

## Chapter 6

# Energy Conversion Technologies



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## Energy Conversion Technologies

### INTRODUCTION AND SUMMARY

#### *Introduction to the Energy Supply Sector*

*The* previous chapters analyzed the services that energy provides to consumers in the major end-use sectors. The analysis identified many cost-effective and often capital-saving technical opportunities for improving the efficiency of energy use in all sectors. Despite these benefits, institutional problems, a variety of market failures, and many other factors frequently discourage the adoption of these energy efficient technologies even when they are mature and well known.

Even under the most optimistic assumptions about improvements in energy efficiency, however, energy supplies will need to increase. Rapid population growth, economic growth, and structural change are creating a demand for energy services (see ch. 2) that cannot be met by efficiency gains alone. According to the U.S. Agency for International Development, for example, approximately 1,500 gigawatts (GW) of new electricity generating capacity could be needed in the developing world by 2008. Under an aggressive program of efficiency improvements in both the supply and demand sectors, this growth in demand could be reduced to about 700 GW, which would still require more than a doubling of present day capacity.<sup>1</sup>

Chapters 6 and 7 therefore turn to the ways in which energy is supplied in developing countries—the processes and technologies by which energy is produced, converted from one form into another, and delivered to users. Parallel to the analysis of end-use sectors in chapters 3 to 5, a range of energy supply technologies are examined, particularly in relation to their suitability for the special circumstances and opportunities of developing countries, the problems that could impede their adoption, and the policy issues involved. Many of these technologies have

also been discussed in other recent OTA reports,<sup>2</sup> so the discussion here will be primarily limited to issues of particular relevance to developing countries.

Chapter 6—the conversion sector—covers that part of the energy sector devoted to turning primary or raw energy, such as coal, crude oil, gas, biomass, and other resources, into high quality forms for end users. Currently, the major conversion processes include electricity generation, oil refining, and, for biomass fuels, the production of charcoal from wood and ethanol from sugar cane (largely confined in the developing world to Brazil). In the future, the biomass conversion sector could expand to include a wider range of liquid fuels, gases, and electricity.<sup>3</sup>

Chapter 7—primary energy supplies—completes the exploration of the energy system back upstream to its sources: the exploration and mining of fossil fuels and the growth and collection of biomass. The energy resources available to a country invariably determine the composition of its fuel supply.

Table 6-1 and figure 6-1 illustrate the current structure of primary energy supplies in developing countries. According to these data, biomass is the most important fuel, closely followed by oil and coal. There is considerable variation between countries. For example, coal accounts for 70 percent of energy use in China and almost 40 percent in India but is little used elsewhere. For the rest of the developing countries, oil is the major source of commercial primary energy. Natural gas accounts for a relatively small share in all countries. Primary electricity (e.g., hydroelectricity) is an important component of the energy supply mix. A large quantity of electricity is also generated from fossil fuels. Developing countries meet a much higher share of their needs with biomass and much less with natural gas than the industrial nations. The share of biomass in the total energy supply mix of developing

<sup>1</sup>U.S. Agency for International Development, Office of Energy, *Power Shortages in Developing Countries: Magnitude, Impacts, Solutions, and the Role of the Private Sector* (Washington DC: U.S. Agency for International Development, March 1988). Forecasts quoted here are for the medium economic growth rate scenario.

<sup>2</sup>See, for example: U.S. Congress, Office of Technology Assessment, *Energy Technology Choices: Shaping Our Future, OTA-E-493* (Washington, DC: U.S. Government Printing Office, July 1991),

<sup>3</sup>See also, U.S. Congress, Office of Technology Assessment, *Renewable Energy Technology: Research, Development, and Commercial prospects* (forthcoming).

Table 6-1—1985 Primary Energy Supplies (exajoules)

	Coal	Oil	Gas	Primary electricity	Total commercial	Biomass	Total energy
World . . . . .	88.7	104.6	58.2	33.0	284.5	36.9	321.3
Industrial countries . . . . .	63.5	77.0	51.7	26.6	218.7	5.5	224.2
Developing countries . . . . .	25.2	27.7	6.5	6.4	65.7	31.3	97.1
Share of industrial countries . . . . .	72%	74%	89%	81%	77%	15%	70%
Share of developing countries . . . . .	28%	26%	11%	19%	23%	85%	30%

NOTE: As in table 2-1, the values reported for developing country biomass are too low. Field surveys indicate that biomass accounts for roughly one-third of the energy used in developing countries.

SOURCE: World Energy Conference, *Global Energy Perspectives 2000-2020*, 14th Congress, Montreal 1989 (Paris: 1989).

countries generally declines as the standards of living and the extent of urbanization rises.

The developing world as a whole produces more energy than it consumes, and significant amounts of both oil and gas are exported. Again, there are large disparities among countries. Only a few developing countries, primarily the OPEC nations, export energy; most are heavily import dependent.

Reliable and affordable supplies of energy are critical for economic and social development. Conversely, inadequate or unreliable energy supplies frustrate the development process. Electricity supplies in many developing countries are characterized by disruptions, including blackouts, brownouts, and sharp power surges. Lost industrial output caused by shortages of electricity have had noticeable detrimental effects on Gross Domestic Product (GDP) in India and Pakistan. Supplies of household fuels are notoriously intermittent, leading households to install a wide range of cooking systems in order to ensure against the shortage of any one fuel. Transportation services are similarly subject to disruption because of unreliable fuel supplies. Unreliable supplies of high quality fuels and electricity also impede the diffusion of improved technologies that are sensitive to fuel or power quality.

On the other hand, energy supply systems are expensive to build and maintain. Capital intensive electricity generating stations and petroleum refineries already account for a large part of all public investment budgets in developing countries, with electric utilities taking as much as 40 percent of public investment in some.<sup>4</sup> Overall, annual power sector investments would have to double to meet

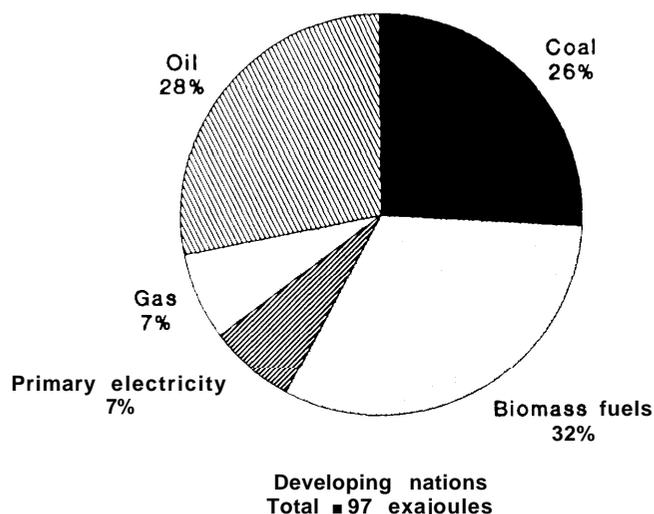
rapidly growing demands. This would take up virtually the entire projected annual increase in the combined Gross National Product (GNP) of the developing countries, leaving little for other pressing development needs. Further, a large part of the investment in capital equipment for energy facilities and in fuel to operate them must be paid for in scarce foreign exchange, which is already under pressure in many countries to service foreign debt. Similarly, there is often a shortage of local currency to pay for energy development due to inadequate revenues from existing operations. The energy supply sector also relies heavily on other scarce resources, such as skilled labor and management, and can cause environmental damage.

### *Energy Conversion Technologies*

The conversion sector covers the processing of primary-or raw-energy such as coal and crude oil into forms (e.g., electricity, gasoline, and diesel) required by end users. Historically, most fuels passed from the production phase to final consumers with minimum processing or conversion; this remains the case today in many developing countries. As development takes place, however, an increasing amount of processing takes place in order to make these fuels cleaner and more effective, notably in the share of fossil fuels converted into electricity. If biomass based fuels are to provide an increasing share of developing country energy supplies, they too will have to undergo further processing into convenient forms, such as liquids, gases, and electricity with properties that can enable them to compete with energy products based on fossil fuels.

<sup>4</sup>U.S. Congress, Office of Technology Assessment *Energy in Developing Countries*, OTA-E-486 (Washington DC: U.S. Government Printing Office, March 1991), p. 93.

**Figure 6-I—1 1985 Energy Consumption in Developing Countries**



SOURCE: World Energy Conference, *Global Energy Perspectives 2000-2020*, 14th Congress, Montreal 1989 (Paris: 1989).

The following survey of the three major conversion sectors--electricity; oil refining; and liquids, gases, and electricity from biomass—indicates that there are many technologies presently available or under development to meet the rapidly growing needs of this sector. There are problems, however, in financing the expansion of these sectors on the scale projected, and in improving the poor technical performance that dogs the electricity and refining sectors in many developing countries. These problems also could impede the timely adoption of energy efficient equipment.

#### Electricity

Electric utilities in developing countries face a rapidly growing demand for electricity, stimulated in many cases by low, subsidized prices. With large segments of the population typically still without electricity, the political and social pressures for system expansion are strong. Many utilities, however, have difficulty meeting even present day demand. Electricity systems in many developing countries are poorly maintained, resulting in unreliable service and frequent system breakdowns. The operating efficiency of electricity generating equipment in developing countries—with some notable exceptions—is often substantially below that of industrialized countries with similar technology, and the financial performance of many developing

country utilities is deteriorating. Management attention must often focus on short term remedial measures, to the detriment of sound long term planning. Industry is frequently forced into self generation on a large scale, often with diesel generators dependent on high-cost imported oil.

Although the electricity systems of the developing world are as diverse as the countries themselves, several common issues underlie their frequently poor technical and financial performance:

- overstaffing, but shortages of trained manpower;
- lack of standardization of equipment;
- limited system integration and planning;
- political and social obligations to provide parts of the population with electricity at less than cost;
- shortages of foreign exchange to buy spare parts; and
- a regulatory framework that discourages competition,

Poor current performance raises doubts about the ability of the system to meet the projected rapid rise in demand even if the financial resources were available for capacity expansion. The effective deployment of technology will therefore depend on addressing these related financial, policy, and institutional issues.

Given low operational efficiencies, technologies relating to plant rehabilitation, life extension, system interconnections, and improvements in transmission and distribution (T&D) systems often offer higher returns to capital investment than new generating technologies. Plans for system expansion, reflecting indigenous energy resources, center on coal and hydro, followed by gas, nuclear, oil, and geothermal. Developing countries could benefit from several technologies in this expansion.

Fluidized bed combustion (FBC) with its greater tolerance for low quality coal could improve plant availability--offsetting its higher initial capital cost—as well as reduce SO<sub>x</sub> and NO<sub>x</sub> emissions. Combined cycle coal plants, specifically integrated gasification combined cycle (IGCC) plants, have much higher efficiencies than conventional coal plants, but uncertainties remain over IGCC's performance with lower quality coals. Gas turbines operated in a steam injection mode also promise to be attractive for electricity generation in the devel-

oping world. Gas turbines are small and modular with short construction lead times and high operating efficiencies.<sup>5</sup> These characteristics make gas turbines particularly attractive to private power producers with limited capital. Natural gas or gasified biomass also have environmental benefits relative to coal and oil.

Although hydropower is a viable option for many developing countries, concerns about environmental and social impacts are coming to the fore. Growing knowledge of the environmental impacts of large scale hydro projects can, however, contribute to better project design with lesser environmental impacts and a longer productive life for the plant.

Much of the planned expansion in nuclear power (in countries with large systems such as South Korea, China, and Taiwan) is based on existing nuclear technology. Smaller, modular, and safer nuclear power technologies under development in the industrialized countries might extend the market for nuclear power in developing countries depending on their ultimate cost and performance characteristics. The technical skill requirements of nuclear power may continue to limit its use in the developing world, as may the larger problems of nuclear proliferation and waste disposal.

Rural electrification is an important component of economic and social development in the developing world. While costs are variable, site specific, and poorly documented, the costs of stand alone renewables--notably microhydro, wind turbines, and photovoltaics--are competitive in many cases with diesel generators and grid extension, and in addition have significant environmental benefits compared to conventional systems.

Thus, there are many opportunities for technical improvement--in improving the existing system, in system expansion, and in rural electrification--but there are serious financial and institutional impediments. There are several ways in which the United States might help. The United States could work with the multilateral development agencies, which are major providers of finance to the electricity sector, to:

- . improve the operational and financial efficiency of the sector;

- encourage the use of integrated resource management approaches, giving equal weight to conservation and renewable as alternatives to conventional supply expansion; and
- . stimulate, through institutional and other reform, greater participation by the private sector.

Lack of training and familiarity with modern concepts of utility management could be addressed in part through training programs and "twinning" arrangements with U.S. and other utilities.

### Oil Refining

Although there is a wide variation among countries, refinery operations in many developing nations are substantially below international norms in terms of efficiency and cost. Average refinery operating costs in Africa, for example, are \$2 per barrel compared with \$0.75 in the rest of the world.

A variety of technologies are available today that can improve refinery performance. Examples of cost-effective retrofits include heat recovery from stack gas and recuperation of flared relief valve and other gas. By the end of the decade, new catalysts are expected to improve product yields. These technology improvements would increase operational efficiencies and somewhat reduce the adverse environmental impacts of oil refining.

Problems hindering investment in the rationalization of refinery operation in the developing world include: lack of foreign exchange for parts; distorted pricing structures and earmarked government subsidies that hide the inefficiency of the plant; global overcapacity; and, in some countries, local markets that are too small to support efficient equipment.

An alternative to refineries for those countries with natural gas is methanol conversion. New technologies permit the direct conversion of methane to methanol near the well head cheaply enough to be used for such energy services as transport.

### Biomass Fuels

Increases in energy consumption in developing countries are spurring efforts to use domestic resources, including biomass. If biomass fuels are to gain consumer acceptability, however, they must be converted into clean and convenient fuels. Biogas is, after a rocky start, becoming an established technol-

<sup>5</sup>Note that the operating efficiencies of conventional combustion turbines are lower than many other options; in contrast, the steam-injection mode, particularly with intercooling, provides higher efficiencies.

ogy, although there are significant doubts about its financial viability in small scale (household) applications. Small scale producer gas made from biomass is relatively low in capital cost and can produce a moderate quality gaseous fuel at competitive prices under a range of conditions. These gases can be used directly for process heat or to generate electricity. Electricity from internal combustion engine systems fueled with biogas or larger sized producer gas systems may now be marginally competitive with central station power at remote sites—if the avoided costs of transmission and distribution are taken into account. Larger scale biomass based gas turbine electricity generation is nearing commercial readiness and is expected to be competitive with many central station power plants if adequate biomass feedstocks are available at reasonable prices.

While liquid fuels from biomass are not competitive at the oil prices of today, current or near commercial technologies could be competitive at oil prices of perhaps \$30 a barrel—a price that is widely projected to be attained by the end of the century. Technologies now under development, particularly ethanol by enzymatic hydrolysis, may provide liquid fuels at competitive prices in the future.

Biomass technologies offer the prospect of using domestic resources at competitive costs. There are other benefits as well. Together with other renewable energy technologies such as wind energy, photovoltaics, and microhydro, these small scale systems can bring high quality energy to rural areas—creating jobs and providing important environmental benefits.

On the other hand, there are a variety of obstacles to the introduction of renewable. In some cases, further RD&D are needed; subsidies to other forms of energy may discourage their development; credit may not be as readily available for renewable as for other more traditional energy supply systems; and there may be a lack of information on these alternatives, their costs, and their benefits at the local level. For biomass, in particular, land costs may become too high—due to competition between producing fuels and electricity for the wealthy versus producing food for the poor; environmental impacts on land and water could be excessive if biomass is *grown* too intensively or poorly man-

aged; and infrastructure needs (notably roads) for large scale bioenergy plants could be high. The United States could help in overcoming these obstacles in a number of ways—through supporting RD&D, encouraging financial institutions to lend to such projects, and encouraging the transfer of these and related technologies through the private sector or by other means.

## **THE POWER SECTOR IN THE DEVELOPING WORLD: IMPROVEMENTS TO EXISTING SYSTEMS**

Electric utilities in most developing countries face a rapidly growing demand for electricity; many, however, have difficulty even meeting present demands due to poor technical, operational, and institutional performance. Improvements in existing electricity systems should therefore be considered before or in conjunction with system expansion. Options for system improvement discussed here include:

- . Rehabilitation of existing generating plants,
- Transmission and distribution systems,
- System interconnections,
- . System planning, and
- . Management.

### *Generating System Rehabilitation*

*The* operating efficiency of the electricity generating equipment in developing countries—with some notable exceptions—is often substantially below that achieved in the industrialized countries, despite the fact that the basic technology is the same. An excellent example is the use of low speed diesels for power generation. This technology is widely reputed to be highly reliable, yet in developing countries many such units are out of service for much of the time.

Thermal efficiency is an accepted indicator of the ability of a utility to maintain its thermal power stations in good working order. As can be seen from table 6-2, thermal efficiencies in some Asian countries are comparable to those achieved in the United States. Performance in India and Pakistan, however, is quite poor.

Table 6-2—Thermal Efficiency of Selected Electric Power Plants

Country	Fuel type	Thermal efficiency
Korea . . . . .	oil	35.4
	coal	30.6
Indonesia . . . . .	oil	35.3
Hong Kong . . . . .	oil	34.5
Malaysia . . . . .	oil	30.0
Pakistan . . . . .	gas	26.0
	oil	28.8
India . . . . .	coal	25.9
Thailand . . . . .	brown coal	23.8
	oil	33.8
<b>Typical American Plants</b>		
(with initial year of operation)		
Canal, Massachusetts (1,072MW, 1968) . . . . .	oil	36.4
Ghent, Kentucky (2,226MW, 1973) . . . . .	coal	33.5
Pleasants, W. Virginia (1,368MW, 1979) . . . . .	coal	33.0
Chesterfield, Virginia (1,353MW, 1952) . . . . .	coal	34.8
Tradinghouse, Texas (1,380MW, 1970) . . . . .	gas	33.0
Northport, New York (1,548MW, 1963) . . . . .	oil	33.8

SOURCE: International Development and Energy Associates (IDEA), Inc. "Improving Power Sector Efficiency in Developing Countries," November 1990, OTA contractor report, p. 22; based on *Technology Policy in the Energy Sector: Issues, Scope and Options for Developing Countries*, United Nations Conference on Trade and Development, UNCTAD/TT/90, 1990. American Data from *Electric Plant Cost and Power Production Expenses, 1988*, Energy Information Administration, Department of Energy, DOE/EIA 0455/8.8, Washington, DC, 1989.

A second important measure of maintenance efficiency is the forced outage rate (FOR).<sup>7</sup> Over the past 10 years, there has been considerable progress in reducing forced outage rates in those developing countries that have had unusually high rates in the past. In India, for example, the average FOR for coal fired units in the 1983 to 1984 time period was 24 percent; in 1988, the average had improved to 16 percent.<sup>8</sup>

Over the past decade, the cost effectiveness of generation system rehabilitation has become recognized in the United States and Europe, where a great deal of attention has been placed on what has become known as "life extension" or "life optimization." The average cost of utility refurbishment projects in the United States has been reported to be considerably below the cost of new generating

units.<sup>9</sup> Improved procedures for predictive and preventative maintenance have also contributed to the extended life of many industrialized-country power plants.

A number of major generation rehabilitation projects are now underway in developing countries. For example, a rehabilitation project in Pakistan, funded in part by the World Bank,<sup>10</sup> will refurbish 15 steam and combustion turbine units at Sukkur, Guddu, Faisalabad, Quetta, and Multan.<sup>11</sup> This project will provide additional capacity of 120 megawatts (MW) by restoring original ratings, in addition to improved heat rates and forced outage rates (see table 6-3). The cost for this rehabilitation is about \$110 million. The potential for rehabilitating generation plants in the smaller systems of Africa is illustrated in box 6-A for Kenya.

<sup>6</sup>It might be noted that the use of the plant load factor (PLF), which is often used as a yardstick for comparison of the relatively poor performance of developing country generating units, is not a very useful measure for this purpose, since there may be sound economic dispatch reasons for a plant not to be used for all of the hours in which it is available.

<sup>7</sup>FOR is defined as (forced outage hours)/(service hours + forced outage hours).

<sup>8</sup>0p. Dhamija, *Operation, Maintenance and Rehabilitation of Thermal Power Plants in India* (India: Uttar Pradesh State Electricity Board, 1988).

<sup>9</sup>A. Armor et al., "Utility Implementation of Life Optimization Programs," paper presented at the GEN-UPGRADE Conference, Washington, DC, March 1990, table 2.

<sup>10</sup>In fact the financing plan, as is increasingly the case, involves cofinancing by other entities, including the overseas Development Administration of the U.K. (ODA), USAID (from its Energy Commodities Equipment Program), and the Government of Pakistan.

<sup>11</sup>IDEA, "Clean Coal Technologies for Developing Countries," contractor report prepared for the Office of Technology Assessment, May 1990, p. 72.

Table 6-3—impact of Generating Plant Rehabilitation in Pakistan

Plant	Heat rate before rehabilitation Btu/kWh	Heat rate after rehabilitation Btu/kWh	FOR <sup>a</sup> before rehabilitation percent	FOR after rehabilitation percent
Multan, steam/fuel oil . . . . .	12,808	11,280	13	6
Faisalabad, steam/fuel oil . . . . .	12,850	11,290	13	6
Guddu Steam/fuel oil . . . . .	13,250	11,113	10	6
Quetta Steam/coal . . . . .	20,850	20,850	13	8
Faisalabad gas turbines . . . . .	16,700	15,113	10	5

<sup>a</sup>FOR—forced outage rate.

SOURCE: International Development and Energy Associates (IDEA), Inc., "Improving Power Sector Efficiency in Developing Countries," November 1990, OTA contractor report, p. 72, based on *Integrated Operations Study for WAPDA and KESC*, report by Coopers & Lybrand to the Asian Development Bank, April 1990."

### Transmission and Distribution Systems

System losses are perhaps the most common indicator used to describe the overall efficiency of the transmission and distribution system. T&D losses in the 6 to 9 percent range are regarded as good. In a recent compilation of system losses by the World Bank,<sup>12</sup> however, few developing countries experienced total system losses of below 10 percent. Several other developing countries had considerably higher losses (see table 6-4).<sup>13</sup> The most common way of measuring system losses is to compare generation at the busbar with sales (usually obtainable from billing records). This method measures both technical losses and nontechnical losses—which reflect the failure of many developing country utilities to meter and/or bill consumers and their failure to control illegal connections.

Over the next 20 years there will likely be a substantial effort in developing countries to reduce T&D system technical losses. A number of power system efficiency studies have been conducted by the World Bank and others, and T&D system rehabilitation has been recommended in almost all cases. Often, the recommendations are not just for hardware, but for technical assistance to strengthen T&D departments.

Losses are particularly high at the end of the distribution system, especially in low tension feeders and distribution transformers (see table 6-5). Technical improvements to reduce T&D losses include: providing adequate capacity in overloaded T&D system; adding power factor correction capacitors or overexcited synchronous motors to correct



Photo credit: U.S. Agency for international Development

In some cases, it may be more cost effective to improve transmission and distribution lines than to add new generating capacity.

<sup>12</sup>JEscay *Summary Data Sheets of 1987 Power and Commercial Energy Statistics for ZOO Developing Countries*, Industry and Energy Department Working Paper, Energy Series Paper 23 (Washington, DC: World Bank, 1990).

<sup>13</sup>One might expect slightly higher losses in developing countries than in Western Europe, due to the lower voltages and greater number of rural networks in the developing world; but the loss levels shown in table 6-5 are much larger than would be considered desirable.

**Box 6-A—Thermal Plant Rehabilitation in Kenya**

The Kenya Power and Lighting Co. operates a generally well run and efficient power system, serving about 170,000 customers in Nairobi and other urban centers. The Kenya Power System Efficiency Assessment found that its main hydro plant (335 MW on the Tana River) operates with a high degree of reliability, and is relatively trouble-free. The 2 X 15 MW Geothermal plants at Olkaria, commissioned in 1981-1982, were found to be in "exceptionally good condition, " and operate as base-load units at their fully rated capacity.

The Kipevu thermal power station in Mombasa, however, was in need of immediate rehabilitation. The 12 MW combustion turbine has been derated to 6 MW due to basic design shortcomings. Installation of a forced-air-finned cooler system and forced ventilation systems would permit uprating. The condensers and sea-watercooling systems are in severe disrepair due to corrosion and lack of proper maintenance: the cathodic protection system has not functioned for many years. The lack of a chlorination system has resulted in extensive fouling of lines and condensers with clams, worms, and other marine life. The 7 steam turbine units are in various stages of disrepair; 1 is no longer functional, 2 of the 12 MW units are derated to 8 and 10 MW, respectively, and even the 2 most recent units, aged 11 and 7 years, require rehabilitation because critical monitoring and metering equipment is nonfunctional. The costs of rehabilitating the power station are estimated at about \$2.8 million, with a resulting benefit valued at about \$1.8 million per year. This is a payback of about 1.5 years.

SOURCE: IDEA, "Improving Power Sector Efficiency in Developing Countries," contractor report prepared for the Office of Technology Assessment, October 1990, p. 73.

the power factor; using low loss distribution transformers;<sup>14</sup> and changing distribution system design.

A number of distribution configurations are used in developing countries. The traditional European system was designed to serve high density urban areas of Europe: the entire system is three phase, and is not the most appropriate for low density rural areas. The modified European system, however, provides good flexibility for single phase extensions to serve lightly loaded areas. The North American system carries a neutral wire along with the three phase wires. Single phase lines consist of a phase wire and an uninsulated neutral conductor, and can be cheaper than the European systems. The single wire earth return system uses a single conductor with the earth as return path; it is especially suitable for very lightly loaded systems involving long distances. The frost reported use of such a system in a developing country is in a project in the Ivory Coast, partly funded by the World Bank.

**High Voltage Direct Current (HVDC)**

Capital investment in developing country transmission systems will need to increase over the next decade. An important innovation likely to come into more widespread use in developing countries is HVDC. HVDC has proven economic for moving large blocks of power over long distances (500

kilometers (km) or more), and increasingly has been used in the United States. Major HVDC projects in developing countries are +500 kilovolts (kV) links in China and India. The Indian project is a **900 km link** between the Singrauli minemouth generating complex and Delhi that will provide a transfer capability of about 1,500 MW, The Chinese HVDC project links the central and East China Regional Grids.

A more immediate use for HVDC in many situations is as asynchronous links between neighboring systems that use different frequencies and voltages. Again in India, such an HVDC link has been made to connect the Northern and Western

**Table 6-4—Technical and Nontechnical Losses (in percent of net generation)**

	Total	Technical	Nontechnical
Sri Lanka . . . . .	18	14	4
Panama . . . . .	22	17	5
Sudan . . . . .	31	17	14
Bangladesh . . . . .	31	14	17
Liberia . . . . .	35	13	22
Malaysia . . . . .	28	11	17
Ivory Coast . . . . .	12	8	4

SOURCE: M. Munasinghe et al., *A Review of World Bank Lending for Electric Power*, World Bank, Washington, DC, Energy Series Paper No. 2, p. 60.

<sup>14</sup>Samuel F. Baldwin, 'Energy-Efficient Electric Motor Drive Systems,' Thomas B. Johansson, Birgit Bodlund, and Robert H. Williams (eds.), *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications* (Lund, Sweden: Lund University Press, 1989).

Table 6-5-Distribution of Technical Energy Losses (percent)

	Madagascar	Kenya	Bangladesh	Target <sup>a</sup>
Power plant transformers .....	2.2	0.5	0.5	0.3
Transmission lines .....	2.7	5.2	2.2	3.8
Substations .....	0.8	0.9	1.1	0.3
Primary lines .....	2.1	2.1	4.2	2.5
Distribution transformers and low tension network .....	4.2	6.3	6.0	1.5
<b>Total .....</b>	<b>12.0</b>	<b>15.0</b>	<b>14.0</b>	<b>8.3</b>

<sup>a</sup>Target levels are those found in a relatively efficient, well-run system.

SOURCE: IDEA, "Improving Power Sector Efficiency in Developing Countries," draft contractor report to the Office of Technology Assessment, October 1990, p. 26

regions as the initial step in the establishment of a national grid. This link provides for the exchange of up to 500 MW of power between the two regional grids.

### Compact Design

Transmission line research over the past decade has indicated substantial potential for reducing transmission line cost, lessening visual impact, and maximizing use of existing rights of way by compact construction involving much lower line spacings than has been traditional practice. The most dramatic reductions have been at the 115 to 138 kV level where traditional clearance specifications were established long before technical requirements were clearly understood.

In the United States, a number of 138 kV lines have been uprated to 230 kV without any change in either conductor or insulation system, a practice that has been made possible because of better understanding of insulation and clearance requirements, and the need for large design margins correspondingly diminished. Particularly in the 50 to 230 kV range, attractive opportunities for uprating will often exist. Voltage uprating of a line greatly increases its load carrying capacity.

### System Interconnections

*The* systems of India, Brazil, and China, in particular, are not single integrated systems, but consist of a set of regional systems, each no more than about 10 to 15 GW in size. The Chinese system,

for example, consists of six regional grids--of which four exceed 10 GW in size--plus seven provincial grids. In this respect, these countries are similar to the United States, where individual power pools are the basic dispatch entities.<sup>15</sup> While interconnections do exist for power transfers to exploit interregional diversity, or for emergency assistance, a national power grid for large scale transfers of power does not yet exist.

The effects of capacity shortages and skewed financial incentives on economic dispatch and regional operation of interconnected systems are well illustrated in India.<sup>16</sup> Regional electricity boards were established in India as the primary mechanism for integrated regional operation. Each regional board consists of several State Electricity Boards, which are, in theory, subordinate to the regional dispatch centers but, in practice, often resist dispatch instructions.<sup>17</sup> The practice of allocating shares in large central sector plants to individual States creates particular difficulties, because during peak periods States tend to overdraw power from the central stations, which results in the frequency of the system falling from the nominal 50 Hz to as little as 48 Hz. During off-peak hours power is dumped into the system, resulting in frequency increases to 51 Hz or higher. Grid management problems arise when frequency falls outside the normal range of  $50 \pm 0.2$  Hz, including the potential of grid collapse and damage to large thermal and nuclear generating sets.

The difficulties of backing down local plants during off-peak periods, even though these are less

<sup>15</sup>A detailed study of system interconnection issues can be found in U.S. Congress, Office of Technology Assessment, *Electric Power Wheeling and Dealing: Technological Considerations for Increasing Competition*, OTA-E-409 (Washington DC: U.S. Government Printing Office, May 1989).

<sup>16</sup> Swarup, K., "Inter-state Power Exchanges and Integrated Grid Operations Proceedings," *Planning for the Power Sector* (Agra, India: September 1989).

<sup>17</sup> Another reason for the reluctance of State Electric Boards to back down units is the increasing use of the PLF as a yardstick of plant performance in India; the higher the Plant Load Factor (PLF), the "better" the performance of the plant. As noted in footnote 6, however, use of the PLF for such purposes is questionable.

efficient than the large central sector plants, is largely a matter of tariffs that provide few incentives for efficient operation. Moreover, because of financial difficulties, States are reluctant to permit net transfers of energy for fear of not getting paid by the recipient.

Trade in electricity among developing countries is very small compared to that in Europe and North America and far less than the technical and economic potential. The largest import dependency among African countries appears to be that of Zimbabwe on Zambia, reaching 25 percent of supply in the early 1980's. One major reason for the low level of intercountry trade in electricity is the question of payment. Exporting countries expect to get paid in a timely way, and in foreign exchange—not in inconvertible national currency. National security concerns also play a role. Box 6-B describes opportunities for interconnection, regional integration, and joint development of electricity systems in the developing world.

### *Improved System Planning Procedures*

*In the* past, power system planning in the developing world has meant finding the least expensive generating mix to meet forecasted demand.<sup>18</sup> Although such least-cost analysis is essential, these methods conventionally have not incorporated demand side options and environmental impacts. There are three basic improvements that could enhance system planning in developing countries. First, the analysis itself could account for uncertainty, particularly in availability of foreign exchange and in demand growth. This could help avoid the sort of overbuilding characteristic of some Central American hydropower facilities in the last decade. Second, demand reduction and load management could be considered as investment opportunities and even as alternatives to new generation. Finally, the analysis could incorporate the social and environmental costs of power supply, which often are not reflected in cost estimates and regulations.

In the United States, many utility- and State-level regulators are paying considerable attention to the need for improved system planning. Although a single integrated approach to system planning has not been agreed on, many of the utilities and State

regulators have adopted the concept of “integrated resource planning” (IRP) (see box 3-G on IRP in ch. 3). IRP allows for consideration of both demand and supply side investments and externalities. These planning methods could help promote energy efficient technologies in the developing world as well. Integrated resource planning may be particularly appropriate for developing countries, where there are often severe capital constraints and an untapped potential for demand reduction. The United States (particularly utilities and State regulatory agencies) could help the developing countries by providing policy advice, training, and technical assistance.

### *Improved Management*

*The* issue of effective management of electric utilities is not just one of public versus private sector ownership, since there are many public sector utilities throughout the world that are well run, and private sector utilities whose technical and financial management has been consistently poor. In the case of government-owned entities, which applies to most developing countries, top management of utilities is sometimes appointed primarily for political reasons. In other cases, appointments are made on the basis of technical competence, and managers are held accountable in exchange for a certain degree of autonomy.

The Volta River Authority (VRA) of Ghana is a good example of a well run facility. The VRA was established primarily to own and operate the 1,000 MW hydro facility at the Akosombo Dam. The 1961 Volta River Development Act requires VRA to operate its plants according to sound public utility practices, a requirement that has in fact been met. In addition, the international institutions that financed the project insisted from the beginning on high standards of technical management. The tradition of technical competence in management has endured, coupled with a degree of autonomy from government interference.

Although competent management at the head of a utility is a key condition for good performance, it alone is not sufficient. A utility must also buildup and maintain a competent technical staff (see box 6-C). Training is required at all levels—college level

<sup>18</sup>D. Jhirad, “Power Sector Innovation in Developing Countries: Implementing Multifaceted Solutions,” *Annual Review of Energy*, vol. 15, 1990, p. 377.

**Box 6-B--Opportunities for Interconnection, Regional Integration, and Joint Development of Electricity Systems in the Developing World**

A 330 kV interconnection between the Ivory Coast, Ghana, Togo, Benin, and Nigeria has long been discussed.<sup>1</sup> The Nigerian system, with a strong potential for low cost gas fired generation, would complement the hydro-based system in Ghana. Even with the large storage capacity at Akosombo in Ghana, 2 or 3 wet years in a row necessitates spilling, which could instead be used to produce power for export to Nigeria. On the other hand, dry years cause serious problems for Ghana, since the 1,072 MW Akosombo project accounts for all but 50 MW of the installed capacity of Ghana. Shortfalls could be filled in with thermal power from Nigeria.

The possibility of linking Burkino Faso with Ghana has also been examined as part of extending the Ghanaian grid to its northern regions. For Ghana, electricity sales would generate sufficient export revenues to justify the investment, and enable its northernmost loads to be served more economically by increasing the capacity utilization of the grid extension. Economic analyses of this proposal indicate rates of return of about 15 percent on the cost of the grid extension.

Although cooperation among the East African countries has been impeded for many years by political factors, the potential for joint development of hydroelectric resources remains. Tanzania plans to develop significant hydro capacity on the Rufiji river, and could export expected surpluses in the late 1990s. This would require construction of a 220 kV intertie between Mombasa in Kenya and Tanga in Tanzania, and would enhance reliability in both systems as well. In Uganda, there is a potential for 500 MW of hydro at Ayago, which could be developed jointly with Kenya.

Two separate systems serve Pakistan: the smaller Karachi Electric Supply Corp. (KESC) and the larger Water and Power Development Authority (WAPDA). The former is a 100 MW all thermal system serving the Karachi area (93 percent of whose shares are owned by government) and the latter is an autonomous government body with an installed capacity of 2,900 MW of hydro and 2,000 MW of thermal, serving the rest of Pakistan.

At present two single circuit 132 kV lines and one double circuit 220 kV line interconnect these two systems. While exchanges between the two systems do occur, the interconnected system is still operated on the basis of avoiding load shedding, rather than on economic dispatch of an integrated system. A recent study found that integrated system operation could provide savings in:<sup>2</sup>

- capital costs on new generating capacity—because a larger system needs less total capacity to meet an identical reliability criterion than the sum of two separate systems;
- fuel costs—achieved through least cost dispatch of available plants; and
- energy—achieved through more effective use of plants to reduce load shedding.

The economic analysis indicated overall benefits of about \$1 billion (expressed as a present worth at 10-percent discount rate) over the 20-year planning period, equal to about 5.7 percent of total system costs of separate KESC and WAPDA systems. About 90 percent of the benefits are in fuel cost savings.

<sup>1</sup>See, for example, World Bank, *Ghana: Issues and options in the Energy Sector*, Report 6234-GH (Washington, DC: November 1986).

<sup>2</sup>Coopers and Lybrand, *Integrated Operations Study for WAPDA and KESC*, Report to the Asian Development Bank (April 1990).

training<sup>19</sup> for electrical engineers and in-country, on-the-job training programs, perhaps in conjunction with utilities from the industrial countries.

### **Environmental Considerations**

The degree to which electricity generating equipment in the developing world currently incorporates pollution control equipment varies. Modern electro-

static precipitators (ESP) for particulate control are now routinely fitted to new coal-fired power plants in developing countries: a recent survey of World Bank financed projects indicates that over the past decade, all such plants were so equipped. The extent to which such equipment is properly maintained, however, is not clear. If the plant as a whole is in poor condition, ESPs may be among the first items

<sup>19</sup>College level training is often done at institutions in the United States or Europe. In an attempt to ensure that foreign trained nationals return home, some developing country institutions now require the posting of bonds prior to departure on overseas University courses to ensure return, sometimes in amounts of as much as 3 months salary. Yet with a degree in hand, graduates discover that industrial country salaries are so attractive in comparison that such bonds can easily be forfeited.

of equipment not to be properly maintained as their failure does not require the plant to shut down. Moreover, where ash contents are far in excess of design norms (as is the case at many Indian plants, for example), failure rates of ESPs will be high.

Environmental considerations are now playing a larger role in system expansion decisions. For example, concerns over the environmental impacts of large hydropower development have influenced system planning in India, China, and Brazil. Environmental issues are likely to be even more important in the future as concerns over the regional and global environment grow.

## TECHNICAL OPTIONS FOR NEW ON-GRID GENERATION

The improvements to the existing system described above could lead to substantial increases in supplies from existing capacity. Sooner or later, however, additional capacity will be required.

The selection of a technology for electricity generation is based on many factors, but a principal factor is and will continue to be availability of the fuel needed to power the technology. Several Asian countries have access to coal and therefore can be expected to continue to build new coal-fired generation. Hydropower resources in many areas, notably Latin America, are abundant and will probably continue to be exploited for electricity generation. Oil is a less popular fuel for new on-grid electricity generation due to its volatile price. Even those developing countries with domestic oil reserves may prefer to export their oil rather than consume it domestically. Natural gas is still unavailable in many areas, although the gas resource base is considerable (see ch. 7).

Much of the planned expansion in electricity generating capacity in the developing world reflects these resource considerations (see table 6-6). Coal and hydro will supply much of the expected expansion, followed by gas, nuclear, oil, and geothermal.

In this section, the technologies for expanding the supply of on-grid electricity generation in the developing world are reviewed. Many technologies could potentially play a role, but the analysis here will be limited by two principal criteria: those likely to play a large role in near term expansion (coal, hydro, etc.); and those playing a smaller role in current plans but with significant environmental or

### ***Box 6-C—Training Programs for Utility Planning***

There are several examples of successful training programs in utility planning procedures. The training program at Argonne National Laboratory, financed for more than a decade by the International Atomic Energy Agency (IAEA) in Vienna, covers many aspects of power sector planning, and has played a significant role in raising the level of power sector planning in developing countries. A second example is the Brookhaven/Stony Brook Energy Management Training Program, sponsored for many years by Agency for International Development in Washington, whose objective was to train energy sector planners. Some 40 percent of the more than 350 senior individuals who attended the course were from electric utilities. In some countries almost the entire cadre of senior energy sector planners attended the course. The energy planning program at the University of Pennsylvania as well as activities of the National Rural Electric Cooperative Association (NRECA), are two more successful and well-regarded training programs.

Developing effective programs requires an institutional commitment over substantial time periods, sufficient for adequate curriculum development and for the planning philosophy to become established. For demand-side management and integrated resource planning to gain widespread acceptance, a long-term training effort must be launched. A major training effort will similarly be necessary if new agencies with environmental planning and regulatory functions are to be adequately staffed.

other benefits (gas turbines, renewable) and substantial long term potential. The focus is on those technologies that are currently commercially available or expected to become so in the near future. Due to the diversity of the developing world, it is not appropriate to identify a specific technology as the best for all situations; nevertheless, the analysis identifies issues influencing the choice of technologies for electricity supply expansion in the developing world.

### ***Clean Coal***

*The* conventional technology for utilizing coal to produce electricity—the pulverized coal boiler—is reliable and technically straightforward, but results in relatively high emissions of NO<sub>x</sub>, SO<sub>x</sub>, particulate, and solid wastes. These pollutants can have adverse impacts on human health, ecosystems, and

**Table 6-6-Planned Expansion in Electric Power Facilities of the Developing World, 1989-99**

Plant type	Planned new capacity	
	(Gw)	(percent)
Coal thermal .....	172	45
Hydro .....	137	36
Gas thermal .....	34	9
Nuclear .....	24	6
Oil thermal .....	14	4
Geothermal .....	3	1
<b>Total .....</b>	<b>384</b>	<b>100</b>

NOTE: Data reflect official country plans, and do not reflect capital or other constraints.

SOURCE: World Bank, *Capita/ Expenditures for Electric Power in the Developing Countries in the 1990s*, Industry and Energy Department Working Paper, Energy Series Paper No. 21, February 1990, p. i.

structures such as bridges and buildings. Coal burning also releases significant amounts of the greenhouse gas CO<sub>2</sub>; about 11 percent more than oil combustion; and 67 percent more than natural gas combustion per unit of energy output.<sup>20</sup>

As a result of the Clean Air Act Amendments of 1977, coal burning power plants in the United States were fit with flue gas desulfurization (FGD) or ‘scrubbers,’ a technology for removing SO<sub>x</sub> from the post-combustion gas stream. SO<sub>x</sub> scrubbing techniques currently in use include lime/limestone and double alkali scrubbing in which SO<sub>x</sub> is captured from the gas stream and consolidated as sludge. Disposal of the sludge remains an environmental problem, though in some cases the sludge can be regenerated. There are also wet scrubbers and fabric filters for removing particulate from the flue gas.<sup>21</sup>

FGD is effective at removing SO<sub>x</sub>, but is expensive, reduces overall plant efficiency, and does little to reduce NO<sub>x</sub>, CO<sub>2</sub>, and other emissions. A recent Indian study concluded that the addition of a FGD

system would increase costs per kWh output by about 15 percent.<sup>22</sup> Although common in the United States,<sup>23</sup> FGD is almost unknown in India and China<sup>24</sup> as their coals are, on average, relatively low sulfur.

The high cost of FGD in the United States led to a search for other methods to burn coal with reduced emissions. The resulting technologies are often called ‘clean coal’ technologies. They include improved coal processing before combustion (see ch. 7), improved ways to burn coal, and improved ways to treat waste gases. Some ‘clean coal’ technologies offer important benefits in addition to reduced emissions, such as greater tolerance for low quality coal, but their major benefit is reduced emissions and this usually comes at a cost in comparison to conventional pulverized coal technologies.

### *Fluidized Bed Combustion (FBC)*<sup>25</sup>

Fluidized bed combustion combines pulverized coal with limestone particles in a hot bed fluidized by upflowing air. Calcium in the limestone combines with sulfur in the coal to reduce SO<sub>x</sub> emissions, and the relatively low combustion temperatures also reduce NO<sub>x</sub> formation. FBC systems can be either pressurized (PFBC—operating at about 10 atmospheres air pressure) or atmospheric (AFBC—operating at ambient air pressure). PFBC is still in the development stage, although there are demonstration projects running in Stockholm and in Ohio.<sup>26</sup> AFBC technology can be retrofit onto an existing power plant, and appears to be quite tolerant of low quality coals.

Many AFBC units are in operation worldwide, including about 280 in the industrialized countries (some for industrial use).<sup>27</sup> India and China both

<sup>20</sup>United Nations Department of Technical Cooperation for Development, *Energy and Environment: Impacts and Controls* (New York, NY: October 1990), p. 10.

<sup>21</sup>United Nations Department of Technical Cooperation for Development, *Ibid.*, pp. 24-26.

<sup>22</sup>IDEA, ‘Clean Coal Technologies for Developing Countries,’ contractor report prepared for the Office of Technology Assessment May 1990, p. 25.

<sup>23</sup>As of 1988, about 22% of coal-fired power plants in the United States used FGD systems. U.S. Department of Energy, Assistant Secretary for Fossil Energy, *Clean Coal Technology, DOE/FE-0149* (Washington DC: U.S. Department of Energy, November 1989), p. 10.

<sup>24</sup>IDEA, ‘Clean Coal Technologies for Developing Countries,’ contractor report prepared for the Office of Technology Assessment, May 1990, p. 25.

<sup>25</sup>For more information on FBC technologies, see U.S. Congress, Office of Technology Assessment, *New Electric Power Technologies*, OTA-E-246 (Washington, DC: U.S. Government Printing Office, July 1985).

<sup>26</sup>PFBC Industry Newsletter, ‘Clean Coal Technology,’ No. 1, 1991.

<sup>27</sup>World Bank, *The Current State of Atmospheric Fluidized-Bed Combustion Technology*, World Bank Technical Paper Number 107, September 1989, p. 13.

Table 6-7-Costs of AFBC and PC Coal-Burning Power Plants

Cost component	Conventional PC	AFBC	PC with FGD	PC with 15 percent lower availability
Total costs (cents/kWh) . . . . .	5.5	6.1	6.2	6.4

NOTES: Estimates are for a single 60 mW unit, and include levelized capital costs. PC=pulverized coal; Technology Assessment, May 1990, p. 32.

have hundreds of small AFBC bubbling bed plants.<sup>28</sup> Most of the small Indian and Chinese plants are used for steam heat rather than for electrical generation. A few, such as the **30 MW** plant in Trichy, India, do generate electricity.

The advantages of AFBC over traditional pulverized coal (PC) technology are reduced emissions and increased tolerance to a wide range of low quality fuels. PC plants tend to break down when the ash in low quality fuels melts and clogs the boiler machinery. AFBC plants have reported successful burning of fuels with ash contents of from 4 to 40 percent,<sup>29</sup> and AFBC can also burn rice husks and other agricultural wastes. The costs of AFBC are thought to be "competitive" with PC plants, depending on the local situation.<sup>30</sup> A cost analysis for AFBC plants in U.S. applications found that AFBC had lower capital requirements and a similar cost of electricity when burning high quality fuels, when compared to pulverized coal with flue gas desulfurization.<sup>31</sup> Few plants in India or China presently use FGD, however, so this comparison may be misleading.<sup>32</sup>

The benefits associated with the greater flexibility of AFBC can be evaluated by comparing the costs of AFBC to those of a conventional plant burning low quality coals. AFBC is more expensive than a conventional (PC) plant, but less expensive than a PC plant with FGD (see table 6-7). If the reduced

availability of a PC plant due to low quality fuel is taken into account, AFBC becomes less expensive. This analysis assigns no value to the reduced air emissions of AFBC in comparison to PC. Despite increasing use of FBC plants, they are a relatively new, still evolving technology. There is, therefore, a certain amount of uncertainty about the future costs of FBC technologies.

### *Integrated Gasification Combined Cycle (IGCC)*<sup>33</sup>

Integrated Gasification Combined Cycle (IGCC) combines several advanced technologies: a gasifier that reacts coal with oxygen to produce a mixture of combustible gases, a gas cleaning process to remove sulfur and other pollutants from the gas prior to combustion, a turbine that burns the gas to produce electricity, a waste heat recovery boiler that produces steam, and a steam turbine to generate additional electricity. Several demonstration projects in the 100 to 200 megawatts electric (MWe) size are being designed or operated.

IGCC systems have several advantages. IGCC plants have somewhat higher efficiencies than conventional pulverized coal plants. Unlike most coal-fired electricity technologies, relatively small (100 MW) IGCC plants can be built that are similar in cost per kW to large (500 MW) IGCC plants; and

<sup>28</sup>Stratos Tavoulareas, Senior Energy Consultant, U.S. Agency for International Development, unpublished memorandum, Apr. 26, 1991.

<sup>29</sup>World Bank, *The Current State of Atmospheric Fluidized-Bed Combustion Technology*, World Bank Technical Paper Number 107, September 1989, p. xviii.

<sup>30</sup>Ibid., p. xviii.

<sup>31</sup>Ibid., p. 52.

<sup>32</sup>Differences in plant size also complicate the comparison. AFBC plants have been built up to 200 MWe in size, while traditional pulverized coal plants are often 300 MWe or larger.

<sup>33</sup>For more information on IGCC technologies, see U.S. Congress, office of Technology Assessment, *New Electric Power Technologies*, OTA-E-246 (Washington DC: U.S. Government Printing Office, July 1985).

<sup>34</sup>IDEA, "Clean Coal Technologies for Developing Countries," contractor report prepared for the Office of Technology Assessment May 1990, p. 54. The efficiency gain of the IGCC process comes from the use of a combined (2-stage) cycle—a concept that can also be applied to oil and natural gas plants.

**Table 6-8-Incremental Effects of Improved Coal Technologies Relative to a Conventional (PC) Plant Without FGD**

Technology	SO <sub>2</sub> reduction (percent)	NO <sub>x</sub> reduction	Plant efficiency	Total electricity costs (cents/kWh)
PC w/out FGD .....	—	—	—	5.5
FGD .....	90	No change	Decrease	6.2
AFBC .....	85-90	Moderate	No change	6.1
IGCC .....	95-99	Moderate	Small increase	6.4

NOTES: AFBC = atmospheric fluidized bed combustion; FGD = flue gas desulfurization; IGCC = integrated gasification combined cycle; PC = pulverized coal.  
SOURCE: IDEA, "Clean Coal Technologies for Developing Countries," contractor report prepared for the Office of Technology Assessment, May 1990, pp. 32, 47.

IGCC plants have low SO<sub>2</sub> emissions.<sup>34</sup> The tolerance of IGCC plants to lower quality coals is not yet clear. IGCC plants have been operated with coals with up to 28 percent ash content,<sup>35</sup> but not at the ash levels of 40 percent typical of Indian coals.

### *Applications to the Developing World*

AFBC and IGCC technologies have higher first costs than conventional coal plants—but they offer several advantages, including reduced emissions, increased efficiency for IGCC, and increased fuel quality tolerance for AFBC (see table 6-8). Both AFBC and IGCC are promising technologies for those developing countries with domestic coal reserves, though improved coal washing alone would do much to improve plant availability and efficiency in conventional PC plants in India and China (see ch. 7). AFBC would allow use of lower grade, relatively dirty coals and would result in reduced SO<sub>2</sub> and NO<sub>x</sub> emissions.

Coal burning technologies allow use of a vast, inexpensive resource but have environmental impacts and costs. The use of AFBC and/or IGCC technologies reduces both SO<sub>2</sub> and NO<sub>x</sub> emissions, but CO<sub>2</sub> and the remaining NO<sub>x</sub> emissions will still be considerable. The costs of these technologies (see app. B, at the end of this report) are relatively high as well, depending on plant availability and other factors.

### *Large Hydro*

Hydroelectric power plants currently supply a significant fraction of the developing world's electricity (see table 6-9). By one estimate, an additional 137 GW of hydroelectric power maybe added in the developing world by 2000.<sup>36</sup> Although hydropower has many advantages, notably use of an indigenous renewable resource, it often has relatively high capital costs (see app. B). A number of specific sites, such as the Narmada River project in India and the Three Gorges project in China, are also controversial due to adverse environmental and social impacts.

Although regions differ in their hydropower resources, according to one estimate, less than 10 percent of the technically usable hydropower potential in developing countries has been developed.<sup>37</sup> There are many valid reasons why this huge technical potential is not being fully utilized. In some cases, existing markets are too small. Zaire, for example, has 120 GW of technical hydro potential—about 50 times their current system capacity.<sup>38</sup> The estimates for technical hydro potential do not account for costs,<sup>39</sup> and many of the potential sites are located in remote areas, making construction costs unaffordably high and markets for the power distant. Construction times can be long. Large projects in China, for example, can require up to 7 to

<sup>35</sup>Government of India, Ministry of Energy, Department of Coal, *IGCC Power Generation 100-120 MWe Demonstration Plant Based on High Ash Indian Coals*, January 1988, p. VIII.

<sup>36</sup>E. Moore and G. Smith, World Bank, Industry and Energy Department, *Capital Expenditures for Electric power in the Developing Countries in the 1990s*, Industry and Energy Department Working Paper, Energy Series Paper No. 21, February 1990, p. i.

<sup>37</sup>J. Besant-Jones, World Bank, *The Future Role of Hydropower in Developing Countries*, Energy Series Paper No. 15, April 1989, p. 15.

<sup>38</sup>World Bank, *A Survey of the Future Role of Hydroelectric Power in 100 Developing Countries*, Energy Department Paper No. 17, August 1984, Annex II. World Bank, *Summary Data Sheets of 1987 Power and Commercial Energy Statistics for 100 Developing Countries*, Industry and Energy Department Working Paper No. 23, March 1990.

<sup>39</sup>As much of the costs of hydropower construction are site specific and for locally available labor and materials, construction costs vary widely. The average is typically \$1,500-\$2,000/kW. See World Bank, *ibid.*, p. 19

**Table 6-9-Hydroelectric Power Generation in Developing World Countries**

Country	Hydroelectric power generation	
	(terawatt-hours)	(percent of total generation)
Africa .....	50	18
Asia .....	241	22
Latin America .....	330	63
U.S. ....	250	10

SOURCE: International Energy Agency, *World Energy Structure and Balances 1971-1987* (Paris: OECD, 1989); Energy Information Administration, *Annual Energy Review 1989* DOE/EIA-0384(89), p. 203.

10 years for construction.<sup>40</sup> In many cases, these factors constitute a major drain on developing country economies. Other problems include seasonal fluctuations in precipitation, which may limit plant output, and accommodating competing uses for water.

Large hydropower can also have significant environmental costs. Large land areas are cleared for access, construction materials, or for the reservoirs themselves and are then flooded. This can affect the watershed, displace people and flood fertile agricultural land, and destroy forests and wildlife habitats.<sup>41</sup> If the area to be flooded is not adequately cleared, the resulting rotting vegetation can release large quantities of methane, a greenhouse gas. Environmental problems also arise when a dam is operational. Dams may cause detrimental downstream effects due to changes in the level of sedimentation and flood patterns. New reservoirs can also mean an increase in diseases, such as schistosomiasis, which flourish in still water.

### *Nuclear Power*

Nuclear power currently supplies a relatively small amount of electricity in the developing world—less than 5 percent of total generation.<sup>42</sup> Both South Korea and Taiwan make heavy use of nuclear power,

and are expected to continue to do so. Several developing countries are currently building nuclear power plants (see table 6-10). Other countries with nuclear power programs, including Argentina, India, and the Philippines, have had problems similar to those of the United States<sup>43</sup>--high capital costs, construction delays, cost overruns, low reliability, and concerns over waste disposal. Several countries, including Argentina, Brazil, Mexico, Pakistan, and the Philippines have scaled back or canceled their nuclear power plant construction plans.<sup>44</sup>

Most existing nuclear power plants are of two main types: boiling water reactors (BWRs) and pressurized water reactors (PWRs). BWRs use the heat of fission to cause water to boil, and the resulting steam is then used to drive the turbine. PWRs keep the primary cooling water at high pressure to prevent boiling, and have a secondary water system that absorbs heat from the cooling water and generates steam, which then drives a turbine. Both systems are in widespread use. Heavy water reactors, which use water in which hydrogen contains an additional neutron to moderate the fission rate, are used in Canada, Argentina, and India. Gas-cooled reactors, which use a gas as a coolant, are used in the United Kingdom. Advanced technologies, including breeder reactors and fusion, are not currently in commercial use.

Recent R&D efforts have focused on making reactors safer, simpler, and of a more standardized design. These designs vary, but common features include smaller unit size, use of so called “passive” safety features (which do not require external power, signals, or forces to operate), and overall simplified design, potentially reducing costs and opportunities for operator error.<sup>45</sup> Data on costs and performance however, are not yet available. The proponents of these new technologies argue that they will offer high performance and safety at a reasonable cost, while others suggest that costs will be high and

<sup>40</sup>H. Yicheng, “Relying on Reform to Speed up Hydropower Development” *JPRS Report, Science and Technology-China: Energy*, JPRS-CEN-90-014, Nov. 13, 1990, p. 11.

<sup>41</sup>“Impacts of Hydroelectric Development on the Environment,” *Energy Policy*, vol. 10, No. 6, 1982, p. 351.

<sup>42</sup>U.S. Congress, Office of Technology Assessment, *Energy in Developing Countries*, OTA-E-486 (Washington, DC: U.S. Government Printing Office, January 1991).

<sup>43</sup>U.S. Congress, Office of Technology Assessment, *Nuclear Power in an Age of Uncertainty*, OTA-E-216 (Washington, DC: U.S. Government Printing Office, February 1984).

<sup>44</sup>J. Perera, “Power Generation,” *South*, No. 102, April 1989, p. 65; John Surrey, “Nuclear Power: An Option for the Third World?,” *Energy Policy*, vol. 16, No. 5, October 1988, pp. 461-479.

<sup>45</sup>C. W. Forsberg and A. Weinberg, “Advanced Reactors, Passive Safety, and Acceptance of Nuclear Energy,” *Annual Review of Energy*, vol. 15, 1990, p. 140.

**Table 6-10-Status of Nuclear Power Plants in the Developing World**  
(as of December 1988)

Country	Electricity supplied by nuclear power plants		Nuclear power plants under construction (MWe)
	(GWh)	(percent of total)	
Argentina .....	5,100	11.2	692
Brazil .....	600	0.3	0
China .....	0	0.0	2,148
Cuba .....	0	0.0	816
India .....	5,400	3.0	1,760
Mexico .....	0	0.0	1,308
Pakistan .....	200	0.6	0
S. Africa .....	10,500	7.3	0
S. Korea .....	38,000	46.9	900
Taiwan .....	29,300	41.0	0
Us. ....	526,900	19.5	7,689

SOURCE: B. Semenov et al., "Growth Projections and Development Trends for Nuclear Power." IAEA Bulletin, vol. 31, No. 3, 1989, p. 7.

reliability low. Historically, nuclear power systems have cost more and operated at lower capacity factors than anticipated, suggesting that it maybe appropriate for risk-averse potential users of nuclear power with limited capital to wait for these systems to operate commercially, thereby demonstrating their cost and performance characteristics.

There are several issues related to nuclear power in the developing countries that differ from those in the industrialized countries. These include scale, technical skill requirements, environmental constraints, and proliferation.

- Scale: it is sometimes argued that nuclear power is too large for developing countries, If the rule-of-thumb that no single facility should supply more than 10 percent of total system electricity is used, then a 600 MW nuclear power plant would be appropriate only for systems 6,000 MW or larger. According to official capacity expansion plans,<sup>46</sup> over 20 developing countries will have systems this size or larger by 1999. Although the World Bank projections are essentially a "business-as-usual" scenario, excluding aggressive efficiency improvements, it appears that 600 MW power plants, nuclear or otherwise, are not oversized for at least the larger developing countries. Moreover, the new nuclear plants

currently under development are expected to be about 150 MWe in size, making them a feasible size for some smaller countries as well.

- Technical Skill Requirements: Nuclear technology is complex, requiring a high level of skilled personnel. Few developing countries currently have sufficient domestic training facilities to produce these personnel, and would therefore be dependent on other countries for both the equipment and the operation of nuclear power plants. This could further aggravate foreign debt problems. This is not true for those countries, like China, that have considerable experience with and infrastructure for nuclear technologies (see box 6-D).
- Environmental Aspects: Nuclear power releases little of the air pollution associated with fossil fuel combustion. Every stage of the nuclear fuel cycle, however, poses the risk of releasing radioactive pollutants. Wastes vary from mining dust with a low level of radiation to the highly radioactive spent fuel rods, requiring careful<sup>47</sup> handling and long term disposal strategies. The probability of a large scale nuclear accident—such as Chernobyl—may be small, but poses serious implications for the environment and human health.
- Proliferation: Concern over nuclear weapons proliferation limits the attractiveness of export-

<sup>46</sup>E. Moore and G. Smith, World Bank, Industry and Energy Department, *Capital Expenditures for Electric power in the Developing Countries in the 1990s*, Industry and Energy Department Working Paper No. 21, February 1990, p. 49.

<sup>47</sup>United Nations Department of Technical Cooperation for Development, *Energy and Environment: Impacts and Controls* (New York, NY: October, 1990), p. 33.

ing nuclear power technologies. The links between nuclear power and nuclear weapons are subject to some dispute, but the basic issue is straightforward. Nuclear power requires nuclear fuels, facilities to process them, and trained personnel, and these facilities hypothetically could be used to produce nuclear weapons.<sup>48</sup> India's first demonstration of a nuclear weapon, detonated in 1974, was believed to be derived from research facilities.<sup>49</sup> More recently, the discovery of Iraq's nuclear weapons program has cast serious doubts on the ability of the existing nonproliferation regime or even much more stringent criteria<sup>50</sup> to control the spread of nuclear weapons.<sup>51</sup>

### Gas Turbines

A basic gas turbine is a conceptually straightforward device. Air is compressed and then mixed with natural gas. The mixture is ignited, and the expanding hot gas turns a turbine. The turbine drives both the air compressor and an electric generator.

Gas turbines have long served as peaking power plants for electric utilities in the United States. A number of innovative technologies have increased the efficiency of gas turbines from about 25 percent for a standard gas turbine<sup>52</sup> to up to 47 percent for the most advanced turbine systems using steam injection and other improvements.<sup>53</sup> These efficiency improvements are lowering costs to the point that gas turbines are no longer necessarily limited to peaking. Gas turbine costs are also relatively insensitive to scale,<sup>54</sup> and therefore can be sized to meet relatively small loads with only a modest cost penalty.

### Box 6-D—Nuclear Power in China

China suffers from severe power shortages, and coal and hydropower reserves, although plentiful, are expensive to use, aggravate environmental problems, and are located far from population centers. China, unlike other developing countries, also has a relatively large and experienced nuclear industry. These factors have led to ambitious plans for nuclear power generation. As with other technologies, China has shown a clear preference for domestic production over imports. In the case of nuclear power, China is both importing selected technologies where necessary while also working to develop indigenous production capabilities.

China's first nuclear power plant was a 300 MW PWR reactor using mostly indigenous technology located near Shanghai. Two 900 MW units, using imported technology, are under construction in Daya Bay. It is expected that much of the electricity from these units will be sold to Hong Kong. Also planned are two 600 MW units using domestic technology and two 1,000 MW units using Soviet technology.

SOURCES: Foreign Broadcast Information Service, *JPRS Report, Science and Technology—China: Energy*, JPRS-CEN-89-005, May 17, 1989. Y. Lu, "The Prospects and Economic Costs of the Reduction of the CO<sub>2</sub> Emissions in the PRC," presented at the Global Climate Change: The Economic Costs of Mitigation and Adaptation Conference, Dec. 4-5, 1990, Washington DC. U.S. Congress, Office of Technology Assessment, *Energy Technology Transfer to China, A Technical Memorandum*, OTA-TM-ISC-30 (Washington DC: U.S. Government Printing Office, September 1985).

One effective modification to the basic gas turbine is to use its hot waste gas to heat water and power a separate steam turbine. This combined cycle

<sup>48</sup>Proliferation concerns are discussed in more detail in U.S. Congress, Office of Technology Assessment, *Energy Technology Transfer to China*, OTA-TM-ISC-30 (Washington, DC: U.S. Government Printing Office, September 1985); U.S. Congress, Office of Technology Assessment, *Nuclear Power in an Age of Uncertainty*, OTA-E-216 (Washington DC: U.S. Government Printing Office, February 1984), pp. 200-203; U.S. Congress, Office of Technology Assessment, *Nuclear Proliferation and Safeguards* (New York: Praeger Publishing Co., June 1977).

<sup>49</sup>U.S. Congress, Office of Technology Assessment, *Nuclear Power in an Age of Uncertainty*, *Ibid.*, p. 202.

<sup>50</sup>R.H. Williams and H.A. Feiveson, "Derivation-Restricte Criteria for Future Nuclear Power," Center for Energy and Environmental Studies, Princeton University, May 26, 1989.

<sup>51</sup>R. Jeffrey Smith, "The Secret A-Arms Effort: Grim Lessons for the World," *The Washington Post*, Aug. 11, 1991, p. C1; see also, George W. Rathjens and Marvin M. Miller, "Nuclear Proliferation after the Cold War," *Technology Review*, August/September 1991, pp. 25-32.

<sup>52</sup>Electric Power Research Institute (EPRI), *TAG-Technical Assessment Guide, Electricity Supply 1989*, EPRI P-6587-L (Palo Alto, CA: Electric Power Research Institute, September 1989), p. 7-56, average annual heat rates. All heat rates given here are measured at higher heating value (HHV), that is they include the latent heat of condensation of the water produced.

<sup>53</sup>Natural gas fired ISTIG. See R. Williams and E. Larson, "Expanding Roles for Gas Turbines in power Generation," Thomas B. Johansson, Birgit Bodlund, and Robert H. Williams (eds.), *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications* (Lund, Sweden: Lund University Press, 1989), p. 524.

<sup>54</sup>*Ibid.*, p. 515.

process increases overall efficiency but at an increased capital cost (see app. B).<sup>55</sup> Construction can be phased, whereby the gas turbine can be built and operated, and the steam turbine added when needed.

Alternatively, the hot waste gas from the gas turbine can be used to heat water and the resulting steam injected directly back into the turbine. Again, this increases efficiency, but at some increase in capital cost (see app. B).<sup>56</sup> Several steam injected gas turbines, or STIGs, are already in use for industrial cogeneration.<sup>57</sup> Further modifications, such as intercooling, increase the efficiency even more,<sup>58</sup> but costs are uncertain.

Gas turbines are a promising technology for the developing world. As discussed in chapter 7, many developing countries have untapped natural gas reserves that could be a supply for future electricity needs. Gas turbines have a relatively low initial cost, and when combined with low cost domestically produced natural gas could produce electricity at a low total cost. Gas turbines can be sized to fit a wide range of needs, and there is little cost penalty for installing smaller units. Construction times can be quite short—less than 1 year.<sup>59</sup>

The technological sophistication of advanced gas turbines poses potential difficulties in maintenance for developing countries, but these could be overcome if modular aircraft derivative turbine designs are used. In this case, spares could be kept at a central regional facility and quickly transported to the site and swapped for a turbine needing maintenance.

Concerns over air quality and global warming also favor gas turbines, as they give off little SO<sub>x</sub> and up to 60 percent less CO<sub>2</sub> per kWh produced than

coal-fired plants.<sup>60</sup> NO<sub>x</sub> emissions, however, are a continuing concern: technologies for reducing NO<sub>x</sub> emissions, such as water or steam injection, are being explored.

### Cogeneration

Cogeneration is the combined production of electric or mechanical power plus thermal energy in a single process and from the same primary energy resource. A typical cogeneration system will produce electricity for running factory motors or for sale to the electric utility grid, and at the same time use the waste heat from electricity production to provide process heat for the plant or, in some cases, to be sold to neighboring industry, commerce, government buildings, or residential housing for heating. The passage of the Public Utility Regulatory Policies Act (PURPA) in 1978 has led to a substantial increase in cogeneration in the United States with large sales of privately cogenerated or otherwise produced electricity to the utility grid.<sup>61</sup>

Cogeneration is also heavily used in some developing countries. In China, for example, 4.6 GW of steam extraction turbines for cogeneration were on line in 1980, representing 11 percent of all steam turbine units. The thermal output from central station power plants used for cogeneration totaled about 11 percent of total national heating demand; 85 percent of this was used for process heat, 15 percent for space heat. For example, roughly 7 percent of building space heating in Beijing is supplied by cogeneration facilities.<sup>62</sup>

Yet cogeneration faces substantial obstacles in many countries.<sup>63</sup> In India, for example, many state

<sup>55</sup>Electric Power Research Institute (EPRI), *TAG-Technical Assessment Guide, Electricity Supply 1989*, EPRI P-6587-L (Palo Alto, CA: Electric Power Research Institute, September 1989), p. 7-61.

<sup>56</sup>*Ibid.*, pp. 7-57.

<sup>57</sup>R. Williams and E. Larson, "Expanding Roles for Gas Turbines in Power Generation," Thomas B. Johansson, Birgit Bodlund, and Robert H. Williams (eds.), *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications* (Lund, Sweden: Lund University Press, 1989), p. 529.

<sup>58</sup>*Ibid.*, p. 531.

<sup>59</sup>Electric Power Research Institute (EPRI), *TAG-Technical Assessment Guide, Electricity Supply 1989*, EPRI P-6587-L (Palo Alto, CA: Electric Power Research Institute, September 1989), p. 7-58.

<sup>60</sup>For ISTIG. R. Williams and E. Larson, "Expanding Roles for Gas Turbines in Power Generation" Thomas B. Johansson, Birgit Bodlund, and Robert H. Williams (eds.), *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications* (Lund, Sweden: Lund University Press, 1989), p. 539.

<sup>61</sup>U.S. Congress, Office of Technology Assessment, *Industrial and Commercial Cogeneration*, OTA-E-192 (Washington, DC: U.S. Government Printing Office, February 1983).

<sup>62</sup>Qu Yu, "Cogeneration in the People's Republic of China," *The Energy Journal*, vol. 5, No. 2, 1984, pp. 133-137.

<sup>63</sup>An OTA report has examined many of the issues surrounding cogeneration; U.S. Congress, Office of Technology Assessment, *Industrial and Commercial Cogeneration*, OTA-E-192 (Washington, DC: U.S. Government Printing Office, February 1983).

Table 6-1 I-Geothermal Electricity y Generation in Developing Countries (1990)

Country	Geothermal capacity (MW)	Technology
Philippines . . . . .	894	Single flash
Mexico . . . . .	725	Dry steam, single flash, double flash
Indonesia . . . . .	142	Dry steam, single flash
El Salvador . . . . .	95	Single flash, double flash
Nicaragua . . . . .	70	Single flash
Kenya . . . . .	45	Single flash
Argentina . . . . .	<1	Binary
Zambia . . . . .	<1	Binary
Us. . . . .	2,827	All

SOURCE: R. DiPippo, "Geothermal Energy," on Proceedings of the *Energy and Environment in the 21st Century Conference*, Mar. 26-28, 1990, Cambridge, MA.

electricity boards may refuse to take privately generated power at all; others may impose a sales tax on self-generated electricity; some may decrease the maximum power available to industries with on-site generation capabilities, and then may be reluctant to provide backup power for occasions when the cogeneration systems are down.<sup>64</sup> Responses to these barriers include requirements for state electricity boards to purchase self-generated power at reasonable—i. e., avoided cost with some small adjustments—rates as in the United States under PURPA regulations; the development of generic contract forms for cogeneration arrangements with state or national grids; and the provision of backup power.

### Geothermal <sup>65</sup>

Heat inside the Earth can be used to produce electricity. Worldwide geothermal generating capacity, which includes several developing countries, is almost 5 GW (see table 6-11).<sup>66</sup> Recent technological advances may allow for the expanded use of geothermal energy. Worldwide geothermal resource estimates are very uncertain and must generally be quantified locally by drilling wells (see table 6-12).

Technologies for utilizing geothermal resources include direct steam, single-flash, dual-flash, and binary systems. The simplest technology is direct steam, in which steam is piped directly from underground reservoirs and used to drive turbines. The initial capital cost of a direct steam geothermal unit is estimated at about \$1,100/kW.<sup>67</sup> Single-flash units are quite similar, except they make use of underground hot water that is "flashed" into steam. Most existing geothermal plants are direct steam or single-flash. A dual-flash system uses a second flash-tank to capture energy that would otherwise not be utilized. This can increase the overall efficiency by up to one-fifth, but at a somewhat higher cost—capital costs for dual-flash units are estimated at \$1,600 to 1,900/kWe.<sup>68</sup> Several dual-flash systems are currently operating.<sup>69</sup>

A new technology of special relevance to developing countries is the binary cycle unit. This technology uses an intermediate working fluid to transfer energy from the geothermal resource to the turbine. This allows for the use of relatively low temperature resources, typically 170 to 180 °C.<sup>70</sup> Binary plants can be quite small (typically 5 to 10 MWe) and can be erected and operated in as little as

<sup>64</sup>Ahmad Faruqi et al., "Application of Demand-Side Management to Relieve Electricity Shortages in India," contractor report prepared for the Office of Technology Assessment, April 1990.

<sup>65</sup>This discussion does not include geopressed or hot dry rock resources, as these resources cannot be utilized for electricity generation with existing technology.

<sup>66</sup>R. DiPippo, "Geothermal Energy: Electricity Production and Environmental Impact A Worldwide Perspective," paper presented at the Energy and Environment in the 21st Century Conference, Cambridge, MA, Mar. 26-28, 1990, p. DIII-21.

<sup>67</sup>Electric Power Research Institute (EPRI), *TAG-Technical Assessment Guide, Electricity Supply 1989*, EPRI P-6587-L (Palo Alto, CA: Electric Power Research Institute, September 1989), pp. 7-73. 1990 dollars.

<sup>68</sup>U.S. Congress, Office of Technology Assessment, *New Electric Power Technologies*, OTA-E-246 (Washington, DC: U.S. Government Printing Office, July 1985), p. 99, in 1990\$. These costs do not include costs to extract, pump, transport, or reinject the water/steam.

<sup>69</sup>For a more detailed discussion of the dual-flash technology, see *ibid.*, p. 97.

<sup>70</sup>The Heber binary-cycle demonstration plant in Northern California makes use of brine at 170-180 °C. See Electric Power Research Institute (EPRI), *TAG-Technical Assessment Guide, Electricity Supply 1989*, EPRI P-6587-L (Palo Alto, CA: Electric Power Research Institute, September 1989), p. 7-75.

**Table 6-12-Geothermal Resources Suitable for Electricity Generation in Selected Developing Countries**

Country	Geothermal electric power potential (GW)	Country	Geothermal electric power potential (GW)
China .....	160	Bolivia .....	22
Indonesia .....	130	Philippines .....	20
Peru .....	86	Venezuela .....	12
Mexico .....	77	Vietnam .....	11
Chile .....	54	Nicaragua .....	10
Ethiopia .....	50	Chad .....	9
Ecuador .....	30	Zambia .....	8
Brazil .....	29	Guatemala .....	7
Kenya .....	24	Korea .....	7
Colombia .....	23	Us. ....	150

SOURCE: Electric Power Research Institute, "Geothermal Energy Prospects for the Next 50 Years," EPRI ER-611-SR, February 1978. Estimates are uncertain, and do not consider costs.

100 days.<sup>71</sup> Costs for a large (54 MWe) plant are estimated at about \$1,800/kWe<sup>72</sup>, smaller plants are estimated to cost \$1,800 to \$2,400/kWe.<sup>73</sup> Other costs associated with geothermal energy include drilling wells, pumping, and reinfected water. These costs are heavily site dependent, but are estimated at 2.4 to 8.5 cents/kWh.<sup>74</sup>

The major advantages of geothermal technologies are its use of an indigenous resource (see table 6-12), its lowland requirements, and, if modular technologies such as binary systems are used, short construction lead times.

The major constraints on greater use of geothermal resources for electricity production are resource limits and costs. Although geological studies can help to locate geothermal potential, this resource can only be quantified by expensive drilling.<sup>75</sup> The subsequent resource extraction also requires technical expertise and can be costly. Finally, geothermal energy can be depleted if oversubscribed, as has occurred at The Geysers in northern California.<sup>76</sup>

The environmental effects of geothermal power include CO<sub>2</sub> and H<sub>2</sub>S emissions and high water consumption. The CO<sub>2</sub> emissions are dependent on the CO<sub>2</sub> content of the resource, but are on average about 5 percent of the CO<sub>2</sub> emissions of a coal plant, per kWh output. H<sub>2</sub>S emissions are regulated in the United States to 30 parts per billion. There are several H<sub>2</sub>S control technologies in use in the United States, while many other countries do not currently control H<sub>2</sub>S emissions. Binary technology has no emissions of CO<sub>2</sub> or H<sub>2</sub>S. Water requirements vary, depending on the plant design. Large binary plants can require as much as five times as much water, per kW, as a coal plant. Small binary plants, however, can use air-cooled condensers.<sup>77</sup>

Site specific environmental problems can include subsidence of land overlying wells; contamination of water supplies by saline (and sometimes toxic) geothermal fluids and reinfected water; and the generation of surplus high temperature liquid effluents containing metals and dissolved solids.<sup>78</sup> These problems can be controlled.

<sup>71</sup>U.S. Congress, Office of Technology Assessment, *New Electric Power Technologies*, OTA-E-246 (Washington, DC: U.S. Government Printing Office, July 1985), p. 101. This does not include the time required to locate or tap the resource.

<sup>72</sup>Electric Power Research Institute (EPRI), *TAG-Technical Assessment Guide, Electricity Supply 1989*, EPRI P-6587-L (Palo Alto, CA: Electric Power Research Institute, September 1989), pp. 7-73.

<sup>73</sup>U.S. Congress, Office of Technology Assessment, *New Electric Power Technologies*, OTA-E-246 (Washington, DC: U.S. Government Printing Office, July 1985), p. 102, in 1990S.

<sup>74</sup>*Ibid.*, p. 309.

<sup>75</sup>By one estimate, geothermal drilling costs in Kenya are roughly \$250/foot. From E.Eliasson, "Geothermal Conversion and Its Role," paper presented at The Advanced Technology Alert System Meeting on New Energy Technologies, Moscow, U. S. S.R., October 1988, p. 8.

<sup>76</sup>Richard A. Kerr, "Geothermal Tragedy of the Commons," *Science*, vol. 253, No. 5016, pp. 134-135, July 12, 1991.

<sup>77</sup>R. DiPippo, "Geothermal Energy: Electricity Production and Environmental Impact A Worldwide Perspective," paper presented at the Energy and Environment in the 21st Century Conference, Cambridge, MA, Mar. 26-28, 1990, pp. DIII-13, DIII-16.

<sup>78</sup>U.S. Congress, Office of Technology Assessment, *Energy in Developing Countries*, OTA-E-486 (Washington, DC: U.S. Government Printing Office, January 1991), p. 130.

### Solar Thermal

Solar thermal electric technologies use sunlight to heat a fluid, and then use the hot fluid and steam to turn a turbine that generates electricity. The parabolic trough is the most mature of the solar thermal electric technologies. Parabolic troughs are long channels that focus sunlight onto a pipe at the center, heating a liquid (oil, water, or brine) that is then used to heat steam, powering a turbine generator. Several hundred MW of solar thermal electric capacity using the parabolic trough design is now in place in California. These systems are gas and solar hybrids, with the gas supplementing solar radiation at night or during cloudy periods.<sup>79</sup> Other technologies include parabolic dishes and central receivers. Their costs and performance, however, remain uncertain.<sup>80</sup>

Although the costs for solar thermal electric technologies remain somewhat higher than conventional fossil steam plants, they have been declining in recent years due to improvements in the technology gained largely through demonstration projects in southern California.<sup>81</sup>

Off-grid generation of electricity through solar thermal-electric technology has yet to be demonstrated, but such an application is thought possible.<sup>82</sup> The modular nature of the technology could lessen problems of economies of scale that often inhibit electrification in developing countries. For many developing countries, the abundance of sunshine and the potential for off-grid generation make these technologies promising. Since the areas with the highest incidence of solar radiation tend to be dry and hot (see table 6-13), water used as a transfer medium or to operate the turbine generator may be a scarce resource. Without further research, development, and demonstration, however, these technologies may not be cost effective for grid applications in many developing countries in the near term.

Table &13-Solar Radiation in Selected Countries

Region	Solar radiation (kWh/m <sup>2</sup> /year)
Mali.....	2,490
Niger.....	2,450
Mexico.....	2,080
Sierra Leone.....	2,000
Venezuela.....	2,000
India.....	1,950
Brazil.....	1,880
Chile.....	1,630

SOURCE: California Energy Commission, *Renewable Energy Resources Market Analysis of the World*, P50G87-015, pp. 14-16. Average annual horizontal insolation.

### Fuel Cells

Fuel cells are another promising future electric power source for developing countries. Fuel cells are conceptually similar to a battery in that they convert chemical energy in a fuel to direct current electricity, achieving high efficiencies (40 to 60 percent, and 85 percent with cogeneration<sup>83</sup>) with low emissions. The cells are modular and can be sized to fit different and changing applications. This highly sophisticated technology is still being developed and is just beginning to see commercialization in industrialized countries. Further commercial experience is needed to resolve some of the uncertainties about cost and performance before fuel cells can be used with confidence in developing countries.

### Comparing the Technologies

*If* choice of technology were based solely on the levelized costs of generation, abstracting from site specific factors that can strongly influence the costs, then many technologies are available within the same broad cost range (see figure 6-2 and app. B at the back of this report). Even some of the highest cost options, such as decentralized renewable, may still be competitive in many situations as they avoid transmission and distribution losses and costs.

<sup>79</sup>U.S. Department of Energy, Solar Energy Research Institute, *The Potential of Renewable Energy: An Interlaboratory White Paper*, Report No. SERVI/P-260-3674 (Golden, CO: Solar Energy Research Institute, March 1990), p. E-1; Electric Power Research Institute (EPRI), *TAG-Technical Assessment Guide, Electricity Supply 1989*, EPRI P-6587-L (Palo Alto, CA: Electric Power Research Institute, September 1989), p. 7-82.

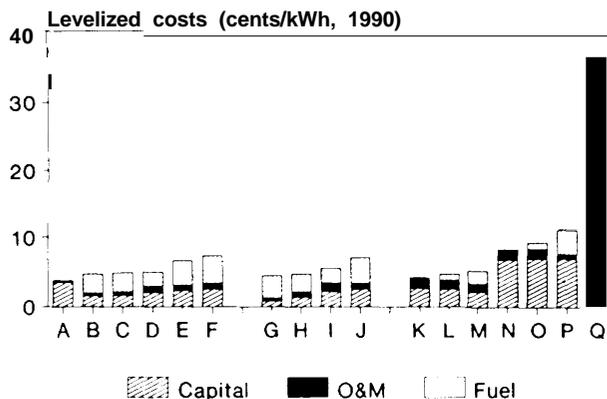
<sup>80</sup>Charles Y. Wereko-Brobby and Frederick O. Akuffo, *Solar Power Generation: Stares and Prospects for Developing Countries*, unpublished paper (October 1988), p. 24, table 3.

<sup>81</sup>U.S. Department of Energy, Solar Energy Research Institute, *The Potential of Renewable Energy: An Interlaboratory White Paper*, SERI/TP-260-3674 (Golden, CO: Solar Energy Research Institute, March 1990), p. E-6.

<sup>82</sup>Ibid., p. E-5.

<sup>83</sup>Fred Kemp, Program Manager, International Fuel Cells, presentation to the Office of Technology Assessment, May 22, 1991.

Figure 6-2—Levelized Costs of Electricity Generating Technologies (1990)



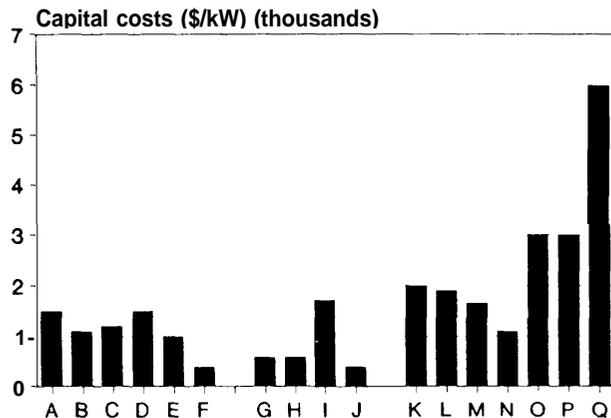
Technologies A-Q are described in app. B. Technologies A-F are conventional technologies: A = hydroelectric power; B = natural gas-fired steam plant; C = oil-fired steam plant; D = coal-fired steam plant; E = diesel engine generator; F = combustion turbine. Technologies G-J are improvements to existing technologies: G = distillate-fired combined-cycle plant; H = natural gas-fired steam-injected gas turbine; I = coal-fired fluidized bed; J = natural gas-fired advanced combustion turbine run on a simple cycle. Technologies K-Q are innovative technologies: K = binary geothermal; L = advanced nuclear; M = integrated gasification combined cycle; N = wind turbine; O = solar thermal/natural gas hybrid; P = fuel cell; and Q = photovoltaic. Note that these costs do not include other costs associated with operations on a systemwide basis. See app. A and app. B for details.

SOURCE: U.S. Congress, Office of Technology Assessment, 1992. See app. B for more detail.

The initial capital cost of the different technologies is an important factor for many developing countries. With capital costs, the range is much wider; gas turbine and oil combined cycle are on the low end and hydro and nuclear are on the high end (see figure 6-3). Though developing countries generally are capital constrained, the electricity sector may be less affected than others due to the availability of relatively low cost public sector funds for supply expansion. If the role of private generators, -dependent on raising funds from local markets—grows, initial capital costs may become of mounting importance in technology choice.

Technology choice is also affected by the resource and other characteristics of the individual country. Most countries will wish to adopt technologies that use domestic resources, especially when these resources (e.g., coal and hydro) are of limited commer-

Figure 6-3—Capital Costs of Electricity y Generating Technologies (1990)



Technologies A-Q are described in app. B. Technologies A-F are conventional technologies: A = hydroelectric power; B = natural gas-fired steam plant; C = oil-fired steam plant; D = coal-fired steam plant; E = diesel engine generator; F = combustion turbine. Technologies G-J are improvements to existing technologies: G = distillate-fired combined-cycle plant; H = natural gas-fired steam-injected gas turbine; I = coal-fired fluidized bed; J = natural gas-fired advanced combustion turbine run on a simple cycle. Technologies K-Q are innovative technologies: K = binary geothermal; L = advanced nuclear; M = integrated gasification combined cycle; N = wind turbine; O = solar thermal/natural gas hybrid; P = fuel cell; and Q = photovoltaic. Note that these costs do not include other costs associated with operations on a systemwide basis. See app. A and app. B for details.

SOURCE: U.S. Congress, Office of Technology Assessment, 1992. See app. B for more detail.

cial value in other uses. In some cases, however, development of domestic resources may be limited by their inaccessibility. The size of the country and its grid influence technology choice. Countries with small grids cannot accommodate technologies (e.g., present day nuclear facilities) that are inherently large scale. Uncertainty over load growth can lead to favoring small scale technologies that are well known, such as diesel generators.

## OPTIONS FOR RURAL ELECTRICITY SERVICE

The provision of electric service to rural areas is an important aspect of social and economic development.<sup>84</sup> The traditional means of rural electrification is extension of the existing electricity grid. An alternative method is to produce electricity off-grid, using diesel or gasoline powered engine generators.

<sup>84</sup>A recent World Bank report states, "most of the rural population in developing countries are not served by electricity and even in those countries where there have been rural electrification programs over the last 10-20 years, only a few serve more than 20% of their rural population." From M. Mason, *Rural Electrification—A Review of World Bank and USAID Financed Projects*, background paper for the World Bank April 1990, p. 1.

This avoids the need for expensive transmission lines to remote areas, but engenders problems with expensive, scarce, and unreliable fuel supplies.

Renewable electricity generating technologies—small wind turbines, photovoltaics, and microhydro—may be able to play an important role here. They are not dependent on fossil fuels and recent advances have reduced their costs to competitive levels for many remote power generation applications.

### *Wind Turbines*

Wind power has long been used to pump water, grind grain, and meet other mechanical needs (see box 6-E). The amount of electricity generated by wind remained small, however, until the early 1980s when a combination of new legislation and tax credits in the United States led to the installation of a large number of wind turbines. Many of these were large (100+ kW) grid-connected units in California,<sup>85</sup> but smaller, off-grid turbines were installed as well. Although many of the tax credits have been eliminated, wind turbine technology has continued to progress and now appears to be competitive with traditional generation in some applications. The major constraints on widespread use of wind turbines are wind resource limitations and backup requirements.

Wind turbines come in all sizes, from units as small as 100 watts used in China to 100+ kW units used for utility scale generation. Furthermore, units can be combined into large wind farms like the Altamont Pass area in California, with a generating capacity of over 600 MW.<sup>86</sup>

Wind resources are distributed very unevenly over the Earth's surface and are strongly influenced by climate and terrain. Several studies have used spot measurements and climatological data to identify regions with high windpower potential. A recent study for the World Bank identified developing countries<sup>87</sup> that would be appropriate for grid-connected wind turbines. The criteria for inclusion included sufficient wind resource within 50 km of

### **Box 6-E—Wind Turbines for Water Pumping**

*The* Naima region of Northeast Morocco is very dry and the soil is relatively unfertile, making water the key to sustaining life. Donor aid had provided a diesel pumping system that tapped a local spring and pumped the water to holding tanks—but the local residents found the operations, maintenance, and fuel costs of the system made it all but unaffordable.

The need for a sustainable system, which would not be dependent on the residents' scarce cash income, was needed. In 1986 the Moroccan Government, along with the U.S. Agency for International Development (AID), implemented the Naima Wind Project. This project used two 10 kW wind turbines, designed and manufactured in the United States, to replace the diesel pumps.

After several delays and problems (including poor timing—Ramadan, the Islamic month of fasting, began 1 day after the installation team arrived), the wind pumping system began operations in 1990. Reliability has been quite high (88 to 100 percent), and replication costs are estimated at about \$2,500/kW. A detailed economic analysis found that the lifecycle costs for the wind system were lower than for a comparable diesel system—and the benefits to the local residents of a dependable, low-cost water supply, although difficult to measure, are large.

**SOURCE:** M. Bergey, "Sustainable Community Water Supply: A Case Study from Morocco," paper presented at the American Wind Energy Association National Conference, September 1990.

the existing electricity grid, so this list is not appropriate for identifying all off-grid potential sites. A separate study identified the western and eastern coasts of Africa, eastern Asia, and western and southern South America as most promising for wind-generated electricity.<sup>88</sup>

There are two principal components of costs for wind turbines—the initial capital costs, and the operation and maintenance (O&M) costs. The capital costs of small turbines varies from about \$5,500/

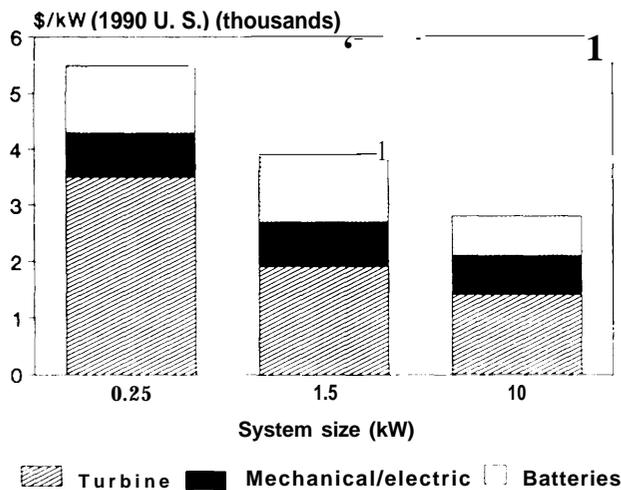
<sup>85</sup>B, 1985, California wind turbines were generating 670 GWh/year. D.R. Smith, "The Wind Farms of the Altamont Pass Area," *Annual Review of Energy*, vol. 12, 1987, p. 146.

<sup>86</sup>D.R. Smith, "The Wind Farms of the Altamont Pass Area," *Annual Review of Energy*, vol. 12, 1987, p. 145, as of December 1986.

<sup>87</sup>Strategies Unlimited, "Study of the Potential for Wind Turbines in Developing Countries," contractor paper prepared for the U.S. Department of Energy and the World Bank, March 1987. The identified countries include Argentina, Brazil, Chile, China, Colombia, Costa Rica, India, Kenya, Pakistan, Peru, Sri Lanka, Tanzania, Uruguay, Venezuela, Zambia, and Zimbabwe.

<sup>88</sup>Based on data collected by Battelle Pacific Northwest Laboratory, and reported in California Energy Commission, *Renewal (sic) Energy Resources Market Analysis of the World*, CEC P500-87-015, p. 34.

Figure 6-4-Capital Costs of Wind Turbines



SOURCE: U.S. Congress, Office of Technology Assessment, 1992.

kW for a small 250 W system to about \$2,800/kW for a larger 10 kW system, including storage (see figure 6-4).<sup>89</sup> The cost of large wind turbines for on-grid applications (not including storage) are much lower than this. By some estimates, the capital cost of large turbines could be as low as \$600 per installed kilowatt by the mid-1990s.<sup>90</sup>

The operations and maintenance costs of intermediate size turbines are estimated at 0.7 to 1.5 cents per kWh.<sup>91</sup> Data on O&M costs for small turbines are not well documented. Data from a 5-year field test of a 10 kW turbine conducted by Wisconsin Power and Light Co. suggest O&M costs as low as 0.3 cents per kWh.<sup>92</sup> The leveled costs of wind-generated electricity are compared with those of other generating technologies in figure 6-5.

Wind turbines are dependent on a resource that, unlike fossil fuels, cannot be stored. The best wind

turbines in California achieve a 90 percent reliability,<sup>93</sup> but this translates to a capacity factor of 35 percent (see glossary for definitions) because the wind does not blow steadily year round. Although the reliability of the wind turbines has improved considerably, resource limits will continue to be the major constraint to widespread use of this technology.

Stand alone applications often require a backup generating system or a storage system depending on the specific application and the characteristics of the local wind resource. Small wind turbines are used for battery charging in Inner Mongolia, for example,<sup>94</sup> and for this application short term fluctuations in wind are less important. For services such as lighting or refrigeration, however, a battery or other backup supply is needed, considerably adding to the system cost. For grid-connected wind turbines, fluctuations in output due to changes in wind speed can be moderated by other generating units in the grid and no storage is necessary.

The land requirements of wind turbines can be large. A typical 100 kW turbine in California, for example, requires about 1.2 hectares (ha) of land, or 12 ha/MW.<sup>95</sup> Crop production and livestock grazing can still be done on this land, however. Otherwise, wind turbines have few adverse environmental impacts. There are no direct air emissions or water requirements, and noise levels are generally low (except in the immediate vicinity of the turbine). Concerns have been raised, however, about the impact of wind turbines on local bird populations.

The design and fabrication of the wind turbine itself is somewhat complex and may not be readily done in many developing countries. The manufac-

<sup>89</sup>These costs are for the entire wind-electric system, including batteries.

<sup>90</sup>Judith M. Siegel and Associates, "Wind Electric, Photovoltaic, and Micro-Hydro Technologies for Developing World Applications," contractor report prepared for the Office of Technology Assessment, October 1990, p. 22.; Michael L.S. Bergey, Bergey Windpower Co., *Comments on the Maturation and Future Prospects of Small Wind Turbine Technology*, paper presented at the A. S.E.S. Solar '90 Conference, Norman, OK, Mar. 22, 1990; Michael L.S. Bergey, *Small Wind Turbines for Rural Energy Supply in Developing Countries* (Norman, OK: Bergey Windpower Co., June 1988, revised June 1989).

<sup>91</sup>Judith M. Siegel and Associates, "Wind Electric, Photovoltaic, and Micro-Hydro Technologies for Developing World Applications," contractor report prepared for the Office of Technology Assessment, October 1990, p. 23.

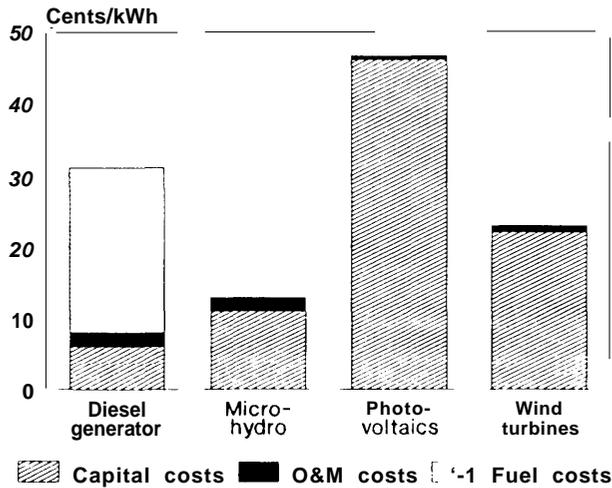
<sup>92</sup>Michael L.S. Bergey, Bergey Windpower Company, *Comments on the Maturation and Future Prospects of Small Wind Turbine Technology*, paper presented at the A. S.E.S. Solar '90 Conference, Norman, OK, Mar. 22, 1990, page 6.

<sup>93</sup>T. Moore, "Excellent Forecast for Wind," *EPRI Journal*, vol. 15, No. 4, June 1990, p. 19.

<sup>94</sup>Judith M. Siegel and Associates, "Wind Electric, Photovoltaic, and Micro-Hydro Technologies for Developing World Applications," contractor report prepared for the Office of Technology Assessment, October 1990, p. 28

<sup>95</sup>D.R. Smith, "The Wind Farms of the Altamont Pass Arm," *Annual Review Energy*, vol. 12, 1987, p. 145.

**Figure 6-5--Levelized Cost of Remote Electricity Generating Technologies**



This figure compares nominal costs for different technologies where good wind, hydro, and solar resources are present. Note that these figures do not include system losses of power conditioning or battery storage and will vary widely depending on local conditions.

SOURCE: U.S. Congress, Office of Technology Assessment, 1992.

turing and assembly of most other components—such as the tower, cabling, etc., however, account for half the initial cost of the system and might be done within the country.<sup>96</sup>

### Photovoltaics (PVs)

Photovoltaics convert sunlight directly into electricity with no moving parts and no direct fuel consumption. Their modular design lends itself to both small and large scale applications, they are reliable, and they require little maintenance. The major disadvantages of photovoltaics are high first cost and, as in wind turbines, the intermittent nature of the resource. There are several types of photovoltaics, with varying costs, performance, and potential for future cost reductions.

Crystalline silicon photovoltaic cells have been the dominant technology since the first solar cell was produced in 1954, and still account for a large fraction of commercial photovoltaic production. The efficiencies of these cells are as high as 23 to 24 percent in the laboratory (with no concentration) and typically 12 to 13 percent in commercially available form. The manufacturing costs and material requirements of crystalline silicon photovoltaic cells are relatively high, which has led to research into using other manufacturing approaches and materials. Polycrystalline thin films of silicon are lower cost than single crystal silicon, but have somewhat lower laboratory and commercial unit conversion efficiencies.<sup>97</sup>

Amorphous silicon photovoltaic cells are used in consumer products, such as watches and calculators. Efficiencies of these cells in commercial modules are typically 4 to 5 percent after several months of use, although laboratory efficiencies as high as 9.5 percent have been achieved.<sup>98</sup> Present designs suffer from light induced degradation to about five-sixths of their initial efficiency in the first year,<sup>99</sup> although alternative designs to reduce this are being explored. Amorphous silicon cells have the potential for low cost manufacturing.

Compound semiconductors, made up of combinations of semiconductor materials other than silicon, are also produced, although in considerably lower volumes than silicon based solar cells. Recent laboratory breakthroughs have pushed the efficiency of thin film cadmium telluride cells to roughly 14.5 percent. The required materials for compound photovoltaics could be environmentally harmful if mis-handled.

Concentrators use mirrors or lenses to concentrate solar radiation onto photovoltaic cells. Laboratory efficiencies of more than 28 percent have been achieved with concentrators using single crystal

<sup>96</sup>The turbine blades, however, would probably need to be imported, but they account for only about 5-15% of total material costs. Michael L.S. Bergey, Bergey Windpower Co., letter to Office of Technology Assessment, Feb. 6, 1991.

<sup>97</sup>Department of Energy, "Photovoltaic Energy Program Summary Volume I: Overview, Fiscal Year 1989"; D. Carlson, "Photovoltaic Technologies for Commercial Power Generation," *Annual Review of Energy*, vol. 15, 1990, pp. 85-119. Also T. Moore, "Thin Films: Expanding the Solar Marketplace," *EPRI Journal*, March 1989, p. 4. Efficiency, as used here, is the amount of electric output divided by the amount of energy, as sunlight, received as input. It is a useful criterion because the cells are the major expense of PV systems, and greater efficiency means less cell area required to produce a given electrical output. PV efficiencies given here are for commercial products, which can be considerably lower than that achieved in the laboratory under ideal conditions.

<sup>98</sup>Department of Energy, "Photovoltaic Energy Program Summary: Volume I: Overview, Fiscal Year 1989" D. Carlson, "Photovoltaic Technologies for Commercial Power Generation" *Annual Review of Energy*, vol. 15, 1990, p. 85-119. Also T. Moore, "Thin Films: Expanding the Solar Marketplace," *EPRI Journal*, March 1989, p. 4.

<sup>99</sup>T. Peterson, "Amorphous Silicon Thin-Film Solar Cells," *EPRI Journal*, vol. 13, No. 4, June 1988, p. 42.

silicon cells.<sup>100</sup> The additional cost of the mirrors or lenses can be offset by the smaller cells; concentrators may, however, require more frequent cleaning, adding to the O&M costs of the system.

There are two components of photovoltaic system capital costs—the photovoltaic cells and the balance-of-system (BOS) components, which includes everything else—the structures holding the photovoltaic cell, power conditioning equipment to convert direct current electricity to commonly used alternating current, controls, possibly battery storage, and others. Costs of photovoltaic cells have dropped dramatically due to technical advances, but still remain higher than many alternatives. Current prices are about \$4,000 to \$6,000/kW<sub>p</sub>, excluding balance-of-system costs.<sup>101</sup> Prices are expected to continue to fall, due to advances in photovoltaics design, advances in manufacturing, and economies of scale from increased production volumes.<sup>102</sup>

Balance-of-system costs depend on the specific application. AC systems require an inverter to convert the photovoltaic DC current to AC current. There are, however, lights, refrigerators, and other appliances that can use DC current directly. Small, remote systems commonly use batteries to store power. The size (and therefore cost) of the battery system will depend on the load and on how long one requires the backup system to produce electricity. Shown in table 6-14 are some representative costs for specific systems.

Operating and maintenance (O&M) costs for photovoltaic systems are in general quite low. O&M

**Table 6-14-Representative Balance of System (BOS) Costs for Specific Photovoltaic Applications**

	Dominican Republic
Application:	Small residential system, 38 W <sub>p</sub>
BOS rests:	Battery \$1,050/kW (lasts 3-5 years) Electronic control equipment \$1,000/kW
	United States
Application:	Residential mixed use system, 200 W <sub>p</sub>
BOS costs:	Battery \$1,400/kW (lasts 3-5 years) Mounting hardware \$800/kW Electronic control equipment \$1,800/kW

SOURCE: Data for Dominican Republic from D. Waddle, R. Perlack, and R. Hansen, "Rural Based Photovoltaic Systems in the Dominican Republic: An Agenda for Future Activities," Report to the U.S. DOE by ORNL. Data for United States from Real Goods Trading Company, Ukiah, CA.

costs for existing systems can usually be traced to problems with the BOS components. By one estimate, O&M costs for small photovoltaic systems are about 0.5 cents/kWh.<sup>103</sup> Systems with battery storage require battery replacement every 3 to 5 years. The Electric Power Research Institute examined O&M costs for utility scale systems, and found that flat plate photovoltaic systems had actual O&M costs of 0.39 to 1.44 cents/Wh.<sup>104</sup>

Photovoltaic systems have been found to be highly reliable in developing countries,<sup>105</sup> as well as the United States. For example, a survey of residential photovoltaic systems in the United States found most systems were operating properly 90 percent or more of the time.<sup>106</sup>

<sup>100</sup>Department of Energy, "Photovoltaic Energy Program Summary, Volume I: Overview, Fiscal Year 1989."

IO ID, Carlson, "Photovoltaic Technologies for Commercial Power Generation," *Annual Review of Energy*, vol. 15, 1990, p. 92, estimates \$4,000/kW<sub>p</sub> in 1988. United Nations, Committee on the Development and Utilization of New and Renewable Sources of Energy, "Direct Solar-to-Electrical Energy Conversion" Report of the Secretary-General, Mar. 8, 1990, estimates price for crystalline silicon of \$4,000/kW<sub>p</sub> for large orders, excluding delivery and taxes. A retailer in the U.S. sells PV panels for about \$6,000/kW<sub>p</sub> in small quantities. Current price in the Dominican Republic for a 38 watt (peak) panel is \$226, or about \$6,000/kW<sub>p</sub>. See D. Waddle, R. Perlack, and R. Hansen, U.S. Department of Energy, Oak Ridge National Laboratory, *Rural Based Photovoltaic Systems in the Dominican Republic: An Agenda for Future Activities*, Report No. DE-84OR21400 (Oak Ridge, TN: Oak Ridge National Laboratory).

<sup>102</sup>U.S. Department of Energy, Solar Energy Research Institute, *The Potential of Renewable Energy*, SERI/TP-260-3674 (Golden, CO: Solar Energy Research Institute, March 1990), reports PV industry representatives forecasting \$1,000/kW<sub>p</sub> by 1995. Electric Power Research Institute (EPRI), *TAG-Technical Assessment Guide, Electricity Supply 1989*, EPRI P-6587-L (Palo Alto, CA: Electric Power Research Institute, September 1989), p. 7-81 forecasts \$1,500/kW<sub>p</sub> in 1994 for a large flat-plate system.

<sup>103</sup>Meridian Corp., "Evacuation of international Photovoltaic Projects, Volume II: Technical Report," prepared by Sandia for DOE and AID, SAND85-7018/2, September 1986, p. 13-4.

<sup>104</sup>Lynette and Associates, "Photovoltaic Operation and Maintenance Evaluation," GS-6625 (Palo Alto, CA: Electric Power Research Institute, December 1989).

<sup>105</sup>Meridian Corp., "Evaluation of International Photovoltaic Projects, Volume II: Technical Report," prepared by Sandia for DOE and AID, SAND85-7018/2, September 1986. Reliability refers to the fraction of time the system is operating correctly, and does not include resource limits. A PV system with 100% reliability will have zero output at night, and diminished output when solar radiation levels are low.

<sup>106</sup>Electric Power Research Institute, "Survey of U.S. Line-Connected Photovoltaic Systems," EPRI GS-6306 (Palo Alto, CA: Electric Power Research Institute, March 1989), pp. 3-7.

### **Box 6-F—Photovoltaic Powered Vaccine Refrigerators**

Vaccines must be kept cold to maintain effectiveness. Vaccine refrigerators powered by fossil fuels are dependent on expensive and erratic fuel supplies, leading to loss of vaccines. The World Health Organization (WHO) has examined the potential of photovoltaic-powered refrigerators for vaccine storage and is installing them in rural health care centers and hospitals in several developing countries. Photovoltaic powered refrigerators offer independence from fossil fuels, longer system life, improved temperature control, and greater mechanical reliability.

In Zaire, domestically designed and produced photovoltaic powered refrigerators using imported compressors and batteries have been placed in rural areas and have been reported as more reliable than kerosene refrigerators. In India, there are more than 200 rural health care centers without grid access, and photovoltaic powered refrigerators are now being tested under Indian conditions. Mali, Sudan, Indonesia, and several other countries are now using photovoltaic powered vaccine refrigerators.

Although the initial capital costs of the photovoltaic system are high, the longer life, fuel cost savings, and increased reliability of the photovoltaic system lead to a cost of about 32 cents per dose for the photovoltaic system, as compared to 47 cents for the kerosene system.

**SOURCES:** United Nations, Committee on the Development and Utilization of New and Renewable Sources of Energy, "Direct Solar-to-Electrical Energy Conversion" Report of the Secretary-General, Mar. 8, 1990. Government of India, Ministry of Energy, Department of Non-Conventional Energy Sources, *Annual Report 1988-89*, p. 53. See also C. Rovero and D. Waddle, *Vaccine Refrigeration Technologies and Power Sources*, Report No. ORNL-6558 (Oak Ridge, TN: Oak Ridge National Laboratory, April 1989).

The lifetimes of photovoltaic cells vary. Cells used for vaccine refrigeration systems are expected to last 15 years (see box 6-F).<sup>107</sup> Utility scale systems are forecasted to last 20 years.<sup>108</sup> Balance-of-system components, particularly batteries, rather than the cells themselves, may often be the limiting factor in system lifetimes.

Photovoltaic systems can be sized to fit any application. Installed photovoltaic systems range from 38 W household systems found in the Dominican Republic (see box 6-G) to a 5.2 MW grid-connected system in California.

The operation of photovoltaics requires no fuel, and therefore avoids the detrimental environmental effects of fuel combustion. Manufacturing some types of photovoltaics does require the use of potentially harmful chemicals, if released.<sup>109</sup>

Electricity generation by photovoltaics is not land constrained. For example, India's entire electricity needs could be met with photovoltaic cells covering 1,120 km<sup>2</sup>, or about 0.034 percent of the land.<sup>110</sup> Some argue that traditional centralized generation, such as coal and nuclear, requires more land than do photovoltaics if mining, transportation, and waste disposal are taken into account.<sup>111</sup>

### **MicroHydropower**

Microhydroelectric plants<sup>112</sup> are common in several Asian countries—notably China and India—and are also found in some African and Latin American countries. Like all renewable resources, hydropower requires no direct use of fossil fuels and therefore has low operating costs. Although microhydropower systems can have relatively high initial capital costs, much of this is in labor and locally available materials for site preparation.

<sup>107</sup>United Nations, Committee on the Development and Utilization of New and Renewable Sources of Energy, "Direct Solar-to-Electrical Energy Conversion," Report of the Secretary-General, Mar. 8, 1990, p. 9.

<sup>108</sup>Electric Power Research Institute (EPRI), *TAG-Technical Assessment Guide, Electricity Supply 1989*, EPRI P-6587-L (Palo Alto, CA: Electric Power Research Institute, September 1989), p. 7-81.

<sup>109</sup>D. Carlson, "Photovoltaic Technologies for Commercial Power Generation" *Annual Review Of Energy*, vol.15, 1990, p. 90.

<sup>110</sup>Electricity consumption in 1987 from International Energy Agency, *World Energy Statistics and Balances 1971 to 1987* (Paris: OECD, 1989). Land area from World Bank, *World Development Report 1989* (New York, NY: Oxford University Press, 1989). Ten percent conversion efficiency assumed.

<sup>111</sup>H.M. Hubbard, "Photovoltaics Today and Tomorrow," *Science*, vol. 244, No. 902, Apr. 21, 1989, p. 300.

<sup>112</sup>This discussion focuses on small systems of up to 100 kW, called "micro-hydro," which are suitable for off-grid applications. This is a subset of "small hydro" which refers to systems of up to 15 MW.

### Box 6-G—Residential Photovoltaic Systems in the Dominican Republic

A simple, low-cost residential photovoltaic system, costing about \$500, now supplies electricity for lights and radios in households in the Dominican Republic. Enersol, a U.S.-based nonprofit organization, began photovoltaics demonstrations in the Dominican Republic in 1984, and has since installed the systems in over 1,000 households. This has been done with minimal outside funding, and has made use of local resources and the private sector wherever possible.

The photovoltaic system consists of a 38 watt (peak) photovoltaics array, a 12-volt car battery, associated electrical components, and lights and other appliances. The photovoltaics array is imported from the United States and faces a 70-percent import tax. The battery is manufactured domestically and is relatively inexpensive, although it must be replaced every few years. Service centers and trained technicians provide system repair when needed (most commonly blown fuses and dead batteries). A revolving loan program is used to provide the capital for initial purchase.

**SOURCE:** R. Hansen and J. Martin, "Photovoltaics for Rural Electrification in the Dominican Republic," *Natural Resources Forum*, vol. 12, No. 2, 1988, pp. 115-128.

Unlike large hydropower projects, microhydro-power can often be installed quickly and usually does not require the flooding of large areas.<sup>113</sup> Sites for microhydro are limited, however, and hydro resources are often highly seasonal. With sufficient long term, site specific water flow data, electrical output can be predicted with reasonable accuracy. These data can be expensive to collect, however, adding to the total cost of the system.

Hydropower potential depends on annual runoff, seasonal distribution of the runoff, topography, and other factors. Some estimates of the potential for small hydro (up to 15 MW) have been made. For example, a recent report identified a small hydro-power potential of over 40 GW in the developing

world.<sup>114</sup> The fraction of this potential suitable for microhydro (less than 100 kW) is unclear. Furthermore, these data are based only on large scale hydrologic information and do not consider local factors, such as the distance between the potential system installation site and the area needing the power.

Hydropower converts the kinetic energy of falling or flowing water to drive a turbine connected to an electrical generator. The hydropower potential of a specific site is proportional to the water flow rate and the "head," which is the vertical distance the water falls.<sup>115</sup> The system design varies, depending on whether or not storage is incorporated and on the type of turbine used.

The simplest hydropower system is a waterwheel. These have long been used to produce mechanical power for crushing, grinding, and other similar mechanical tasks. Waterwheels are simple to construct, and require little in the way of special tools or materials, but their slow speed makes them unsuitable for generating electricity.

A complete hydropower system consists of a river and dam (if used), a pipe carrying water to the turbine, the turbine itself, the generator, various controls, and other components,

For hydroelectricity generation, either impulse turbines—which use a nozzle to direct the water at high speed against the turbine blades—or reaction turbines—that are powered by the pressurized flow of water through the unit—can be used. Reaction turbines are more common in low-head<sup>116</sup> microhydro applications.

Hydropower systems to generate electricity can be divided into "run-of-river" systems that do not incorporate storage; and storage systems, which use a dam or basin to store water. A run-of-river system is less expensive to build and has reduced downstream impacts as the river flow will be affected less significantly. The electricity output will fluctuate with changes in river flow, however, requiring storage or other systems to offset variations in output. Alternatively, a dam or basin can be used to

<sup>113</sup>In aggregate, however, microhydro systems may flood substantial areas.

<sup>114</sup>California Energy Commission, "International Market Evaluations: Small-Scale Hydropower Prospects," Report No. P500-87-005, p. 25.

<sup>115</sup>The governing equation is  $P = \rho g Q H e$ , where  $P$  is the power output of the system in kW,  $Q$  is the water flow rate in m<sup>3</sup>/sec,  $H$  is net head in meters, and  $e$  is the conversion efficiency.

<sup>116</sup>Low-head means that the water falls less than about 15 meters (50 feet).

store water so that electric output can be tailored to meet demand.

The initial capital costs for microhydropower systems vary widely, depending on the site characteristics and how one accounts for local labor and materials. Reported system costs range from as low as \$290/kW in Pakistan<sup>117</sup> (see box 6-H) to \$2,350/kW in Thailand.<sup>118</sup> Typical costs are in the range of \$1,000 to \$2,000/kW.<sup>119</sup> Site specific construction costs are 15 to 45 percent of total costs (see table 6-15). If these costs are met with low cost local labor and with locally available materials (concrete, wood, etc.), then total system costs can be quite low while benefiting the local economy and saving foreign exchange.

Costs for the mechanical components—the turbine, generator, and associated electronic control equipment—benefit from economies of scale, making larger systems less expensive per kW than small systems. Mechanical equipment costs in the United States range from about \$2,800/kW for a small, 500 W, 12 V DC system to about \$700/kW for a larger 50 kW 120/240 V AC system.<sup>120</sup> These costs are not expected to change significantly in the future, as the technology for microhydropower is in general already mature and little R&D work is being done.<sup>121</sup>

Costs for operation and maintenance of microhydro systems are not well known. O&M costs of about 2 cents/kWh are reported,<sup>122</sup> but are highly variable. Routine operation and maintenance may only involve periodic cleaning of water intakes. If major repair is needed, however, the costs of skilled labor may be high, especially in remote areas. Microhydro systems can be quite reliable—many

### Box 6-H—Micro-Hydropower in Pakistan

Less than one-quarter of rural villages in Pakistan have electric service. Extending the electric grid to these remote villages is prohibitively expensive, as is diesel fuel for diesel generators. The Appropriate Technology Development Organization (ATDO), an agency of the Government of Pakistan, has pursued the use of micro-hydropower projects to supply electricity to remote villages.

The program emphasis is on the use of local resources. All decisions regarding project size, location, operation, etc. are made by the villagers. The ATDO staff work with the villagers, and encourage the use of locally available materials and labor wherever possible. Costs are shared and the community decides on the electricity rates to users. The end result is rural electrification at a very low cost—typically \$250 to \$400 per kW. Efforts are continuing to further reduce costs with local fabrication of generators and penstock piping.

**SOURCE:** M. Abdullah, "Micro-Hydroelectric Schemes in Pakistan," *Small-Scale Hydropower in Africa-Workshop Proceedings*, Abidjan, Ivory Coast, March 1982, pp. 27-30.

plants installed in the 1940s and 1950s are still operating.<sup>123</sup>

The environmental impacts of microhydro systems can include flow disruption due to diversion of water from the stream and sedimentation due to changes in river flow. Depending on the design of the system, water quality and aquatic organisms can be affected—for example, a system using a dam provides a habitat for mosquitoes, which can spread malaria or other diseases.

<sup>117</sup>M. Abdullah, "Micro-Hydroelectric Schemes in Pakistan," *Small-Scale Hydropower in Africa-Workshop Proceedings* (Abidjan, Ivory Coast: March 1982), p. 29.

<sup>118</sup>P. Clark, "Cost Implications of Small Hydropower Systems," *Small-Scale Hydropower in Africa-Workshop Proceedings* (Abidjan, Ivory Coast: March 1982), p. 100.

<sup>119</sup>United Nations Conference on Trade and Development, *Technology Policy in the Energy Sector: Issues, Scope and Options for Developing Countries*, UNCTAD/TT/90 (Geneva, Switzerland: United Nations, November 1989), p. 80, reports an average cost of \$2,350/kW for small (6-21 kW) systems in Nepal. P. Clark, "Cost Implications of Small Hydropower Systems," *Small-Scale Hydropower in Africa-Workshop Proceedings* (Abidjan, Ivory Coast: March 1982), p. 106 reports an average cost of \$1,000/kW for 7 projects under 50 kW in size in Asia.

<sup>120</sup>Dan New, Canyon Industries, Deming, WA, personal communication, November 1990. Five kW systems are about \$1,400/kW, 20 kW are about \$1,000/kW. All prices include turbine, generator, and electrical equipment.

<sup>121</sup>Improved materials and manufacturing processes, and large volume production, however, might impact costs.

<sup>122</sup>M. wa Kabasele, "Small Hydroelectric Power Development in the," *Small-Scale Hydropower in Africa-Workshop Proceedings* (Abidjan, Ivory Coast: March 1982), p. 36; J. Fritz, "Cost Aspects of Mini-Hydropower Systems," *Small-Scale Hydropower in Africa-Workshop Proceedings* (Abidjan, Ivory Coast: March 1982), p. 116; California Energy Commission, "International Market Evaluations: Small-Scale Hydropower Prospects," Report No. P500-87-005, p. 19. Fifty percent capacity factor assumed.

<sup>123</sup>California Energy Commission, "International Market Evaluations: Small-Scale Hydropower Prospects," Report No. P500-87-005, p. 18.

Table 6-1 5-Breakdown of Micro-Hydro Capital Costs

Item	Percent of cost
Turbine-generator .....	18-39
Other electrical and plant equipment .....	7-16
Site-specific Construction.....	15-45
Engineering .....	20
Other .....	10

SOURCE: P. Clark, "Cost Implications of Small Hydropower Systems," *Small-Scale Hydropower in Africa-Workshop Proceedings*, March 1982, Abidjan, Ivory Coast, p. 106.

### Engine Generators

The most common technology today for remote generation of electricity is usually an engine generator—a small internal combustion engine using gasoline or diesel fuel to generate electricity. This technology is popular for good reason—it has a relatively low initial cost, it is widely available, it can be installed anywhere, and it uses a technology already familiar in the form of cars, trucks, and buses. It is dependent on scarce and expensive fossil fuels, however, which are often imported. The costs and other characteristics of engine generators<sup>124</sup> are summarized here, as they are the technology against which off-grid renewable must compete.

Small (5 to 10 kW) engine generators typically use gasoline and have initial costs of \$600 to \$700/kW. Medium sized systems (10 to 100 kW) usually use diesel fuel and have initial costs of \$200 to \$700/kW. Very large systems (250 kW and more) exclusively use diesel and have initial costs of about \$125/kW.<sup>125</sup>

Operation and maintenance costs for engine generators can be divided into fuel and nonfuel costs. Nonfuel costs include routine maintenance, such as oil and filter changes, as well as repair. A considerable amount of scheduled maintenance is required, which costs about 1.3 to 2 cents/kWh.<sup>126</sup> In addition, a complete overhaul is required about every 10,000 hours of operation, at a cost of about 15 percent of the capital cost. The lifetimes for engine

Table 6-16-Some Typical Fuel Consumption Rates for Engine Generators

Size (kW)	Fuel	Consumption rate liters/kWh	Fuel operating costs \$/kwh
4.0	gasoline	0.71	0.71
7.5	gasoline	0.63	0.63
20	diesel	0.40	0.20
50	diesel	0.28	0.14
100	diesel	0.24	0.12
1,000	diesel	0.28	0.14

Fuel priced at 50 cents/liter.

SOURCE for fuel consumption rates: Real Goods Trading Co., Ukiah, CA; Onan Corp., Minneapolis, MN.

generators are quite short—about 20,000 hours for diesel units and 3,000 to 5,000 hours for gasoline units.<sup>127</sup> Engine generators have a reputation for high reliability as long as maintenance requirements are met.

Fuel costs depend on fuel prices (table 6-16). In many rural areas, fuel supplies for engine generators are unreliable and expensive due to difficult and time consuming transport. For oil importing countries, fuel expenditures require a large fraction of foreign exchange. As long as fuel supplies are available, engine generators can operate at very high capacity factors. As the fuel supply can be stored, no battery backup is required for engine generators. In addition, no site surveys are needed to measure the resource, and the engine generator can be moved to a new location if desired.

The environmental effects of engine generators include noise and air pollution. Noise effects can be minimized by locating the engine away from residences, however, and in rural areas at least the local air quality effects may be readily dispersed.

### Comparing the Technologies

There is no one "best" technology: each specific application must be considered on its own. Costs are also uncertain, changing—rapidly in some cases—over time, and are site dependent. The values given here are approximate.<sup>128</sup> Capital, O&M, fuel costs,

<sup>124</sup>The term "engine generator" is used to mean an integrated system, including an engine, an electrical generator, and associated electrical equipment.

<sup>125</sup>Prices are approximate, and are from Real Goods Trading Company, Ukiah, CA, and from Curtis Engine Equipment, Inc., Baltimore, MD. Prices quoted here are retail prices in the U.S.—prices in developing countries will differ due to transport costs, import duties, and other factors.

<sup>126</sup>Typical requirements include checking engine oil every 8 hours, changing engine oil and oil filter every 150 hours, and changing fuel and air filter every 500 hours. The cost for these parts in the U.S. is about 2 cents/kWh. Others estimate maintenance and repair at 1.3 cents/kWh (Sandia National Laboratories, *Evaluation of International Photovoltaic Projects Volume II: Technical Report, SAND85-7018/2, September 1986, p. 13-5*).

<sup>127</sup>*Ibid.*, 8-7.

<sup>128</sup>See also, U.S. Congress, Office of Technology Assessment, *Renewable Energy Technologies: Research, Development, and Commercial Prospects*, forthcoming.

**Table 6-17—initial Capital Costs of Electricity Generating Systems**

Technology	Size (kW <sub>p</sub> )	Initial capital cost (\$/kW <sub>p</sub> )
<b>Engine generator:</b>		
Gasoline . . . . .	4.0	760
Diesel . . . . .	20.0	500
Microhydro . . . . .	10-20	1,000-2,400
Photovoltaic . . . . .	0.07	11,200
Photovoltaic . . . . .	0.19	8,400
Wind turbine . . . . .	0.25	5,500
Wind turbine . . . . .	4	3,900
Wind turbine . . . . .	10	2,800

NOTE: Costs are for entire system, including conversion device, electric generator, and associated electrical equipment. Prices for wind turbine and photovoltaic systems include batteries. kW<sub>p</sub> ratings are for peak output, average output will be somewhat lower depending on the resource. Prices for wind turbine, photovoltaic, and engine generators are actual retail prices in the U.S. in 1990. Prices for microhydro are averages across several installations.

SOURCES: Bergey Windpower Co., Norman, OK; Onan Corp., Minneapolis, MN; Real Goods Trading Co., Ukiah, CA.

equipment lifetimes, and other data for these technologies are shown in tables 6-17 to 6-19. Capital costs-of particular concern for developing countries--are lowest for engine generators. Life cycle operating costs for a 10 kW system-enough to supply a small village-however, indicate that for a variety of applications, various renewable energy technologies may be more attractive than engine generators (see app. B).

Obtaining the results shown in figure 6-5 required making a number of assumptions. These results are particularly sensitive to the assumed discount rate and fuel price (see app. B). Access to good quality resources that are reliable throughout the year, or at least when power is needed, is also important.<sup>129</sup> At high discount rates, those technologies with a high initial cost—notably photovoltaics--look less attractive (see app B). Individual consumers in developing countries often can borrow money only at very high rates--40 percent per year in the Dominican Republic,<sup>130</sup> for example, while governments and large institutions can often borrow capital at much lower rates—5 to 10 percent. If the selection of remote generating technologies is made by individuals facing capital constraints and high interest rates, renewable technologies with high capital costs will be less attractive. If these decisions are made by

**Table 6-18—Operating, Maintenance, and Fuel Costs (diesel fuel price of \$0.50/liter assumed)**

Technology	O&M costs (cents/kWh)	Fuel costs (cents/kWh)
Engine generator . . . . .	2	20 (diesel)
Micro Hydro . . . . .	2	0
Photovoltaics . . . . .	0.5	0
Wind turbines . . . . .	1	0

SOURCE: Office of Technology Assessment, 1992.

**Table 6-19—Approximate Lifetimes of Off-Grid Renewable Generating Technologies**

Technology	Lifetime (years)
Engine Generator . . . . .	8-10 (diesel)
Micro Hydro . . . . .	20-30
Photovoltaics . . . . .	20-30
Wind Turbine . . . . .	15-25
Batteries . . . . .	3-5

SOURCE: Office of Technology Assessment, 1992.

larger institutions and governments, these technologies are more financially attractive.

The cost of fuel is an important determinant of the cost of diesel generation. At 50 cents/liter for diesel, the cost of generating electricity with diesel sets is two-thirds the cost achieved of photovoltaic power, while at \$1/liter, engine generated electricity costs about 10 percent more than that from photovoltaics (see figure 6-6 and app. B).

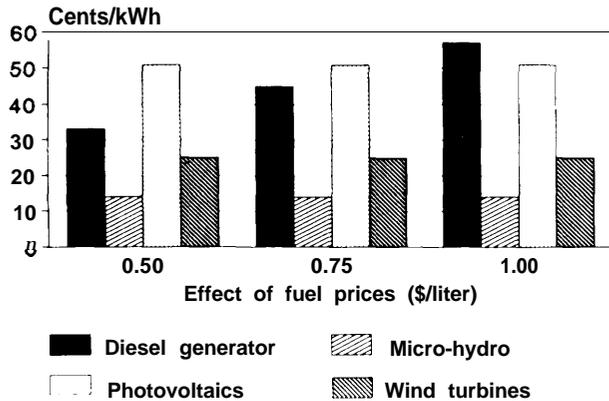
Given the large uncertainty in the cost data, it is not appropriate to interpret these cost data as applying to any specific situation. Other factors, such as those listed in table 6-20, may be as or more important than cost. Nevertheless, the following tentative conclusions can be drawn:

- With reasonable assumptions concerning discount rates, capacity factors, and fuel cost, microhydro and wind turbines can have the lowest life cycle costs in locations where the resource is sufficient.
- Diesel generators have by far the lowest initial capital cost, but when fuel and O&M costs are considered, diesel generators are of comparable expense to renewable technologies—more expensive than wind turbines and microhydro, and less expensive than photovoltaics. The cost

<sup>129</sup>For example, the best hydropower resources are during the rainy season when irrigation pumping is not needed. Conversely, when irrigation pumping is needed during the dry season—hydropower resources are usually at their lowest.

<sup>130</sup>R. Hansen and J. Martin, "Photovolhcs for Rural Electrification in the Dominican Republic," *Natural Resources Forum*, vol. 12, No. 21988, p. 120.

Figure 6-6-Costs of Remote Generating Technologies



10 kW systems with storage

This figure shows the relative cost of remote generating technologies for three different diesel fuel prices.

SOURCE: U.S. Congress, Office of Technology Assessment, 1992. See app. B for more detail.

of electricity production from diesel engine generators is heavily dependent on fuel prices and quality of maintenance.

- Photovoltaics are expensive, due largely to the cost of the panels themselves. Panel costs are expected to continue to drop in the near future, however. Further, the analysis presented here is for a 10 kW system. Photovoltaic systems are more economically attractive for smaller applications, such as household or agricultural pump (less than 1 kW) systems.

### Grid Extension

The alternative to remote generation of electricity, either by renewable technologies or by diesel generators, is to extend the existing electricity grid. Grid extension costs have several components: the capital cost of extending the electricity lines themselves; the operations and maintenance costs of the lines; and the cost of generating the electricity. The cost of electricity distribution lines varies with line voltage and capacity, topography, and other factors, and is estimated at \$4,600 to \$12,700 per kilometer,

Table 6-20-Non-Cost Attributes of Off-Grid Electricity Generating Technologies

#### Engine generators

- Independent of renewable resource fluctuations
- Dependent on fuel supply system
- Susceptible to fuel price increases

#### Micro-hydro

- Large part of costs for instruction, can be paid with local currency
- Proven, mature technology, highly reliable and long lifetimes
- Output dependent on water flow

#### Photovoltaics

- Low maintenance requirements
- Low availability due to solar resource dependence
- Requires batteries for energy storage

#### Wind turbines

- Low maintenance requirements
- Suitable only for areas with sufficient wind resource
- Requires batteries for energy storage

SOURCE: Office of Technology Assessment, 1992.

with an average of about \$9,000/km in the United States.<sup>131</sup> The operations and maintenance costs of these lines are estimated at 2 to 4 percent of the capital costs per year,<sup>132</sup> or about \$270/km year for the average line. The cost of generating the electricity varies widely, depending on fuel used, power plant efficiency, and other factors. Long run marginal costs of electricity generation, which include fuel costs, operation and maintenance costs, and levelized capital costs, were estimated at from 4.4 cents/kWh to 13 cents/kWh, with an average of 9 cents/kWh, in a recent study of developing countries.<sup>133</sup>

The cost of grid extension increases with distance. In contrast, the costs of remote generation are not affected by distance from the grid. At some distance, called the "break even" distance, the costs of grid extension exceed those of remote generation. The results of such a calculation, first considering only capital costs and then considering life cycle costs, are shown in table 6-21. Calculations and assump-

<sup>131</sup> For single phase systems. From National Rural Electric Cooperative Association, *Understanding Electric Utility Operations* (Washington, DC: National Rural Electric Cooperative, 1989), p. 106. There are alternatives to this technology—for example, a single-wire earth return system—common in rural Australia, could be used in developing countries, and costs as little as half as much as a traditional single-phase system (Allen Inverson, NRECA, personal communication, 12/4/90).

<sup>132</sup> M. Mason, R. ... *Electrification—A Review of World Bank and USAID Financed Projects*, Background Paper for the World Bank, April 1990, p. 27.

<sup>133</sup> *Ibid.*, p. 27. The median long-run marginal cost would be somewhat lower.

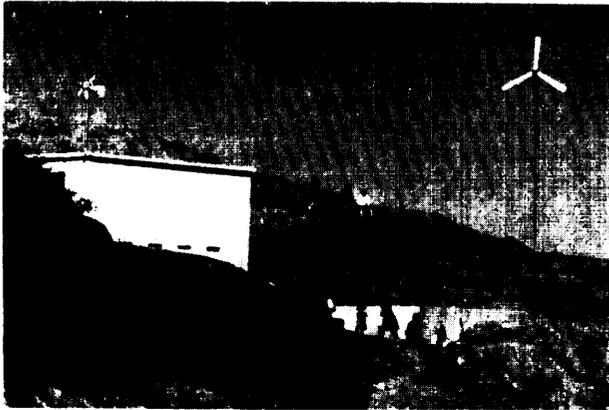


Photo credit: Bergey Windpower Company

Wind turbines may be less expensive than grid extension in some areas.

tions are given in appendix B.<sup>134</sup> For the assumed system size, the break even distance varies from less than 2 km for microhydro to 14 km for photovoltaics when life cycle costing is used. Smaller system loads than the assumed 10 kW reduce this break even distance sharply.<sup>135</sup> Different assumptions of grid extension costs also change this break even distance. For example, assuming the typical U.S. cost of \$9,000/km (rather than \$4,500/km) the break even distance for photovoltaics drops to 7km (from 14). In contrast to remote generation, however, costs for grid extension can be spread over several villages if multiple service drops to several villages are possible.

## OIL REFINING

Petroleum products are obtained in the developing world through a combination of direct import of refined products and local processing of crude oil—usually imported—in local refineries. About one-quarter of world refining capacity is located in the developing world.

The scale and other characteristics of refineries in the developing countries varies widely—from the large state-of-the-art refineries of the major oil producers, such as Venezuela and Mexico, to the small uneconomic refineries operated in several of the smaller African countries. One common characteristic, however, is widespread state ownership. The government, generally acting through a parastatal enterprise, such as the national oil company,

takes a majority interest or even owns the facility outright. A foreign company is generally involved in designing, building, and sometimes managing the refinery under a service contract. Such companies often provide access to crude oil feedstock for the refinery from their integrated international system, though some state owners of refineries rely mostly on government-to-government supply agreements.

The major oil producers apart, refineries in developing countries face a number of problems. In many cases, developing country refineries do not produce a range of light and heavy products appropriate to the consumption patterns in the country. This comes about for two reasons. First, much of refinery technology is based on the product demand of the industrial countries. In developing countries, between 60 and 70 percent of refinery demand is diesel and residual, compared with 30 percent for the United States. On the other hand, gasoline accounts for about half of U.S. production, compared with about 20 percent in developing countries. Further, developing-country consumers do not use the petroleum products designed for use in cold climates.

Second, most of the plants use the simplest refining process—primary distillation (or hydro-skimming)—which is limited in its flexibility. When crude oil prices rose in the 1970s, demand for petroleum products shifted. Developing-country refineries, which typically do not have secondary conversion technologies, could not adjust to these changes. The only flexibility available in such cases (without huge investments) lies in varying the quality of the imported crude feedstock. Many developing countries now import crude oil, refine it locally, and re-export the excess (typically residual fuel oil and gasoline). As the quantities exported are small, they are often sold for prices well below the world average.

Diseconomies of scale cause refining costs to be much higher than in the developed world. Average refinery operating costs in Africa are \$2 per barrel, compared to \$0.75 in the rest of the world. Very few developing country refineries can process crude for less than \$1 per barrel, except the large export refineries in the Far East and the Caribbean. Refinery losses, which should not exceed 1 percent

<sup>134</sup>See also, Chandra Shekhar Sinha and Tara Chandra Kandpal, "Decentralized v. Grid Electricity for Rural India," *Energy Policy* June 1991, pp. 441-44s.

<sup>135</sup>See also, "Utility Applications for Photovoltaics," *EPRI Journal*, March 1991, p. 26.

**Table 6-21—Break-Even Distances for Comparing Grid Extension to Remote Generation, (10 kW system operating at 20% capacity factor)**

Considering only initial costs	
Technology	Break-even distance
Diesel generator .....	1.4 km
Micro-hydro .....	3.5 km
Photovoltaics .....	18.0km
Wind turbine .....	7.9 km
Considering initial, operating and maintenance, and fuel costs	
Technology	Break-even distance
Diesel generator .....	8.1 km
Micro-hydro .....	2.1 km
Photovoltaics .....	13.9km
Wind turbine .....	5.6 km

SOURCE: Office of Technology Assessment, 1992. See app. B for details.

in a properly maintained and operated refinery, often exceed 2 or even 4 percent in developing-country facilities.

Technology could improve the performance of the refinery sector in developing countries. This is of particular importance as old and inefficient refineries in many countries are among the largest single consumers of petroleum fuels.

Besides repair and replacement of worn out or obsolete equipment, the main targets of increased efficiency are connected with the heat used to process crude. For example, reducing excess air mixing into the flue gas can result in energy savings of about 2 percent in the heaters and 30 percent in the catalytic reformer. This technology has been common in industrial-country refineries since the 1970s, is relatively low cost, but is still the exception in developing countries. Heater efficiency can also be improved through the installation of heat exchangers to recover heat from the stack gas, where temperatures can reach 1,000 °F. Retrofitting to take advantage of previously flared relief valve and other gas, reducing evaporation from storage tanks, and other measures, can result in substantial savings at moderate cost.

These technology improvements could also curtail some of the adverse environmental impacts of oil refining. Obsolete and poorly maintained equipment can lead to increased leaks of oil and a number of toxic emissions, with negative effects on soil, water,

and air quality. Refineries also have solid and liquid wastes that require special handling and disposal. Many of the pollutants associated with refining could be mitigated through properly maintained or improved equipment.

More generally, prospects are for a continual incremental improvement in oil refinery technology and energy efficiencies, using improved separation techniques and more intensive use of computer technology to improve product quality. A major change could be in new catalysts for the light end of petroleum fraction and natural gas liquids. Present day catalytic crackers produce excessive quantities of the light ends such as off gas, methane, and ethane. By the end of the decade, new catalysts are expected to improve the yield of gasoline from these light ends. Membrane separation technologies are under development but appear to be more suitable for use in large scale refineries rather than the smaller operations typical of many developing countries.

The low level of refinery efficiencies in developing countries is due largely to lack of investment. Problems hindering investment in the rationalization of refinery operation in the developing world include lack of foreign exchange for parts; artificial refinery profits stemming from subsidized feedstock, distorted pricing structures and earmarked government subsidies; and noneconomic reasons such as “ security of supply.”

It is estimated that between 1991 and 1995, refinery rehabilitation and conservation in the developing world will require an investment of almost \$2 billion.<sup>136</sup> The extent of the problems existing in some countries and the large amounts of money needed for rehabilitation raise the question of whether some refineries should not be closed down, meeting local needs through a combination of regional restructuring and direct import of refined products. Refining is capital rather than labor intensive and so often requires highly paid expatriate personnel and creates relatively few spinoffs for the local economy. Where a small local market constrains capacity utilization and/or the facility is old and/or decrepit and inefficient, the decision to close the facility, politically painful as that may be, would reduce economic losses.

<sup>136</sup>Theodore J. Gorton, ‘Oil and Gas Development in the Third World,’ contractor report prepared for the Office of Technology Assessment, June 1990.

Generalization is, however, difficult. Some developing country refineries benefit from strategic regional location and good management and are clearly success cases. For example, the Societe Ivoirienne de Raffinage (SIR) in Abidjan, Cote d'Ivoire, exports products to neighboring countries and consistently makes a foreign-exchange profit for its public and private shareholders.

An alternative for refineries in those countries with natural gas is methanol conversion. There are technologies to convert gaseous methane to liquid methanol, allowing smaller scale liquefaction to a versatile and easily transportable fuel. The disadvantages of methanol include the energy cost of natural gas conversion to methanol and the low volumetric energy content of methanol—about half that of gasoline. Methanol can be exported, however, getting around the problem of how to generate foreign exchange in a project and allowing foreign investors to remit profits. A recent example of a methanol export project is that of the government of Chile, the U.S. company Allied Signal, and the World Bank affiliate—the International Finance Corp. (IFC).<sup>137</sup> In 1987, the project set up a methanol plant worth \$298 million at Cabo Negro in the remote south of Chile on a “non recourse” basis.<sup>138</sup> This project is, however, probably more suitable for countries with large gas reserves, such as Nigeria.

## BIOMASS<sup>139</sup>

Biomass is the principal energy source for the half of the world's population living in rural areas and accounts for about one-third of all primary energy used in developing countries today. As presently used, biomass is an inconvenient and inefficient

fuel, which contributes to high levels of indoor air pollution and resource depletion.

To play a larger role in supplying energy services, biomass must be converted into cleaner and more convenient fuels (gases, liquids, electricity). A modern biomass industry would have many advantages. In some cases, there would be a decrease in the amount of biomass needed for a given energy service. For example, cooking with a gas produced efficiently from biomass could use less total biomass than cooking directly with wood in a traditional stove (see ch. 3).<sup>140</sup> If operated on a renewable basis, biomass makes no net contribution to atmospheric CO<sub>2</sub>. Biomass use could have economic benefits; as an indigenous energy source, biomass could save valuable foreign exchange. Establishing bioenergy industries also would bring increased activity and jobs into rural areas.

On the other hand, establishing a modern biomass industry presents challenges. The physical and chemical composition of biomass feedstocks varies widely, potentially requiring the tailoring of conversion technologies to specific biofuels. The relatively low bulk densities of biomass and possibly large required collection areas limit the amount of biomass at any given site. This constrains the size of individual conversion systems and limits the extent to which economies of scale in capital and other costs can be captured.<sup>141</sup> Although there are a large number of biomass technologies, the selected few examined here appear to hold particular promise for the future. This review does not include mature technologies such as charcoal production or the use of wood or agricultural wastes in boilers to produce process heat and electricity. Some of these applications were already discussed in chapters 3 and 4.

<sup>137</sup>Some of these are analyzed in G. Greenwald, “Encouraging Natural Gas Exploration in Developing Countries,” in *Natural Resources Forum*, vol. 12, No. 3, 1988.

<sup>138</sup>This means that the operator puts in a modest level of equity capital and gives a completion guarantee for the facilities, but does not assume any further risk; the project financing is arranged solely on the basis of the assets of the project, in this case substantial gas reserves.

<sup>139</sup>This section is drawn primarily from Eric D. Larson, “A Developing Country-Oriented Overview of Technologies and Costs for Converting Biomass Feedstocks into Gases, Liquids, and Electricity,” contractor report to the Office of Technology Assessment, September 1991.

<sup>140</sup>G.S. Dutt and N.H. Ravindranath, “Alternative Bioenergy Strategies (Direct Use of Biomass, Charcoal, Biogas, Producer Gas, Alcohol) for Cooking,” draft manuscript for *Fuels and Electricity from Renewable Sources of Energy*, Johansson, Kelly, Reddy, Williams (eds), 1S91 (forthcoming).

<sup>141</sup>Typical rates of biomass fuel production or use at individual sites range from 1–4 kW<sub>FUEL</sub> (0.2 to 0.4 kg/hr of dry biomass, assuming a dry-biomass energy content of 20 MJ/kg) for residential cooking up to a maximum of some 300–400 MW<sub>FUEL</sub> (54–72 dry tonnes/hr) at large factories that produce biomass as a byproduct and use it for energy (e.g. cane sugar and craft pulp factories) (This can be compared to the 800 to 4,000 MW of coal consumed at central station electric power plants.) Larger concentrations of biomass could be made available, e.g. from plantations dedicated to producing biomass for energy. Under such schemes, transportation costs and land availability will be limiting factors on the quantity of biomass that can be concentrated at a single site.

## Gases and Electricity From Biomass

Combustible gas can be produced from biomass through thermochemical processes (producer gas) or through biological processes (biogas). Both can be burned directly to produce heat, e.g., for residential cooking or industrial process heating, and can be used to produce electricity.<sup>142</sup>

### Producer Gas<sup>143</sup>

Producer gas is a long established technology, though largely abandoned with the development of inexpensive petroleum supplies after the second world war.<sup>144</sup> Since the early 1970s, there have been many efforts to resurrect producer gas technology, largely for small scale use in the rural areas of developing countries.<sup>145</sup>

Gasification systems can be classified as either small scale—those with a fuel input of less than about 2 GJ/hr (100 kg/hr dry biomass)—or large scale. Economies of scale permit large scale systems to be generally more technologically sophisticated. Two basic gasifiers, updraft and downdraft, are used in small scale applications using raw biomass. In an updraft unit, biomass is fed in the top of the reactor and air is injected into the bottom of the fuel bed. Updraft gasifiers have high energy efficiencies, typically 80 to 90 percent (chemical energy in gas output divided by feed stock energy input), due to the efficient counter-current heat exchange between the rising gases and descending solids. However, the tars produced by updraft gasifiers mean that the gas must be cooled before it can be used in internal combustion engines. Thus, in practical operation, updraft units are used almost exclusively for direct heat applications. For use in internal combustion

engines, downdraft technologies are needed. Even so, fairly elaborate additional gas cleaning systems are required in the downdraft technology, resulting in lower overall energy efficiencies of 60 to 70 percent.

Large scale applications include more elaborate versions of the small scale updraft and downdraft technologies, and fluidized bed technologies. The superior heat and mass transfer of fluidized beds leads to relatively uniform temperatures throughout the bed, better fuel moisture utilization, and faster reactions than in fixed beds, resulting in higher throughput capabilities.<sup>146</sup> Fluidized beds are, however, generally more expensive than fixed beds below a fuel input rate of 35 to 40 GJ/hr (1.8 to 2.0 tonnes/hr of dry biomass), due to the high unit cost of blowers, continuous feed systems, and control systems and other instrumentation.<sup>147</sup>

**Direct Heat Applications-Producer** gas has been used most widely (the country with the most experience is Brazil) for direct heating in industrial applications. In part, this is because such applications are often characterized by relatively high capacity utilization rates and, more importantly, because biomass is often available relatively inexpensively, e.g., as in the forest products industries. For relatively small capacity units, the estimated cost of gas ranges from \$3.20 to \$4.80 per GJ (\$3.40 to \$5.10/million Btu) for wood-fueled systems and \$4.70 to \$7.40 per GJ (\$5.00 to \$7.80/million Btu) for charcoal-fueled systems, competitive with fuel oil when crude is priced at about \$38 per barrel (see table 6-22).<sup>148</sup> Producer gas is generally not used for cooking,<sup>149</sup> but it would offer advantages over raw biomass—higher systems efficiencies, reductions in indoor smoke and particulate, and reduced collec-

<sup>142</sup>Thermochemical gasification is also the first step in producing methanol, a liquid fuel, from biomass.

<sup>143</sup>Producer gas derives its name from the "gas producer" in which it is made and is a combustible mixture consisting primarily of carbon monoxide, hydrogen, carbon dioxide and nitrogen, and having a heating value of 4 to 6MJ/Nm<sup>3</sup>, or 10% to 15% of the heating value of natural gas. It can be made from essentially any carbon-containing feedstock, including woody or herbaceous biomass (lignocellulose), charcoal, or coal.

<sup>144</sup>The use of producer gas dates back well into the 1800s when coal-derived producer gas was used in a number of cities worldwide for cooking and heating. This "town gas" is still used in Calcutta, Beijing, and Shanghai, where about half of all households use it for cooking. Producer gas from wood-charcoal was a prominent civilian fuel in Europe during the Second World War running several hundred thousand vehicles and powering industrial machinery.

<sup>145</sup>G. Foley and G. Barnard, "Biomass Gasification in Developing Countries," Earthscan Technical Report No. 1 (London: 1982).

<sup>146</sup>E. D. Larson, P. Svenningsson, and I. Bjerle, "Biomass Gasification for Gas Turbine Power Generation" Thomas B. Johansson, Birgit Bodlund, and Robert H. William (eds.), *Electricity: Efficient End-Use and New Generation Technologies, and their Planning Implications* (Lund, Sweden: Lund University Press, 1989), pp. 697-739.

<sup>147</sup>Ibid.

<sup>148</sup> Assuming that the per barrel wholesale price of residual fuel oil is 0.87 times the refiner acquisition cost of crude oil (characteristic for the United States) and that a barrel of residual oil contains 6.6GJ.

<sup>149</sup>See, Samuel F. Baldwin, "Cooking Technologies," OTA staffworking paper, 1991.

Table 6-22-Comparative Summary of Calculated Costs for Modern Energy Carriers Produced From Biomass

	Production capacities		Installed capital costs		Total production Costs <sup>b</sup>	
	103 GJ/yr	kW	\$ per GJ/yr	\$/kW	\$/GJ	\$/kWh
<b>Biogas</b>						
Domestic (E) . . . . .	0.016-1.2	0.50-38	30-12	950-375	11-5	NA
Industrial (E) . . . . .	3.6-167	114-5290	13-2.5	410-80	1.4-2.5	NA
<b>Producer gas<sup>c</sup></b>						
Small (E) . . . . .	1-12	32-380	2-0.7	65-20	5-3	NA
Medium (E) . . . . .	20-200	634-6,340	6-3	190-95	NA	NA
<b>Electricity</b>						
Steam-turbine (E) . . . . .		5-50,000	60	1,900	NA	0.05-0.07 <sup>d</sup>
Biogas-IC engine (E)	0.16	5	38	1,200	NA	0.10
Producer gas-IC engine (E) . . . . .	0.16-3.2	5-100	22-13	680-420	NA	0.24-0.15
Gas turbines						
(NC) . . . . .	1,580	50,000	36	1,150	NA	0.04-0.05 <sup>d</sup>
(Y2) . . . . .	3,260	100,000	28	890	NA	0.03-0.04 <sup>d</sup>
<b>Methanol</b>						
(Y2) . . . . .	10,000	316X10 <sup>e</sup>	30-50	950-1,580	10-13	NA
. . . . . 10,000-40,000		316X10 <sup>e</sup>	30-12	630-315	5-9	NA
		1,268X10 <sup>e</sup>				
<b>Ethanol from cane</b>						
(E) . . . . .	1,000	32X10 <sup>e</sup>	10	315	10	NA
(Y2) . . . . .	2,000	63X10 <sup>e</sup>	9	280	8.5"	NA
<b>Ethanol acid hydrolysis</b>						
(CR) . . . . .	1,000-2,000	32-63X10 <sup>e</sup>	80-60	25-1,890	19-21	NA
(Y2) . . . . .	2,000	63X10 <sup>e</sup>	50	1,580	15	NA
<b>Enzymatic</b>						
(NC) . . . . .	5,500-27,000	142X10 <sup>e</sup>	18-27	1,260	9-11	NA
(Y2) . . . . .	6,500-12,700	205X10 <sup>e</sup>	11-15	500	6-6.5	NA

NA = not applicable or not available.

<sup>a</sup>All figures are approximate for purposes of cross-fuel comparisons. Total production costs assume a 7% discount, \$2/GJ for biomass, and capacity utilization rates as discussed in appropriate sections of the report. Blanks indicate no estimate was made in this study.

<sup>b</sup>Units are \$/kWh where the product is electricity and \$/GJ where the product is a gas or a liquid.

<sup>c</sup>Wood fuel (not charcoal).

<sup>d</sup>Low cost is for electricity production via cogeneration at industrial sites. High cost is for stand-alone electric power generation.

<sup>e</sup>Assumes use of biomass-gasifier/gas turbine cogeneration, with export of excess electricity, the revenues from which are credited against the cost of ethanol production.

NOTE: (E) indicates the results are based on operating experiences; (CR) on commercially-ready, but not commercially implemented technologies; (NC) on technologies that are near commercialization; and (Y2) technologies which could become available by the year 2000 with a concerted RD&D effort. All costs are in 1990 U.S. dollars.<sup>a</sup>

SOURCE: Eric D. Larson, "A Developing-Country-Oriented Overview of Technologies and Costs for Converting Biomass Feedstocks into Gases, Liquids, and Electricity," September 1991. Office of Technology Assessment, contractor report, p. 74.

tion times. Cooking with producer gas also involves disadvantages, such as increased risk of exposure to carbon monoxide in poorly maintained or operated systems. Because of its low capital intensity, the cost of producer gas is strongly affected by the cost of the feedstock.

#### *Internal Combustion Engine Applications*—

Producer gas from downdraft gasifiers can be used in either compression ignition (diesel) engines or spark ignition (gasoline) engines. These stationary

engines, particularly diesel engines, have a proven record in developing countries as a versatile, relatively durable technology for producing mechanical drive and small increments of stationary power, e.g., for irrigation pumping, lighting, cottage industries, and rural processing facilities. In India alone, some 4 million small diesel engines are used solely to drive irrigation pumpsets,<sup>150</sup> with each engine consuming energy at about the same rate as the average automobile in the United States—1,500 liters of diesel fuel annually. Producer gas can typically

<sup>150</sup>B.C. J@ "Assessment of Current Status and the Potential for Commercial Exploitation of Biomass Gasification in India," *Biomass*, vol. 18, 1989, pp. 205-19.

replace 70 to 80 percent of the diesel fuel that would be used in normal operation of a diesel engine. Some diesel fuel is still needed because the low energy density of producer gas prevents it from self-igniting under compression.

Reported unit capital costs for producer gas engine generator electricity plants are generally below \$1,000/kW, even for very small (5 kW) units. Calculated costs of electricity production with gasifier engine systems, assuming a 50 percent capacity factor, range from \$0.13 to 0.24/kWh for small units (4 to 5 kW capacity) and from \$0.10 to 0.15/kWh for units larger than about 100 kW (see table 6-20). This compares with an average, highly subsidized, price of \$0.05/kWh currently being charged in the developing countries. The most important cost component for small units is labor; for larger units it is fuel.

The costs of electricity from producer gas are thus higher than the busbar cost of electricity from new central stations, but for remote use a more appropriate comparison would include transmission and distribution costs. Such an analysis for the state of Karnataka, India indicated that gasifier engine systems could produce electricity on a competitive basis with a large coal and nuclear central station power plants.<sup>151</sup> Electricity from producer gas could have additional advantages for developing countries, including lower capital intensity, shorter lead times (6 months versus 3 to 6 years for coal-fired central station plants), and the use of indigenous rather than imported fuel. Counting only investment costs and foreign exchange expenditures for fuel (zero for biomass),<sup>152</sup> the Karnataka analysis indicated that irrigation pumping could be about 10

percent less costly with gasifier-based systems than through extension of the national grid.

Despite these advantages, obstacles have been encountered to more rapid diffusion. It has proven difficult to reduce tar to tolerable levels even in downdraft technologies (tar entering an engine is deposited on components, causing loss of performance and, if unchecked, complete engine failure<sup>153</sup>). Both fundamental and applied research efforts are continuing.<sup>154</sup> For example, a 5 kW gasifier engine generator system developed by the Centre for the Application of Science and Technology to Rural Areas (ASTRA) relies on strict specification of the feedstock and careful design, operation and maintenance of the gasifier and gas cleaning system. The design has proven to be a technical success in the field.

The importance of institutional and management issues in introducing new technologies is illustrated by comparing major gasifier engine implementation efforts undertaken beginning in 1981 in the Philippines with a more recently initiated effort in India (see box 6-I).

**Gas Turbine Applications-Producer** gas can also serve as a feedstock for gas turbines that operate at much larger scales than internal combustion engines. In a biomass gasifier/gas turbine system (BIG/GT), biomass is gasified in a pressurized air-blown reactor and the products cleaned of particulate and other contaminants before being burned in an efficient power cycle based on aeroderivative gas turbines, such as the steam injected gas turbine (STIG), intercooled STIG (ISTIG), or a

<sup>151</sup>A.K.N. Reddy et al., "Comparative Costs of Electricity Conservation: Centralized and Decentralized Electricity Generation," *Economic and Political Weekly*, June 2, 1990, pp. 1201-1216.

<sup>152</sup>B.C. Jain, "Assessment of Current Status and the potential for Commercial Exploitation of Biomass Gasification in India," *Biomass*, vol. 18, 1989, pp. 205-19.

<sup>153</sup>Tar problems with gasifier-engine systems have been widely reported. See: N. Coovattanachai, W. Chongchareon, and C. Kooptarnond, "The Feasibility of Producer Gas in Electricity Generation%" *Reg. J. Energy Heat Mass Transfer*, vol. 4, No. 4, 1982; S. Kumar, et al., "Design and Development of a Biomass Based Small Gasifier-Engine System Suitable for Irrigational Needs in Remote Areas of Developing Countries," *Energy from Biomass and Wastes VIII* (Chicago, IL: Institute of Gas Technology, 1984), pp. 723-745; T. Zijp and H.E.M. Stassen, "Operating Experience with Producer Gas Plants in Tanzanian Villages," Department of Chemical Engineering, Twente University of Technology (Enschede, The Netherlands: 1984).

<sup>154</sup>See A. Kaupp, "Gasification of Rice Hulls: Theory and Praxis," German Appropriate Technology Exchange, Eschborn, Germany, 1984; M.J. Groeneveld, *The Co-Current Moving Bed Gasifier*, Ph.D. thesis for the Department of Chemical Technology, Twente University (Eindhoven, The Netherlands: 1980); H. Susanto, *Moving Bed Gasifier with Internal Recycle and Separate Combustion of Pyrolysis Gas*, Ph.D. thesis for the Institut Teknologi (Bandung, Indonesia: 1984); T.B. Reed and A. Das, *Handbook of Biomass Downdraft Gasifier Engine Systems* (Golden, CO: Solar Energy Research Institute, 1988).

combined cycle.<sup>155</sup> Hot gas cleanup avoids cost and efficiency penalties, and pressurized gasification avoids energy losses associated with compressing the fuel gas after gasification. While particulate cleanup requirements are much stricter than for heating applications and comparable to those for internal combustion engines, tar removal is not required. As with hot gas cleanup, the tar would remain in its vapor state until it is burned in the combustor. Thus, the fundamental technical problem that has plagued gasifier internal combustion engines would not be present in gas turbine applications. A complication, however, is the need to remove trace amounts of alkali vapor from the gas before it enters the gas turbine. There appears to be a basic understanding of the means for adequately cleaning gases for gas turbine applications with either fluidized bed gasifiers<sup>156</sup> or updraft gasifiers, although there has been no commercial demonstration of alkali removal. Box 6-J gives a description of current efforts in gas turbine research.

Given the lack of commercial operation, cost estimates must necessarily be tentative. BIG/GTs are characterized by high conversion efficiencies and low expected unit capital costs (\$/kW) in the 5 to 100 MW<sub>e</sub> size range.<sup>157</sup> The upper end of this range is probably near the practical upper limit on the size of a biomass installation. The expected performance and costs compare favorably with direct combustion steam turbine systems and with much larger central station fossil fuel and nuclear plants. The higher fuel cost figure corresponds to a target fuel cost for biomass (after processing for use in the gasifier) from energy plantations in the United States. Plantations in many developing countries could probably produce biomass at a lower cost than this.

While the economics of plantation based BIG/GT power generation appear attractive, initial BIG/GT applications are likely to be at industrial sites where biomass processing residues are readily available today, such as at cane sugar processing mills<sup>158</sup> and mills in the forest products industry<sup>159</sup>—replacing the currently used biomass-fired steam turbine cogeneration systems. BIG/GT systems have much higher electrical efficiencies that would permit them to meet onsite electricity needs and produce excess electricity that could be sold to utilities. Because BIG/GTs would produce less steam than steam turbines, however, steam use efficiency would generally need to be improved in a factory to enable BIG/GT systems to meet onsite steam needs.

BIG/GT systems have a number of characteristics that make them particularly attractive for developing country applications, including their low anticipated capital costs and high share of local content. With the primary exception of the high technology core of the gas turbine, most components could probably be manufactured locally. U.S. companies appear to have a strong competitive advantage in this technology.

The maintenance characteristics of the high technology core of the aeroderivative gas turbines at the heart of a BIG/GT system are also attractive. Their compact, modular nature makes it possible to replace failed parts and even whole engines quickly, with replacements flown or trucked in from centralized maintenance facilities. The required maintenance network is already largely in place in most developing countries that have their own commercial airlines. The scale characteristics of these systems are also well suited to developing countries.

<sup>155</sup>See E.D. Larson and R.H. Williams, "Steam-Injected Gas Turbines," *ASME Journal of Engineering for Gas Turbines and Power*, vol. 109, No. 7, 1987, pp. 55-63; R.H. Williams and E.D. Larson, "Expanding Roles for Gas Turbines in Power Generation" T.B. Johansson, et al., (eds.), *Electricity: Efficient End Use and New Generation Technologies, and Their Planning Implications* (Lund, Sweden: Lund University Press, 1989), pp. 503-553; R.H. Williams and E.D. Larson, "Advanced Gasification-Based Biomass Power Generation and Cogeneration," *Fuels and Electricity from Renewable Sources of Energy*, T.B. Johansson et al., (eds), (forthcoming).

<sup>156</sup>E. Kurkela, et al., "Removal of Particulates, Alkali, and Trace Metals from pressurized Fluid-Bed Biomass Gasification Products—Gas Cleanup for Gas Turbine Applications," paper presented at Conference on Energy from Biomass and Wastes XV, Washington, DC, Mar. 25-29, 1991.

<sup>157</sup>See E.D. Larson and R.H. Williams, "Biomass-Gasifier/Steam-Injected Gas Turbine Cogeneration," *Journal of Engineering for Gas Turbines and Power*, vol. 112, April 1990, pp. 157-63; P. Elliott and R. Booth, "Sustainable Biomass Energy," Selected Paper (London: Shell International Petroleum Co., Ltd., December 1990).

<sup>158</sup>See E.D. Larson et al., "Biomass-Gasifier Steam-Injected Gas Turbine Cogeneration for the Cane Sugar Industry," *Energy from Biomass and Wastes XIV*, Elsevier Applied Science, 1991; J.M. Ogden, R.H. Williams, and M.E. Fulmer, "Cogeneration Applications of Biomass Gasifier/Gas Turbine Technologies in the Cane Sugar and Alcohol Industries," *Energy and Environment in the 21st Century* (Cambridge, MA: MIT Press, 1990).

<sup>159</sup>E.D. Larson, "Biomass-Gasifier/Gas Turbine Cogeneration in the Pulp and Paper Industry," paper presented at 36th ASME International Gas Turbine and Aeroengine Congress, Orlando, FL, June 1991.

### ***Box 6-1--Gasifier-Engine Implementation in the Philippines and India***

A 1981 presidential decree in the Philippines called for a strong national commitment and effort at reducing dependence on imported oil through use of gasifier-engine systems. Irrigation pumpsets were identified as an important target market, and a goal was set of replacing 1,150 diesel fueled units with biomass/diesel dual fuel gasifier-engine systems. By 1985, when implementation efforts were halted, 319 units were installed, and by 1987 an estimated 99 percent of these were nonfunctioning, primarily due to lack of maintenance. According to a recent analysis,<sup>1</sup> the fundamental reasons for the failure of the program were institutional and management-related rather than technical problems. Political pressures pushed an un-debugged technology (charcoal gasifiers) into the field prematurely and without a full understanding of the users needs.<sup>2</sup> A single quasigovernment agency (the Farm Systems Development Corp. --FSDC) was given responsibility for technology development, dissemination, financing, and maintenance, as well as for implementation of a new fuel (charcoal) supply infrastructure. Together with its other responsibilities, the under-funded, over-burdened FSDC was unable to provide adequate service to the user: training of users was inadequate; monitoring equipment needed for proper operation and maintenance was not installed in order to reduce costs; and the charcoal production system was insufficiently developed to meet demand, which resulted in high charcoal prices and thus marginal or negative fuel cost savings to farmers. Furthermore, gasifiers were produced by a single quasi-governmental company (GEMCOR) controlled by the FSDC, so that competitive market pressures were absent in the program.

There is a strong national commitment to gasifier systems in India, as there was in the Philippines, but the Indian program appears to be proceeding at a more deliberate pace, with a keen appreciation of the need for evolutionary development of the technology. The prospects for developing sound technologies is auspicious in India, given its generally strong technological infrastructure. Also, market pressures are present, as there are several competing manufacturers of gasifier-engine systems. Some 250 units are now installed (mostly for small—3.5 to 7.5 kW—irrigation engine-pumpsets), with hardware monitoring/feedback efforts in-built in many cases. Carefully measured efforts to understand and meet user needs are ongoing.<sup>3</sup> Furthermore, many of the constraints to commercial implementation that were recognized only in retrospect in the Philippines appear to be well understood in India: the need for sound technology and a maintenance infrastructure, the need for committed and trained users, the need to understand and meet user demands, and the need for financing to help small farmers.

<sup>1</sup>F. P. Bernardo and G. U. Kilayko, "Promoting Rural Energy Technology: The Case of Gasifiers in the Philippines," *World Development*, vol. 18, No. 4, 1990, pp. 565-574.

<sup>2</sup>For example, farmers generally saw less benefit in irrigation than presumed. Thus, the actual number of hours per year a typical farmer irrigated his land was relatively low, contributing to marginal cost effectiveness of switching from diesel fuel to biomass.

<sup>3</sup>R. Bhatia, "Diffusion of Renewable Energy Technologies in Developing Countries: A Case Study of Biogas Engines in India," *World Development*, vol. 18, No. 4, 1990, pp. 575-90.

## Biogas

Biogas is produced by the biological process of anaerobic (without air) digestion of organic feedstocks. It consists primarily of methane and carbon dioxide and has a heating value of about 22 megaJoules/normal cubic meter or (590 Btu/ft<sup>3</sup>). In the absence of oxygen, organic matter introduced into the digester is degraded by the action of three classes of bacteria. Proper operation of the digester relies on a dynamic equilibrium among the three bacterial groups. This balance, and hence the quality and quantity of gas produced, are affected by changes in digester temperature and acidity, and by the composition and rate of loading of the feedstock.

Two basic digester designs have been used most widely in developing countries. The floating cover digester (India) and the fixed dome digester (China).

A third design, the bag digester, is gaining in popularity. In the floating cover digester, a gas holder floats on a central guide and provides constant pressurization of the gas produced. The reactor walls are typically brick or concrete. Traditionally the cover is made of mild steel, though more corrosion resistant materials are also being used. The digester is fed semi-continuously, with input slurry displacing an equivalent amount of effluent sludge. The primary drawback of the floating cover design as developed by the Indian Khadi Village Industries Commission (KVIC) is the high cost of the steel cover. The floating cover digester is suitable for both household size and larger scale community or commercial operation.

In the Chinese fixed dome digester, biogas collects under a fixed brick or concrete dome,

### Box 6-J-Current Gas Turbine Research

**Biomass** integrated gasification/gas turbines (BIG/GT) systems are likely to be available by the mid-1990s, based on development efforts ongoing in Scandinavia, Brazil, and the United States.<sup>1</sup> Ahlstrom, a Finnish producer of biomass gasifiers, plans to build a 6-10 MWe BIG/GT plant in southern Sweden in collaboration with Sydkraft, a major Swedish electric utility.<sup>2</sup> The plant will operate in a cogeneration mode, using an Ahlstrom pressurized circulating fluidized-bed gasifier and a sophisticated hot gas cleanup system, including ceramic filters for particulate.

In Brazil, a major electric utility has an ongoing R&D program to develop biomass from planted forests as a major fuel source for power generation, with conversion to electricity using BIG/GT units.<sup>3</sup> The utility is currently planning to build an 18 MWe demonstration BIG/GT plant. The overall program goal is commercial implementation of plantation-based BIG/GT systems starting in 1998.

The U.S. Department of Energy (DOE) announced in late 1990 a major new program initiative to commercialize BIG/GT technology<sup>4</sup> by the late 1990s. The DOE recently selected the pressurized bubbling-fluidized bed RENGAS gasifier developed by the Institute of Gas Technology (IGT) for a large scale gasification demonstration.<sup>5</sup> A scaled-up unit will be built in Hawaii and be run initially on sugarcane bagasse (50 tonne per day capacity). Start-up is anticipated in late 1992. Also in the United States, the Vermont Department of Public Service, in cooperation with in-state electric utilities, is exploring possibilities for a commercial demonstration of BIG/GT technology fueled by wood chips derived from forest management operations.<sup>6</sup> The DOE, U.S. Environmental Protection Agency, U.S. Agency for International Development, and GE are also participating.

<sup>1</sup>E.D. Larson, "Biomass-Gasifier/Gas Turbine Cogeneration in the Pulp and Paper Industry," *Journal of Engineering for Gas Turbines and Power*, forthcoming.

<sup>2</sup>Ahlstrom Corp. and A.B. Sydkraft, "Finland Goes Ahead with Unique Gasification Recess," press release, Helsinki, Finland and Malmo, Sweden, Nov. 7, 1990.

<sup>3</sup>E.A. Carpentieri, Chief of Alternative Energy Research, Companhia Hidroeletrica do Sao Francisco, Recife, Brazil, personal communication August 1991.

<sup>4</sup>R. San Martin, U.S. Department of Energy, Deputy Assistant Secretary, Office of Utility Technologies, Division of Conservation and Renewable, "DOE Research on Biomass Power Production," presentation at Conference on Biomass for Utility Applications, Tampa, Florida, Oct. 23-25, 1990.

<sup>5</sup>s. Babu, Institute of Gas Technology, Chicago, IL, personal communication, November IWO.

<sup>6</sup>R. Sedano, Department of Public Service, State of Vermont, Montpelier, VT, personal communication, January 1991.

displacing effluent sludge as the gas pressure builds. The dome geometry is used to withstand the higher pressures generated. This technology has been widely used for small household scale units. Relatively few large scale units have been built, due to the difficulty of constructing large domes. A major shortcoming of the freed cover units, even in small sizes, has been the difficulty of constructing leak-proof domes. However, a number of improved versions of the freed dome design have been introduced, including those designed to operate with plug flow conditions and/or with storage of gas in variable volume "bags." <sup>160</sup>

The typical digester feedstock in India is wet cattle dung mixed-with water in a 1:1 ratio. A typical yield of gas with the KVIC digester is 0.02 to 0.04 m<sup>3</sup> per kg of fresh manure input at a design ambient temperature of 27 °C.<sup>161</sup> A family of 5 would therefore need the dung output from a minimum of 2 to 3 animals to meet their cooking fuel needs.<sup>162</sup> This is beyond the means of the majority of rural Indian households. In China, the feedstock is typically a mix of nitrogen-rich pig manure, cow manure and night soil, and carbon-rich straw and grass<sup>163</sup> with water added to achieve a total input solids concentration of about 10 percent. This technology

<sup>160</sup>Wu Wen, "Biomass Utilization in China," draft paper for Energy Research Group, Ottawa, Canada, July 1984.

<sup>161</sup>C. Kashkari, "Biogas Plants in India," *Energy in the Developing World: The Real Energy Crisis* (Oxford, United Kingdom: Oxford University Press, 1980), pp. 208-14.

<sup>162</sup>Assuming a daily gas yield of 0.2 m<sup>3</sup> per m<sup>3</sup> of digester volume.

<sup>163</sup>See Wu Wen, "Biomass Utilization in China," draft paper for Energy Research Group, Ottawa, Cam@ July 1984; Q. Daxiong, et al., "Diffusion and Innovation in the Chinese Biogas Program," *World Development*, vol. 18, No. 4, 1990, pp. 555-563.

is therefore accessible to a larger share of households than for the KVIC digester.

There is general agreement that the capital costs of freed dome units are significantly lower than floating domes, at least for household scale digesters, primarily because they do not require a steel cover. Capital costs for both technologies are declining,<sup>164</sup> indicating significant learning from the experiences of the 1970s and 1980s. Labor is required in the production of biogas to collect water and dung, mix and load inputs, distribute sludge, clean out the plant, and for maintenance. Total costs (both capital and operating) of community sized digesters (100 GJ/yr to 1,000 GJ/yr capacity) are estimated at \$9/gigajoules to \$5/GJ (\$9.50 to \$5.25/MMBtu). At the household scale, the cost appears to be higher, about \$11/GJ.<sup>165</sup> These high costs greatly limit the applicability of biogas units where justified by energy output alone. At the present time, much of the labor involved in small scale units may be performed by household members, lowering the financial cost; in the future, such low cost or "free" labor will not be so readily available at either the household or community scale and may limit biogas operations to locations where large quantities of waste materials are already collected for sanitation or other purposes.

A major advantage of biogas over the direct use of raw biomass is that valuable nutrients are retained in the slurry, instead of being partially lost in the combustion process. For example, the wet slurry output from a digester fed with fresh cattle dung has essentially the same nitrogen fertilizer value as the input dung. Because water is also added to the digester, however, about twice as much fresh di-

gestor effluent is needed to supply the same amount of nitrogen.

Biogas digesters also have an important sanitation advantage, reducing or eliminating pathogens present in animal and human wastes. Significant declines in parasite infections, enteritis, and bacillary dysentery have been noted in areas following installation of digesters.<sup>166</sup> Air drying or composting of digester effluent can further reduce or completely eliminate pathogens. An additional health benefit where biogas replaces wood used in traditional cook stoves is the elimination of noxious gases and particulate from wood fires.

Biogas, like producer gas, can be used to fuel either compression or spark ignited internal combustion engines, which can provide shaft power or drive an electrical generator. Gas from an innovative floating cover gasifier developed by researchers from<sup>167</sup> ASTRA of the Indian Institute of Science (Bangalore) is used to replace about 70 percent of the diesel fuel needed to run a 5 kW diesel engine generating electricity used for pumping water and providing lighting. Villagers are paid a fee of \$0.0016/kg for delivered dung and are also returned digester sludge in proportion to their dung contribution. The sludge is passed through a simple sand bed filter system to concentrate the solids content before it is returned. The village biogas engine operation employs two village youths full time. With the current operating hours of the system (4.3 hours/day), corresponding to a capacity factor of about 18 percent, the total leveled cost of electricity is about 15 cents/kWh.

There are an estimated 5 million digesters operating in China today, mostly at the household scale

<sup>164</sup>The five sets of data referred to here are all based on experiences with digesters in India, and thus comparisons among the data sets are meaningful. The Rijal and Orcullo estimates are from experiences in Nepal and the Philippines and are thus probably not strictly comparable to the Indian data. See M.T.Santerre and K.R.Smith, "Measures of Appropriateness: The Resource Requirements of Anaerobic Digestion (Biogas) Systems," *World Development*, vol. 10, No. 3, 1982, pp. 239-61; N.A.Orcullo, "Biogas Technology Development and Diffusion: the Philippine Experience," *Biogas Technology, Transfer and Diffusion, El-Halwagi (ed)* (London: Elsevier Applied Science Publishers, 1986), pp. 669-86; K. Rijal, "Resource Potential and Economic Evaluation of Bio-Gas Utilization in Nepal," *Energy*, vol. 11, No. 6, 1986, pp. 545-50.

<sup>165</sup> For household-sized units, an alternative perspective on production cost might be more appropriate, however. Householders would probably use family labor to operate and maintain a digester and might not consider this a cost. In addition, capital costs converted using a purchasing-power-parity (PPP) exchange rate might better represent the capital cost for a rural dweller with little or no access to hard currency. Also, capital is generally likely to be scarce for the household, which would be reflected by a much higher discount rate than the 7% assumed above. Neglecting labor and maintenance costs, converting capital costs to U.S.\$ using a PPP exchange rate, and applying a 30% discount rate would result in biogas costs up to five times those shown for household-sized units (25 GJ/yr), corresponding to a gas cost of perhaps \$25/GJ (R. Summers and A. Heston, "A New Set of International Comparisons of Real Product and Price Levels Estimates for 130 Countries, 1950 to 1985," *Review of Income and Wealth*, March 1988, pp. 1-25 (with accompanying data diskettes).

<sup>166</sup>C.G. Gunnerson and DC Stuckey, *Integrated Resource Recovery: Anaerobic Digestion*, Technical Paper 49, World Bank, Washington, DC, 1986.

<sup>167</sup>A.K.N. Reddy et al., "Studies in Biogas Technology. Part IV. A Novel Biogas Plant Incorporating Solar Water-Heater and Solar Still," *Proceedings of the Indian Academy of Sciences*, C2(3), Bangalore, India, Sept. 1979, pp. 387-93.

and some 300,000 in India.<sup>168</sup> The efforts in China and India to popularize biogas have been very different in nature historically, which permits some lessons to be drawn on implementation. These include:

- the need for national commitment (this has helped address key problems such as distorted user economics due to subsidized prices for electricity and alternative fossil fuels, valuing of nonpecuniary benefits such as improved sanitation, and supporting R&D efforts aimed at cost reduction and technology improvement);
- the need for several stages of development, including a strong technology base, and an experimental and limited field test stage before large scale dissemination;
- an interdisciplinary approach;
- the importance of training of disseminators and users;
- a mix of centralized and decentralized institutions; and
- competitive market-type forces.

### *Gas Cost Comparisons*

From our analysis of costs we conclude that among gas generating technologies, biogas systems are an order of magnitude more capital intensive than producer gas systems up to the quite high production level of 1,000 GJ/yr, when producer gas and biogas are about equal in cost due to the high feedstock cost for producer gas. At a very small scale (less than 20 GJ/yr) biogas may likely be more costly than producer gas, but the health and fertilizer benefits of biogas technology are not included in the biogas cost, and further reduction in costs of floating cover digesters can be expected.

### *Liquid Fuels From Biomass*

*The* production of liquid fuels from biomass, with the exception of ethanol from sugarcane and corn, has not been widely implemented commercially

because of their high cost. In the case of ethanol from cane and corn, government subsidies have supported commercial production. Research and development work to reduce costs and improve yields have been modest, except in the case of ethanol from sugarcane in Brazil. Advances may make liquid biofuels more competitive with fossil fuels over the next decade.

This section discusses three alternative liquid fuels from biomass: methanol from lignocellulose (any woody or herbaceous biomass), ethanol from sugarcane (ethanol from corn is generally not considered a practical option for most developing countries), and ethanol from lignocellulose.

#### Methanol From Lignocellulose

Methanol is produced today primarily from natural gas. But it can also be produced from coal and, through a similar process, from lignocellulosic biomass feedstocks.<sup>169</sup> Biomass-to-methanol plants would typically convert 50 to 60 percent of the energy content of the input biomass into methanol, though some designs have been proposed with conversion efficiencies of over 70 percent.

Three basic thermochemical processes are involved in methanol production from biomass:

1. A 'synthesis gas' (a close relative of producer gas) is produced via thermochemical gasification, but by using oxygen rather than air in order to eliminate dilution of the product gas with nitrogen (in air). Oxygen plants have strong capital cost scale economies, which contributes to most proposed biomass-to-methanol facilities being relatively large (typically 2,000 tonnes/day or more input of dry biomass). Biomass gasifiers designed for methanol production are not commercially available. A number of pilot and demonstration scale units were built and operated in the late 1970s/early 1980s,<sup>170</sup> but most of these efforts were halted when oil prices fell. Work on one (a fluidized bed unit developed by the Institute

<sup>168</sup>Q. Daxiong et al., "Diffusion and Innovation in the Chinese Biogas Program," *World Development*, vol. 18, No. 4, 1990, pp. 555-563; D.L. Klass, "Energy from Biomass and Wastes: 1985 Update and Review," *Resources and Conservation*, vol. 15, Nos. 1 and 2, 1987, pp. 7-84.

<sup>169</sup>C.E. Wyman, et al., "Ethanol and Methanol From Cellulosic Materials," *Fuels and Electricity from Renewable Sources of Energy*, T. Johansson et al., (eds), (forthcoming).

<sup>170</sup>See A. A.C.M. Beenaekers and W.P.M. van Swaaij, "The Biomass to Synthesis Gas Pilot Plant Programme of the CEC: A First Evaluation of Results," *Energy from Biomass, 3rd EC Conference (Essex, United Kingdom: Elsevier Applied Science, 1985)*, pp. 120-45; E.D. Larson, P. Svenningsson, and I. Bjerle, "Biomass Gasification for Gas Turbine Power Generation," T.B. Johansson et al., (eds.), *Electricity: Efficient End-Use and New Generation Technologies, and their Planning Implications* (Lund, Sweden: Lund University Press, 1989), pp. 697-739.

of Gas Technology<sup>171</sup>) has recently been revived, with the construction of a bagasse-fueled demonstration unit now being planned. In addition, there are some commercial gasifiers originally designed for coal that could be used for biomass use.<sup>172</sup>

2. The synthesis gas is cleaned and its chemical composition is adjusted to produce a gas consisting purely of hydrogen (H<sub>2</sub>) and carbon monoxide (CO) in a molar ratio of 2:1. The specific equipment configuration in the second step in methanol production will vary depending on the gasifier used. A reactor common to all systems is a "shift" reactor used to achieve the desired 2:1 ratio of H<sub>2</sub> to CO by reacting steam with the synthesis gas. The shift reactor is a commercially established technology. Other processing may be required before the shift stage, however, depending on the composition of the synthesis gas leaving the gasifier. For example, tars contained in the synthesis gas must be removed or cracked into permanent gases.
3. The gas is compressed and passed through a pressurized catalytic reactor—that converts the CO and H<sub>2</sub> into liquid methanol. A variety of commercial processes can be used.

As biomass to methanol plants are not yet commercially available, costs are uncertain. From scattered cost data, mainly based on U.S. experience, it is estimated, however, that methanol could be produced for about \$11 to \$14/GJ (\$1 1.50 to \$14.75/MMBtu) with commercially ready technology in a plant with a capacity of about 10 million GJ/yr (about 500 million liters/yr). At larger scale—40 million GJ/year—costs would be \$7/GJ to \$8/GJ (\$7.50-\$8.50/MMBtu). Capital represents the largest fraction of the total cost of methanol produced in small plants, while feedstock is the dominant cost in large plants. Thus, capital cost reductions will be most important in reducing methanol costs from

small plants while increases in biomass conversion efficiency will be most important at large scale.

#### Ethanol From Biomass by Fermentation

Two varieties of ethanol are being produced today from sugarcane for use as fuel in developing countries: anhydrous ethanol—essentially pure ethanol—and hydrous ethanol containing about 5 percent water. Anhydrous ethanol (apart from Brazil the most common in developing countries) can be blended with gasoline up to a maximum ethanol content of about 20 percent without need for modifying conventional spark ignition vehicle engines.<sup>173</sup> Hydrous ethanol cannot be blended with gasoline, but can be used alone as a fuel in engines specifically designed for ethanol. Most national anhydrous ethanol programs are small, due to uncertainty over oil prices and the limited size of market (20 percent of gasoline consumption). In Brazil, however, 90 percent of new cars are designed to use hydrous ethanol.

At an autonomous alcohol distillery (i.e., not associated with sugar production), raw sugarcane is washed, chopped, and crushed in rolling mills to separate the sugar laden juice from the bagasse, the fiber portion of the cane. The raw cane juice, containing over 90 percent of the sucrose in the cane, is filtered and heated, and is either sent directly to a fermentation tank after cooling, or limed, clarified, and concentrated before fermentation. The fermented mixture contains water and ethanol in about a 10:1 ratio. The mixture is then distilled, typically through two distillation columns to concentrate the ethanol.<sup>174</sup> A typical yield of hydrous alcohol is 70 liters per tonne of cane processed. Stillage, a potassium-rich liquid, is drained from the bottom of the distillation columns.

The bagasse, accounting for about 30 percent of the weight of fresh cane, or about 60 percent of the cane's energy content,<sup>175</sup> can be used to produce both electricity and steam for process heating. The

<sup>171</sup>R.J. Evans et al., *Development of Biomass Gasification to Produce Substitute Fuels*, PNL-6518, Battelle Pacific Northwest Laboratory, Richland, WA, 1988.

<sup>172</sup>See Chem Systems, "Assessment of Cost of Production of Methanol from Biomass" (draft) (Golden, CO: Solar Energy Research Institute, December 1989); E.D. Larson, P. Svenningsson, and I. Bjertle, "Biomass Gasification for Gas Turbine Power Generation," Thomas B. Johansson, Birgit Bodlund, and Robert H. Williams (eds.), *Electricity: Efficient End-Use and New Generation Technologies, and their Planning Implications* (Lund, Sweden: Lund University Press, 1989), pp. 697-739; V. Brecheret Filho, A.J. Ayres Zagatto, "Methanol From Wood in Brazil," presented at the 179th American Chemical Society National Meeting, Houston, TX, Mar. 23-28, 1980;

<sup>173</sup>World Bank, *Alcohol Production from Biomass in the Developing Countries* (Washington, DC: The World Bank, 1980).

<sup>174</sup>Additional distillation steps are needed to produce anhydrous ethanol.

<sup>175</sup>About 35% of the original energy in the sugar cane stalk brought to a mill is converted to alcohol, 59% to bagasse, and 6% to stillage.

potential for selling excess electricity from alcohol distilleries could be high as a result of new process technologies that reduce onsite energy needs, and new cogeneration technologies that increase the ratio of electricity to heat produced.<sup>176</sup> Credits for these sales could significantly improve the economics of ethanol production. Stillage, which contains about 6 percent of the energy contained in the cane, also has economic potential as a fertilizer for sugarcane<sup>177</sup> and as a feedstock for biogas production. If sugarcane tops and leaves (typically burned in the fields and contributing to local air pollution) could also be economically used for electricity production, ethanol production costs would be further reduced.

In a distillery annexed to a sugar factory, the fermentation feedstock is typically molasses produced as a minor byproduct of sugar processing. Some Brazilian factories are designed to use either molasses or a mixture of molasses and raw cane juice as the fermentation feedstock, thus permitting them to vary their production of sugar and ethanol to better match market demands.<sup>178</sup>

Estimating costs of ethanol from annexed distilleries is complicated by the multitude of options for feedstocks and relative product mixes.<sup>179</sup> The application for which hydrous ethanol is most often considered is as an automotive fuel to replace gasoline. The cost of hydrous alcohol in the most efficient mills in Brazil is about \$9.00/GJ (\$0.20/liter). Correcting both for the lower energy content of ethanol and its higher thermodynamic efficiency in an engine, ethanol at this price would be competitive with gasoline when crude oil prices are about \$30 per barrel. An average production cost, including some less efficient plants, would be \$0.22 to \$0.26 per liter (\$10.00 to \$11.80 per GJ),

corresponding to an equivalent crude oil price of about \$30 to \$35 per barrel (see table 6-23).

Costs have been falling since the inception of the program, due in part to more efficient distillery operation (increased liters of ethanol per tonne of cane) and, more importantly, increased land productivity. The cost of delivered cane is the largest single determinant of ethanol costs. Cane growing, harvesting, and transporting costs vary significantly from one region of the world to another with Brazilian costs among the lowest because of the large scale of production and emphasis on cane varieties and cultivation practices to maximize yield.<sup>180</sup> Production costs in other countries would be higher, leading to higher ethanol prices, which in turn would only become competitive with gasoline prices at crude oil prices over \$35.

The economics of ethanol could be improved by more intensive use of byproducts such as bagasse, stillage, and sugarcane leaves. Crediting revenues from the sale of electricity or stillage for fertilizer would reduce the cost of the ethanol operation. A recent study illustrates some of the possibilities, based on Brazilian conditions and assuming the use of three different cogeneration technologies.<sup>181</sup> This study found that with state-of-the-art steam turbine technology (CEST), ethanol costs could be reduced to levels competitive with gasoline, but the cost of exported electricity would not be competitive with most central station alternatives. More importantly, the study found, the use of advanced gas turbine cogeneration technologies (BIG/STIG and BIG/ISTIG) could also lead to ethanol production costs substantially lower than today's level, and simultaneously to electricity production costs that would be competitive in many cases with central station alternatives.

<sup>176</sup>M. Fulmer, "Electricity-Ethanol Co-Production from Sugar Cane: A Technical and Economic Assessment" MSE thesis, Mechanical and Aerospace Engineering Department Princeton University, Princeton, NJ, January 1991.

<sup>177</sup>J. Goldemberg and L.C. Monaco, "Ethanol as Alternative Fuel: Successes and Difficulties in Brazil," draft manuscript for *Fuels and Electricity from Renewable Energy Sources*, T. Johansson et al., (eds), forthcoming.

<sup>178</sup>J.M. Ogden and M. Fulmer, "Assessment of New Technologies for Co-Production of Alcohol, Sugar and Electricity From Sugar Cane," PU/CEES Report 250, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, 1990.

<sup>179</sup>M. Fulmer, "Electricity-Ethanol Co-Production From Sugar Cane: A Technical and Economic Assessment," MSE thesis, Mechanical and Aerospace Engineering Department, Princeton University, Princeton, NJ, January 1991.

<sup>180</sup>J.M. Ogden and M. Fulmer, "Assessment of New Technologies for Co-Production of Alcohol, Sugar and Electricity from Sugar Cane" PU/CEES Rpt. 250, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, 1990.

<sup>181</sup>See J.M. Ogden, R.H. Williams, and M.E. Fulmer, "Cogeneration Applications of Biomass Gasifier/Gas Turbine Technologies in the Cane Sugar and Alcohol Industries," *Energy and Environment in the 21st Century* (Cambridge, MA: MIT Press, 1990); M. Fulmer, "Electricity-Ethanol Co-Production from Sugar Cane: A Technical and Economic Assessment" MSE thesis, Mechanical and Aerospace Engineering Department, Princeton University, Princeton, NJ, January 1991.

Table 6-23—Required Production Cost of Ethanol for Competition With Wholesale Gasoline<sup>a</sup>

Crude oil price (\$/bbl)	Gasoline price <sup>a</sup>		Equivalent hydrous ethanol price <sup>b</sup>		Equivalent anhydrous ethanol price <sup>c</sup>	
	(\$/bbl)	(\$/lit)	(\$/lit)	(\$/GJ) <sup>d</sup>	(\$/lit)	(\$/GJ) <sup>d</sup>
20 .....	28	0.176	0.148	6.73	0.204	8.71
25 .....	35	0.220	0.185	8.42	0.255	10.91
30 .....	42	0.264	0.222	10.10	0.306	13.09
35 .....	49	0.308	0.259	11.78	0.357	15.27
40 .....	56	0.352	0.296	13.47	0.408	17.45

NOTE: All dollars are U.S. 1990\$.

<sup>a</sup>Gasoline price relative to crude price is based on Brazilian conditions [96].

<sup>b</sup>Assumes 1 liter of hydrous ethanol as a neat fuel is worth 0.84 liters of gasoline [123].

<sup>c</sup>Assumes 1 liter of anhydrous ethanol is worth 1.16 liters of gasoline when the ethanol is used as an octane-boosting additive [124].

<sup>d</sup>Higher heating value basis.

SOURCE: Eric D. Larson, "A Developing-Country-Oriented Overview of Technologies and Costs for Converting Biomass Feedstocks into Gases, Liquids, and Electricity," September 1991. Office of Technology Assessment contractor report, p. 71.

Much of the controversy over alcohol programs centers on its indirect social and economic impacts. The Brazilian PROALCOOL program—the only large scale program yet in developing countries—has been considered successful in achieving three of its major initial goals: reduced dependence on foreign oil, increased employment, and expanded capital goods (distillery equipment) production capabilities in Brazil.<sup>182</sup>

Its success in creating jobs is, however, ambiguous. On the one hand, the current program supports about 800,000 direct jobs, or 570,000 full time equivalent jobs. The labor intensity of the industry is much greater in the Northeast, the area of greatest unemployment, than in the South-Central region. The capital invested to create these jobs—some \$32,000 per job in the South-Central region and \$8,200 per job in the Northeast—has been relatively small compared to other industries. The average for all industry in Brazil is some \$53,000; for the paper and pulp industry, \$88,000; and for petrochemicals, **\$250,000**. On the other hand, the quality of jobs is more debatable. The large component of seasonal

labor has led in some cases to low wages, poor working and living conditions, and a lack of social benefits for workers,<sup>183</sup> especially in the Northeast. One strategy has been to extend the harvest period from 6 to 8 or 9 months by planting cane varieties that mature at different times.<sup>184</sup> In addition to extending the period of employment, a longer production season increases output and improves capital utilization.

The impact of the ethanol program on land use is similarly debatable. Some 4.3 million hectares are currently planted with sugar cane in Brazil,<sup>185</sup> compared with a total crop area of 52 million hectares<sup>186</sup> and a total potential agricultural area of 520 million hectares.<sup>187</sup> About half the cane area is devoted exclusively to ethanol production.<sup>188</sup> Many analysts appear to agree that cane production has not displaced domestic crop production.<sup>189</sup> On the other hand, production of export crops such as soybeans has been growing faster than domestic crops, due to agricultural pricing policies that make export crop production more attractive to farmers.<sup>190</sup>

<sup>182</sup>J. Goldemberg, L.C. Monaco and I. Macedo, "The Brazilian Fuel Alcohol Program," *Fuels and Electricity from Renewable Energy Sources*, T. Johansson et al., (eds), (forthcoming).

<sup>183</sup>H.S. Geller, "Ethanol from Sugarcane in Brazil," *Annual Review of Energy*, vol. 10, 1985, pp. 135-64.

<sup>184</sup>Ibid.

<sup>185</sup>*Anuario Estatístico do Brasil*, IBGE, Rio de Janeiro, 1989.

<sup>186</sup>*Agricultural Land Use Census*, IBGE, Rio de Janeiro, 1985.

<sup>187</sup>F. Rosillo-Calle, "Brazil: A Biomass Society," *Biomass: Regenerable Energy* (Chichester, United Kingdom: John Wiley & Sons, 1987), pp. 329-348.

<sup>188</sup>J. Goldemberg, L.C. Monaco and I. Macedo, op. cit., footnote 188.

<sup>189</sup>See H.S. Geller, "Ethanol from Sugar Cane in Brazil," *Annual Review of Energy*, vol. 10, 1985, pp. 135-164; J. Goldemberg, L.C. Monaco and I. Macedo, op. cit., footnote 188, F. Rosillo-Calle, "Brazil: A Biomass Society," *Biomass: Regenerable Energy* (Chichester, United Kingdom: John Wiley & Sons, 1987), pp. 329-48.

<sup>190</sup>H.S. Geller, "Ethanol from Sugarcane in Brazil," *Annual Review of Energy*, vol. 10, 1985, pp. 135-64.

## Ethanol From Lignocellulose

The high costs of sugarcane (and corn in the United States) has motivated efforts to convert lower cost biomass, primarily woody and herbaceous materials, into ethanol. These feedstocks are less costly largely because they do not compete as food crops. However, they are more difficult (and to date more costly) to convert into ethanol. Woody and herbaceous biomass, referred to generally as lignocellulosic materials, consist of three chemically distinct components: cellulose (about 50 percent), hemicellulose (25 percent), and lignin (25 percent).<sup>191</sup> Most proposed processes involve separate processing (either hydrolysis or enzymatic) of these components. In the first step, pretreatment, the hemicellulose is broken down into its component sugars and separated out. The lignin is also removed. The cellulose is then converted into fermentable glucose through hydrolysis. Following fermentation, the products are distilled to remove the ethanol. Byproducts of the separation process, such as furfural and lignin, can be used as fuel.

**Acid Hydrolysis**—A number of variants on the basic process have been proposed, each typically involving use of a different acid and/or reactor configuration.<sup>192</sup> One system incorporates two stages of hydrolysis using dilute sulfuric acid. In the first step, the acid breaks the feedstock down into simple sugars. However, the acids also degrade some of the product sugars so that they cannot be fermented, thus reducing overall yield. R&D effort has been aimed at improving the relatively low yields (55 to 75 percent of the cellulose) through the use of other acids.<sup>193</sup> Low cost recovery and reuse of the acids is necessary to keep production costs down,<sup>194</sup> but has yet to be commercially proven.

The conversion process becomes more competitive when furfural production from the hemicellulose fraction is maximized<sup>195</sup> and sold, but the

furfural market is too small to support a large scale fuel ethanol industry. Byproduct electricity could also offset ethanol costs, but the amounts of exportable electricity coproduced in process configurations to date are relatively small. This situation might change if more advanced cogeneration technologies are considered.

**Enzymatic Hydrolysis**—In enzymatic hydrolysis, biological enzymes take the place of acid in the hydrolysis step. Enzymes typically break down only the cellulose and do not attack the product sugars. Thus, in principle, yields near 100 percent from cellulose can be achieved. Typically, a feedstock pretreatment step is required since biomass is naturally resistant to enzyme attack. The most promising of several options for pretreatment appears to be treatment by a dilute acid,<sup>196</sup> in which the hemicellulose is converted to xylose sugars that are separated out, leaving a porous material of cellulose and lignin that can more readily be attacked by enzymes.

A number of bacteria and yeasts have been identified and tested as catalyzers of cellulose hydrolysis, of which three process configurations have received the most attention from researchers.

- In the Separate Hydrolysis and Fermentation (SHF) of cellulose, three separate operations are used to produce enzymes, hydrolyze cellulose, and ferment the glucose. The presence of glucose produced during hydrolysis slows the catalytic effect of the enzymes, thus increasing costs of ethanol production. Some enzymes have been identified that are less susceptible to end product inhibition, but the improvement in overall economics of the SHF process are relatively modest.
- A more promising modification of the SHF process involves simultaneous saccharification and fermentation (SSF), permitting higher prod-

<sup>191</sup>J.D. Wright, "Ethanol from Lignocellulose: An Overview," *Energy Progress*, vol. 8, No. 2, 1988, pp. 71-78.

<sup>192</sup>C.E. Wyman, *Op. cit.*, footnote 175.

<sup>193</sup>J.D. Wright, "Ethanol from Lignocellulose: An Overview," *Energy Progress*, vol. 8, No. 2, 1988, pp. 71-78; See J.D. Wright, A.J. Power, and P.W. Bergeron, "Evaluation of Concentrated Halogen Acid Hydrolysis Processes for Alcohol Fuel Production," SERI/TR-232-2386 (Golden, CO: Solar Energy Research Institute, 1985); C.E. Wyman, *Op. cit.*, footnote 175.

<sup>194</sup>J.D. Wright, A.J. Power, and P.W. Bergeron, "Evaluation of Concentrated Halogen Acid Hydrolysis Processes for Alcohol Fuel Production," SERI/TR-232-2386 (Golden, CO: Solar Energy Research Institute, 1985).

<sup>195</sup>See P.W. Bergeron, J.D. Wright, and C.E. Wyman, "Dilute Acid Hydrolysis of Biomass for Ethanol Production," *Energy from Biomass and Wastes XII* (Chicago, IL: Institute for Gas Technology, 1989), pp. 1277-1296; M.M. Bulls et al., "Conversion of Cellulosic Feedstocks to Ethanol and Other Chemicals Using TVA's Dilute Sulfuric Acid Hydrolysis Process," *Energy from Biomass and Wastes XIV* (London: Elsevier Applied Science, 1991) pp. 1167-1179.

<sup>196</sup>J.D. Wright, "Ethanol from Biomass by Enzymatic Hydrolysis," *Chemical Engineering Progress*, August 1988, pp. 62-74.

uct yield and use of a single reaction vessel. This improves the economics substantially.<sup>197</sup> However, the yeasts and bacteria used in SSF processes cannot ferment xylose sugars to ethanol. Incorporating xylose fermentation with SSF cellulose fermentation promises significant reductions in cost for ethanol from biomass.<sup>198</sup>

- Single reactor Direct Microbial Conversion (DMC) combines enzyme production, cellulose hydrolysis and glucose fermentation in a single process. In limited efforts to date, however, DMC ethanol yields have been lower than for the SHF or SSF processes, and a

number of undesired products in addition to ethanol have been produced.

The next anticipated advancement is increased xylose conversion to ethanol, which would double efficiencies to 50 percent and reduce capital costs. If this target can be achieved at a commercial scale, hydrous ethanol from enzymatic hydrolysis might become competitive with gasoline when the crude oil price is as low as \$20 per barrel, with most of the cost in the feedstock. Advances in this technology and in biotechnology more generally, suggest economically competitive commercial systems might be developed by the year 2000.

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<sup>197</sup>J.D. Wright, C.E. Wyman, and K. Grohmann, *Simultaneous Saccharification and Fermentation of Lignocellulose: process Evaluation* (Golden, CO: Solar Energy Research Institute, 1988).

<sup>198</sup>L.R. Lynd, et al., "Fuel Ethanol From Cellulosic Biomass," *Science*, vol. 251, No. 4999, March 1991, pp. 1318-1323.