Chapter 7

Energy Resources and Supplies

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INTRODUCTION AND SUMMARY

Developing countries are projected to require substantial increases in primary[1] energy supplies. The World Energy Conference predicts that with an annual economic expansion of 4.4 percent, the developing countries will require more than a three-fold increase in commercial energy supply by 2020.[2] An increase on this scale raises issues of the availability of financial resources, the extent of the domestic energy resource base, and the environmental impacts of rapidly expanding energy production.

Attention has already been drawn to the large investments in the electricity sector. Roughly similar amounts are invested in fossil fuel production, mainly oil and gas. As in electricity, much of the investment is in the form of foreign exchange, though unlike electricity, private foreign investment plays a much greater role. In addition to investments in domestic energy production, developing countries also incur large foreign exchange costs for imported energy, in some cases accounting for 40 percent and more of total export earnings. As consumption continues to rise, import dependence could rise, or in the case of exporting countries, the export surplus could disappear.[3]

These considerations focus particular attention on technologies that could develop domestic energy resources, while minimizing the environmental impacts of rising domestic energy production. Coal, already the largest single source of fossil fuels in the developing countries, presents both opportunities and problems. Coal resources are much more abundant than are oil and gas, though coal is widely used in relatively few developing countries—notably India, China, and South Korea. As these countries are among the biggest energy consumers of the developing world, coal accounts for almost one-third of total developing-country energy consumption. Many other countries in Asia, Africa, and Latin America also have significant proved or probable coal reserves.

In addition to its abundance, coal has other advantages. Per unit of heat value, coal is cheaper than oil and, in most cases, gas. Coal is a familiar fuel with a long established technology. Finally, coal mine capital costs are low and in many countries have a high content of locally manufactured goods and services.

At the same time, coal suffers from serious disadvantages. As a solid fuel it is difficult to handle and transport, and is less versatile than oil. Its variable and frequently poor quality discourages the use of advanced combustion technologies and may contribute to poor power plant performance. There are also significant environmental drawbacks to all phases of coal production, from mining to combustion. Mining operations can cause local air and water pollution and are associated with severe occupational health hazards. Coal combustion results in large amounts of solid wastes and airborne pollutants, including acid rain precursors and the greenhouse gas, carbon dioxide. Carbon dioxide emissions from coal are higher per unit energy than those from other fuels so that the projected rapid expansion in coal use will contribute to high levels of greenhouse gas emissions.

Technologies exist to mitigate at least some of these problems. The introduction of mechanized open cast and longwall mining into those parts of the still unmechanized Indian and Chinese industries could improve productivity, reduce occupational hazards, and reduce incombustible waste. The simplest coal cleaning techniques (physically removing impurities such as dirt and stones) could result in

[1] The term "primary energy" includes fossil fuels (such as coal, crude oil, gas) and biomass in their crude or raw state before processing into a form suitable for usc by consumers. The term also includes electricity generated by geothermal, wind and solar resources, and nuclear power. Electricity generated from fossil fuels or biomass is not included in primary energy to avoid double counting.

[2] World Energy Conference, *Global Energy: Perspectives 2000-2020,* Conservation and Studies Committee 14th Congress Montreal 1988 (London, England: World Energy Conference, 1988), tables 3 and 5.

[3] According to one study of 15 major energy consuming developing countries, if the trends of the 1980s and 1990s continued into the future, oil import dependence in the five oil importing countries would reach around 88 percent of the total oil needs by 2010 (compared with 37 percent in 1988) and three oil exporting developing countries could become oil importers (Mudassar Imran and P. Barnes, *Energy Demand in the Developing Countries: Prospects for the Future,* World Bank Staff Commodity Working Paper No. 23 (Washington, DC: World Bark 1990).

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important benefits such as reduced airborne particulate, lower transport cost, increased plant availability, and the use of higher performance coal burning equipment.

Despite the promising resource situation, there exist several obstacles to the further development of coal in many of the developing countries. In many cases, governments (especially in countries without domestic resources) give coal a low priority, preferring other forms of energy. Both China and India are exceptions; with well established industries, they are committed to a rapid expansion in output (doubling by 2010). Shortages of capital, the ready availability of low-cost labor, and other factors, however, may deter the introduction of improved production technologies. Finally, global climate change negotiations may ultimately limit the use of coal due to its high level of carbon dioxide emissions per unit energy.

The United States is a leader in coal production and combustion technologies. Recognizing these opportunities, the U.S. Department of Energy (DOE) has established programs to explore export opportunities for American coal-based technologies in developing countries.

For most of the developing countries (India and China are the major exceptions), oil is the mainstay of their commercial energy supplies, accounting for about two-thirds of the total. Oil is easy to transport and versatile in use in all sectors, at all scales of operation. These qualities led to an average annual growth of 4.5 percent in oil consumption in the developing countries from 1971 through 1987. This growth is expected to continue at almost the same rate (4 percent) in the future. In the absence of sizable increases in domestic production, import dependence will rise sharply.

The developing world[4] possesses only limited crude oil reserves with a reserves/production ratio of 26 years, compared with a worldwide ratio of 43 years. These reserves are concentrated in a few countries; one-half of the developing countries do not have any discovered recoverable reserves. The industry consensus is that oil reserves likely to be proved in developing countries will be relatively small. Development of such fields, while traditionally not attractive to the major oil companies, is important for the developing countries themselves, especially the poorer ones.

A number of recent technical developments in oil exploration and development may reduce risks and costs, thus making small field development more attractive than before, particularly for smaller oil companies. These technologies include 3-D seismic modeling, advanced drill bits, slim hole drilling, directional drilling, and innovations in offshore production. These technologies could also benefit exploration for gas, a relatively undeveloped resource.[5] Many developing countries, including several poor sub-Saharan African countries,[6] have significant natural gas reserves, and the number of nations with proven gas resources is following an upward trend.

Despite promising geological prospects, the degree of exploration activity (density of wells drilled) in the developing countries is much lower than the world average, and is concentrated in countries where resources have already been developed. In the developing world, investment in petroleum exploration and development is carried out (with the exception of a few, large-population, countries) almost exclusively by international oil companies. Thus the fiscal and contractual arrangements between country and company are important in providing the appropriate incentives. These incentives have traditionally been biased in favor of large, low cost rather than small, higher cost fields. Gas development faces additional obstacles. Unlike oil, markets have to be developed simultaneously with the resource, thus adding to the start-up costs and complexity of gas projects. Moreover, gas sold in local markets does not directly generate the foreign exchange needed to repatriate profits to foreign investors.

Efforts are already being made to overcome some of these obstacles. The multilateral development banks, notably the World Bank, finance preinvestment studies, help countries towards agreements with foreign investors, and encourage the development of fiscal systems and financial agreements

[4] The definition of "developing world" (see ch. 2) includes several OPEC countries but not the high income organization of Petroleum Exporting Countries (OPEC) members, such as Saudi Arabia.

[5] The gas reserves/production ratio for the developing world is about 88 years, which is significantly higher than the 32.4 years for crude oil,

[6] Mozambique, Ethiopia, Somalia, Madagascar, Côte d'Ivoire, Equatorial Guinea, Sudan, Senegal, Tanzania, and Namibia.

recognizing the special characteristics of gas. Given the importance of oil and the great potential of gas, ' there is room for further extension of such programs.

For the longer term, renewable forms of energy offer the potential for sustainable, domestically produced energy supplies. As discussed in chapter 6, extensive hydro, wind, solar, and geothermal resources are present in many countries, and indeed are particularly abundant in some of the poorest. Chapter 6 also showed that there are opportunities to convert biomass fuels into modern efficient energy carriers. The question here is to what extent the feed stock for a modern biomass conversion industry can be supplied at a competitive price on a truly sustainable basis, without major adverse environmental and social impacts.

Developing countries have the potential to greatly improve utilization of their biomass energy resources. Large scale use of modern biomass energy technologies could have major advantages for developing countries, and for the world. If produced on a sustainable basis, biomass would not add to net greenhouse gas emissions. If substituted for fossil fuels, sustainably grown biomass could actually decrease greenhouse gas emissions as well as improve local environments through reduced emissions of SO_2 and NO_x. As an indigenous resource, biomass could reduce energy import dependence and stimulate rural development.

In practical terms, there are several obstacles to the development of dependable and large scale biomass supplies for a modern biomass industry. Data on the extent of forest area and the annual increment of forest growth are sparse and unreliable, creating uncertainty over how much biomass can be produced and collected. There is also uncertainty over costs; current estimates suggest that woody biomass could be available at the competitive price of $2 per gigajoule (GJ) ($1.90 per million British thermal units (BTUs)), but this estimate will be subject to wide local variations. The basic incentives to growing biomass, however, are often absent. Improvements in forest management are notoriously difficult to achieve, and the introduction of high yield field crops will require long term sustained efforts. The long term environmental impacts of sylvan monoculture and high yield crops are unknown.

There are also difficulties setting up a large scale commercial biomass feedstock industry in rural areas with inadequate infrastructure, especially when national pricing policies often favor established energy supply industries. Meshing a commercial biomass industry with the current, largely noncommercial usage of biomass could raise problems of access to traditional fuel supplies by the poor and issues of equity between Landholders and the landless. In many developing countries, energy plantations might compete with food crops for limited land resources, particularly as populations continue to grow. Existing biomass resources (dung, agricultural residues) may have important uses other than fuel, including livestock feed, fiber, and fertilizer. Any diversion of land or resources could adversely affect the poor, through decreased availability of food and previously "free" fuel, fodder, fiber, and fertilizer,

In the technical arena, several advances have been made in improving plant productivity in recent years. Physiological knowledge of plant growth processes have improved, particularly through biotechnology. These and other efforts have identified and developed fast growing species. Planting methods, such as intercropping, have also improved. Successful experiments with crop residue densification have increased energy content, reducing transport and handling costs. The United States has contributed to these and other technology improvements through experimental trials funded by the U.S. Department of Energy and the U.S. Department of Agriculture, and has unrivaled experience with agricultural extension. Many institutional issues and uncertainties will have to be addressed, however, before large scale biomass feedstock supplies can be developed beyond existing agricultural and forestry residues.

The most promising innovations for biomass resources have been in waste-to-energy technologies. Agricultural and industrial wastes, such as sugar cane residues (bagasse, etc.) and sawdust, are readily available energy resources in developing countries. Many developing countries do not now use these resources, or use them inefficiently.

OIL AND GAS SUPPLY

For most of the developing countries (India and China are the major exceptions), oil is the mainstay of their commercial energy supplies, accounting for about two-thirds of the total. Oil is easy to transport and versatile in use in all sectors and at all scales of operation. These qualities led to an average annual growth of 4.5 percent in oil consumption in the developing countries from 1971 through 1987. Projections of energy consumption in the developing countries[7] foresee a continuation of this rapid rise, though at a slightly lower rate—about 4 percent. Domestic production of oil in the developing countries is projected to stabilize or even decline, so that the level of imports rises sharply. For five major oil importing countries (Brazil, India, Pakistan, Philippines, and Thailand) oil import dependence is projected to rise from 37 percent now to over 80 percent by 2010. Over the same time period, a group of oil exporting developing countries (China, Indonesia, Malaysia) could become net importers.

Such developments would impose severe strains on the foreign exchange budgets of these countries. Half of the oil-importing developing countries already must import over three-quarters of their commercial energy requirements in the form of petroleum products.[8] For many of the poor African countries, foreign exchange budgets are already strained by oil imports, which account in several cases for 50 percent and more of total foreign exchange earnings.

This imbalance between projected consumption and production underlines the need for improving energy efficiencies, and the substitution of other cheaper fuels for oil where possible. The imbalance also suggests that opportunities to increase domestic production of oil, gas, and other fuels should be pursued. Many of the developing countries have under-utilized known reserves of oil and natural gas. Recovery of these reserves and resources could bring in foreign exchange through exports, or could supply domestic energy markets. Many factors are involved in the successful exploration, production, and marketing of oil (and even more with gas). These include the size and nature of the resource base, the availability of suitable technology to develop these resources, and the complex institutional factors that determine the incentives for investors to engage in oil and gas development.

Oil and Gas Reserves

The starting point is the resource base.[9] The world's proved recoverable crude oil reserves[10] total approximately 932 billion barrels (see table 7-l). The Middle East accounts for two-thirds of the total. Outside the Middle East, the former Soviet Union has the largest share-about 80 billion barrels. The developing world possesses only 17.5 percent of world crude oil reserves. About half of these are in Latin America of which three-quarters is in just two countries, Mexico and Venezuela; the other half is divided almost equally between Asia and Africa. Only one-half of the developing countries have discovered recoverable reserves.

Assuming a static rate of production and discovery, and of population growth, the developing world has a reserves/production ratio of 26 years, com-

7Mudassar Imran and Philip Barnes, Op. cit., footnote 3.

'T. Gorton, "Petroleum in the Developing World," contractor report prepared for the Office of Technology Assessment, July 1990, p. 1.

9The estimation of hydrocarbon reserves involves more than a geologically based analysis of the original or remaining hydrocarbon endowment. While the amount of oil originally generated or thought to have been trapped and potentially available is scientific question (though still subject to differences of opinion), there are additional factors involved in assessing actual reserves: how much oil and gas has actually been proven to exist at the present time? How much is economically producible (that is, the value of the production brought to market exceeds the costs of producing and transporting it)? At what point will discovered but currently uneconomic reserves become viable, if ever? These nongeological factors include the price that reserves produced in the middle to distant future will fetch, and even the uses to which it will be put and the political relations along the spectrum of producers and consumers. There are a multitude of uncertainties in estimates of the petroleum resource base.

10*Proved recoverable reserves* are defined by the Society of Petroleum Engineers as follows. Proved reserves can be estimated with reasonable certainty to be recoverable under current economic conditions. Current economic conditions include prices and costs prevailing at the time of the estimate. Proved reserves may be developed or undeveloped. In general, reserves are considered proved if commercial producibility of the reservoir is supported by actual production or formation tests. The term proved refers to the estimated volume of reserves and not just to the productivity of the well or reservoir. The salient points in this definition are the word "reasonable' applied to the certainty required; and the criterion of 'current economic conditions. ' This recognizes the fact that certainty is unattainable in this endeavor, and that reserves will not be counted if they are not economic to produce *at the present time.* Discovered reserves that are expected to become economic under the market conditions they expect to prevail at a given time in the *future are* not included; besides most of the shale oil, tar sands, and deep offshore oil (which may or may not be exploited even under future high-price scenarios), this excludes reserves closer to viability such as the Orinoco Heavy Oil Belt in Venezuela. While this is a restrictive definition in some respects, it has the advantage of economic realism at least over the next 30 years or so.

Table 7-l—World Oil and Natural Gas Resources

	Proved oil reserves		Proved gas reserves	
	Billion barrels	Percent share of world	Trillion cubic feet	Percent share of world
World	932	100	3,997	100
Developing countries	163	17	727	18
Latin America	(81)	(9)	(240)	(6)
Asia	(40)	(4)	(247)	(6)
Africa	(42)	(4)	(240)	(6)

SOURCE: T. Gorton, "Oil and Gas Development in Developing Countries," OTA contractor report, 1991.

pared with a worldwide ratio of 43 years.[11] There are wide variations among developing countries: Mexico is expected to produce oil at current rates for another 35 years (though there is much controversy over South American reserves in general and Mexican ones in particular), while Pakistan will exhaust current reserves in 9 years, Cameroon in 8, Gabon in 12, and Peru in 7 years.

Estimates of world oil reserves change over time as new reserves are discovered or reevaluated. According to the World Energy Conference, as well as other authoritative current estimates, global proved reserves have been revised upward by 32 percent over the past 3 years,[12] due to successful exploration and exploitation activities.[13] Decreases in drilling and other oilfield costs over the past 5 or 6 years also have led to reserve increases. In so far as future developments in technology (see below) lead to lower exploration and drilling costs, reserves will further increase. The industry consensus is that oil reserves likely to be proved in developing countries will be relatively small in size. Although such fields may not add much to the overall global supply, they are very important to the developing countries themselves.

While gas is a fuel and feedstock that in many ways is as useful as crude oil, it is relatively undeveloped. Worldwide proved reserves of natural gas amount to some 4,000 trillion cubic feet (TCF), providing 1988 production of about 67 TCF per year.[14] At those rates, the world's natural gas reserves will last for 60 years, about half again as long as global proved crude oil reserves. The developing nations account for 18 percent of global raw natural gas reserves, but only 13 percent of global natural gas consumption. This suggests that these countries are not taking full advantage of their endowment of natural gas resources. The reserves/production ratio for the developing world is about 88 years, which is significantly higher than the 32.4 years for crude oil in these countries.

At least 52 developing countries have significant natural gas reserves (about 10 more than the number of nations that possess oil reserves). Several poor sub-Saharan African countries that are greatly in need of additional energy supplies contain undeveloped gasfields: Mozambique, Ethiopia, Somalia, Madagascar, Cote d'Ivoire, Equatorial Guinea, Sudan, Senegal, Tanzania, and Namibia. Furthermore, the number of nations with discovered reserves has

[11] It Should be kept in mind here, as for the discussion on Natural Gas reserves below, that the definition of reserves does not include undiscovered resources or growth of existing fields through investment or reevaluation. This figure is also distorted by the enormous reserve ''overhang' from Middle East OPEC countries (with an average oil reserve/production ratio of over 100 years even by conservative estimation). This figure also obscures that the position of the industrialized oil producers is much further along the decline-and-depletion curve.

[12] World Energy Conference, op cit., footnote 2, p. 35.

[13] In the mid-1970s, the non-OPEC developing nation Oman, for example, was expecting its production to level off at about 330,000 barrels per day (b/d) In 1977 and decline to depletion within 5 years Production is now currently over 600,000 b/d and holding steady.

[14] These figures do not include '' natural gas liquids'' (NGLs) or liquid hydrocarbons which, though generally gaseous under original reservoir conditions of temperature and pressure, may be separated or extracted from the gas at the wellhead and produced as condensate (also called ''natural gasoline'') and liquefied petroleum gas (LPG), the latter referring to butane and propane fractions that arc separated from condensate and sold in bottled form as fuel. Though NGLs share many of the uses and economic properties of crude oil, NGLs arc generally considered together with natural gas reserves (of which they are a constituent part in the reservoir) for the purposes of global or national energy supply analysis. This is defensible because all the economic properties of NGLs produced from a given gas field arc determined by the general reservoir and other parameters of that field, so that the ''wetness' or richness m NGLs of a given gas field is best treated as part of the quality description of the gas field rather than as a separate resource. For project-specific economic analysis, however, the NGL production stream is always given separate treatment because it is generally marketed very differently from the ' 'dry' gas left over after (he liquids have been removed. Worldwide NGL reserves total about 65 billion barrels.

followed an upward trend. While only 40 nations of the world claimed to possess natural gas resources in 1960, 85 countries claimed natural gas reserves by 1987.[15] Some observers have noted that natural gas reserves in developing nations are underestimated because the majority of discoveries have been a by-product of the search for crude oil. There has been little exploration for gas itself. The opportunities for discovering non-associated gas in the developing world have yet to be fully explored,[16] especially as gas costs are competitive and expected to remain so.[17] In the developing nations, a significant amount of natural gas is lost through flaring processes; in 1975, 80 percent of all natural gas produced in oil producing developing nations was flared.[18] In Nigeria, 97 percent of natural gas is currently flared.

Aside from its relative abundance and competitive costs, gas also is attractive for its environmental considerations. While coal produces 25 kilograms (kg) of carbon per GJ (this number is a weighted average of industry and utility), oil produces 19 kg of carbon, and natural gas only 13.6 kg.

However, geologic promise is not a sufficient condition for investment in exploration activity .19 Whether such promises lead to exploration and production depends on a number of factors, including developments in technology and economic incentives.

Oil and Gas Exploration and Production Technologies

In the developing world, investment in petroleum exploration and development is carried out (with a few exceptions) by international oil companies, many of which are American. American companies are, therefore, key players in determining the type of oil and gas supply technologies used. At the same time, the developing countries offer a major market for U.S. hydrocarbon development services.

The two major and complementary components of exploration for oil and gas are characterization and exploration drilling. Characterizing a reservoir helps to determine the best area to drill, and material uncovered by exploratory drilling helps characterize in detail the subsurface.

Drilling can be the most expensive component of exploration and development, costing anywhere from 15 to 40 percent of offshore development costs, and as much as 80 percent of the less expensive land development costs.[20] Disposal of wastes accounts for a portion of these costs. Exploration and production activities produce brine, drilling muds-a combination of water, clay, and various chemicals—and rock cuttings that must be discarded. There may be as much as 50 tons of mud to dispose of by the time a well is completed.[21] Offshore, these muds are generally discharged into the surrounding waters.[22] Onshore, the mud wastes are disposed of on land or through reinfection processes. Land disposal of wastes has to be managed carefully to avoid contamination of ground and surface waters.

Technological advances have decreased the high costs and mitigated the environmental problems associated with exploration and drilling. These exploration technologies are applicable to developing countries and are already used in some places. United States companies enjoy the technological lead in this area, particularly in identifying smaller reservoirs.[23]

Characterization technologies consist of compiling and analyzing geological and geophysical infor-

15World Energy conference, ***Survey** of World Resources 1989, p.* **61**

16Afsaneh Mashayekhi *''Nawal* **Gas Supply and Demand in Less Developed Counties, "** ***Annual** Review of Energy,* **vol. 13, 1988, p, 122**

17Ibid.

18Jae Edmonds and John M. Reilly, *Global Energy: Assessing the Future* (New York: Oxford University press, 1985).

19See discussion in Harry G. Broadman "Determinants of Oil Exploration and Development in Non-OPEC Developing Countries, ' Discussion Paper D-1 14, Resources for the Future, 1983, and "An Econometric Analysis of the Determinants of Exploration for Petroleum Outside North America," unpublished manuscript.

20Shell Briefing Service, Producing *Oil and Gas* (London: Group Public Affairs, Shell International Petroleum Company, Ltd. 1989), p. 2.

21United Nations Department of Technical Cooperation for Development, Energy *and Environment: Impacts and Controls* (New York, NY: October 1990), p. 15.

22U.S. Department of Energy, Assistant Secretary for the Environment, Office of Technology Impacts, *Environmental Data Energy Technology Characterizations: Petroleum,* April 1980, p. 1-9, 1-10.

23RCG/Hagler, Bailly, Inc., Washington, DC, "U.S. Exports of Oil and Gas Exploration and Production Equipment and Services, " a draft paper prepared for the Agency for International Development Office of Energy, 1990, p. 6.

mation on a given reservoir. Characterization enhances three important stages of exploration. In the first stage, specialists choose the location for "appraisal wells" (wells that define a reservoir and provide data for more detailed characterization). In the second, they perform the detailed geological characterization and analysis, including the likelihood of finding a commercially viable well. And finally, if hydrocarbons are found, they assess the properties of the reservoir that will affect production.

Advances in these three stages of geophysical research greatly enhance the likelihood of successful drilling. The costs of this sophisticated research have declined so that these technologies increasingly are used worldwide.[24] Lowered costs may allow marginal or small fields, often found in developing countries, to be economically viable. In addition, detailed knowledge of a reservoir before production can lessen negative environmental impacts, including contamination of subsurface water supplies.

The principle characterization tool in the three stages of exploration is Computer-Aided Exploration and Development (CAEX), also called 3-dimensional seismic modeling. 3-D seismic modeling is based on information on regional and reservoir geology, as well as material samples from a particular site. Petrophysical studies provide data on types, porosity, hydrocarbon saturation, permeability and capillary pressure of the reservoir rock, as well as on the nature of trapped hydrocarbons.[25] A detailed analysis of extremely small fossils, found on the surface or in wells, helps identify precise rock intervals and ages. Geochemical tests are used to predict the existence and thermal maturation qualities of rocks that may hold oil.[26]

The 3-D seismic studies take this geophysical and geological data, process them on a minicomputer, and turn the data into ''reservoir maps. ' The maps describe the "trends in sand quality, structural properties, and tectonic history" of an area, providing a 3-D picture of the reservoir.[27] A second "reservoir simulation" model, derived from the geological model, tests and forecasts the production performance of a reservoir. Although the simulation model usually requires computers that may not be widely available to developing countries, other stages of characterization are within reach. In addition, material left-over from older, ' 'unsuccessful" drilling can be used in the analysis, expanding the knowledge base of a reservoir without the expense of acquiring new raw data.[28]

The oil business is almost by definition a risky one. No matter how sophisticated the techniques for evaluating the possibility of a find, the final answer can only come through the expensive process of drilling a well. Worldwide, about 9 out of 10 exploratory wells are dry or recover only subcommercial quantities or qualities of hydrocarbons. Improved drilling technologies, by reducing the element of risk, can enhance the discovery of commercially viable oil and gas wells. Exploration drilling has especially benefited from advanced drill bits, slim hole drilling, directional drilling, and measurements-while-drilling.

- *Advanced drill bits. Drills* must be sharp and durable to cut through rock, and they must also carry the rock cuttings and drilling muds out of the well to the surface. A sharp drill bit allows a high penetration rate, and a faster drilling process. Drill bit durability also speeds the process by cutting the number of times drilling must stop for replacement of worn bits. In the past, there was a trade-off between durability and sharpness, but advanced drill bits allow for both, decreasing overall drilling time and costs. American companies have the technological lead in advanced drill bits.[29]
- *Slim hole drilling.* A simple and highly cost-effective drilling technology is slim hole drilling. Reducing the size of a bore hole reduces the costs of drilling a well for exploration or production by up to 50 percent.[30] Bore holes are lined with heavy steel pipes, which are cemented into place to prevent collapse or con-

[24] Gorton, op. cit., footnote 8, p. 11.

[25] Shell Briefing Service, op. cit., footnote 20, p. 1.

[26] Gorton, op. cit., footnote 8, p. 11.

[27] Shell Briefing Service, op. cit., footnote 20, p. 1.

[28] Gorton, op. cit. footnote 8, p. 11.

[29] RCG/Hagler, Bailly, Inc., op. cit., footnote 23, p. 8.

[30] Shell Briefing Service, op. cit., footnote 20, p. 2.

tamination from surrounding fluids. Both the process and materials can be costly, and a smaller hole cuts costs. Although some of the detritus brought up out of a bore hole is analyzed, much is waste. Slim hole drilling is environmentally desirable as it reduces the amount of waste muds and rock cuttings-as much as 70 percent. Characterization information can be used to determine the smallest hole that can be drilled without compromising effectiveness in gathering core material or conveying gas and oil.

- *Directional drilling. In the* past, drilling was only vertical, chiefly leading to the discovery of deposits oriented along the vertical bore hole. Some deposits, however, deviate from the vertical pattern. New drilling technologies allow for flexible directional or horizontal drilling, which allows the drill to probe horizontally into previously inaccessible wells. Directional drilling is already being used in developing countries. For example, the American company Amoco extensively used horizontal drilling offshore in China in 1989.[31]

In exploratory drilling, whether exploring for appraisal or for an actual deposit, constant measurements are necessary. The angle, depth, and diameter of the bore hole must be monitored, mostly by tracking the position of the bit.[32] Information on the condition at the far end of the hole also needs to be measured. Conventionally, drilling is periodically halted and directional surveys and wireline logging (lowering special measuring instruments into the drill hole) are used to determine when drilling is complete. A new technology for this process is ‘ ‘measurement-while-drilling. With this technology, the measurement instruments are incorporated into the drill above the bit, transmitting information to the surface while the drill is in operation. Measurement-while-drilling (MWD) allows for continuous drilling, which saves money, and provides more information than conventional wireline logging, MWD can provide detailed directional surveys and data on the environment surrounding the drill, including electrical resistivity, density, natural gamma ray radiation, and porosity .33

Drilling technologies benefit exploration, but in many cases, they also benefit production. Directional drilling is a particularly useful new technology for recovering oil and gas. When a bore hole passes through a deposit, oil or gas flows through a perforated casing at the bottom of the pipe. Conventional vertical drilling may bypass horizontally deposited wells, causing only a small amount of the deposit to flow through the perforations. Such fields are therefore abandoned. If further recovery is attempted with the conventional technology, numerous vertical bore holes have to be drilled, driving up production expenses and increasing environmental risks. With directional drilling, however, these horizontal deposits can be recovered by drilling one well, making previously unproductive fields more accessible and attractive.

For offshore production, extended-reach wells are drilled diagonally from a platform, allowing access to a larger area than vertical drilling allows. Ocean platforms are expensive to construct and maintain, especially in deep water. Extended-reach can cut costs by reducing the number of platform installments required for one field.[34]

A key stage in the production process is recovery, or drawing the deposit from underground to the surface. Oil and gas will flow from a reservoir at varying rates, depending on the environment around the deposit and the bore hole. An ideal reservoir environment would include: a fairly simple layout that enables easy drilling access to the deposit; highly permeable rock; crude oil or gas with low viscosity; and natural pressure in the reservoir exceeding that in the bore hole.[35]

In such an ideal case, oil or gas can flow unaided to the surface. This ‘‘primary recovery’ involves natural drive mechanisms, naturally occurring factors that help push oil and gas upward. Such mechanisms ‘‘account for more oil production than all other recovery methods combined.”[36] In order for gas or oil to flow into the bore, the pressure in the

[31] Gorton, op. cit., footnote 8, p. 11.

[32] RCG/Hagler, Bailly, Inc., op. cit., footnote 23, p. 7.

[33] Shell Briefing Service, op. cit., footnote 20, p. 2.

[34] RCG/Hagler, Bailly, Inc., op. cit., footnote 23, p. 7.

[35] Shell Briefing Service, op. Cit., footnote 20, p. 4.

[36] Ibid.

surrounding rock must be more than that in the bore. This natural drive can be enhanced by artificial lift, which consists of reinfecting gas into the oil flowing in the bore. Injecting gas enhances the pressure in the reservoir, reducing the amount of natural drive needed for an upward flow.

Well-stimulation technologies, such as fracture stimulation and matrix stimulation, by improving the permeability of the reservoir rock, also enhance drive. Fracture stimulation involves actually cracking the rock by forcing fluid into the well at high pressures, The cracks are propped open with a fine sand, keeping the channels to the well open when the applied pressure is released.[37] Matrix stimulation involves injecting a chemical solution into the rock to dissolve any material blocking the pores. Fracture stimulation is very expensive, and both techniques must be applied carefully to avoid environmental damage.

Many oil and gas fields in developing countries do not have ideal conditions, A "tight' or less than ideal reservoir may require extra energy to move the hydrocarbons to the surface. A growing proportion of the world's oil supply, particularly in the developing countries, comes from such ' 'tight' reservoirs .38 Conditions also become tight in older reservoirs, as natural drive flags. A deposit extracted in these cases is considered a ''secondary recovery. ' '[39] Although the oil industry has the know-how to make a tight reservoir more productive, these technologies are not often applied in developing countries, for economic rather than technical reasons.[40]

Secondary or enhanced oil recovery technologies include thermal, gas, chemical, and microbial methods. Thermal oil recovery is the most common, and has been used in some developing countries. In some fields, the crude oil can be too viscous to flow out of the rock formation. Steam or hot water can be injected down the well, and the heat will decrease oil viscosity and increase the flow rate. The gas method is used when medium or light viscosity oil gets trapped in pores during oil flows. The injection of a gas into the bore can displace the residual oil, and move it upward. Enriched hydrocarbon gas, carbon dioxide, and nitrogen have all been used.

Chemical enhanced oil recovery is less common. The natural drive mechanisms begin moving oil when a well is drilled; underlying water displaces the oil, providing the drive upward. A gas cap lying above the oil may similarly force the oil upward in the well. When entrained water is not providing enough natural pressure (in an old well, for example), chemicals can be added. The chemicals modify the water, changing the way the oil is displaced and moved through the reservoir rock, These chemical methods are technically difficult to execute, and can be especially threatening to the subsurface environment.[41]

Although the United States leads in enhanced oil recovery technologies, low oil prices have limited the market for such techniques. In some cases, however, foreign projects have been led by foreign companies. For example, steamflood enhanced recovery in Venezuela is operated by the Venezuelan companies Lagoven, Maraven, and Corpoven.[42]

Offshore Production

Since the construction of the first offshore platform in 1947, offshore oil production has come to account for a growing share of world production, A number of innovations are lowering the costs and difficulties of offshore production, and the United States has the lead in most of these technologies.[43] There are offshore fields in many developing countries, and in particular, Brazil and Mexico have used new technologies.

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[37] Ibid.

[38] Ibid.

[39] The distinction between primary and secondary recovery is not always clearcut. For example, artificial lift and well stimulation are sometimes considered technologies for secondary recovery.

[40] Gorton, op. cit., footnote 8, p. 13.

[41] There are other less common techniques, Microbial technologies are still in the laboratory stage, though there may be some limited field testing. This method consists of rejecting microbes into the reservoir. These microbes generate carbon dioxide vapor pressure that forces the oil out. This technology could be difficult in practice as conditions in reservoirs—no air and the presence of metals—are hostile to microbes. There is no evidence to date to suggest that this could be done cost effectively. Another enhanced recovery technology that is not widely used is in situ combustion. Similar to the thermal technologies, this involves burning some of the oil in the reservoir to generate heat and decrease the viscosity of heavy crude. One method for doing this is to inject air underground, causing the combustion of a small amount of the oil.

[42] RCG/Hagler, Bailly, Inc., op. cit., footnote 23, p. 9.

[43] The United States does not have a technological lead in multiphase pumping. RCG/Hagler, Bailly, Inc., op. cit., footnote 23, p. 11.

Conventional offshore technologies can be very expensive, especially in deep or rough water. Traditionally, offshore production has required the installation of permanent platforms with heavy equipment and crew accommodations. Vertical drilling brings up deposits of oil, mixed with the gas and other liquids often found in association with oil. Oil has to be separated on the platform and then pumped through underwater pipes back to shore for further refining. Undersea maintenance of the platforms also is costly. Wastes from offshore drilling, including residual oil, are often dumped back into the ocean. There is some evidence that drilling and production waste may be harmful to aquatic life. Oil leaking and spilling from these operations makes up about 10 percent of all oceanic oil pollution.[44]

Almost all aspects of offshore production have been affected by recent innovations. In some developing countries, production costs may be reduced by using tankers as floating storage for offshore production. This system is called ''single-point mooring. '' Single-point mooring may be especially valuable for the small or marginal fields that become unfeasible with the added costs of subsea pipelines. This system may, however, increase the likelihood of minor oil spills as oil is transferred from the platform to the ship.

Platforms no longer have to be rigid structures attached to the sea floor. Lighter platforms can float on the surface, held in place by cables fastened to the sea floor. This tension leg platform design with a simplified deck or ''topsides' reduces the cost and complexity of offshore production. Temporary drilling, also called jack-up rigs, packaged rigs, or semisubmersible tenders, are particularly cost-effective. Such rigs reduce capital costs by up to 25 percent, and operating costs by up to 40 percent.[45]

Staffing an ocean platform is expensive, and the work is difficult and involves risks. The introduction of lighter and less complex rigs allows for easier operation and maintenance. In addition, two technologies allow for automated platforms: remotely operated vehicles and multiphase pumping. Remotely operated vehicles are underwater maintenance robots that repair subsea pipes and valves. Multiphase pumping eliminates the need for crews to separate the oil from its accompanying liquids. Multiphase pumps can pump oil, gas, and other condensates back to land-based production facilities. With such pumps, small platforms can be located further from shore.[46]

Weather satellites can also lower the costs of offshore production. Strong ocean currents and inclement weather can halt drilling and maintenance programs. Advanced weather and ocean current forecasting can help prevent "downtime in drilling and production operations. ' '[47]

Natural Gas

Hydrocarbons that exist in a gaseous state at atmospheric conditions of temperature and pressure are called natural gas. While gas is in many ways as useful as crude oil, it is definitely the poor relation of the hydrocarbon family, with relatively low exploitation in the developing countries. Frequently, natural gas is discovered in connection with oil. In many developing countries, however, there is little production infrastructure for gas. Gas may then be burned off, or a well yielding gas maybe treated as a "dry hole. " The most significant technological change for developing countries may be developing the infrastructure for recovering and refining natural gas.

The high start-up costs of conventional gas production technologies have discouraged many developing countries from utilizing gas reserves. Imminent technological innovations may lower these costs, however. Characterization and exploration technologies as well as multiphase pumping already have contributed to lower costs. One technology that may encourage the use of gas is conversion of gas to electricity through combined-cycle or advanced steam injected gas turbines (see ch. 6). Conversion to electricity eliminates the need for expensive pipelines and can help turn resources into commercially viable reserves.

Natural gas liquids (NGLs) or liquid hydrocarbons, though generally gaseous under original reser-

[44]United Nations Department of Technical Cooperation for Development, *Environment and Energy: Impacts and Controls* (New York, NY: October 1990), p. 15.

[45]Shell Briefing Service, op. cit., footnote 20, p. 3.

[46]Ibid.

[47]RCG/Hagler, Bailly, Inc., op. cit., footnote 23, p. 11.

voir conditions of temperature and pressure, may be separated or extracted from the gas at the wellhead and produced as condensate (also called ‘‘natural gasoline’ ‘). Lower cost and smaller scale technology is becoming available for removing natural gas liquids from gas that was previously being flared or simply shut in. The presence of such liquids is of considerable economic importance to a domestic gas project as they can be sold as oil and thus generate foreign exchange earnings. Natural gas liquids can also be produced as liquefied petroleum gas (LPG) and sold in bottled form as fuel. Both natural gas liquids and liquefied petroleum gas can be used for conventional services such as heating and transportation. The Nigerian government is studying plans for a dramatic increase in liquefied petroleum gas supplies, and countries such as Equatorial Guinea, although with much more limited supply and market possibilities, also are investigating such possibilities.

There are a few projects in the United States for extracting coal-bed methane gas that could be applied in the developing world. This technology consists of drilling just above a coal bed and injecting a mix of water and gas into the well. The injection creates a cavity at the bottom of the well. Once the water is pumped out, methane flows in through a perforated casing that allows gas in while keeping coal out.[48] Currently, however, this technology is costly and is supported in the United States through special tax credits.

Whether burned as NGL or in a gaseous state, gas retains an important distinction from other hydrocarbons. Natural gas combustion releases less greenhouse gas, such as carbon dioxide, and less localized pollution than do crude oil and other fossil fuels. Natural gas will gain attention as a relatively clean fuel, since ‘‘environmental concerns are likely to be among the strongest influences acting on the oil and gas industry in the next decade. ’ ’[49]

Institutional Issues

Despite the geological promise for oil and gas discoveries in the developing countries, the density of wells drilled averages just 7 per 1,000 square miles in non-OPEC developing countries compared with a world average of 109.[50] Furthermore, within the developing countries, much of the exploration takes place in countries where resources already have been developed. One recent study of exploration by the international industry in the 66 Lome Convention countries (which constitute a representative sample of the African, Caribbean, and Pacific (ACP) countries) reported that exploration in ACP countries is almost wholly confined to countries already producing oil, particularly Nigeria, Cameroon, Congo, Gabon, Angola, and Trinidad.[51] Only 12 of the 66 countries studied had produced oil to date, and those 12 received all but a negligible amount of the total investment in seismic surveys and exploration drilling. Although they overlie extensive sedimentary basins, the ACP countries remain, with some notable exceptions, among the least explored countries.[52]

In the developing world, investment in petroleum exploration and development is carried out, with the exception of a few large-population countries like Mexico and Venezuela, by international oil companies. The cash and foreign exchange position of low-reserve developing countries does not lend itself to such capital-intensive high-technology and high-risk investments.

During the high-energy-price era of the mid-1970s and early 1980s, a number of developing countries with proven or potential hydrocarbon reserves formed or expanded national oil companies such as CEPE in Ecuador, YPF in Argentina, Braspetro in Brazil, Petronas in Malaysia, Pertamina in Indonesia, and NNPC in Nigeria. In the mid-1980s, however, increasing debt and general budgetary pressures led many of these governments to moderate their policies towards foreign investment. Algeria and Burma have invited the international industry to apply for exploration and production

[48] Hayes, Thomas, “Drillers Find Coalbeds Yield Gas and Profits, ” *The New York Times,* Dec. 26, 1990, p. D3.

[49] Shell Briefing Service, Op. Cit., P. 9.

[50] R. Vedavelli, *Petroleum and Gas in Non-Opec Developing Countries: 1976-1985, Staff* Working Paper No. 289 (Washington, DC: World Bank, 1978), p. 9.

[51] A. Fee, ‘‘Oil and Gas Exploration and Production in the ACP Countries,” *OPEC Review,* vol. XIII, *No. 2, summer* 1989, pp. 137-151.

[52] Ibid, p. 141.

rights, and Venezuela has begun to discuss the possibility of allowing foreign companies to form joint ventures for the implementation of secondary recovery schemes on some of the country more mature oilfields. Algeria has also expressed interest in similar schemes.

There are several factors affecting companies' decisions to invest. Oil is a risky business: no matter how sophisticated the techniques used, oil and gas can only be found by expensive drilling. In the long run, the value of a successful case must be large enough to accommodate the exploration risk and cost of roughly nine dry wells.

In addition to the technical risks there is a host of risks referred to as ' 'country, ' ' or political risk. These risks, which are not intrinsic to the oil business, include "war, riot, and civil commotion." Violent local turmoil can damage property, halt or disrupt operations, or threaten the safety of a company's employees. Nationalization can mean the sudden involuntary divestiture of the foreign assets of a corporation in favor of the local government. Private interests also are wary of "creeping nationalization, the gradual process of the host state exerting greater control over operations and extending its share of ownership and/or of profits.

There are dramatic examples of how "war, riot, and civil commotion' have disrupted oil and gas development. Chevron has been waiting since the early 1980s for the situation in southern Sudan to stabilize to begin the development of substantial oil reserves discovered there. Meanwhile, the nearly $1 billion invested to date by Chevron and former consortium members is immobilized. Exxon, Royal Dutch/Shell and others are similarly engaged in Chad. Instability in Mozambique has hindered exploration efforts in that country, and in neighboring landlocked Malawi. Operations in northern Somalia have been suspended pending stabilization of the situation there.

On the other hand there are several examples where development has continued throughout periods of instability. Chevron has been producing oil offshore at Angola's Cabinda enclave throughout the past decade of instability and guerrilla warfare. Nigeria's frequent coups d'etat have taken place without disturbing the activities of the numerous oil multinationals producing Nigeria's high quality crude oil. Though an oil company is likely to prefer a stable political situation over an unstable situation, one analysis concluded[53] that political risk has only a slight influence on decisions to engage in geophysical testing and exploratory drilling.

The other major factor in deciding to undertake investment in exploratory activities in developing countries is the economic incentive. Most modern legislative systems reserve the State's sovereignty over petroleum operations. Most governments, however, reserve the right to contract with foreign companies for exploration and production of petroleum. The contract also includes terms under which country and company will share the net income, or rent, of the project.

The concession agreement was the most common arrangement before and immediately following the Second World War. More recently, these agreements have given place to the production sharing agreement, which provides that hydrocarbons extracted by the private companies be shared with the government or the national oil company according to predetermined rates. Other countries, notably in Latin America, have adopted a third category of arrangement called the service contract, which specifies that the contractor will spend certain sums to explore and, if successful, develop and produce hydrocarbons. In return, he will recover his expenses plus some profit by means of a service fee, which is sometimes calculated as a percentage of costs incurred or as a percentage of production achieved.[54] Companies now generally prefer production-sharing when given the choice.

In the industrial oil-producing countries (e.g., the United Kingdom or Norway), taxation of petroleum activities is now almost wholly profit-related. Profit-related taxation has an important advantage for developing countries as it favors exploration for and development of small, high-cost, or otherwise marginal deposits—precisely the type of resource typical of oil-importing developing countries. As the investor does not begin paying a significant amount of tax or other consideration to the state until he has a positive cumulative cashflow (with allowance for

[53]Broadman, op. cit., footnote 19.

[54]The latter formula occurs mainly in the so-called "service contracts with risk,'' and the bottom-line economic difference between them and production-sharing agreements is negligible.

depreciation), he will have an incentive to develop almost any field that has economic value. Such a system could also be important to the increasing numbers of smaller independent oil companies, which seek low-cost licenses and smaller developments at lower costs than would the majors.

The measures currently used by most developing countries (royalties or flat proportions of gross production), however, bear no relation to profitability.[55] The effect of profitability-insensitive systems is to achieve higher effective tax rates from small or marginal fields than from large, profitable ones. As a result, small fields go undeveloped and declining fields are prematurely abandoned. This factor is all the more important as oil companies in general have little interest in pursuing the smaller end of the probability spectrum and tend to be willing to forgo the modest benefits to be derived from developing marginal accumulations.

The Special Characteristics of Gas

Despite the obvious advantages of gas, industry and lesser developed countries' (LDC) governments have found it difficult to take the steps necessary to bring about a significant increase in the development of gas reserves in countries not now consuming natural gas. There are a number of reasons for this low level of resource development:

- due to its physical characteristics, gas is expensive to transport, requiring high front-loaded capital investment (pipelines from producing to consuming regions, or costly facilities and tankers to liquefy and transport the gas internationally).
- whereas markets for oil are well developed, markets for gas have typically to be developed at the same time as the resource is developed, adding to the total costs and complexity of the project.
- the sale of the gas gives rise to revenues in local currency rather than foreign exchange, leaving investors uncertain about their ability to repatriate profits. This last difficulty is especially acute in the case of highly indebted developing countries, where the bulk of scarce hard currency is earmarked in advance for debt service.
- in many such countries, the fiscal/contractual terms under which the gas was discovered by foreign operators are inappropriate for the special characteristics of gas. As a result, companies tend to treat a gas discovery as a "dry hole' from their economic point of view.

Together, these factors lead many developing countries to import large quantities of crude or fuel oil to generate electricity, even though they possess reserves of natural gas that could do this more economically and with less harm to the global and local environment.

Policy ***options***

Exploration and production of oil and gas in developing countries involves several main factors, including resources, technological advances, contractual arrangements, and the special problems of gas development. There are a number of possibilities for stimulating or improving oil and gas development.

Oil companies are reluctant to engage in exploration in countries that do not now have production. Part of this reluctance may be based on lack of geological and other preliminary knowledge about the resource base. The World Bank has addressed this barrier by helping countries prepare prospectuses based on existing geological data and other relevant material, thereby saving prospective investors the time and expense of collecting such information. This could be particularly useful for small independents.

Some investors may shy away from developing countries due to nontechnical risks such as nationalization and currency conversion and transferability. Insurance against such risks can be obtained by U.S. investors from the Overseas Private Investment Corporation and from the Export-Import Bank through its agent, the Foreign Credit Insurance Association. The Multilateral Investment Guarantee Agency, a new World Bank unit, also offers investor insurance with fewer limitations on the nationality of the investor and the nature of the investment.

Contract/fiscal questions often have been contentious. There may be room for the development banks to act as impartial arbiters of disputes and to help countries not experienced in oil and gas negotiations to understand the issues so that they can work towards satisfactory, long term agreements.

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[55]A. Kemp, ''Petroleum Exploitation and Contract Terms in Developing Countries After the Oil Price Collapse,'' *Natural Resources Forum*, vol. 13, No. 2, May **1989, pp. 116-126.**

If gas can displace more expensive fuels or if there is potential for an export project, then a favorable environment for investors is especially important. Egypt, Tunisia, Pakistan and other countries have adopted improved fiscal systems that have brought about a dramatic increase in exploration specifically for gas. The lowest income countries and highly indebted countries will need to seek the assistance of the international aid donors in order to secure the "lumpy," front-end investments needed to develop gas fields. In 1989, the World Bank created a Natural Gas Unit to bring increased gas projects to developing countries through preinvestment support.

Ultimately, the problem lies in altering a well-established system to take account of new needs. In the oil and gas sector, the need for timely development of gas resources for local markets is foremost. Closer collaboration among energy firms, governments, national operating entities, and providers of finance and other services could facilitate the process.

COAL

Coal is the most abundant fossil fuel in the world. According to the United Nations, coal reserves are currently about 10 times as large in energy content as world oil and gas reserves combined.[56] Due to its abundance and relatively low price, coal is widely used in those countries with domestic coal reserves. Coal does have some drawbacks, however; it is expensive to transport, it cannot easily be converted to a liquid transport fuel,[57] and it is a major contributor to several environmental pollutants, including NO_x, SO_x, CO_2, and particulate. These pollutants have a deleterious effect on local and global environmental quality and on human health.

Due to its availability and low price, coal will continue to be widely used as a fuel in the near future. Currently, China and India-by far the largest coal producers in the developing world—produce and consume large amounts of relatively low quality coal. From 1983 to 1986, coal production in China and India increased on average about 6.6 and 7 percent a year respectively, higher than the world average annual production increase of about 4.1 percent over that same period. Rapid increases in production have been due to growing populations and lack of energy alternatives. Many other developing countries with coal reserves are facing similar circumstances, and projections show coal use in the developing world doubling over the next 30 years.

Table 7-2—Developing Countries With Significant Coal Reserves or Coal Consumption

Country	Proved reserves in place (million metric tons)	Consumption (PJ/year)
China	737,100	17,858
India	27,912	4,178
South Africa	115,530	3,111
Korea, DPR	2,300	1,457
South Korea	200	912
Brazil	3,088	395
Mexico	2,401	189
Viet Nam	312	147
Colombia	2,073	135
Zimbabwe	2,500	120
Indonesia	23,232	66
Mongolia	12,000	61
Chile	4,579	55
Swaziland	2,020	NA

Criteria for inclusion: Proved reserves in place of greater than 2,000 million metric tons, or consumption greater than 100 PJ/year. Proved reserves in place include anthracite, bituminous, sub-bituminous, and lignite.
NA = not available.

SOURCE: United Nations, 1986 *Energy Statistics Yearbook,* United Nations, New York, NY, 1988, pp. 58-85, 424-427.

Coal Reserves and Consumption in the Developing World

Coal reserves worldwide are quite concentrated, with just three countries-China, the former Soviet Union, and the United States-possessing about two-thirds of the world's coal.[58] In the developing countries, large coal reserves are found in China, India, Indonesia, and S. Africa, with the reserves of these four countries accounting for about 97 percent of developing-country proved recoverable reserves. Other developing countries with significant coal reserves include Mongolia, Chile, Brazil, Zimbabwe, Mexico, North Korea, Colombia, and Swaziland (see table 7-2). Coal consumption does not correlate directly with coal reserves, as some coun-

[56] United Nations, *1986 Energy Statistics* yearbook (New York, NY: United Nations, 1988), pp. 424-426. Proved reserves of anthracite, bituminous, sub-bituminous, and lignite.

[57] Coal liquefaction, widely used in S. Africa, converts coal into a liquid fuel which can be used for transport. This process is relatively expensive and complex.

[58] United Nations, *1986 Energy Statistics* yearbook, op. cit., footnote 56, pp. 424-426. Proved reserves of anthracite, bituminous, sub-bituminous, and lignite.

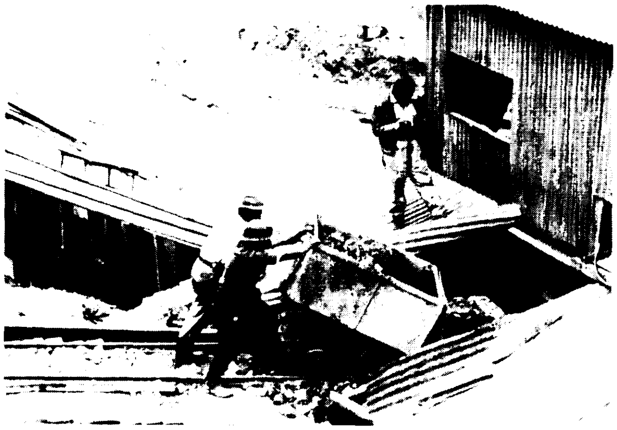

Photo credit: U.S. Agency for International Development

India and China account for most developing-country coal use, though several other countries have deposits.

tries with coal (e.g., Indonesia) have not so far developed it extensively. China, India, South Africa, North Korea, and South Korea are the largest coal consumers in the developing world.

Coal varies considerably in quality. Hard coal (anthracite) and soft coal (bituminous) have higher calorific values than lignite. While the Central African Republic, Ecuador, Ethiopia, Haiti, and Mali all possess coal resources, all has been identified as lignite. The seventh largest coal producer in the developing world, Thailand, only produces lignite coal. For many developing countries, therefore, other resources may be more attractive than coal, Brazil, for example, has substantial recoverable coal reserves, but produces a relatively small amount, Brazil's coal is low quality lignite, with little export potential. Moreover, for domestic use, Brazil has access to other high quality resources, such as oil and hydropower.

The relative importance of coal as a commercial energy source is shown in table 7-3. In China, India, and South Africa, coal is the single largest commercial energy source. Electricity generation and industry are typically the large coal users. In some countries, coal is also used in transportation. In South Africa, for example, coal liquefaction (a chemical process for turning coal into a liquid fuel) accounts for 21 percent of coal use. Liquefaction is too expensive and complex, however, to be a viable technology for most developing countries. In India and China, consumption by steam locomotives accounts for a substantial part of coal use. In China, the residential sector uses about 35 percent of China's coal (mostly for space heating and cooking).

Coal Production

As the bulk of coal use in the developing world occurs in India and China, this discussion focuses on coal production in these two countries. Coal mining and processing in China varies in scale and technological sophistication. Large, state-run mines account for about 44 percent of coal production. These mines are becoming mechanized rapidly—in 1981, 18 percent of these mines were fully mechanized, by 1988 this number had climbed to 31 percent.[59] The remaining 56 percent of China's coal comes from village and individual mines, which are typically small, labor-intensive, dangerous to work in, and environmentally damaging.

Coal mining affects land, air, and water quality. The extent of the environmental impacts depends largely on the mining techniques used, though in any case, fugitive dust emissions and leaching from tailings contribute to local air and water pollution. Mining methods are selected according to the depth of the coal, the thickness of the seams, and/or the availability of capital and equipment. The underground mining that accounts for about 95 percent of China's coal production can cause land subsidence and acid drainage, which can contaminate local water supplies and damage aquifers. In addition, underground mines involve hazardous conditions for miners.

China has plans to increase the relative share of surface mining. Surface mining can require the removal of large amounts of top soil and overburden, leading to soil erosion, siltation, and water contamination, In many cases, soil productivity permanently diminishes. The increase in surface mining planned in China could lead to an annual destruction of nearly 150,000 ha by the year 2000.[61] Fortunately, much of China's planned increase in mining is in

[59]Ministry of Energy, People's Republic of China, "Energy in China," 1989.

[60]Vaclav Smil, '<China's Energy, " contractor report prepared for the Office of Technology Assessment, 1990, p. 62,

[61]Ibid.

Table 7-3-Coal Use (1985)

Country	Coal as a percent of total commercial energy use	Coal use breakdown (percent)			
		Electric	Industry	Residential	Other
China	76.8	18	46	25	11
India	56.5	40	39	2	19
South Africa.	85.3	49	17	1	33
United States	24.7	83	13	<1	4

SOURCE: International Eneregy Agency, *World Energy Statistics and Balances* 1971 -1987(Paris: Organization for Economic Cooperation and Development, 1989), pp. 366, 384, 204; International Energy Agency, *Energy Balances of OECD Countries 1970/1985* (Paris: Organization for Economic Cooperation and Development, 1987), p. 541.

arid or semi-arid areas that have little or no arable farmland.[62] Even though the surface mines will lead to significant land loss and degradation, such surface mines could be an improvement over underground mines currently in production. Although these mines produce badly needed coal with relatively little capital, they produce coal of poor quality at great risk to laborers and make inefficient use of the coal resource.

Coal in China is typically low sulfur (less than 2 percent) and high ash (more than 20 percent).[63] Low sulfur coal emits less SO_x, a component of acid rain. Ash is incombustible material (rocks, dirt, and other contaminants), which requires transportation and disposal but gives no energy. Due to the low mechanization rate and existence of many small, manual mines, Chinese coal has as much as 30 to 40 percent incombustible waste.[64] Simple coal cleaning to remove gross impurities could decrease transportation costs and allow for the use of more advanced coal burning technologies.

In India, over 80 percent of total coal output is produced by Coal India Limited-a government agency. The remainder is produced by both private and government-owned mines.[65] Mining in India has traditionally been similar to that in China; highly labor-intensive and underground. India has, however, made a shift to mechanized, open-cast mining and is beginning to move to longwall mining.[66] These methods of mining are feasible as much of India's coal is in thick seams near the surface. The sulfur and ash content of India's coal varies, but on average Indian coal is medium sulfur and high ash—rocks, dirt, and other incombustible material.

The expansion of longwall mining in India has been slow. In addition to unexpected geological difficulties, longwall mining in India may have lacked sufficient scale and concentration to provide adequate learning and adapting of the needed equipment to Indian conditions. It also appears that the transfer of this technology (under the British bilateral aid program) was ineffective as it did not include adequate incentives for the primarily British equipment manufacturers to participate and ensure success of the technology, Even more important in the poor performance of the Indian coal industry in general have been other management and engineering failures, including extensive political interference in managerial decisions, inadequate capital investment, and lack of wage incentives.[67]

Coal Cleaning Techniques

Coal cleaning refers to processing of the coal before it is burnt. Coal can be cleaned at the mine, at the power plant, or in-between, using a variety of methods. If a significant fraction of the overall weight is removed in cleaning, transport costs can be reduced. Environmental costs likewise can be lessened through cleaning; fly ash is emitted during combustion as particles, some of which contain harmful trace elements, sulfates, and nitrates.[68] Particulate contribute to haze and poor local air

[62] Ibid.

[63] IDEA, "Clean Coal Technologies for Developing Countries," contractor report prepared for the Office of Technology Assessment, May 1990, p. 8.

[64] Vaclav Smil, op. cit., footnote 60, p. 23.

[65] A. Desai, "Energy, Technology and Environment in India," contractor report prepared for the Office of Technology Assessment 1990, p. 16.

[66] Ibid.

[67] Ibid.

[68] United Nations Department of Technical Cooperation in Development, op. cit., P. 49.

quality and they can be a health risk, causing pulmonary irritation and respiratory disease. Cleaning prior to combustion can reduce the amount of airborne particulate. Coal cleaning also can improve power plant availability,[69] as the use of dirty coal contributes to power plant breakdowns .70 In one test, a 1 percent drop in ash due to coal cleaning led to a 2 percent increase in plant availability .7* In another example in India, plant availability increased from 73 to ***96*** percent when coal with 40 percent ash was cleaned to 32 percent ash.[72]

Coal cleaning processes are, in order of increasing complexity and cost, physical, chemical, and biological. Physical cleaning is simply removing the noncoal particles, such as dirt, stones, pyritic sulfur, and other contaminants. Physical cleaning can remove about 60 percent of ash, as well as about 10 to 30 percent of sulfur.[73] Fly ash must be disposed of, usually by land application, though ash can be mixed into construction material. About 40 percent of coal used for electricity in the United States receives physical cleaning, most of which occurs at the minemouth.[74] In India, none of the coal used for electricity generation is cleaned, although there are plans to implement some washing of coal for electricity.[75] In China, about 18 percent of all coal is cleaned.[76] Costs for simple physical cleaning are estimated at about $6/ton, and by one estimate is cost-effective for the transport savings alone, whenever transport distances are greater than about 600 kilometers (km).[77]

Advanced cleaning processes include chemical and biological cleaning, both of which use various processes to remove organic sulfur and other contaminants. These processes may be able to remove up to 99 percent of ash and 90 percent of sulfur,[78] but their commercial availability and costs are unclear.

As the largest industrial producer of coal, the United States has developed extensive coal production and combustion technologies, Although many of the advanced technologies, such as chemical beneficiation, are too costly for developing countries, there may be a future market. DOE has a new program to explore these export opportunities in developing countries for American coal-based technologies, including clean coal technologies.

BIOMASS RESOURCES

Biomass provides about 14 percent of the world's energy and 35 percent of the total energy supply in developing countries. Overall, Africa obtains about two-thirds of its energy from biomass, Asia about a third or more, and Latin America about one-quarter. Some developing countries are almost wholly dependent on biomass for energy; Ethiopia, Nepal, and Tanzania, for example, rely on biomass for 90 percent or more of their energy supply. In rural and poor urban areas of most developing countries, biomass is often the only accessible and affordable source of energy. As discussed elsewhere, harvesting biomass for use by small industries and in urban areas plays an important role in the traditional rural economy, particularly in employment for the poorest.[79]

Demand for biomass will rise in the future. The rural and urban poor populations in developing countries are growing rapidly and are unlikely to make a quick transition to cleaner, higher quality fuels. Therefore, subsistence-level populations will require increasing biomass supplies to meet household and small industry needs.

Biomass, as it is currently used (see chs. 3 and 4), is often a dirty and low efficiency fuel. In the future, an increasing amount of biomass could be converted

[69] IDEA, op. cit., footnote 63, p. 34.

[70] Availability is the amount of time a power plant is operating divided by the amount of time the plant would operate if it worked perfectly.

[71] IDEA, op. cit., footnote 63, **p. 34.**

[72] IDEA, *op.* cit., footnote 63, p. 35.

[73] U.S. Department of Energy, Assistant Secretary for Fossil Energy, **C/can** *Coal* **Technology, DOE/FE-0217P,** revised January 1991, **p. 13.**

[74] Ibid.

[75] Tata Energy Research Institute, **Ten'** *Energy Data Directory and Yearbook 1988* (New Delhi, India: Urhnak and Arvind, 1988) p. 41.

[76] Ministry of Energy, People's Republic of China, *Energy in China*, 1989, op. cit., footnote 60, p. 17.

[77] IDEA, op. cit., footnote **63, p. 36.**

[78] U.S. Department of Energy, Assistant Secretary **for Fossil Energy, op. cit., p. 14.**

[79] U.S. **Congress,** Office **of Technology Assessment** *Energy* in *Developing Countries*, OTA-E-486 (Washington DC: U.S. Government Printing Office, January **1991).**

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to a cleaner, higher quality fuel using the processes described in chapter 6. Biomass could be burned directly for process heat and electricity, fermented or hydrolyzed to form alcohol fuels for transport, thermochemically gasified or anaerobically digested to produce gas for direct use or to generate electricity, or converted to charcoal for high temperature process heat for industries. These uses could increase commercial demand for biomass resources.

The potential biomass resource base is enormous. The biomass energy theoretically available worldwide from residues alone is equal to about 85 exajoules (81 quads), 25 exajoules (24 quads) from crop residues, and 30 exajoules *(29* quads) each from forest residues and animal dung.[80] Dedicated energy crops could add significantly to the resource base.

There are a number of advantages to increasing the use of biomass. If produced on a sustainable basis, biomass would not add to greenhouse emissions and could improve local environments through reduced emissions of SO_x. Fuel switching to biomass could also reduce energy import dependence and stimulate rural development.

Increased use of biomass for energy also has potential disadvantages. Use of these resources will require careful consideration of environmental impacts, especially the risks of negative effects on soil and water availability and quality. Increased use of biomass for energy also raises social equity issues, including the possibility of growing fuel for the rich rather than food for the poor and exacerbating inequalities between landowners and landless.

Increasing biomass availability on a sustainable basis requires considerable effort. In light of all their needs, developing countries may not view the enhancement of biomass resources as a priority. Therefore, development of these natural resources cannot occur independent of the larger context of development.

Nonetheless, there are a number of opportunities for expanding the use of biomass resources in an environmentally and economically supportable fashion. In the near term, greater use of industrial wood wastes, some agro-processing wastes, and some agricultural residues are feasible options. In the mid term, careful management and use of natural forest resources could provide additional energy supplies. In the long term, there are opportunities for growing woody or herbaceous crops for energy production.

Agricultural/Industrial Residues

In the near term, agricultural and industrial residues[81] are the most promising bioenergy resource. The biomass residues from agricultural and industrial (e.g., forest products industry) processing can be used to provide power in the form of process heat or electricity. These resources already are used to a limited extent for such purposes in most industrialized and developing countries, though they usually could be used more extensively and efficiently (see also ch. 4 for the pulp and paper industry and ch. 6).

The availability of field wastes raises the issue of ‘‘determining g when a waste is really a waste.”[82] In developing countries, the potential availability of field residues varies widely. Worldwide estimates for annual residue production are 3.1 billion tonnes of food crop residues and 1.7 billion tonnes of animal dung,[83] but it is not known how much of this amount is actually available for use as fuel. In wood-scarce areas such as China, Pakistan, Bangladesh, and parts of India, agricultural residues are often already heavily used as cooking fuels in rural households. Agricultural residues also can be plowed into fertilize fields. Decomposing crop and animal wastes add both nutrients and fibrous matter to the soil. As soil degradation and erosion are chronic problems in many parts of the world, collection of agricultural residues has to be managed so that fields are not deprived of these resources.

In many cases, however, there is room for multiple uses of these residues. The portion of crop residues recycled for fertilizer and soil stability may actually be small, due to the physical difficulty of replowing. Farmers using hand implements may burn or landfill residues, particularly dry residues such as coconut shells, rather than replowing them. If this is so, then using some of the residues for fuel

[80] D.O. Hall, “Biomass Energy,” *Energy Policy,* October 1991, pp. 711-737.

[81] Forest residues will be discussed under the “forest management’ heading.

[82] William Ramsay, *Bioenergy and Economic Development: planning for Biomass Energy Programs in the Third World* (Boulder, CO: Westview Press, 1985), p. 65.

[83] G.W. Bamard, “Use of Agricultural Residues as Fuel,” *Bioenergy and the Environment* (Boulder, CO: Westview Press, c. 1990), p. 87.

will not hurt the productivity of the soil.[84] However, availability of residues for combustible fuel will still be site specific. For example, in some places field residues may have other uses such as fiber or fodder. Residues might be used for thatching, or sold to small industries, such as paper manufacturers .85

Dung is important to agricultural productivity both as a fertilizer and in maintaining soil structure. Using dung for fuel (or occasionally as a building material) raises issues similar to those concerning field residues. Collecting dung from grazing animals is time-consuming and much of the dung may just be left where it falls. Moreover, dung that sits in the sun before being plowed under can lose as much as 80 percent of its nitrogen content, a key soil nutrient in dung.[86] In contrast to direct burning of dung for fuel, biogas digesters allow use of dung for fuel while still retaining (or even improving) its value as a fertilizer if applied to fields and plowed in.[87]

Densification of agricultural and forestry residues to briquettes or pellets increases the energy content per unit volume, reducing transport and handling costs. These reduced costs can help to open commercial markets for residues and therefore stimulate demand for these resources. For example, the cost of delivering briquettes to Addis Ababa in Ethiopia from a farm 300 km away would be about one-third the cost of delivering baled wheat straw. The processing costs can be considerable, however, limiting the use of densified fuels to rural and urban industries and middle to high income households in countries where other fuel prices are high.

In Ethiopia, for example, agricultural residues from small farms are currently used as a fuelwood substitute throughout the country. At least 3.3 million tons of surplus coffee, cotton, wheat, and maize residues are produced annually, including surpluses from State-owned lands. Although costs for densifying and transporting residues are site specific, costs for Ethiopia are summarized in table 7-4. The "ready-to-burn" costs at the market are equivalent to unprocessed crude oil prices of $15 to $20 per barrel. For industrial use, agricultural residue briquettes can be produced and delivered to users in Addis Ababa at a lower cost than most other industrial fuels.

In Sri Lanka, on the other hand, the delivered cost of coir dust (derived from coconut husks) briquettes is more than three times that of fuelwood per unit weight and the energy cost per unit of energy content is twice that of fuelwood. Sri Lanka has, however, large coir dust resources with an energy potential of 84 million GJ (80 trillion Btus).[88] Fuelwood resources are predicted to dwindle in Sri Lanka, so coir dust briquettes may become an economically viable alternative. In general, briquette and pellet costs will vary considerably according to the densification process, the scale of processing, and the original biomass feedstock.

Expanded use of agricultural residues and dung requires careful planning, whether for household use or when briquette for commercial use. The availability of some agro-processing residues, however, is less constrained by competing uses and environmental concerns. Residues resulting from industrial processes, such as bagasse from sugar refining or sawdust from sawmills, present a "ready" resource.[89] Many developing countries already use these resources for energy, though often inefficiently. Improvements in system efficiencies could enable industries to sell to the grid some of the power they produce from residues.

In summary, the overall picture for increased use of agricultural and industrial residues is mixed. Field residues are a promising resource, especially when briquette, but they must be carefully collected to protect agricultural and livestock productivity. Other competing uses of the field resources also must be taken into account. Waste-to-energy schemes for using residues are, however, an immediate opportunity for developing countries. In fact, many developing countries already take advantage of this econom-

'Ibid., p. 93.

85Ibid., p. 94.

86Ibid., p. 93.

87Many families in the developing world can not afford sufficient livestock to supply their own biogas needs, however. In order to meet cooking needs with biogas, a typical family would need three head of cattle. Few families in the developing world can afford to own or feed so many cattle. See ch. 6 for more detail. David Pimentel, personal communication, Apr. 23, 1991.

88V.R. Nanayakkara, *Wood Energy Systems for Rural and Other Industries* (Bangkok: Food and Agriculture organization of the United Nations), p. 15 and p. 40.

89William Ramsay, op. cit., footnote 83, p. 66.

Table 7-4-Production Cost Estimates **for Commercial Scale Crop Residue Briquetting in Ethiopia (US$ (1983)/ton of product)**

	Residue		
Stage of production	(1) Cotton stalks	(2) Corn and sorgum stover	(3) Wheat and barley straw
Harvesting	7.23	19.03	10.85
Capital charges	(4.22)	(10.40)	(2.39)
Energy and lube	(1.35)	(4.11)	(1.64)
Maintenance and other	(1.50)	(4.32)	(6.40)
Labor	(0.16)	(0.20)	(0.42)
Grinding	—	1.44	1.44
Briquetting	11.80	8.54	8.54
Capital charges	(5.56)	(2.37)	(2.37)
Energy and lube	(1.76)	(5.25)	(5.25)
Maintenance and other	(4.37)	(0.80)	(0.80)
Labor	(0.11)	(0.12)	(0.12)
Storage, etc.	1.0	0.88	0.88
Financial cost ex-plant	20.05	29.89	21.71
Economic cost ex-plant	25.02	32.15	27.35
Economic costs of transport and tagging, etc.	19.41	19.41	19.41
Bagging (40 kg sacks)	(3.38)	(3.38)	(3.38)
Transport[a]	(14.03)	(14.03)	(14.03)
Handling at each end	(2.01)	(2.01)	(2.01)
Economic cost delivered to market ("ready to burn")	44.43	51.56	46.76
Net heating value: MJ/kg	17.3	15.0	17.4
Moisture content: % (wb)	(12)	(15)	(15)
Economic cost per energy unit delivered to market: US$/GJ	2.57	3.44	2.69

[a]Transport: 22 ton trucks over 300 km of deteriorated paved roads to Addis Ababa.

SOURCE: K. Newcombe, "The Commercial Potential of Agricultural Residue Fuels: Case Studies on Cereals, Coffee, Cotton and Coconut Crops," World Bank Energy Department Paper No. 26 (Washington, DC: World Bank, June 1985).

ically viable resource, though in an inefficient manner in many instances. Overall, residues present both near and longterm resource expansion possibilities.

Forest Management

Forests are an important resource for developing countries. Woodlands furnish fuelwood, timber, fiber, food products, fodder, pesticides, and medicine. Forest products are the main industrial base for a number of developing countries, and many subsistence populations depend on natural woodlands for their livelihood. Forests are also an integral part of the ecosystem, promoting healthy soils, maintaining diverse plant and animal life, regulating the flow of water, and controlling flooding and other potential hazards.[90] Moreover, tropical forests in developing countries are critical to global environmental quality; these forests store a significant share of the world's carbon stock.

Despite the importance of forests to developing-country economies and environments, many natural woodlands are being depleted faster than they can regenerate. Management techniques can slow the degradation of forests, however, and still allow for commercial and small-scale harvesting.

Commercial and subsistence wood harvesters need different forest management strategies. Generally, rural subsistence farmers cause relatively little damage to forests when they are collecting wood. These farmers tend to take dead wood or cut branches and leaves from trees, often lacking even the tools for cutting whole trees. In some cases, farmers may use hedges and other vegetation growing on their farms for fuel. A study of West Java found, for example, that three-fourths of all the fuel collected came from within family courtyards and gardens, and two-thirds of this fuel was branches and twigs.[91]

[90]U.S. Congress, Office of Technology Assessment, *Technologies to Sustain Tropical Forest Resources, OTA-F-214* (Springfield, VA: National Technical Information Service, March 1984), p. 10.

[91]M. Hadi Soesastro, "Policy Analysis of Rural Household Energy Needs in West Java," *Rural Energy to Meet Development Needs: Asian Village Approaches,* M. Nurul Islam, Richard Morse, and M. Hadi Soesastro (eds.) (Boulder, CO: WestView Press, 1984), p. 114. See also, U.S. Congress, Office of Technology Assessment, *Energy in Developing Countries,* OTA-E-486 (Washington, DC: U.S. Government Printing Office, January 1991), p. 119.

In cases where farmers are cutting down whole trees, a number of techniques are available to minimize damage. ''Thiming" (cutting trees selectively) may actually stimulate growth in the remaining forest as there is less competition for nutrients, light, and water. "Pollarding" (cutting off branches and twigs, rather than felling whole trees) can also stimulate forest growth by reducing competition for nutrients, water, and light.

In contrast to the rural foragers, commercialized fuelwood and charcoal harvesters routinely fell whole trees, damaging or even clear-cutting entire forests. Even so, there are techniques, such as thinning or cutting in strips rather than clear-cutting a whole area, to minimize damage. After harvesting, forest lands can be reseeded or replanted. Adequate maintenance or upgrades of cutting and harvesting equipment also minimizes damage to trees and soil surrounding the logging site.[92] Better charcoal conversion processes could decrease the number of trees cut. In the long run, though, commercial logging for fuel may sometimes be demand-constrained as consumers switch to other fuels when wood becomes scarce and prices climb .93 There is no guarantee, though, that this will occur early enough to prevent serious damage to forest resources in some areas.

Putting forest management techniques into practice can be difficult. Intervention by governments or nongovernmental organizations often is required. Governments can encourage forestry techniques through taxes on wood and charcoal, tax incentives, laws, and enforcement of laws.[94] Governments and nongovernmental organizations can teach forest management techniques through extension staff and forestry projects. These measures have proven difficult to instill in the past. Taxes or laws requiring certain forestry practices tend to be difficult and costly to enforce and forestry projects often fail when overseas funds dry up.[95] Management techniques may have limited success in conserving

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forests because forests are usually cleared to make room for migrants, agriculture, and livestock,[96] rather than by fuelwood gatherers.

Energy Crops

Some developing countries already successfully grow crops dedicated to energy production. Energy crops can be divided into two broad categories; herbaceous field crops and woody biomass plantations. These crops can be planted as separate lots or fields devoted to energy production or as stands ''intercropped' between other crops and around residential areas. Five key variables govern the viability of woody and field energy crops: technical feasibility; availability of suitable land; economic viability; implementation; and environmental impacts.[97]

Technical Feasibility

Research and development on plant species and methods of planting have greatly enhanced the technical feasibility of energy cropping. Energy crops are highly site specific, however; species that respond well to test conditions may be vulnerable to

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92U.S. Congress, Office of Technology Assessment, *Changing By Degrees: Steps to Reduce Greenhouse Gases*, OTA-O-482 (Washington, D. C.: U.S. Government Printing Office, February 1991).

93U.S. Congress, office of Technology Assessment, *Energy in Developing Countries*, Op. cit., footnote 79, p. 119.

94Keith Openshaw and Charles Feinstein, World Bank, Industry and Energy Department, "Fuelwood Stumpage: Considerations for Developing Country Energy Planning," Industry and Energy Department Working Paper, Energy Series Paper No. 16 (Washington DC: World Bank, June 1989).

95Paul Kerkhoff, *Agroforestry in Africa: A Survey of Project Experience* (London: Panos Publications, Ltd., 1990).

96For more detail on deforestation, see U.S. Congress, offic, of Technology Assessment, *Energy in Developing Countries*, op. cit., footnote 79, ch. 5.

97David Hall, "Biomass, Bioenergy and Agriculture in Europe, " *Biologue*, vol. 6, No. 4, September/October 1989.

actual site conditions. Flexibility of a given species in different environments is one of the most important technical characteristics for energy crops in developing countries.[98]

For woody biomass plantations, other desirable characteristics include fast growth; high density (high heat value per unit of volume); robustness (ability to withstand weather, pests, and disease); nitrogen fixing capability (a trait that reduces the need for fertilizer); and good potential for coppicing (ability to regrow from stumps). Since 1978, the U.S. DOE has supported research and development of Short Rotation Intensive Culture (SRIC) woody energy crops that incorporate most of these features. SRIC plantations consist of a fast-growing single tree[99] species (a "monoculture' '), planted in carefully spaced patterns, harvested in 3 to 10 year cycles, and intensively managed.[100]

DOE and other researchers have tested a wide variety of species and found them to be appropriate for SRIC plantations.[101] Although some Species native to the region in question can be used, especially in the tropics, exotic species with particularly favorable characteristics are often brought in. Especially versatile species include acacia, grevillea, eucalyptus, calliandra calothyrus, populus (poplar), salix (willow), sesbania, and leucaena.[102] Leucaena, native to Central America and Hawaii, is especially popular for energy crops because it is drought tolerant, coppices readily, has the highest measured yields of any tree species, has a very high density, and is a good source of wood and foliage for fuel, fodder, construction, or pulp.[103] Even leucaena does not universally grow well, however. A project supported by the Cooperative for American Relief Everywhere to grow leucaena leucocephala, calliandra calothyrus, and sesbania sesban in Ethiopia:

> . . . showed abysmal growth. It was a painful lesson in the risks of putting too much trust in the textbook. One project worker said, "I was devastated when leucaena didn't work. We inoculated it, we did everything to make it grow, and it was like we were growing a dwarf variety."[104]

Even the most versatile, fast-growing, and resilient species may not grow well in any given environment. Monoculture short-rotation forests are susceptible to a variety of hostile environments. Poor soil characteristics, harsh microclimates, pests, fires, weeds, and diseases may all devastate or stunt plantation growth. There is some evidence that monoculture plots are more susceptible than the more diverse natural stands, in which some trees may have characteristics that ward off disease or fix nitrogen in the soil, protecting the surrounding trees. In many cases, monoculture trees perform better in trials because they are nurtured under very controlled situations on small plots, conditions that are hard to replicate in the field.[105] Other technical problems resulting from monoculture SRIC plantations include possible exhaustion of the land and loss of biodiversity.[106]

Bioengineering has the potential to overcome some of these problems, such as vulnerability to pests and environmental stress. Desirable characteristics, such as nitrogen fixation and fast growth, also may be augmented through bioengineering.[107] Bioengineering technologies that have proven successful in some cases are cloning and hybridization.[108] For example, the U.S. DOE has produced hybrid black cottonwoods that have yields that exceed those of the parent stock by a factor of 1.5 to 2.[109] Genetic engineering of trees is a relatively new field, however. In comparison, agricultural biotechnology is much further advanced. Technology transfer from agricul-

98 W. Ramsay, op. cit., footnote 82, p. 58.

99 In tbis section, references to trees include shrubs.

100 U.S. Congress, Office of Technology Assessment, op. cit., footnote 79, p. 214.

101 W. Ramsay, oP. cit., footnote 82, pp. 71-87.

102 I. Stjernquist, ' 'Modern Wood Fuels," *Bioenergy and the Environment* (Boulder, CO: Westview Press, c. 1990), pp. 61-65.

103 Ramsay, op. cit., footnote 82, p. 83.

104 P. Kerkhof, op. cit., footnote 95, p. 83.

105 Edward A. Hansen, "SRIC Yields: A Look to the Future," unpublished manuscript, 1990, p. 3.

106 U.S. Congress, Office of Technology Assessment, op. cit., footnote 92, p. 223.

107 Ramsay, op. cit., footnote 82, p. 88.

108 Edwin H. White, Lawrence P. Abrahamson et. al., "Bioenergy Plantations in Northeastern North America," paper presented at Energy from Biomass and Wastes XV in Washington, DC, Mar. 25, 1991, p. 10.

109 Philip A. Abelson, "Improved Yields Of Biomass," *Science*, vol. 252, No. 5012, June 14, 1991, p. 1469.

ture will speed SRIC genetic engineering, but only to a point; trees and shrubs have unique characteristics, including a long breeding cycle.[110] Nonetheless, the potential to increase yields through biotechnology is enormous-according to one researcher, even more significant than the successes already achieved in agricultural genetic engineering.[111]

Field crops dedicated to energy production in the developing world have focussed in part on starches or sugars that can be fermented to alcohol fuels. For example, Brazil grows a large amount of sugarcane exclusively for production of ethanol. In temperate climates, other crops that can be grown for energy include cereals, pasture plants, cassava, sugar beet, sweet sorghum, potatoes, oilseed crops, Jerusalem artichoke, and Japanese knotwood. Crops with high oil contents can be grown for conversion to vegetable oils, and some experimentation has occurred with hydrocarbon-producing species, such as euphorbia lathyrus, in arid or semi-arid regions.[112] "Energy grasses, ' often indigenous grasses that will grow on marginal land, are also feasible. These grasses generally have high nitrogen requirements, however, and would need to be 'intercropped' between nitrogen-fixing trees or crops.[113]

A technical barrier for developing countries is that much of the research and development on energy crops does not reflect developing-country needs and conditions. For example, there is little research and development on tree species indigenous to developing countries.[114] In practice, determining ***the Viabil***ity of indigenous species for energy crops may be a trial and error process. More demonstration and in-the-field testing of SRIC and engineered species would increase their effective deployment in developing countries. Even though more research and development could certainly enhance energy cropping, however, current knowledge suggests that prospects for high-yield SRIC plantations and field crops in developing countries are encouraging.

Availability of Suitable Land

To be a reliable source of energy, biomass plantations would require significant amounts of land, especially as biomass conversion is energy intensive. For example, with short-rotation intensive culture trees, about 8 percent of the energy provided would have to be used to plant, harvest, and dry the trees. About one-third of the energy then would be lost if the wood were converted to a liquid or gaseous fuel. Conversion to other forms, such as charcoal, involve even higher losses (the majority of charcoal kilns in Minas Gerais, Brazil have conversion efficiencies of about 50 percent, for example).[115] To break even economically, plantations would have to be large and may require fertilizer and other inputs to achieve a sufficiently high level of productivity.

In many countries, plantations of this size and productivity would have to compete with agriculture for the same land resources and inputs. According to the United Nations Food and Agriculture Organization (FAO), 46 percent of the developing countries surveyed already lack sufficient land resources to support their populations at low levels of agricultural inputs.[116] With projected population growth and the contined low agricultural inputs, 55 percent of the countries would lack sufficient land resources to feed their populations by 2000.[117] According to the FAO's analysis, Central and South America are the regions most likely to be able to support energy crops. Many of the most populous African countries, however, lack sufficient land resources to sustain their populations, let alone energy crops given current low levels of agricultural inputs. For the countries with insufficient land resources for energy cropping, small scale agroforestry projects, discussed below, may still be viable.

For countries with adequate land resources, a growing market for biomass resources could have national and local benefits. Developing countries could save foreign exchange dollars now spent on oil

110 Edward A. Hansen, op. Cit., footnote 105, p. 12.

111 Ibid.

112 I. Stjernquist, "Modem Wood Fuels," *Bioenergy* and *the Environment* (Boulder, CO: Westview Press, 1990), p. 70.

113 Ramsay, op. cit., footnote 82, pp. 59-60.

114 Cynthia C. Cook and Mikael Grut, *Agroforestry in Sub-Saharan Africa: A Farmer's Perspective* (Washington, DC: The World Bank, 1989), p. 37.

115 J. Warren Ranney, Lynn L. Wright, et al., "Hardwood Energy Crops: The Technology of Intensive Culture," *Journal of Forestry*, vol. 85, pp. 17-28.

116 United Nations Food and Agriculture Organization, *Potential Population Supporting Capacities of Lands in the Developing World*, Technical Report of Project INT/75/P13 (Rome: United Nations Food and Agriculture Organization% 1982), Table 3.4, pp. 134-136.

117 Ibid.

imports and reinvest the money within the country. Local economies could benefit by growing biomass as a cash crop, stimulating rural development. There are, however, risks. New technologies could lead to an increase in deforestation if they rely solely on existing biomass resources.

Economic Viability

The expenses involved in establishing energy crops include land opportunity costs, the cost of inputs, and the costs of maintaining, harvesting, and transporting the crops. For energy crops to be viable, the price at which the fuel can be sold must exceed the sum of these costs. If this is not the case, energy crops may still be viable if other benefits justify the costs, or if there is an external source of financial support, such as an international aid organization.

In rural areas, with woodlots meant for local fuel uses, trees may be planted on farms without many inputs and with almost no mechanization, particularly where there is subsistence farming. Transportation costs may also be irrelevant as many of the products (poles, fodder, fuelwood) will be used locally, rather than transported and sold in markets. In these cases, economic viability may be determined by number of hours spent rather than mone-@Y gain. The World Bank estimates that an attractive time savings to farmers would involve a rate of return greater than 30 percent.[118]

Large scale woody plantations have mixed economic results. Many plantations, particularly community woodlots, fail economically for a number of reasons. The returns on planting trees for energy are inherently long term; the time between planting and harvesting is 3 to 10 years. Farmers, community members, and other investors are generally reluctant to make the investment due to this long lead time, particularly with current low prices for other forms of energy, including gathered wood.[119] On the other hand, tree plantations with multiple end-uses—trees that provide fruit or timber-may well be economically viable, as is the case in Gujarat, India.[120]

Another plantation strategy could be large industries growing trees specifically to support industrial processes. There are examples of such industrially dedicated plantations. A study of Sri Lankan industries using wood for fuel concluded that 49 percent of the total fuelwood consumed came from man-made rubber plantations. Another 2 percent came from other forest plantations.[121]

Markets are the key to economic viability, and yet, according to one analyst, ''it is probably a safe guess . . . that more renewable energy projects have come to grief through omitting a thorough investigation of potential markets than through any other cause. '[122] Generalizing about markets for energy crops is extremely difficult, however. There are scant data available and there are significant differences between commercial and noncommercial markets, rural and urban markets, and markets in different regions and nations.

In rural areas, "non timber products tend to be marketed locally and in a decentralized manner, [so] their value is generally hard to recognize and assess. 123 Wood is gathered from the forests for "free," so developing a market for marginal small scale industrial and residential users would be difficult. In some rural areas with scarce wood resources, however, there is a small market for wood, and in such areas, wood is an important source of income. Even with scarcity, local subsistence populations are likely to substitute other forms of energy-such as crop residues-rather than pay cash for wood fuel. Some communities have been encouraged to pursue social forestry, or community woodlots, but returns often are insufficient to attract investment-either time or money.[124]

Markets also can be created, as is the case with field energy crops for ethanol fuels in Brazil (see ch. 6). Through a mixture of price controls, subsidies, and tax breaks, the Brazilian government has been

118C. Cook and M. Grut, op. cit., footnote 114, p. 13.

119Ramsay, op. cit., footnote 82, p. 167.

120Ibid.

121V.R. Nanayakkara, *Wood Energy Systems for Rural and Other Industries: Sri Lanka* (Bangkok: United Nations Food and Agriculture Organiza tion), pp. 20-21.

122Ramsay, op. cit., footnote 82, p. 161.

123U.S. Congress, Office of Technology Assessment, op. cit., footnote 92, p. 221.

124Samuel F. Baldwin, *Bioenergizing Rural Development*, unpublished manuscript, February 1988, p. 1.

able to create and maintain a market for fuel ethanol.[125] Few developing counties can afford to' run programs on this scale, though. Other smaller scale market interventions are possible, however. For example, a tobacco company in Kenya in effect creates a market for woodfuels by placing the farmers under a contractual obligation to plant trees. Farmers must demonstrate that they grow a certain number of trees before the tobacco company will purchase tobacco from those farmers.[126]

Urban areas of developing countries often depend on a commercialized fuelwood and charcoal market. Many urban residents still rely on wood and charcoal for fuel. As fuelwood generally is not located close enough to cities for collection, supplies are purchased. Often, these supplies originate in distant areas. A study of fuelwood use in two Indian cities revealed that in one Indian city, Bangalore, one-half of the fuelwood consumed was transported from between 120 and 300 km away and 17 percent from as far as 700 km from the city borders. In another Indian city, Hyderabad, about 55 percent of all fuelwood supplies were brought in from forests over 100 km away.[127] Transportation infrastructure is therefore an important precursor for an urban fuelwood market. In Thailand, for example, transportation systems are fairly well developed and a large segment of the urban population derives its energy from tropical forests located far from the cities.[128]

The introduction of the technologies discussed in chapter 6 could improve the economic viability of both field and woody energy crops, by making biomass resources competitive with fossil fuels in the provision of such desirable energy carriers as gas and electricity. As these biomass conversion technologies become available, they may well create a market for biomass resources.

Implementation

There are two different types of energy crop planting schemes; dedicated energy crops and plants or trees intercropped between agricultural crops. In the former case, crops or trees are planted exclusively for energy production. In the latter case, also referred to above as "agroforestry," the provision of fuel is a secondary reason for planting the trees or crops. Implementation issues differ for these two scenarios.

In the past, tree-planting schemes (both for large scale plantations and for smaller scale agroforestry) in developing countries sometimes have been introduced without adequate attention to local needs and local environments. As a result, these schemes have needed extensive infrastructures to initiate and maintain and, with some exceptions, have resulted in widespread failures.[129]

Experience suggests that dedicated energy crops and agroforestry have a better chance of success if the local farmers are intrinsic to the process. Tree schemes that cost the farmers time, money, and land without any clear benefits require extensive, costly, and long-term intercessions from governmental or nongovernmental organization extension staff. Even with incentives and proper training, farmers may not be attracted to energy cropping.

Given the land availability and economic viability problems discussed above, farmers will weigh the advantages of biomass against the other possible uses for the limited land available. Energy projects designed by outside experts often fail because they do not respond to local priorities.[130] Sometimes, afforestation strategies are based on wrong assumptions. For example, it has been assumed that local people would use wood resources until the resource was completely, irreversibly depleted. In many

125 Marcia Gowen, "Biofuel v. Fossil Fuel Economics in Developing Countries," *Energy Policy*, vol. 17, No. 5, October 1989, p. 460.

126 P. Kerkhof, op. cit., footnote 95, p. 63. Although this program has resulted in successful tree growth, the farmers continue to cut the natural growth for wood, preferring to use the cultivated trees for poles.

127 Manzoor Alam, Joy Dunkerley, Amulya Reddy, "Fuelwood Use in the Cities of the Developing World: Two Case Studies from India,' Natural Resources Forurn, United Nations, 1985, p. 207.

128 Norman Myers, *The Primary Source: Tropical Forests and our Future* (New York: W.W. Norton and Co., 1984), p. 119.

129 P. Kerkhof op. cit., footnote 95; C. Cook, and M. Grut, op. cit., footnote 114.

130 Steven Meyers and Gerald Leach, U.S. Department of Energy, Oak Ridge National Laboratory, Office of Scientific and Technical Information, *Biomass Fuels in the Developing Countries: An Overview* (Oak Ridge, TN: U.S. Department of Energy, 1989).

developing countries, however, local populations respond of their own accord to woodfuel shortages.[131] In these cases, building on the foundation already provided by local practices will speed and ease project implementation. Increasingly, developing-country governments and foreign donors are realizing that local knowledge and aspirations must be included if these projects are to be successful and that the problem of biomass energy must be considered in the broader context of development.

Environmental Impacts

With sound management, environmental impacts of energy cropping can be minimal or even favorable.[132] Environmental problems associated with energy crops are very similar to those associated with agricultural crops, with the degradation of soils being a key risk. Although specific problems and benefits vary, the general environmental benefits and costs are valid not only for the developing countries, but also for the industrial nations.

If grown sustainably, biomass energy does not make a net contribution to the buildup in atmospheric CO_2 from anthropogenic sources. When trees are harvested, a certain amount of stored carbon is released. If vegetation with comparable carbon storage is replanted, carbon emissions resulting from the decomposition, combustion, or harvest of the original trees may be offset.[133]

Large-scale woody plantations or energy field crops can further offset carbon emissions if they replace fossil fuels.[134] Biomass also contains little sulfur, so combustion produces less sulfur oxides than are emitted during fossil fuel (especially coal) combustion.[135] Sulfur oxides are a component of local air pollution and acid rain, and a serious problem in many cities in developing countries[136] (see figure 7-l).

Negative local environmental impacts of biomass depend on the crop grown, the site characteristics, and the circumstances. Impacts can range from "minor changes, easily accommodated within the existing ecosystem,' to "major changes drastically altering the site or its surroundings.''[137] Effects of energy cropping can include soil erosion, increased water runoff, loss of soil nutrients and organic matter, negative effects on hydrologic systems, and reduction in biological diversity as fast-growing monoculture are substituted for indigenous vegetation.[138]

Although these effects are site and crop specific, changes in the soil are very likely to occur. Soil is composed of mineral matter and organic matter, largely from decaying trees or animals. Removing the original trees will therefore change the composition of the soil by changing the organic component. In most forest ecosystems, the decaying vegetation contributes organic matter and helps stabilize soils. Soil is extremely slow to reform; forests are estimated to take 1,000 years or more to reform 2.5 centimeters of soil.[139] Clearing a site for an energy crop and then leaving the soil exposed before or during planting can result in significant soil erosion. Removing forest debris and interrelated ecosystems also can lead to erosion. The soil and water runoff can hurt local hydrological systems by increasing the levels of sedimentation in the water. Runoff polluted by herbicides, pesticides, and fertilizers can exacerbate the damage to aquatic ecosystems and foul drinking water.

Soil conservation techniques, such as terrace and contour planting, can moderate or mitigate these

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131 U.S. Congress, Office of Technology Assessment, op. cit., footnote 79, p. 119.

132 James Pasztor and Lars A. Kristoferson, ''Bioenergy and the Environment—the challenge, ' *Bioenergy and the Environment* (Boulder, CO: Westview Press, 1990), p. 28.

133 For more on the carbon cycle and the variables that effect carbon releases by trees, see U.S. Congress, Office of Technology Assessment *Changing By Degrees: Steps to Reduce Greenhouse Gases,* op. cit., footnote *92,* ch. 7.

134 D.O. Hall, H.E. Mynick, and R.H. Williams, ''Cooling the Greenhouse with Biomass Energy,' *'Nature,* vol. 353, No. 6339, Sept. 5, 1991, pp. 11-12; D.O. Hall, H.E. Mynick, and R.H. Williams, "Alternative Roles for Biomass in Coping with Greenhouse Warming, " *Science and Global Security,* vol. 2, 1991, pp. 1-39.

135 Samuel F. Baldwin, op. cit., footnote 126, p. 2.

136 For more information on pollution from biomass combustion, see chs. 2 and 3 and U.S. Congress, Office of Technology Assessment, *Op. Cit.,* footnote 79.

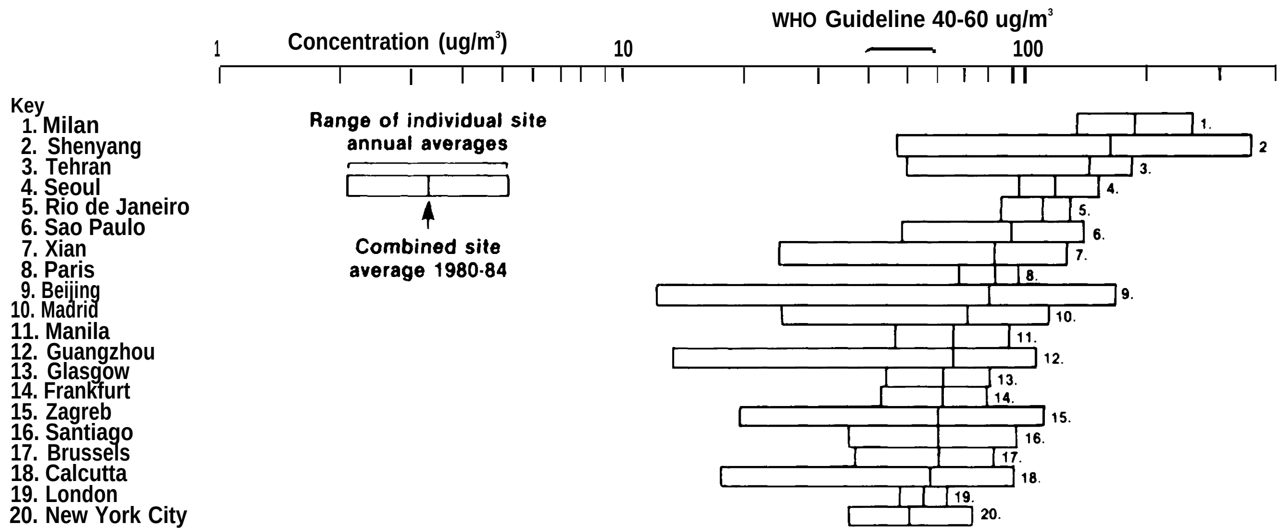
137 William Ramsay, op. cit., footnote 82, p. 91.

138 David Pimentel, personal communication, Apr. 23, 1991.

139 David Pimentel, Alan F. Warneke, et al, ''Food Versus Biomass Fuel: Socioeconomic and Environmental Impacts in the United States, Brazil, India, and Kenya,'' *Advances in Food Research (New* York, NY: Academic Press, Inc, 1988), p. 216.

Figure 7-l—Sulfur Dioxide Levels in Selected Cities, 1980-84

Shown is the range of annual values at individual sites and the composite 5-year average for the city.



SOURCES: World Health Organization and United Nations Environment Fund, *Global Pollution and Health* (London: Yale University Press, 1987), figure 2.

effects. However, "because of their high labor or capital costs, many of these techniques are only of interest to large-scale biomass energy production schemes."[140] For small scale biomass planting, agroforestry can be an alternative. Soil has been estimated to erode 12 to 150 times faster than it is formed world wide, with the bulk of losses due to agricultural crops.[141] Trees, bushes, and grasses planted among crops and around houses can stabilize soils, slow erosion rates, and provide fuel. Intercropped vegetation also can enhance the organic makeup of the soil since some tree and bush species contribute or ''fro' important soil nutrients, such as nitrogen.

Energy cropping and agroforestry also can alter or destroy ecosystems. To make plantations economically viable, fast growing crops generally have to be planted, particularly if biomass is to be a fossil fuel substitute. Monoculture short-rotation intensive culture plantations usually best meet this need. These monoculture plantations often replace diverse tree and plant species, however, which were a habitat for diverse animal and insect populations. Not only will the various flora be lost, most of the fauna may not be able to survive in the new habitat.[142] Planting strategies exist that maintain biological diversity, such as multiple species cropping or retaining patches of old growth within the plantation. These strategies are likely to mean lower crop yields, though.[143] Although agroforestry also may rely on exotics, there is better potential to maintain the indigenous species. Since the trees usually are planted for multiple purposes, fast growth is not essential to economic viability.

Energy cropping must be carefully planned and implemented in order to minimize negative environmental impacts. With such careful planning, crops and agroforestry have the potential to benefit local and global environmental quality by stabilizing soils, adding soil nutrients such as nitrogen, and acting as a net carbon sink.

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[140] D.R. Newman and D.O. Hall, "Land-Use Impacts,' *Bioenergy and the Environment* (Boulder, CO: Westview Press, 1990), p. 242.

[141] D. Pimentel, op. cit., footnote 141, p. 216.

[142] J.H. Cook and J. Beyea, "Preserving Biological Diversity in the Face of Large-Scale Demands for Biofuels,' paper presented at the Energy from Biomass and Wastes Conference XV, Washington DC, Mar. 25, 1991, p. 3.

[143] Ibid., p. 5.

Conclusions

Biomass resources are extremely important to developing countries. Urban and rural subsistence populations rely on biomass for fuel and are likely to continue relying on biomass in the future. Small and large scale industries already use biomass and could use it more in the future. The present resource base may not be able to support this increasing demand from a growing population.

There are a number of strategies for enhancing the biomass resource base. In the near term, use of processing wastes is the most promising opportunity. United States industries have extensive experience in this area and could provide assistance and exports to developing-country industries. In the future, briquetting field residues, managing existing forest resources better, and growing crops dedicated to energy hold out the possibility of resource expansion. The United States already encourages developing countries to pursue these strategies through the Agency for International Development, the Department of Energy, the Peace Corps, and other bilateral aid programs. All of these strategies must be planned, however, with the larger developmental context in mind. Larger issues of deforestation, land ownership, rural development, and food production need to be considered in allocating project funds.