CHAPTER 10

rural energy in developing countries

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ABSTRACT Supplying modern energy services to the 2 billion people who still cook with traditional solid fuels and lack access to electricity is probably one of the most pressing problems facing humanity today. The amount of energy needed to satisfy the basic needs of rural populations around the world is relatively small, and appropriate technologies are available. However, widening access to modern energy services is limited by the extreme poverty found particularly in the least developed countries.

Living standards in rural areas can be significantly improved by promoting a shift from direct combustion of biomass fuels (dung, crop residues, and fuelwood) or coal in inefficient and polluting stoves to clean, efficient liquid or gaseous fuels and electricity. Although consumers tend to shift to these modern, higher-quality energy carriers as their incomes rise and the carriers become more affordable, the process is slow. Yet a shift to such carriers can reduce the damage to human health and the drudgery associated with continued reliance on inefficient, polluting solid fuels.

This chapter describes experience with and prospects for improving the technologies used to cook with biomass in several countries, as well as the development of clean, non-toxic cooking fuels. Progress in rural electrification—using both centralised, grid-based approaches and small-scale, decentralised technologies—is also described.

Technological developments alone, however, will not improve access or promote greater equity. New institutional measures are also needed, including financing to cover the initial capital costs of devices and equipment. Energy initiatives will be most successful when integrated with other policies that promote development. And because local populations will ultimately use, maintain, and pay for energy services, they should be involved in making decisions about energy systems. ■

Accelerating the introduction of modern energy is a key strategy for promoting sustainable development in rural areas.

The lack of adequate energy services in rural areas of developing countries has social dimensions (chapter 2) as well as serious environmental and health effects (chapter 3). Many of these problems are exacerbated by the almost exclusive reliance of rural populations in most areas on traditional fuels coupled with simple technologies characterised by low energy efficiency and harmful emissions. This chapter thus focuses on technological opportunities, as well as other strategies, for delivering adequate, affordable, cleaner energy supplies to rural areas.

The second half of the 20th century witnessed a strong urbanisation trend and the emergence of megacities (those containing more than 10 million people) in most developing countries. Between 1970 and 1990 the share of people living in cities grew from 28 to 50 percent. But while the rural population relatively decreased during this period, the absolute number of people living in rural areas increased to 3 billion. Despite this, rural development often remains low on government agendas because of increasing demands of growing, politically and economically dominant urban populations. Thus the explosive growth of cities makes it difficult for policy-makers to give rural development the attention it deserves.

The dispersed character of rural populations and their low commercial energy consumption result in poor capacity utilisation efficiency for transmission and distribution systems and other energy infrastructure. Extending an electric grid to a few households in a rural setting can result in energy costs of up to $0.70 per kilowatt-hour, seven times the cost of providing electricity in an urban area (World Bank, 1996). Thus conventional approaches to extending energy infrastructure are economically inefficient, for both public and private providers—which is another reason the energy problems of rural populations are given low priority by governments.

Because the poor people in rural areas lack access to electricity and modern fuels, they rely primarily on human and animal power for mechanical tasks, such as agricultural activities and transport, and on the direct combustion of biomass (wood, crop residues, dung) for activities that require heat or lighting. Human energy is expended for household work (gathering and preparing biomass for fuel, fetching water, washing clothes), agriculture, and small industry. Biomass fuels are typically used for cooking (which dominates inanimate energy consumption in most warm regions), space heating, heating water for bathing, and meeting some industrial heating needs. Kerosene is used predominantly for lighting, and to a small extent in rural industry. Although much of the world's rural population has no access to electricity generation, many have small battery-operated devices such as radios and flashlights.

Rungs on the energy ladder

Large amounts of human energy are spent gathering fuelwood in many parts of the world, and the burden tends to fall more heavily on women and children.[1] Although there are exceptions, history has generally shown that when alternatives are available and affordable, consumers opt for more modern energy carriers. As incomes rise and opportunities for using better technologies become available, consumer preferences shift to more efficient, convenient, cleaner energy systems as they become more affordable. That is, consumers move up the energy ladder (chapter 3). This involves a shift to modern energy carriers or to more convenient and energy-efficient conversion devices.

For cooking and other heating purposes, the lowest rungs on the energy ladder involve use of dung or crop residues, with fuelwood, charcoal, kerosene, and liquefied petroleum gas (LPG) or natural gas representing successively higher rungs. For lighting, the lowest rung is represented by fire, followed in turn by liquid-fuelled (such as kerosene) lamps, gas lanterns, and electric bulbs. To do mechanical work, consumers shift from human and animal energy to diesel fuel and electricity as soon as they become available, because they are almost always more cost-effective. Often a synergy between modern energy carriers and more efficient end-use devices occurs.

One of the aims of this chapter is to explore the technological, economic, social, and institutional prospects for more rapidly introducing modern energy carriers into rural areas—which would allow households to move quickly to the top of the energy ladder, ideally skipping (leapfrogging) some of its rungs. Accelerating the introduction of modern energy, then, is a key strategy for promoting sustainable development in rural areas of developing countries. Principally, it involves providing:

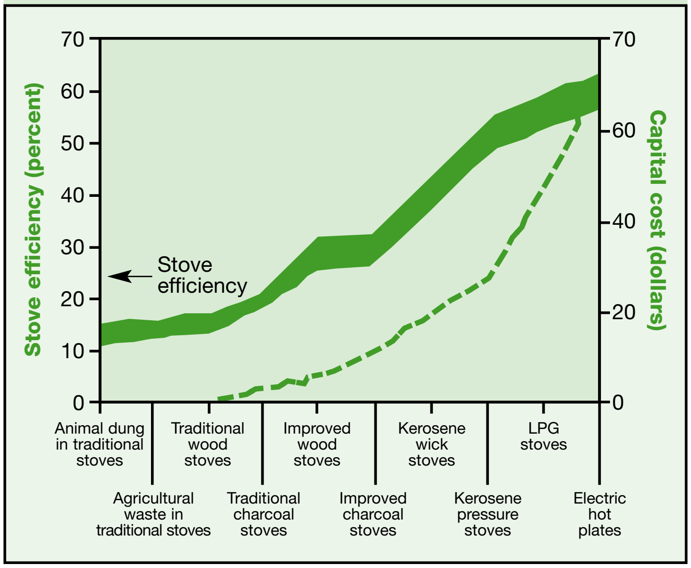
- Clean liquid or gaseous fuels for cooking, and electricity for lighting and other basic household amenities.
- Liquid fuels and electricity to mechanise agriculture.
- Electricity sufficiently low in cost to attract industrial activity to rural areas (thereby providing well-paying jobs and helping to stem migration to urban settlements).

It is desirable to skip rungs and advance to the highest rungs on the energy ladder wherever feasible.[2] But because the 2 billion rural poor live in many different circumstances, a complete range of approaches need to be explored, and those that work best in each set of circumstances need to be encouraged. Appropriate public policies should be implemented to accelerate the process and reduce human suffering.

Satisfying basic human needs with modern energy carriers requires relatively small amounts of energy in absolute terms. In regions that do not require space heating, final household energy requirements for satisfying basic needs are estimated to be about 2,000 kilocalories per capita per day, or 0.1 kilowatt per capita in average power provided (80 percent for cooking and 20 percent for electricity; Reddy, 1999). The cooking needs of the 2 billion people not served by modern fuels correspond to about 120 million tonnes of oil equivalent of LPG a year—which equals 1 percent of global commercial energy consumption or 3 percent of global oil consumption. This is less than is currently lost flaring natural gas in oil fields and refineries.

Thus commercial energy requirements for satisfying basic needs

FIGURE 10.1. EFFICIENCY OF STOVES WITH COMMERCIAL AND NON-COMMERCIAL FUELS



Source: Baldwin, 1987.

BOX 10.1. COMPARISON OF STOVE PROGRAMMES IN CHINA AND INDIA

China	India
The programme focused on areas with the greatest need and selected pilot counties with biomass fuel deficits.	The programme was implemented country-wide, resulting in dispersion of effort and dilution of financial resources.
Direct contracts between the central government and the county bypassed much bureaucracy. This arrangement generated self-sustaining rural energy companies that manufacture, install, and service stoves and other energy technologies.	The programme administration was cumbersome, moving from the centre to the state level, then to the district, and finally to the *taluka,* where the stove programme is just one of many national efforts being implemented locally by the same people.
Local rural energy offices run by provincial governments are in charge of technical training, service, implementation, and monitoring for the programmes. These efforts are separately funded and relatively independent.	Lack of a strong monitoring plan was a severe weakness in early programmes. Some improvement has occurred through assignment of the task to university-based technical backup units. Coverage is still incomplete, however.
Stoves are not only suitable for fuel savings and reduction of household smoke, but also are designed for convenience and attractiveness, highlighting the lessons learned from problems in early programmes that stressed only fuel savings.	India has made a wide variety of attempts to integrate efficiency and convenience, which have suffered from the top-down structure of the programme.
Stove adopters pay the full cost of materials and labour. The government helps producers through stove construction training, administration, and promotion support.	Stove adopters pay about half the cost of stoves; the government pays the rest. As a result the producer's incentive to construct stoves is oriented towards the government.
Emphasis has been on long-lived stoves made of ceramic or metal and otherwise designed to be a significant household asset for a number of years.	Many of the stoves have been made from local materials and by villagers without artisanal skills, resulting in short lifetimes in day-to-day household use.

Source: Smith and others, 1993; Barnes and others, 1993; Ramakrishna, 1991a, b.

in rural areas are truly modest. Yet provision of even these modest amounts of energy to rural areas would offer the potential for enormous increases in amenities, particularly if these modern energy carriers were coupled with energy-efficient end-use devices.[3]

Progress in delivering modern energy to rural areas has been slow. But as will be shown, technical options to provide rural people with access to convenient, affordable energy services are commercially available (or nearly so). This is particularly the case in regions where modern energy carriers, such as biogas or producer gas, can be derived from local biomass and where gathering biomass feedstock can provide opportunity for income generation. The challenge of making modern energy available to the very poorest households is primarily institutional, notwithstanding the economic costs and risks inherent in developing and disseminating untried systems. New financial mechanisms and other innovative policy approaches are needed, as discussed below.

Fuels in rural areas: climbing the energy ladder

The oldest human energy technology, the home cooking fire, persists as the most prevalent fuel-using technology in the world. For much of the world's population, household fuel demand makes up more than half of total energy demand. The energy ladder (discussed briefly above and in chapter 3) is used here as a framework for examining the trends and impacts of household fuel use. As figure 10.1 illustrates, the fuel-stove combinations that represent rungs on the ladder tend to increase in cleanliness, efficiency, and controllability. Conversely, capital cost and dependence on centralised fuel cycles also tend to increase with movement up the ladder.

Shortages of local wood supplies combined with institutional and economic constraints on petroleum-based fuels often lead to household coal use, which is widespread in Eastern Europe, China, and South Africa. Coal has a higher energy density than wood and so is easier to store. Coal's high energy density also makes it cost-effective to ship over longer distances than wood to efficiently supply urban or rural markets. In these senses, coal is similar to other household fossil fuels. Unlike kerosene and gas, however, coal often represents a decrease in cleanliness relative to wood. Like wood, another solid fuel, coal is difficult to use efficiently in household appliances.

Climbing the energy ladder for cooking can be accomplished using commercially available technologies such as improved cooking stoves and kerosene or LPG. As discussed below, biogas and producer gas are almost at the point of commercialisation, and additional and cleaner advanced technologies for meeting cooking needs are under development.

> The cooking needs of the 2 billion people not served by modern fuels correspond to about 1 percent of global commercial energy consumption or 3 percent of global oil consumption.

Improved cooking stoves

Since about 1980, several hundred programmes around the world have focussed on developing and disseminating improved biomass cooking stoves in the villages and urban slums of the developing world. These programmes have ranged in size from the introduction of a few hundred stoves by local non-governmental organisations to huge national efforts in China and India that have affected millions of households. The programmes seek to accelerate the natural trend for people to move towards cleaner, more efficient devices when they are available and affordable.

Such programmes have had mixed success. Some have disseminated many improved stoves with significant lifetimes. Others have not. The failures, however, represent progress along a learning curve, and more recent programmes have tended to have higher success rates. In this regard, it is instructive to compare the two largest initiatives, those of China and India (box 10.1).

Over the past 20 years, perhaps 90 percent of world-wide installations of improved cooking stoves occurred in China. From 1982–99 the Chinese National Improved Stoves Programme reported the installation of improved stoves in more than 175 million rural households. These were mainly biomass stoves used for cooking. But in the northern states of China, where temperatures drop during the winter, dual-use stoves for cooking and heating were included. In China improved stoves are affordable, and the government contribution is low. An improved stove in China costs about 85 yuan ($10), and the government contributes an average of 4.2 yuan per stove ($0.84). Part of the success of the programme is attributed to the attention—including well-publicised national competitions and awards—given to improved stove design.

The Indian programme, initiated in 1983, is called the National Programme on Improved Chulhas (cooking stoves). So far, nearly 30 million stoves have been disseminated. A mix of portable (without chimneys) and fixed designs have been approved. The government subsidises at least half of the costs of the stoves, which amounts to 200 rupees ($4.50) per stove. Although dissemination has been impressive, follow-up surveys suggest that less than one-third of the improved stoves are still in use. Some reasons given for discontinuing use are that the stoves did not really save energy, did not eliminate smoke, or broke down. Other surveys found that adopters felt that stoves were consuming less energy and producing less smoke. The mixed perceptions indicate differing levels of success in implementation.

Several lessons can be learned from the two programmes. The greater success in China can be attributed to programme design and implementation, including the factors described in box 10.1. Both programmes now face pressure to reduce subsidies in a more market-based approach. In addition, although both programmes now incorporate monitoring for energy efficiency, neither includes evaluations of the smoke-exposure benefits.

Another commonly cited example of success is the introduction of a more efficient ceramic charcoal cooking stove, the *jiko,* developed in Kenya. At least 700,000 such stoves are now in use in that country, in more than 50 percent of urban homes and in about 16 percent of rural homes. About 200 small-scale businesses and artisans produce more than 13,000 stoves each month. Both the stove itself and the general programme for disseminating it have been adapted for use in a number of other African nations (table 10.1).

The process of research, development, demonstration, and commercialisation that led first to the improved jiko and then to other high-efficiency stoves was seeded by international and local development funds (in contrast to the Indian and Chinese programmes, which were almost entirely organised and funded domestically). Most important, policy-makers decided not to directly subsidise the production and dissemination of these stoves but to provide support to designers and manufacturers.

Because the stoves were relatively expensive ($15) and their quality was highly variable, sales were slow at first. But continued research and increased competition among manufacturers and vendors spurred innovations in both the materials used and the methods of production. An extensive marketing network for those stoves is flourishing, and prices have fallen to $1–3, depending on size, design, and quality. This outcome is consistent with the learning curve theory, whereby the price of a new technology decreases by a uniform amount (often about 20 percent) for each doubling of cumulative sales (chapter 12).

Part of the success of the jiko, however, is due to its use of a relatively high-quality fuel, charcoal. It is much easier to design simple stoves with high energy efficiency for use with such low-volatility solid fuels relative to those that use the unprocessed biomass that is the main source of household energy in the world's

TABLE 10.1. NUMBER OF IMPROVED STOVES DISSEMINATED IN EAST AND SOUTHERN AFRICA, 1995

Country	Urban	Rural	Total
Kenya	600,000	180,000	780,000
Tanzania	54,000	n.a.	54,000
Uganda	52,000	n.a.	52,000
Ethiopia	23,000	22,000	45,000
Rwanda[a]	30,000	n.a.	30,000
Sudan	27,000	1,400	28,400
Zimbabwe	11,000	10,000	21,000
Burundi[a]	20,500	n.a.	20,500
Somalia[a]	15,400	n.a.	15,400

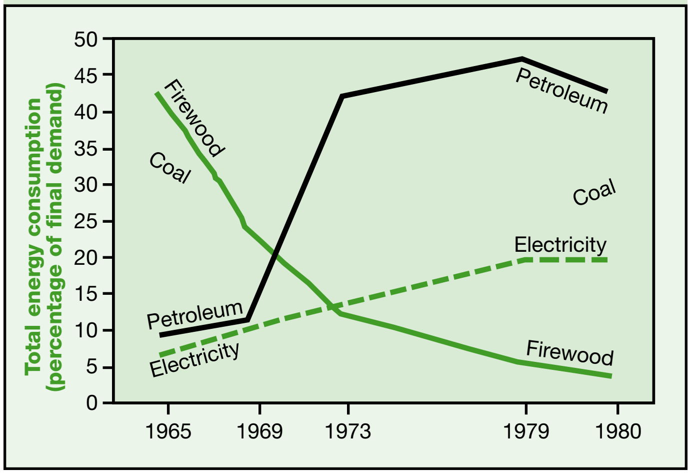
n.a. – Not available.
a. Civil strife has significantly affected stove programmes and reduced the number of improved stoves in use. *Source: Karekezi and Ranja, 1997.*

villages. Charcoal stoves are also inherently less polluting than those burning unprocessed biomass, and thus do not incorporate chimneys. Like other low-volatility solid fuels—such as some coals—charcoal produces fewer health-damaging particles and gases than wood, but it does produce substantial carbon monoxide. Households relying on such low-volatility fuels, therefore, risk overnight carbon monoxide poisoning, which annually causes thousands of deaths world-wide.

In addition, the process of making charcoal from wood is often quite inefficient, leading to heavy pressure on forests in much of Africa to supply urban areas. The inefficiency of charcoal kilns means that the charcoal fuel cycle is probably the most greenhouse-gas-intensive major fuel cycle in the world, even when the wood is harvested renewably, and often it is not. Thus charcoal could not be a sustainable rural energy option in the long run, unless its supply system were to be drastically altered.

Even the best biomass stoves available today do not greatly reduce the health-damaging pollution from biomass combustion, although they may put it outside through well-operating chimneys or hoods. This is certainly better than releasing the smoke inside; but in densely populated villages and slums, it can lead to heavy neighbourhood pollution. Thus even nearby households using clean (or no!) fuels may suffer from high levels of exposure. Therefore, because of health concerns—unless truly clean-burning biomass stoves can be developed at reasonable costs—in many areas, improved stoves are probably not sustainable in the long run. They may continue to play an important interim role in improving the quality of life of the rural and urban poor; but as concluded in chapter 3, the long-term goal should be to eliminate household use of unprocessed solid fuels.

FIGURE 10.2. POST-BIOMASS ENERGY TRANSITION IN THE REPUBLIC OF KOREA, 1965–80



Source: Baldwin, 1987.

Kerosene and LPG actually produce fewer greenhouse gas emissions per unit of energy service than biomass fuels used in traditional ways.

Kerosene and liquefied petroleum gas

In countries that achieved successful rural development during the past 50 years, kerosene and then LPG replaced biomass fuels. Figure 10.2 shows the changing household fuel picture in the Republic of Korea as rural development proceeded in the 1960s. At the start of the period, wood was the chief fuel, but 15 years later it had been replaced almost entirely by petroleum-based fuels. Similar transitions have occurred in other regions as well. Natural gas and town gas (made from coal) have continuing important roles in urban development (but rarely in rural areas, because of pipeline transmission requirements).

As consumers climb the energy ladder, kerosene is usually the first modern fuel to be used, because it is more easily transported and stored than LPG. However some countries—notably China—have restricted the availability of kerosene, thereby encouraging the direct movement to LPG. Kerosene, although substantially superior to biomass in efficiency and cleanliness, is not as desirable as LPG, which burns nearly without pollution in comparison with fuels on lower rungs. Of course, liquid and gaseous fuels pose other risks: For LPG, the most important are fires and explosions; in the case of kerosene, children may suffer poisoning due to careless household storage. Experience has shown, however, that these risks are lower than those posed by biomass fuels.

LPG must be distributed in pressurised canisters that, along with the stove, involve significant up-front investments by households. In addition, both LPG and kerosene require a stable, reliable distribution system running from the refinery to neighbourhood distributors, something that does not exist in many parts of the developing world. The combination of these two factors often prevents LPG from being used by many households that could otherwise afford its daily cost. Indeed, in many developing-country cities, the daily cost of LPG would be less than the cost of shipping biomass from rural areas. Lack of capital for the stove and canister and poor supply reliability, however, prevent households from shifting to LPG.

Despite these problems, LPG programmes have been very successful in most of Latin America, particularly in Brazil, where LPG has replaced all other fuels for cooking—even in many remote rural areas. The main reason for this success was a very dependable system of distribution and replacement of LPG canisters.

A study in Hyderabad, India, found that the simple measure of stabilising LPG supplies by the local government encouraged many urban households to shift to LPG. This is a policy without fuel subsidies that saves money for households and has a beneficial impact on the environment (Barnes and others, 1994). If users have a first-cost constraint, the programme should provide low-interest loans towards initial costs. Subsidies to help households meet the up-front costs for equipment such as stoves and canisters are much more acceptable policies than subsidising fuel. Fuel subsidies alone tend to divert use of fuel to industry, transport, and households that already have stoves, making the subsidies very costly, economically inefficient ways to help the poor.

Because fossil fuels such as kerosene and LPG are non-renewable and their combustion contributes to greenhouse-gas emissions, some may question their role in sustainable energy strategies. However, the quantity of LPG needed to support cooking for the current unserved population of 2 billion is trivial at the global level (see above). Moreover, kerosene and LPG actually produce fewer greenhouse gas emissions per unit of energy service than biomass fuels used in traditional ways (chapter 3).

Nevertheless, instead of relying on fossil fuels with substantial new infrastructure requirements, it is sometimes desirable to produce clean fuels that can be used efficiently from local biomass resources. Biogas and producer gas systems, as well as advanced technology options such as synthetic LPG or dimethyl ether (DME), appear promising in the longer term.

Biogas for cooking

Biogas, a clean-burning methane-rich fuel gas produced through anaerobic digestion (bacterial action in a tank without air) of suitable biomass feedstocks, is the only biomass-derived modern energy carrier for household applications with which there is widespread experience. Biogas can be generated from cattle dung and animal wastes, and with substantially more difficulty, from some crop residues. Although these feedstocks are frequently used directly as cooking fuel, in most areas they are not preferred fuels and are used only when wood is not available. Biogas systems offer multiple benefits. The digester-effluent is usually a good fertiliser, and, if connected to latrines, biogas plants can provide valuable sanitation services. For cooking and other thermal household tasks, it is simple and reasonably efficient to use the gas directly in conventional low-pressure gas burners. Biogas can also provide lighting when used in mantle lamps.

In societies where suitable feedstocks are readily available, small family-sized biogas digesters were thought to have considerable potential. A number of countries initiated programmes—China and India on a large scale. Results have been mixed, especially in the early stages. China's efforts resulted in the construction of 7 million household-scale digesters from 1973–78. But quality control and management problems resulted in a large number of failures. More recently, coordinated efforts have focused on regions thought to be most promising for the technology. Service organisations and biogas services stations have been established. By 1994, 5 million domestic plants were operating satisfactorily. India's experience has been on a slightly smaller scale, but the numbers are still impressive—by the end of 1998, almost 2.8 million domestic plants were installed. India's Ministry of Non-Conventional Energy Sources has identified a potential for 12 million digesters.

Biogas experience in Africa has been on a far smaller scale and has been generally disappointing at the household level. The capital cost, maintenance, and management support required have been higher than expected. Moreover, under subsistence agriculture, access to cattle dung and to water that must be mixed with slurry has been more of an obstacle than expected. However, possibilities are better where farming is done with more actively managed livestock and where dung supply is abundant—as in rearing feedlot-based livestock.

The initial enthusiasm for biogas has thus been somewhat dampened by experience. Because of its requirement for relatively large amounts of animal dung, the niche for household biogas plants is likely to remain small. Poor families do not have access to enough dung, and better-off families with sufficient animals often prefer to purchase fuel and fertiliser rather than spend time gathering dung and managing the often-temperamental digesters. Even so, in the right social and institutional context, and with appropriate technical expertise, the potential for biogas remains significant. These conditions seem to have been achieved in the Biogas Support Programme in Nepal through an innovative financial scheme (box 10.2).

BOX 10.2. BIOGAS IN NEPAL

The principal objective of the Biogas Support Programme in Nepal is to promote the wide-scale use of biogas as a substitute for the wood, agricultural residues, animal dung, and kerosene that presently meet the cooking and lighting needs of most rural households in the country. The rising demand for locally available biomass from a rapidly increasing population has helped accelerate the rates of deforestation, soil degradation, and environmental decline in densely inhabited areas. In addition, use of biomass fuels and kerosene has compromised health and welfare—especially of women and children, who are most often subjected to the smoke and fumes associated with the use of these fuels.

Since its inception, the programme has installed more than 40,000 family-size biogas units benefiting more than 200,000 members of rural households. The programme's target is to install an additional 100,000 units by the middle of 2003. This compares to only 6,000 biogas units installed before the programme. This substantial increase has been achieved while simultaneously reducing the costs and increasing the reliability and efficiency of biogas plants.

A critical element in developing the commercial market for these plants has been the programme's innovative financial engineering and judicious application of consumer subsidies. The subsidy, fixed at three levels, accounted for 35 percent of the total cost of biogas plants in 1998. The objective of the programme is to eliminate dependency on direct subsidies by 2003. The programme has also strengthened institutional support for the biogas market.

At the start of the programme, essentially only one state-owned company, the Gobar Gas Company, was producing biogas plants. By the end of 1998, as a direct result of market development, 38 private companies besides Gobar had entered the business. To be eligible to receive the subsidy provided to farmers, all participating companies must meet strict production quality and service standards for their plants. As a result of the growing competition, technical design modifications, and better quality control measures, the overall cost of biogas plants in Nepal has declined by more than 30 percent since 1992. In addition to the institutional improvements, employment for skilled as well as unskilled labour in rural areas has been generated.

Source: Mendis, 1999.

Producer gas for cooking

An alternative to biogas is producer gas, a mixture consisting largely of carbon monoxide, hydrogen, and nitrogen. Producer gas is generated in a thermochemical conversion process through partial oxidation in air of biomass feedstocks (Stassen, 1995). The basic principles of generating producer gas have been known since the 18th century. Producer gas derived from biomass has been used for domestic and industrial heating purposes, for cooking, for stationary power, and for motor vehicle applications. (During World War II more than a million gasifier-powered vehicles helped to keep basic transport systems running in Europe and Asia.)

Subsidies to help households meet the up-front costs for equipment such as stoves and canisters are much more acceptable policies than subsidising fuel.

During periods of peace and wide availability of cheap, more convenient fossil fuels, interest in biomass-derived producer gas has been low. The energy crises of the 1970s rekindled interest in producer gas technology, but interest waned again with the collapse of world oil prices in the mid-1980s. Once again, there is growing interest in technology for making producer gas from biomass for cooking, heating, and electricity generation. Power generation applications of producer gas are discussed later in this chapter. Here the focus is on domestic cooking.

Part of the reason for renewed interest in producer gas technology is increasing concern about the adverse health effects of indoor air pollution caused by biomass and coal burned for domestic cooking and heating (chapter 3) and the large role that producer gas used in gas-burning stoves could play in reducing this pollution—the air pollution from these stoves is nearly zero. In typical agricultural regions, the energy generation potential from producer gas is greater than that from biogas, because crop residues tend to be more abundant than dung.[4] And whereas biogas generation is often the preferred energy conversion technology for making use of the energy content of dung, producer gas generation is a far easier approach for exploiting the energy content of crop residues.

In addition, because it is a chemical rather than biological process, producer gas manufacture is not sensitive to ambient temperature, greatly increasing the potential geographic extent of its application. Another reason for renewed interest in biomass-derived producer gas in China is a severe new air pollution problem caused by the burning of crop residues in fields—a consequence of the rising affluence of farmers (see the annex to this chapter). This problem is forcing a search for new productive uses of crop residues.

Several Chinese provinces are making efforts to convert residues into producer gas in centralised village-scale gasifiers and to distribute the cooking gas by pipes to households. For example, the Shangdong Academy of Sciences has developed crop residue gasifiers and centralised gas supply system technology for cooking gas applications, and 20 such village-scale gasification systems are operating in the province (Dai and Lu, 1998). Monitoring and assessment of a village experience in Shangdong Province (case 1 in the annex) shows that current technology has considerable consumer appeal and would be highly competitive if the gas were properly priced. The technology for making producer gas from crop residues promises to be widely deployable for cooking applications, and thus to largely solve the indoor air pollution problem caused by stoves that burn biomass or coal.

TABLE 10.2. GLOBAL POPULATION AND ACCESS TO ELECTRICITY, 1970–90 (MILLIONS OF PEOPLE)

Country	1970	1980	1990
World population	3,600	4,400	5,300
Rural population	2,600	3.000	3,200
With access to electricity[a]	610	1,000	1,400
Without access to electricity	2,000	2,000	1,800
Percentage of rural population with access	23	33	44

a. Access includes people living in villages connected to power lines. This does not necessarily mean that most households are hooked up to electricity.

Source: Davis, 1995.

One problem posed by current gasifiers used in China is that they produce substantial tars (condensable hydrocarbons that are scrubbed from the gas before delivery to consumers). If disposed of without adequate treatment to groundwater or surface water, these tar wastes would pose significant water pollution problems. Moreover, the option of using crop residues or producer gas for cooking will not solve the air pollution problem in China that arises from burning excess crop residues in the field. The producer gas option is about twice as efficient as direct combustion in providing cooking services, so that only about half as much residue is required for cooking relative to direct-combustion stove systems.[5] At the national level, use of just 60 percent of all crop residues potentially available for energy purposes would be adequate to meet all rural cooking needs.

In addition, the producer gas cooking option poses another public health risk: Typically, about 20 percent of producer gas is carbon monoxide—of which accidental leaks into houses can be lethal. Although some hydrocarbon impurities in the gas impart an odour to producer gas that is usually noticed before a lethal dose is inhaled, occasional accidents are inevitable. Therefore (as discussed below), safe, clean, advanced technological options for producing cooking fuel from biomass should be the focus of research and development.

Rural electrification

Electricity is at the top of the energy ladder and is highly efficient and convenient for some specialised cooking appliances, such as rice cookers and microwave ovens. But for many years to come, electricity is unlikely to be practical for general cooking in most rural areas of the developing world. Nevertheless, for lighting, communication, refrigeration, and motor applications, electricity is essential for a satisfactory quality of life. Moreover, electricity is key to improving agricultural productivity through mechanisation and is essential for many rural industrial activities. Considerable progress has been made in rural electrification programmes designed to extend electricity services to isolated villages (table 10.2).

The centralised approach

Between 1970 and 1990, 800 million people in rural areas gained access to electricity. Yet of the 3 billion people living in rural areas of developing countries in 1990, 2 billion were still without access to electricity. This global total masks significant variations between regions and countries. In particular, China's rapid electrification programme—through which 365 million rural residents gained access to electricity from 1970–90—significantly increased the world total. If China were excluded, current access levels would drop from 44 to 33 percent, or exactly the level of 1980.[6]

The distinction between access to electricity by villages and households should also be noted. India, for example, has an ambitious rural electrification programme, targeting agricultural end use. But while 80 percent of villages have electricity, less than 50 percent of households can afford it.

Several studies highlight an important point for economic success: electrification cannot by itself ensure economic development. It is a necessary but insufficient condition. Electrification works best when overall conditions are right for rural income growth and when it is complemented by social and economic infrastructure development—such as rural water supplies, health programmes, primary and secondary education, and regional and feeder roads. Thus rural electrification contributes to but is not a substitute for other rural development measures.

Rural electrification programmes have typically concentrated on connecting villages and remote areas to a national grid—often owned and operated by a public utility. The tendency has been to extend the grid incrementally, reaching towns and settlements in order of increasing capital costs. Thus remote areas with small populations are likely to be the last to receive electricity. Moreover, many rural areas face high transmission and distribution costs, for several reasons:

- The capacity of power lines is inefficiently used because of low population.
- Densities and demand levels are low.
- Villages may have very peaky (undiversified) demand profiles.
- Line losses tend to be high.

In addition, incremental extension of the grid (rather than extension optimised to minimise losses) causes lines to be strung haphazardly, resulting in greater losses.

The decentralised approach

Because of the problems of supplying grid electricity for small, scattered, peaky loads, decentralised electricity generation is becoming more attractive. With decentralised systems, the high costs of transmission and distribution networks can be avoided. But small-scale, decentralised solutions face other barriers. The decentralised generation technologies discussed below are diesel-engine generator sets, small-scale hydropower, photovoltaics, wind, and small-scale biopower using producer gas. No attempt is made to be comprehensive on the technological opportunities for decentralised electricity generation. Instead, the discussion illustrates key features of different technologies, highlighting advantages and drawbacks for rural development needs.

Diesel-engine generator sets. Diesel generators are common in many remote settlements, either for a single user or as part of a local distribution network. Such systems may be operated by a power utility or, more commonly, by private enterprises. Rural hospitals, government offices, and police stations in remote areas typically have their own diesel generators.

Diesel sets with capacities of 50–500 kilowatts of electricity are widely used in rural Latin America and Asia but have only recently been disseminated in Africa. The electricity produced by diesel sets typically costs $0.30 a kilowatt-hour—two to three times the cost of electricity from grids in urban areas but still cost-effective relative to grid extension. (This cost is typical of the Amazonia region of Brazil, where there are 900 diesel sets with a total generating capacity of 391 megawatts.) The high costs of maintenance and of transporting diesel fuel and lubricating oil to remote places make electricity fairly expensive.[7] Despite these costs, electricity is typically highly valued by local populations because of the enormous improvements in living standards that it brings (box 10.3). But while high-cost electricity may be acceptable for satisfying basic needs in households and for some agricultural and cottage industry applications, lower costs are needed to attract a greater job-generating industrial base to rural areas.

Small-scale hydropower. Small-scale hydropower is a locally available resource that in some regions can be exploited to deliver electricity or mechanical power (for pumping water and other applications) to rural areas. The resource potential for small-scale hydropower is discussed in chapter 5; its technology, costs, and future prospects are discussed in chapter 7. Here the focus is on current activities and the prospects for using small-scale hydropower to address rural development needs.

Small-scale hydropower technology, which is being pursued in about 100 countries, is often divided into three categories: micro hydro (less than 100 kilowatts), mini hydro (100–1,000 kilowatts), and small hydro (1–30 megawatts). By the end of 1994 China alone had 6,000 small-scale hydropower stations with a total installed capacity of 15,650 megawatts, supplying 49 terawatt-hours of electricity (Qui and others, 1996)—29 percent of hydroelectric power generation and nearly 8 percent of rural electricity consumption (Deng and others, 1996). In 1989 China accounted for about 38 percent of world-wide small hydropower (23.5 gigawatts), at which time more than 130 companies manufactured equipment specifically for plants with capacities ranging from 10 kilowatts to more than 10 megawatts. Of the 205 turbines ordered world-wide in 1989, the size distribution was micro hydro, 15 percent; mini hydro, 57 percent; and small hydro, 28 percent (Moreira and Poole, 1993). In China and Viet Nam even sub-kilowatt systems have been sold for household electrification. Such turbines are installed at the end of hose-pipes, with somewhat unreliable but serviceable results. However, the potential market for such systems is limited by the availability of water resources.

On a somewhat larger scale, hydropower plants of 50 kilowatts and more can be used to electrify communities or small regions by establishing mini grids. Costs are highly variable (chapter 7), depending on the site topography, proximity of the site to the main load area, and hydrological conditions.

Small-scale hydropower has one drawback: it is almost always obtained from run-of-river plants that lack the reservoir capacity to store water. Consequently, severe seasonal variations in power output may occur, depending on a site's hydrology. Thus the long-term viability of small-scale hydropower may depend on backup electricity that is supplied either locally or through the grid (Moreira and Poole, 1993).

Photovoltaics. Photovoltaic technology is cost-effective in providing electricity to rural areas at the very smallest scales (typically less than 100 watts) in areas with no access to grid electricity and where electricity demand is characterised by such low levels and infrequency that even diesel electricity cannot compete (see chapter 7 for details about photovoltaic technology and its economics in such applications). The potential for photovoltaic technology to support rural development arises from the fact that it can be used for household lighting, radios, and television sets, and to refrigerate medicines at rural clinics.

In 1999 global photovoltaic sales totalled 200 megawatts, 10 percent of which was for off-grid applications in rural areas of developing countries. One important obstacle to wider rural deployment of photovoltaic technology is the limited financing available for such small systems (see section below on the time horizon for technological options). Kenya has the world's highest penetration rate of household photovoltaic systems, with more than 80,000 systems in place and annual sales of 20,000 systems. Fifty local and fifteen international importers, assemblers, installers, and after-sales providers serve this market, which developed without significant aid, subsidies, or other support. Although the current market is strong, there is still a tremendous need to standardise equipment, as well as improve batteries, lighting fixtures, and electronic ballasts used in integrated household photovoltaic systems. In addition, possible credit arrangements need to be studied, as do the relative advantages of leasing a system rather than purchasing it.

In 1999 South Africa's power utility, Eskom, entered into a joint venture with Shell Solar Systems to provide 50,000 homes with photovoltaic systems in areas where grid connection is not considered feasible. This three-year programme contributes to a market that is

BOX 10.3. DIESEL ENGINES IN A MULTIPURPOSE PLATFORM PROJECT IN MALI

In Mali a project is under way to introduce, by 2003, 450 multipurpose platforms to provide, at the village scale, mechanical power and electricity through diesel engines to 10 percent of the country's rural population. At least two-thirds of these platforms will be coupled to water and electricity distribution networks. By 2003 rural access to electricity is expected to be more than 3 percentage points higher than urban access. Although the project is based on the use of diesel fuel oil, it is envisaged that in the future pourghere nut oil or some other liquid biofuel will be used.

The engine selected for this project is a 1950s-vintage slow diesel engine (a Lister engine, from India). This engine was chosen because of its low initial capital cost; low prices for its spare parts; its ability to operate without damage on the relatively low-quality diesel fuel typically available in villages; its ease of operation, maintenance, and repair by local artisans (blacksmiths, mechanics, carpenters); and the availability of a network of sellers and servicers for it throughout much of Mali.

It is intended that the engine in a typical platform would power various types of equipment, such as a cereal mill, husker, alternator, battery charger, pump, welder, and carpentry machine. Thus the platforms would reduce many rural women's burdensome tasks (fetching water, grinding cereal); offer them income-generating opportunities and management experience; and, as they become more economically independent, help them improve their social status. Because so many activities would be supported by the platforms, their economic and social benefits would be felt at multiple levels, resulting in an overall empowerment of women. In the pilot phase of the project (1996–98), during which 45 platforms with 14 water or electricity networks were installed, the platforms' availability stimulated the creation, development, and modernisation of artisanal activities in participating villages. The platforms are being operated and maintained on a cost-recovery basis by private enterprise.

By design, the acquisition of a multipurpose platform is a demand-driven process. The initial request has to be made by a recognised, registered women's association at the grass-roots level. International donors are subsidising equipment costs (including the engine, mill, de-huller, alternator, battery charger, and building) at up to $1,500 per module. In situations where the supply of electricity and running water is requested, the contribution of the international donor can be increased by up to $10,000 per module. An equity contribution of at least 50 percent is required of the women's associations. Operation and maintenance costs are borne entirely by beneficiaries.

The mechanical work provided by the engines costs about $0.25 per kilowatt-hour (see table). Notably, more than 70 percent of the cost is for diesel fuel and lubricating oil, which must be imported into the region. If the mechanical work were converted to electricity, the added cost associated with the generator and conversion losses would increase the electricity cost to at least $0.30 per kilowatt-hour. If liquid biofuels produced in the region eventually could be substituted for imported oil, the region's balance of payments would be improved, although costs would probably not be reduced much or at all, because liquid biofuels tend to be more costly than petroleum fuels.

Although this project is interesting in revealing consumer wants, it is in its initial phase of implementation, and only experience will supply information on real costs. Nevertheless, the project shows that there are attractive alternatives to grid extension, that rural electrification does not necessarily mean grid electrification, that decentralised electrification is a serious option, and that entrepreneur-driven participatory development is crucial.

Cost of mechanical work for a diesel engine, Mali multipurpose platform

Cost	Dollars per year	Dollars per kilowatt-hour
Capital[a]	131	0.018
Fuel[b]	1,140	0.138
Maintenance		
Every 100 hours		
Lubricating oil	158	0.022
Other	36	0.005
Every 500 hours	179	0.025
Every 1,000 hours	104	0.015
Every 1,500 hours	74	0.010
Total	1,820	0.233

a. For an 8-horsepower (6-kilowatt) Indian Lister diesel engine with a 7-year plant life costing $600 (excluding the cost of a generator) and operated 1,500 hours a year at 80 percent of rated capacity, on average, so that the annual average capacity factor is 13.7 percent. Assuming a 12 percent discount rate, the capital recovery factor is 21.9 percent a year.

b. For a diesel fuel price of $0.44 a litre and an engine efficiency of 30 percent (higher heating value basis).

Source: Mali and UNDP, 1999.

believed to exceed 2 million households. Customers pay a monthly rate to lease and use the equipment, which allows a reasonable rate of return to Eskom.

Household-scale wind turbines (of about 100 watts) offer benefits to wind-rich regions similar to those offered by domestic photovoltaic systems.

Still another approach to reach a greater portion of low-income rural people was adopted by Soluz. This company developed a system to lease small photovoltaic battery systems to provide high-quality electric services at an affordable price while offering a positive financial return to its investors. In 1993, with assistance from the Rockefeller Foundation, Soluz conducted a pre-feasibility study for a solar electricity delivery company and construction of a company prototype for 200 rural homes in the Dominican Republic. The company installs standalone photovoltaic battery systems on or near rural homes yet retains ownership of the systems. The photovoltaic systems provide lighting and access to information services (through radio and television). Users make regular payments, as determined in the lease agreement, and the company is responsible for maintaining the systems.

In Central America customers pay a monthly fee of $15–20, depending on the size of the photovoltaic system leased. The company has an on-time collection rate exceeding 90 percent. Many customers are small businesses, for whom the provision of high-quality energy services contributes to increased profitability.

But even where appropriate financing is made available, the poorest households often cannot afford photovoltaic systems (box 10.4). In considering measures to support photovoltaic programmes for rural areas, it is important to pay particular attention to the poorest households and to strategies to make the technology available to them.

Although significant in improving the quality of life in rural areas, without major cost reductions, photovoltaic technology will be limited mainly to remote household and other small-scale applications and will not be able to compete in the provision of electricity for manufacturing or even most cottage industrial applications.

BOX 10.4. EQUITY ISSUES RELATING TO PHOTOVOLTAIC TECHNOLOGY FOR RURAL AREAS IN INDIA

Of the 79 million rural households in India without electricity (out of a total of 114 million rural households), 7, 17, and 75 percent of households could afford, respectively, 37-watt (four-light), 20-watt (two-light), and 10-watt (one-light) photovoltaic systems with Grameen-type financing (five-year loans at 12 percent interest with a 15 percent down payment; see box 10.7). Thus it appears that the poorest 25 percent of households cannot afford any photovoltaic purchase, even with financing.

But such findings, which are based on willingness-to-pay considerations, might be overly simplistic. The availability of lighting might be exploited to earn extra income that could make a photovoltaic system affordable for even the poorest household. If, for example, a poor Indian household could weave two extra baskets a night by the light made available by a 10-watt photovoltaic system, the technology would become affordable.

Source: Reddy, 1999; Hande, 1999.

Wind. There are two promising ways to exploit wind power to meet rural energy needs. The first is household units that provide electricity at scales where neither grid power nor mini-grid power from diesel units is cost-effective. The second is village-scale wind-battery-diesel hybrid systems (using wind turbines with capacities typically of 5–100 kilowatts).

Household-scale wind turbines (of about 100 watts) offer benefits to wind-rich regions similar to those offered by domestic photovoltaic systems. Such turbines have been developed, produced, and deployed, for example, in China, mostly in the Inner Mongolian Autonomous Region. The dispersion of houses in this region of low population density (18 people per square kilometre) makes household wind systems a viable option for providing electricity. In Inner Mongolia an estimated 130,000 small-scale (mostly 50–200 watt) wind energy systems have been installed, providing electricity for lighting, radios, television, and small appliances to more than 500,000 people, mostly rural herdsmen (about one-third of the population). About 89,000 of these systems are operating routinely, producing from 8.7 megawatts of installed capacity about 15.7 gigawatt-hours a year (Wu, 1995).

The success of the Chinese programme was achieved through careful planning and the creation of an effective regional and local infrastructure for manufacturing, sales, maintenance, and training. This included the development of a market for individual household systems through various subsidy mechanisms. The government of Inner Mongolia also recognised and allowed for the long gestation period and sustained support needed to create a thriving local industry. The project has also led to technology transfers at many levels—between Inner Mongolia and local, regional, and national organisations within China, as well as with other countries. Replicating the programme would require enough institutional capacity to support such ventures.

Where rural households are clustered in villages far from electric grids that are served instead by diesel-engine generator sets, an alternative option is to deploy wind turbines in wind-diesel or wind-battery-diesel hybrid configurations, which have been installed in many parts of the world (Baring-Gould and others, 1999). In regions where diesel fuel is costly, these hybrid systems can lead to lower electricity costs and less air pollution than conventional diesel-engine generator sets.

Unlike the household-scale wind turbines being developed in China, however, many components of these hybrid systems are based on technology developed in industrialised countries, and costs of imported systems are often prohibitive. But if these systems can be mass produced in developing countries under arrangements—such as international industrial joint ventures—that are conducive to technology transfer, substantial cost reductions are possible (see chapter 7 for an example).

Small-scale biopower using producer gas. Biomass-derived producer gas (see above) can be used to make electricity at scales

Historically, electric utilities have discouraged independent power producers from selling electricity into grids, but this situation is changing as electricity markets are becoming more competitive.

comparable to those associated with diesel-engine generator sets. The potential benefits are:

- The capacity to use locally available biomass as fuel instead of oil imported into the region.
- Lower electricity generation costs than with diesel.
- Increased rural income generation, and possibly rural industrialisation, as a result of the lower electricity cost.

The reciprocating compression-ignition (diesel) engine is the main commercially viable engine available for these applications.[8] When producer gas is used with such engines, it must be supplemented with a pilot oil to assist ignition because mixtures of producer gas and air do not auto-ignite at the pressures and temperatures realised when the gas is compressed. As a result producer gas can typically displace about 70 percent of diesel fuel consumption. When operated with producer gas in the dual-fuel mode, diesel-engine generators have somewhat lower efficiencies and rated capacities (typically about 20 percent lower than when operating on pure diesel fuel).

Producer gas must meet far higher standards for reciprocating engine operation than for cooking or heating (domestic or industrial) applications. The main problem is the propensity of tars formed in the gasifier to condense on downstream surfaces, causing problems such as the sticking of engine gas intake valves. Most early gasifiers generated so much tar that adequate gas clean-up for engine operation was impractical, and tar removal would significantly reduce the potential for power generation from a given amount of biomass feedstock. But in recent years, gasifiers have been developed (notably in India) that generate tars at levels that make engine operation on producer gas acceptable (Kartha and Larson, 2000).

Biomass-derived technology for producer gas, reciprocating-engine generators is commercially ready. In India, for example, the Ministry of Non-Conventional Energy Sources has supported development efforts that have led to technically sound gasifier-engine systems and trial implementation of more than 1,600 such systems with a total installed capacity of more than 28 megawatts (Kartha and Larson, 2000). For engines operated on producer gas and pilot oil, fuel costs are typically much lower than for conventional diesel systems. But capital, operation, and maintenance costs are higher (see table A10.1).

In fact, the savings derived from diesel replacement have to pay for the extra initial capital cost as well as the extra operation and maintenance costs incurred for the gasifier. The technology can be cost-effective, either where diesel fuel costs are very high (for example, $0.35–0.40 a litre or more, as is often the case for extremely remote regions) or, with efficient capital utilisation, in regions where diesel fuel prices are more moderate. If the diesel fuel price is $0.25 a litre, a typical system must be operated at full capacity for 3,000 hours a year to break even with a conventional diesel system. About 6,000 hours of annual operation are needed to realise a cost savings of 25 percent (see table A10.1). It is desirable to seek opportunities for such high rates of capacity utilisation because consumers are likely to be more motivated to adopt the technology if they can realise substantial cost savings. Unfortunately, achieving high rates of capital utilisation is often difficult because local electricity demand is typically low and sporadic but peaky, with very little electric load diversity.

A promising strategy for launching a producer gas, engine-generator technology industry would be to focus initially on market opportunities where the technology could be deployed in large numbers in baseload configurations. This requires that two conditions be satisfied. Biomass supplies have to be adequate for fuelling baseload plants, and the demand for electricity has to be adequate to justify baseload operation. Strong candidate regions for doing this are agricultural regions of China where crop residues are abundant and where grid connections exist (87 percent of the rural population in China is grid-connected), so that electricity generated in excess of local needs can be sold into the grid (Li, Bai, and Overend, 1998). Historically, electric utilities have discouraged independent power producers from selling electricity into grids, but this situation is changing as electricity markets are becoming more competitive (chapter 12).

New technologies that might be commercialised in the near term (5–10 years) offer the potential for electricity generation at costs significantly lower than with current technology. One promising new technology is the microturbine, which might be deployed with essentially the same gasifiers that have been developed to provide producer gas for use with diesel dual-fuel engine generator sets.

Microturbines are gas turbines designed for operation at scales of 50–250 kilowatts of electricity, with electric efficiencies (lower heating value) of 25–30 percent for larger units. Microturbines were originally developed for military and aerospace applications and are now offered by several companies for applications in distributed power and cogeneration markets, mainly for use with natural gas or diesel fuel. Developers expect microturbine use to grow rapidly for such applications in regions where there is competition in electricity markets (chapter 8). The technology appears to be readily adaptable for use with biomass-derived producer gas (Henderick, 2000).

Microturbines are less complex (some variants have only one moving part) than reciprocating engines. They can be fuelled with producer gas without de-rating and without loss of efficiency relative to operation on natural gas or diesel fuel. Most important, they need no costly pilot oil (Henderick, 2000). In regions where crop residues or other low-cost biomass feedstocks are readily available, there are reasonably good prospects that the technology could become widely competitive in grid-connected applications (Henderick and Williams, 2000). Case 2 in the annex describes a potential application of the technology to the trigeneration of cooking gas, electricity, and space heating through district heating in a hypothetical village in northern China.

To illustrate the aggregate potential of this technology, consider that in China, 376 million tonnes of crop residues a year are potentially available for energy purposes.[9] Committing these residues to trigeneration (case 2 in the annex) could provide enough cooking gas for 230 million people (27 percent of China's rural population) plus 270 terawatt-hours a year of electricity (equivalent to 30 percent of coal power generation in China in 1997) plus hot water for space heating in regions where it is needed (for example, in regions with cold winters).

Several public policy initiatives could facilitate the creation of a viable industry for small-scale biopower technologies. One important measure would be to eliminate or phase out diesel fuel subsidies that exist in many regions. Another would be market reforms that facilitate the sale of electricity into electric grids, coupled with incentives to encourage the extension of electric grids to more rural areas. Notably, the commercial availability of competitive baseload biopower technology could profoundly influence the economics of extending electric grids to rural areas. In contrast to the poor capacity utilisation (and hence poor economics) of transmission-distribution lines sending electrons from centralised power plants to rural areas, high capacity factors (and thus more favourable economics) could be realised if electrons instead flowed to urban centres from baseload village-scale biopower plants.

Finally, demonstration projects are needed to prove the viability of new technological concepts for biopower. Projects are needed for biopower systems based on gasification of alternative crop residue feedstocks, for which tar production rates are higher than for wood chips (Henderick and Williams, 2000). Such projects could involve the use of commercially established diesel dual-fuel engine technologies. Demonstrations are also needed of microturbines in producer gas applications. If carried out together with the above institutional reforms, these projects could lead to commercially viable microturbine-based products for biopower applications in the near term (2005–10).

Leapfrogging to new rungs on the energy ladder

The previous sections have shown that existing and near-term energy technologies have great potential for improving the quality of life in rural areas. But advanced technologies have residual problems that might need to be addressed. For instance, fuels such as LPG are highly desirable for cooking, but making LPG widely available requires considerable infrastructure for distribution, and finding ways to make LPG affordable to the poorest households is a major challenge. Moreover, because LPG is derived from petroleum—a commodity for which price swings can be substantial, as recent experience has shown—price spikes are likely to be burdensome for lower-income households that depend on LPG for their cooking needs.

Local manufacture of clean cooking fuels (such as biogas and producer gas derived from biomass feedstocks) is a strategy for addressing the fuel-infrastructure challenges and price volatility concerns posed by exclusive reliance on LPG. This strategy also provides opportunities for addressing the needs of the very poorest households, because the need to gather typically dispersed biomass feedstocks (such as dung for biogas or crop residues for producer gas) and deliver them to the conversion facility can sometimes make it possible for the poor to monetise their labour and thereby earn income to help pay for these clean cooking fuels (case 2 in the annex).

But today's available gaseous cooking fuel technologies have limitations. Biogas technologies, though well suited for use with dung feedstocks, are not easily applied to crop residues, which tend to be much more abundant. And a persistent concern about producer gas is that it contains carbon monoxide, accidental leaks of which might lead to fatalities. Odourants added to producer gas could greatly reduce the risk of poisoning, but accidents are difficult to avoid completely.

Advanced technologies can make it possible to manufacture synthetic cooking fuels from biomass that are non-toxic as well as clean. A promising approach is to adapt to biomass some of the technologies being developed for fossil fuels—specifically, syngas-based fluid fuels (chapter 8). Strong candidates are synthetic LPG (SLPG) and dimethyl ether (DME), which can be made from any carbonaceous feedstock by catalytic synthesis from syngas (a gaseous mixture consisting largely of carbon monoxide and hydrogen). SLPG (like petroleum-derived LPG, a mixture of propane and butane) and DME are superclean, non-toxic cooking fuels that are gaseous at ambient conditions but can be stored and delivered to consumers as liquids in moderately pressurised canisters. These fuels can be produced from crop residues or other biomass feedstocks through thermochemical gasification to produce the needed syngas. (Case 3 in the annex discusses the potential offered by such technologies for rural regions of China rich in crop residues.)

In addition to the toxicity advantages offered by SLPG and DME, both fuels could be readily transported in canisters by truck or donkey cart to remote, scattered households. Producer gas, by contrast, is a viable option primarily for villages in which houses are clustered closely enough to make pipe transport economically viable. Thus SLPG and DME extend the scope of the cooking fuel markets that could be served relative to producer gas. DME is also a potentially strong low-polluting synthetic fuel for diesel-engine vehicle applications (chapter 8) and might be used as tractor fuel, thereby facilitating the mechanisation of agriculture.

Neither SLPG nor DME is currently produced for fuel applications, but either fuel derived from biomass feedstocks could probably be brought to market readiness by 2010–15 if there were sufficient market interest and a focused development effort. Because neither SLPG nor DME is currently on the market anywhere in the world, a shift from the use of current low-quality fuels to either might be described as jumping to entirely new rungs at the top of the energy ladder (technological leapfrogging).

The time horizon for technological options

Chapters 6–8 and this chapter show that there are abundant opportun-ities for technological change relating to rural energy. Technological change is desirable to the extent that it serves development needs. Rural development planners can help shape the course of technological change for desirable options, taking into account the time horizons required for development and implementation—demanding more of the longer-term options in addressing societal needs. Options that warrant focussed attention in the near term (that is, implementation in the next 5 years) as alternatives to current technology should offer the potential for immediate improvement. For the medium term (5–15 years), planners should emphasise technologies that can potentially achieve dramatic improvements relative to current technology. To the extent that technologies realisable in the medium term fall short of performance consistent with sustainable development goals, policymakers should also encourage for the long-term (15–30 years) technologies that are fully consistent with sustainable development goals.

It is also wise to have a balanced portfolio with a combination of near-, medium-, and long-term options, to ensure a continuing flow of improved technologies into rural energy markets. Successes with near-term improvements can help win political support for the development of longer-term options. Some important technological options for rural energy in the near, medium, and long terms are summarised in table 10.3.

Accelerating rural energy development

The preceding sections show that there are many technological opportunities for implementing the goals set forth at the start of this chapter: providing clean liquid or gaseous fuels for cooking and electricity for lighting and other basic household amenities, and making bulk electricity available at low cost for mechanising rural agriculture and promoting rural industrialisation.

Both centralised and decentralised energy technologies and strategies can make contributions to reaching these ends. But new strategies and policies are needed to increase access to these modern energy services and to make modern energy services widely affordable. Coordinated efforts that include the active participation of rural people can accelerate the process.

Integrated rural development

Making modern energy services more readily available is a necessary but insufficient condition for rural development. To be most effective, certain forms of energy (such as grid-based electricity) should be introduced into rural areas only after, or along with, other development inputs or infrastructure components. To achieve this integration, it is essential that there be horizontal communication among all agencies involved in rural development.

Many rural development activities—agriculture, transport, water supply, education, income generation, health care—have energy requirements. Yet the ministries and departments responsible for these activities rarely coordinate or cooperate with the ministry of energy, or with one another, to arrive at the most rational, integrated solution

TABLE 10.3. SOME NEAR-, MEDIUM-, AND LONG-TERM TECHNOLOGICAL OPTIONS FOR RURAL ENERGY

Energy source or task	Present	Near term	Medium term	Long term
Source				
Electricity	Grid or no electricity	Natural gas combined cycles, biomass-based generation using gasifiers coupled to internal combustion engines, photovoltaic, small wind, small hydroelectric for applications remote from grids	Biomass-based generation using gasifiers coupled to micro-turbines and integrated gasifier combined cycles, mini grids involving various combinations of photovoltaic, wind, small hydroelectric, batteries	Grid-connected photovoltaic and solar thermal, biomass-based generation using gasifiers coupled to fuel cells and fuel cell/turbine hybrids
Fuel	Wood, charcoal, dung, crop residues	Natural gas, LPG, producer gas, biogas	Syngas, DME	Biomass-derived DME with electricity coproduct
Cogeneration (combined heat and power)		Internal combustion engines, turbines	Microturbines and integrated gasifier combined cycles	Fuel cells, fuel cell/turbine hybrids
Task				
Cooking	Woodstoves	Improved woodstoves, LPG stoves, biogas	Producer gas, natural gas and DME stoves	Electric stoves, catalytic burners
Lighting	Oil and kerosene lamps	Electric lights	Fluorescent and compact fluorescent lamps	Improved fluorescent and compact fluorescent lamps
Motive power	Human- and animal-powered devices	Internal combustion engines, electric motors	Biofueled prime movers, improved motors	Fuel cells
Process heat	Wood, biomass	Electric furnaces, cogeneration, producer gas, NG/solar thermal furnaces	Induction furnaces, biomass/solar thermal furnaces	Solar thermal furnaces with heat storage

to their energy needs. Decentralisation of rural energy planning may help achieve this. But optimising the allocation of development resources requires attention at the central government planning level as well. In the many places where integrated rural development has been pursued, the availability of affordable modern energy supplies has proven to be a catalyst for economic and social transformation.

The provision of affordable financial services for rural people has long been a prime component of rural development strategies. Originally, these strategies focussed on concessional loans to farmers. More recently, however, this approach has been replaced by much wider financing for rural activities, with lower transaction costs. By creating rural financial markets and integrating them with general financial markets, it may be possible to mobilise substantial domestic savings as the main capital resource for rural people—and to reduce their dependence on concessional outside funds. Where urban-biased financial policies have inhibited the creation of effective rural financial institutions, new policies and strategies should seek to integrate rural and urban financial services and thus promote the greatest financial efficiency and lowest credit costs for rural people.

Involving rural people (particularly women) in decision-making

Above all, planning for rural energy development should have a decentralised component and should involve rural people—the customers—in planning and decision-making. And special attention should be devoted to involving women, because they bear the burden of traditional energy systems and are likely to be the greatest beneficiaries of improved systems. A major driving force for the move towards decentralisation has been the recognition of the limited extent to which benefits have flowed to rural people from the investments already made. More active involvement of rural people (particularly women) and their institutions in identifying rural energy problems, and in formulating and implementing plans to overcome them, would result in more efficient, rational use of resources and more equitable sharing of the benefits of development.

Decentralisation of rural energy planning is wise for other reasons as well. Rural energy systems are based primarily on biomass, a local energy resource. Although historically this has involved direct combustion of biomass for cooking or heating (as this chapter has shown), clean, convenient, modern energy carriers can also be derived from biomass. Consequently, an assessment of the demand and supply flows and of desirable interventions must all also occur on the same geographic scale. Through their superior knowledge of the local situation, local people—women in particular—can be integral parts of the solution.

Strategies for expanding access to modern energy services

Often, policies ensuring that supplies—even from centralised production sources—are reliable and stable can promote the use of modern energy carriers. The Hyderabad, India, example (see above) shows that by the simple expedient of stabilising LPG supplies, the local government was able to encourage many households to shift from biomass to LPG for cooking.

Where integrated rural development has been pursued, the availability of affordable modern energy supplies has proven to be a catalyst for economic and social transformation.

For rural electrification through grid extension, rural cooperatives seem to be a viable alternative to grid extension by the large parastatals that have dominated power generation in developing countries. In Bangladesh financial and technical failures of public power utilities in 1980 led to a government-supported take-over of its parastatals by rural electrification cooperatives. Now numbering 45, the cooperatives have engineered a rapid expansion of grid-based rural electricity supply that serves 1.6 million consumers—as many as the public sector in urban areas. Power outages have fallen dramatically, while revenue collection has improved from 91 to 98 percent, despite higher tariffs. Most important, the cooperatives have fostered an alternative structure to meet a demand that was previously unexpected in such a poor country. They have also demonstrated that consumers have considerable interest in getting access to electricity and are willing to pay for reliable service.

More effective electric grid extension measures can also help promote the wider availability of electricity from local biomass sources by making village-scale biopower-generating technology more attractive to investors. Grid access would make it possible to operate biopower plants as baseload units, thereby increasing capacity utilisation and reducing generation costs per kilowatt-hour. Grid access would enable rural populations to sell into the grid electricity produced in excess of local needs—until local rural industrial capacity could be increased to more fully use the electricity produced this way (case 2 in the annex). Thus a promising new approach would be to couple grid extension in regions rich in crop residues (or other suitable biomass resources) to measures that encourage village-scale biopower generation.

This strategy would also make investments in grid extension more attractive. The availability of baseload biopower on these grids would enhance grid capacity utilisation and make transmission costs per kilowatt-hour much lower than when electrons instead flow from large central power plants to rural areas to serve small, scattered, peaky rural electrical loads.

Policies that make grid access possible are needed to facilitate the launch of such baseload biopower technologies on the market. Policies promoting increasing competition in electricity generation would be helpful. But consideration also has to be given to the fact that, when any new technology is introduced, its cost is higher than that of the established technology it would replace. That remains the case until enough new plants have been built to buy down the cost of the new technology along its learning curve to prospective market-clearing price levels (chapter 12).

One way to pursue technology cost buydown in a competitive electricity market is to require that each electricity provider include in its portfolio a small but growing fraction provided by biopower or other renewable energy supplies. This requirement would be imposed during a transitional period as new renewable energy industries are being launched on the market. Power generators could either produce this renewable electricity themselves or purchase renewable energy credits that are sold in a credit trading market. Experiments with this mechanism are being conducted in the United States (where it is called a renewable portfolio standard) and in Europe (where it is called green certificate markets). The concept has great promise for developing countries.

A major challenge in extending energy services to rural areas is to find and pursue the least costly mix of energy options (centralised and decentralised, fossil and renewable, end-use efficiency improvements) for a particular region. This might be achieved, for example, through concessions for both cooking fuels and electricity. Concessions grant the exclusive right to provide energy services in exchange for the obligation to serve all customers in the region. They offer the advantage of being able to reduce transaction costs greatly in serving large numbers of small customers, relative to other mechanisms. Concessionaires ought to have the flexibility to choose the least costly combinations of technologies in meeting their obligations. The rural energy concessions recently introduced in Argentina illustrate how the concept might work (box 10.5).

BOX 10.5. A CONCESSION SCHEME FOR RURAL ENERGY DEVELOPMENT IN ARGENTINA

Argentina recently began implementing an innovative rural energy plan to encourage private sector involvement in rural energy services. To begin with, the programme targets eight provinces with 1.4 million people and 6,000 facilities without access. In each province, private companies bid for the right to provide electricity to the people and to the schools, medical centres, drinking water facilities, and other public facilities without access. Solar photovoltaic panels, small wind turbines, micro hydropower, and diesel-driven generators compete on a least-cost basis.

Preliminary analyses show that in most cases renewable technologies will be competitive with diesel generators. A large share of household supply will be through solar photovoltaic home systems. Total investment for all provinces amounts to $314 million, with a 55 percent subsidy from provincial, federal, and World Bank funds to cover initial capital investments. The winning bids will be those seeking the lowest government subsidy per energy hook-up.

In 1996 two concessions were awarded in Jujuy and Salta provinces. In Jujuy, after solving some initial problems with the tariff structure proposed in the bidding papers, 500 of 2,000 new users are now served through renewable sources, and a programme to supply 550 additional users through solar home systems is in progress. By 1998 solar systems were installed in 220 schools in Salta province, which aims to achieve full coverage of public service electrification (including schools and first-aid medical centres) in 2000.

In April 1999 a $30 million loan from the World Bank and a $10 million subsidy from the Global Environment Facility were approved. These funds will help finance the national government's share of subsidies for the first eight provinces to adopt the programme, as well as overcome barriers to the use of renewable energies. Concessions to provide electric power to significant portions of the population within three years were granted in the next six provinces to adopt the programme in late 1999 and early 2000. Eventually, all rural Argentine provinces will participate in the programme.

Source: Covarrubias and Reiche, 2000.

Strategies for making modern energy services affordable

Although policies aimed at widening access to modern energy services are necessary, they are often insufficient to deliver modern energy services to all rural residents. Modern energy technologies are useful only to those who can afford to adopt them. Even the more affluent rural households typically cannot afford to purchase photovoltaic systems, which may be the only plausible electrification option for scattered rural households. Moreover, the very poorest households are unable to pay for even less capital-intensive modern energy options. And such households are the majority in the poorest countries: 37 of the countries listed in the World Bank's *World Development Report 1998/99* had a 1997 GDP per capita below $500 (unadjusted for purchasing power parity).

Historically, energy price subsidies have been used extensively to promote wider use of modern energy carriers. But energy price subsidies are problematic. The welfare objective embodied in such subsidies is often not realised because of their diversion to unintended uses. Typically, there is a disproportionate exploitation of the subsidies by the more affluent, who could afford to pay unsubsidised prices. Such subsidies help explain the poor financial conditions of many parastatal energy companies, and have made continued expansion of energy supplies difficult (chapter 12). Energy price subsidies should be a policy of last resort to deliver modern energy services to rural areas.

When attempting to increase the level of energy services provided, a central question is: what is affordable? There is frequent mention of affordability, but there has been no rigorous quantification of this concept. One might argue that a consumer's current energy expenditures—for example, on kerosene for lighting—are a good indicator of what that consumer is prepared to spend for electric lighting. In some cases, however, the consumer is prepared to spend more for a new technology if it is safer or more convenient.

Policy reforms to make capital resources more readily available for small-scale rural energy investments would be especially helpful in making modern energy affordable to small rural consumers. Various microfinance schemes are being tried (box 10.6), and some are proving quite successful. When the poor have access to microfinance, they are no longer beneficiaries of government and donor largesse but clients with assets, whose preferences and needs must be respected. Microfinance has demonstrated success not only in providing access to energy services for poor households, but also in generating income and alternative economic activities. Microfinance is facilitating access to affordable modern energy technologies for which many people are willing to pay the full cost.

Poor Indian households that currently buy kerosene for lighting could afford electric lighting if energy-efficient fluorescent bulbs were used (Reddy, 1999). An appropriate microfinance scheme could make investment in fluorescent lights a viable option, even for poor households, if total spending on electricity plus debt servicing was less than maximum household spending on energy (about 15 percent). The combination of modern technology and microfinance can thus widen the window of opportunity. Because of the capital-intensive nature of photovoltaic and other renewable energy technologies,

BOX 10.6. ALTERNATIVE APPROACHES FOR FINANCING SMALL-SCALE RURAL ENERGY TECHNOLOGIES

At the smallest scales, many sustainable energy technologies (including small-scale wind and hydropower supplies and photovoltaics for homes) cost a few hundred dollars. Buying them outright is impossible for most rural households in developing countries. But an important minority of households, communities, and small businesses can afford to buy them with credit. The main obstacle to serving this crucial market is the reluctance of banks to manage numerous small loans and to lend without collateral or other guarantees against loan defaults. A variety of innovative approaches are being used to overcome this obstacle:

- **Financing through dealers.** Banks transfer the collateral problem from the end user to dealers by lending to dealers, who in turn lend to purchasers using payment schemes compatible with their income. Dealers must bear the financial risk along with technical risks. This system is best suited to large, relatively high-income rural markets.
- **Financing through energy service companies.** These companies can replace dealers as the financing intermediary. Companies typically require greater efforts to establish higher funding levels, because they provide a more comprehensive installation and back-up service to clients.
- **Revolving funds (with grant support).** A bank takes on the risk of operating a revolving loan fund, usually with start-up capital provided by a grant.
- **Loan aggregation through cooperatives.** To avoid the high costs of servicing many small loans, prospective borrowers form a community association (or enlarge the functions of an existing village or farmer cooperative). Banks lend to the cooperative or lease the energy systems but retain ownership of the equipment in case of payment defaults.
- **Concessional funding for public sector objectives.** The government contracts and pays a local company to provide energy services that meet development objectives, such as photovoltaic lighting for schools. This provides entry capital for the company to offer credit and expand its business to other local markets, such as photovoltaics for households, health clinics, and community centres.
- **Payment for energy services.** Payment for outputs, such as irrigation and drinking water, have been used to fund the recurrent operation and maintenance costs of small-scale energy systems. These cost streams are usually hard to fund, or remain unfunded, when loans target the capital cost.

Most of these approaches demand high levels of local participation and so take time to mature. Participation must start at the concept development stage, so that local people can decide which schemes and parameters are most appropriate.

Source: EC and UNDP, 1999.

BOX 10.7. THE GRAMEEN SHAKTI PHOTOVOLTAIC PROGRAMME IN BANGLADESH

In 1996 the Grameen Bank of Bangladesh, a microlending agency with more than 1,000 branches and 2 million members, initiated a programme of loans for photovoltaic home systems to serve those without access to electricity. The loans are administered by a non-profit rural energy company, Grameen Shakti, and call for a small down payment.

Grameen Shakti's first initiative has been a 1,000-unit project to understand better a number of important issues concerning household photovoltaic systems. These include:

- Technical performance of these systems in rural Bangladesh.
- Acceptance of the systems by the poor.
- Income-generating potential of light in the evening.
- Affordability, factoring in technical improvements and economies of scale.
- The training, monitoring, and evaluation expertise that would be required to replicate this project if it proves successful.

Grameen Shakti expects that 100,000 photovoltaic systems will be operating in rural Bangladeshi homes in 2000. The bank plans to expand this service by offering small loans for wind power and biogas plants. Demonstration projects are under way to determine the most appropriate financing packages for these technologies.

microfinance schemes are especially important to promote their widespread dissemination (box 10.7).

Microfinance by itself is no panacea, however. Two other factors limit the affordability of energy services: the high costs of imported energy products (including high inherent costs and inefficient procurement of small quantities) and the low incomes of the very poorest households. But international industrial joint ventures that manufacture modern energy technology with gradually increasing domestic content can, over time, reduce costs relative to the cost of the same technology if imported (Weise and others, 1995; see also the case study of wind-diesel hybrid technology in China in chapter 7). Such cost reductions lead to expanded market opportunities, which lead to further cost reductions resulting from higher production volumes. The keys to success in creating this kind of virtuous cycle of cost reduction and market expansion are policies that facilitate the formation of such joint ventures and steer them towards the provision of energy services for rural areas (chapter 12).

The very poorest households may need higher incomes as well as microfinance to afford modern energy supplies and end-use devices. Increasing the incomes of the rural poor through macroeconomic policies is an especially daunting challenge and takes a long time. But energy policies that facilitate the introduction of low-cost electricity generation for rural industrialisation could effectively promote income generation.

Especially promising are the possibilities for electricity generation from low-cost crop residues in agriculture-intensive regions. Moreover, village-scale, crop-residue-based biopower technologies offer the possibility of near-term income from gathering biomass and delivering it to conversion facilities. This could help the poor pay for modern energy supplies without having to wait for rural industrialisation opportunities to materialise (case 2 in the annex). A key to making such income-generating activities viable seems to be the opportunity to sell into the grid electricity produced in excess of local needs (see the section above on small-scale biopower).

Pursuing all the above strategies might still leave the very poorest households in some areas unable to afford convenient energy services. If so, subsidies may still be needed. As noted, to stimulate the use of new technologies (such as fluorescent light bulbs), one-time equipment subsidies are preferable to continued price subsidies.

To sum up, sustainable development implies that modern energy carriers need to be made affordable to satisfy the basic needs of all rural residents. Policies are needed that will make pursuing this objective profitable. If a subsidy is needed, it might be provided as an integral part of a new social contract that creates highly competitive conditions in the energy sector (a key element of ongoing energy reforms), complemented by the establishment of a public benefits fund financed with wire and pipe charges imposed on electricity, oil, and gas providers to protect the public interest under new

Through their superior knowledge of the local situation, local people—women in particular—can be integral parts of the solution.

competitive market conditions (see chapter 12 for a discussion of public benefits funds). Specifically, some fund revenues could subsidise the basic energy needs.

This public benefits fund strategy could be made entirely consistent with a shift to greater reliance on market forces to more efficiently allocate resources. If, for example, an energy concession proved to be the preferred way to deliver modern energy services to a particular rural area, and if the concession was awarded competitively, market forces would be brought into play to find the least costly mix of energy technologies with the least amount of subsidy to satisfy the concessionaire's obligation to provide modern energy services to all.

Conclusion

Between 1970 and 1990 rural electrification from grids brought electricity to 800 million additional people. In addition, in the past 20–30 years a number of innovative schemes have been developed to commercialise improved cooking stove, biogas, and producer gas systems; photovoltaics; wind; and so on—with the result that several hundred million people have improved their access to energy. Perhaps as many as 600 million people have benefited from these innovations. Yet despite these efforts to improve energy services to rural areas, the population without access to such services has stayed about the same: 2 billion.

The task is daunting but not hopeless. Technologies can be deployed immediately or in the near term to improve energy services for rural areas. These technologies will lead to dramatic advances in the quality of life for rural populations. These advances can be achieved at costs that are within the means of governments and beneficiaries. They also require quite modest increases in the magnitudes of total energy supplied to the countries involved. They offer attractive options for decision-makers seeking quick political pay-offs before the next popular judgement of their performance. Even more exciting is the possibility of interesting new technologies that might be developed and exploited. All such possibilities would enable rural populations to climb up the energy ladder, leapfrog to higher rungs on the ladder, or even reach new rungs that could be added near the top of the ladder.

New policies are needed to bring the top of the energy ladder within reach of all rural people. Past efforts to deliver modern energy to rural areas have often been ineffective and inefficient. Some recent programmes are showing good results, but more promising new approaches need to be tested to determine if they can address poverty, equity, environmental, and public health concerns in the context of the ongoing global restructuring of energy industries. Much can be done towards these ends without resorting to large subsidies if competitive market conditions are fostered and complemented by measures to protect the public interest. Subsidies should be reserved for situations in which new strategies alone cannot make modern energy widely available. Even then, fuel price subsidies should be avoided if basic needs can be addressed by alternatives, such as subsidised purchases of energy-efficient equipment. Sound policies to accelerate the wide availability of modern energy services in rural areas could lead to even more dramatic improvements in the rural quality of life without creating large demands on public treasuries. ■

ANNEX Case studies of crop-residue-derived modern energy carriers in China

In densely populated countries that are largely self-sufficient in food production and are prolific generators of crop residues, thermochemical gasification of crop residues can provide an attractive means of providing both clean cooking fuel and electricity or combined heat and power (CHP) to satisfy basic human needs and generate additional electricity in support of income generation and rural industrialisation. Prospects in this regard are here illustrated by three case studies for China that illustrate the prospects for providing:

- With existing technology, residue-derived producer gas as a clean cooking fuel at the village scale.
- With medium-term (5–10 year) technology, cooking gas plus CHP at the village scale, with residue-derived producer gas.
- With long-term (10–20 year) technology, both electricity suitable for rural industrialisation and a synthetic fluid fuel for cooking (synthetic LPG or DME derived from synthesis gas; see chapter 8) that is safe as well as clean.

There are three reasons to focus on China in studying this approach to making modern energy carriers widely available in rural areas. First, China satisfies the criteria of being densely populated, self-sufficient in food, and a prolific generator of crop residues. About 376 million tonnes a year (about half the total residue generation rate) are potentially available for energy; the rest is used for paper-making, forage, or returned to the fields to sustain soil quality (Li, Bai, and Overend, 1998). The energy content of these residues is equivalent to 15 percent of the coal energy use in China in 1998.

Second, China has a severe new air pollution problem caused by the burning of crop residues in the field at harvest time, a consequence of the rising affluence of farmers. Traditionally, in poor agricultural communities of China, residues were fully utilised for heating, cooking, and other purposes. But as incomes have risen, growing numbers of farmers have become less willing to gather residues from the fields and store them for use throughout the year—preferring instead to buy coal briquettes or LPG as needed. As a result, excess crop residues that do not readily decay (because they dry out too quickly) for incorporation into the soils have been burned off in the fields to avoid insect infestation problems. The resulting air pollution has been severe—often even closing airports near harvest time. As a response, the government in 1999 banned burning crop residues near airports, railroads, and highways. The ban will be difficult to enforce, however, unless alternative productive uses of residues can be found.

Third, a key to providing low-cost electricity from crop residues as a coproduct of cooking gas is being able to produce baseload electricity and to sell electricity produced in excess of local needs into the electric grid. In most developing countries, this is not yet feasible because few rural communities are hooked up to grids. But in China, 87 percent of rural households are connected, in comparison with an average of about 33 percent for all other developing countries. Thus China stands out as a strong candidate country for launching small-scale biopower technologies in the market.

Case 1. Cooking with producer gas generated at the village scale

With technology currently available in China, it is feasible to provide clean cooking gas derived from crop residues at the village scale through partial oxidation in air, as illustrated by recent experience in Shangdong Province.[10]

In May 1996 a village-scale crop residue gasification system serving village households with producer gas for cooking went into operation in Tengzhai village (216 households, 800 people), Huantai County, Shangdong Province (the second village-scale gasification system installed in the province), using an atmospheric pressure, air-blown, downdraft gasifier developed by the Energy Research Institute of the Shangdong Academy of Sciences. Researchers at the institute also carried out detailed socio-economic studies of the implications of the technology and of costs in relation to benefits.

The gasifier requires 0.25 tonnes of crop residue per capita to meet the annual cooking needs of villagers. About 12 percent of the residues generated by the village's wheat and corn crops are adequate to meet all its cooking energy requirements. Researchers estimated that, with the producer gas cooking system, cooking time for housewives is reduced from 3.0 to 1.5 hours a day.

In a survey of 30 randomly selected households, the researchers found that this technology was regarded as being as good as or better than coal or LPG (the major technologies displaced) with regard to price, convenience, reliability of supply, environmental impact, and working intensity of housewives (all the issues investigated in the survey) by 97.5 percent or more of all households surveyed for each issue.

The total capital cost for the entire project (with an expected 10-year project life) was 378,000 yuan ($47,000, or $220 a household), a third of which was provided by a government subsidy. The producer gas is sold to villagers at a price that is a third of the market price for LPG on an equivalent-cooking-service-provided basis.[11] At this selling price, the project is not cost-effective, even with the capital subsidy. However, if the gas selling price were raised to two-thirds of the equivalent market price for LPG, the technology would be cost-effective without any capital subsidy, generating an internal rate of return of 17 percent. At this higher gas price, the annual cost of cooking fuel per household would be 360 yuan ($45) a year, about 25 percent less than the fuel cost for cooking with coal.

Case 2. Combined heat and power systems using producer gas generated at the village scale

Although desirable as a way to make an affordable, clean, convenient cooking fuel available to villagers, the strategy described above will not solve the air pollution problem caused by burning excess residues. However, using residues in excess of what are needed to make cooking gas power generation or CHP could solve the problem.

This case discusses the prospects for improving village living conditions through the 'trigeneration' of cooking gas, hot water for space heating, and electricity from a village-scale gasifier that converts crop residues (corn stalks) into producer gas (Henderick and Williams, 2000). The system is designed to satisfy all cooking needs in the village with a clean gas, plus meet all village electricity needs, plus generate much more electricity for sale into the grid, plus generate hot water through waste heat recovery at the biopower plant for distribution to village households through a district heating system that would satisfy all space-heating needs (especially important in Jilin Province, where winters are very cold). For specificity, the analysis is for a hypothetical 100-household village (400 residents) in Jilin Province, where about half the residue generated could potentially be exploited for energy purposes at a rate of about 6.5 tonnes a household per year (Cao and others, 1998).

With currently available biopower technology, electricity could be produced at the least cost with diesel-engine generator sets operated in dual-fuel mode, using producer gas as the primary fuel, plus pilot diesel fuel for ignition purposes (see the section in the main text of the chapter on small-scale biopower using producer gas). Because this technology is more capital-intensive than conventional diesel technology (table A10.1), a high level of capital utilisation (high capacity factor) is often required to reach economically attractive generation costs. Local electricity demand in poor rural areas is often inadequate to make the required high capacity factors feasible. If electricity could be sold into the electric grid, high capacity factors could often be realised.

A microturbine providing 75 kilowatts of electricity, a second-generation small-scale biopower technology (see the section on small-scale biopower using producer gas), was selected for the detailed design of a village trigeneration system. The microturbine is a technology for which the potential generating cost using low-cost residues is low enough (see table A10.1) to make the technology quite attractive for selling electricity into the grid. The energy balance for the village trigeneration system based on the use of this microturbine is shown in figure A10.1.

The estimated initial investment (base case) for the system is $1,800 a household, a third of which is for gas and for infrastructure to pipe hot water. It is assumed that the infrastructure investment is covered by a loan from the government at 6 percent interest, and that the rest of the investment is covered by equity capital provided

TABLE A10.1 COSTS OF ELECTRICITY WITH ALTERNATIVE ENGINE-GENERATORS FUELLED WITH DIESEL OIL AND/OR PRODUCER GAS DERIVED FROM CROP RESIDUES

System type[a]	Diesel engine		Spark-ignition engine	Microturbine
	Diesel only	Dual-fuel[b]		
Engine-generator set				
Equipment lifetime (years)[c]	6	6	6	10
Rated power output (kilowatts)	80	100	160	80
De-rated power output (kilowatts)[d]	80	80	80	80
Thermal efficiency, lower heating value (percent)[e]	34	27	21	28
Installed equipment cost (dollars per rated kilowatt)[f]	181	181	362	350
Installed equipment cost (dollars per de-rated kilowatt)	181	226	724	350
Present value of lifecycle capital investment for the engine-generator set (dollars per de-rated kilowatt)[g]	330	413	1,320	463
Total system (including building plus gasifier plus gas clean-up)[h]				
Initial cost (dollars per de-rated kilowatt)[i]	243	680	1,280	850
Present value of lifecycle capital investment for the total system (dollars per de-rated kilowatt)[j]	392	960	1,970	1,070
Operating costs				
Diesel fuel (dollars per hour, at full power output)[k]	5.48	1.65	0	0
Crop residues (dollars per hour, at full power output)[l]	0	0.39	0.66	0.50
Lubricating oil (dollars per hour, at full power output)[m]	0.21	0.42	0.42	0
Labour (dollars per hour during operation, at full power output)[n]	0.12	0.23	0.23	0.23
System maintenance (dollars per year)[o]	1,500	2,800	2,800	3,300
Levelised life-cycle electricity generation cost (cents per kilowatt-hour)				
Total capital cost	0.92	2.26	4.63	2.51
Diesel fuel	6.85	2.06	0	0
Biomass	0	0.49	0.83	0.62
Lubricating oil	0.26	0.53	0.53	0
Maintenance	0.34	0.62	0.62	0.73
Labour	0.16	0.33	0.33	0.33
Total (cents per kilowatt-hour)	**8.5**	**6.3**	**6.9**	**4.2**

a. All costs are in 1998 U.S. dollars. All systems are designed for an electrical output capacity of 80 kilowatts of electricity, and operation at 65 percent average capacity factor, so that annual electricity generation is 456,000 kilowatt-hours. Costs are calculated for a 12 percent real discount rate and a system lifetime of 20 years, so that the capital recovery factor is 0.134. b. Dual fuel refers to operation on producer gas plus pilot oil. It is assumed that producer gas displaces 70 percent of the diesel fuel required for standard operation on diesel fuel only. c. It is assumed that reciprocating internal combustion engines have 6-year (34,000-hour) lifetimes. The 10-year (57,000-hour) lifetime for the microturbine is an estimate by Honeywell. d. Relative to operation on diesel fuel, a diesel engine operated on producer gas plus pilot oil is typically de-rated 20 percent. For spark-ignited engines operated on producer gas, a 50 percent de-rating relative to operation on gasoline is typical. There is no de-rating penalty for microturbines operated on producer gas (Henderick, 2000). e. The assumed efficiencies (producer gas to electricity) for internal combustion engines converted to run on producer gas (21 percent for spark-ignition engines and 27 percent for diesel engines) are representative (Reed and Das, 1988). For the microturbine, 28 percent is representative of Honeywell's 75-kilowatt model (their target is 30 percent). The overall conversion efficiency (crop residue to electricity) is obtained by multiplying these efficiencies by the 70 percent gasifier efficiency. f. The diesel engine capital cost is from Mukunda and others (1993). The spark-ignition engine is assumed to be an industrial gas engine, for which the capital cost is typically twice that of a diesel (McKeon, 1998). Honeywell product literature (1998) estimates year 2003 installed equipment cost at $350–450 a kilowatt for its 75-kilowatt microturbine. g. Present value of the life-cycle capital investment includes the installed equipment cost plus future replacements during the 20-year life cycle, less equipment salvage value at 20 years. h. On the basis of Mukunda and others (1993), capital costs for gasification and gas clean-up are assumed to be $1,160 for the gasifier, $8,700 for the cooling and cleaning system, $11,600 for a control system, and $5,800 for a building ($1,740 if diesel only). For the microturbine, an additional fine filtration cleaning unit costing $20 a kilowatt is assumed. i. The total initial cost includes a 20 percent increment over the installed equipment cost to allow for engineering and contingencies. j. During the 20-year life cycle, the gasifier is replaced three times (6-year life), and the clean-up and control systems are replaced once (10-year life), while the building requires no replacement (Mukunda and others, 1993). k. The cost of diesel fuel is assumed to be $0.25 a litre. l. For rural Jilin Province, China, the cost of gathering corn stalks from the field and delivering them to the trigeneration facility modelled in Henderick and Williams (2000) is estimated to be 45 yuan a tonne ($0.33 a gigajoule), on the basis of data for the province provided by Cao and others (1998). m. On the basis of Mukunda and others (1993), lubricating oil requirements are assumed to be 1.36 grams a kilowatt-hour for dual-fuel engines; for spark-ignition engines the same value is assumed, and half this rate is assumed for conventional diesel engines; microturbines require no lubricating oil. Also on the basis of Mukunda and others (1993), the lubricating oil cost is assumed to be $3.50 a litre ($3.87 a kilogram). n. On the basis of Mukunda and others (1993) for rural India, during the 65 percent of the time the engine is assumed to be operating at full output, labour costs are $0.23 an hour (4 rupees an hour) for two workers for dual-fuel systems—assumed to be the same for spark-ignition engines and microturbines. Labour costs at half this rate are assumed for conventional diesel engines. In addition, it is assumed that these labour cost rates are applicable for 14 hours a week during downtime, for maintenance, preparation, and so on. o. On the basis of Mukunda and others (1993), annual maintenance costs are estimated as fixed percentages of installed building and equipment costs (not including engineering and contingencies) for the diesel, dual-fuel, and microturbine cases. The assumed percentage for diesel and dual-fuel engines is 10 percent; that for microturbines is assumed to be 8 percent. The assumed percentage for the building, gasifier, and gas clean-up is 5 percent; for the control system, 2 percent. It is assumed that the maintenance costs for the spark-ignited engine case are the same as for the dual-fuel engine case.

Source: Based on Henderick and Williams, 2000.

either by an independent power producer or by a villager-owned corporation. (Village corporation financing is plausible because the required capital is equivalent to less than three years of the average savings rate—38 percent of income in 1998—for Jilin's rural population.) For the village corporation option, the average net cash flow to villagers (income from crop residue sales plus revenues to the corporation minus expenses of the corporation) is adequate to cover all expenditures on energy by the villagers for the 20-year life of the system.[12]

The low-interest government loan for piping infrastructure might be justified as a cost-effective measure for avoiding the health costs of indoor air pollution associated with burning solid fuels for cooking and heating. For the hypothetical village, the annual health damage costs avoided would be $4,800 (assuming the average per capita value for all rural China; World Bank, 1997), more than three times the cost savings to the villagers, as a result of having debt instead of equity financing for piping.

Poor households that own no crop residues might earn income to cover energy expenditures by being paid by rich farmers to remove crop residues from their fields (for example, to enable them to comply with the ban on field burning of residues); residue recovery from the farmland of less than five average households would enable a poor household to earn enough income to cover all energy expenditures.

Case 3. Coproduction at industrial-scale of synthetic liquid petroleum gas and electricity from crop residues

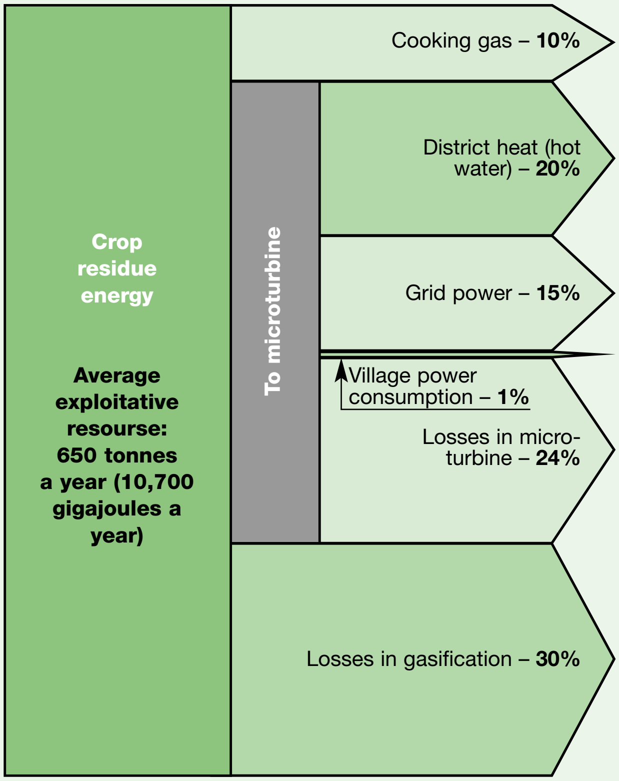
The trigeneration technology described above could be improved if the cooking fuel provided were safe as well as clean (for example, producer gas contains carbon monoxide, so the risk of leaks poses a danger). This might be realised through the coproduction, at industrial scales, of electricity and synthetic liquid petroleum gas (SLPG) or dimethyl ether (DME)—synthetic fuels well suited for cooking, the use of which would involve no risk of carbon monoxide poisoning.

A preliminary design of a plant that would convert grain crop residues into SLPG and electricity using a once-through Fischer-Tropsch liquids plant coupled to a biomass integrated gasifier combined cycle (IGCC) plant has been carried out (Larson and Jin, 1999) at plant scales appropriate for Jilin Province, the corn belt of China, which produced 15 million tonnes of corn in 1995 (13 percent of the country's total). The technology would build on advances that are being made for liquid-phase syngas reactors that are being developed for the coproduction of synthetic liquid fuels and electricity from fossil fuel feedstocks (chapter 8).

The design involves 10-megawatt-electric biomass IGCC plants producing SLPG as a coproduct (250 barrels of crude oil equivalent a day). For the corn crop residue densities characteristic of Jilin, residues would have to be gathered from cornfields within a 11-kilometre radius to meet feedstock needs at the plant. Such plants could convert 15 percent of the biomass feedstock to electricity and 28 percent to LPG. Preliminary estimates are that the SLPG produced this way in rural Jilin might be competitive with conventional LPG, once biomass IGCC technology is established in the market (Larson and Jin, 1999). As discussed in chapter 7, biomass IGCC technology has advanced to the point where it is now being demonstrated in various parts of the world, building on the experience that has already brought coal IGCC technology to commercial readiness (chapter 8).[13]

If the technology could be used with all the 376 million tonnes of crop residues per year potentially available for energy purposes in China, it could provide 1.4 exajoules a year of SLPG along with 210 terawatt-hours a year of electricity. This much LPG could meet—in the form of a super-clean fuel—the cooking needs of 560 million people (about 70 percent of the rural population projected for 2010), while generating electricity at a rate equivalent to the output of 2.5 Three Gorges power plants (the Three Gorges plant's output is 18 gigawatts of electricity). And whereas the electricity from the Three Gorges plant would have to be transmitted long distances to most customers, this residue-generated electricity would be

FIGURE A10.1. ENERGY BALANCE FOR A TRIGENERATION SYSTEM BASED ON THE USE OF PRODUCER GAS DERIVED FROM CROP RESIDUES IN A HYPOTHETICAL 100-HOUSEHOLD VILLAGE, JILIN PROVINCE, CHINA



Source: Henderick and Williams, 2000.

produced in 3,400 power plants (each with output of 10 megawatts of electricity), which would typically be located close to the consumers they serve.

As in the case of the village-scale trigeneration system described above, with this technology the very poorest households could pay enough for electricity and clean cooking fuel to satisfy their basic needs by gathering residues from the fields of rich farmers and delivering the residues to the energy conversion plants, thereby monetising their labour.

DME, which is expected to be easier to manufacture as a synthetic fuel than SLPG, would have similar properties as a cooking fuel. Although the technology for making DME is not as far advanced as that for SLPG, either option could probably be commercially ready by 2010–15 with a concerted development effort. The Institute of Coal Chemistry at the Chinese Academy of Sciences is investigating prospects for making DME from coal for cooking fuel applications (Niu, 2000). ■

Notes

1. The amount of time varies widely depending on the availability of biomass. Surveys have shown that in some regions, women spend close to an hour a day collecting firewood, and could spend more than two hours a day in areas where fuels are scarce (World Bank, 1996).

2. As discussed in the next section, many of the technologies associated with the intermediate rungs on the ladder pose greater development challenges than technologies associated with the top rungs.

3. For a family of five, 0.08 kilowatts per capita consumption for cooking is equivalent to 21 kilograms of LPG per month. Assuming that 30 percent of the 0.02 kilowatts per capita of electricity is consumed to support community activities, the remaining electricity would be adequate to support six compact fluorescent light bulbs used for four hours a day in addition to a television for two hours a day plus a refrigerator-freezer with the average energy efficiency projected for new U.S. units in 2001.

4. For example, in China the energy content of crop residues is twice that of animal excrement on large and medium-size farms, and the fraction of crop residues recoverable for energy purposes (about half the total generation rate) is equivalent in terms of contained energy to about 20 percent of China's coal consumption rate (Li and others, 1998; Su and others, 1998).

5. Gasifiers are about 70 percent efficient in converting biomass energy into gas energy, and producer gas stoves are about 50 percent efficient. Thus the overall efficiency of converting biomass into heat energy used in cooking is about 35 percent, which is double or more the efficiency of typical biomass stoves.

6. In China the number without access to electricity in 1996 was only 110 million, less than 13 percent of China's rural population (Dai, Liu, and Lu, 1998).

7. Lubricating oil can contribute as much to the generation cost as natural gas fuel contributes to the generation costs of a modern large combined-cycle power plant—compare tables 10.3 and 8.4.

8. If spark-ignited instead of compression-ignited engines were used for power generation, the need for diesel fuel could be eliminated entirely. But such engines are less efficient and more capital intensive than diesel engines, and they must be de-rated more (about 50 percent relative to operation on gasoline) than compression-ignition engines. As a result or are often not competitive (Henderick and Williams, 2000).

9. This is about half the total residue generation rate. The rest is used for paper-making, forage, or returned to the fields to sustain soil quality (Li, Bai, and Overend, 1998).

10. This case is based on Dai and Lu (1998), Dai and Sun (1998), and Dai, Liu, and Lu (1998).

11. The market price for LPG in the village is 3.3 yuan per kilogram ($8.30 per gigajoule).

12. It is assumed that villagers are paid $0.33 a gigajoule for residues delivered to the conversion facility. It is also assumed that gas is sold for $6 a gigajoule (somewhat less than the LPG price) and hot water is sold for $5 a gigajoule (lower than the gas price to discourage gas burning for heat), and that electricity is sold to villagers for $0.10 a kilowatt-hour (the price they would otherwise pay for grid electricity) and to the grid for $0.05 a kilowatt-hour.

13. Demonstration projects include a Global Environment Facility–sponsored, 30-megawatt-electric IGCC project in northeast Brazil (chapter 7).

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