start, particularly in cold weather, and this problem worsens as the proof of the fuel decreases.

It is often overcome by starting the engine (in cold weather) on gasoline, warming it up, and then switching to the alcohol fuel. (Some operators prefer to switch back to gasoline before shutting it off.) Another possibility is ether injection upon starting, although this must be done with considerable care or the engine can be severely damaged.

Significant attention has also been given to operating diesel engines partly on ethanol. Ordinary diesel fuel has significant lubricating as well as combustion properties, and diesel engines depend upon the former to obtain injection pump lubrication. Therefore, it is not practical to use plain alcohol, which has no lubricating capability. However, alcohol can be mixed with the diesel fuel before it passes through the fuel injection pump. Tests at the John Deere Laboratories have indicated that a diesel engine will run quite satisfactorily with mixtures of up to 30 percent alcohol and 70 percent diesel fuel without obvious adverse effects on the engine. Dynamometer tests indicated that engine efficiency remained essentially unchanged from its efficiency on diesel fuel alone.

The practice of directly mixing fuels for diesels is, however, potentially more damaging than would be the case in spark ignition engines. The alcohol proof must be kept extremely high (perhaps 195 or better) because of the injection pump problem. If there is any water separation, as could occur easily in cool or cold weather, the lubricating capability of the fuel mixture can break down, thus destroying the costly injection pump. However, if diesel fuel is injected by the fuel injection pump in the normal way, and an alcohol spray is injected into the air intake, all lubrication requirements are met, the fuel injection pump is protected, less diesel fuel is required, and the alcohol can be as low as 100 proof and still achieve adequate operation. The higher alcohol proofs (around 150 or more) probably give more efficient operation. With 150 proof or better, engines have been run on mixtures as high as 85 percent alcohol and 15 percent diesel fuel. It is desirable to start the engine on pure diesel fuel and warm it up before beginning alcohol injection, however.

For turbocharged diesel engines, work has been done on alcohol/water injection both before and after the turbocharger. In the former case, the input air draft is adequate, but fuel metering is difficult. If there are droplets of any size in the spray, the turbocharger can be severely damaged or destroyed. For injection after the turbocharger directly into the manifold, a separate injector pump will be required. However, it need develop pressures of only two or three atmospheres for a relatively small volume flow (of the alcohol/water spray). This system inherently provides an easy way of metering fuel, and since it cools the air charge before it enters the combustion chambers, the engine may actually be under somewhat less heat stress in its overall operation.

Work will continue on ways to operate engines on alcohol, but most of the problems have been identified. There do not appear to be any technical rea-

sons why this technology could not be applied widely in the near future; however, such widespread application will be determined more by economic and political factors than technical ones.

This subject will be covered more thoroughly in a forthcoming National Academy of Sciences publication, *The Potential for Alcohol Fuels in Developing Countries* (working title).

Chemical or Enzymatic Hydrolysis of Cellulose

Hydrolysis is a process in which cellulose molecules can be reduced to constituent sugars which can then be fermented. Enzymatic and chemical (acid) hydrolysis of cellulose are two lines of current research and development that could have a significant impact on the future of ethanol as a fuel. If hydrolysis by either method becomes practical, then essentially all plant biomass becomes a potential feedstock for alcohol production, and the threat of alcohol production competing with the food chain becomes far less serious.

Cellulosic waste materials are broadly composed of cellulose, which can be hydrolyzed into glucose; hemicellulose, which can be hydrolyzed into its constituent five carbon sugars; and lignin, which bonds the cellulosic materials together. To decompose cellulosic wastes, it is necessary to remove the lignin and break the crystalline structure of the cellulose so that it can be hydrolyzed either chemically or biologically.

Biological decomposition of cellulose has been the subject of research for a number of years by the U.S. Army Natick Research and Development Command (Spano 1976). The Natick laboratory has isolated a fungus, *Trichoderma reesei*, certain strains of which are highly efficient in the saccharification of cellulose into glucose. The problem with this process, however, is efficiently removing the lignin and breaking the crystalline structure of the cellulose so that the *Trichoderma reesei* can perform hydrolysis.

A University of Arkansas research program uses a mutant strain of *Trichoderma reesei* that is grown continuously to produce a complete cellulolytic system. This process features a simultaneous saccharification and fermentation process that results in approximately 60 percent conversion of the cellulosic waste within a 48-hour period, more than twice the conversion obtained by saccharification alone. Reportedly, this process is now commercially feasible and available for licensing.

Chemical hydrolysis of cellulosic waste materials, primarily wood, has been the subject of research and commercial application for more than 100 years. Until recently, very little commercial interest was generated by this technology because of its high cost of producing sugar as compared with agricultural techniques. However, with the advent of a heavy demand for fuel ethanol, this research has been accelerated.

A process developed by Purdue University (Ladisch, et al. 1978) involves a hemicellulose extraction of the five carbon sugars, a solvent pretreatment of the cellulose residue, hydrolysis of the treated cellulose into glucose, and subsequent fermentation of the glucose into fuel ethanol. Lignin is the most significant by-product of this process. Reportedly, a commercial plant is being designed for demonstration of this process.

J. W. Jelks, an Oklahoma inventor, has been issued U.S. patents on processes that treat plant organic matter to improve its digestibility by ruminants. Seven such plants have been built and are operating commercially, demonstrating a high degree of conversion of cellulose and hemicellulose into digestible sugars. Jelks is presently adapting his processes to utilization of the sugars for fermentation to fuel ethanol.

THERMOCHEMICAL CONVERSION OF BIOMASS

Selected types of thermochemical conversion technologies appear to be applicable generally to rural development in developing countries (Table 5). However, here the primary emphasis is on direct combustion (burning or incineration) and pyrolysis which are near-term technologies of importance to these countries. The prospects for the introduction of reliable, small-scale gasifiers in developing countries may be realized in the intermediate term (5-10 years).

Direct Combustion Processes*

Direct combustion, undoubtedly the most widespread process for the thermochemical conversion of biomass, is a direct process for production of bioenergy, but in its most commonly used form it is also the least efficient. An estimated nine-tenths of the people in poor countries heat and cook with firewood which has resulted in serious environmental degradation and increasing economic burdens caused by a growing scarcity of firewood (Eckholm 1975). The firewood energy crisis is the most acute today in the countries of the Indian subcontinent and in the semiarid stretches of Central Africa bordering

TABLE 5   Thermochemical processes for bioenergy applicable to rural development.

Process	Principal bioenergy/biofuel products
Direct combustion	Heat, hot water, steam, electric power
Pyrolysis	Combustible char, pyroligneous oil, and low-Btu gas
Gasification	Low- and medium-Btu gas

*Direct combustion processes are also dealt with in a NAS publication, Firewood Crops: Shrub and Tree Species for Energy Production (1980a).

the Sahara Desert. Other regions, such as Latin America, also suffer from the same problem. Wood and charcoal scarcity afflicts most of the Andean region, Central America, and the Caribbean.

Most rural areas of developing countries depend upon notoriously inefficient open fires for cooking and heating. For cooking, perhaps 2-5 percent of the energy produced by burning or direct combustion is used effectively while the rest is wasted. Devices or hardware that harness this energy efficiently for both cooking and heating are needed (see VITA/Intermediate Technology Development Group 1980).

Domestic Heating and Cooking (Family Level). An efficient, simple, wood-burning cookstove should not only confine the fire to the cooking area but conserve the heat produced by minimizing heat loss to the surrounding area, such as the walls of the fire container itself.

Walton and co-workers (1978) investigated simple, wood-burning stoves for use at the individual family level in sub-Sahara Africa, and found that much of the equipment that has evolved outside Africa for wood burning is appropriate, with modifications, for application in developing countries. Figure 47 shows a design that incorporates many of the features of the very efficient, ancient Japanese earthenware cooker, the Kamado, but that could be built with inexpensive raw materials. The cookstove consists of five essential components: (1) a 5-gal paint can and lid, with vent holes cut in the lid
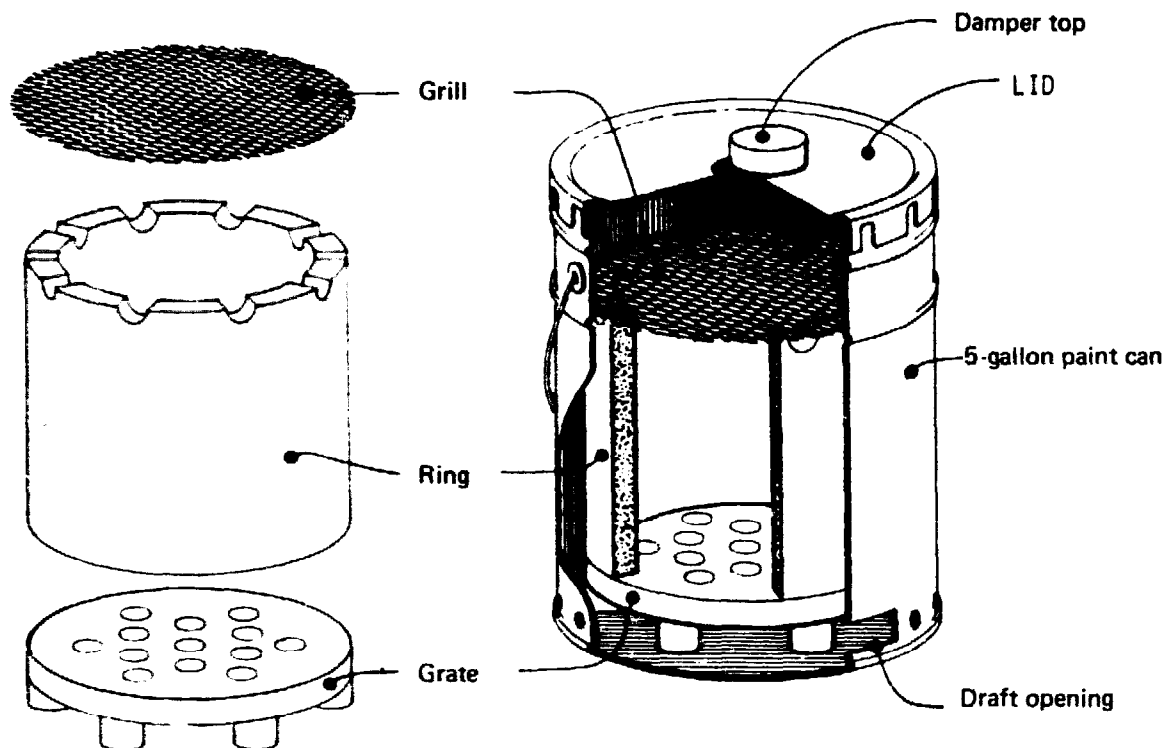
FIGURE 47   Schematic of a wood-burning cook stove constructed from a 5-gal paint can.

and at the base of the can to control draft; (2) two ceramic blocks or stones to support the grate; (3) a ceramic grate to support the fire with holes or air passages to admit air for combustion; (4) a ceramic liner (or shell) to insulate the fire from the can; and (5) a metal grill or other structure to support the food being cooked.

The ceramic components used in this cookstove are easily fabricated, and, as they can be of relatively low strength, they need not be fired in a high-temperature kiln. The 5-gal paint can could be replaced by a simple sheet metal shell which could be rolled and used as an open-ended support structure.

McGill University's Brace Research Institute (1977) has also developed a simple and cheap ($1.50) wood-burning cookstove for family use which is based on a simple, mass-produced galvanized bucket.

Closed wood stoves have been improved in Western countries to a point where efficiencies range from 25 to 60 percent. Stoves can be better controlled, and there is less leakage of air into a stove, more control of air input, and better use of the flue gas heat. By use of air heat extractors, additional heat can be extracted from flue gases above that normally gained through the stove and stovepipe. Increased energy efficiencies of from 3 to 20 percent are reported, which correspond to a reduction of 6-40 percent in the amount of fuel consumed for the same useful heat output (Shelton and Shapiro 1978).

Wood-burning furnaces are gaining increasing attention for use in larger buildings and are equivalent in efficiency to wood stoves. Their application in developing countries at the family level is questionable, although they might be adapted for multi-unit housing or industrial or government buildings.

Centralized Energy Systems. Electricity, of course, can be produced by direct combustion of biomass residues, as can steam. The Forest Products Research Society (1979) has published a series of case histories of operational biomass combustion systems for energy production, and Karchesy and Koch (1979) have reviewed industrial-scale biomass combustion systems and component hardware suitable for application to rural development.

Industrial wood-burning furnaces are commonly incorporated into boiler systems to produce steam. They range in size from shop-fabricated units with steam capacities up to 100,000 lb/hr (45,000 kg/hr) to large field-erected units that can generate up to 600,000 lb/hr of steam (273,000 kg/hr). Wood-fired boilers that produce 15,000-100,000 lb/hr (6,800-45,000 kg/hr) of steam are the most common type among recent installations.

Furnace design for wood burning falls into two basic classes: grate burners and suspension burners. Dutch ovens, inclined grate furnaces, and spreader stokers burn the fuel on a grate, either in a pile or spread as a thin bed. In suspension burning, the fuel is supported by air during its combustion—for example, suspension-fired burners, cyclonic burners, and fluidized bed burners (see Karchesy and Koch 1979).

The overall conversion efficiency for conventional steam generation of electricity from wood is about 25 percent, including boiler efficiency, steam cycle efficiency, and auxiliary power requirements, all of which are variable (Benemann 1978). Thus if hardwood containing 42 percent moisture were used as a fuel (at a conversion efficiency of 25 percent), 1.8 t/day of biomass would be needed to support a 50-kW electrical generating plant, 5.4 t/day for a 150-kW plant, 18 t/day for a 500-kW plant, and 36 t/day for a 1-MW plant (see Karchesy and Koch 1979).

Pyrolysis

Pyrolysis is a thermochemical process in which a material is thermally decomposed into less complex, mainly volatile, organic compounds in an air- (oxygen-) starved environment. A carbonaceous residue (or char), as well as combustible gas and an oily liquid, are normally produced.

Virtually every form of terrestrial biomass is amenable to thermochemical conversion. Pyrolysis has been applied principally to wood in developing countries, but the process is also applicable to a wide variety of other cellulosic materials: rice husks, peanut shells, cotton gin waste, coconut shells, bagasse, etc. (see Beagle 1978).

The most widely recognized pyrolysis process is "destructive distillation," in which organic or carbonaceous materials are heated to several hundred degrees Celsius in the absence of air and the condensable liquids of decomposition are condensed and collected. A solid, nonvolatile residue—charcoal—is produced. Bituminous coal is used to produce coke, coal tar, and coal gas by destructive distillation. Formerly, wood was used extensively to produce "pyroligneous acid" (methanol, acetone, acetic acid, and other chemicals) by destructive distillation. However, because this method of producing these chemicals could not compete economically with fossil-based systems, the destructive distillation of wood is used almost entirely to produce charcoal, a vital fuel in developing countries.

Established Pyrolysis Technologies. Modern pyrolytic processes and actual commercial applications are well advanced in North America (Bio-Energy Council 1978) and Europe and Japan (Jones, *et al.* 1978). These newer technologies contrast significantly with established methods that are more generally applied in developing countries.

Pyrolytic conversion can occur in batch processes, such as those used historically for making charcoal, or in continuous processes. For batch processes, simple earth-covered kilns and pits are generally used in areas lacking capital and materials; however, kilns constructed of brick, concrete, and metal allow better control of yields and eliminate contamination of the product with earth and stones.

There are generally two types of fabricated kilns: fixed or portable. Some typical kilns are the French Nilmelior system, German DRP kilns, beehive

kilns, masonry block kilns, Missouri kilns, CUSAB (charcoal-from-useless-shrubs-and-bushes) kilns, and Mark V kilns (Earl 1974). The first four kilns are cheap and easy to construct and are adaptable to mechanized working methods, but they have not proved strong enough to withstand high pyrolysis (carbonization) temperatures. The Missouri kiln incorporates the advantages of the first four systems and overcomes their disadvantages. Its chief advantage is its strength which allows trucks and tractors to enter the kiln for loading and discharging of products. The Mark V is an adaptation of the CUSAB kiln. Both are portable kilns, relatively inexpensive, and practical to use.

The selection of fixed or portable kilns depends greatly on the location of the available biomass supply and the relative cost of labor.

Retorts overcome the disadvantages of kilns, which do not allow the collection of the volatile oils and gases that are the co-products of pyrolysis, and also permit better control of the process which results in higher charcoal yields. However, retorts are more expensive to manufacture, and they require an external source of energy to maintain the process.

Modern, continuous-flow pyrolysis processes, as developed in the United States and Europe, are high-temperature porcesses that tend to maximize gas production, minimize oil production, and reduce solid residues virtually to ash. This emphasis arises from a concern with municipal solid waste disposal and the assumption of the proximate location of a large, gas-fired industrial or utility-type boiler.

A number of continuous, low-temperature ($572°-1112°F$ or $300°-600°C$) processes, applicable to the thermochemical conversion of agricultural and forestry products, have been developed. The simplest, most promising systems appear to be based on vertical retorts through which the feedstock passes. In most cases, because the chemical reactions are exothermic, these processes can be self-sustaining: however, most continuous-flow processes require external heat to dry the as-received biomass feedstock and to maintain acceptable production rates. All these processes are basically similar and differ chiefly in the manner in which the auxiliary heating is introduced.

Shaft furnaces have been designed in a variety of forms to allow for flexibility in handling a wide variety of biomass feedstocks. Although designs differ in the source of auxiliary energy, the following steps are generally employed in all such processes: the biomass feedstock is introduced at the top of the retort; char is removed from the bottom of the retort; the hot volatile gases are passed upward through the downward-moving bed; and the gases are then removed at the top of the retort, and scrubbed, condensed, and collected as liquid fractions (pyroligneous acid or pyrolytic oils). Frequently, the biomass feedstock is dried externally, rather than in the reactor bed itself, by using the noncondensable gas fraction resulting from pyrolysis.

Some examples of this continuous, vertical retort-based conversion system

include the Stafford, Mellman (Othmer 1952), Lambiotte, and DeBartolomeis retort designs, and the Barneby and Georgia Tech processes (Knight 1976).

New Pyrolysis Technologies. Pyrolysis of biomass residues is normally accomplished under starved, but controlled, air oxidation conditions. Recently, however, new pyrolysis technologies have resulted from the realization that higher energy efficiencies are obtainable by means of direct combustion or incineration processes. Figure 48 shows a 25-t/day pyrolysis unit developed by the Engineering Experiment Station of the Georgia Institute of Technology. The biomass residues are convertible into more readily usable, more transportable, more compact, and more environmentally acceptable fuels. Figure 49 depicts a flow diagram of a modern pyrolysis process that produces biofuels in three forms: char, with a fuel value of 28–31.5 kJ/kg; oil, at 21–23 kJ/kg; and gas, at 5.6–7.5 MJ/m^3. In a controlled pyrolysis operation, the relative yields of the three products can be varied to suit the needs of the local region.

The variety of products produced, high energy conversion efficiencies (up to 95 percent based on recoverable energy in the dry biomass feedstock), adaptability in developing countries, and consumer acceptance in developing countries of similar fuel products (kerosene and charcoal) make pyrolytic processes highly attractive for energy production in these countries, particularly where large quantities of otherwise unproductive agricultural residues exist. It must be emphasized, however, that all suggestions for the use of pyrolysis depend on recovery of the heat of combustion for reasonable thermodynamic efficiency.

Although pyrolytic oils cannot presently be used directly as fuels in

FIGURE 48   A 25-t/day pyrolysis unit developed by the Engineering Experiment Station of the Georgia Institute of Technology.

1.39 x 10⁶ Btu

Wood — Drying — Pyrolysis unit — Condenser — Gas

1 t
(50-percent H₂O)
8.7 x 10⁶ Btu

1.38 x 10⁶ Btu

Char

Oil

0.175 t
4.3 x 10⁶ Btu

11 gals
1.21 x 10⁶ Btu
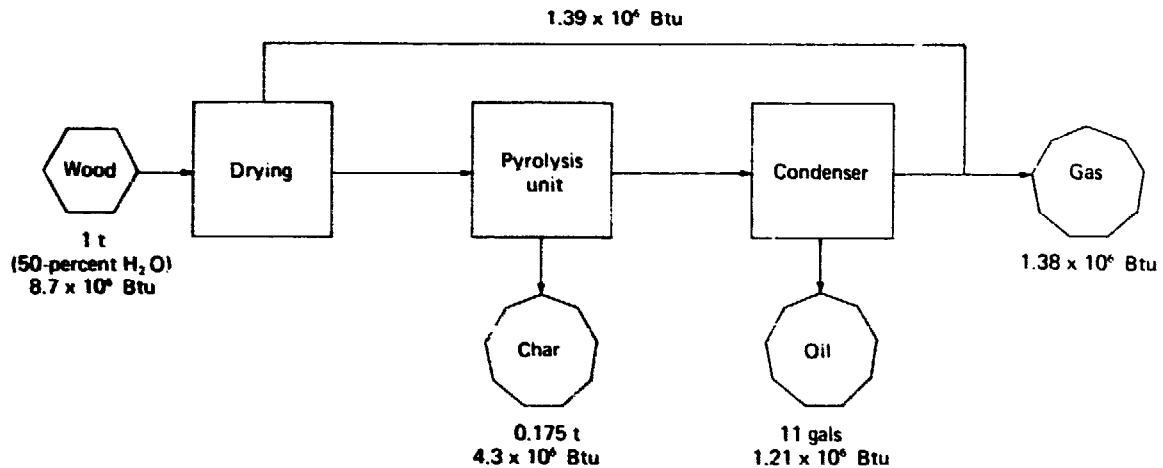
FIGURE 49   Mass-energy flow diagram of a pyrolysis unit.

internal combustion engines, they can be used as fuels for cooking, drying, steam and electrical power generation, and lighting, and they can be substituted for firewood in industrial processes, e.g., the firing of kilns for roof tile or brick manufacture. By mixing pyrolytic oils and charcoal, the fuel can be used to fire boilers for factories, trains, power stations, and steamships (Table 6). Charcoal has long played a prominent role in meeting the energy needs of many developing countries (Table 7).

Since char and oil are storable and more easily transported, they are of greater importance than the low-energy gas produced in the pyrolytic conversion of agricultural wastes. Pyrolytic gases are most practically used on-site for drying feed materials or for firing utility boilers.

Applications for Developing Countries. Developing countries have shown increased interest in the development of pyrolytic conversion systems appro-

TABLE 6   Energy-related applications of pyrolytic oil.

Application	Features/uses
Cooking	Quick starting, clean burning, easy to control
Lighting	Used in lamps (need to modify or control viscosity for wicking)
Heating	Replaces wood or kerosene
Boiler fuel/electrical steam	With charcoal, as slurry
	Rural electrification
	Industrial steam
	District heating
	Transportation (steam engines)
Drying and baking	Kiln fuels
	Structural materials (bricks, roof tiles, etc.)
	Pottery
	Ceramics

TABLE 7 Energy-related applications of charcoal.

Application	Features/uses
Domestic heating and cooking	Smokeless, sulfur-free Adaptable to stoves for cooking and hot water production
Direct drying (agricultural)	Drying, e.g., hops, tobacco, and other crops in same environment
Indirect drying (agricultural)	Central heating system fuel
Internal fuel (industrial)	For lime and cement manufacture Mix with limestone and fire to quicklime Portland cement manufacture using charcoal in rotary kilns (spontaneous ignition)
Metal extraction (industrial)	Charcoal combines with ores of metal oxides and sulfides, reducing the ore to pure metal Copper, iron, steel manufacture
Briquetted charcoal fuel	Cooking (barbecue) fuel
Activated carbon (industrial, agricultural)	Environmental control Sanitation Water purification
Boiler fuel/electrical steam (utility)	Alone or with coal or oil Low sulfur Rural electrification Industrial steam District heating

priate to local needs. The Engineering Experiment Station of the Georgia Institute of Technology collaborated with the Building and Road Research Institute in Kumasi, Ghana, on a feasibility study of the use of pyrolytic conversion of agricultural and forest wastes in Ghana (Chiang, *et al.* 1976). The study concluded that pyrolysis could be feasible economically and presented a preliminary design for an appropriate technology version of a continuous/batch converter based on processing 6 dry tons of sawdust per day (Figure 50). Current work in Ghana involves the construction and demonstration of four 1.5-metric tons-per-day pyrolytic converters, fabricated chiefly from locally available materials and intentionally labor-intensive (Moh and Potts 1976).

Four different conceptual designs were developed for Indonesia by a Georgia Institute of Technology team in Bandung when it became evident that pyrolysis was technically and economically attractive in terms of both domestic energy production and possible export of pyrolysis products (Tatom, *et al.* 1977). Designs were based on processing 1 t/day of biomass (rice hulls, wood waste, etc.) and ranged from a simplified labor-intensive system (two annual crops, sun-drying, three shifts, located at a local rice mill) to a relatively mechanized system (three rice crops, a gas-fired drier, three shifts, located at a local rice mill) to a more capital-intensive system (single-shift

Kilns sheet metal kilns, fabricated in Ghana
Ducting sheet metal, insulated, fabricated in Ghana
Cyclone: sheet metal, insulated, fabricated in Ghana
Condenser: 3-pass, tube type, fabricated in Ghana
Draft fan: centrifugal, probably imported
Modified International Rice Research Institute drier batch drier, composed of both locally fabricated and imported parts

FIGURE 50   A 6-t/day pyrolytic conversion system for Ghana.

operation). All designs essentially use the same kiln design but differ as to the nature of the off-gas systems and inclusion of a drier.

A small-scale pyrolytic converter (Figure 51) has been constructed at the University of the Philippines with the technical support of Georgia Institute of Technology in a U.N. Industrial Development Organization (UNIDO) program (Ministry of Energy, Republic of the Philippines 1979). It employs a design similar to the Georgia Tech converters in Ghana.

Other developments include operation of a 1-t/day pyrolysis unit in New Guinea which is to be followed by construction of a 25-t/day prototype, industrial-scale system in 1980 (Ministry of Minerals and Energy, New Guinea 1979).

The International Development Association has recently approved credits of $4.5 million and $4.3 million for wood energy usage surveys in Mali and Burundi, respectively (see National Research Council 1980b). The projects will focus on wood-burning systems and charcoal kilns.

At the regional level, the U.N. Development Program (UNDP) is completing engineering feasibility studies for a large rural electrification project on the island of Savaii in Samoa. The electrical generator will be powered by the combustion of wood wastes and sawdust from a commercial sawmill on the island. It is estimated that electrical power will be provided to 31,000 of the 42,000 inhabitants at a price less than $.07/kWh.

Gasification

This is not a new technology. In the past, particularly during World War II, "producer gas" was commonly used in Europe, Japan, China, Brazil, New Zealand, and Australia, and this technology is now being reevaluated for use

loop process. A 2,000-t/day facility is planned. It is projected that 1 t of methanol can be produced from 3 t of eucalyptus containing 35 percent moisture (Webber 1979).

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PART III
OTHER
TECHNOLOGIES

Geothermal Energy

Exploration and development of geothermal resources are formidably large tasks for the rural or village economies in developing countries. Although there have been recent developments in both technology and processing, these have not significantly improved the economic, geologic, or engineering feasibility of most geothermal projects. However, these developments could make the use of geothermal energy highly desirable in specific circumstances, depending upon resource availability, energy needs, and the economics of alternatives.

The costs and risks of geothermal exploration remain high. Detailed geophysical and geochemical surveys may cost from $2,000 to $5,000 each per day. Expenditures for detailed geologic investigations of a small prospect several tens of square kilometers in area may amount to $200,000 or more. A single geothermal resource may well cost as little as $300,000 if shallow and small in diameter, or as much as $2 million if more drilling is required or if engineering problems are encountered. While individual wells may yield anywhere from 100 kWe to 10,000 kWe or more when connected to an appropriate conversion facility, even the best geologic exploration program will not guarantee discovery of a reservoir or the output of any one well. (See Appendix C for a list of recent literature on geothermal energy.)

RECENT DEVELOPMENTS IN GEOTHERMAL TECHNOLOGY

Recent developments in the technology for single geothermal wellhead electric generators hold the most promise for use in the rural areas of developing countries. Single wellhead turbogenerating equipment produces electricity in

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relatively small amounts with a relatively small financial investment. Such devices are capable of generating electricity from a single geothermal well in the range of 20 kW to as much as 10 MW, depending in large part upon the resource capabilities of the well.

Significant effort has been expended recently to develop such wellhead devices for commercial operation, and some wellhead generating systems are now available. Others are still being tested and developed, but may be available in the near future. The following descriptions are offered only as examples of equipment now available or being developed (see Appendix B for a listing of research and development centers). Information on costs, availability, and performance specifications should be obtained from individual manufacturers (see Appendix A).

The helical rotary screw expander system has undergone extensive field tests with hydrothermal fluids in the United States, and a 1-MW packaged power plant was successfully operated for several months. This system is a total flow conversion process, utilizing the entire well flow to turn the turbine. It was designed and built by the Hydrothermal Power Company (USA) with funding from the U.S. National Science Foundation and the U.S. Department of Energy (DOE). The California Institute of Technology's Jet Propulsion Laboratory in Pasadena, California, performed the testing. Units in other sizes may be available in the near future. A similar total flow system is available from Turbines Incorporated (USA), in sizes from 5 to 10 MW. A third total flow turbogenerator system is being made available by the Roto-flow Corporation (USA), which adapted its units from the system it constructs for hydrocarbon pipelines.

A prepackaged wellhead generating unit is available from the Geothermal Power Company, Inc. (USA). The "Mono-Blok" unit utilizes separated steam from the geothermal resource and is available in units from 100-kW to 2.5-MW capacity. A 500-kW Mono-Blok unit has been installed and operated in Indonesia. Mitsubishi (Japan) offers a similar portable geothermal turbine generator with capacities of from 500 kW to 5 MW. Units of this type have been ordered for Japan, the Philippines, and El Salvador. The Philippine government has undertaken a fairly extensive geothermal development program on the island of Luzon. Several wells have been drilled and are being connected to a central steam plant in order to produce electric power.

Biphase Energy Systems (USA) has designed and tested a two-phase rotary turbine for use with geothermal hot water systems. A 20-kW turbine generator system has undergone extensive testing in the Imperial Valley, California, and this company advertises that they are prepared to enter into fixed-price contracts for the manufacture and installation of Biphase turbines for certain applications with appropriate performance warranties. The Ormat turbine, although designed to be used as a solar energy conversion system, appears quite

capable of using geothermal heat as its energy source. This closed-cycle, vapor turbogenerator is available from Ormat Turbines, Ltd. (Israel).

Two other wellhead-type, geothermal generating systems are now commencing commercial-size testing operations in the Imperial Valley. Barber-Nichols Engineering Company, under contract to the Lawrence Berkeley Laboratories and funded by DOE, is constructing a 500-kW direct contact, heat exchanger/geothermal power plant at East Mesa. This system will use isobutane as the working fluid for the turbine generator system. The direct contact heat exchanger uses the hot geothermal fluid to heat the isobutane working fluid in a direct contact counterflow system, which eliminates many of the scaling problems inherent in other heat exchangers.

The Sperry Research Center (USA), under contract to DOE, will begin field tests in East Mesa on a 4.3-MW gravity head power plant. In this system, a specially designed heat exchanger is placed in the geothermal well at a depth of approximately 2,000 ft (610 m). The freon working fluid is heated as it is pumped down to the heat exchanger and back up to the turbogenerator system on the surface. A small pump at the bottom of the heat exchanger pumps the geothermal fluid back up to the surface, at which point the fluid has had its heat extracted. Both the Sperry and the Barber–Nichols systems are being designed to increase the efficiency of the geothermal generation system. However, it appears that neither system will be available in the near future.

DIRECT APPLICATIONS OF
GEOTHERMAL HEAT ENERGY

Low-temperature (100°-200°F or 38°-93°C) waters are the most abundant accessible geothermal resource and, for the near term, will likely offer the most benefit to developing countries. One potential advantage of utilizing low-temperature geothermal waters for direct applications is that the geothermal fluid can also be used for irrigation, crop drying, or even as a potable water supply, if its salt content is low. Such waters could also be used directly for aquacultural applications. The potential for multiple use of a geothermal resource for space heating or other direct application, and subsequently using the fluid as a traditional water resource, is especially attractive for developing countries with cold climates.

Over the past few years, a number of schemes have been proposed that would successively utilize geothermal waters in a series of increasingly lower-temperature heat applications in an energy cascade. However, most energy cascade systems are capital-intensive, which would limit their suitability in developing countries. In addition, many of these systems are designed to be economical when a medium-temperature (approximately 300°F or 148°C)

geothermal resource is available, and it is unlikely that a resource at this temperature would be available at shallow depths except in rare instances. The cascade systems could make economic sense in developing countries if waste heat from geothermal power plants were utilized or if suitable medium-temperature resources were available from otherwise noncommercial exploratory deep wells.

Energy Storage

With current technology, there are ways to store energy in chemical, mechanical, and thermal forms. Significant advances have been made in the chemical and mechanical forms during the past 5 years, particularly in the areas of improved batteries (chemical form) for photovoltaic and wind energy applications and improved flywheel energy storage systems (mechanical form), both of which are discussed here. Another form of mechanical storage, isothermal hydraulic air compression, is discussed in the chapter, "Energy from Falling Water." (See Appendix C for a listing of recent literature on energy storage techniques.) Considerable cost reductions are desirable before energy storage in these forms becomes widely used in developing countries.

STORAGE BATTERIES

Since publication of the original volume of *Energy for Rural Development*, research and development on batteries has, generally, been directed at developing batteries suitable for electric vehicles, stationary energy storage applications, and photovoltaic and wind energy applications (see Appendixes A and B for listings of manufacturers and research and development centers, respectively). As the photovoltaic and wind energy applications seem more suitable for rural areas of developing countries, they are stressed here.

Both photovoltaic arrays and windmills generate direct current suitable for storage in batteries. However, for efficient use of the battery and to prolong its life, it is desirable to adjust the voltage and control the battery-charging current by means of a power conditioning system. If alternating current of closely regulated voltage is the desired output of the energy source, an inverter will be required within the power conditioning system. Thus a complete

photovoltaic or wind energy system will consist of three units: the energy source (windmill or photovoltaic array), a power conditioning system, and a battery energy storage system.

Battery manufacturers will design an entire battery system for photovoltaic or wind applications, including the selection of the power conditioning equipment. For applications in the near term, only two types of batteries should be considered—lead–acid and nickel–cadmium. However, lead–acid batteries should be selected for almost all situations in developing countries.

Several types of lead–acid cells have been developed to meet various applications, and these are summarized in Table 8. The SLI (starting, lighting, and ignition) batteries deliver very high power, but have short cycle life. Such batteries could be considered for photovoltaic or wind energy storage applications only if a low initial cost is an important consideration and if deep discharges occur relatively infrequently. Motive power batteries have thicker plates, and thus lower discharge rate capability, but they have long cycle life. The types made for forklifts and mine vehicles would have sufficient cycle life for many photovoltaic and wind energy installations. Stationary batteries were designed for stand-by and emergency power applications requiring few cycles. They have low self-discharge rates and long calendar life when used under the conditions for which they were designed. For many photovoltaic power systems, the stationary type of battery is satisfactory and is the basis for the design of several photovoltaic batteries. For some small-scale applications, sealed lead–acid batteries that have a relatively poor cycle life, but do not require water addition or ventilation, have been developed.

TABLE 8 Types of lead–acid batteries.

Type	Characteristics	Applications
Automotive (SLI) and diesel starting	High discharge rate, relatively low cost, poor cycle life	Automobile starting, lighting, and ignition; tractor, snowmobile, and other small engine starting; large diesel engine starting
Motive power (traction)	Moderate discharge rate, good cycle life	Forklifts; mine vehicles; golf carts, submarines; other electric vehicles
Stationary	Medium discharge rate, long life (years). Some types have low self-discharge rates, poor cycle life.	Telephone power supplies, uninterruptable power supplies, other standby and emergency power supply applications
Photovoltaic	Low maintenance, low self-discharge, special designs for high and low ambient temperatures, poor deep cycle life	Remote, daily shallow discharge, large reserve (stand-alone) photovoltaic power systems
Sealed	No maintenance, moderate rate, poor cycle life	Lanterns, portable tools, portable electronic equipment

SOURCE: Bechtel National, Inc. (1980).

The positive electrodes of lead-acid batteries frequently contain either antimony or calcium alloying elements. Antimony is added to increase cycle life. Cells containing lead-calcium positive grids have the advantage of low self-discharge rates of a fraction of a percent per week at 70°F (21°C), as compared to self-discharge rates of about 4 percent per week for lead-antimony grids. This self-discharge rate can become as high as 15-20 percent per week for lead-antimony grids near the end of life. If self-discharge is not included, lead-acid batteries will deliver about 70-80 percent of the energy charged.

Nickel-cadmium batteries are very expensive and cost about $340/kWh for large, vented, pocketplate cells to over $900/kWh for sintered-plate, sealed cells (Bechtel National, Inc. 1980). These batteries should be considered for applications requiring long cycle life, high rates of discharge, and relatively small capacity (5 kWh or less).

When selecting a lead-acid battery for a particular application, the following considerations should be kept in mind:

- *Capacity* depends on how the battery is used, and is defined in terms of the number of hours or days of service the battery will provide when fully charged and at the average load. If year-round operation without a back-up system is required, the battery may be designed for as much as one month of operation at the average load without recharging. As solar arrays become less expensive relative to the cost of the battery, larger solar arrays relative to the load may be used. This would permit faster recharging of the battery, which would then be reduced in capacity to as little as 3-5 days of service for stand-alone systems. Wind energy units, even if designed for stand-alone service, are usually provided with only a few days of storage capacity.

- *Cycle life* is inversely related to capacity, as measured in days of storage at normal load conditions. For most photovoltaic and wind energy installations, only 50-500 cycles would be required for 10-year battery life. This can be achieved with batteries having lead-calcium alloy grids and designed for photovoltaic applications. Such batteries also have the important advantages of low gassing rates, low water-addition requirements, low self-discharge rates, and high efficiency. Lead-calcium batteries should be chosen for most photovoltaic applications.

- *Extent of discharge* is best limited to about 60-80 percent of the rated capacity of the battery. Beyond 80 percent discharge, the battery life is shortened considerably.

- *Maintenance* includes (1) proper maintenance of charging conditions by the power conditioning system to achieve a high state of charge in each cycle, acceptable charging efficiency, and long life; and (2) proper temperature control which is important in determining battery capacity, the rate at which a battery will accept a charge, and the lifetime of the battery.

- *Cost* varies considerably with the level of production and service costs, but for many uses it will be in the range of $60–$200/kWh (in 1980 U.S. dollars). (See Appendix A for a list of battery manufacturers from whom prices are available.)

Research and Development Programs

The U.S. Department of Energy (DOE) is sponsoring battery development for both electric vehicles and stationary energy storage applications; most of the latter effort has been directed toward load leveling for electric utilities. One program recently initiated by DOE to develop batteries for photovoltaic and wind energy applications was in the evaluation and planning stage at this writing. This effort is being managed by Sandia Laboratories, Albuquerque, New Mexico.

The Electric Power Research Institute (EPRI, USA) is also concerned with load-leveling applications and has funded several battery programs. Table 9 lists those programs supported by DOE and EPRI, among others, that show promise of developing batteries for stationary storage applications and that may be applicable to photovoltaic and wind energy devices.

Programs aimed at developing advanced lead–acid batteries for utility load-leveling applications are striving to develop large cells having very long life (>2,000 cycles) and low cost. For those applications having back-up energy systems and only a few hours of storage, long cycle life will be very desirable. However, for most rural applications, stand-alone service and therefore at least several days of energy storage are required. Under these conditions, the batteries will probably undergo less than the equivalent of 50 full cycles per year; long life is not needed for these applications. The lowest total cost for purchase and operation of the battery system is likely to be achieved with a battery developed specifically for stand-alone service in photovoltaic and wind energy applications. These applications will be addressed in the new DOE program.

All of the battery systems in Table 9 are expected to be available for engineering demonstration for photovoltaic or wind applications by 1984–86. However, none is expected to be an economical alternative to lead–acid batteries until well into the 1990s. When manufacturing experience has been gained, means of producing reliable batteries at a cost below that of lead–acid batteries may evolve. In that case, one or more of these battery systems may become economically attractive for photovoltaic and wind energy systems.

For stand-alone service, which may be needed in developing countries, the large storage requirement relative to the load favors the reduction–oxidation flow systems under development at NASA's (U.S. National Aeronautics and Space Administration) Lewis Research Center. However, it is not certain that any of the battery storage systems will be economical for a week or more of

TABLE 9   Advanced batteries under development in the United States show promise for photovoltaic and wind energy applications.

Battery type	Major developer[a]
Advanced lead–acid	ESB Corp.[b] Eltra Corp.[b]
Flow systems Zinc/chlorine	Energy Development Associates
Zinc/bromine	Exxon Enterprises, Inc. Gould, Inc. General Electric Co.
Reduction/oxidation	NASA–Lewis Research Center
High temperature Sodium/sulfur	Ford Motor Co. General Electric Co. Dow Chemical Co.
Lithium/metal sulfide	Eagle–Picher Industries[b] Gould Inc.[b] General Motors Corp. Rockwell International Corp.

[a]Most of these efforts are funded by the U.S. Department of Energy or the Electric Power Research Institute, but some are supported wholly or in part by the developer.
[b]Contracts managed by Argonne National Laboratory (USA).

storage when compared to one day of storage and a back-up energy system such as an engine-generator.

Applications of Battery Systems

In many developing countries, little power is available to rural areas from the new, large power projects installed for industrial or domestic use in large urban communities. Many small villages in such countries have no electric energy, except what is provided by dry cells for flashlights and small radios (Doshi 1977). Below are several examples of the type of battery storage systems required for electrification of such small villages with solar or wind-power devices (Bifano, *et al.* 1979; Ratajczak and Bifano 1979; Solarex Corporation 1979).

Schuchuli, a small, remote village on the Papago Indian reservation in southwestern Arizona, utilizes a 3.5-kWp solar photovoltaic electric system provided by DOE (see "Photovoltaics"). All electrical items in the village operate on 12-volt DC in order to avoid the complexity of an inverter system. The Schuchuli system has two batteries—a main battery of 120 volts and 2,380 amp-hr capacity, and a small 12-volt instrumentation and control battery

which is charged from the 120-volt system through a DC–DC converter. The batteries are installed in a ventilated room, and they consist of cells that have lead–calcium grids and are designed for deep cycling, low gas evolution, and low self-discharge. The batteries provide approximately 15–20 times the anticipated daily energy requirement; thus interruption of electric power is not expected. However, because of uncertainty in the energy demand of the village, the instrumentation system has been designed to shed the load as battery discharge increases as a result of higher than anticipated demand.

A similar photovoltaic system, with a peak power of 18 kW, was installed in the African village of Tangaye in Upper Volta, and became operational in March 1979 (Ratajczak and Bifano 1979). Like Schuchuli, it is a stand-alone system consisting of a photovoltaic array, batteries, and a control and instrumentation unit (see "Photovoltaics"). This system operates at 120 volts DC to avoid the cost and complexities of DC–AC inverters. The main battery has a capacity of 540 amp-hr, and the 12-volt instrumentation and control battery has a capacity of 200 amp-hr. The latter is charged from a separate 12-volt, 74-W photovoltaic array.

Both the Schuchuli and Tangaye systems have sufficient battery capacity for many days of operation without recharging. Calculations indicate that under the worst conditions the main battery at Schuchuli would discharge to 60 percent and at Tangaye to 30 percent. Because of the high prices of photovoltaic arrays, the battery systems were designed to have large capacities relative to the power of photovoltaic arrays. Combinations of larger photovoltaic arrays and smaller batteries could fulfill the needs just as reliably as the combinations presently used. However, the present systems, both designed by the NASA–Lewis Research Center, provide the maximum service and reliability for the funding available and for the existing price structure.

A photovoltaic system that provides power for irrigation of an 80-a (32-ha) cornfield was installed in Mead, Nebraska, in 1977 (Romaine 1979; Millner 1979c). The power from the system operates a 15-hp pump capable of pumping 1,000 gal/min (3,785 l/min) from an irrigation reservoir. Initially, the pump was driven either by a 120-volt DC motor powered by the photovoltaic system or by a 3-phase 240-volt AC motor driven by the utility power back-up system. In a later revision, a 3-phase inverter was installed, enabling the photovoltaic system to operate the 3-phase pump motor and two 3-phase crop-drying fans, which were added to the load.

The energy storage system for the Mead unit consists of two parallel banks of 6-volt lead–acid batteries, C&D Type 3CBSB-11, rated 375 amp-hr each at an 8-hr discharge rate. These batteries were designed for railroad caboose service and have an expected life of 5 years when deep discharged once a day. The cells have lead–antimony anodes and lead–calcium cathodes. There are 20 6-volt batteries in each bank and a total terminal voltage of 120 volts. The battery bus bar is operated between normal limits of 146 volts maximum dur-

ing battery charging and a low of 110 volts on discharge. Battery voltage is managed by removing load when the battery reaches a suitable depth of discharge and allowing the photovoltaic array to recharge the battery to near the fully charged state before reapplying load to the photovoltaic system. The battery system at Mead stores enough energy for only about one day of operation at full load. It should be noted that the battery capacity relative to the load is much smaller in the Mead system than in the Schuchuli and Tangaye systems because of the availability of the utility back-up system at Mead.

In addition to the moderately large installations discussed above, many small solar photovoltaic systems with battery storage units have been installed in, for example, New Hampshire, near Washington, D.C., and in Montana (see Solarex Corporation 1976, 1977, 1978). Some additional examples of battery storage systems used in conjunction with photovoltaic arrays are given in Table 10. These examples illustrate that the use of batteries in combination with photovoltaic systems is a well-established commercial technology and that systems are readily available from many companies eager to sell their products.

Wind energy systems that are designed to stand alone usually require a battery system sufficient to supply the load for several days without recharging. If a windmill is designed to supply a full load at very low wind speeds, only a few hours of storage will be required. However, this is impractical, requiring that the windmill be several times larger than if several days of battery storage are provided.

In a design study carried out for installation of a wind energy system at a site near Harlow, Essex, in southeastern England, provision was made for a continuous electrical supply of either 50-volts DC or 240-volts, 50-cycle AC (Hirst and Rees 1976). This unit was envisioned as an energy supply for communications repeaters, navigational aids, or similar applications. In the design study, the battery consisted of 24 lead–acid cells manufactured for stationary storage duty. It was shown that the storage capacity required was inversely related to the power of the windmill. Storage capacity for about one week would be sufficient for a windmill designed for moderate wind speeds of about 7 kmph (4.3 mph).

In another study, required storage capacity was evaluated for wind energy installations designed to supply electricity for homes in a housing project (Littler and Thomas 1978). A vertical-axis unit with a swept area of 24 m^2 (258 ft^2) was investigated. A study of hourly wind speeds at two sites in England considered for the installations showed that the periods of very low wind speed differed considerably from year to year. It was concluded that standby power batteries should be used, because a computer model indicated that the cells are within 80 percent of complete charge for 60 percent of the time and undergo a deep discharge only once or twice a year. Such duty cycles are easily met by lead–calcium batteries.

TABLE 10 Photovoltaic battery systems in operation in the United States.

Location/application	Date installed	Array power (W)	Battery storage Capacity (amp-hr)	Manufacture/information	Cost (US$)
Isle Royale, Michigan Refrigerator, 12-volt DC	5/76	220	600	J. C. Penney 29 F, 6 in parallel, 100 amp-hr, 12-volt, sealed automotive battery	$240
Papago Indian Village, Sil Nakya, Arizona Refrigerator, 12-volt DC	7/76 8/77	220 330	600 600	Globe Union EV 27, 6 in parallel, 100 amp-hr, 12-volt; battery replaced with same type	$240
Antelope Peak, California Water pump, refrigerator, lights, communications, 12-volt DC	10/76	294	3,015	C&D, KCPA 1005 cells, 6 cells in series, 3 in parallel, 18 total, 1,005-amp-hr cells, lead–calcium photovoltaic type	$2,160
Pilot Peak, California Same as Antelope Peak	10/76	294	3,015	Same as Antelope Peak	$2,160
Stratfort Shoals, New York Remote weather instruments, 24-volt DC	5/77	111	60	Globe Union gel cell 1220, 2 in series, 3 in parallel, 6 total, 20 amp-hr, 12-volt, batteries: sealed, gelled electrolyte	$252
Halfway Rock, Maine	9/77	111	60	Same as Stratfort Shoals	$252
Loggerhead Key, Florida	10/77	74	60	Same as Stratfort Shoals	$252
Clines Corners, New Mexico	4/77	74	60	Same as Stratfort Shoals	$252
South Point, Hawaii	6/77	74	60	Same as Stratfort Shoals	$252
Pt. Retreat, Alaska (near Juneau)	7/77	148	60 1,005	Same as Stratfort Shoals plus C&D, KCPA 1005 cells, 12 cells in series, lead–calcium photovoltaic cells, 1,005 amp-hr	$252 $1,440
Tucson/Phoenix, Arizona Interstate highway sign, lights, communications, 12-volt DC	4/77	116	200	Globe Union EV 27, 2 in parallel, 100 amp-hr, 12-volt	$80
College Station, Texas Insect survey traps, 12-volt DC	5/77	23 163	100 400	Globe Union EV 27, 100 amp-hr, 12-volt Globe Union GC2-8144, 2 in series, 2 in parallel, 4 total, 200 amp-hr, 6-volt golf cart battery	$40 $140
Lone Pine, California Chilled water, 120-volt DC	10/77	446	100	Globe Union EV 27, 9 in series, 100 amp-hr, 12-volt electric vehicle battery	$360

SOURCE: Matlin and Sacco (1978).

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FLYWHEEL ENERGY STORAGE SYSTEMS

A flywheel (rotor) is a mechanical device that stores kinetic energy by spinning and then releases the energy as the spinning slows down. Flywheels are found most commonly in every automobile that has an internal combustion engine.

The modern flywheel is emerging from the experimental stages. Several flywheel energy storage systems (FESS) have been tested as experimental prototypes since 1976, and such testing will undoubtedly continue during the 1980s. Technological advances achieved in recent years (Chang and Hirschfeld 1978; Renner-Smith 1979; Millner 1979a, 1979b; Notti, *et al.* 1975) indicate that commercial manufacture of small systems (up to 40 kWh) will most likely commence in the mid-1980s in industrialized nations. Subsequent applications of FESS technology in rural areas of developing nations may become significant after 1985.

A comprehensive, interdisciplinary investigation was conducted during 1976-78 to determine the proper use of energy storage in conjunction with solar photovoltaic and wind energy conversion systems (Johnson, *et al.* 1979). Of the 11 energy storage methods considered (aboveground pumped hydro, underground pumped hydro, thermal-oil, thermal-steam, underground compressed air, small pneumatic systems, lead-acid batteries, advanced batteries, flywheels, hydrogen, and superconducting magnetic systems), the flywheel was found to be the second best choice for residential photovoltaic systems. Advanced batteries were the top choice with attractive projected economics after 1985 (General Electric Co. 1978). The flywheel system considered, however, did not possess such beneficial features as power conditioning, conversion, and magnetic bearings. With the recent advances in flywheel technology, the relative attractiveness of flywheels has improved drastically, and today they are considered competitive with batteries. Even if the projected initial cost of flywheels were several times that of batteries, they would still be competitive, since the flywheel can be designed to last the life of a system, without the need for replacement. In most stationary storage system applications, batteries would have to be replaced several times during the anticipated 20-year system life.

A series of flywheels made of high-strength Kevlar (and glass and graphite) fibers and epoxy resin have been fabricated and tested within the last 4 years by several university laboratories and industrial organizations, resulting in much improved performance. The typical range of energy density of such "composite flywheels" is from 40 to 80 Wh/kg of rotor mass (Chang and Stone 1977), as compared to the typical 7-9 Wh/kg for metal flywheels. Another attractive feature of the composite flywheel is its safety: it disintegrates into something resembling cotton candy or ruptured plywood boards, in contrast to metal flywheels which explode into extremely dangerous jagged

projectiles (Chang and Stone 1977; Lustenader, *et al.* 1978). Figure 52 shows the rather safe failure mode of a multi-ring composite rotor capable of storing a few kilowatt-hours of energy. It is made of Kevlar/epoxy resin (with small amounts of s-glass), and is mounted on an aluminum hub. Additional recent technological advances are discussed below.

Recent Advances
in Flywheel Technology

Although the basic energy input and output of the FESS is electricity, the flywheel system is capable of accepting, and discharging, mechanical shaft power from various sources such as windmills and hydraulic turbines. Flywheels are particularly suited for the photovoltaic system, in which the FESS serves as an interface between a photovoltaic array and an AC load, providing energy storage as well as regulating the output waveform.

Tenth-Scale FESS Unit for Photovoltaics. A recent (1978–1980) experimental FESS unit designed and tested at the Massachusetts Institute of Technology's (MIT) Lincoln Laboratory includes a low-cost flywheel rotor, an
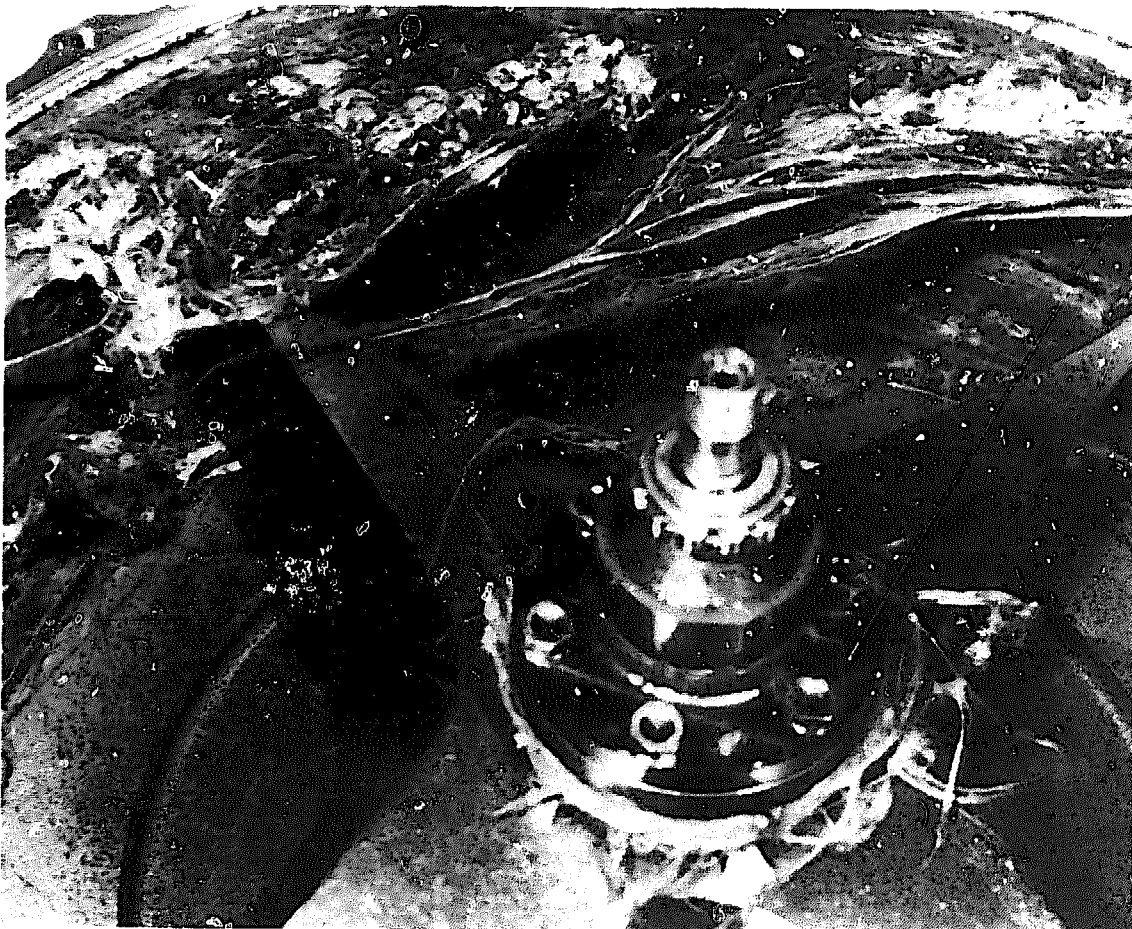
FIGURE 52   The safe failure mode of a composite flywheel.
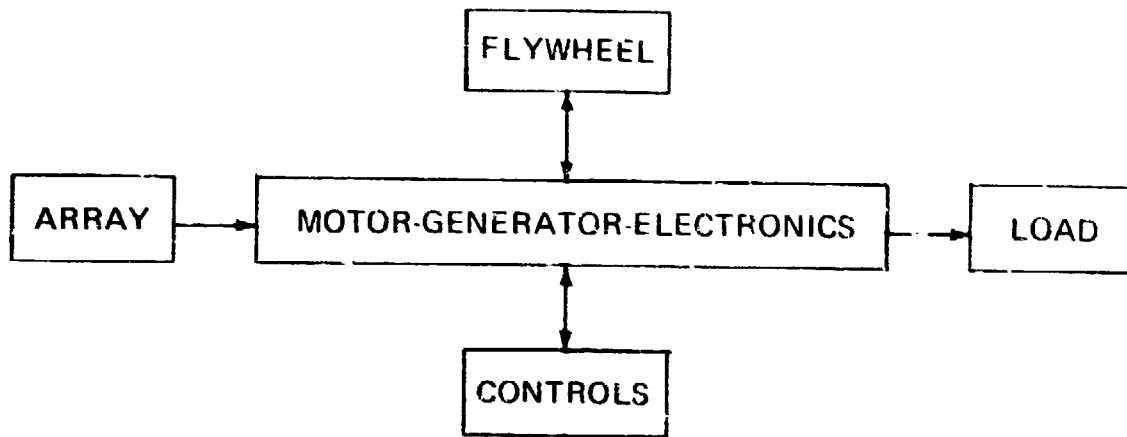
FIGURE 53   Advanced flywheel energy storage and power conditioning.
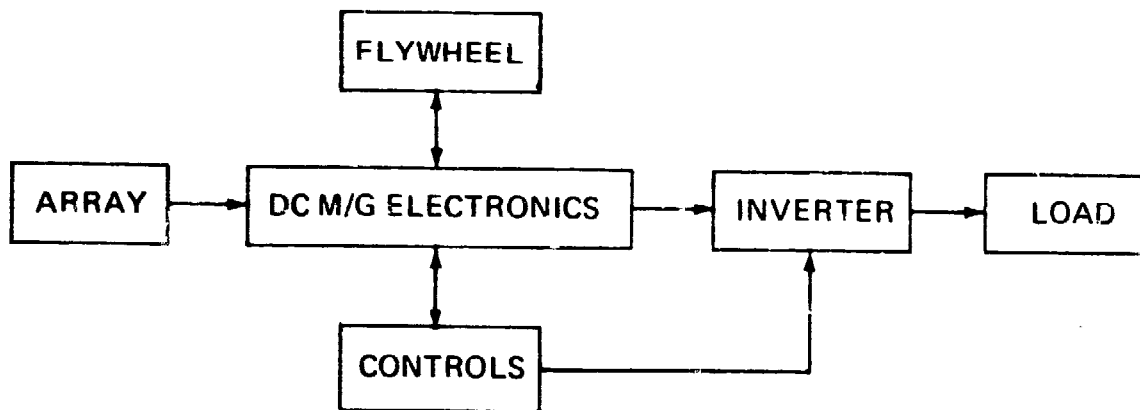
FIGURE 54   Conventional flywheel storage with inverter.
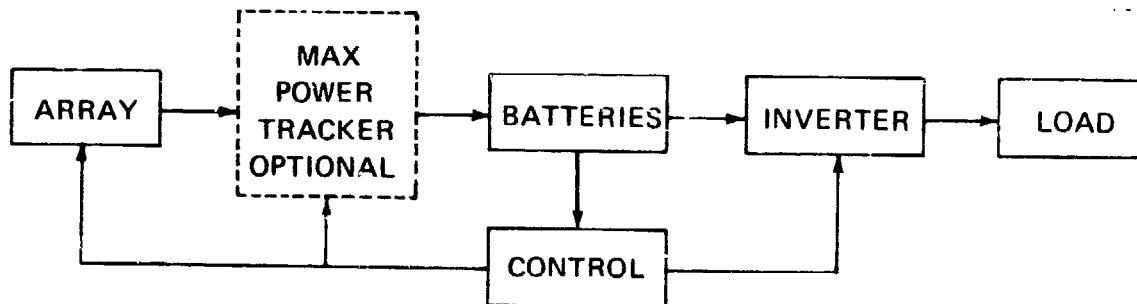
FIGURE 55   Battery storage with inverter.

ironless armature motor-generator, and magnetic bearings (Millner 1979a, 1979b). The schematics of this system are shown in Figure 53.

The MIT system concept contrasts with the more conventional FESS deployment shown in Figure 54, in which an inverter is utilized. In Figure 55, the schematics of a rather common storage/conversion system involving the use of electrochemical batteries are shown for comparison. It can be seen that the advanced MIT system is far simpler than the two competing systems.

The advanced solar photovoltaic/flywheel unit shown in Figures 53 and 56 hinges on the use of an efficient, low-loss motor-generator (Millner 1979a, 1979b). The DC drive motor and a permanent magnetic motor-generator
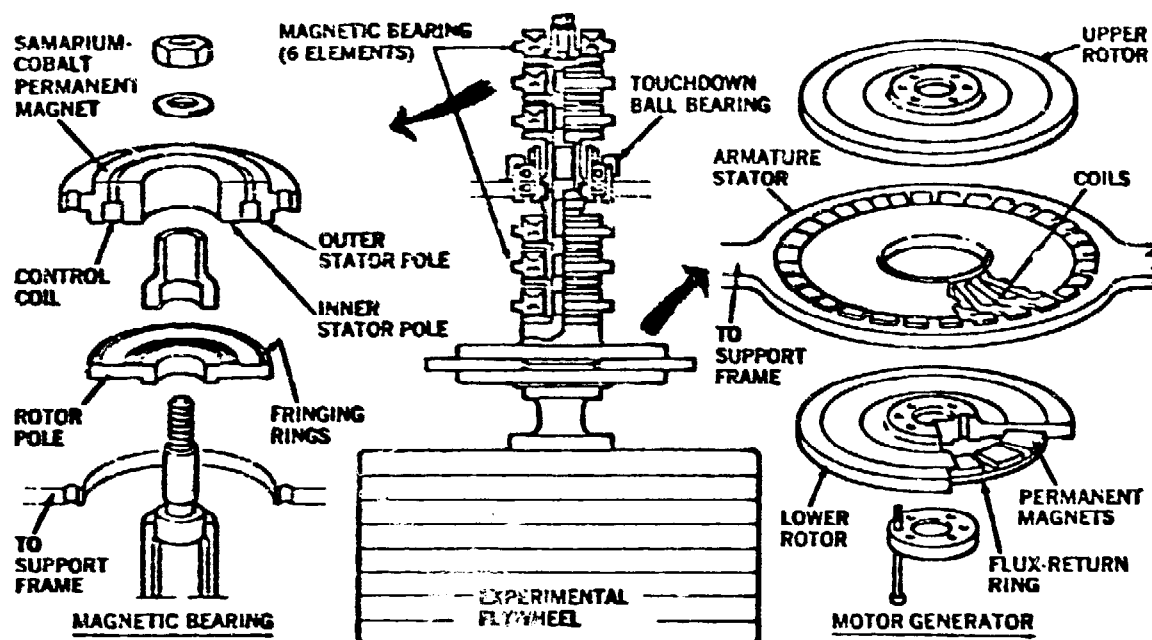
selected for this purpose serve as the input–output mechanisms for the fly-wheel, which has a top speed of 15,000 rpm. This unit, which stores up to 4 kWh of electricity, has a magnetic bearing that permits low-loss operation.

The flywheel and motor–generator are supported on magnetic bearings in a crude vacuum housing (approximately 10^{-2} Torr). The brushless motor and the generator are in fact the same device with separate input and output electronics. All solar photovoltaic electric power would go through the DC motor to spin up the flywheel. Consequently, the advanced FESS unit provides a good impedance match between the photovoltaic array and the load in order to maximize the electric power extracted from the array. The FESS unit also serves as an inverter to convert the low-voltage DC output from the photovoltaic array to a high-voltage (e.g., 110 volts) AC waveform. Nominally, the motor–generator is rated at 600 W.

As of the end of 1979, this unit contained a 500-lb (227 kg) steel test rotor, which will be replaced by the more desirable low-cost wound rotor and will be ready for prototype testing in 1981. The rotor is expected to coast for days without having to be recharged, and the overall system efficiency is approximately 73 percent.

In the event of foul weather, causing near-zero output from the arrays, the FESS unit will continue to supply electricity for 2–3 days at a satisfactory level.

Full-Size FESS for a Single-Residence Photovoltaic System. Based on the test results of the MIT tenth-scale FESS unit, a full-size unit with a 20-year life is projected to possess the cost characteristics shown in Table 11 (Millner

TABLE 11   Cost characteristics of a full-size FESS for a single-residence photovoltaic system (40 kWh + 8-kW DC + 10-kW AC).

| Item | Cost[a] | | |
	1985 low	1985 high	1978 cost
Rotor[b]	$2,000	$ 4,000	$ 8,000
Motor–generator	750	1,000	1,160
Magnetic bearing	400	800	3,000
Vacuum housing	1,000	1,600	2,680
Generator electronics	300	1,000	1,000
Motor electronics	240	600	800
Enclosure	960	1,280	1,280
Total	$5,650	$10,280	$17,920

[a]All figures are in 1975 U.S. dollars based on American manufacturing costs.

[b]Weight estimates: 4,000 lb (1,814 kg), 2,800 lb (1,270 kg), and 5,000 lb (2,268 kg) for the 1985 low, 1985 high, and 1978 cost, respectively.

1979a, 1979b; Millner and Hay 1979). The low-cost rotor is based on the bare-filament concept developed at the Applied Physics Laboratory of Johns Hopkins University, Baltimore, Maryland (Rabenhorst 1979). The higher rotor cost figure ($4,000) refers to General Electric's (USA) pseudoisotropic fiberglass/epoxy resin design. The vacuum system is based on a tank 1.2 m (4 ft) in diameter, 1.2 m (4 ft) in length, sealed and pumped out every 6 months, and maintaining a pressure of 10 μ maximum. This insures low losses during operation, since no concurrent vacuum pumping is required. This passive vacuum system is only practical with steel wire or steel tape composite rotors. The enclosure is a 3.375 m^3 (119 ft^3) concrete pit. The overall input–output efficiency can be as high as 73 percent, which is some 5 percentage points higher than the competing batteries.

Portable FESS Unit. In 1976, the Garrett Corporation (USA) designed and fabricated a small FESS unit that was capable of receiving 20 Wh of electricity from wall receptacles and used a small AC motor (rated under 76 W). The steel rotor was supported by conventional ball bearings. All components, including a generator, can be neatly packed into a small briefcase with a volume of less than one cubic foot.

Once charging is completed, the unit can be carried around with ease, with the gyroscopic effect felt only when rapid turning motions are applied to the FESS case. The flywheel energy can be converted upon demand to alternating current through conventional power generation and inversion techniques.

Although no attempt was made to optimize the performance of this unit, the rundown time was found to be on the order of nearly an hour. Indeed,

the whole unit behaved much like a portable battery, with the self-contained capability for AC-DC-AC conversion.

Integrated Power and Control System. In the mid-1970s, a flywheel unit, known as IPACS, was developed and tested by Rockwell International (USA) for spacecraft electrical power storage as well as attitude control. This special FESS unit has a single titanium rotor rated at 2.5 kW which stores up to 1.5 kWh. Rotor diameter is 454.1 mm (17.9 in.), and it operates with a maximum speed of 35,000 rpm. The Samarium-Cobalt permanent magnet rotors for the dual-purpose motor-generators are integral with the shafts of the flywheel.

Inductor Motor/Alternator/Flywheel Energy Storage System. From 1976 to 1978, General Electric Co. (USA), partially supported by the U.S. Energy Research and Development Administration (ERDA), undertook a FESS development project, the Inductor Motor/Alternator/Flywheel Energy Storage System (Lustenader, *et al.* 1978).

The entire unit, diagrammed in Figure 57, was made into a single package, hermetically sealed, with the rotor assembly operating in a near vacuum with an inert residual gas (helium). Although the unit was primarily developed for electric vehicles, it could be adapted for other applications, such as solar photovoltaic or wind power systems.

The demonstration unit, shown in Figure 58, consists of a 20-kVA, solid-rotor, inductor-type, synchronous motor/alternator coupled directly to a three-disk composite rotor. The entire rotor assembly is hermetically sealed and operates in the range of from 630 to 762 mm (25 to 30 in.) of mercury vacuum. The rotor, 756 mm (30 in.) in diameter, is made of fiberglass layups, operating between 7,500 and 15,000 rpm. The usable energy is 1 kWh, with a rotor weight estimated at 60 kg (132 lb).
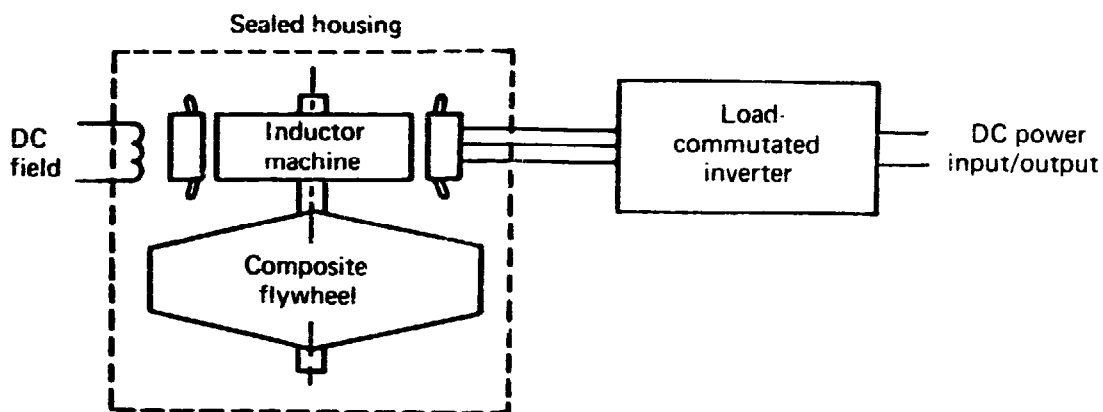
FIGURE 57 Basic concept of the General Electric Inductor Motor/Alternator/Flywheel Energy Storage System.
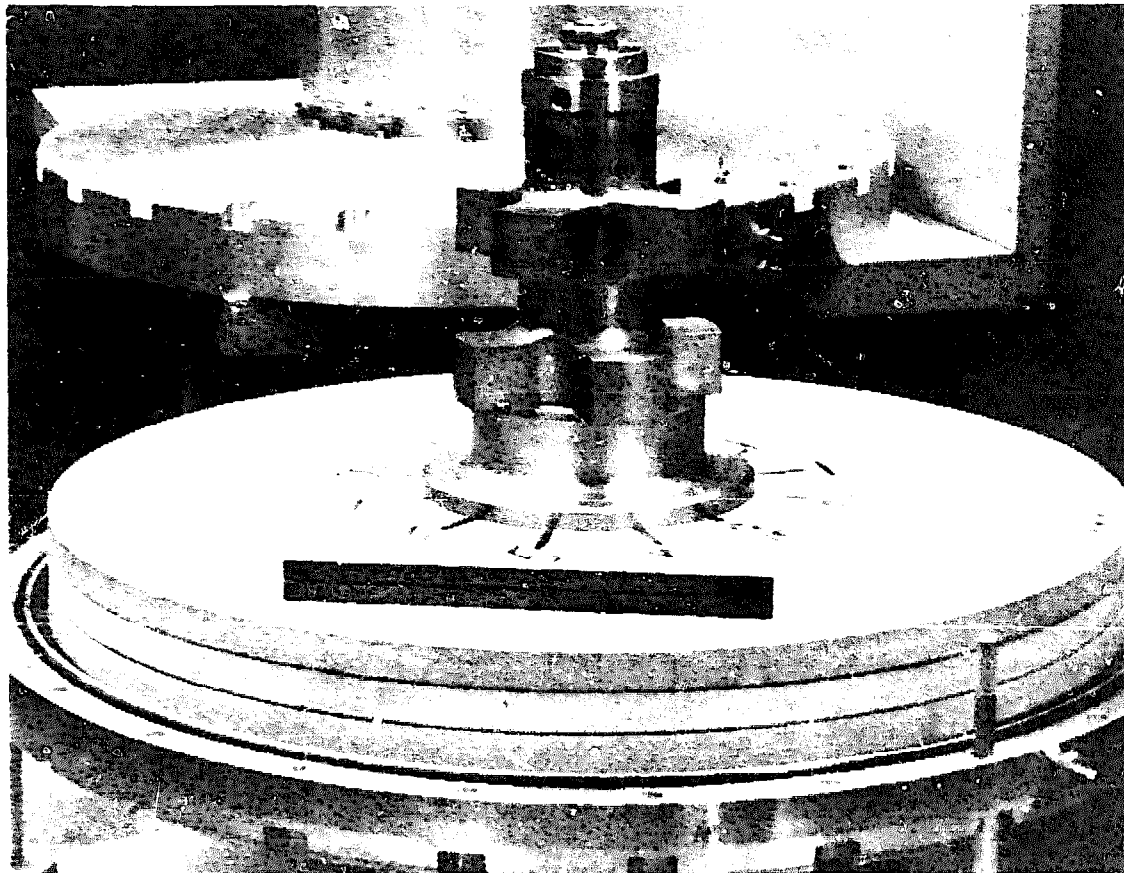
FIGURE 58   Inductor Motor/Alternator/Flywheel Unit.

This demonstration established the technical feasibility of the underlying concept, but also pointed out the need for better understanding of the composite flywheel.

Residential Flywheel with Wind Turbine Supply. Flywheels can be used to store excess wind energy for a windless day (Place 1979). In late 1978, the Garrett Corporation (USA) was commissioned by the U.S. Department of Energy to develop an engineering design for a mini-residential FESS rated at 5-kW electric output. Then-current low technology was utilized in this design which was completed in late 1979.

After evaluating five candidate systems, the design shown in Figures 59 and 60 was selected for further refinement. Considering cost and safety, the E-glass/epoxy, rim-shaped rotor was selected. The flywheel is housed in a metal container evacuated to less than 10 μ.

If it were produced in quantity (1,000 units per year), the 10-kWh FESS is estimated to cost $3,300 per unit, excluding installation. The unit storage cost, therefore, is $330/kWh, which is slightly lower than the corresponding figure ($448/kWh) for the MIT FESS discussed earlier. However, this unit cost is higher than the average MIT flywheel storage cost based on 1985 technology (i.e., $200/kWh in 1975 dollars).

Projected Technological Trends

During the past 4 years, research and development on flywheel energy storage systems has emphasized flywheels used in transportation largely because alternate energy systems (notably solar and wind energy) are still in the early stages of development. Within a few years, the emphasis may shift toward "stationary" flywheel storage systems intended for residential or industrial applications. Such a shift, aided by the natural technology transfer process in which advances associated with transportation flywheels (and other technologies in general) are incorporated into stationary flywheel systems, will greatly accelerate the development of the stationary flywheels under discussion.

Based on the literature to date, and discussions with professionals in the energy and flywheel areas, some aspects of the FESS technological trends can be projected (Table 12). The FESS system envisioned will likely be capable of accepting either direct current from solar photovoltaic arrays or mechanical shaft power from wind turbines. Alternatively, the unit should be capable of receiving power from wall receptacles connected with a central generating power system—possibly a large solar electric system or a conventional electric

TABLE 12   Stationary FESS performance projections.

Factors	Current	Near term (4-5 yr)	Far term (9-10 yr)
Isotropic material rotor energy density (Wh/kg)	7-32	11-31	11-31
Composite rotor energy density (Wh/kg)	22-44	66-88	66-132
Ball bearings			
Life (yr)	3-5	3-5	3-5
Losses (percent of stored energy per hour)	2-4	1-2	1-2
Magnetic bearings			
Life (yr)	A few	6-8	10-20
Losses (percent of ball bearings)	7-10	5-7	<3
Motor-generator efficiency (percent)	60-94	88-97	88-97
System life (yr)	3-5	10-15	20
System energy density (Wh/kg)	6-11	35-44	35-88
System spinning loss (percent of energy per hour)	3-5	1-3	0.5-1.0
Round-trip efficiency (percent)	68-76	73-77	78-83
System cost (US$/kWh)[a]	300-600	200-300	130-170

[a]With complete storage and conversion capabilities; in 1976 dollars.

utility. This residential flywheel unit could have a storage capacity of 20-40 kWh, with a maximum power rating of 5-10 kW, although a much larger growth version of this machine should not be dismissed. Its construction will be dictated by the operating economics as well as reliability (and safety).

Overall efficiency (electrical to electrical) of the FESS unit will probably be more important to the user than the system's energy density. Most likely, the rotor will be made of inexpensive, easy-to-fabricate types of material, and will be supported by magnetic bearings featuring low-cost permanent magnets, operating in a hermetically sealed, crude vacuum of the type discussed (Lustenader, *et al.* 1978; Millner 1979a, 1979b; Place and Rabenhorst 1979). In short, the trend will be for the development of a safe, rugged, highly economical FESS unit.

Toward pursuing these objectives, DOE has taken steps, through its flywheel program at the Lawrence Livermore Laboratory (Livermore, California), to initiate a full-scale home flywheel storage program, and has received proposals from a number of industrial firms. This hardware program, which is expected to run for about 2 years, will emphasize low-cost, fail-safe flywheel technology, low-loss magnetic flywheel suspension, low-loss vacuum systems, and low-cost but highly efficient electrical machines. It will also emphasize commercialization prospects. The program will begin with development of a 10-kWh flywheel energy storage system, and will culminate in a 40-kWh system.

FESS units will likely become more widely utilized when rural areas of the developing world begin using more solar energy—particularly photovoltaic systems, wind turbines, and solar thermal electric-generating systems. FESS units may also be used to store cheap off-peak electricity on a daily basis from a central generating source (such as a conventional utility or a rural alternate energy co-op). Because of the low load factors for central station electricity in many rural areas, this could well be the principal use of the FESS in the next 10 decades.

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Pedal Power

INTRODUCTION

One of the most efficient mechanical devices developed by man is the bicycle, and pedaling is the key to the most efficient use of leg power. The thigh muscle (the quadricep) is the largest and most powerful muscle in the human body. Through pedaling, this muscle can be used to perform a variety of useful tasks.

Pedaling enhances the power of the legs, which are then relieved of the effort of standing or supporting the body. The usual pedaling speed, 60–80 rpm, uses leg muscles at their maximum efficiency. Studies have shown that this speed yields somewhat less than 0.1 hp (74.6 W). In some cases, professional cyclists have produced up to 1 hp for short periods of time.

Pedal power is particularly appropriate when small amounts of power are needed at irregular intervals, or when a mobile power source is desirable. Because many pedal power devices are lightweight, they can be carried easily to a worksite to power such devices as winnowers, threshers, and water pumps.

Pedal power units are sometimes referred to as "dynapods" (Greek for power and foot), and usually consist of a stationary bicycle frame, seat, handlebars, and pedals which drive a series of chains or belts. The number of revolutions per minute (rpm) can be changed by adding or subtracting pulleys or gears. Usually a flywheel is necessary to smooth out the high and low power output of a person's natural pedaling rhythm. The use of the flywheel assures constant speed and power to the device being driven by the dynapod (see Weir 1979).

During the past 5 years, new pedal power technologies have evolved that can be used in the transportation, agricultural, and domestic sectors of

developing countries. Most of the technologies described in this chapter are discussed in more detail in a book entitled *Pedal Power In Work, Leisure, and Transportation* (McCullagh 1977).

TRANSPORTATION

Oxtrike

A carrier bicycle with a large basket over the front wheel is effective for loads up to 100 lb (45 kg), but heavier weights require three wheels. The Oxtrike (see Figures 61, 62, and 63), designed by Stuart Wilson of Oxford University, is a basic three-wheeled chassis with a choice of bodies to carry a variety of goods or people with a payload up to 330 lb (150 kg).

For the sake of greater strength, the wheels of the Oxtrike are 20 in. (51 cm) in diameter. The rear wheels—Raleigh "Chopper" type (20 × 2.12 in. or 51 × 5.4 cm)—are especially strong against side load, a requirement that
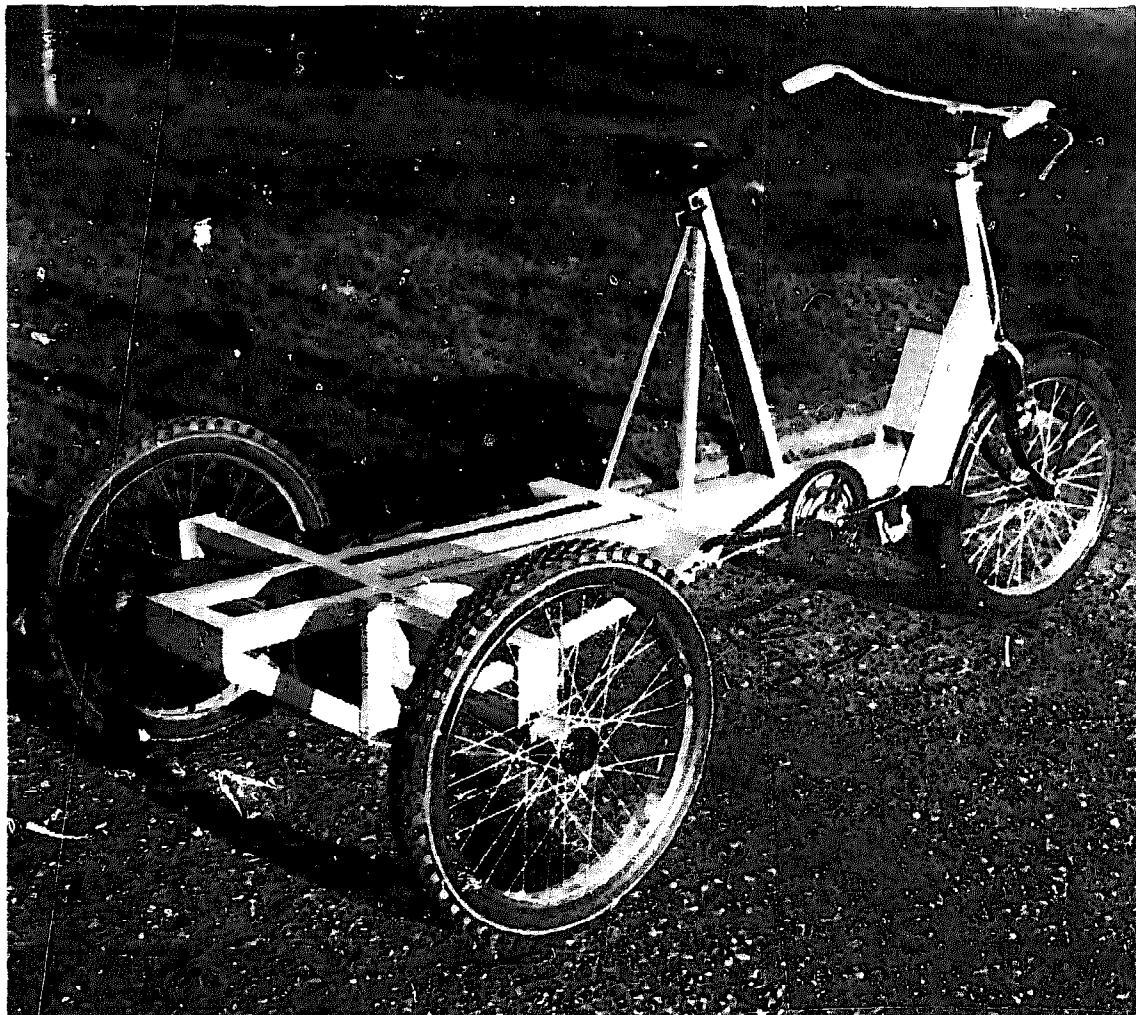
FIGURE 61   Oxtrike chassis. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

does not arise on a bicycle but is a very real problem on a tricycle. They also lower the center of gravity of the load (but give adequate ground clearance), and permit easier access by elderly or infirm passengers and a full-width rear

FIGURE 62   Up-ended view of the Oxtrike chassis, allowing ability to park in a small space, easy inspection of transmission and brakes, and ability to tip out the load. Note Sturmey-Archer three-speed hub gear with double adjustment for primary and secondary chains. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

seat without an increase in the overall vehicle width, which is only 36 in. (91.4 cm). The use of small wheels also reduces the overall length of the tricycle to just over 6.6 ft. (2 m). The front wheel (20 ⨉ 1.75 in. or 51 ⨉ 4.4 cm) and fork are of the carrier-bicycle type and are designed to carry a large load forward from the frame over the front wheel.

The Oxtrike's three-speed gearbox, a standard Sturmey–Archer hum gear, is used as an intermediate gearbox, as on many motorcycles, with a primary and secondary chain. The overall "gear" of the Oxtrike is 31.5 in. (80 cm) in the bottom gear, 42 in. (1 m) in the middle, and 56 in. (1.4 m) in the top, compared to 66.5 in. (1.7 m) for a normal bicycle with 26-in. (66-cm) wheels, which greatly improves the driver's ability to start with a heavy load and to climb at least a slight gradient, thus improving the range and mobility.

The front brake is the standard pull-rod stirrup type, but the rear brakes are inboard band brakes applied by a foot pedal. This is a powerful and effective method of applying a braking force; each wheel has its own brake drum, mounted at the inboard end of the half-shaft, and the braking effect is applied equally by means of a balance bar. Location of the brakes ensures protection from rain. The brake pedal can be held down by a lever catch to act as a parking brake, an essential feature on a tricycle.

The construction of a normal bicycle frame requires thin-walled tubing brazed into special sockets, which is not really suitable for small-scale local manufacture in developing countries. For this reason, the Oxtrike was des-
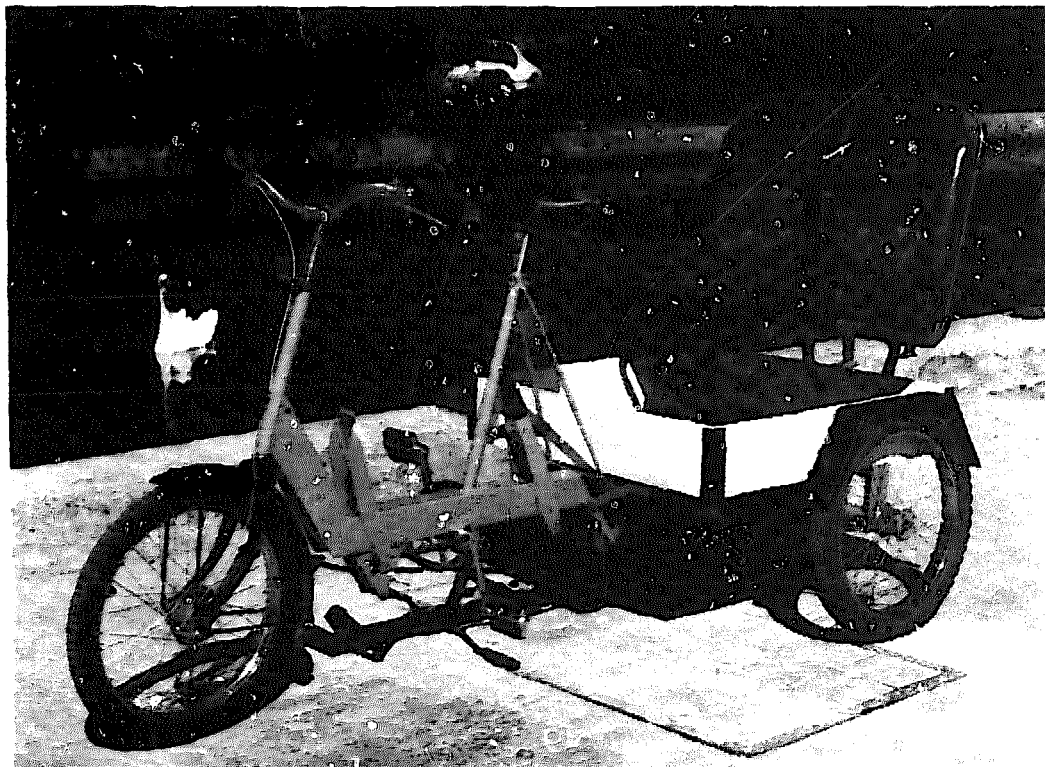
FIGURE 63   Oxtrike with temporary seat. (Reprinted from *Pedal Power* ©1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

signed to use a mild steel sheet of a standard thickness, which can be readily cut on a foot-powered guillotine, folded on a hand-operated folding machine, and joined by almost any method of welding, brazing, or riveting.

A variety of bodywork types has been designed, including a two-passenger rickshaw with a hinged tailboard. When the tailboard is lowered, two passengers can sit facing backward; when it is raised, three children can sit facing forward or goods can be transported. Larger loads can be carried with the tailboard horizontal.

The chassis can be fitted with a simple open truck body or an enclosed box body for carrying parcels. A hopper body with sloping ends would be suitable for carrying sand, gravel, or other loose materials (the size of the hopper should be restricted to prevent overloading). Finally, a 40-gal (151-l) drum can be fitted for carrying liquids.

Railbike

The railbike is a regular bike fitted with special attachments so that it can be ridden on train rails (see Figures 64 and 65), and it can take many forms and shapes. It can be fitted with a stationary bar between the bicycle and a third wheel, or it can take the form of a scooter that effectively applies human power.

FIGURE 64   The railbike. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)
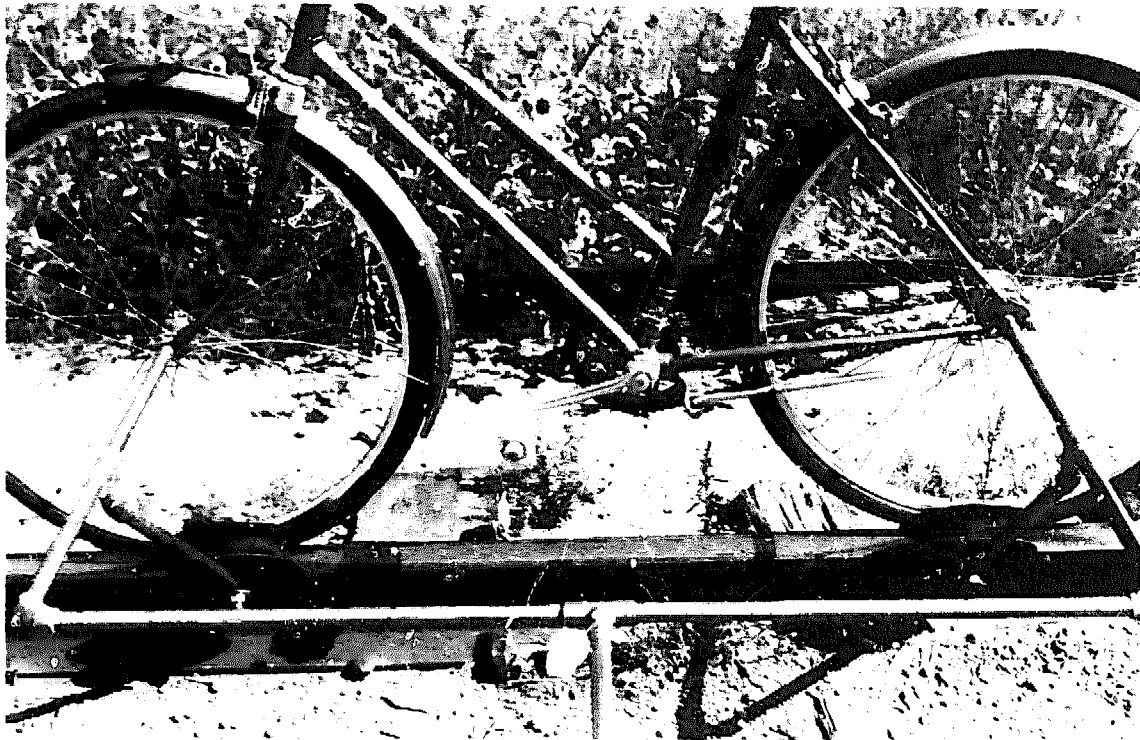
FIGURE 65   Details of railbike attachments. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

A U.S. inventor, Mark Hansen, of Onamia, Minnesota, has enlarged the concept of the railbike by building a vehicle that will support 2-3 people or 700 lb (315 kg) (see Hansen 1976).

AGRICULTURE

Pumping

Probably one of the oldest applications of pedal power is pumping water. Wood is an excellent material for constructing water pumps. In low salt-flat areas, corrosion of metal pumps would cause maintenance problems. In Taiwan, foot pumps made in the ancient Chinese way use few if any metal parts (see Figure 66). The water being pumped acts as a lubricant, making such a pump quite easy to operate. In large, flat, marshy areas, the water usually needs to be lifted about 2 ft (0.6 m) and the depth of the evaporation ponds is only a few inches. Two people work together to operate the pump as the power rotor has two sets of pedals.

At the International Rice Research Institute (IRRI) at Los Baños, Laguna, the Philippines, engineers have developed a small, lightweight, inexpensive foot-powered pump that will lift large quantities of water several feet, using only moderate amounts of human power. The operator simply stands on two footrests at either end of the pump and rocks back and forth (see Figure 67).

FIGURE 66   Old-style wooden water pumps used in Taiwan for raising sea water into salt-evaporation beds at a coastal town. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

This effort compresses a diaphragm, which forces water from the outlet valve. By operating the pump in a rhythmic manner, a continuous flow of water is pumped. It is estimated that the foot pump will cost only $25–$30 to manufacture. IRRI gives designs for its machines at no charge to fabricators throughout Asia.*

Pedal power can also be applied to existing hand pumps. Figure 68 depicts a pitcher pump; an activator rod from a reciprocating pedal power device can supply the up and down motion to pump water.

A simple, inexpensive (less than $5) centrifugal pump can also be attached to a pedal-driven device (Figure 69). These devices can pump 3,500 gal/hr (13,248 l/hr), sending water streaming out 30 ft (9 m) through a hose nozzle.

*More information on this technology is available from the International Rice Research Institute, Agriculture Engineering Department, Post Office Box 933, Manila, Philippines, and from Volunteers in Technical Assistance, 3706 Rhode Island Avenue, Mt. Rainier, Maryland 20822, USA.

FIGURE 66   Old-style wooden water pumps used in Taiwan for raising sea water into salt-evaporation beds at a coastal town. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

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FIGURE 67   Pedal pump designed by the International Rice Research Institute, Los Baños, Laguna, the Phillippines. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, inc., Emmaus, PA 18049)

Plowing, Cultivating, and Harrowing

The research and development laboratories of Rodale Press, Inc. (Emmaus, Pennsylvania (USA) have developed a pedal power farming system, the Mechanical Mule^{TM} (see Figure 70). This two-person operation consists of a pedal power winch that is used to reel in a steel cable attached to a mobile tool carrier. The tool carrier can be equipped with a plow, harrow, cultivator, or other tools, all quickly interchangeable.
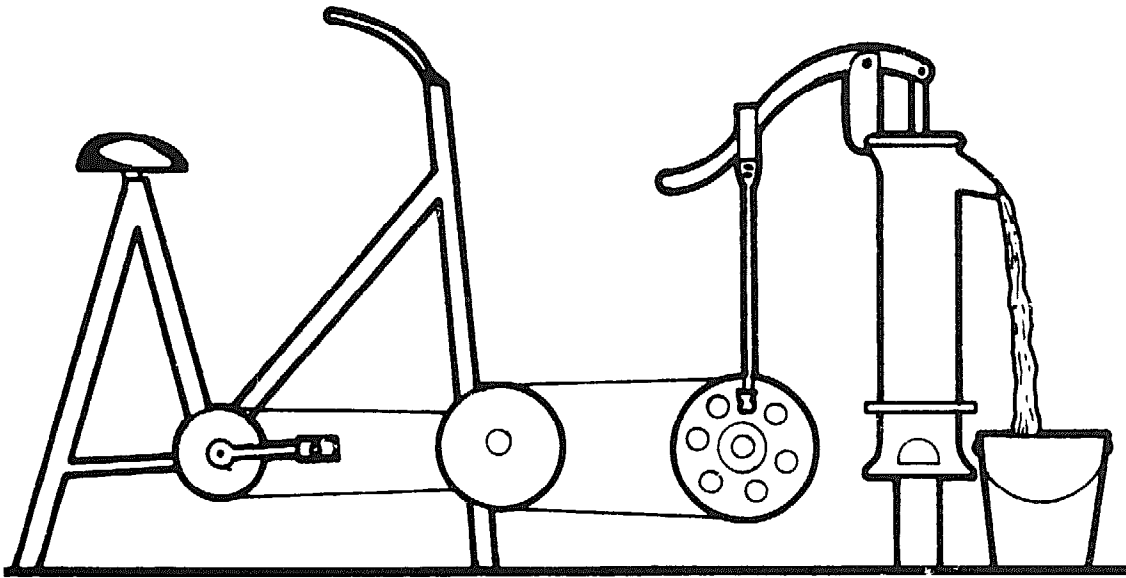
FIGURE 68 Pitcher pump (prototype).

FIGURE 69 Pumping water using a centrifugal pump and a pedal-driven device. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

Seated in the pedal power unit which is positioned at the head of the garden row (spade blades keep it in position), the operator pedals to reel in the cable attached to the tool carrier, which is guided by a helper. The tool carrier, equipped with the right tool for the desired operation (say, a plow), is

FIGURE 70   Plowing operation using the Mechanical Mule^{TM}.

positioned at the foot of the same row. When the tool carrier reaches the head of the row, the operator stops pedaling and pushes a lever that slips the reel into "free-reeling" position. The helper then wheels the tool carrier to the foot of the next row, thus unreeling the cable. Simultaneously, the operator moves the pedal power unit to the head of the next row. This sequence is followed until the entire plot of ground is cultivated or plowed.

The pedal power unit or winch (Figure 71) is designed with a three-speed sprocket-and-chain drive (Figure 72) which permits over 1,000 lb (453 kg) of pull with normal pedaling effort. "Low gear" is used for jobs requiring a slow, powerful pull, such as plowing through heavy turf. "Second" or "high" gears are used for easier jobs, such as harrowing or cultivating. The pedal power is much faster than hand spading and raking. Because the unit's design is simple, repairs or adjustments can be handled using simple tools. The unit can be built for less than $150 in quantities of 25 units.

DOMESTIC APPLICATIONS

Most domestic chores require a stationary power source. The use of pedal power in such a capacity necessitates overcoming a number of problems, in-

FIGURE 71   Pedal power winch unit of the Mechanical Mule^{TM}.

cluding: (1) cycle torque; (2) the need for a rigid brace between the driving and the driven sprockets to take the pull of the chain, which can be as much as twice the rider's weight; (3) some provision for adjusting the chain; and (4) the varying lengths of legs.

The principle behind the stationary Energy Cycle®-powered generator is simple. The energy generated by pedaling is transmitted by a power take-off head, and a conventional chain-and-sprocket is used as the drive chain. The input shaft of the machine or tool to be powered is coupled directly to the power take-off shaft (Figure 73).

If the unit is expected to do a number of jobs, it must be capable of speeds of from 60 to 1,800 rpm. When the higher speed is required, gearing up will be necessary. However, it is best to use a 1:1 ratio whenever possible. As a note of caution, one should never attempt to power a mechanism that requires more than a one-third horsepower motor; one-fourth horsepower or less is feasible.

Stationary pedal-powered units can perform a variety of food preparation tasks, including food grinding, food shredding, dough kneading, batter beating, butter churning, etc. Farm machinery applications include pumping

FIGURE 72   Gearshift mechanism of the Mechanical Mule^{TM}.

water, shelling corn, cleaning grain, polishing rice, and rolling oatmeal. Still other pedal-tested tools include a wheel grinder, stone polisher and buffer, drill, jeweler's lathe, wood carver, potter's wheel, and battery charger (see Figure 74).* Finally, a stationary pedal-powered unit can provide power for television sets and other electronic equipment. A simple kit—auto generator, 12-volt battery, and inverter—makes it possible to generate and store electricity for use in rural areas. It is possible to use an inverter that converts the

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*Plans and more information on pedal-powered devices are available from a number of sources. Plans for a bicycle-operated power take-off unit are available from the American Society of Agricultural Engineers, Box 440, St. Joseph, Michigan 49085, USA. Intermediate Technology Publications, Ltd., 9 King Street, London WC2E 8HN, England, has more information available on a pedal-powered cassava grinding machine. Information on foot-operated machines is available from the American Village Institute, Route 3, Box 3486, Selah, Washington 98942, USA, and information on a foot-powered wood lathe is available from Volunteers in Technical Assistance, 3706 Rhode Island Avenue, Mt. Rainier, Maryland 20822, USA. *Free-wheeling Magazine*, 37 Warrender Park Road, Edinburgh EH1 3JT, England, provides current information on pedal power technologies.
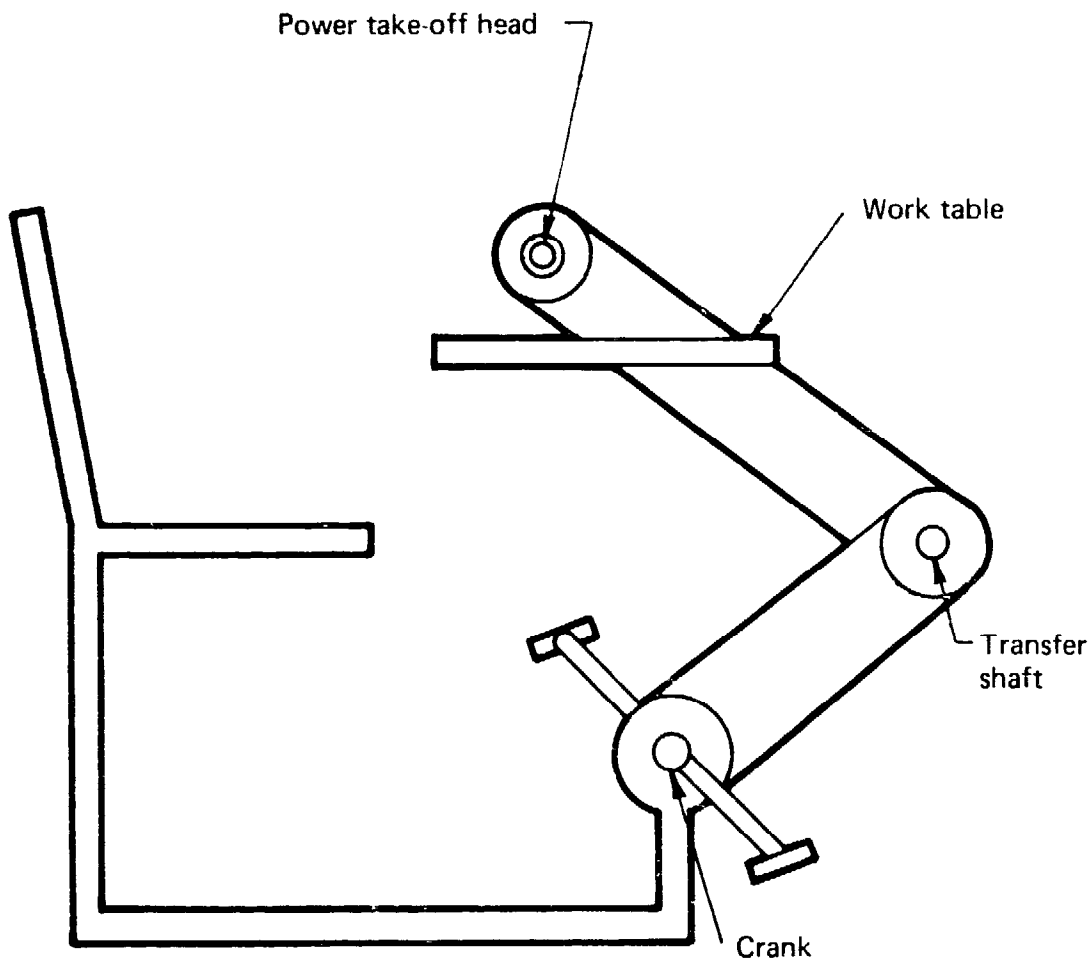
FIGURE 73 Diagram of the Energy Cycle®. Input shaft of the machine or tool to be powered is coupled directly to the power take-off shaft.

power stored in a 12-volt car battery into the 110 volts needed to operate standard electrical appliances.

The cost of building a stationary Energy Cycle® is estimated at $70-$100 in new and used parts, plus about 12 hours of labor.*

Other stationary devices include the Bik-O-Generator†, which will grind grain or generate electricity (Figure 75), and a commercially available maize sheller which is driven by a very simple but effective form of a bolted-on pedal drive unit. The latter is sold in several countries in Africa and can shell two cobs at a time. A heavy cast-iron fan serves both as flywheel and winnower to blow away the husks.

*Instructions for building the Energy Cycle® are contained in *Pedal Power in Work, Leisure, and Transportation*, edited by James C. McCullagh, Rodale Press, Emmaus, Pennsylvania, USA, 1977.
†Plans for this device are available from Homestead Industries, Ananda Village, Nevada City, California 95959, USA, and from the North Shore Ecology Center, 3070 Dato, Highland Park, Illinois 60035, USA.
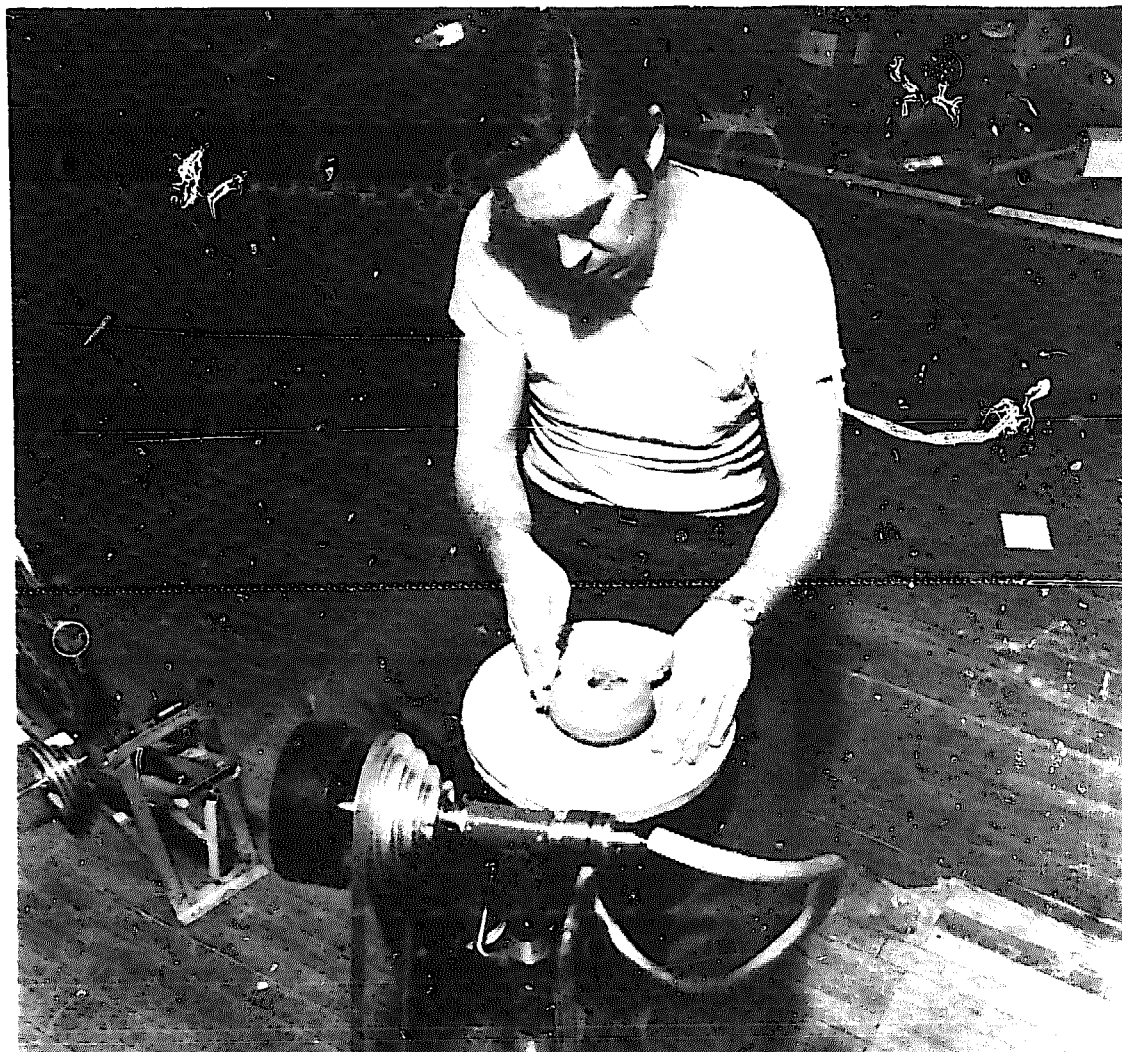
FIGURE 74 Potter's wheel powered by the Energy Cycle®. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

Another important application, shown in Figure 76, is a four-person, pedal-powered grain thresher/mill for sorghum, millet, and wheat (Weir/VITA 1979).* An inexpensive two-person dynapod that can be used to power a variety of mechanical devices or used for limited electrical generation (200 W) has also been developed (Weir/VITA 1979).

*Working diagrams for construction of the four-person, pedal-powered grain thresher/ mill are available from Volunteers in Technical Assistance, 3706 Rhode Island Avenue, Mt. Rainier, Maryland 20822, USA. More information on a thresher for rice and other small grains is available from the South Pacific Appropriate Technology Foundation, Post Office Box 6937, Boroko, Papua New Guinea. Complete technical drawings for a treadle-operated peanut thresher are available from Intermediate Technology Publications, Ltd., 9 King Street, London WC2E 8HN, England. One should inquire about the prices of these plans before ordering.

FIGURE 75 The Bik-O-Generator will power a grain mill or generate electricity. A pulley attached to a power take-off wheel could be attached to many other belt-powered tools as well. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)
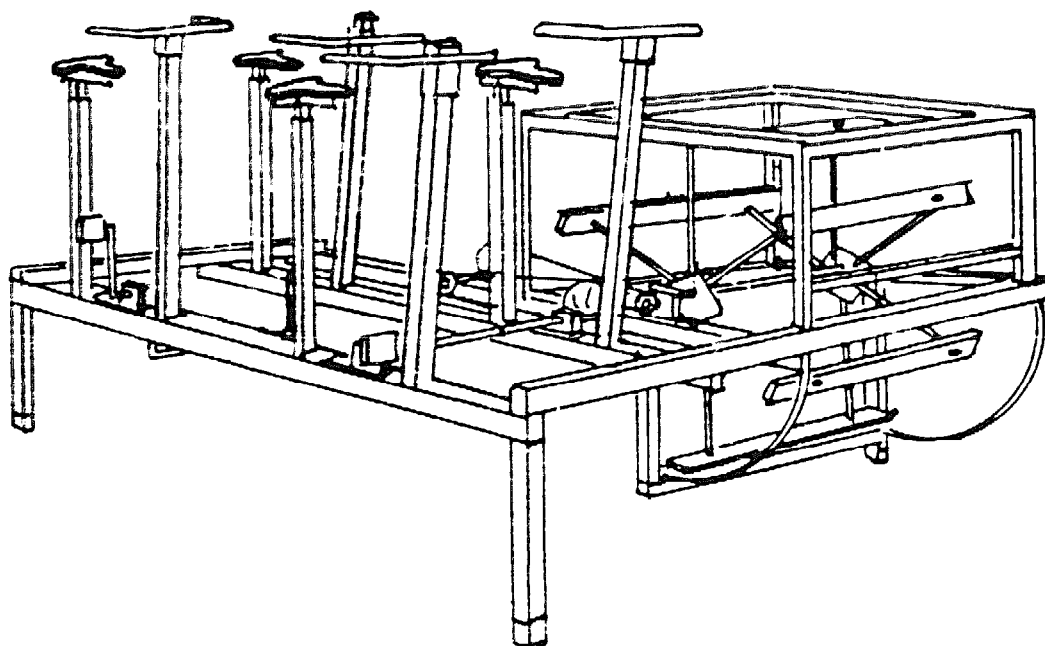
FIGURE 76 Four-pedaler/two-feeder thresher with plain wooden beaters, incorporating a grain milling device.

REFERENCES

Hansen, M. (1976)   Rail bike, *Alternative Sources of Energy*. No. 23, December.

McCullagh, J. C. (1977) *Pedal Power in Work, Leisure, and Transportation*. Rodale Press, Emmaus, Pennsylvania, USA.

Weir, A. (1979)   The Dynapod: A Pedal-Power Unit. Volunteers in Technical Assistance, Mt. Rainier, Maryland, USA.

Weir, A./VITA (1979)   Four-Person Pedal-Powered Grain Thresher/Mill. Volunteers in Technical Assistance, Mt. Rainier, Maryland, USA.

Stirling Engines

Stirling engines are external combustion heat engines that usually utilize air or other gases as working fluid. They are capable of operating on any source of heat such as sun, wood, coal, or field waste. The Stirling cycle lends itself to a wide, and by no means fully explored, variety of physical forms. Some of these forms are sufficiently simple to make and yet sufficiently effective to be strong candidates for power generation in developing countries, using any local fuel or solar energy as their heat source.

There has been a rapid increase in Stirling engine research and development since publication of the first edition of *Energy for Rural Development*. This is evidenced by the number of papers published yearly in the proceedings of the Intersociety Energy Conversion Engineering Conference (IECEC), the recognized forum for dissemination of the latest in Stirling engine work. (See Appendix C for suggested reading.) Of this work, an increasingly larger percentage is being directed toward the free-piston Stirling engine, reflecting the fact that its lack of critical seals and its mechanical simplicity make it the favored form for many applications.

RECENT TECHNOLOGICAL ADVANCES

A large proportion of the work in the United States, the Netherlands, and Sweden is being directed toward automotive applications under the impetus of the heavily funded U.S. Government automotive Stirling engine program. Significant work on solar-electric Stirling engines is also being conducted under the auspices of the U.S. Department of Energy (DOE), targeted toward development of a highly efficient, point-focusing Stirling electric system in the early 1980s. The target price of power from this system is $.05/kWh.
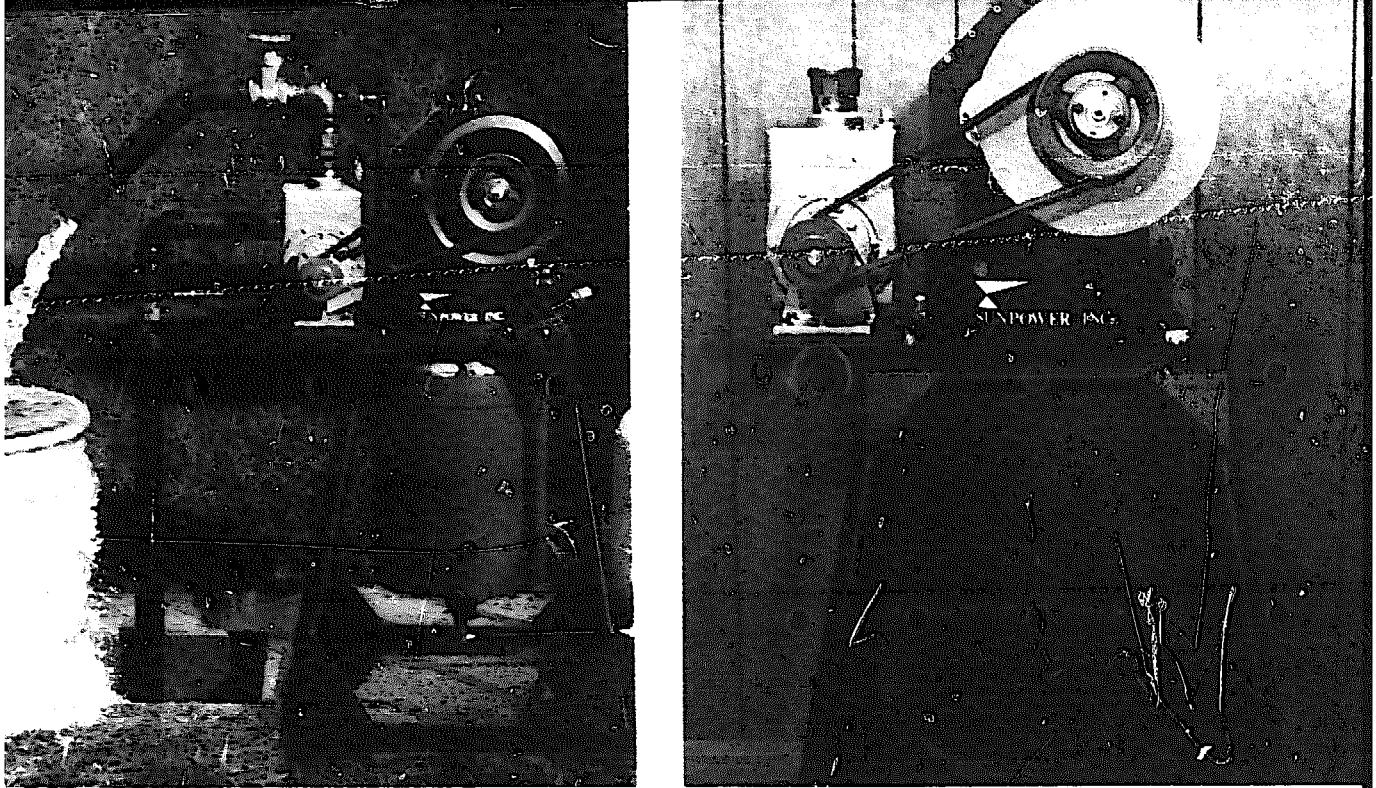
FIGURE 78 Low-pressure engine designed specifically for pumping water, using a solid fuel.

higher pressure version specifically intended for water pumping using solid fuel is now being developed by Sunpower, Inc. (USA). Its design criteria are simplicity, repairability, low maintenance, and insensitivity to heater fouling (Figure 78).

Free-Cylinder Engine

These extremely simple mechanisms have only a piston, a displacer, and a cylinder that move to produce work. In their simplest form, they use only an annular gap around the displacer to serve the heat exchange and regenerative function. They are hermetically sealed and can use hydrogen or helium without danger of leakage. These engines have an advantageous stroke-force-frequency relationship with very high forces available as cylinder stroke is reduced, and adequate speed stability as external load is removed, thus permitting harmless operation under no load.

Figure 79 shows a small demonstration model arranged as a water pump (Beale 1979). The thermodynamic performance of these machines is in no way inferior to that of more conventional free-piston or crank Stirling engines. They can be used to pump fluids, dig, process grain, and can perform many other tasks including turning a shaft through a tension cable wrapped around a ratchet or sprag clutch.

Free-Piston Alternator Engine

Used today as demonstrators, as research tools, and for other special purposes, these engines are ready for mass production when a market appears. Figure 80 shows the interior arrangement of a typical small alternator engine

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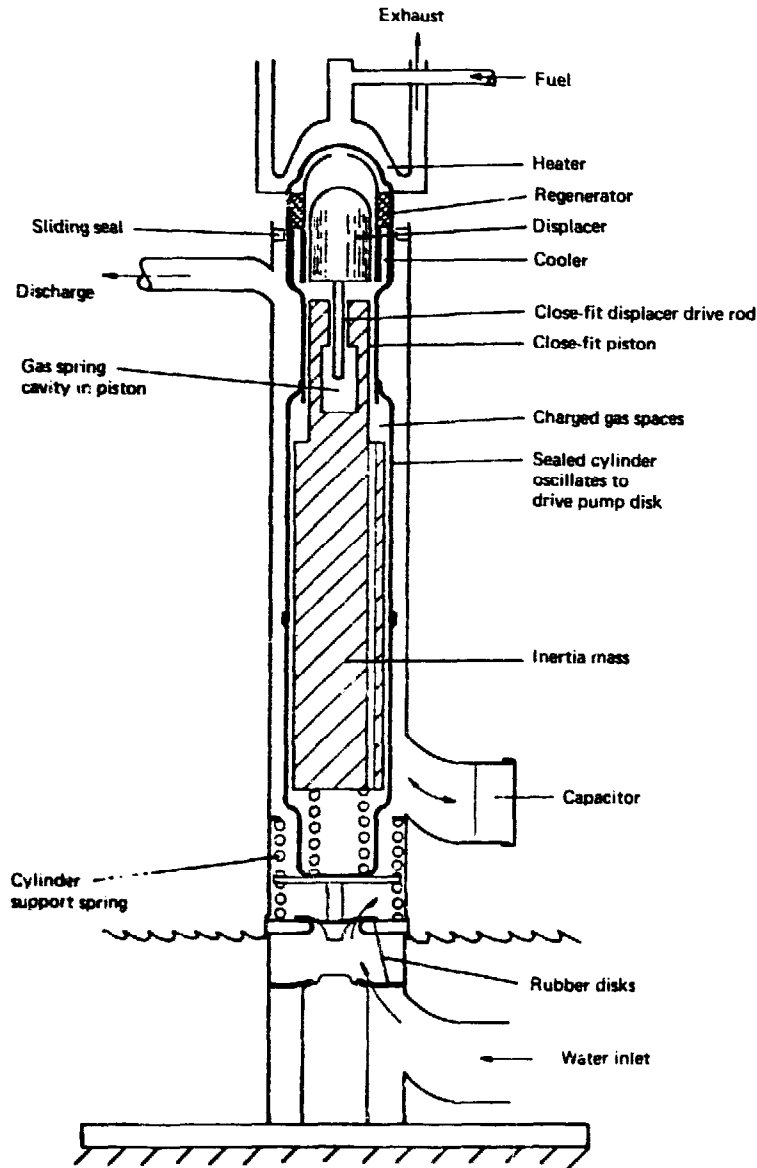
FIGURE 79 Free-cylinder Stirling engine with inductance pump.

of about 100-W output. Very refined machines of this general type using helium as their working gas are being developed under DOE funding for aerospace uses and for large-scale solar power projects (West 1974).

These machines can be scaled up to much larger sizes on the order of 100 kW per cylinder, and used together to form large stationary power plants producing power in the megawatt range. They promise long life, low maintenance, and high thermal efficiency while using solid fuels as their heat source.

In developing countries, simplified designs of the linear alternator engine could be built locally to provide electric power for lighting, communication, and other uses. Its exceptionally low noise and its ability to use solar heat or agricultural wastes make it compatible with village life.
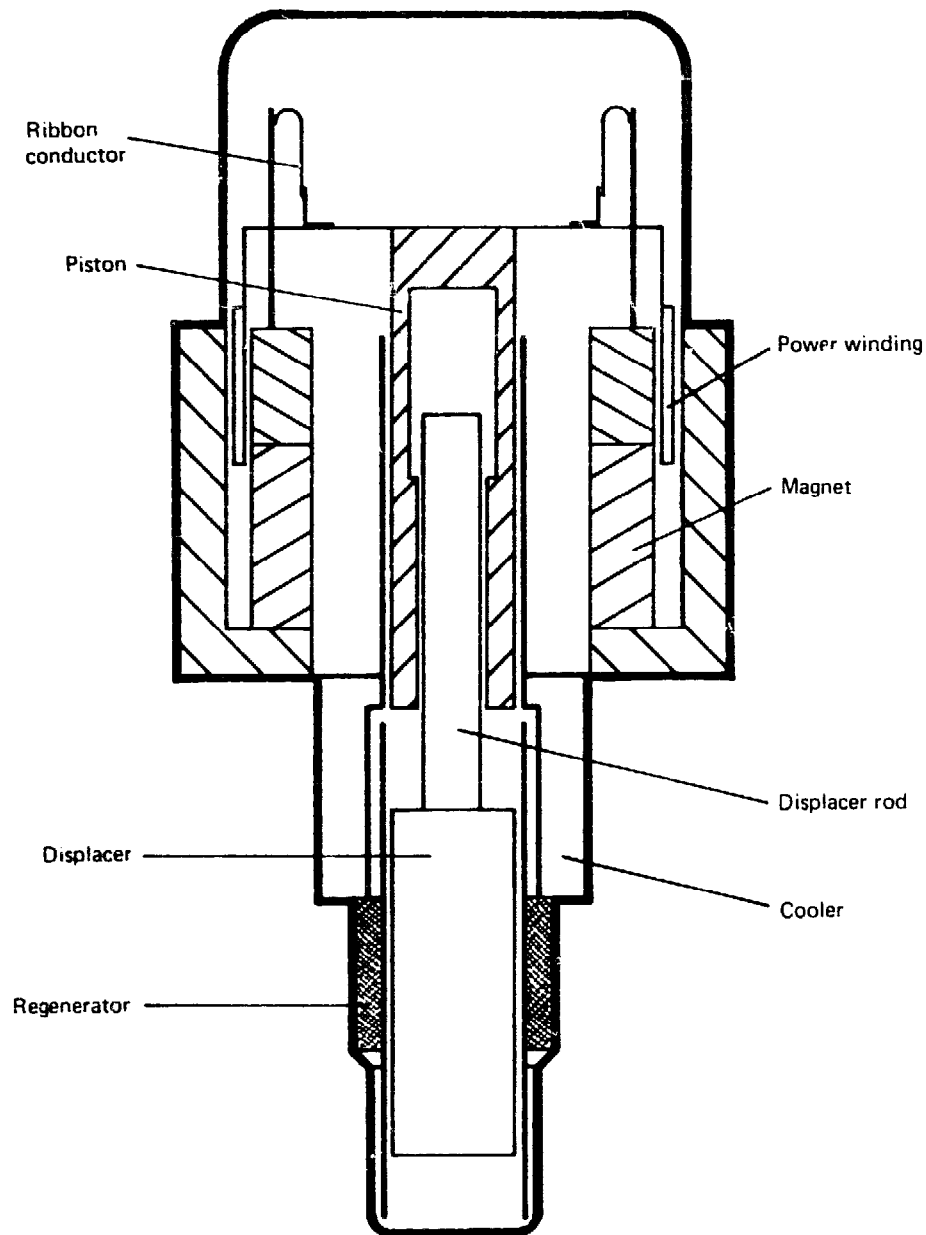
FIGURE 80   Free-piston alternator engine of about 100-W output.

Free-Piston Stirling Heat Pump

One of the simplest yet most effective arrangements of Stirling machines is the duplex Stirling engine, heat-driven heat pump (Figure 81). This machine currently exists only in small sizes and a low-temperature design, but its scaling characteristics are well understood so that it can be made in any size and temperature range. It requires no higher level of manufacturing skill than the free-cylinder engine or alternator engine and is no more complex mechanically than the simple free-cylinder engine. It can be expected to be much more fuel-efficient than absorption refrigeration devices designed for the same purpose, and it requires no lubricant, is hermetically sealed, and is very quiet in
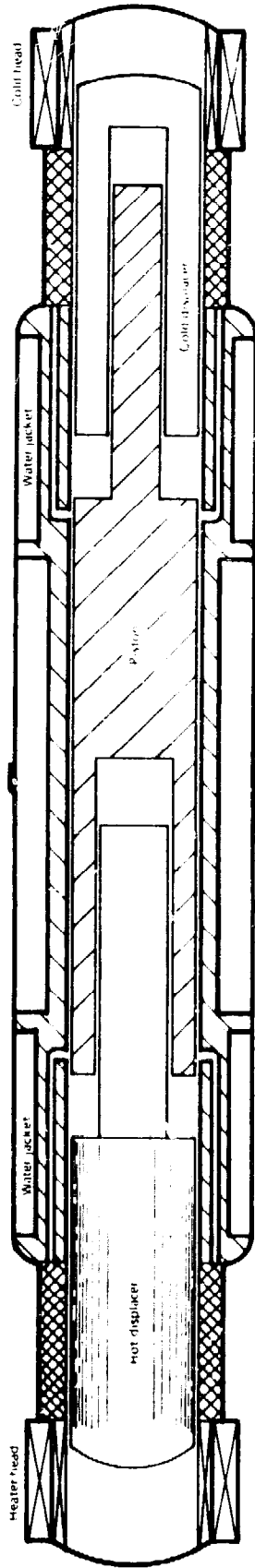
FIGURE 81   Duplex Stirling, heat-driven heat pump.

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operation. It would be ideally suited, for example, as a milk cooler heated by biogas from cattle manure, and is readily adaptable to refrigeration, food freezing, space cooling, and similar tasks.

Liquid-Piston Engine

Liquid-piston engines have the advantage of being simple mechanically in their elementary form; however, they have a large volume for the useful power produced and very low efficiency unless modified by the addition of some sort of interface between the water columns and the air working fluid.

Liquid-piston engine development is just beginning in earnest, and it is possible that efforts may soon bear fruit. A practical water pump may result in the future. The question remains as to its competitiveness with the possibly more complex but smaller Stirling engines of the types described here.

FUTURE OUTLOOK

With modest development funding, Stirling engines could be commercially available within 5 years in the following forms: (1) simple hot-air engines up to a few kilowatts in shaft power, (2) specialized hot-air engines for water pumping, (3) free-cylinder water pumps, (4) free-piston electric generators up to 10 kW in output, and (5) heat-driven cooling machines. All of the above machines could be designed to burn solid fuel at about 10 percent overall conversion efficiency using only low-carbon steel, cast iron, and aluminum for their major structure. The free-cylinder and free-piston engines could use solar energy from an inexpensive inflated film collector. If 300-series stainless steel is available for the hot end of the cylinder, significant improvements in life and efficiency would result, with moderate increases in manufacturing cost.

From the viewpoint of the technologist, there is no impediment to the successful design of the entire spectrum of Stirling engines described in this chapter within 10 years. Which ones become economically competitive depends on the capital invested and the nature of the competition, and, probably equally if not more importantly, on the future fuel situation. Increasingly expensive petroleum would lead toward greater popularity of external combustion Stirling engines or those driven by solar heat.

In the far future (10-15 years), it is probable that low-temperature Stirling engines of respectable efficiency will be available, extending the Stirling range of utility into the areas now dominated by Rankine cycles. This can be expected from liquid-piston engines and from those using working fluids other than ideal gases. The other types of engines—water pumps, alternator and heat pump free-piston engines, and crank engines of the low-pressure air type as well as of the high-pressure hydrogen type—will have found their proper best applications in relation to the competition.

DESIGNS FOR LOCAL AVAILABILITY

While the Stirling engine can be very simple mechanically, its design process is not; it requires a deep understanding of complex mechanical, thermodynamic, and dynamic interactions. The problem of introducing Stirling engines in developing countries is essentially one of directing available capital toward that end. Likely end users have little capital, and groups with the design knowledge have no economic incentive to invest their effort in the expensive job of engineering a practical design.

Is it possible to make an effective Stirling engine from material already found in developing countries or from materials easily acquired? Some materials already available that can be used to fabricate these devices include low-carbon steel, cast iron, and aluminum; containers of various sizes (cans, drums, barrels); automotive and bicycle parts (tires, inner tubes); indigenous materials (brick, clay, glass, wood, and fibers); and, by no means least, human ingenuity, determination, and effort.

As an example, any of the engines described in this chapter could be used to pump water, as could the 1900 Erickson engine, although less efficiently
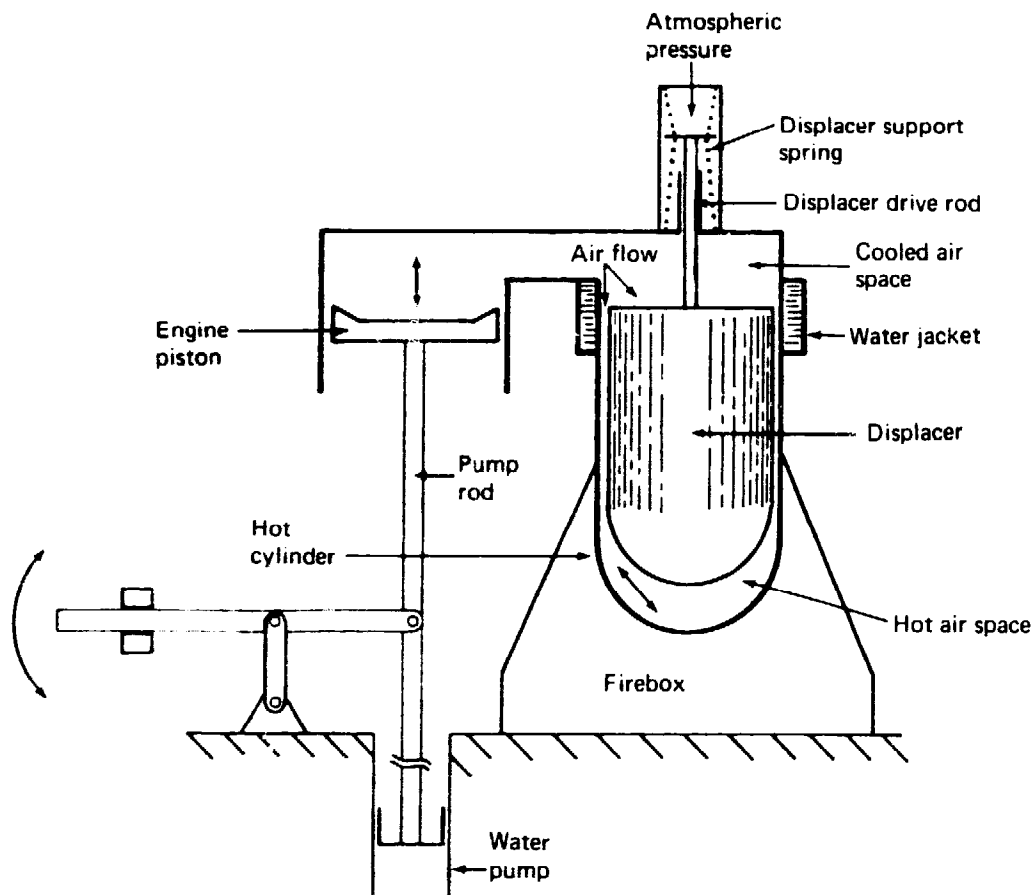
FIGURE 82 Rudimentary Stirling engine-driven system for water pumping.

and with much more metal weight. However, if an otherwise unused agricultural by-product is used as fuel, and abundant low-quality cast iron, perhaps with food containers modified as displacers, is used as the metal, then the Erickson engine has the primary quality of availability, if designs and examples are made available for local artisans to copy.

Even simpler configurations are possible. For example, Figure 82 shows a conceptual layout that could well be used to pump water. It could be constructed of sheet steel, and could use a leather cup seal around a wooden disk for the working piston. It would have no cranks or bearings, and would be self-starting. The firebox could be made of brick or clay and the hot cylinder of either steel, cast iron, or possibly even reinforced, fired clay.

REFERENCES

Beale, W. T. (1979)   A Free Cylinder Stirling Engine Water Pump. Paper presented at the 1979 International Solar Energy Society Meeting, August 1979, Atlanta, Georgia, USA. ISES, Victoria, Australia.

Senft, J. R. (1979) *IECEC Proceedings*. Intersociety Energy Conversion Engineering Conference, Boston, Massachusetts, USA.

West, C. D. (1974)   Fluidyne Heat Engine. Paper No. 5, Record of the International Solar Energy Society (U.K. Section).

Solid-State Electric Inverters

Renewable energy sources generally produce direct current that is unregulated and/or intermittent. However, most devices that use electricity are designed to operate over a reasonably narrow range of voltages and frequencies, and thus cannot be attached directly to most renewable energy sources. For that reason, suitable power conditioning equipment is essential for use of renewable energy sources, and that equipment will almost certainly be in the form of solid-state power converters, sometimes used in conjunction with battery, or perhaps flywheel, storage.

The most difficult problem connected with electric power conditioning is converting an intermittent source of electricity, continuously varying in voltage, to a continuous source of relatively constant voltage and frequency, which is required for electronic equipment, television sets, standard refrigeration units, etc. Sometimes the cost of such a power conditioning system, when battery storage is included, is more than the cost of the original electrical energy source.

Most electrical appliances are designed to be operated from a stable electrical supply from a grid system (or at least a motor-driven electric generator) capable of handling many times the size of the load of any individual appliance. Thus electric motors, which may draw many times as much starting current as they do normal running load current, present particularly difficult problems. A power source with a 3- or 4-kW instantaneous capacity or more is required to line start a motor that draws only a kilowatt at full load. A solid-state inverter capable of delivering such power surges must necessarily be significantly overdesigned for its average load and therefore rather expensive on a per-kilowatt basis. Further, whatever source is used to power the solid-state inverter must be stable and capable of the surge currents required.

Some low-cost inverters on the market have very poor waveform and surge capability for their average wattage rating. As a result, their performance and reliability in practical field applications have been very disappointing. Consequently, solid-state inverters in general have been considered unreliable. It is quite possible to design solid-state inverters with adequate surge capability and excellent reliability, but at somewhat higher overall cost, of course.

It is obviously uneconomical to buy or build electrical generation systems operated from renewable energy sources that have the surge capability, and therefore capacity, of several times the average load requirement. Thus, in remote regions methods must be developed for delivering suitable energy to difficult types of loads when that energy is derived from essentially unstable sources. There are two approaches to dealing with this problem:

- Build one central power conditioning and storage system capable of handling the most extreme load conditions. This method allows the use of standard appliances, motors, and other commercially available units. For small power sources, however, the cost per installed kilowatt is generally prohibitively high.

- Accept the electrical energy sources as they are and find ways to use the intermittent and variable energy as effectively as possible. This generally would not allow the use of unmodified commercial appliances. However, extensive modification sometimes is not required and the overall cost is often less than for the first approach.

METHODS FOR POWER CONDITIONING
WITH INTERMEDIATE STORAGE

If the power source is intermittent to the extent that for some period of time there is no power, or if the type of load calls for short but heavy surge currents, then an intermediate storage system must be used. Most likely, this storage device might be a lead-acid battery, the size of which is determined by the surge peaks required and the time duration of the outages expected. Power conditioning equipment requirements under these conditions are essentially the same as those of a system operating directly from batteries, since batteries (particularly lead-acid batteries) are superb power smoothing devices and have excellent surge capabilities, at least for 10-20 sec. Thus if the solid-state inversion system can withstand the surge currents required, the battery system can provide them even though the original power source cannot. The battery is often necessary for that reason alone, irrespective of long-term storage needs.

Higher-quality solid-state inverters have become available in recent years, while, at the same time, the cost of inverter systems has been decreasing

slightly, even in the face of rapid inflation. The surge-current capabilities of silicon control rectifiers, for example, have been increasing, and the cost per kilowatt of energy-handling capability has been decreasing. Thus power inverters in the 25-100-kW range have decreased in price from about $2,000/kW to about $500/kW.

Inverters (DC-AC) operating at power levels under 25 kW are more expensive on a per-unit basis, but there are also encouraging developments in this area. High-current transistors that can operate at up to several hundred volts are becoming available, and the price of such devices is dropping. Recently, field effect transistors (FETs) that operate at 10 amp and 600 volts have been developed. The price is currently high, but as production proceeds, the price should drop an order of magnitude or more.

In short, while there are not now many reasonably priced, reliable and efficient DC-AC inversion systems on the market, it appears that they may become available within the next 5 years. For those applications where well-regulated AC power with controlled frequency and good sine waveform is necessary, suitable units will be available.

METHODS FOR POWER CONDITIONING WITHOUT INTERMEDIATE STORAGE

A number of available generation schemes can be applied in situations in which stable utility-grade power is to be generated from a variable-speed mechanical energy source, but battery storage is not used. Such situations might include: windmills operated in the variable-speed (constant tip-speed ratio) mode; steam turbines fed from geothermal wells; and point-focusing, distributed-receiver, solar–thermal–electric systems employing high-speed (Brayton cycle) turbines operating in the variable-speed mode.

Variable-Speed, Constant-Frequency (v sc f) Power Generation

Several VSCF generation schemes have been developed by judiciously combining rotating electrical machines with mechanical (commutator) and/or electronic (thyristors and diodes) switching devices. Some promising schemes are the AC-DC-AC link and the special generator/AC link or DC-AC link, which could take the form of a field-modulated generator system, double-output induction generator, or an AC commutator generator.

AC-DC-AC Link. In this case, a conventional AC alternator and rectifiers are used to generate DC power to be fed to a DC-AC inverter. Naturally commutated (also known as line-commutated) inverters are used for converting direct current into alternating current. They utilize a timing device (either

electronic, or perhaps an existing power line) that periodically reverses polarity and causes commutation to occur naturally. Such converters are controlled by building controllable phase delay into the switching control signal generator. They can be used either to feed power directly to an existing power grid, or to provide alternating current independently, depending on variations in design.

Special Generator/AC Link or DC-AC Link. A *field-modulated generator-system* employs a three-phase, high-frequency alternator to generate single-phase power at the required low frequency. The rotating field coil of the alternator is supplied with alternating current at the desired low frequency instead of with conventional direct current.

Power delivered by a field-modulated generator system to a power grid can be controlled by regulating the magnitude and phase of excitation voltage applied to the rotor terminals from the power grid. Alternatively, a separate field excitation AC source will permit the system to stand alone. This generation scheme has many unique features, such as operation in a single-, two-, or three-phase mode and self-excitation, which allow versatility in operation and control.

Conventional induction generators, by their very nature, must operate at essentially constant speeds. One approach to overcoming this restriction and allowing the induction generator to become a variable-speed, constant-frequency device is the use of rotor power regeneration. The squirrel cage rotor is replaced by a wound rotor with leads brought out through slip rings. Rotor power output at slip frequency is converted to line-frequency power by an AC-DC-AC link consisting of a rectifier and inverter.

Because output power is obtained both from the stator and rotor, this device is called a *double-output induction generator*. Rotor output power has the electrical equivalence of an additional impedance in a rotor circuit, and thus increasing rotor outputs leads to increasing slips and higher speeds. Such an operation broadens the operating speed range from synchronous to twice the synchronous speed. This corresponds to a slip range per unit of 0-1.0.

The AC commutator generator, also known as a Scherbius machine, has two polyphase windings in the stator. The exciting winding provides the basic excitation to the magnetic circuit and sets up the rotating field, while the compensating winding is connected in series with the brushes in such a way as to neutralize the armature reaction field se up by the armature (rotor) currents. The rotor winding is of the commutator type and is connected to the commutator.

For a given rotating field in the air gap, the frequency of the voltage and current collected by the polyphase brush gear resting on the commutator is the same as in the stator, irrespective of the rotational speed. In essence, the

commutator acts as a mechanical frequency changer. Therefore, the brush gear can be connected in series with the stator (compensating) winding, and the frequency of the output is independent of the shaft speed. The principle of operation is similar to that of a compensated DC generator except that instead of direct current there is constant (line) frequency alternating current and three leads instead of two.

Additional windings, such as interpole and damping windings, may be provided to improve commutation. Basic problems in employing this device are the cost and the additional maintenance and care required by the commutator and the brush gear.

DIRECT USE OF INTERMITTENT ELECTRICITY

Water pumping, space heating, crop drying, grain grinding, small lathes, hydraulic logsplitters, small plows and tillers similar to those described in the chapter on pedal power, and other small machines, can use intermittent (as available) electricity. If the intermittent sources provide energy on at least a daily basis, perhaps even small refrigeration units could be operated. However, some equipment may require modification so that electric sources that vary widely in voltage, frequency, and energy availability can be used.

For any application requiring low-grade heat (e.g., water heating, space heating, grain drying), the problem is relatively simple. A resistive (heat-producing) load must be designed that fully absorbs the output of the electric generator. For example, if a simple fixed-pitch wind turbine is to deliver full power for any wind speed, it must operate at an approximately constant tip-speed ratio, which means that the turbine's revolutions per minute must vary proportionately to the wind velocity. However, the available power output varies as the third power of the wind velocity. Thus a nonlinear resistive load or some method of automatic generator voltage adjustment is required. Considerable progress is being made in the development of such loads and automatic controls.

One problem with using sources of intermittent electricity such as geothermal wells, windmills, or solar thermal collectors (driving free-piston, sealed Stirling engines or small, simple turbines) is that the electric generators they drive sometimes operate over wide speed, voltage, frequency, and power ranges. It must be kept in mind that most small mechanical devices and machines run at more or less constant speed because the electric motor driving them is generally a single-phase induction motor operating on a power line of more or less constant frequency and voltage.

Typical mechanical loads do not necessarily have to operate over a narrow range of speeds. Further, induction motors (particularly polyphase motors) will run successfully over a wide range of speeds if the input voltage and frequency vary over a similar range. The primary concern with these motors is

that the maximum load, applied voltage, and power line frequency all remain proportional to each other. To provide continuous rotational torque, it is desirable that the power source and motors both be polyphase. Otherwise, there is no simple way to start the motor.

One of the simplest generation schemes that can be used to deal with these problems is a permanent magnet alternator. The stator of the alternator is wound for polyphase (two- or three-phase) output, and the rotor consists of permanent magnets of alternating polarity mechanically embedded around the rotor periphery. The output frequency is strictly proportional to the rotational speed. Under open-circuit (no-load) conditions, output voltage is also proportional to the rotational speed. However, under load, armature reaction effects and internal impedance drops contribute to a departure from this proportionality.

If the prime mover is operated at a constant speed, the output under load will be at a constant frequency, but the voltage will be variable, depending on the load. If operated at variable speed, the output will be variable both in voltage and in frequency. Either of these outputs can be converted to constant-voltage, constant-frequency alternating current using a solid-state rectifier–inverter combination with appropriate controls, but that requirement can sometimes be avoided.

It is well known that a conventional squirrel cage induction motor can be operated in the variable-speed mode by supplying its stator with variable-voltage, variable-frequency power. To avoid saturating the magnetic circuit, the applied voltage and the load demand should vary proportionally with the frequency. The air-gap flux will then be approximately constant and satisfactory operation will result. Hence, the output of a variable-speed, permanent magnet alternator is ideally suited for connection to an induction motor.

Such an induction motor can be used to drive a centrifugal water pump, a small shop lathe, a grain grinder, or even a small plow (see "Pedal Power"). The result will be simply an electrical transmission between the prime mover and the electric motor. In all of the cases discussed above, a set of capacitors connected across the machine terminals improves performance significantly because of the leading currents drawn by them and the resulting self-excitation of the alternator caused by the leading current.

A small, three-phase alternator (driven by a variable-speed mechanical source), which could, in turn, drive a small, three-phase electrical motor, can be constructed relatively simply. First, the rotor from a standard three-phase induction electric motor is slotted in a milling machine. Then rare earth (samarium-cobalt) magnets are glued (with a high-temperature epoxy glue) into the slots and the rotor is reground to the proper diameter and rebalanced. Finally, the rotor is reinserted in the original stator assembly. The result is a polyphase permanent magnet alternator. Alternators built this way have been used successfully to drive deep-well water pumps and for other motor-drive

applications. Such a system can transmit the mechanical power of a windmill (or other intermittent mechanical source) to some suitable remote location easily and without any inverters, batteries, or other high-technology equipment. Systems of this type, up to several horsepower, have been built and successfully operated in the field for several years. (See Appendix A for a list of manufacturers of solid-state electric inverters and Appendix C for a list of suggested reading.)

APPENDIXES

Appendix A
MANUFACTURERS OF ENERGY-RELATED DEVICES

This appendix represents the best information available to the NAS staff at the time of publication, but is not necessarily complete. It was not possible to verify many of the following addresses.

Country	Company/address	Product
TERRESTRIAL PHOTOVOLTAIC **SYSTEM AND COMPONENT MANUFACTURERS**[a]		
Australia	Amalgamated Wireless Australasia, Ltd. 47 York Street Sydney, New South Wales 2000	
	Lucas Industries Australia Batteries Division 1156 Nepean Highway Cheltenham, Victoria 3192	Solar cell power generation systems
	Philips 161 Starts Street South Melbourne, Victoria	
	Spectrolab 34–40 Clayton Road North Clayton, Victoria 3168	
Federal Republic of Germany	AEG-Telefunken Raumfahrttechnik und neue Technologien Industriestrasse 29 2000 Wedel, Holstein	Solar cell module, solar cell array field
	Christeva Sonnenenergietechnik GmbH Schramminger Weg 74a 8000 Munich	Storage tanks, solar cell array field, flat plate collectors
	Contronic Peer-G, Cruse Postfach 605, 344 2000 Hamburg 60	Solar cell array field
	Contronic Solar–Electronic Bornstrasse 32 2000 Hamburg 13	Solar cell array field

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ELMEG GmbH, Abt. ESOTRON Rudigerstrasse 12 5300 Bonn 2	Novelty items
Ferranti GmbH Widenmayerstrasse 5 8000 Munich 22	Solar cell module, solar cells, solar cell array field
Herrmann Helfried Postfach 1450 8998 Lindenberg	Solar cell power generation systems
Herwi Solar GmbH Am Stein 7 8755 Alzenau	Solar cells
Leybold–Heraeus GmbH & Co. KG Postfach 549, Wilhelm-Rohn-Strasse 25 6450 Hanau 1	
Philips GmbH, Unternehmensbereich Licht und Anlagen–Energie–Systeme Monckebergstrasse 7 2000 Hamburg 1	Heat pumps, evacuated tube concentrating collectors, solar cell array field
Rucker GmbH, UB Solartechnik Postfach 1232 5210 Troisdorf 1	Solar cell power generation systems
Siemans AG Postfach 103 8000 Munich 1	Solar cell module, silicon solar cells
Valvo GmbH Burchardstrasse 19 Postfach 106.323 2000 Hamburg 1	Solar cell array field, electric batteries

Country	Company/address	Product
	TERRESTRIAL PHOTOVOLTAIC SYSTEM AND COMPONENT MANUFACTURERS[a]	
	Wacker–Chemitronic Gesellschaft fur Elektronik-Grundstoffe MbH Johannes-Hess-Strasse 24 Postfach 1140 8263 Burghausen	Silicon solar cells
France	Aérospatiale 37, Boulevard de Montmorency 75781 Paris Cedex 16	Flywheels/inertial systems, heliostats, solar cell array, tower focus power plant components
	Centre National d'Etudes des Télécommunications (CNET) 38–40, rue du General Leclerc 92131 Issy les Moulineaux	Solar cell array field, wind turbine generator systems
	Compagnie Industrielle des Piles Electriques (CIPEL) Division des Produits Industriels 125, rue du President Wilson 92302 Levallois Perret	Solar cell array field, electric batteries
	France Photon BP 119 Usine des Agriers 16004 Angoulême Cedex	Solar cell array, solar cells
	(R.T.C.) La Radiotechnique–Compelec 130, Avenue Ledru-Rollin 75540 Paris Cedex 11	Solar cells, space power satellite systems
	Leroy W. Somer Boulevard Marcellin Leroy 16004 Angoulême	Heat pumps, educational aids, vertical-axis wind machines, small hydropower systems, solar cell array field

	Motorola Semi-Conducteur S.A. 126, Chemin de Canto Laouzetto 31000 Toulouse	Solar cell module, solar cells, solar cell array field
	Pompes Gutnard Etablissements 179, Boulevard Saint Denis 92402 Courbevoie	Solar cell system components
	Société des Applications de Hélioénergie (SAHEL) 50, rue J. P. Timbaud BP 301 92402 Courbevoie Cedex Paris	
	Thomson–CSF S.A. 173, Boulevard Haussmann 75008 Paris	Solar cell system components
Great Britain	Ferranti Engineering, Ltd. Electronic Components Division Post Office Box 20 Hollinwood Avenue Chadderton Oldham OL9 8EL	Solar cell array field, solar cells, solar cell protective coating
	Grumann International, Inc. 64–65 Grosvenor Street London W1X DB	Solar cell power generation systems
	International Research and Development Fossway Newcastle upon Tyne	Solar cells
	Lucas Electrical, Ltd. Pes Division Great Hampton Street Birmingham B18 6AH	Solar cell power generation systems

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Country	Company/address	Product
	TERRESTRIAL PHOTOVOLTAIC SYSTEM AND COMPONENT MANUFACTURERS[a]	
	Solar Power, Ltd. 101-111 Strand London WC2R 0AA	Solar cell power generation systems
Italy	Aerimpianti S.p.A. Via Bergano, 21 20135 Milano	Solar cell power generation systems
	Ansaldo Electric Systems Division Via A. Pacinotti, 20 16151 Genova-San Pier d'Arena	Tower focus power plants, dispersed solar electric power plants, domestic hot water systems, solar cell array fields
	Officine Galileo Meccanotessile ESO (Solar Energy Dept.) Via Carlo Bini, 44 50134 Firenze	Tower focus plants, solar cell array field
	Termomeccanica Italiana Via del Molo, 1 19100 La Spezia	Solar cell power generation systems
Mexico	Philips Mexicana, S.A. de C.V., Division Energia Solar Durango 167 Mexico 1, D.F. 07	
The Netherlands	N. V. Philips' Gloeilampenfabrieken Bldg. Tam Pieter Zeemanstraat 6 Eindhoven, Nb 5621 CT	Solar cell panels, solar cell module, solar cell array field

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United States

Acurex Corporation Alternate Energy Division 485 Clyde Avenue Mountain View, CA 94042	Domestic hot water/space heating/cooling systems, steam supply systems, decentralized power plants, process hot water systems, irrigation systems, parabolic trough collectors, concentrator solar cell assembly
Aidco Maine Corporation Orr's Island, ME 04066	Domestic hot water systems, space heating systems, solar cell array fields, decentralized power plants, thermal collector subsystems, process heat systems, greenhouses, wind turbine generator systems, solar ponds
Applied Solar Energy Corporation (formerly Optical Coating Lab, Inc.) 15251 East Don Julian Road City of Industry, CA 91746	Solar cell module, silicon solar cells
ARCO Solar, Inc. 20554 Plummer Street Chatsworth, CA 91311	Solar cells, solar cell protective coating, solar cell array, solar cell module
Arthur D. Little, Inc. 25 Acorn Park Cambridge, MA 02140	Photoelectric solar energy satellite systems, solar cell array field
Automatic Power, Inc. Post Office Box 18738 Houston, TX 77023	Solar cell array, solar cell module
Columbia Chase Corporation Solar Energy Division 55 High Street Holbrook, MA 02243	Solar cells; solar cell array field; do-it-yourself domestic hot water systems; domestic hot water systems, liquid; absorbers, copper; flat plate collectors, liquid; housing/framing
Crystal Systems, Inc. Shetland Industrial Park 35 Congress Street Salem, MA 01970	Solar cells
Dow Chemical USA FP&S/TS&D, Lab 3, 2020 Dow Center Midland, MI 48640	Latent heat storage modules, pipe insulation, collector insulation, vapor barriers, neoprene sealants and adhesives, plastic sheets and films, protective coatings, solar cell materials, solar cell protective coating, silicone sealants and adhesives, antifreeze, eutectic salts

Country	Company/address	Product

TERRESTRIAL PHOTOVOLTAIC
SYSTEM AND COMPONENT MANUFACTURERS[a]

Country	Company/address	Product
	Dow Corning Corporation Solar Energy 2200 West Salzburg Road, Box 1767 Midland, MI 48640	Solar cell protective coating, collector insulation, solar cell materials, special insulating units, silicone sealants and adhesives, silicone heat transfer fluids, protective coatings, plastic sheets and films
	Ecotronics, Inc. 8502 E. Cactus Wren Road Scottsdale, AZ 85253	Microprocessors, proportional controls, power conditioning equipment, solar cells
	Free Energy Systems, Inc. Price & Pine Streets Holmes, PA 19043	Solar cell module, solar cell protective coating, solar cell array field
	General Electric Company Advanced Energy Programs Post Office Box 13601 Philadelphia, PA 19101	Solar cell panels, solar cell module, solar cell array field, heat pumps, v-trough concentrating collectors, evacuated tube collectors, large wind turbine generator systems
	Gould, Inc. Gould Laboratories 540 East 105th Street Cleveland, OH 44108	Electric batteries, solar cell system components, heat pipe heat exchangers
	International Rectifier Semiconductor Division 233 Kansas Street El Segundo, CA 90245	Solar cell module, silicon solar cells
	International Solar Leasing Company 7010 Convoy Court San Diego, CA 92111	

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InterTechnology/Solar Corporation 100 Main Street Warrenton, VA 22186	Heat pump systems, water-to-air; compound parabolic concentrators; domestic hot water systems, liquid; flat plate collectors, liquid; parabolic trough collectors; support systems; sealants, adhesives, and gaskets; space heating systems, liquid; solar-assisted heat pump systems; domestic hot water/space heating/cooling systems; process hot water systems; energy management systems; air-to-water heat pumps; water-to-water heat pumps; special insulating units; solar cell array field; solar cell module; concentrator solar cell assembly; wood-burning tools/fireplace accessories; gasification systems; organic decomposition systems; liquefaction systems; conversion plants; educational aids
Lockheed Missiles & Space Company, Inc. P.O. Box 504 Sunnyvale, CA 94088	Solar cells, ocean thermal gradient systems, electric batteries, domestic hot water/space heating/cooling systems
Martin–Marietta Aerospace 12250 S. Highway 75, Box 179 Denver, CO 80201	Tower focus power plants, concentrator solar cell assembly
McGraw–Edison Company Power Systems Division Post Office Box 28-T Bloomfield, NJ 07003	Solar cell module
Megatech Corporation 29 Cook Street Billerica, MA 01821	Educational aids, solar cell array field
Mobil Tyco Solar Energy Corporation 16 Hickory Drive Waltham, MA 02154	Concentrator solar cell assembly, solar cell module, solar cells, solar cell array field, silicon solar cells
Monsanto Industrial Chemicals Company 800 North Lindbergh Boulevard St. Louis, MO 63166	Greenhouses, special insulating units, plastic sheets and films, silicon solar cells, coolants

Country	Company/address	Product

**TERRESTRIAL PHOTOVOLTAIC
SYSTEM AND COMPONENT MANUFACTURERS[a]**

	Motorola, Inc. Semiconductor Group 1303 Algonquin Road Schaumburg, IL 60196	Collector support subsystems, power conditioning equipment, solar cell array, solar cell module, silicon solar cells
	National Semiconductors, Ltd. 331 Cornelia Street Plattsburgh, NY 12901	Silicon solar cells
	Semicon, Inc. 10 North Avenue Burlington, MA 01803	Silicon solar cells
	SES, Inc. (Subsidiary of Shell Oil Company) Tralee Industrial Park Newark, DE 19711	Solar cell array field, solar cell protective coating, solar cell panels, solar cell module, cadmium sulfide solar cells
	Silicon Material, Inc. 341 Moffett Boulevard Mountain View, CA 94043	Solar cell module, silicon solar cells
	Silicon Sensors, Inc. Solar Systems Division Highway 18 East Dodgeville, WI 53533	Cadmium sulfide solar cells, selenium solar cells, solar cell array field, silicon solar cells, solar cell module, radiation measurement devices
	Siltec Corporation 3717 Haven Avenue Menlo Park, CA 94025	Solar cells

Solar Energy Products, Inc.
1208 N.W. 8th Avenue
Gainesville, FL 32601

Roll bond heat exchangers; steel tanks; back-up water heaters; pumps; differential controls; flat plate collectors, liquid; support systems; solar cell module; absorption cooling systems; domestic hot water systems, liquid; heat pump systems, water-to-air; domestic hot water/space heating/cooling systems

Solar Power Corporation
5-T North Executive Park Drive
North Billerica, MA 01862

Power conditioning equipment, solar cell panels, solar cell module, silicon solar cells, solar cell array field

Solarex Corporation
1335 Piccard Drive
Rockville, MD 20850

Blowers, educational aids, tracking devices, housing/framing, antireflective glazing coatings, solar cell panels, solar cell module, silicon solar cells, solar cell array field

Solec International, Inc.
12533 Chadron Avenue
Hawthorne, CA 90250

Concentrator solar cell assembly, solar cell module, solar cells, parabolic trough collectors, solar cell array field, active–passive hybrid systems

Solectro Thermo, Inc.
1934 Lakeview Avenue
Dracut, MA 01826

Point-focusing collectors, concentrator solar cell assembly, active–passive hybrid systems, nontracking concentrating collectors

Solenergy Corporation
23 North Avenue
Wakefield, MA 01880

Solar cell protective coating, solar cell panels, solar cell module, power conditioning equipment

Sollos, Inc.
2231 Carmelina Avenue
Los Angeles, CA 90064

Solar cell array field, solar cells, solar cell module

Spectrolab
12500 Gladstone Avenue
Sylmar, CA 91342

Solar simulators, solar cell panels, concentrator solar cell assembly, solar cell array, solar cell module, silicon solar cells, solar cell array field

Spire Corporation
Patriots Park
Bedford, MA 01730

Solar cells, gallium arsenide solar cells, silicon solar cells, solar cell protective coating, solar cell array, solar cell module

Country	Company/address	Product
	TERRESTRIAL PHOTOVOLTAIC	
	SYSTEM AND COMPONENT MANUFACTURERS[a]	
	Sun Tap, Inc. Post Office Box 754 Arlington Heights, IL 60006	Power conditioning equipment, solar cell array field
	Sun Trac Corporation 540 Zenith Drive Glenview, IL 60025	Solar cell array field, solar cell module, concentrator solar cell assembly
	Technidyne Associates 58-06 69th Place Maspeth, NY 11378	Linear-focusing collectors, decentralized power plants, solar cell array field, window unit collectors
	Thermo Electron Corporation, Energy Systems Department T 101 First Avenue Waltham, MA 02154	Irrigation systems, Rankine cycle engines, total energy systems, solar cell array field
	Tideland Signal Corporation 4310 Directors Row Houston, TX 77052	Solar cell array, solar cell protective coating, power conditioning equipment, solar cell array field, solar cell module
	Uce, Inc. 20 North Main East Norwalk, CT 06854	Solar cell array field
	Vactec, Inc. 2423 Northline Ind. Boulevard Maryland Heights, MO 63043	Radiation measurement devices, solar cell module, selenium solar cells, silicon solar cells
	Varian Associates 611 Hansen Way Palo Alto, CA 94303	Concentrator solar cell assembly, gallium arsenide solar cells

	Westinghouse Electric Corporation Advanced Energy Systems Division Post Office Box 10864 Pittsburgh, PA 15236	Tower focus power plants; concrete tanks; large wind turbine generator systems; heat pump systems, air-to-air; cooling systems; space heating systems; solar cell systems components; solar cell array field; total energy systems; heliostats

ELECTRICAL- AND MECHANICAL-OUTPUT WIND MACHINES[b]

Australia	Davey-Dunlite (Division of Pye Industries) 2 Hargreaves Street Huntingdale, Victoria 3166	Electrical-output
Canada	Bristol Aerospace, Ltd. Post Office Box 874 Winnipeg R3C 2S4	Electrical-output
	Crowfield Associates, Ltd. Crapaud RR1 Prince Edward Island C0A 1J0	Electrical- and mechanical-output
	Dominion Aluminum Fabricating, Ltd. 3570 Hawkstone Road Mississauga, Ontario L5C 2V8	Electrical-output
	Winflo Power, Ltd. 90 Esna Drive, Unit 15 Markham, Ontario L3R 2R7	Electrical-output (Wingen machines)
Denmark	Dansk Vindkraft Industri ApS Vendevej 6 Bureso 3350 Slangerup	Electrical- and mechanical-output
	Riisager El-Vindmolle Skaerbaek 7400 Herning	Electrical-output

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Country	Company/address	Product
ELECTRICAL- AND MECHANICAL-OUTPUT WIND MACHINES[b]		
	S-J Wind-Power ApS Suderborej 4 990 Frederikshavn	Electrical-output
	Sparco c/o Enertech, Inc. P.O. Box 420 Norwich, VT 05055 USA	Mechanical-output
Federal Republic of Germany	Dornier-System GmbH Friedrichshafen 7559 Immenstadt	Electrical-output (Darrieus-type systems)
	Lubing Maschinenfabrik Postfach 110 2847 Barnstorf	Electrical- and mechanical-output
	Noah Energie Systeme GmbH Wippenhohnerstrasse 31 5202 Hennef 1	Electrical-output
France	Aerowatt Company 37, rue Chanzy 75011 Paris	Electrical-output
	ENAG S.A. Rue de Pont-l'Abbé 29000 Quimper Finistère	Electrical-output
Great Britain	Industrial Institute, Ltd. Stanley Road Bromley BR2 9JF Kent	Electrical-output

	P.I. Enquiries, Ltd. The Dean Alresford Hants	Electrical- and mechanical-output
Italy	Domenico Sperandio & Ager Via Cimarosa 13-21 58022 Folloncia (GR)	Electrical-output
Japan	Japan Wind Power Generator Co., Ltd. Sudo Building 1-4-2 Nakameguro Meguro-Ku Tokyo	Electrical-output
The Netherlands	Fokker-VFW Post Office Box 7600 Schiphol-cost	Electrical-output
South Africa	P. Andrag and Sons (Pty.), Ltd. Post Office Box 364 Belleville, Cape Province	Mechanical-output (Aermotor)
Sweden	Ingenjorsfirma Ture Ekenburg AB Sleipnevagen 15 136 42 Handen	Electrical-output
	Saab-Scania AB Linköping, Ostergtlnd 581 88	Electrical-output
	Sikob AB Engineering Centre S-19178 Sollentuna	Electrical-output
Switzerland	Elektro GmbH St. Gallerstrasse 27 8400 Winterhur	Electrical-output

Country	Company/address	Product
ELECTRICAL- AND MECHANICAL-OUTPUT WIND MACHINES[b]		
Union of Soviet Socialist Republics	USSR Enercgomashexport 35 Mosfilmovskaya UI Moscow V-330	Electrical-output
	USSR Institute for Farm Electrification I-U Veshniakovski Prc. Dom Moscow J-456	Electrical-output
United States	Aero Lectric 13517 Winter Lane Cresaptown, MD 21502	Electrical-output (Wind Wizard)
	Aermotor Post Office Box 1364 Conway, AZ 72032	Mechanical-output
	Aero Power 2398 Fourth Street Berkeley, CA 94710	Electrical-output
	Aerospace Systems 1620 S. Broadmoor Wichita, KS 67207	
	Alcoa Corporation Alcoa Building Pittsburgh, PA 15219	Electrical-output
	All-American Engineering Co. Post Office Box 1247 Wilmington, DE 19899	
	Altos: The Alternate Current Post Office Box 905 Boulder, CO 80302	Electrical-output

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Country	Company/address	Product

ELECTRICAL- AND MECHANICAL-OUTPUT WIND MACHINES[b]

Country	Company/address	Product
	Grumman Energy Systems 4175 Veterans Memorial Highway Ronkonkoma, NY 11779	Electrical-output
	Heller–Aller Company Post Office Box 29 Napoleon, OH 43545	Mechanical-output (Baker windmills)
	Hinton Research 417 Kensington Salt Lake City, UT 84115	Electrical-output
	Independent Energy Systems, Inc. 6043 Sterrettania Road Fairview, PA 16415	Electrical-output (Skyhawk)
	Jacobs Wind Electric Co., Inc. Route 13, Box 722 Fort Myers, FL 33908	Electrical-output
	Kaman Aerospace Corporation Old Windsor Road Bloomfield, CT 06002	
	Kedco, Inc. 9016 Aviation Boulevard Inglewood, CA 90301	Electrical-output
	McDonnell Douglas Corporation P.O. Box 516 St. Louis, MO 63166	
	Megatech Corporation 29 Cook Street Billerica, MA 01866	Electrical-output

Astral/Wilcon Post Office Box 291 Millbury, MA 01527	Electrical-output
Automatic Power, Inc. Post Office Box 18738 Houston, TX 77023	Wind machine generators, dual blade wind machines, small wind turbine generator systems, towers, wind turbine blades, controllers
Bertoia Studio 644 Main Street Bally, PA 19503	Electrical-output
Bowjon 2829 Burton Avenue Burbank, CA 91504	Mechanical-output
Jay Carter Enterprises Post Office Box 684 Burkburnett, TX 76354	Electrical-output
Dakota Wind & Sun, Ltd. Post Office Box 178 Aberdeen, SD 57401	Electrical-output
Dempster Industries, Inc. Post Office Box 848 Beatrice, NB 68310	Mechanical-output
Dragonfly Wind Electric Post Office Box 155 Elk, CA 95432	Electrical-output
Dynergy Corporation Post Office Box 428 1269 Union Avenue Laconia, NH 03246	Electrical- and mechanical-output
Enertech Corporation Post Office Box 420 Norwich, VT 05055	Electrical-output

Millville Windmills & Solar Equipment Company Post Office Box 32 Millville, CA 96062	Electrical-output
North Wind Power Company, Inc. Post Office Box 315 Warren, VT 05674	Electrical-output
Pinson Energy Corporation Post Office Box 7 Marston Mills, MA 02648	Electrical-output
Power Group International Corp. Suite 106 13315 Stuebener-Airline Road Houston, TX 77014	Electrical-output (Hummingbird)
Product Development Institute 508 South Byrne Road Toledo, OH 43609	Electrical-output (Wind Jennie)
Sencenbaugh Wind Electric Post Office Box 11174 Palo Alto, CA 94306	Electrical-output
Tumac Industries 650 Fort Street Colorado Springs, CO 80915	Electrical-output
TWR Enterprises Sun-Wind-Home Concepts 72 West Meadow Lane Sandy, UT 84070	Electrical-output (Wind Titan)
United Technologies Research Center Silver Lane East Hartford, CT 06118	

Country	Company/address	Product
ELECTRICAL- AND MECHANICAL-OUTPUT WIND MACHINES[b]		
	Wadler Manufacturing Co., Inc. Route 2, Box 76 Galena, KS 66739	Mechanical-output
	Whirlwind Power Company Box 18530 Denver, CO 80211	Electrical-output
	Windco Dyna Technology, Inc. Post Office Box 3263 Sioux City, IA 51102	Electrical-output (Wincharger)
	Wind Engineering Corporation Box 5926 Lubbock, TX 79417	
	Wind Power Systems, Inc. Post Office Box 17323 San Diego, CA 92117	Electrical-output (Storm Master)
	Windworks Post Office Box 329, Route 3 Mukwonago, WI 53149	Electrical-output
	WTG Energy Systems, Inc. Post Office Box 87, 1 La Salle Street Angola, NY 14006	Electrical-output
	Zephyr Wind Dynamo Company Post Office Box 241 Brunswick, ME 09011	Electrical-output

SMALL-SCALE HYDROELECTRIC SYSTEMS AND COMPONENTS

Austria	Maschinenfabrik Kössler GmbH A-3151 St. Pölten	Two types of small-scale hydroelectric systems, with outputs varying from 12 to 1,250 kVA
Canada	Niagara Waterwheels, Ltd. 706 East Main Street Welland, Ontario L3B 3Y4	Six models of horizontal-axis, axial flow propeller turbine packages, with outputs in the 20–300-kW range
Federal Republic of Germany	Drees & Co. GmbH 4760 Werl/Schützenstrasse 36	Small micro-hydro plants to full-size hydroelectric stations
France	Briau S.A. BP 43 37009 Tours Cedex	Packaged low-head turbine–generator systems with outputs from 4 to 50 kVA
Great Britain	Evans Engineering Land & Leisure (Services), Ltd. Priory Lane, St. Thomas Launceston PL15 8DQ, Cornwall	Simple bare-shaft turbines, packaged reaction and impulse turbines, electronic control units, instrument and control panels, simple and duplex hydraulic rams
	Gilbert Gilkes & Gordon, Ltd. Canal Iron Works Kendal Cumbria LA9 7BZ	Wide range of turbines–"Hydec," spiral-cased Francis, open-type Francis, Pelton wheels, and water motors
	Westward Mouldings, Ltd. Greenhill Works Delaware Road Gunnislake, Cornwall	Made-to-order fiberglass water wheels
India	Jyoti Limited Industrial Area P.O. Chemical Industries Baroda, Gujarat 390 003	Range of turbines with outputs from 25 to 100 kW

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Country	Company/address	Product
SMALL-SCALE HYDROELECTRIC SYSTEMS AND COMPONENTS		
Sweden	Karlstads Mekaniska Werkstad Fack. S-681 01 Kristinehamn	Turbines from micro to large multi-megawatt units
Switzerland	Elektro GmbH St. Gallerstrasse 27 8400 Winterthur	Various models of Pelton and Francis turbines
United States	Allis-Chalmers Hydro-Turbine Division Post Office Box 712 York, PA 17405	Range of standardized hydroelectric generating units, starting at an output of 50 kW
	Independent Power Developers, Inc. Route 3, Box 174H Sand Point, ID 83864	Range of small turbines
	James Leffel & Company Springfield, OH 45501	Water turbine units ranging in output from 5,000 hp down
	Northern Waterpower, Inc. Post Office Box 49 Harrisville, NH 03450	Six models of horizontal-axis, axial flow propeller turbine packages, with outputs in the 20-300 kW range
	Small Hydroelectric Systems Post Office Box 124 Custer, WA 98240	Small impulse (Pelton) hydroelectric systems producing 5-25 kW
METHANE DIGESTER UNITS AND DESIGNS		
Australia	Sanamatic Tanks Pty., Ltd. Post Office Box 119 Bendigo 3550	Range of biogas plants for utilizing 500 lb to 120 t of effluent per day

Great Britain	Farm Gas, Ltd. Heath Workshop Lydham Bishops Castle Salop SY9 5HB	Two chief types of methane digesters—2,500-gal (11.25-m^3) capacity for farms and a 400-gal (1.8-m^3) capacity for domestic wastes, etc.
India	Khadi & Village Industries Commission Gramodaya 3 Irla Road Vile Parle (West) Bombay 400 056	Biogas plant designs for construction by approved makers
Kenya	Tunnel Co., Ltd. Tunnel Estate P.O. Fort Ternan	Hutchinson methane plants and others
United States	Aidco Maine Corporation Orr's Island, ME 04066	Biomass conversion systems, ethanol plant equipment
	Bio Gas of Colorado, Inc. 5620 Kendall Court, Unit G Arvada, CO 80002	Biogas plant designs, consultancy services

GEOTHERMAL EQUIPMENT

Israel	Ormat Turbines, Ltd. Post Office Box 68 Yavne	Low-maintenance, closed-cycle, vapor turbogenerators proven in fossil fuel and solar applications
Japan	Mitsubishi Heavy Industries, Ltd. 5-1, Marunouchi 2-chome Chiyoda-Ku, Tokyo 100 Also: Suite 3000, Union Bank Building 50 California Street San Francisco, CA 94111	Portable geothermal turbine generators with capacities of 500–5,000 kW (back pressure type) and 5,000–10,000 kW (condensing type)

Country	Company/address	Product
GEOTHERMAL EQUIPMENT		
United States	Barber–Nichols Engineering Co. Arvada, CO 80002	Now testing a 500-kW power plant that uses a direct contact heat exchanger
	Biphase Energy Systems (Subsidiary of Research-Cottrell, Inc.) 2800 Airport Avenue Santa Monica, CA 90405	Two-phase turbine–separator system that uses steam and hot liquid is now available for certain applications
	Geothermal Power Co., Inc. 1460 West Water Street Elmira, NY 14905	Geothermal Power Mono-Blok, a self-contained power-generating system of from 100-kW to 2,500-kW capacity
	Hydrothermal Power Co. Post Office Box 2794 Mission Viejo, CA 92790	Packaged geothermal power plants up to 5,000 kW using the helical screw expander
	Rotoflow Corporation 2235 Carmelina Avenue Los Angeles, CA 90064	Total flow geothermal turbogenerators
	Sperry Rand Research Center 100 North Road Sudbury, MA 01776	Now testing a 4,300-kW gravity-head power plant that uses a down-hole heat exchanger system
	Turbines Incorporated 950 East Katella Avenue, Suite 9 Orange, CA 92667	Total flow geothermal turbogenerators up to 10,000-kW capacity
STORAGE BATTERIES AND INVERTERS		
Federal Republic of Germany	Accumulatorenfabrik Sonnenschein GmbH Thiergarten 6470 Buedingen/Hessen	Maintenance-free, portable lead–acid batteries, power supply units, battery chargers

Great Britain	Chloride Alcad Post Office Box 4 Union Street Redditch Worcs. B98 7BW	Nickel–cadmium batteries
	Varley Dry Accumulators, Ltd. Alfred's Way Barking Essex 1G11 OTB	Lead-acid batteries that have the electrolyte absorbed in a porous separating medium
United States	Allied Electronics 2400 W. Washington Boulevard Chicago, IL 60612	Inverters: 350–1,000 W; 12-volt input
	ATR Electronics, Inc. 300 East 4th Street St. Paul, MN 55101	Inverters: 275–1,100 W; 12-volt input
	Best Energy Systems for Tomorrow, Route 1 Post Office Box 280 Necedah, WI 54646	Inverters: 1,000–5,000 W; 12–48-volt input
	Carter Motor Company 2711 West George Street Chicago, IL 60618	Inverters: 210–740 W; variable voltage input
	C&D Batteries Division 3404 Walton Road Plymouth Meeting, PA 19462	Almost every type of lead-acid battery
	Delatron Systems Corporation 553 Lively Boulevard Elk Grove Village, IL 60007	Lead-acid deep discharge batteries
	Dynamote Corporation 1130 N.W. 85th Street Seattle, WA 98117	Inverters: automatic DC to 120-volt AC; 60 Hz static inverters

Country	Company/address	Product

STORAGE BATTERIES AND INVERTERS

	Company/address	Product
	Eico Electronic Instrument Co. 283 Malta Street Brooklyn, NY 11207	Inverters: 110–220 W; 12-volt input
	Electro Sales Co., Inc. 100 Fellsway West Somerville, MA 02145	Inverters: 20–2,000 W; 12–200-volt input
	Elgar Corporation 8225 Mercury Court San Diego, CA 92111	Inverters: 600–1,000 W; 24–48-volt DC input
	ESB Inc. Five Penn Center Plaza Philadelphia, PA 19103	
	Gemini Synchronous Inverters Windworks Box 329, Route 3 Mukwonago, WI 53149	Inverters: 4–1,000 kW; variable voltage input
	Globe Battery Globe–Union Inc. 5757 N. Green Bay Avenue Milwaukee, WI 53201	Storage batteries
	Gould Inc. Industrial Battery Division 2050 Cabot Boulevard West Langhorne, PA 19047	
	Heath Company Benton Harbor, MI 49022	Inverters: 175 W; 12-volt input
	Independent Power Developers, Inc. Route 3, Box 174H Sand Point, ID 83864	Inverters in 7 models—1–12 kW—for use with wind-electric and micro-hydro systems

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INEN Corporation 1016 East Airport Road Stillwater, OK 74078	Custom-manufactured inverters up to 500 kW
La Marche Manufacturing Co. 106 Bradrock Drive Des Plaines, IL 60018	Inverters: 100-10,000 W; 24-120-volt input
Newark Electronics 500 N. Pulaski Road Chicago, IL 60624	Inverters: 100-250 W; 12-volt input
North Wind Power Company, Inc. Post Office Box 315 Warren, VT 05674	Synchronous inverters
Ratelco, Inc. 610 Pontius Avenue, N. Seattle, WA 98109	Inverters: 250-2,500 W; 24-100-volt input
Real Gas & Electric, Inc. Box A Guerneville, CA 95446	Inverters: 5-kVA maximum AC output; 75-200-volt DC input
Soleq Corporation 5969 Elston Avenue Chicago, IL 60646	Inverters: 1,500-6,000 W; 12-112-volt input
Westinghouse Electric Corporation Gateway Center Westinghouse Boulevard Pittsburgh, PA 15222	Storage batteries

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[a]This list was prepared by the Solar Energy Information Center, Solar Energy Research Institute, 1617 Cole Boulevard, Golden, CO 80401, USA.

[b]This list was compiled by the Energy Systems Group, Rocky Flats Plant, Rockwell International, Post Office Box 464, Golden, CO 80401, USA.

APPENDIX B
Centers of Research and Development

This appendix represents the best information available to the NAS staff at the time of publication, but is not necessarily complete. It was not possible to verify many of the following addresses.

Country	Company/location	Activity

PHOTOVOLTAICS

Country	Company/location	Activity
France	Centre de Recherches Nucléaires de Strasbourg BP 20 CR Cronenbourg 67037 Strasbourg Cedex	
	Centre National de la Recherche Scientifique 15 Quai Anatole France 75700 Paris	
	Commissariat à l'Energie Solaire (COMES) Ministère de l'Industrie 208, rue Raymond Losserand 75014 Paris	
	Laboratoires d'Electronique et de Physique Appliquée BP 15 3, Avenue Descartes 94450 Limeil-Brezannes	
United States	Institute of Energy Conversion University of Delaware One Pike Creek Center Wilmington, DE 19808	
	Jet Propulsion Laboratory California Institute of Technology Pasadena, CA 91106	
	NASA–Lewis Research Center Technology Utilization Office 21000 Brookpark Road Cleveland, OH 44135	
	Solar Energy Research Institute 1617 Cole Boulevard Golden, CO 80401	

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Country	Company/location	Activity
WIND ENERGY		
Canada	Brace Research Institute McDonald College of McGill University Ste. Anne de Bellevue Quebec HOA ICO	
	Institute of Research of Hydro-Quebec 1800 Montec Ste. Julie Varrenes, Quebec JOL 2 PO	
	National Research Council of Canada Research Office Building M-2, Montreal Road Ottawa, Ontario KLA ORS	
Denmark	Aalborg Universitets Center Institute of Industrial Structures & Engineering Langagervej, Post Office Box 159 9100 Aalborg	
	Danish Wind Power Projects Government of Denmark Copenhagen	
	DEFU 100 Lundtoftevej 2800 Lyngby	
Federal Republic of Germany	Center for Wind Energy Research Forschungsprojekt Windenergie University of Regensburg 8440 Regensburg	
Great Britain	Energy Technology Support Unit AERE, Harwell Oxford OX11 ORA	

The Netherlands	Netherlands Energy Research Foundation Westerduinweg 3 Petten N.H.
New Zealand	Department of Mechanical Engineering University of Canterbury Private Bag Christchurch
Sweden	National Swedish Board for 　　Energy Source Development 77 Karlsbergsvagen Box 21048 S-100 31 Stockholm
	Namnden For Energiproduktionforskning Box 1103 S16312 Spanga
United States	Agricultural Research Service Rural and Remote Wind Energy Applications U.S. Department of Agriculture Beltsville, MD 20705
	Battelle-Pacific Northwest Laboratories Wind Characteristics Program Post Office Box 999 Richland, WA 99352
	NASA-Lewis Research Center Large Wind Turbine Program 21000 Brookpark Road Cleveland, OH 44135

Country	Company/location	Activity

WIND ENERGY

Rockwell International
Energy Systems Group
Small Wind Systems Program
Post Office Box 464
Golden, CO 80401

Sandia Laboratories
Darrieus Wind Systems Program
Division 4715
Albuquerque, NM 87185

Solar Energy Research Institute
Wind Systems Research and Analysis
1617 Cole Boulevard
Golden, CO 80401

United Technologies Research Center
Silver Lane
East Hartford, CT 06108

West Wind Co.
Box 1465
Farmington, NM 87401

GEOTHERMAL

Country	Company/location	Activity
United States	EG&G Idaho, Inc. Idaho National Engineering Laboratory P.O. Box 1625 Idaho Falls, ID 83401	Major clearinghouse for information on direct heat applications of geothermal energy and a major research and development contractor to the U.S. Department of Energy
	Geo-Heat Utilization Center Oregon Institute of Technology Klamath Falls, OR 97601	Major center for information on direct heat applications of geothermal energy

U.S. Department of Energy
Division of Geothermal Energy
Washington, D.C. 20545

Primary information and funding source for technological developments in geothermal energy production and utilization

Lawrence Livermore Laboratories
University of California
P.O. Box 808
Livermore, CA 94550

STORAGE BATTERIES

United States	Dow Chemical Co. 2030 Dow Center Midland, MI 48640	Sodium/sulphur high-temperature batteries
	Eagle-Picher Industries, Inc. 580 Walnut Street Cincinnati, OH 45201	Lithium/metal sulfide high-temperature batteries
	Eltra Corporation 2 Pennsylvania Plaza New York, NY 10001	Advanced lead-acid batteries
	Energy Development Associates 1100 W. Whitcomb Avenue Madison Heights, MI 48071	Zinc/chlorine flow systems
	ESB Corporation Five Penn Center Plaza Philadelphia, PA 19103	Advanced lead-acid batteries
	Exxon Research and Engineering Company P.O. Box 101 Florham, NJ 07932	Zinc/bromine flow systems
	Ford Motor Company American Road Dearborn, MI 48121	Sodium/sulfur high-temperature batteries

Country	Company/location	Activity
STORAGE BATTERIES		
	General Electric Company 1 River Road Schenectady, NY 12345	Sodium/sulfur high-temperature batteries
	General Motors Corporation 767 Fifth Avenue New York, NY 10022	Lithium/metal sulfide high-temperature batteries
	Gould Inc. 8550 Bryn Mawr Avenue Chicago, IL 60631	Lithium/metal sulfide high-temperature batteries
	NASA–Lewis Research Center 21000 Brookpark Road Cleveland, OH 44135	Reduction/oxidation flow systems
	Rockwell International Corporation 600 Grant Street Pittsburgh, PA 15219	Lithium/metal sulfide high-temperature batteries
STIRLING ENGINES		
Canada	University of Calgary Department of Mechanical Engineering Calgary, Alberta T2N 1N4	Student projects on all aspects of Stirling engine design and experimental work
Federal Republic of Germany	Maschinenfabrik-Augsburg-Nurnburg Stadtbachstrasse 1 8900 Augsburg 1	Large automotive and stationary power plants
Great Britain	Harwell Laboratory Instrumentation and Applied Physics Division AERE, Harwell Oxford OX11 ORA	Electric generators, diaphragm type; liquid-piston

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	University of Reading Department of Engineering and Cybernetics Whiteknights Reading, Berks RG6 ZAY	Analysis and experimental work on fluidized bed-heated Stirling engines, liquid-piston
India	Metal Box India Limited B2 Hide Road 700 043 Calcutta	Liquid-piston engines
The Netherlands	Philips Nederland BV Stirling Engine Division Boschdiji 525 Eindhoven	Free-piston, linear-alternator cooling engines; hot air, crank-type engines
South Africa	University of Witwatersrand Department of Mechanical Engineering 1 Jan Smuts Avenue Johannesburg 2001	Analytical studies of a wide variety of Stirling engines; experimental work on liquid-piston, free-piston, and others
Sweden	United Stirling (Sweden) AB and Co. Fack 201 10 Malmo 1	Automotive Stirlings, solar-electric
United States	Energy Research and Generation Inc. Lowell and 57th Streets Oakland, CA 94608	Solar-electric, cooling, cryogenic coolers, automotive Stirlings
	Mechanical Technology, Inc. 968 Albany–Shaker Road Latham, NY 12110	Advanced designs for aerospace, military and U.S. domestic service, automotive Stirlings, solar-electric generators

Country	Company/location	Activity
STIRLING ENGINES		
	Stirling Power Systems Corp. 7101 Jackson Road Ann Arbor, MI 48103	10-kW electric generator-crank engine
	Sunpower, Inc. 6 Byard Street Athens, OH 45701	Analysis, design, and construction of free-piston engines; alternators; heat-driven coolers; water pumps; hot-air crank engines; solar-powered Stirling engines of all types

APPENDIX C
Suggested Reading

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